DISSERTATION

Titel der Dissertation

Investigating the role of humans as (dis)connecting agents in fluvial systems - new concepts and applications for fluvial geomorphology and landscape research

Verfasser

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Overview of the scientific approach and structure of this thesis

This chapter introduces the epistemological background of this thesis and provides an overview of how the thesis is structured. The aim of the chapter is to equip the reader with necessary background information that guides him/her through the layout and content of the thesis.

Epistemology

The present thesis is rooted in the theory of critical realism which is based on the following assumptions (Rhoads and Thorne 1994): reality exists independently of human thought; the methods of science prove a means for determining the approximate truth of all aspects of scientific theories (including statements about unobservables); the progress of science consists of the development of successive theories that become more truth-like over time – current theories are approximately true and are the foundation for scientific progress; all aspects of scientific inquiry are theory laden.

Structure of the thesis

This thesis is a cumulative dissertation which unites own work that has been published in international peer-reviewed journal articles. It consists of a monographic part in which the contents of the journal articles are scientifically synthesized and the published or submitted articles in the appendix (A. Articles). The structure of this thesis implies that not all details have been presented in the monographic part, but clear reference is given to the respective articles in which extensive information is available. Although the articles were developed by several authors, the monographic part was solely written by the author of this thesis. Contents of the articles have been rewritten and presented in the monographic part to meet the structure of the present thesis. Clear reference is given to the respective article the contents were taken from and the contributions of each author to the respective article publication are indicated separately ahead of each article in the appendix.

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1. Human impacts on fluvial systems and why to study connectivity?

Human settlements have been established adjacent to water sources, especially rivers, as these areas had preferred terrain and soils favourable for agricultural development and were located along trade routes (Brierley and Fryirs 2005). The risks associated with living in these areas due to fluvial processes such as floods and erosion has meant that human have sought to control and stabilize rivers to reduce these risks. The intensity of human modifications has especially pronounced over the past 100 - 500 years with the gaining development of land and water resources (Petts 1989). In terms of changing flow and sediment regime of rivers, dam installations as well as changes of land use and land cover are often regarded as being the most dominant forms of human impact on fluvial systems. Evidence of human activity in river catchments can be traced back over thousands of years to the early phases of valley floor sedimentation and have been associated with periods of forest clearance and agricultural expansion (Charlton 2008). Many forest regions in Europe have been cleared for cultivation since 8,000 years. According to Dynesius and Nilsson (1994), 77 percent of the 139 largest river systems in North America, Europe and in the republics of the former Soviet Union are impacted by humans through the construction of dams, reservoir operation, inter-basin diversions, and water extraction for irrigation. There are currently approximately 7,000 large dams in Europe (EEA 2009) and approximately 8,100 in the United States (PCFFA 2012), not including the much higher number of small ones.

Human impacts can be identified as being direct and indirect (Park 1977, 1981). Direct human impacts take place in the river channel due to direct removal/addition of sediments or by hindering or forcing the movement of water and sediments (Poeppl et al. 2012a, A.1). These are modifications made to the channel bed and/or banks due to resource development activities such as water supply, power generation, gravel extraction or structural engineering works to mitigate unintended fluvio-geomorphic effects (e.g. flooding, channel bed incision; Brierley and Fryirs 2005). Indirect human impacts occur in the catchment apart from the river channels themselves but also modify discharge and sediment load of the river (Poeppl et al. 2012a, A.1). These include land use changes, the alteration of vegetation cover or groundwater withdrawals. Most direct modifications are intended, while indirect modifications are often done inadvertent (Brierley and Fryirs 2005).

The motivations for studying human impacts on fluvial systems are manifold. According to James and Marcus (2006) these include documentation, inventory, and explanation of change as well as the need to reduce the destructive influences of humans on nature. Nowadays, reasons for investigating human impacts on rivers are also governed by concerns over future environmental change, institutional needs, and a growing desire to restore the natural functionality of streams (James and Marcus 2006). These rationales reflect the challenges of river management in "trying to understand and predict future response of rivers in order to stabilize and maintain present river environments or to develop adaptive policies in response to these changes" (James and Marcus 2006, p. 158). This also includes the consideration of direct and indirect human-induced channel changes on different spatial and temporal scales, and the effects of human-induced global change. Furthermore, studying the role of humans in altering fluvial systems is driven by the need to predict and mitigate geomorphic hazards in order to protect human property and lives.

One of the first investigations on the impact of humans on river morphology was performed by Lawson (1925) who dealt with the effects of Rio Grande Dam storage on river erosion and deposition. The investigative work of Lane (1955), 30 years later, highlighted the importance of fluvial geomorphology in hydraulic engineering. Lane already addressed geomorphic channel responses ('types of channel change') related to the presence of dams and their implications for river engineering. Strahler (1956) identified that human-induced gullying or channel extension upstream complemented by aggradation downstream resulted from changing land use over time. Wolman (1967) and Leopold (1972) related channel condition to building activity and urbanization. The notion of river metamorphosis and the importance of thresholds for geomorphic response (Schumm 1969) and the application of a rate law (Graf 1977) involving reaction- and relaxation-times as parts of the response time were further crucial steps to better understand geomorphic response to human disturbances. An overview on the hitherto outlined key models interpreting human impact on river channels is presented in Table 1:

Table 1: Some key models interpreting human impact on river channels (Source: Gregory 2006, p. 173)

Contribution	**Implementation**	**Source**
Types of channel change	QsD ≈ QwS involving bed material load (Qs), particle diameter (D), water discharge (Qw) and stream slope (S) used to indicate implications of different types of channel change	Lane (1955)
Induced aggradation	Gullying or channel extension upstream complemented by aggradation downstream due to land use change over time	Strahler (1956)
Cycle of erosion in urban channels	Changing channel morphology depicted during land use change from forest through agricultural land to urbanisation	Wolman (1967)
River metamorphosis, thresholds and complex response	Effects of changing discharge and sediment load on channel morphology indicated by equalities such as: Qs +,Qw ++ ≈ S−, d50+,D+,W+, using equality to relate sediment (Qs) and water	Schumm (1969)

	discharge (Qw) to slope (S), median diameter of bed material (d50), flow depth (D) and flow width (W)	
Rate law	Change from one equilibrium to another through a response time and a reaction time	Graf (1977)

Since the beginnings in the 1950s, the foci of geomorphological research on human impacts on fluvial systems can be summarized as follows: channel changes, scales of observation, integrated watershed analysis, and climate change (James and Marcus 2006). Since 1977, research on the fluvio-geomorphic consequences of human activities has been further elaborated and various categories of human influence have been considered on different perspectives (Gregory 2006) using different methods of analysis. Several different methods of assessing geomorphic response to human interventions exist, ranging from field-based approaches to historical records, remote sensing and computer simulation. A historical overview of these methods summarized from James and Marcus (2006) and Charlton (2008) is given below.

Field-based approaches. Approaches to collect field data such as the use of coring and erosion pins enhanced by new data collection technologies for field, laboratory and analytical methods; repeat measurements and continuous monitoring of flow and sediment transport, channel form and erosion rates; analyzing fluvial records such as sediments which are stored on floodplains, terraces and palaeochannels as well as palaeosoils to interpret past channel behavior and channel changes; relative dating derived from stratigraphy or absolute dates derived from dendrochronology, varves or long-term written records; dating methods using ^{14}C and additional isotopes like ^{137}Cs and ^{210}Pb to date stratigraphy, identifying sources of water and sediment (fingerprinting) and constraining environmental changes; optical simulated luminescence dating (OSL) and cosmogenic exposure age dating for dating Holocene sediments. (James and Marcus 2006, p. 162)

Historical records and remote sensing. Information about past channel changes obtained via documents, survey notes, maps, newspaper reports, personal accounts, flood marks, and photographs; assessing changes using aerial photography and satellite remote sensing; airborne and terrestrial light detection and ranging (LiDAR) used to create digital elevation models (DEM) for highly complex spatio-temporally analyses in GIS environments; ground penetrating radar (GPR) and acoustic doppler current profilers for detailed mapping of topography with radar and measurements of key hydraulic parameters. (James and Marcus 2006, p. 162)

Computer simulation. Numerical models and automated simulations of physical systems to interpret the complexity of change; on the reach scale, computational fluid dynamics models (CFD) are widely utilized to simulate fluvial processes for short time periods; cellular models are applied to simulate the transfer of water and sediment between cells using simple rules that are based on the underlying physics that govern these processes (Nicholas 2005); landscape evolution models used to model the geomorphic development of drainage basins over thousands and millions of years applied to simulate geomorphic response to external changes such as human activity and climate. (Charlton 2008, p. 166-167)

Investigations of human-induced changes in fluvial systems can be based on looking on connectivity relationships examining the linkages between the different system compartments in a geomorphological context, but also by observing interrelationships between the human system and the fluvial system in the context of landscape research. Both perspectives are considered in this thesis. In the following chapters (1.1 and 1.2), a brief historical overview on the history of connectivity approaches in geomorphology and landscape research as well as definitions will be presented and the importance of connectivity research will be discussed. Furthermore, research gaps will be identified and the chapter closes with the formulation of the hypotheses and the related objectives and research questions which direct the further course of this study.

1.1 Connectivity in geomorphology

An early consideration of connectivity in a geomorphological context can be found in the Systems Approach of Chorley and Kennedy (1971) where connectivity is implicitly defined as the transfer of energy and matter between two landscape compartments or within a system as a whole. Another precursor of present connectivity concepts in geomorphology is the coupling concept which was introduced by Brunsden and Thornes (1979), Brunsden (1993, 2001) and extended by Harvey (1997, 2002) to explain landscape sensitivity and geomorphic change (see also chapter 2.1.1). Brunsden and Thornes (1979) stated that landscape sensitivity is mainly controlled by the capacity of the various components of the landscape to transmit an impulse, while this capacity is dependent on the path density of the process and the strength of the coupling between the system components.

Connectivity can generally be divided in structural and functional connectivity. Structural connectivity refers to the extent to which landscape units are contiguous or physically linked to one another (With et al. 1997, Tischendorf and Fahrig 2000, Turnbull et al. 2008). Functional connectivity accounts for the way in which interactions between structural characteristics of the system affect geomorphic, ecologic and hydrological processes (Kimberly et al. 1997, With and King 1997, With et al. 1997, Belisle 2005, Uezu et al. 2005, Turnbull et al. 2008). Croke et al. (2005) further distinguish between two other types of connectivity: direct connectivity via new channels and diffuse connectivity where surface runoff and transported sediments reach the stream network via overland flow pathways.

Concepts that deal with connectivity are increasingly applied within a range of disciplines in Earth and Environmental Sciences. Considering hydrology and geomorphology, Bracken and Croke (2007) classified three major types of connectivity: 1) landscape connectivity, which relates to the physical coupling of landforms (e.g. hillslope-channel coupling); 2) hydrological connectivity, which refers to the transfer of water from one part of the landscape to another; 3) sediment(ological) connectivity, which relates to the physical transfer of sediments and attached pollutants. Sediment connectivity as a concept was already implicit in empirical approaches dealing with "sediment delivery ratios" which assumes the physical transfer of sediments from the catchment area to the channel system (Bracken and Croke 2007). In terms of sediments, recent geomorphological studies adopted the concept of connectivity to describe the "transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system" (Hooke 2003, p. 79). Concepts of sediment connectivity are often used to describe the linkages between the sediment source areas and the corresponding sinks within a catchment (Croke et al. 2005). Connectivity assessments are therefore an important tool to estimate sediment conveyance and propagation through a system. As explained by Harvey (2002), sediment connectivity between system compartments occurs at a range of spatial scales and system compartments are said to be connected (coupled) or disconnected (decoupled) over differing timescales. Since landscape sensitivity is mainly controlled by the capacity of the various components of the landscape to transmit an impulse, an effective description and explanation of sediment connectivity conditions in fluvial systems provides a basis to identify transmission linkages and coupling efficiency and therefore sensitive parts of the landscape (Brunsden 2001, Brierley et al. 2006). Therefore, studying sediment connectivity in geomorphic systems offers the opportunity to improve our understanding of how physical linkages govern geomorphic processes (Van Oost et al. 2000, Wainwright et al. 2011). It is further stated by Lexartza-Artza and Wainwright (2011, p. 1090) that "connectivity will reflect the interactions and feedbacks of the different catchment components under changing conditions (Beuselinck et al. 2000) and will determine the propagation of the effects of the changes (Harvey 2007) as flow pathways are modified and the structure of the landscape is transformed." Connectivity assessments can thus be further used to predict geomorphic responses to external forcing and evaluating trajectories of future geomorphic change determined by the propagation of these effects (Harvey 2007). Therefore, connectivity is seen as a key determinant of the influence and persistence of impacts upon geomorphic river condition for any given site (Brierley et al. 2010). However, geomorphic response to human disturbance is often difficult to predict due to inherent complexity in fluvial systems which is generally related to self-regulatory system properties and time-dependent changes that progressively alter the balances between forces and resistances (Brunsden 2002). Nevertheless, self-regulatory system properties are of high relevance when it comes to estimate geomorphic response of fluvial systems to disturbance and system recovery.

Connectivity in fluvial systems generally operates in longitudinal, lateral, and vertical dimensions and over time (Ward 1989, Brierley et al. 2006, Fryirs et al. 2007a) and is mainly governed by the magnitude of flow events (Brunsden and Thornes 1979, Harvey 2002, Brierley et al. 2006, Wainwright et al. 2011). According to Brierley et al. (2006) longitudinal linkages such as upstream-downstream and tributary- main-channel relationships drive the transfer of flow and sediments through the system, while lateral linkages describe channel-floodplain and slope-channel relationships that govern the supply of materials from the catchments to the channels. Vertical linkages refer to surface-subsurface interactions of water, sediment and nutrients. Various types of landforms, i.e. buffers, barriers, blankets and boosters have been recognized to disrupt or enhance longitudinal, lateral and vertical linkages (Brierley et al. 2006). Besides different landforms, direct as well as human interventions can also disrupt or enhance connectivity (Poeppl et al. 2012a, A.1). Nowadays, most fluvial systems have been affected by human impacts such as dam installations or land use changes which can both alter flow and sediment dynamics (e.g. Kondolf et al. 2006) and pathways (Michaelides and Chappell 2009) of fluvial systems.

Although human impact on connectivity relationships in fluvial systems and the related fluvio-geomorphic consequences are considerable, no conceptual model has yet focused on the role of humans as (dis)connectors in fluvial systems further linking concepts of sediment connectivity to principles of geomorphic channel processes. The review presented above led to the identification of the *first research gap* that identifies the lack of a conceptual foundation from which the influence of human activity on sediment connectivity in fluvial systems is studied. The gap extends further with the relating of human-induced changes of sediment connectivity to fluvio-geomorphic consequences also including the importance of self-regulatory system properties for fluvio-geomorphic response. The identified research gap also involves the need to use case study derived knowledge to compare and understand the processes and factors involved in governing sediment connectivity.

Sediment connectivity is further governed by frequency and magnitude characteristics of sediment transport processes (Wolman and Miller 1960) and the temporal evolution of vegetation cover, land use and management in the catchments (Borselli et al. 2008; Poeppl et al. 2012b, A.2). Vegetation cover is most susceptible to human alterations (Brooks and Brierley 1997) and therefore land use and vegetation cover is one of the primary internal factors that govern sediment supply to a river while influencing rates of erosion and sediment delivery ratios (Poeppl et al. 2012b, A.2). In this respect, also riparian vegetation cover plays an important role in the capability of a riparian zone to buffer the sediment fluxes from the catchment areas to the channel network (i.e. lateral buffering) which highly depends on its vegetation cover. Moreover, biogeomorphic processes related to interactions between riparian vegetation and geomorphic processes have been reported to result in significant lateral buffering due to induced sediment trapping processes (Dabney et al. 1995, Meyer et al. 1995, Leguédois et al. 2008, Keesstra 2007, Keesstra et al. 2009a; Poeppl et al. 2012b, A.2). However, the role of riparian vegetation was not integrated in connectivity concepts and only rarely assessed in the context of sediment connectivity so far. Therefore, knowledge about the effects of riparian vegetation on lateral sediment connectivity and the factors and processes that govern them is rare and presents the *second important research gap.*

1.2 Connectivity between humans and the landscape: Human-landscape interactions and landscape change

The meaning of connectivity has been further extended to a broader geographical context by Brierley et al. (2006, p. 165) also including the human system while recognizing the "need to appraise notions of connectivity, whether considered in terms of human-human interactions, human-landscape interactions, or interactions within the landscape itself […] to predict social, economic, climatic or environmental futures." Both, human systems and landscape systems consist of many parts and many connections between these parts exist. Human-landscape connectivity is defined by the existence of interactions between parts of the human system and the landscape system. Since human impacts have substantial effects on landscape change, a focus on human-landscape interactions and feedbacks is recognized as being essential in steering landscape evolution and the response to changing conditions (Murray et al. 2009). As geomorphology is incorporating ever more interdisciplinary research, also recognizing the integral couplings in landscape-forming processes between hydrology, geology, biology, human dynamics, geochemistry, and biochemistry it is poised to play a key role in a new Earth-surface science (Murray et al. 2009).

"Landscape" is a topic of interest for many disciplines and therefore landscape is conceptualized and defined in many ways. At least two different landscape discourses are contrasted in Geography, an "ecological" and a "semiotic" one (Cosgrove 2003). The ecological discourse deals with interactions of natural processes including humans through their interaction with these processes. The semiotic discourse focuses on cultural meanings of landscape and on how these create landscape through perception and representation (Potthoff 2007). Ecological landscape approaches regard landscape as a system that is organized hierarchically (e.g. Forman and Gordon 1986, Leser 1991, Zonneveld 1995, Farina 2000, Burel and Baudry 2003). In ecological landscape approaches human beings can play an important role, but are only one factor in the system, while more "holistic" landscape approaches incorporate humans and natural features into a system of interacting processes (e.g. Naveh 1994, Bastian 2001, Tress and Tress 2001) (Potthoff 2007). One of the first definitions of "landscape" in a geographical context has been given by Alexander von Humboldt who defined "Landschaft" very generally as the "Totalcharakter einer Erdgegend" (Humboldt 1845-1862; i.e. "the total character of a region of the Earth" which includes landforms, vegetation, fields and buildings). Consistent with Humboldt's meaning of "landscape", Slaymaker et al. (2009, p. 1) proposed a definition of landscape as being "an intermediate scale region comprising landforms and landform assemblages, ecosystems and anthropogenically modified land". The landscape definition of Slaymaker et al. (2009) is used in the present thesis.

The impacts of humans on landscape systems is greater now than ever before and landscape modifications exceed natural processes (for global perspective Hooke 2000, Wilkinson and McElroy 2006, for a local and regional perspective Keiler 2004, Keiler et al. 2006; Poeppl et al. 2012c, A.3). Furthermore, geomorphic response of fluvial systems to human impacts is complex in space and time (Petts and Gurnell 2005) and unintended geomorphic consequences such as channel degradation downstream of dams require repeated intervention by river engineering structures such as canalizations and river bed and bank protection (Gregory 2006; Poeppl et al. 2012c, A.3). In turn, these interventions often induce further geomorphic effects (Schumm 2005) and the chain of interactions between the human system and the fluvial system could lead to undesirable feedbacks (Poeppl et al. 2012c, A.3). Existing approaches to analyse the drivers of landscape change have been criticized for being too simplistic (e.g. Leach and Mearns 1996, Lambin et al. 2001, Geist and Lambin 2002) and it is argued that they must be rather matched by enhanced understanding of the causes of change (Committee in Global Change Research 1999) (Poeppl et al. 2012c, A.3). It has further been noted that human activities and landscape change should be viewed together as a co-evolutionary and adaptive process (Holling 2001, Lenton et al. 2004; Poeppl et al. 2012c, A.3). However, research questions on the interlinkages between fluvial systems and human systems have not sufficiently been studied thus far (Gregory 2006, James and Marcus 2006) and as social and natural processes are often driven by system interactions, system behaviour cannot be understood by analysing system components in isolation (Bennett and McGinnis 2007; Poeppl et al. 2012c, A.3). Therefore, concepts and approaches which focus on the connectivity between the human and the landscape system in terms of human-landscape interactions are needed to delineate potential reasons of landscape change (Poeppl et al. 2012c, A.3). However, concepts and approaches which focus on interactions and feedbacks between the human and the fluvial system unravelling reasons for landscape change are still lacking which introduces the *third important research gap*.

Based on the outlined considerations and identified research gaps, the following main hypotheses and related research questions have been formulated:

I) Linking concepts of sediment connectivity to principles of channel processes contributes to a better understanding of geomorphic channel response to dam construction and changes of land use and land cover

Ia) How do different types of human impact on fluvial systems potentially influence the lateral, longitudinal and vertical dimensions of sediment connectivity and how can sediment connectivity be linked to geomorphic channel processes?

Ib) What role do self-regulatory system properties play in the recovery of sediment connectivity in fluvial systems and what are the driving factors of change?

Ic) How do dams and land use changes affect sediment connectivity in fluvial systems and what are the associated geomorphic channel changes?

Two objectives issue from hypothesis I:

1) To develop a conceptual model that links human-induced sediment connectivity changes in fluvial systems with geomorphic channel processes
2) To test the various model assumptions by performing and evaluating case studies in small fluvial systems that are affected by dams and land use/land cover changes

II) Lateral buffering is strongly influenced by riparian vegetation cover type and biogeomorphic processes

Ad II) Which factors and processes govern lateral sediment connectivity and how do different types of riparian vegetation cover affect lateral buffering?

Two objectives originate from hypothesis II:

1) To develop a conceptual model by considering the processes and factors that govern lateral sediment connectivity and buffering in an agricultural catchment with special focus on the influence of riparian vegetation cover
2) To test the model assumptions by performing a case study in a small agricultural catchment

III) Dam construction induces geomorphic channel changes that trigger a series of process-response feedback loops between the human and the fluvial system

IIIa) How does the fluvial system respond geomorphically to the installation of dams?

IIIb) How does the human system respond to dam-induced geomorphic channel changes?

IIIc) Which geomorphic processes result from dam-induced human responses and how does the human system respond to these processes?

IIId) How do dam-induced process-response feedback loops between the human system and the fluvial system change the landscape metrics in the fluvial environment and can changes in landscape metrics be used as indicators for human-landscape interactions?

Two objectives issue from hypothesis III:

1) To develop a model that conceptualises dam-induced connectivity between the fluvial system and the human system and to identify possible implications for landscape change in fluvial environments
2) To test the model assumptions by undertaking a case study in a small dam-impacted fluvial system

2. Connectivity in geomorphology

In this chapter, three existing connectivity concepts in geomorphology are presented (chapter 2.1) since they are seen as important precursors for the conceptual models developed in this thesis. Although the coupling concept of Brunsden and Thornes (1979) does not explicitly refer to the term "connectivity", their work will be presented as the basic model assumptions are comparable with those made in connectivity concepts (chapter 2.1.1). Furthermore, factors that influence connectivity in fluvial systems (chapter 2.2) as well as existing methods and approaches used to investigate connectivity in fluvial systems are reviewed (chapter 2.3).

2.1 Existing connectivity concepts in geomorphology

2.1.1 The coupling concept (Brunsden and Thornes 1979; Brunsden 1993, 2001)

The importance of coupling in a geomorphological context has been introduced by Brunsden and Thornes (1979) within their sensitivity concept. They stated that "[landscape] sensitivity [and geomorphic change] is dependent on the path density of the process and the strength of the coupling between the system components and has two end members, mobile-sensitive systems and slowly responding-insensitive areas." (Brunsden and Thornes 1979, p. 463) If path density is high (e.g. high drainage density) then geomorphic effects are quickly and ubiquitously propagated in all directions. Furthermore, the strength of coupling determines the linear or diffuse propagation of responses which can be damped, sustained or reinforced (Brunsden and Thornes 1979). In his later work, Brunsden (1993, 2001) differentiated between different types of system resistance to disturbance also including structural resistance. He stated that the structure of a system is determined by strength and direction of the relationships between the components and process domains which is known as coupling and takes place at important junctions, joints and boundaries. Brunsden (1993) pays attention to the functions of each domain, the nature of the links between them and any changes in the behavior that take place across the boundary. He further describes 'couples' as "the gear boxes, transmission links and shock absorbers of the system" (Brunsden 1993, p. 9) and differentiates between the following types of linkages (Brunsden 1993, 2001):

1) Coupled: occurs at a boundary or link at which there is a free transmission of energy, material and messages of an impulse of change (e.g. a river channel directly undercutting a hillslope; see Fig. 1, left)

2) Not coupled: a discontinuity between two systems or process domains is present (e.g. a sea cliff cutting back into an ancient plateau surface)
3) Decoupled: a temporary inactive linkage due to a barrier that has been imposed (e.g. a river channel becomes decoupled from a hillslope as a result of floodplain growth; see Fig. 1, right)

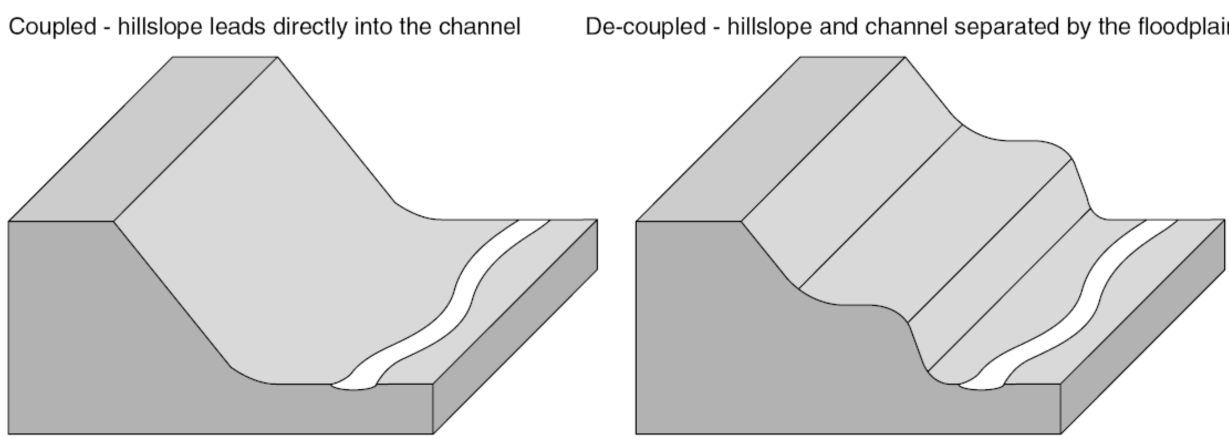


Fig. 1: Hypothetical model to illustrate simple hillslope-channel (de)coupling (Source: Bracken and Croke 2007, p. 1750; adapted from Michaelides and Wainwright 2002)

The coupling concept of Brunsden and Thornes (1979) has been further elaborated by Harvey (2002). Harvey (2002, p. 175) pointed out that "coupling behavior conditions how the system responds to disturbance, and is therefore important in determining geomorphic response to human-induced, climatically-induced or tectonically-induced environmental change." Moreover, Harvey (2002) addressed spatial and temporal aspects in the context of coupling. Effective temporal scales are mainly related to frequency and magnitude characteristics, recovery time and propagation time, while coupling mechanisms in fluvial systems can be viewed at several spatial scales: local scale (e.g. within-hillslope coupling, hillslope-to-channel coupling and within channels i.e. tributary junction and reach-to-reach coupling), zonal coupling (coupling between major zones of the system) and regional coupling (Harvey 2002).

2.1.2 Forms of landscape connectivity (Brierley et al. 2006)

Brierley et al. (2006, p. 166) recognized the understanding of connectivity between landscape compartments to be "pivotal in explaining spatial relationships, the behavior of biophysical fluxes and associated trajectories of adjustment." Referring to Brunsden and Thornes (1979) Brierley et al. (2006) also considered connectivity to be of great importance in the context of landscape history and landscape sensitivity. Brierley et al. (2006) developed a concept considering differing forms and scales of landscape (dis)connectivity. According to a model developed by Ward (1989), which describes linkages in lotic ecosystems, Brierley et al. (2006) delineated different spatial dimensions of connectivity between landscape compartments: longitudinal, lateral and vertical (see chapter 1.1). Brierley et al. (2006) further presented a scalar approach to assess landscape connectivity in which process-understanding of individual landforms is related to the connectivity between landscape compartments intended "to ground the application of modelling techniques in analysis of catchment-scale biophysical fluxes" (Brierley et al. 2006, p. 165) (see Fig. 2). Connectivity has been integrated at the subcatchment and catchment scales: within-compartment scale relates to biophysical fluxes on hillslopes (i.e. the catena compartment) and valley floors (i.e. the alluvial compartment), on a landform-scale and to surface-subsurface interactions. Between-compartment connectivity examines hillslope-valley floor, channel-floodplain, upstream-downstream and tributary-trunk stream linkages in land systems and land system assemblages that make up subcatchments (Brierley et al. 2006).

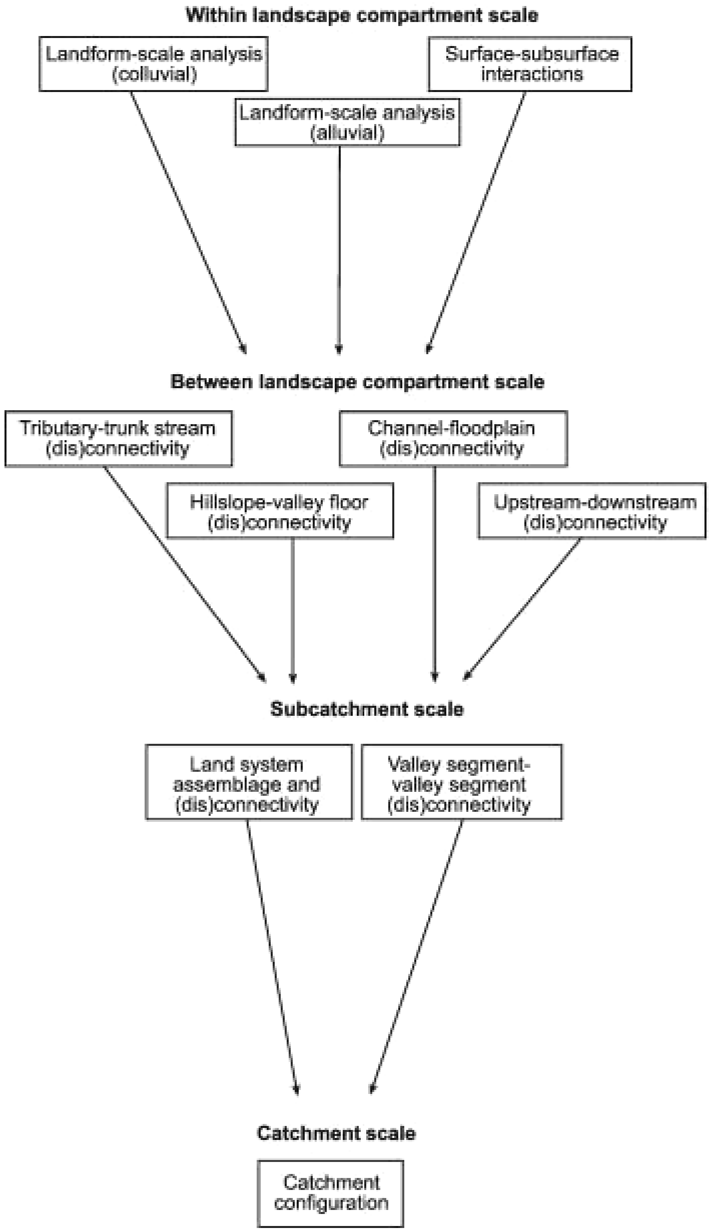


Fig. 2: Scalar approach to assess landscape connectivity (Source: Brierley et al. 2006, p. 170)

2.1.3 Landform impediments in landscape connectivity (Fryirs et al. 2007a)

This concept emphasizes the importance of landforms as (dis)connectors in longitudinal, lateral and vertical dimension influencing sediment cascades within a system by the attenuation of sediment conveyance. These landforms are described as buffers, barriers and blankets (Fryirs et al. 2007a): buffers are defined as landforms that prevent sediment from entering the channels (e.g. alluvial fans or piedmont zones), while barriers are features that disrupt sediment movement along the channel (e.g. bedrock steps, sediment slugs), and blankets are regarded as landforms that smother others by protecting those from reworking (e.g. bed armoring, floodplain sand sheets). On the contrary, channel reaches such as gorges may enhance propagation, acting as boosters for sediment conveyance (Fryirs et al. 2007a). Similarly to Brierley et al. (2006), these various forms of (dis)connectivity are further considered within a nested hierarchy at local, zonal and system scales (Fryirs et al. 2007a following Harvey 2002). Local scale refers to the (dis)connectivity within a system compartment or landform phenomenon (e.g. within-hillslope connectivity), while at the zonal scale (dis)connectivity occurs between system compartments or landforms (e.g. hillslope-channel connectivity). At the system scale, the behavior of whole catchments is observed in the context of (dis)connectivity. Buffers, barriers and blankets are viewed to disconnect areas of a catchment from the primary sediment conveyor belt which influences the 'effective catchment area'. The effective catchment area which reflects the degree of longitudinal, lateral and vertical connectivity in a catchment provides a measure for the contributing area for sediment. The size of the effective catchment area further depends on the frequency-magnitude characteristics of perturbations required to breach sediment impediments and the propagation time for change to be manifest in the system (c.f. Harvey 2002) which Fryirs et al. (2007a) call the 'effective timescales'. In Fig. 3 increasing landscape connectivity and effective catchment area through breaching of landform impediments are considered as a series of switches determining which part of the landscape contribute to the sedimentary cascade over different time intervals (Fryirs et al. 2007a). Related notions of effective catchment area and effective timescales of (dis) connectivity are appraised by Fryirs et al. (2007a, p. 51) as important tools "to interpret sediment budgets, landscape sensitivity and river recovery."

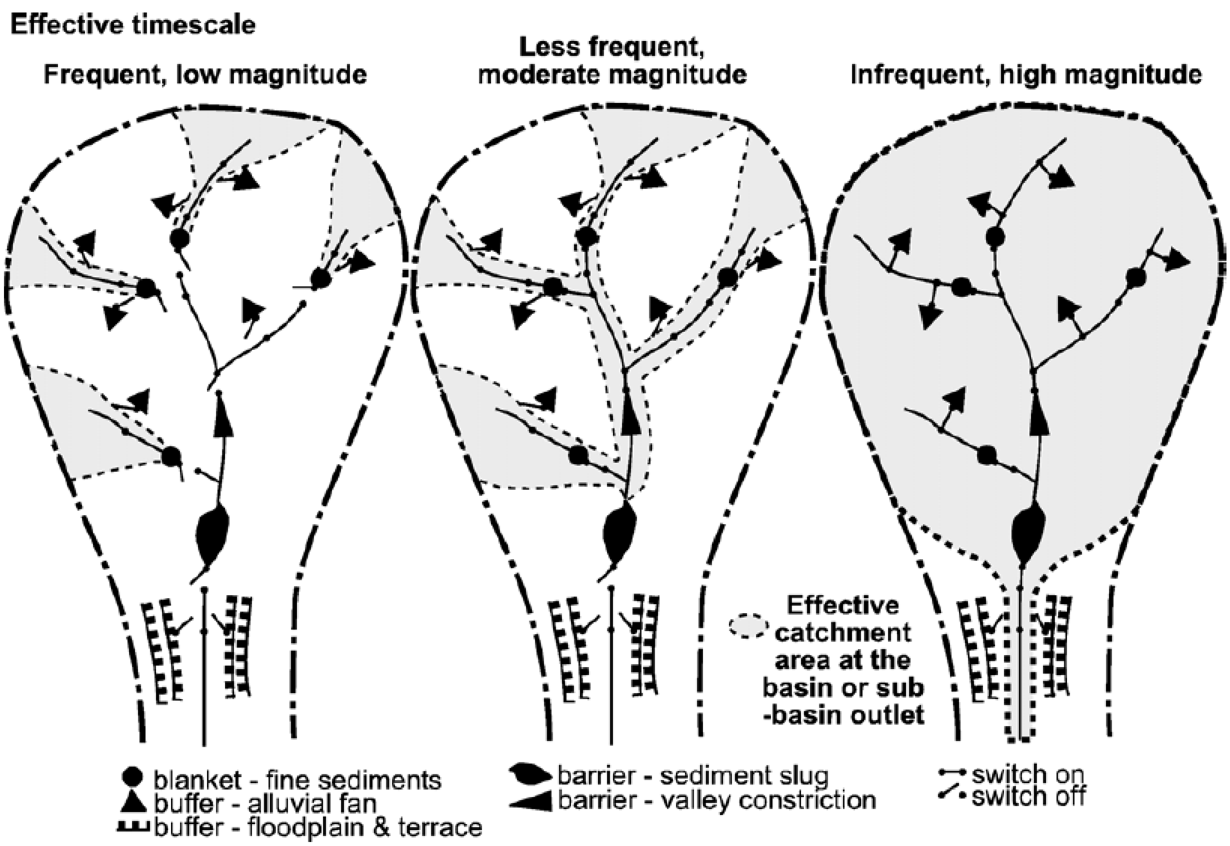


Fig. 3: (Dis)connectivity in catchments (Source: Fryirs et al. 2007a). "The effective catchment area is defined as the spatial area which directly contributes to, or transports sediment along the fluvial network. The effective timescale is expressed as the magnitude of event required to breach buffers, barriers or blankets or the residence time of sediment stores and sinks. It reflects the timeframe over which (dis)connectivity occurs. The effective catchment area increases as the magnitude of the event required to breach buffers, barriers and blankets increases. This is analogous to switching on and off certain parts of catchments over certain timeframes." (Fryirs et al. 2007a, p. 55)

2.2 Factors that influence sediment connectivity

Overland flow is the basic requirement for sediment connectivity (e.g. Poeppl et al. 2012b, A.2). Overland flow processes are governed by a range of factors that determine runon and runoff in a fluvial system. In the paragraphs to follow, the most important components influencing overland flow and hence sediment connectivity will be presented. Major parts are summarized from the work undertaken by Bracken and Croke (2007) who conducted an extensive review on factors governing hydrological connectivity to understand runoff-dominated geomorphic systems.

Climatic environment. Climate is a key control on the distribution and pattern of runoff. Runoff in humid-temperate regions is mainly composed of saturation overland flow, whereas Hortonian overland flow dominates in semi-arid and arid regions. In humid climates, antecedent wetness conditions are important and during a rainfall event wet area expansion and the connectivity of runoff can be relatively easy achieved. Conversely, in semi-arid and arid environments, no areas of saturation are present and hence quick runoff does not occur, because rainfall events are infrequent and of short duration. As rainfall intensity and duration are of major importance for flood generation in all catchment sizes (Costa 1987, Schick 1988, Pitlick 1994), these factors are crucial to producing connectivity. (Source: Bracken and Croke 2007, p. 1752-1753)

Hillslope runoff potential. Many factors have been identified to influence hillslope runoff, including crusting and surface roughness (Auzet et al. 1993, Helming et al. 1998, Singer and Le Bissonnais 1998), heterogeneity within the soil (Fitzjohn et al. 1998), the impact of density and type of vegetation (Imeson et al. 1992, Bergkamp et al. 1996), catchment morphometry and transmission losses in river channels (Reid and Frostick 1997) and the impact of land use (Bull et al. 2000, Lasanta et al. 2000). Infiltration and transmission losses are both factors that are strongly influenced by gradient (Poesen 1984, Govers 1991, Kirkby et al. 2002) and further determine the runoff pathways and connectivity in a catchment. Infiltration can be significantly decreased by crusting which further prevents soil erosion. Spatio-temporal variations of connectivity are strongly influenced by antecedent conditions that determine soil moisture. As soil moisture increases the likelihood of runoff, connectivity increases (Fitzjohn et al. 1998). Runoff is further influenced by surface roughness conditions. With respect to form roughness for example plough lines can channel flow in certain directions (Govers et al. 2000, Kirkby et al. 2002). Conversely, in terms of hydraulic roughness, individual stones and soil aggregates larger than the flow depth can significantly reduce runon velocity. Vegetation is related to all the factors mentioned above and is a major influence on hydrological connectivity at all scales. Vegetation increases soil infiltration capacity by increasing organic matter, lowering bulk density (Thornes 1976, Boix-Fayos et al. 1998, Wilcox et al. 1998) and increasing hydraulic conductivity (Nicolau et al. 1996). Moreover, vegetation reduces rain-splash and crusting, but increases surface roughness and ponding. Land management practices influence runoff response and the spatial integration of source areas at all scales of the landscape and is therefore a key factor for connectivity. Furthermore, the temporal and spatial variability of factors affecting connectivity is important such as the frequency and magnitude of storm events and seasonal differences in vegetation cover. (Source: Bracken and Croke 2007, p. 1754-1756)

Landscape position. Landscape position reflects the relationship between runoff source and distance to the outlet at all scales with the probability of hydrological connectivity generally decreasing with transport distance. At the hillslope and catchment scale, slope length strongly influences connectivity. However, relationship between slope length and rainfall duration and intensity are complicated due to factors such as infiltration capacities, vegetation cover and land management. (Source: Bracken and Croke 2007, p. 1756)

Delivery pathway. Generally, flow pathways can be described as incisional (e.g. rills, gullies and river channels) and dispersive. Controls on the type of flow pathway include factors such as topography (e.g. landforms) but also effects of anthropogenic structures (e.g. roads, tracks, ditches) that collect and guide flow and sediment. (Bracken and Croke 2007, p. 1756)

Lateral buffering. This term refers to factors that limit the transfer of flow, organic matter and sediments from the hillslopes to the river channels. These factors include runoff magnitude but also the presence of wetlands and/or extensive riparian vegetation that potentially act to limit runoff and sediment connectivity to the channel networks. (Source: Bracken and Croke 2007, p. 1757) Furthermore, depositional features can emerge from biogeomorphic processes due to interactions between vegetation and sediment flow, further acting as lateral buffers for flow, organic matter and sediment from the hillslopes to the river channels (e.g. Leguédois et al. 2008; Poeppl et al. 2012b, A.2). Components that influence sediment connectivity are illustrated in Fig. 4, while a general overview of factors that potentially affect connectivity is presented in Table 2.

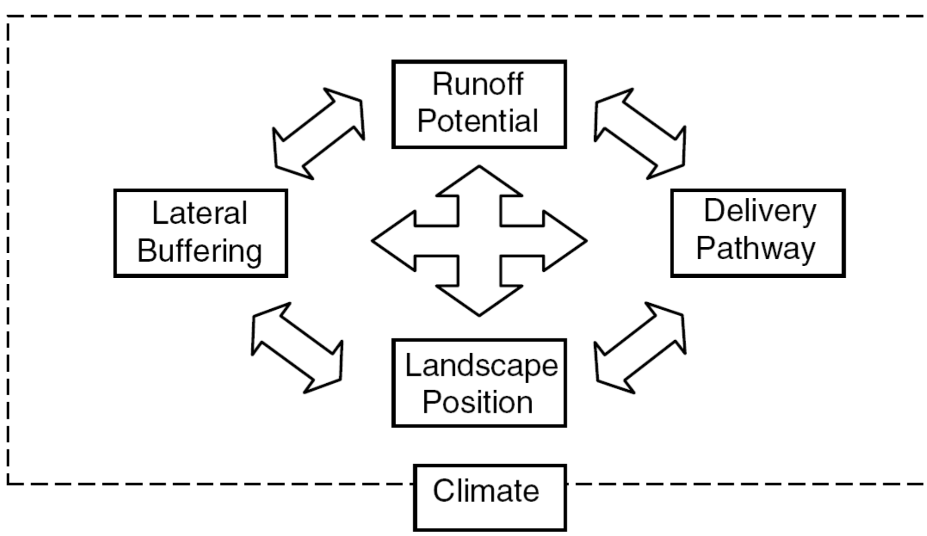


Fig. 4: Components of sediment connectivity (Source: Bracken and Croke 2007, p. 1752)

Table 2: Factors that potentially affect connectivity. Adapted from Lexartza and Wainwright (2009, p. 150) who proposed a guideline list of aspects to look for context-specific connectivity in a system of study.

Physical characteristics
Topography: relief and slope
Surface roughness
Landforms
Soil
Soil type, size and structure
Porosity and permeability
Distribution
Connectivity enhancing/accelerating features
e.g. wheelings, roads/tracks, tills, ditches, field drains, scars etc.
Connectivity limiting/delaying features
e.g. buffer strips, floodplains, ponds, woodland, field boundaries, depositional features
Land cover
Spatial distribution, seasonal changes, long-term changes
Land use
Spatial distribution, changes over time
Evident management
Features created/introduced/modified by management including those related with measures and policies
Rainfall (incl. snow)
Precipitation, distribution of rainfall
Stage
Stage of streams in the catchment
Flow management
Details on flow management such as timing and effect of dams, managed releases etc.
Implementation of measures/policies
Development of measures/policies
Runoff
Runoff discharge and distribution
Pathways
Dominant and secondary pathways (surficial and subsurface), distribution, changes in pathways and in relevance of pathways
Soil moisture
Soil moisture across the catchment

2.3 Assessing connectivity in fluvial systems: existing methods and approaches

The spectrum of methods used to assess connectivity ranges from qualitative to quantitative approaches which include field-based techniques (e.g. geomorphological mapping, sedimentological analyses, dating), lab experiments, map analysis, remote sensing, GIS and numerical modelling. This section gives an overview of the variety of techniques which have been used to investigate connectivity in fluvial systems with a focus on the effects of land use/land cover (incl. riparian vegetation) and dams. Although some studies do not explicitly refer to the term "connectivity", they are presented here since the basic underlying assumptions are comparable to those in connectivity assessments. Table 3 provides an overview of previous studies that have assessed connectivity in fluvial systems while a more detailed account of the approaches outlined in Table 3 sorted according to their overriding research topic is given below (a) sediment connectivity, b) hillslope-channel coupling, c) landscape connectivity, catchment scale).

Table 3: Overview on the overall topics and the methods applied in previous studies on connectivity in fluvial systems

Author(s)	**Topic**	**Method(s)**
Butcher et al. (1992)	Sediment connectivity, effects of dams	Sedimentological analyses
Wemple et al. (1996)	Sediment connectivity, effects of roads	Field surveys, GIS analyses
Fryirs and Brierley (1999)	Hillslope-channel coupling	Sedimentological analyses
Harvey (2001)	Hillslope-channel coupling	Field measurements
Cammeraat (2002)	Sediment connectivity	Sedimentological analyses
Hooke (2003)	Sediment connectivity	Geomorphological mapping
Lee et al. (2003)	Sediment connectivity, effects of riparian vegetation	Field measurements
Toniolo and Schultz (2005)	Sediment connectivity, effects of dams	Lab experiments
Croke et al. (2005)	Sediment connectivity, effects of roads	Field surveys, numerical modelling
Wainwright (2006)	Hillslope-channel coupling	Numerical modelling
Fryirs et al. (2007b)	Landscape connectivity, catchment scale	GIS analyses, aerial photograph interpretation, field mapping
Godfrey et al. (2008)	Landscape connectivity, catchment scale	Field measurements

Boix-Fayos et al. (2008)	Sediment connectivity, effects of land use and dams	Field work, mapping, numerical modelling
Borselli et al. (2008)	Sediment connectivity	GIS analyses, field measurements
Leguédois et al. (2008)	Sediment connectivity, effects of riparian vegetation	Lab experiments
Chiverell at al. (2009)	Sediment connectivity	Geomorphological mapping, sedimentological analyses, radiocarbon dating
Lexartza-Artza and Wainwright (2011)	Sediment connectivity, effects of land use	Sedimentological analyses
Fuller and Marden (2011)	Landscape connectivity, catchment scale	DEM analyses, field surveys

a) Sediment connectivity

Butcher et al. (1992) measured the in- and outflowing sediment at two water supply reservoirs in the southern Pennines (UK) during storm events. Their results revealed trap efficiencies between 97% and 51% depending for medium storm intensities. Toniolo and Schultz (2005) performed laboratory experiments on trap efficiency for fine sediments observing trap efficiencies ranging from 68% to 88% depending on the experimental design. Boix-Fayos et al. (2008) used a combination of field work, mapping and numerical modelling to test the influence of land use scenarios with and without check dams on sediment yield at the catchment scale. Land use changes caused an increase in sediment yield of 54% without the presence of check dams, whereas 77% of the sediment yield were shown to be retained behind the check dams.

Cammeraat (2002) examined linkages between different landscape units by quantifying process rates and fluxes of water and matter to understand which hydro-geomorphological processes are important at which spatio-temporal scales. To do this, he used a nested hierarchical approach measuring runoff over V-notches with monitored open plots, event-based monitoring of flood marks and erosion features together with sediment sampling. His results revealed that connectivity is mainly controlled by rainfall frequency-magnitude-duration characteristics and physical and biologically controlled thresholds. Hooke (2003) confined her research approach to river channel systems and assessed the role of coarse sediment connectivity using geomorphological mapping in an ephemeral channel in SE Spain as well as in a perennial channel from NW England. Her results have shown that coarse sediment connectivity varies spatially, and the variations are closely related to channel morphology.

Lee et al. (2003) investigated the effectiveness of different multi-species buffers in trapping sediment, nitrogen and phosphorus from cropland utilizing triplicate plots exhibiting the highest trapping efficiencies for a switchgrass-woody buffer retaining 97% of the incoming sediment. Leguédois et al. (2008) investigated sediment trapping by tree belts exhibiting a trap efficiency of 94%. They further observed the establishment of depositional features in the backwater areas of trees which were also the locations of highest trapping efficiency. Similar buffering effects have been observed by various authors to be related to the presence of roads. Croke et al. (2005) investigated sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity by applying field surveys and numerical modelling. The results of Croke et al. (2005) have shown that only 5% of the surveyed road drains were predicted to deliver runoff to a stream. Conversely, Wemple et al. (1996) who assessed the hydrologic integration of logging roads with the stream network in two catchments in the western Cascades of Oregon by using field surveys and GIS analyses reported that 57% of the surveyed road lengths were connected to the stream network increasing the drainage density by 21 to 50%.
Borselli et al. (2008) defined two indices of connectivity. One that can be calculated in a GIS-environment, and another that can be evaluated in the field through a direct assessment. Their results indicated that sediment connectivity mainly depends on event intensity, slope gradient and type of land use. Chiverell et al. (2009) used a combination of geomorphological mapping, sedimentological analyses and radiocarbon dating to investigate connectivity relationships between hillslope sediment sources and the downstream fluvial system over late Holocene timescales. Their results revealed that regional climate and land use histories have had a significant influence on sediment flux from the hillslopes to the river channels. Similar findings have been reported by Lexartza-Artza and Wainwright (2011) who studied changing patterns of connectivity under varying conditions within the contexts of recent land-use changes in conjunction with catchment factors that influence erosion and sediment transport pathways by analysing sediment records from reservoirs.

b) Hillslope-channel coupling

Fryirs and Brierley (1999) examined hillslope-channel decoupling in the Wolumla catchment, Australia assessing the influence of on-slope sediment storage and sediment sinks on hillslope-channel coupling by analysing sedimentation rates of farm dams and sediment thickness and composition of auger holes along hillslope transects and in trapped tributary fills. Their results have shown that most of the material eroded from slopes has been stored on-slope, in trapped tributary fills and along low order drainage lines. Harvey (2001) assessed the role of hillslope-channel coupling for the sensitivity of upland geomorphic systems by using evidence from a 30-year monitoring programme of geomorphic change in the Carlingill valley, England. Erosional change on open hillslopes and morphological change in gully systems and stream channels was surveyed by basic photo monitoring of fixed sites and field observations and measurements. His results revealed that there is little sediment supply from the hillslope zone to the channel system, whereas in the footslope-coupling zone basally induced gullies have been shown to be major sediment sources to the river. Wainwright (2006) utilized a cellular modelling approach to show the effects of hillslope-channel coupling conditions on the geomorphic system response under constant climatic conditions. Based on the modelled sediment outputs from the catchment, he concluded that catchment configuration has a very strong effect producing a complex system response implying that there are no simple relationships between climate and catchment output.

c) Landscape connectivity, catchment scale

Fryirs et al. (2007b) utilized a generic approach to analyse landscape (dis)connectivity by applying threshold analysis techniques in GIS enhanced by aerial photograph interpretation and field mapping. This methodology was tested in the upper Hunter catchment, Australia revealing significant dis-connecting effects of landforms termed buffers and barriers that impede catchment-scale sediment flux. Godfrey et al. (2008) explored the degree of landscape connectivity in an arid region of the southwest United States by interpreting data gained from erosion-pin and sediment-trap measurements. Their results indicated that landscape connectivity in the observed system is mainly governed by weather patterns and related mass-movement processes. Similar results have been obtained by Fuller and Marden (2011) who inferred connectivity between landscape compartments using repeated DEM analysis generated from detailed ground surveys.

3. Connectivity between humans and the landscape: Human-landscape interactions and landscape change

In this chapter, existing concepts on connectivity relationships between human systems and landscape systems including factors and processes that govern them are presented (chapter 3.1), since they are seen as important precursors for the conceptual model developed in this thesis. Furthermore, existing methods and approaches to investigate connectivity relationships between human systems and landscape systems and related landscape changes are reviewed (chapter 3.2).

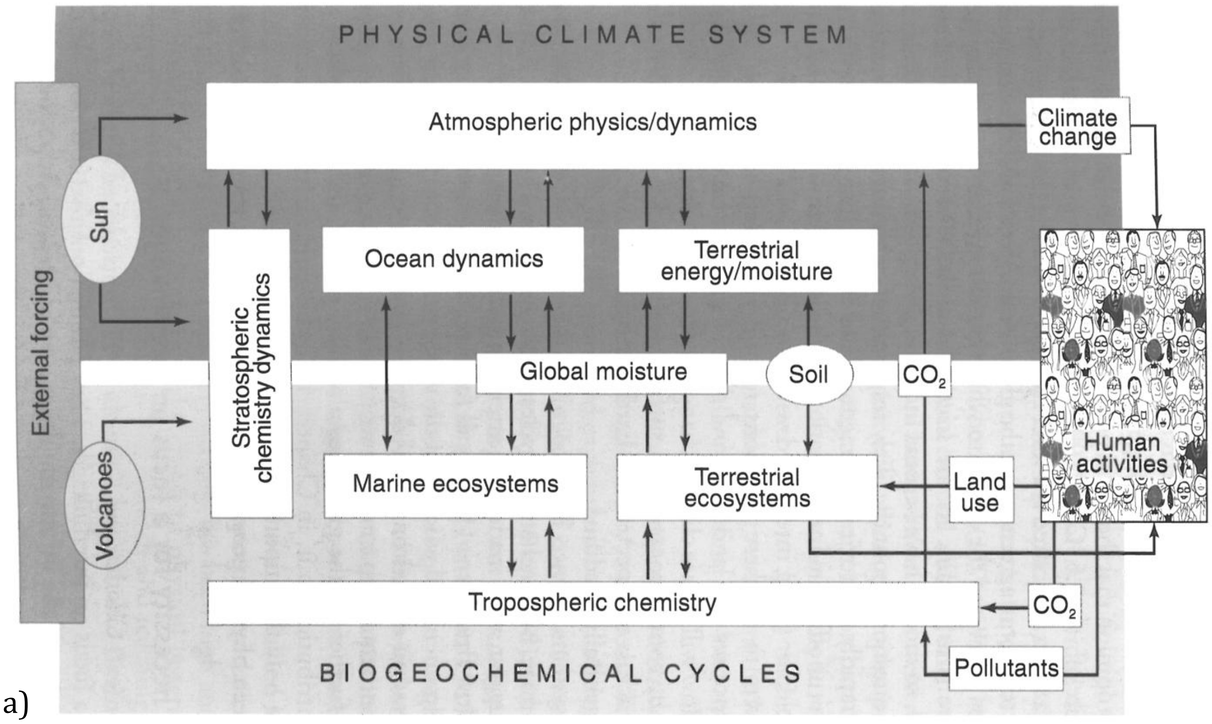
3.1 Existing concepts on human-landscape interactions (connectivity) and landscape change

One of the first systematic approaches to conceptually link the human system to the landscape system has been provided by Chorley and Kennedy (1971) through defining control systems in physical geography. They identified distinctive points in process-response systems called "valves" where intelligence can most effectively intervene to produce operational changes. Moreover, they stressed that the processes of decision making leading up to intervention are extremely complex and that linkage of physical ("natural") and socio-economic ("human") systems involves great difficulties due to two vital differences between them (Chorley and Kennedy 1971, p. 299) which are listed below:

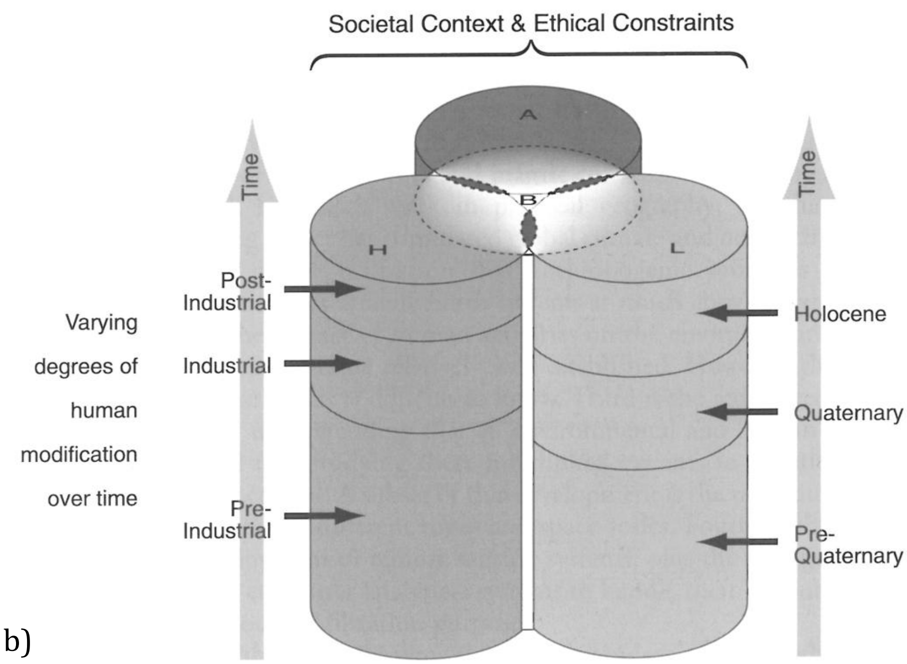
1. "Human and higher biological systems differ from physical systems in that they possess a memory of some kind which exerts some operational control."

2. "[…] the operation of physical systems is dominated by tendency for negative feedback, whereas socio-economic systems possess strong positive-feedback loops which make change ongoing."

Since then, some applied geomorphological studies have attempted to combine societal issues with physical based geomorphic knowledge (Goudie 1986) which contain the disciplinary roots for hazards research and geomorphological approaches to environmental management (Hart 1986). Nevertheless, for the most part, geomorphic research has rather sought out "unspoiled" environments to better understand how biophysical systems operate independent of human influence (Trimble 1992). Although Earth systems science had already recognized the importance of the interlinkages among biophysical processes and human activities in the context of global environmental change (e.g. NASA 1988, see Fig. 5a), Slaymaker and Spencer (1998) addressed the inadequate attention to human agency in this context through the development of a simple conceptual model that highlights the importance of time and modification to the environment in consideration of societal contexts and ethical constraints in physical geography (see Fig. 5b).



a)



b)

Fig. 5: (a) An Earth system science view of global environmental change (Source: Slaymaker and Spencer 1998, p.14; modified from NASA 1988); (b) The nature of Physical Geography as four discrete sub-fields highlighting the importance of time and learning from recent geological history (right) and the record of human modification (left) in the context of societal and ethical constraints. (A) Atmosphere, (B) biosphere, (H) hydrosphere, and (L) lithosphere (Source: Slaymaker and Spencer 1998, p. 19)

The conceptual model developed by Slaymaker and Spencer (1998) has been extended by Urban (2002) by integrating *feedback loops between geomorphic and socio-cultural contexts* (see Fig. 6). The model intends to provide a framework to guide the investigation of human-modified biophysical landscapes by extending the “process in process geomorphology to include human dynamics alongside the more traditional biological, chemical, and physical processes (Gregory 2000)” (Urban 2002, p. 205). The loop to the left in Fig. 6 indicates social processes that may influence the physical state of the landscape. These anthropic forces are guided by social processes which are mediating human behavior such as human perception, valuation, assignation of meaning, and the negotiation of ethical positions (Aitken 1992). The right loop includes environmental impulses that interact to generate systemic change or lead to morphologic stability (Urban 2002) characterized by the traditional physical, chemical and biological processes effecting geomorphic change (Gregory 1985). When joined with human agency in the center, the biophysical system becomes a control system if the impact is of significant magnitude so that human behavior elicits a complex systemic response (Schumm 1991, Urban 2002). Depending on the sensitivity of the environment, the type and magnitude of the event, feedback mechanisms may dampen or undermine system stability (Downs and Gregory 1993, Urban 2002). “Any resulting physical alterations to landscape function or structure are then fed back into the left-hand side of the model through experience and perception.“ (Urban 2002, p. 210) Similarly to Urban (2002), Holling (2001) and Lenton et al. (2004) addressed the need to view human activities and landscape change together as a co-evolutionary and adaptive process.

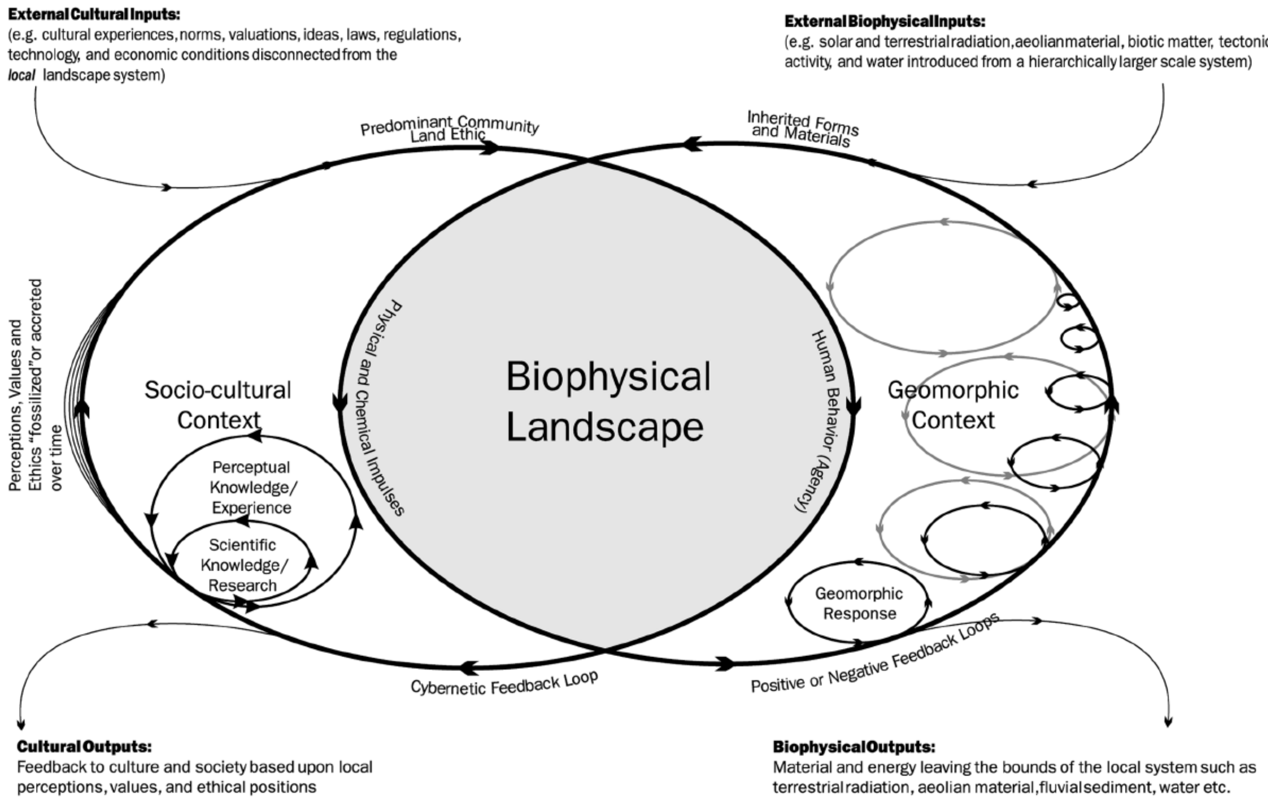


Fig. 6: Conceptualized framework for integrating human agency into the geomorphic system in heavily modified landscapes (Source: Urban 2002, p. 209).

In the context of natural hazard research, Magliocca (2008) stated that human-landscape interactions that result from *protective measures* which have been built by humans to mitigate natural disasters became overwhelmingly complex due to a phenomenon referred to as *induced coupling*. These interactions are seen as being distinct from traditional human-landscape interactions because they are non-linear which means that the actions of the one system (human or landscape) influence and are influenced by the behaviour of another (Magliocca 2008). "Induced coupling creates complex environmental problems because it initiates and drives an iterative cycle that magnifies an initial disruption of natural processes." (Magliocca 2008, p. 4) The concept of induced coupling has been regarded as framework to facing the problem of destructive human-landscape interactions in terms of human manipulations within a hierarchy of natural processes (Magliocca 2008). Werner and McNamara (2007) also report that due to an increased strength of interactions between human and landscape systems human agency and landscape processes should no longer be treated separately, but rather as an inter-weaved, complex coupled system. They developed a schematic of strongly coupled human-landscape systems representing a modeling approach that integrates and couples landscape, damage, economic/political and hazard mitigation models (see Fig. 7). Since human impacts have substantial effects on landscape change (e.g. due to changes in land use/land cover), a focus on human-landscape interactions and feedbacks is recognized as being essential in steering landscape evolution and the response to changing conditions.

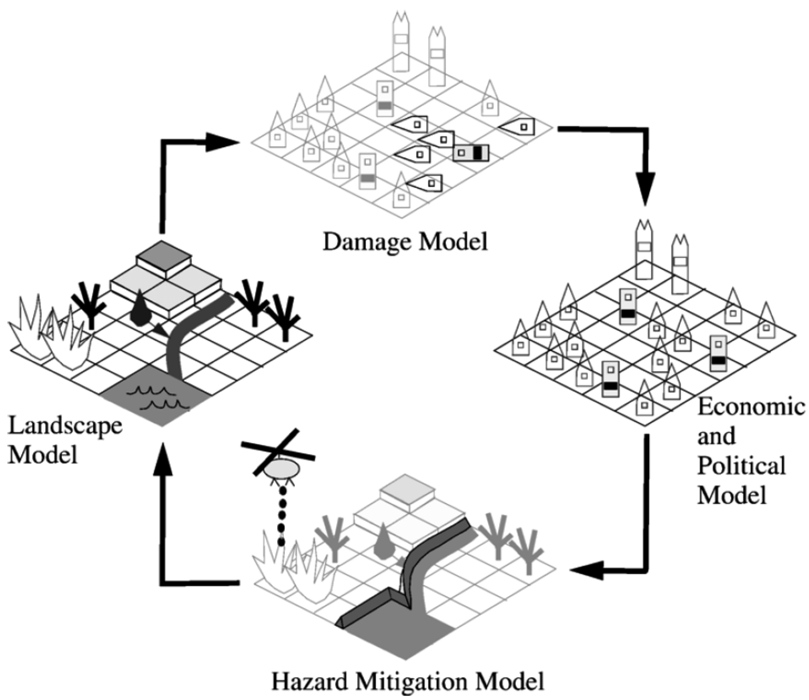


Fig. 7: A schematic of strongly coupled human-landscape systems: landscape processes (left) dominated by water, sediment or biological routing and transformation, with morphology, vegetation, river channel, ocean, fire and surface water flow sketched; human processes (right) dominated by economic and political dynamics, showing homes and businesses; landscapes impact humans (top) through damage (to buildings shown here) from natural disasters and slowly varying changes to landscape; humans impact landscape (bottom) through effects of economically driven landscape modifications to mitigate damage, with a water drop on a fire sketched. (Source: Werner and McNamara 2007, p. 401)

3.2 Investigating landscape change and human-landscape interactions (connectivity): Existing methods and approaches

Landscape change. The character of a landscape is created by particular combinations of physical landscape components (geology, landforms, soils, vegetation) and anthropogenic elements/components (land use, field patterns and human settlement) (Swanwick 2004). The landscape character is further determined by the degree to which human activities and natural processes are interacting or have been interacting in the past. Therefore, landscape character is an expression of the holistic nature of the landscape (Antrop 2003, Jessel 2006). A growing need for landscape inventorying, assessment, and monitoring led to the development of landscape indicators to evaluate landscape change (Van Eetvelde and Antrop 2009). The focus is on conservation and protection of natural and cultural values, but also on sustainable development (Haines-Young 2000), spatial planning and landscape management (Selman 2006). Defining landscapes and analysing landscape change are central issues in landscape ecology. Due to the long history of human modification and design, this discipline began in Europe, with roots in physical geography, aerial photointerpretation (i.e. pattern analysis), and land-use policy and management (Wiens 2002). Two elements have been identified as having central importance: " [1] the role of humans as part of the landscape, and [2] the focus on landscapes at a scale relevant to human perception and actions." (Wiens 2002, p. 502)

Analyzing changes in landscape metrics using landscape indicators can be applied used to different disciplines in a variety of ways and can be performed on different spatial and temporal scales. Landscape indicators generally quantify the amount and arrangement of land cover, human-altered land, and the physical structure of landforms and landform assemblages (e.g. Meyer and Turner 1994). By the late 1980s and early 1990s, a number of studies explored the usefulness of landscape metrics to assist with landscape analysis (e.g. Turner et al. 1989, Cullinan and Thomas 1992). A large number of landscape indices can now be found in the literature (Haines-Young and Chopping 1996). Changes of different types of landscape metrics have been quantified and utilized as indicators for human impacts upon landscapes. These measures are generally derived from aerial photographs, maps, and satellite imagery using GIS (Gergel 2002) and can be complemented by ground surveys. In the following paragraphs, some literature examples of human-induced changes of landscape metrics focusing on dam-induced (a) channel geometry and (b) land use/land cover changes in fluvial environments are presented:

a) Channel geometry

Besides significant changes in channel geometry that are naturally related to river straightening as a result of channelization, the installation of dams has been recognized to induce geomorphic channel changes which lead to a significant amount of geomorphic research focussing on the geomorphic effects up- and downstream of dams. By analysing maps and aerial photos, channel planform changes have been detected and related to the presence of dams (e.g. Williams 1978, Lagasse 1981, Gilvear and Winterbottom 1992, Gordon and Meentemeyer 2006) and channel narrowing downstream of dams have been observed by interpreting aerial photographs and/or river cross sections (e.g. Williams 1978, Petts 1979, Williams and Wolman 1984, Andrews 1986, Wilcock et al. 1996, Grams and Schmidt 2002, Graf 2006). In the late 20th century, unforeseen changes and costs associated with dams became apparent which lead to a need for dam removal (Graf 2003) followed by the exposure of reservoir sediment to fluvial erosion and downstream transport where the material is likely to accumulate. Geomorphic processes that follow dam removal also lead to geomorphic channel changes (e.g. Stanley 2002, Doyle et al. 2005, Wildman and MacBroom 2005, Burroughs et al. 2009), causing significant changes of the channel geometry and hence landscape metrics also change. Changes of channel geometry can be further caused by altered supply of water and sediment from the catchment areas to the channel system which has been shown to be related to land use and land cover changes (e.g. Trimble 1983, Orbock Miller et al. 1993, Kondolf et al. 2002, Keesstra et al. 2005).

b) Land use and land cover change

Changes in land cover and land use are among the most important human alterations of the landscape (Turner et al. 1990, Lambin et al. 1999). Land use changes in outer river areas can also be related to human-induced channel changes such as channel straightening or the construction of dams and have a fundamental reciprocal relationship with fluvial processes in the river channel system. Some recent studies have investigated and quantified land use and land cover changes caused by dam construction by analysing landscape metrics (e.g. Ouyang et al. 2010, Zhao et al. 2012). Furthermore, changes of riparian vegetation cover are often related to the installation of river engineering structures. For example, broad-scale impacts of dams may alter processes that affect riparian vegetation dynamics (e.g. Wootton et al. 1996, Shafroth et al. 2001, Gordon and Meentemeyer 2006, Su et al. 2012) which also modifies the geomorphic structure of a river at various scales. Structural engineering works such as channelization and bank protection measures are generally further accompanied by the clearance of riparian vegetation (Brierley and Fryirs 2005).

For predicting future landscape changes, different kinds of numerical models have been applied. DEM-based landscape evolution models are used to simulate the geomorphic development of catchments which also can be applied to simulate geomorphic response to external changes such as human activity and climate, such as the LAPSUS (Schoorl et al. 2002) or the CAESAR model (Coulthard 2005). Land use change can be simulated such as by the CLUE model which uses empirically quantified relations between land use and its driving factors in combination with dynamic modeling of competition between land use types (Verburg and Overmars 2009). Furthermore, agent-based models of land use and land cover change which combine a cellular model representing the landscape of interest with an agent-based model that represents decision-making entities are applied, such as within the LUCITA model framework (Deadman et al. 2002).

Human-landscape interactions (connectivity). The approaches applied to investigate human-landscape interactions range from empirical studies to numerical modelling. Several empirical studies have investigated changes in the landscape system and have related them to changes in the human system by identifying cause-effect relationships and possible feedback loops. The methods applied include historical investigations of settlement and land use history combined with the study of climatic, environmental, and geomorphological archives (e.g. Bubenzer and Riemer 2007, Holdaway et al. 2008). Interactions between human and landscape processes have been measured and mapped and regression techniques have been used to project future behaviour (e.g. Lent et al. 1999, Smith and Wilen 2003). In other approaches, humans have been incorporated into an existing framework for geological/geomorphic systems (Haff 2003) or ecological systems (Arrow et al. 1995, Holling 2001). In more recent studies, human-landscape interactions have been modelled using multi-agent simulations that integrate human behaviour and environmental factors as applied to decision-making in spatially referenced dynamic environments (Gimblett 2005). Werner and McNamara (2007) developed a cellular model using heterogeneous agents employing prediction models to determine actions to represent the nonlinear behavior of economic and political systems and rule-based routing algorithms to represent landscape processes in coupled human-landscape environments. Le et al. (2008) used a land-use dynamic simulator (LUDAS), which is a multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape systems in which the human population and the landscape environment are all self-organized interactive agents.

4. Methods and materials

This chapter provides an overview of the methods used to test the thesis hypotheses and provides information on the study area settings and the utilized materials and data. Methods used for each research question are presented below. Reference will be given to the relevant chapters and journal articles where more detailed information on methods can be found.

4.1 Human impacts on sediment connectivity in fluvial systems and fluvio-geomorphic response

Hypothesis I) Linking concepts of sediment connectivity to principles of channel processes contributes to a better understanding of geomorphic channel response to dam construction and changes of land use and land cover

Ad research questions Ia) How do different types of human impact on fluvial systems potentially influence the lateral, longitudinal and vertical dimensions of sediment connectivity and how can sediment connectivity be linked to geomorphic channel processes?,
Ib) What role do self-regulatory system properties play in the recovery of sediment connectivity in fluvial systems and what are the driving factors of change?

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

A conceptual model that links human-induced changes of sediment connectivity in fluvial systems to geomorphic channel processes was developed (chapter 6.1.1): Impacts of direct and indirect human interventions on the three spatial dimensions of sediment connectivity in fluvial systems were verbally and graphically conceptualized and causally linked to an equilibrium concept of geomorphic channel processes developed by Lane (1955) (ad research question *Ia*). This was done by considering the potential effects of direct and indirect human impacts on the longitudinal, lateral and vertical dimensions of sediment connectivity further reflecting their consequences on geomorphic channel processes related to changing ratios of stream power and sediment supply within the river channel. The model was extended by focusing on the role of self-regulatory system properties for sediment connectivity after dam construction and land use change by verbally and graphically assuming a recovery of sediment connectivity due to vegetation regrowth and geomorphic channel processes (ad research question *Ib*).

Ad research question Ic) How do dams and land use changes affect sediment connectivity in fluvial systems and what are the associated geomorphic channel changes?

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

The model assumptions were tested by performing and evaluating case studies in small fluvial systems impacted by (1) dams (i.e. case studies 1 and 2) and (2) land use/land cover changes (i.e. case studies 3 and 4) in which different methodical approaches were applied (see below). The results of each of the case studies were interpreted in the context of the newly developed conceptual model on human-induced alterations of sediment connectivity in fluvial systems and fluvio-geomorphic response (chapter 6.1.2).

(1) Dam construction

Case study 1 - The effects of the Sagteich dam on the longitudinal and vertical sediment connectivity of the Kaja River, Austria

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

The aim of this case study was to detect the reach-scale effects of the Sagteich dam on longitudinal and vertical sediment connectivity and the related geomorphic channel changes by applying sediment analyses and fluvio-geomorphic mapping. The study site is located in the Kaja catchment in northern Austria (see Fig. 11). The Kaja River is situated in a low mountain range with temperate climate, has a length of approximately 10.7 km and can be regarded as a mixed-load river (see Table 7). The Kaja River is impacted by a series of dams which were built for extensive fish farming purposes (Poeppl 2010). The investigation was located up- and downstream of an active dam (see

Fig. 8) which was constructed as an overflow dam with a height of about 7 m built before 1782 AD. Approximately 200 meters downstream of the active dam, an inactive embankment dam is still present which was abandoned when the active dam was built. Just upstream of the abandoned dam, retained reservoir sediments are still stored in the former impoundment area and overlain by recent alluvial deposits (see Fig. 8).

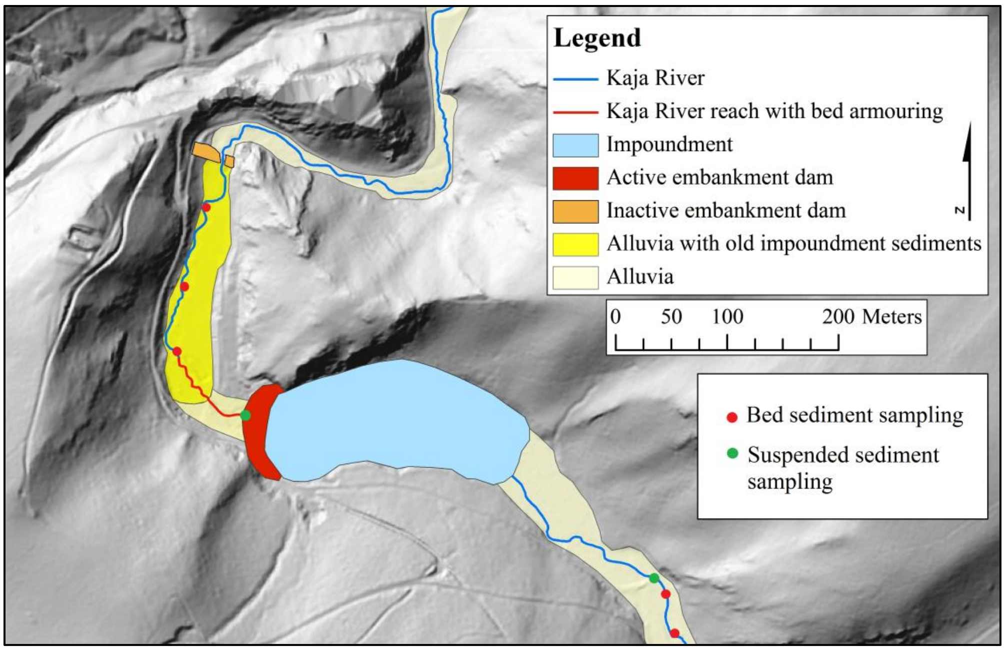


Fig. 8: Study area settings. Data source of the hillshade-DTM (1 m x 1 m resolution): Provincial State Government of Lower Austria, 2010; (Source: Poeppl et al. 2012a, A.1, p. 150)

Sediment samples were taken upstream and downstream of the active dam in May 2011 and upstream data was then compared to downstream data to identify dam-induced longitudinal sediment dis-connectivity. The sample points were selected based on the criterion of similar flow velocity conditions to prevent from dam-related effects on sediment transport capacity such as backwater effects upstream or turbulences downstream (see Fig. 8). Flow velocities were recorded along cross-sectional profiles using an OTT Nautilus electromagnetic flow sensor. Wolman pebble counts (Wolman 1954) were used to survey grain size compositions of the river bed sediment on gravel bars in river reaches approximately 200 m upstream and 200 m downstream of the active dam during low flow conditions. Information on river bed sediment composition was used as an indicator for dam-induced river bed degradation due to dam-induced bed load retention. To investigate dam-induced effects on suspended sediment transport, suspended load samples were taken after a heavy rainfall event on the dam crest as well as in upstream reaches unaffected by backwater. Suspended sediment concentrations per grain size classes were then analysed in the lab by using a Micrometrics Sedigraph III. To survey changes of vertical sediment connectivity, facies mapping was used (for a detailed method description refer to Kondolf et al. 2003) to detect channel bed armouring which is seen as an indicator for reduced vertical sediment connectivity often occurring downstream of dams.

Case study 2 - Check dams and longitudinal sediment connectivity - examples from the Gimbach catchment, Austria

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

This case study dealt with check dam-induced changes of longitudinal sediment connectivity, geomorphic channel responses and the importance of self-regulatory system properties related to geomorphic channel processes for system recovery in steep mountain streams. Geomorphic channel processes occurring in a series of check dams due to reduced longitudinal sediment connectivity were verbally and graphically conceptualized and underpinned by presenting real-world examples from the Gimbach River. The Gimbach catchment is located in a high mountain range in central Austria and has been impacted by a series of check dams (see Fig. 11, Table 7). These check dams were built to mitigate hazards in these areas by promoting the deposition of material in areas of impoundment. In order to investigate geomorphic channel responses to check dam-induced changes of longitudinal sediment connectivity, geomorphic channel development was continuously monitored in the field.

(2) Land use change

Case study 3 - The effects of dirt roads on lateral connectivity in the Barranco de las lenas catchment, NE Spain

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

The aim of this case study was to investigate the effects of human impacts in terms of road building on lateral connectivity and gully development in a semi-arid environment. The case study site is located at the footslopes of the "Plana de Zaragoza" in the Central Ebro Depression in the Huerva valley south of Zaragoza, (see Fig. 11, Table 7). The lithology of this gully catchment consists of Miocene gypsum, marl and clay series with interbedded limestone and sandstone (ITGE 1998). The gully itself can be regarded as a bank type gully (Poesen et al. 2003) which is deeply incised into Holocene alluvial deposits that reach up to 20 m in thickness. An unpaved road and a bike trail cross the catchment upstream of the incised gully. Remnants of old agricultural terraces also lying upstream of the gully created a stepped surface with an almost horizontal inclination in close proximity to the gully headcut. Intensive sheet wash processes and deeply incised rills occur on the steep slopes of the gully headcut catchment. Along the dirt road, which runs almost perpendicular to the hillslope, lines of rill of incision occur which have developed directly leading to a depositional area close to the gully headcut (Seeger et al. 2009) further indicating reduced lateral connectivity.
The effects of human impacts in terms of road building on lateral connectivity were assessed by applying a DEM-based flowpath analyses in a GIS-environment. The flowpath analyses were performed for two scenarios: one with and one without the presence of a dirt road. These two scenarios were then compared to investigate the impact of the dirt road on lateral connectivity. The dirt road was cut with a depth of 50 cm and a width of 3 m into a DEM by using the r.carve function in GRASS-GIS (GRASS Development Team 2008). In order to estimate geomorphic channel changes after road-induced alterations of lateral connectivity, the development of the gully channel was continuously monitored in the field.

Case study 4 - Investigations on lateral sediment connectivity in the Dragonja catchment, SW Slovenia

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

The aim of this case study was to investigate the effects of natural reforestation (due to land abandonment) on lateral sediment connectivity, geomorphic channel responses and to identify the effects of self-regulatory system properties in terms of vegetation regrowth on system recovery. For this, case study results obtained by applying hydrological analyses, sediment budget analyses, geomorphological mapping and different field and laboratory methods published by Keesstra et al.

(2007) and Keesstra et al. (2009a, 2009b) were interpreted in the context of the newly developed conceptual model on human-induced alterations of sediment connectivity in fluvial systems and fluvio-geomorphic response. The investigations were conducted in the Dragonja catchment which is located in southwestern Slovenia (see Fig. 11, Table 7). The catchment has experienced a 60% increase in forest cover on the steep hillslopes adjacent to the river channel which were formerly cultivated on small terraces. Over a 30 year period the abandoned fields have evolved into grassland and dense forest.

4.2 Lateral buffering and the role of riparian vegetation cover

Hypothesis II) Lateral buffering is strongly influenced by riparian vegetation cover type and biogeomorphic processes

Ad research question II) Which factors and processes govern lateral sediment connectivity and how do different types of riparian vegetation cover affect lateral buffering?

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A.2)

A conceptual model was developed considering the factors and processes that govern lateral sediment connectivity and buffering in an agricultural catchment with a special focus being placed on the influence of riparian vegetation cover. Different processes and factors potentially influencing the lateral sediment connectivity between valley floors and river channels were verbally and graphically conceptualized. Special consideration was given to the role of riparian vegetation cover and related biogeomorphic processes in governing lateral buffering (chapter 6.2.1). The key assumptions of the developed model were tested through conducting a case study (i.e. case study 5) in a small agricultural catchment applying a combination of GIS-analyses, field surveys and multivariate statistics (chapter 6.2.2).

Case study 5 - The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A.2)

The main objectives of this case study were (i) to assess the influence of a variety of riparian vegetation cover types on diffuse lateral sediment connectivity between agricultural areas on valley floors and the river channel, and (ii) to investigate the role of biogeomorphic processes acting in forested riparian zones of a medium-sized agricultural catchment. For this, GIS analyses and geomorphic field surveys were combined with multivariate statistics.

Like many river catchments of Austrian lowlands and low mountain ranges, the catchment of the Fugnitz River is highly affected by agricultural land use. The Fugnitz catchment is situated in the eastern part of the Bohemian Massif (low mountain range) in Austria (see Fig. 11) and is characterized by a humid temperate climate. The catchment has a gentle topography with an average slope angle of 4.5% (computed from a DEM with 10 m x 10 m; data source: provincial state government of Lower Austria 2009). The bedrock lithology consists mainly of crystalline mica granite and mica shale which are largely overlain by Quaternary Pleistocene loess layers (silt, fine sand) and locally by Tertiary silts, clays and sands (brackish-maritime) (Roetzel et al. 2008). The dominant soil types are Cambisols (IUSS Working Group WRB 2007). The catchment's land use/vegetation cover is very heterogeneous and has the following land use classes: agricultural land (56%), forests and woodland (34%), grassland (7%), and built up areas (3%). Most parts of the main river channel are lined by a variety of riparian vegetation types that grow adjacent to agricultural areas. Therefore, this study allows for a comprehensive investigation of the effects of different types of riparian vegetation cover on lateral sediment connectivity and allows for the assessment of the role of biogeomorphic processes acting in the riparian zones.

In order to delimit the area of investigation, the study area was subdivided into four different zones (see Fig. 9): upland area and hillslope, valley floor, riparian and river channel. The zonation of the catchment is based on the following criteria: (1) slope angle thresholds related to surface morphology breaklines, (2) changes in land use and vegetation cover (for details refer to Poeppl et al. 2012b, A.2, p. 170).

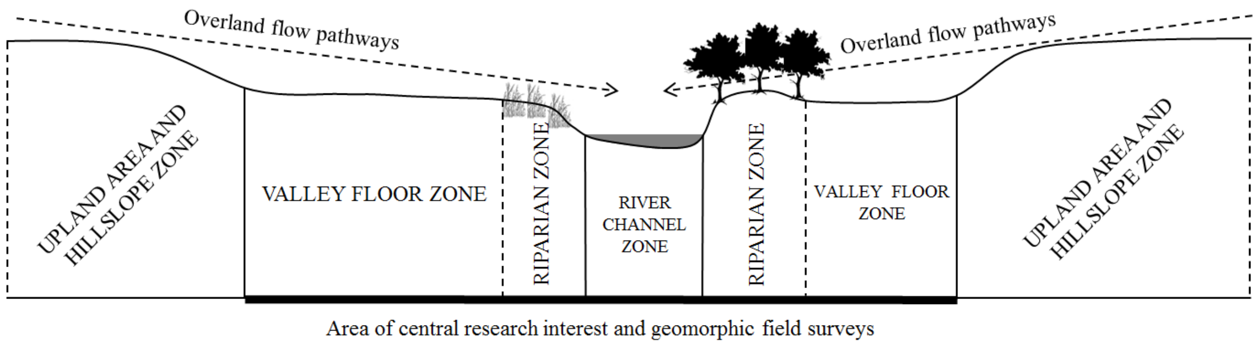


Fig. 9: Zonation of the study area. Dashed arrows indicate overland flow pathways that potentially connect the different study area zones. The area of central research interest and geomorphic field surveys is shown by the bold black line. *Root dams* are present in the forested riparian zones. (Source: Poeppl et al. 2012b, A.2, p. 170)

Ad (i) Lateral sediment connectivity

In order to assess the lateral sediment connectivity within the catchment, two key parameters were assessed: potential sediment source areas and sediment transport along the flow routes. Source areas were delineated by utilizing land use mapping (a), while sediment transport was evaluated using GIS analyses (b), geomorphic field surveys (c) and statistical analyses (d, e). An overview on these methods is presented below.

a) Land use mapping

Land use mapping was conducted by interpreting orthorectified aerial photographs with 0.25 m x 0.25 m resolution using ArcGIS software (data source: provincial state government of Lower Austria 2009). The following land use classes were delineated: agricultural land, grassland, forests and woodland (incl. shrubland) and built up areas. Land use mapping was further verified using field surveys conducted in the course of the geomorphic field surveys (see below).

b) Overland flow pathway modelling

GIS analyses were used to create a simple model of overland flow routing along the valley floor zone. The model was created based on the following criteria: (1) slope angle thresholds related to surface morphology breaklines, (2) changes in land use, and (3) vegetation cover. The modelled flow routes (represented as polylines) were selected based on the following characteristics, i.e. they had to:

- originate in agricultural areas of the valley floor zone
- cross the riparian zone
- end in front of surface morphology breaklines
- end at the border of the river channel zone
- consist of a single line per vegetation cover type, including information on segment length

In order to model overland flow pathways, Flow Accumulation was calculated in ArcGIS 9.3 using a DEM with 1 m x 1 m resolution. After a reclassification of the resulting Flow Accumulation grid which was based on values above the mean, the output raster grid was converted into polyline format. In order to extract single overland flow pathways, the longest line features crossing the last agricultural area within the valley floor zone was extracted and merged manually. All other segments were deleted. This resulted in a single line segment that runs from an agricultural field to the river channel crossing the riparian zone. Line segments were then analysed according to the criteria described above. The line segments were cut accordingly and for each line segment the segment length was calculated (for more details refer to Poeppl et al. 2012b, A.2, p. 176-178).

To obtain information on the factors that potentially influence lateral sediment connectivity (=explanatory variables), the Line Raster Intersection Statistics Tool provided by Hawth´s Analysis Tools for ArcGIS (Beyer 2004) was used. This application calculates the length of each line that falls within a raster cell and creates a statistical summary (i.e. length weighted mean, minimum values, maximum values, standard deviation) for each of the line segments. After processing, the values were stored in the attribute table of the polyline layer and used for statistical analyses. For this procedure, raster layers of the following factors were created for the whole catchment as they are assumed to influence sediment transport and thus sediment connectivity: slope angle in degrees, profile curvature, flow accumulation.

c) Geomorphic field surveys

Geomorphic field surveys were conducted to assess explanatory variables which were not considered in GIS-analyses (i.e. the presence of root dams and farm tracks, plough direction; see also Table 4), and to survey the following features that indicate the presence of structural lateral sediment connectivity (=dependent variable) as they are assumed to represent the occurrence of overland flow connectivity between the agricultural source areas and the river channel:

- Continuous rills (vegetated or non-vegetated)
- Continuous indications of overland flow processes (sheet flow or concentrated flow): plants oriented in flow direction, siltation marks on vegetation

d) Evaluation of overland flow pathway modeling

In order to evaluate factors that influence the overland flow pathway model leading to over- or underestimation, a statistical analysis was performed for all agricultural valley floor segments adjacent to the riparian zone. To obtain information on the factors that caused model over- or underestimation and thus also potentially influence lateral sediment connectivity, values of the statistical summary of line segments where sediment connectivity was observed in the field were compared with segments that exhibited no indicators of sediment connectivity.

e) Statistical analyses

Logistic regression modelling was used to investigate the influence of the different explanatory variables on lateral sediment connectivity (=dependent variable). As some of the explanatory variables were highly correlated, a principal component analysis (PCA) was performed to avoid collinearity problems and to obtain uncorrelated explanatory variables for the logistic regression model. Numerical and binary parameters for each line segment which had been examined in the course of GIS analyses and/or geomorphic field surveys were chosen as explanatory variables. In Table 4, a list of the explanatory variables used as input variables for the PCA and logistic regression modelling is presented, their abbreviations are introduced, and information on the type of input data was provided. The abbreviations were extended by adding suffixes according to the type of land use and vegetation cover ("AL" for agricultural land, "GL" for grassland, and "FL" for forested land including shrubland).

Table 4: Explanatory variables for PCA-analysis and logistic regression modelling including abbreviations and type of input data. All numerical values were log2-transformed. (Source: Poeppl et al. 2012b, A.2, p. 179-180)

Explanatory variable	**Abbreviation**	**Type of input data**
Percentage of riparian vegetation (GL/FL)	Per	Numerical
Cumulative flow length for all segments within the riparian zone in m	CumLen	Numerical
Flow length in m (AL)	Len	Numerical
Slope angle in ° (mean)	Slo	Numerical
Profile curvature (mean)	Cur	Numerical
Flow accumulation (mean)	Flo	Numerical
Difference in slope angle, profile curvature and flow accumulation between valley floor zone and riparian zone (= mean of valley floor zone – mean	Dif_Slo, Dif_Cur, Dif_Flo	Numerical

of riparian zone, 3 variables)		
Root dams: 0 (no root dam present), 1 (root dam present)	Rod	Binary
Plough direction: 0 (parallel to the flow direction of the main river channel), 1 (perpendicular to the flow direction of the main river channel)	Plo	Binary
Farm tracks: 0 (no farm tracks present), 1 (farm tracks present)	Fat	Binary

In order to determine the variables with the highest explanatory power for sediment connectivity (= dependent variable), a backward elimination of explanatory variables was applied in which all explanatory variables were initially included. As 37 of 91 observations of overland flow pathways were only examined in the field but not output by the model, they lacked information on flow length, slope profile curvature ("Cur"), slope angle ("Slo"), and flow accumulation ("Flo") along agricultural areas adjacent to the riparian zone. Information on "Rod", "Per", "CumLen", "Plo" and "Fat" were available for segments in the riparian zone, as these features were surveyed in the field. Two different logistic regression modeling scenarios were applied:

(1) Scenario 1: The three binary variables "Plo", "Fat", and "Rod" as well as the five axes from the PCA were used as explanatory variables, while observations without numerical information on explanatory variables (i.e. observations of overland flow pathways, which had not been modelled, but examined in the field) were excluded from the analysis.

(2) Scenario 2: Only explanatory variables which had been examined in the field were integrated into the logistic regression model (i.e. "Per", "CumLen", "Rod", "Plo", and "Fat").

Ad (ii) Biogeomorphic processes

Root dams were examined in the field while conducting geomorphic field surveys in the modelled overland flow pathways in forested riparian zones (see also c) and Table 4). The presence of a root dam was identified if the following criteria had been met:

- Presence of overland flow pathways within the valley floor zone
- Absence of overland flow pathways within the riparian zone
- Riparian zone lies higher than the adjacent areas of the valley floor zone

Elevation differences between the riparian zone and the adjacent valley floor zone were examined visually and by walking in the field. Furthermore, valley floor cross-sections were drawn to visualize root dams using the 3D Analyst Tool in ArcGIS 9.3. To investigate factors that influence the establishment of root dams, a statistical analysis using cross-tabulations and Fisher´s exact test was performed to relate overland transport pathway segments that exhibit forest cover to the binary explanatory variables (see also Table 4).

The models that have been developed in this thesis so far as well as the related case studies focussed on human-induced changes of connectivity relationships within fluvial systems. This has been done in an unidirectional manner, meaning that only human impacts on fluvial systems and geomorphic responses have been considered neglecting possible subsequent interactions between the fluvial and the human system in terms of responses of humans to human-induced geomorphic changes. In the following chapter, connectivity relationships between the human system and the fluvial system and their importance for landscape change are considered.

4.3 Connectivity between the human and the fluvial system and its implications for landscape change

Hypothesis III) Dam construction induces geomorphic channel changes that trigger a series of process-response feedback loops between the human and the fluvial system

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms*. (Source: Poeppl et al. 2012c, A.3)

A model was developed that conceptualises dam-induced connectivity between the fluvial system and the human system and addresses possible implications for landscape change in fluvial environments. Dam-induced process-response feedback loops between the fluvial system (geomorphic responses) and the human system (human responses) which are seen as indicator for interactions between the fluvial and the human system and their importance for landscape change were verbally and graphically conceptualized (chapter 6.3.1). The key assumptions of the model were tested by performing a case study in a small dam-impacted fluvial system (i.e. case study 6). This was done by applying a combination of GIS analyses, field surveys and landscape evolution modelling (chapter 6.3.2).

Case study 6 - Dam-induced landscape change and the role of human-landscape interactions – a reach-scale case study

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms*. (Source: Poeppl et al. 2012c, A.3)

The objectives of case study 6 were (i) to assess landscape changes in terms of land use/land cover and river planform geometry in a dam-impacted river reach between two points in time, and (ii) to relate these changes to dam-induced geomorphic channel changes considering aspects of dam-induced interactions between the fluvial and the human system. This was done by applying a combination of (1) numerical landscape evolution modeling with CAESAR, (2) GIS-based mapping techniques and geo-statistical analyses and (3) field surveys in a river reach of the Kaja River which has been impacted by a series of dams. The Kaja River is mixed-load single-thread perennial stream located in the northeast of Austria at the border to the Czech Republic (see also case study 1, Fig. 11 and Table 7). Within the study reach, the river has a low gradient, low slope angles and the bedrock mainly consists of mica granite superimposed by quaternary loess layers and partially by tertiary silts and sands which are mainly covered by agricultural land. In total, 15 dams exist along the Kaja River which were constructed as overflow dams (heights ranging from 3 m to 6 m) and reservoirs were used for fish farming purposes (Poeppl 2010). In 1823 three active dams were present in the study river reach, while in 2010 two of them (1 and 3) had already been removed (see Fig. 10).

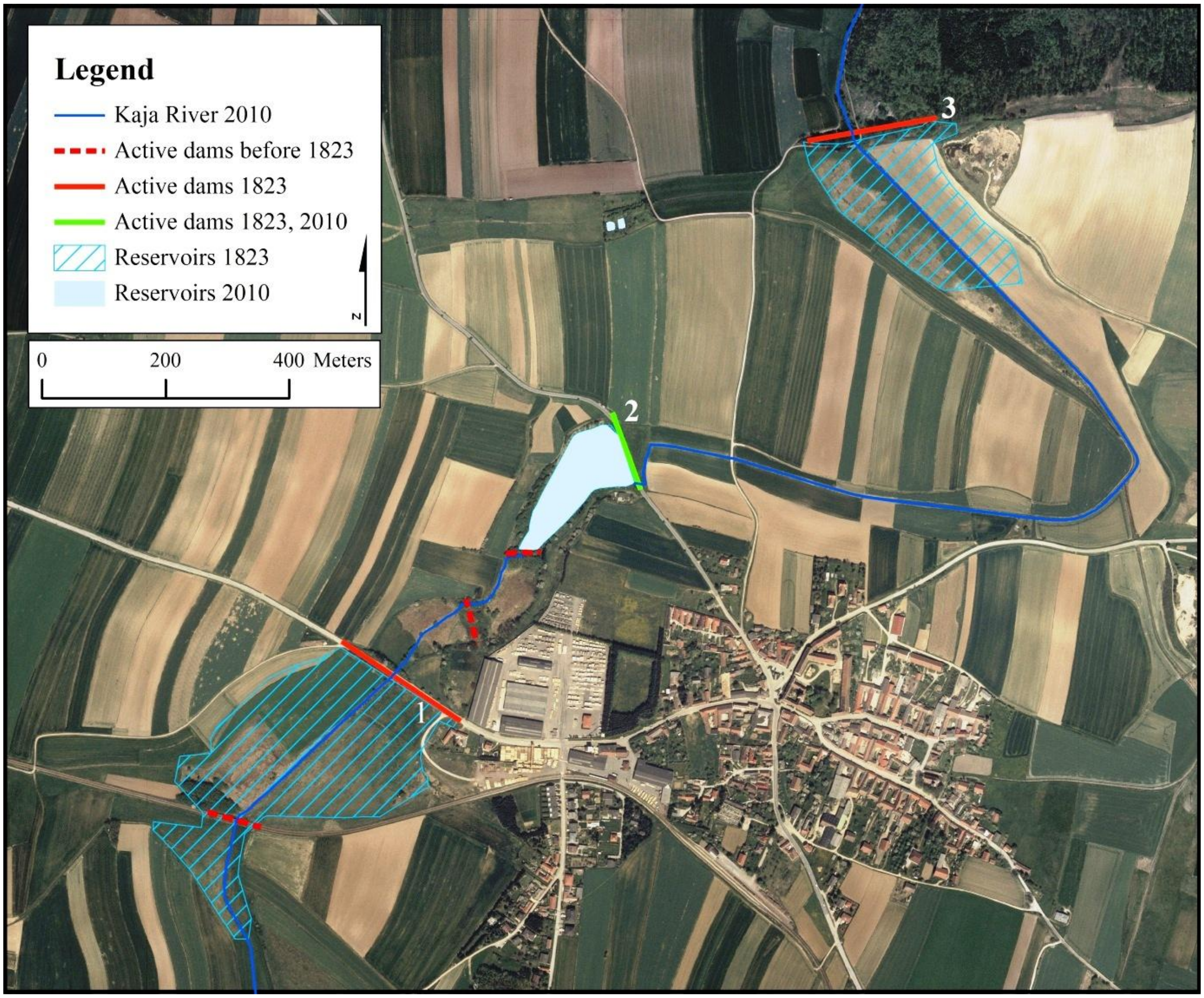


Fig. 10: Map of the study area extent showing active dams and reservoirs of 1823, 2010 and before 1823. Data source (aerial photographs): Provincial state government of Lower Austria 2010. Information on reservoir locations in 1823 have been derived from the "Land register of Francis I" 1823 (data source: BEV Austria 2010). Dam have been numbered from upstream to downstream.. (Source: Poeppl et al. 2012, A.3, p. 201)

Ad research question IIIa) How does the fluvial system respond geomorphically to the installation of dams?

A DEM-based cellular landscape evolution model called CAESAR was utilized to model dam-induced geomorphic channel changes along a river reach of the Kaja River which had been affected by a series of dams in 1823 (see Fig. 10). For this purpose, a DEM from 2010 was adapted according to the river conditions of 1823 in terms of river channel planform geometry, dams and related reservoirs by applying raster editing according to information obtained by digitizing a historical cadastral map of 1823. For details see below: 1) Numerical landscape evolution modeling with CAESAR.

Ad research question IIIb) How does the human system respond to dam-induced geomorphic channel changes?

In order to detect the removal of dams, aerial photographs from 2010 were evaluated and compared with the historical maps of 1823. For details see below: 2) GIS-based mapping techniques and geo-statistical analyses. Field surveys were performed in 2010 to examine the presence and location of river bed and bank protection works. Both, dam removals and the presence of river bed and bank protections structures are viewed as potential indicators for human responses to dam-induced geomorphic effects. For details see below: 3) Field surveys.

Ad research question IIIc) Which geomorphic processes result from dam-induced human responses and how does the human system respond to these processes?

The CAESAR model was used to simulate geomorphic channel changes after dam removal. For this, the output DEM of the 1823 model scenario was adapted by removing dams according to the situation in 2010. For details see below: 1) Numerical landscape evolution modeling with CAESAR. River bed and bank protections structures which had been surveyed in the field (see also research question *IIIb*) are again seen as potential indicators for human responses to geomorphic effects related to dam removal. For details see below: 3) Field surveys.

Ad research question IIId) How do dam-induced process-response feedback loops between the human system and the fluvial system change the landscape metrics in the fluvial environment and can changes in landscape metrics be used as indicators for human-landscape interactions?

Land use maps were created for 1823 and 2010 in ArcGIS by interpreting and digitizing cadastral maps and aerial photographs. Changes of river planform geometry between 1823 and 2010 were analyzed by calculating channel lengths and channel sinuosity in ArcGIS. Land use and land cover changes in the fluvial environment between 1823 and 2010 were evaluated by applying streamside Buffer Analysis and Zonal Statistics in ArcGIS. For details see below: 2) GIS-based mapping techniques and geo-statistical analyses.

1) Landscape evolution modelling with CAESAR

The CAESAR Lisflood 1.2 landscape evolution model (freely available via http://www.coulthard.org.uk/CAESAR.html) was used to model geomorphic responses to dam construction and dam removal. CAESAR is a numerical two dimensional flow and sediment transport model which operates in a cellular automata style used to simulate the evolution of landforms. CAESAR's data requirements are a DEM of the area of interest, either rainfall data (Catchment mode) or water (and sediment) discharges (Reach mode), sediment particle distribution as well as a bedrock depth DEM if required. Two different dam-scenarios were simulated: (a) 3-dam-scenario of 1823 (dam construction) and (b) 1-dam scenario of 2010 (dam removal).

a) 3-dam-scenario of 1823 (dam construction)

A DEM of the whole catchment with a grid cell size of 10 m of 2010 (data source: provincial state government of Lower Austria 2010) was clipped to two different extents: 1) *Catchment DEM*: catchment area of the most upstream dam which has been calculated by using the Watershed Tool of the Spatial Analyst in ArcGIS 10; 2) *River reach DEM*: study river reach. The river reach-DEM was adapted to the physiographic setting of 1823 by filling the river channels which were inherent in the DEM of 2010, and flat floodplain areas were created by applying interpolation within a streamside buffer area of 25 m which corresponds to the extent of the river's natural floodplain area (Poeppl 2010). Finally, river channels were burnt into the DEM by subtracting 1 m according to the river course in 1823. CAESAR was run in catchment mode to generate discharge output data using hourly rainfall data from a raingauge which were available for a period of 10 years (2001 – 2010; data source: Hydrographischer Dienst Niederösterreich). The resulting output was further used as discharge input data for reach mode modelling Sediment particle distribution input parameters were derived from slope and river bed samples (see Table 5) (for more details refer to Poeppl et al. 2012c, A3, p. 204-206).

Table 5: River sediment particle size (% by mass) as input to CAESAR (Data source: Poeppl 2010) (Source: Poeppl et al. 2012c, A.3, p. 205)

Size (mm)	**0.02 (suspended)**	**0.1315**	**0.415**	**1.315**	**3**	**6**	**12**	**23.75**	**60**
% by mass	30	2.4	8.1	16.8	17.1	16.7	6.9	1	1

CAESAR was run for different time-period scenarios according to information on possible dates of dam construction/removal (see Table 6):

- 184 years (1782 – 1966): scenario referring to the max. time of existence of Dam 1
- 151 years (1782 – 1933): scenario referring to the min. time of existence of Dam 1
- 129 years (1782 – 1911): scenario referring to the max. time of existence of Dam 3
- 41 years (1782 – 1823): scenario referring to the min. time of existence of Dam 3

Table 6: Time spans of dam construction/removal; * information derived from a historical aristocratic map of 1782 (data source: Mathias Waldstein 2011) (Source: Poeppl et al. 2012c, A.3, p. 205)

	Dam 1	**Dam 2**	**Dam 3**
Period of construction	≥ 1782*	≥ 1782*	≥ 1782*
Period of removal	1933 - 1966	-	1823 - 1911

The dams were integrated into the modelling procedure by inputting a bedrock-DEM which contained information on bedrock depth as well as on dam height. The integration of this bedrock-DEM layer allowed for limited vertical erosion until the bedrock is reached and flow and sediment to be modelled directly across the dam crest. In order to validate the reach-mode model results for the different time span-scenarios, mean elevation differences between the modelled output DEM and the original DEM of 2010 were evaluated within the reservoir areas of dams 1 and 3. The output DEM of the best fitting time-span scenario was then used as river-reach input DEM for the 1-dam-scenario of 2010 intended to simulate the geomorphic consequences of dam removal. In order to quantify geomorphic changes in the reservoirs and river channels due to dam construction, sediment volume differences in m^3 between the output DEM of the best fitting time-span scenario and the input DEM of 1823 were calculated for each river segment.

b) 1-dam-scenario of 2010 (dam removal)

Dams 1 and 3 were removed from the best fitting DEM output file of the 3-dam-scenario (dam construction) and the bedrock depth DEM of the dam construction scenario was adapted to the conditions of 2010 by removing dams 1 and 3 in ArcGIS and further used as input data (i.e. river-reach DEM, bedrock depth DEM). The same discharge input data and sediment particle distribution parameters as in the 3-dam-scenario (dam construction) were used. The model was run for a period of 44 years according to the time of last dam removal which took place at the latest in year 1966 (see Table 6). In order to quantify geomorphic changes in the river channels and former reservoir areas due to dam removals the same method as described in (a) was applied.

2) GIS-based mapping and geo-statistical analyses

GIS-based mapping and statistical analyses were applied to assess landscape changes between two time periods, the 3-dam-scenario of 1823 and the 1-dam-scenario of 2010. Changes were investigated using data gathered from cadastral maps, aerial photographs and hillshades of a DEM for each of the two time periods where information was available. Changes in the following criteria were considered as indicators for dam-related landscape changes (for more details refer to Poeppl et al. 2012c, A3, p. 201-202):

a) River channel planform geometry (length, sinuosity)
b) Land use and land cover (arable, grass, forest, built up, water)
c) Riparian woodland vegetation (presence/absence)

To relate these changes to the influence of dams, river polyline data was segmented by cutting the lines at dam crests and at locations where the river enters the reservoir. This created two different categories of river segments based on location, i.e. they are located (1) in a recent or former reservoir or (2) downstream of a recent or former dam crest (= upstream of a recent or former reservoir). For each river line segment a statistical analysis was performed in order to examine changes of river channel planform geometry and riparian woodland vegetation. River segment length and sinuosity was calculated using the Line Metrics Tool of Hawth's Analysis Tools Extension for ArcGIS (Beyer 2004). In order to examine land use changes in the surrounding areas of each river segment, streamside Buffer Analysis and Zonal Statistics in ArcGIS were applied within a stream side buffer area of 25 m (natural floodplain area).

3) Field surveys

River bed and bank protection works were surveyed along each river channel line segment in the field. Since these structures are generally built to mitigate unintended dam-induced geomorphic effects they are therefore assumed to be indicators for human responses to geomorphic processes. If detected in the downstream reaches of active dams or in abandoned reservoirs, the presence of these structures was related to dam-induced geomorphic effects.

5. Overview of case studies

The study area locations of each of the case studies (1-6) are displayed in Fig. 11. An overview of catchment name, size, specific topic of investigation, type and duration of human impact, spatial scale of observation, geographic environment as well as the applied methods is given in Table 7. More detailed information on the different study sites as well as on the utilized data is presented in the respective method description in chapter 4.

Fig. 11: Case study locations. *) Case studies 1, 5, 6. Case studies 1, 6: Kaja catchment, Austria; case study 5: Fugnitz catchment, Austria. 2) Barranco de las Lenas, Spain, 3) Dragonja catchment, Slovenia, 4) Gimbach catchment, Austria. (Source: Poeppl et al. 2012a, A.1, p. 149)

Table 7: Overview of the presented case studies providing information on catchment name, size and location, topic of investigation (incl. related hypothesis), type and temporal scale of human impact, spatial scale of observation and geographic environment for each case study ("No.").

No.	**Catchment name, size, location**	**Topic of investigation; related hypothesis**	**Type of human impact**	**Duration of human impact**	**Spatial scale of observation; methods**	**Geographic environment**
1	Kaja, 21.3 km^2, NE Austria	Human-induced alterations of longitudinal and vertical sediment connectivity and fluvio-geomorphic response; hypothesis I	Dams	> 220 years	Reach scale; sediment analyses, geom. mapping	Temperate climate, low mountain range
2	Gimbach, 2.8 ha, Central Austria	Human-induced alterations of longitudinal sediment connectivity and the importance of self-regulatory system properties; hypothesis I	Dams	120 years	Reach scale; conc. modeling, monitoring of channel development	Temperate climate, high mountain range
3	Barranco de las Lenas, 51.3 ha, NE Spain	Human-induced alterations of lateral sediment connectivity and fluvio-geomorphic response; hypothesis I	Land use change	50 years	Catchment scale; GIS-based flowpath analyses, monitoring of channel development	Semi-arid climate, continental Mediterranean basin
4	Dragonja, 91 km^2, SW Slovenia	Human-induced alterations of lateral sediment connectivity and the importance of self-regulatory system properties; hypothesis I	Land use change	50 years	Catchment scale; hydrological and sediment budget analyses, geom. mapping	Sub-Mediterranean hills
5	Fugnitz, 138.4 km^2, NE Austria	Influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes; hypothesis II	Land use change	~ 750 years	Catchment scale; GIS-based modelling, field surveys, multivariate statistics	Temperate climate, low mountain range
6	Kaja, 21.3 km^2, NE Austria	Dam-induced landscape change and the role of human-landscape interactions; hypothesis III	Dams	> 220 years	Reach scale; landscape evolution modelling, field surveys, GIS-based mapping	Temperate climate, low mountain range

6. Results

This chapter provides an overview of primary results of the six case studies undertaken to meet the hypotheses and objectives presented in this thesis. For a more detailed account of specific findings, please refer to respective article from which the results were taken.

6.1 Human impacts on sediment connectivity in fluvial systems and fluvio-geomorphic response

6.1.1 Conceptual model linking human-induced changes of sediment connectivity with geomorphic channel processes

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

Sediment connectivity in fluvial systems can be described as the potential "transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system" (Hooke 2003, p. 79). The main assumption upon which the development of the conceptual model is based on is that direct as well as indirect human impacts modify sediment connectivity on the different spatial dimensions by hindering or forcing sediments to move through the fluvial system. Human-induced modifications of sediment connectivity are further assumed to result in geomorphic channel changes due to changing ratios of stream power and sediment supply within the river channel.

The geomorphic state of a river system is primarily governed by two critical elements, namely the stream power available to transport sediments, and the sediment supply. A balance between stream power and sediment supply exists which is commonly used to estimate geomorphic river response to changes. This balance has been described by Lane (1955) with the following equation:

$$Stream\ power\ P\ (Qw\ \times S)\ \propto Sediment\ supply\ SS\ (Qs\ \times\ D50)$$

Qw…stream discharge, S…stream slope, Qs…sediment load, $D50$…median grain size of the sediment load

If the stream power is sufficient to transport the sediment load, both sides are in balance and the system is in "equilibrium". This means that no net erosion and deposition takes place in the respective river reach. However, an imbalance in this equation leads to significant geomorphic channel changes. If stream power exceeds sediment supply, channel degradation takes place resulting from an excess of energy and erosive power (Stream power P > Sediment supply SS → Degradation D). Conversely, in the case of sediment supply exceeding the ability of a river to transport these sediments, aggradation occurs and causes net deposition (Stream power P < Sediment supply SS → Aggradation A). Imbalances are assumed to be caused by human impacts that induce changes of sediment connectivity on the different spatial dimensions. In the following it is conceptualized how human impacts can alter sediment connectivity on the different spatial dimensions (a) longitudinal, b) lateral, c) vertical) and how these changes are related to geomorphic changes in the channel system. This is done by conceptually linking human-induced changes of sediment connectivity to the model assumptions of Lane (1955):

a) Longitudinal sediment connectivity

A decrease of longitudinal sediment connectivity can be caused by direct human impacts such as the installation of a dam which hinders sediment to move downstream (see Fig. 12). A dam unbalances the ratios between stream power (P) and sediment supply (SS) thus inducing sediment retention and accumulation upstream (P < SS → A) and degradation downstream (P > SS → D) (e.g. Williams and Wolman 1984, Grant et al. 2003). Conversely, human impacts that force the propagation of water and sediments downstream such as the flushing of reservoirs or dam removals increase longitudinal sediment connectivity which is followed by upstream degradation (P > SS → D) and downstream accumulation (P < SS → A) (e.g. Wildman and MacBroom 2005, Burroughs et al. 2009).

b) Lateral sediment connectivity

Lateral sediment connectivity is increased by indirect human impacts such as deforestation in the catchment which generally increases lateral sediment input to the river channels due to enhanced soil erosion rates (see Fig. 12). This causes channel aggradation as a result of sediment supply exceeding stream power (P < SS → A) (e.g. Connor 1986, Miller and Benda 2000, Kasai et al. 2005). Afforestation or reforestation is expected to show the opposite effects (P < SS → A) (e.g. Madej and Ozaki 1996, Kasai et al. 2001, Keesstra 2007). Furthermore, human-induced changes of overland flow routing in the catchment such as by the construction of roads can cause an alteration of lateral sediment connectivity (e.g. Seeger et al. 2009; Poeppl et al. 2012b, A.2). Roads running perpendicular to the hillslope are assumed to decrease lateral sediment connectivity due to the introduction of a surface morphology breakline reducing the transport capacity of water and sediments. Conversely, roads running perpendicular to the hillslope are expected to enhance lateral connectivity as flow is collected and directed downslope until reaching the river channel.

c) Vertical sediment connectivity

Human impacts that lead to an increase or decrease of sediment exchange between the channel subsurface and the channel itself results in an alteration of vertical sediment connectivity (see Fig. 12) as well as in the ratios between stream power (P) and sediment supply (SS) leading to channel degradation or aggradation. Vertical sediment connectivity can be directly decreased by human-induced bed armouring either due to river bed protection works such as by the installation of rock armour, or indirectly by bed armouring and imbrication which often occurs downstream of dams (e.g. Williams and Wolman 1984, Xu 1990). Bed armouring limits bed erosion and also subsurface sediments to reach the channel which potentially causes channel degradation in unprotected channel reaches further downstream due to stream power exceeding sediment supply (P > SS → D). When natural channel bed armouring is destroyed by human activities such as gravel extraction from the river beds and large volumes of readily moveable sediments are released channel and aggradation may occur in the downstream reaches (P < SS → A).

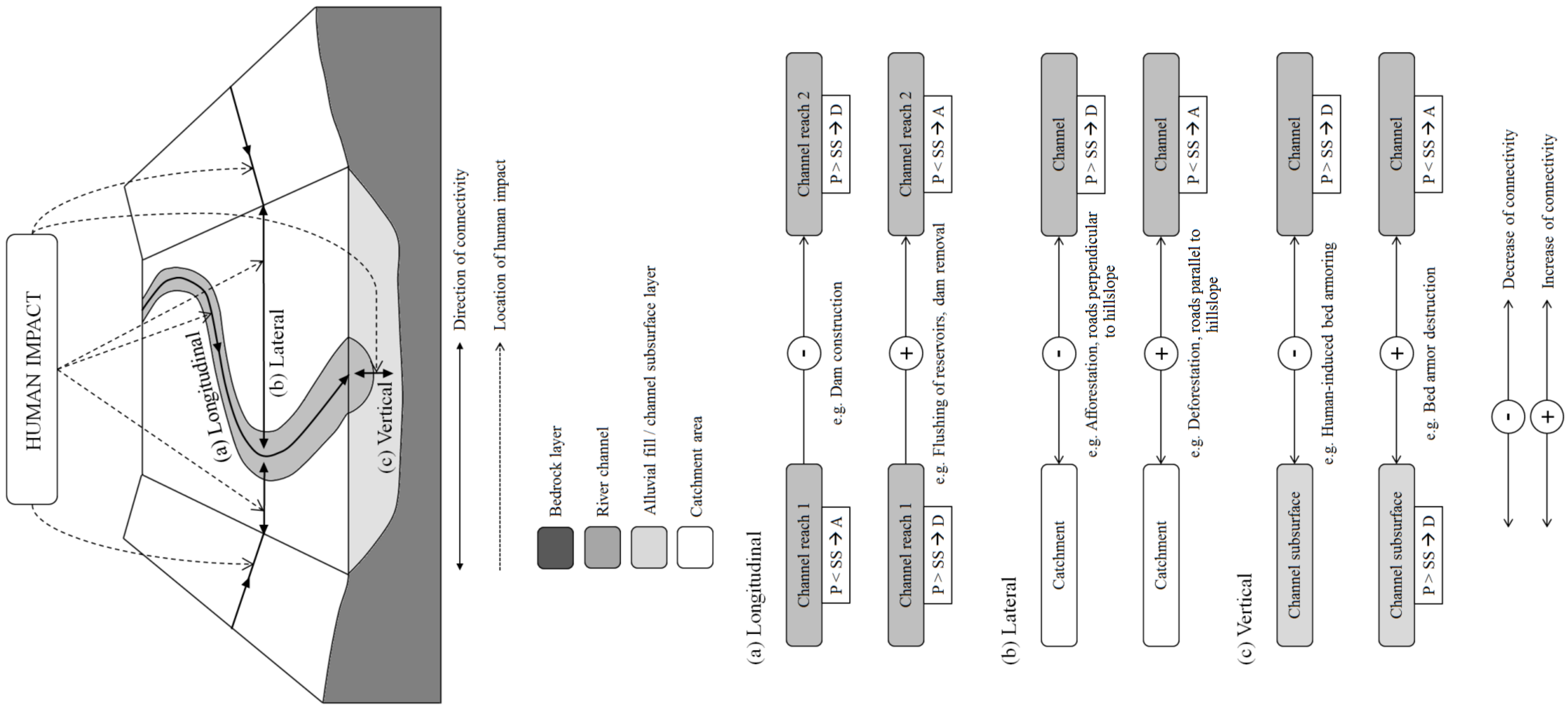


Fig. 12: Conceptual model on human-induced changes of sediment connectivity on different spatial dimensions. These changes cause an imbalance between stream power (P) and sediment supply (SS) which leads to degradation (D) and aggradation processes (A) in the channel system. (Source: Poeppl et al. 2012a, A.1, p. 145)

It is generalized in the presented conceptual model that an increase in sediment connectivity leads to channel aggradation, whereas a decrease leads to channel degradation: If sediment connectivity is decreased less sediment reaches the river channel causing an excess of energy and erosive power ($P > SS \rightarrow D$); if sediment connectivity is increased more sediment reaches the river channel causing an excess of sediment supply which results in net deposition ($P < SS \rightarrow A$). Geomorphic adjustments within river systems further depend on other factors such as boundary conditions (e.g. channel substrate, riparian vegetation, valley confinement etc.), climate, event-magnitude, self-regulatory properties of the system as well as the individual system history.

It is assumed that after human-induced changes of sediment connectivity, self-regulatory properties of the system can lead to a recovery of the original connectivity conditions as a function of vegetation regrowth and geomorphic events. After human-induced alterations of lateral sediment connectivity caused by land use change, self-regulatory properties of the system that are related to vegetation growth lead to a recovery of the original connectivity conditions. It is conceptualized in Fig. 13 that human impact in terms of deforestation causes a significant increase of lateral sediment connectivity due to bare soils and increased soil erosion rates. After deforestation, assuming that no further impact occurs, vegetation recovery takes place until the vegetation cover is fully regrown and the lateral connectivity conditions have recovered (i.e. “recovery time”). However, if agricultural land use remains, a new system state in terms of lateral sediment connectivity establishes (i.e. “post-impact state”).

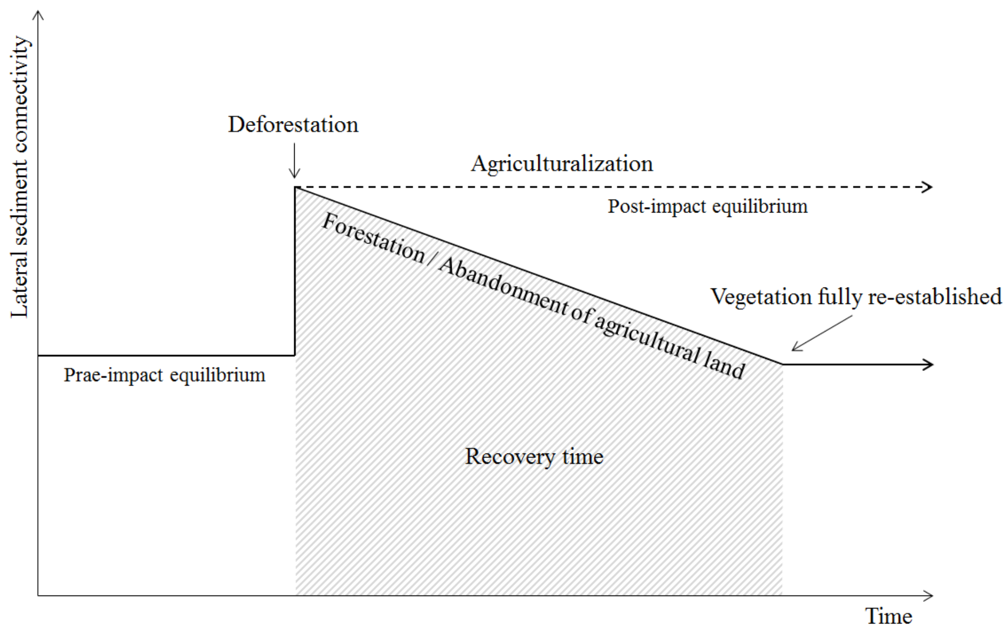


Fig. 13: Recovery of lateral sediment connectivity after deforestation. Vegetation succession takes place until vegetation cover has potentially fully re-established and connectivity conditions are recovered (i.e. "recovery time"). If deforestation is followed by agriculturalization, a new system state in terms of lateral sediment connectivity establishes (i.e. "post-impact state"). (Source: Poeppl et al. 2012a, A.1, p. 146)

Other self-regulatory properties include geomorphic processes and events that reduce the disconnecting efficiency of human-induced features such as dams over time due to continuous and stepwise sediment infilling until a reconnection between the up- and downstream channel reaches occurs (i.e. "recovery time") (see Fig. 14). During mean and low flow conditions continuous infilling takes place where fine sediments are accumulated in the dam impoundments. During high magnitude events stepwise infilling occurs where large amounts of coarse material are deposited. A total infilling of the impoundments results in a reconnection of the up- and downstream reaches. Moreover, high-magnitude geomorphic events such as floods or scouring can lead to dam failure followed by an instantaneous release of water and sediment during a flash flood accompanied by a short-duration increase of sediment connectivity and reconnection of up- and downstream channel reaches in longitudinal direction (see Fig. 15).

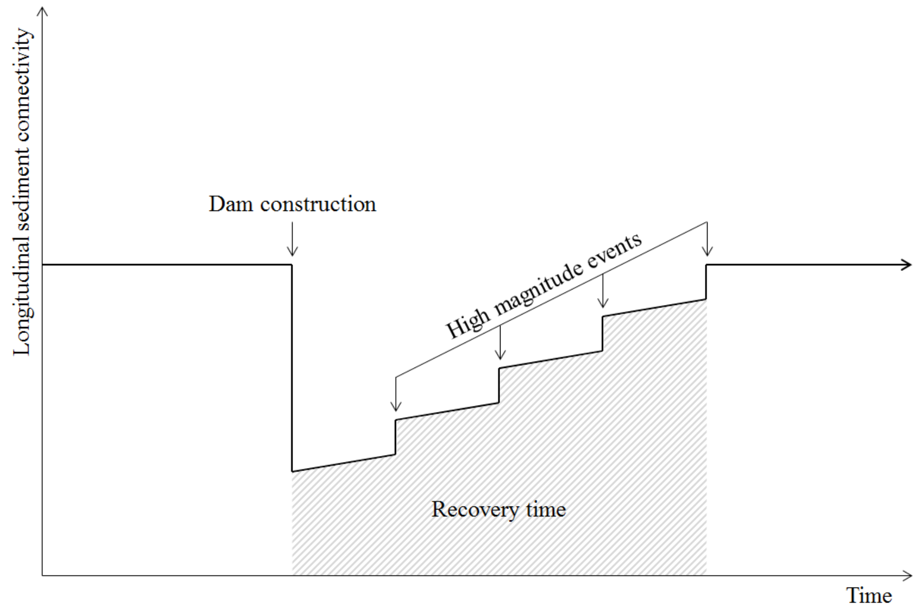


Fig. 14: Recovery of longitudinal sediment connectivity over time (i.e. "recovery time") due to continuous and stepwise sediment infilling after dam construction. Continuous infilling occurs during mean and low flow conditions, while stepwise infilling takes place during high magnitude events leading to a reconnection of the up- and downstream river reaches. (Source: Poeppl et al. 2012a, A.1, p. 147)

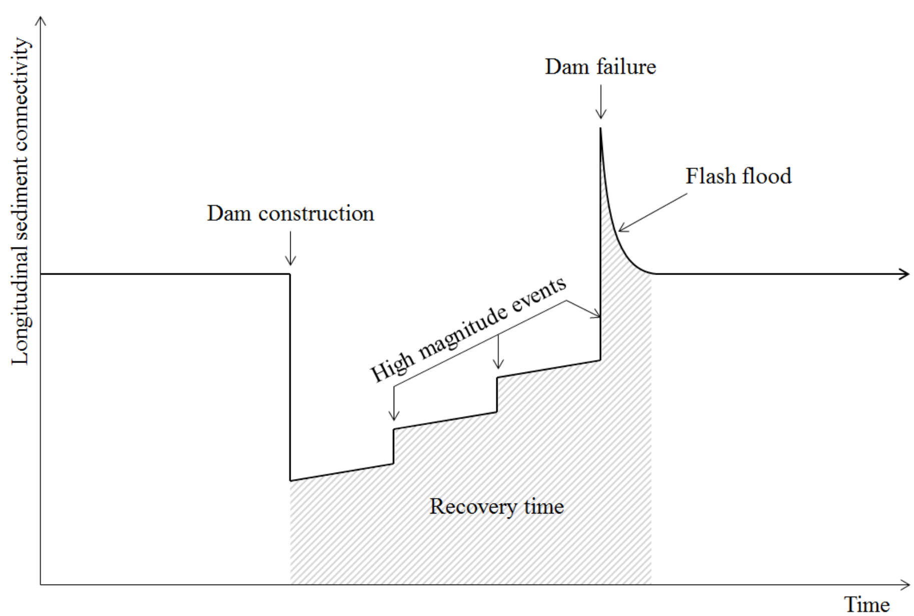


Fig. 15: Recovery of longitudinal sediment connectivity over time (i.e. "recovery time") due to continuous and stepwise sediment infilling after dam construction. Continuous infilling occurs during mean and low flow conditions, while stepwise infilling takes place during high magnitude events. Dam failure leads to an instantaneous reconnection of up- and downstream channel reaches and causes a flash flood which is accompanied by a short-duration increase of sediment connectivity. (Source: Poeppl et al. 2012a, A.1, p. 148)

6.1.2 Testing the conceptual model that links human-induced changes of sediment connectivity with geomorphic channel processes

(1) Dam construction

Case study 1 - The effects of the Sagteich dam on the longitudinal and vertical sediment connectivity of the Kaja River, Austria

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

The river bed sediment analysis showed a downstream deficiency of fine to medium-sized gravels (11 mm – 16 mm) as well as river bed sediment coarsening (see Fig. 16). These findings indicate downstream degradation (P > SS → D) due to dam-induced bedload retention and sediment disconnectivity in longitudinal direction. Nevertheless, the reworking of old alluvia and old reservoir sediments which are still stored in the downstream reaches prevent from a total lack of river bedload (see also Fig. 8). More than 70% of the total suspended sediment load is reduced by the dam (=trap efficiency) (see Fig. 16), retaining the silt fractions while clay fractions are transported through the impoundment until crossing the dam crest (see Fig. 17). Therefore, the dam causes a grain size- selective reduction of longitudinal suspended sediment connectivity. The results of the facies mapping showed that river bed armouring occurred directly downstream of the dam (see Fig. 8). The observed bed armouring is thought to be related to degradation processes caused by a dam-induced unbalance of stream power and sediment supply that results in a decrease of vertical sediment connectivity in these river reaches.

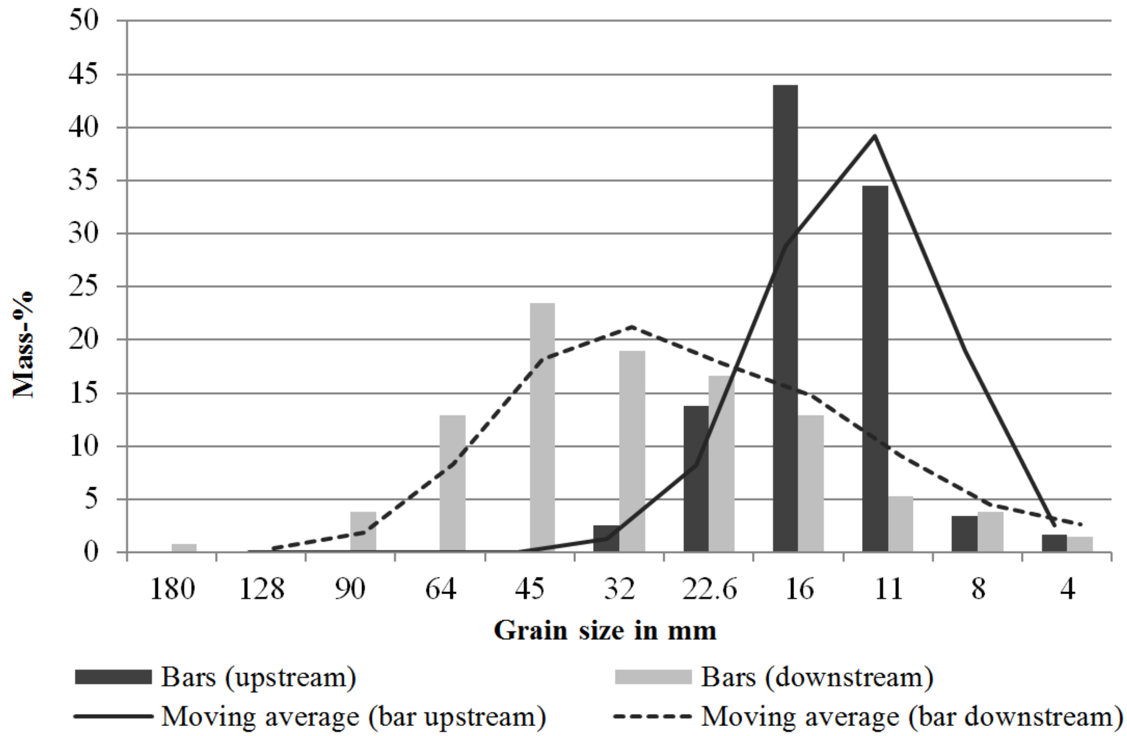


Fig. 16: Results of the Wolman pebble counts (Source: Poeppl et al. 2012a, A.1, p. 151)

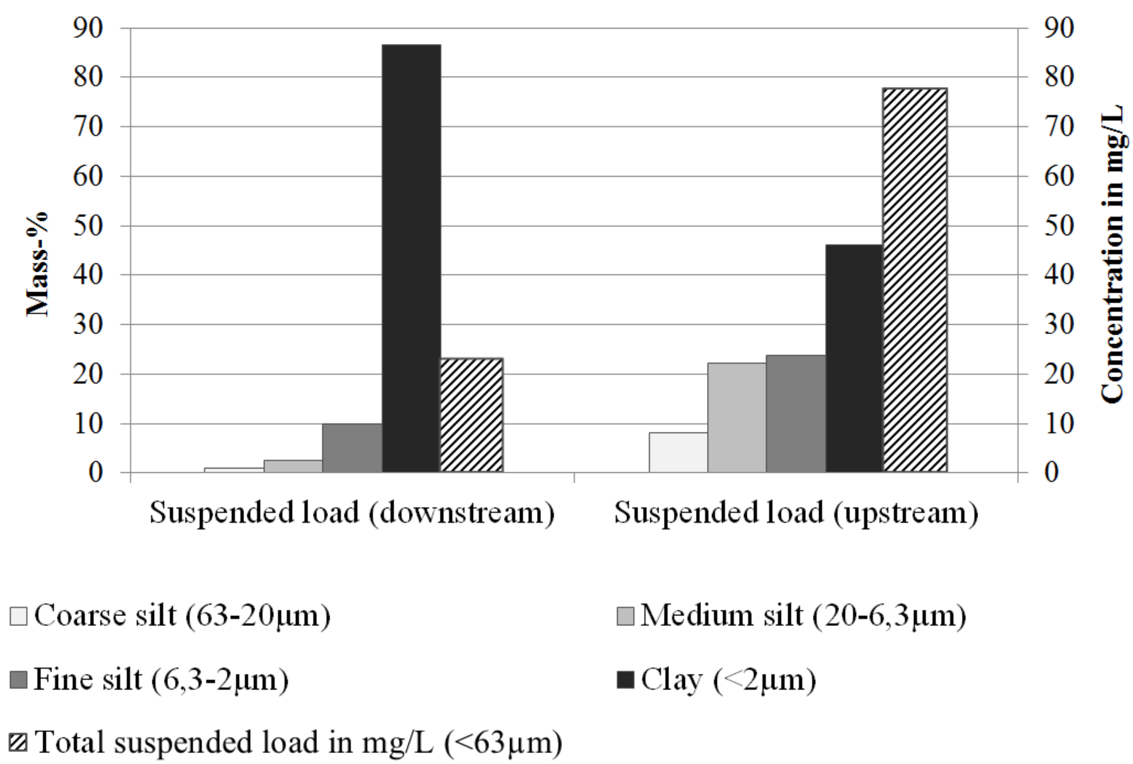


Fig. 17: Results of suspended sediment load sample analysis (Source: Poeppl et al. 2012a, A.1, p. 152)

Case study 2 - Check dams and longitudinal sediment connectivity - examples from the Gimbach catchment, Austria

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

Extreme events such as torrents in steep mountain streams are characterised by a range of geomorphic processes that involve sudden morphological changes in individual channel reaches like intense local erosion or deposition and remobilisation of bedload. Technical mitigation concepts are often implemented to mitigate hazards in these areas including technical structures along channel systems and channel tracks as well as in the deposition areas (Holub and Fuchs 2009). In order to structurally support the upstream bank slopes in steep mountain streams, a series of check dams can be implemented along the channel which promotes the deposition of material in areas of impoundment and stabilises the channel bed by preventing vertical erosion from occurring. The construction of a series of check dams is based on the overarching principle that every check dam in this series protects the foundation of the upstream one from scouring, and a deposition area with a modified channel gradient φ' compared to the original steeper channel gradient φ is built up (see Fig. 18). With this, the series of check dams is targeted at a bedload equilibrium preventing further vertical erosion of the channel bed. Bedload and flood discharge become longitudinally disconnected and the original complex interaction between erosion and deposition (that include the remobilisation of sediment during periods of high discharge) is prevented until the local erosion basis given by the height of the overflow section of every individual check dam.

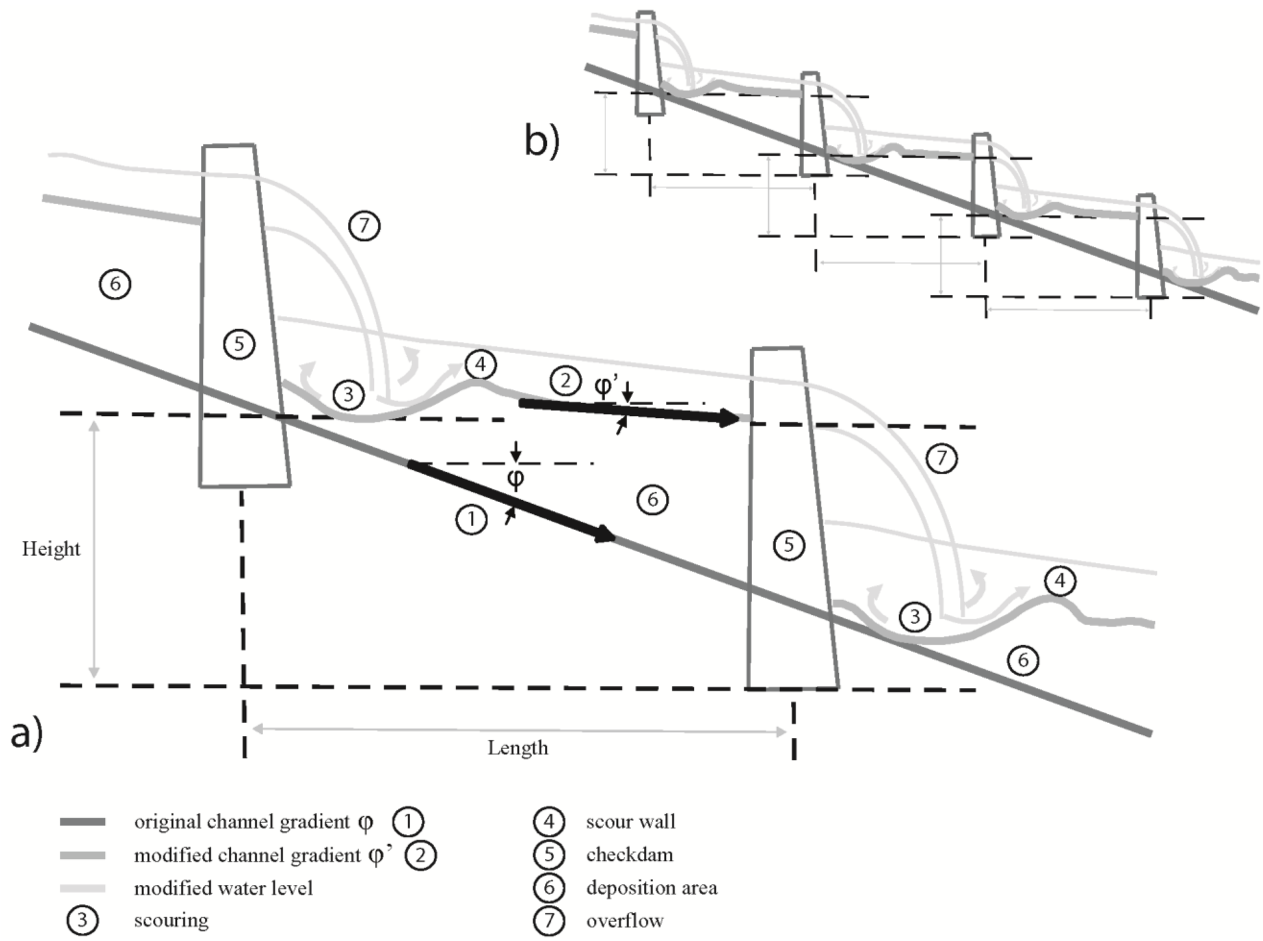


Fig. 18: Schematic cross-section of a check dam series. a) Between two check dams (5) the original channel gradient (1, φ) is modified (2, φ') due to the overall amount of material deposited on the upstream side (6) of each check dam. The development of scour (3) and a scour well (4) is created due to energy dissipation resulting from dam overflow (7). Both the amount of material deposited and development of scour affects the height and the length of the check dam series (5). b) The overall reduction of the channel gradient due to the implementation of a check dam series (modified from Boell 1997). (Source: Poeppl et al. 2012a, A.1, p. 157)

Structural mitigation has its limitations (Fuchs 2009). If the ratio between the length and height of a series of check dams is not properly chosen, scour develops over time at the lowest check dam which results in the destabilisation of the foundation of this structure. As a result of scouring, the channel can become reconnected in longitudinal direction (Fig. 19).

Fig. 19: Scouring of a check dam in the Gimbach catchment (2.8 ha), Austria, due to suboptimal localization and subsequent reconnection within the channel system. The check dam in this figure was constructed in the 1900s (the exact year of construction is unknown). In 2010, the height of the scour is approximately 2 m. Photograph courtesy of Fuchs, 2010 (Source: Poeppl et al. 2012a, A.1, p. 158)

Furthermore, reconnection between the upstream and downstream river reaches can be further caused by aggradation processes (Fig. 20) that depend on the volume of discharge and sediment load. Given enough sediment load, the deposition area within the impoundment will be filled to the height of the dam crest. Upstream of the dam, the channel gradient adjusts to an angle that has a maximum angle equal to the modified channel gradient ((2) in Fig. 18). If the optimal distance between two subsequent check dams is not met or the rates of infilling are underestimated, aggradation can lead to a reconnection in longitudinal direction over time (Fig. 20).

Fig. 20: Aggradation processes resulting in longitudinal reconnection in a check dam series. (Gimbach torrent, Austria. Photograph courtesy of Fuchs, 2010) (Source: Poeppl et al. 2012a, A.1, p. 159)

(2) Land use change

Case study 3 - The effects of dirt roads on lateral connectivity in the Barranco de las lenas catchment, NE Spain

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

Gully development is considered being a phenomenon of high spatio-temporal variability (Fitzjohn et al. 1998, Gábris et al. 2003) and non-linearity (Sidorchuk 2005). Generally, as gully-growth is driven by headcut retreat, the supply of concentrated overland-flow is crucial for gully development. In semi-arid climates overland-flow is generally reduced to low frequency and high magnitude events and a relationship between the mid-term volume loss on gully headcuts and the

catchments size has been identified (Marzolff et al. 2011). Furthermore, catchment size has been shown to regulate the water supply to the headcut. Human-induced modifications of the flowpaths in the catchment due to the building of roads is therefore assumed to significantly affect the gully development, since overland flow connectivity may be enlarged (increasing the catchments size), reduced (cutting down flow paths) or re-directed (leading water flows towards different sites).
Without the presence of a dirt road, flow accumulates at the gully-headcut (Fig. 21a). Conversely, the introduction of a dirt road led to a clear interruption of flow from the headcut catchment towards the gully which caused a reduction of lateral hydrological connectivity that resulted in reduced gully activity and reduced gully headcut retreat (Fig. 21b).

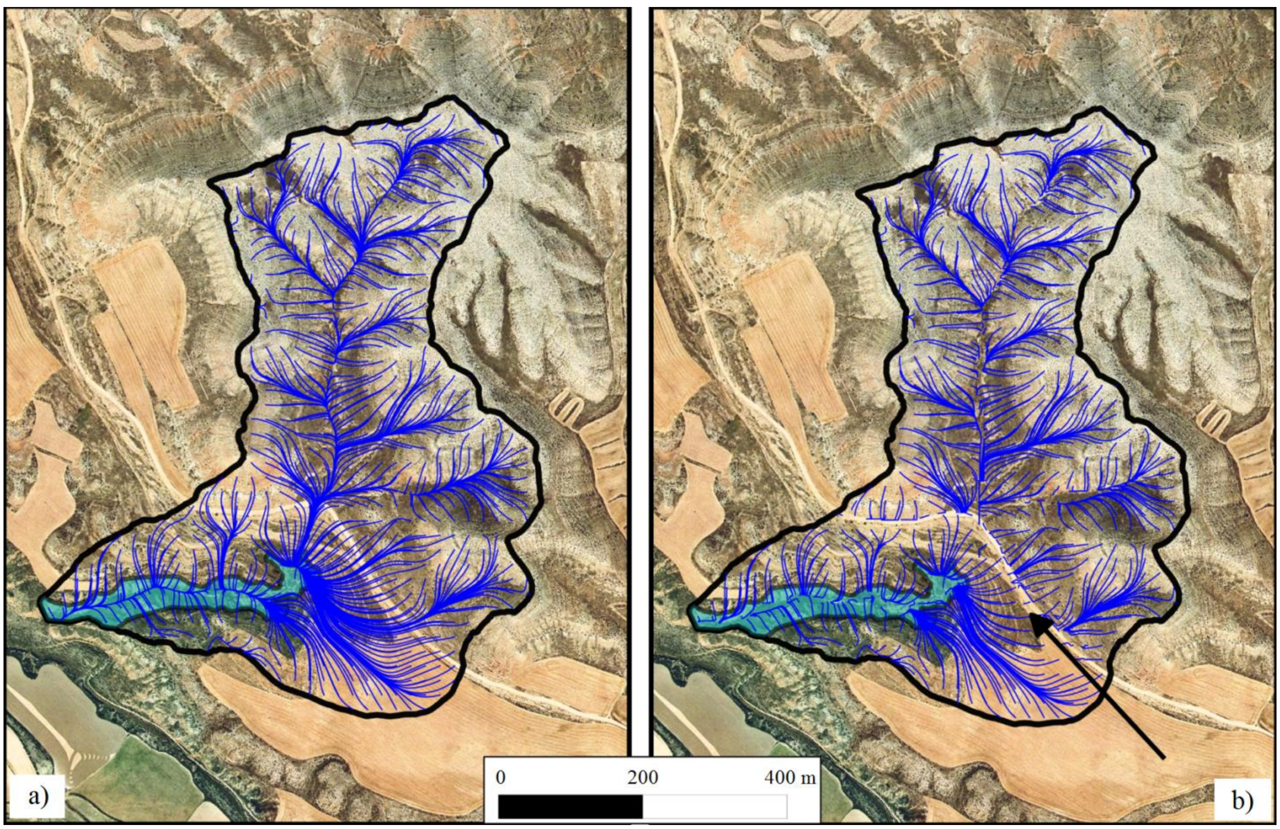


Fig. 21: Flowpath analysis of the catchment of the Barranco de las Lenas gully. a) Flowpaths of hydrological consistent DEM, b) with incision of the dirt road (3 m width, 0.5 m depth). The black arrow marks the generalized flow interruption by the modeled dirt road. Dark blue lines indicate modelled flow lines; light blue polygons indicate gully boundaries and black polygons indicate boundaries of the total gully catchment. (Source: Poeppl et al. 2012a, A.1, p. 156)

Case study 4 - Investigations on lateral sediment connectivity in the Dragonja catchment, SW Slovenia

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A.1)

Reforestation due to land abandonment has led to significant changes of lateral sediment connectivity as a function of vegetation regrowth which were accompanied by geomorphic channel changes. The re-establishment of dense forest vegetation cover caused a 90%-decrease of sediment influx into the channel. Moreover, the water influx from the hillslopes to the channel system decreased due to a higher water demand of the trees. However, the hydrological analyses revealed that changes of water supply to the channels was not as large as the changed sediment supply which changed the ratio of stream power and sediment supply, leading to channel incision (P > SS → D).

Channel incision occurred in two phases. In the first phase, incision occurred after the large-scale abandonment of agricultural land becoming bare fields. These bare fields most susceptible to erosion were then quickly invaded by pioneer herbs and grasses. This led to a significant decrease of the sediment influx from the hillslopes to the channel, while the water discharge had not changed considerably which caused channel incision at a depth of approximately 2 m (see Figs. 22 and 21). The second phase of channel incision occurred about 30 years after the initial land abandonment after a full-grown forest had developed on the former fields. The higher water demand of trees caused a lower water discharge in all periods of the year (Keesstra 2007). Base flow was lowered due to a higher water demand required by the trees compared to the former field crops. Lowering of peak flows has been related to higher interception and infiltration rates caused by the larger leaf area and looser soil structure due to higher root density and litter layers. As a result of higher peak flows, the gravel bars in the river channel began to stabilize as becoming overgrown by pioneer vegetation further contributing to their stabilization. These bars form the current floodplain area and the river meanders and incises into its now oversized channel bed (see Figs. 22 and 23).

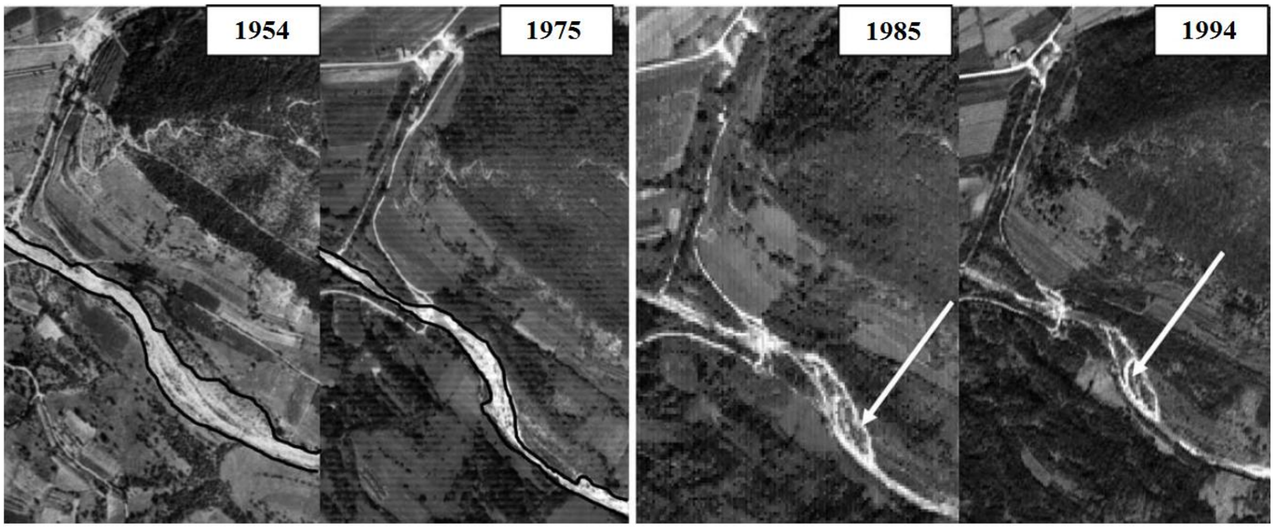


Fig. 22: Geomorphic channel changes of the Dragonja River. The narrowing and incising of the river is clearly visible on aerial photographs taken from the area just upstream from the confluence of the Dragonja River and the Rokava River, its major tributary. Channel narrowing is identified by black borders, while channel incision is indicated by white arrows. From left to right, the photographs were taken in 1954, 1975, 1985 and 1994. (Source: Poeppl et al. 2012a, A.1, p. 153)

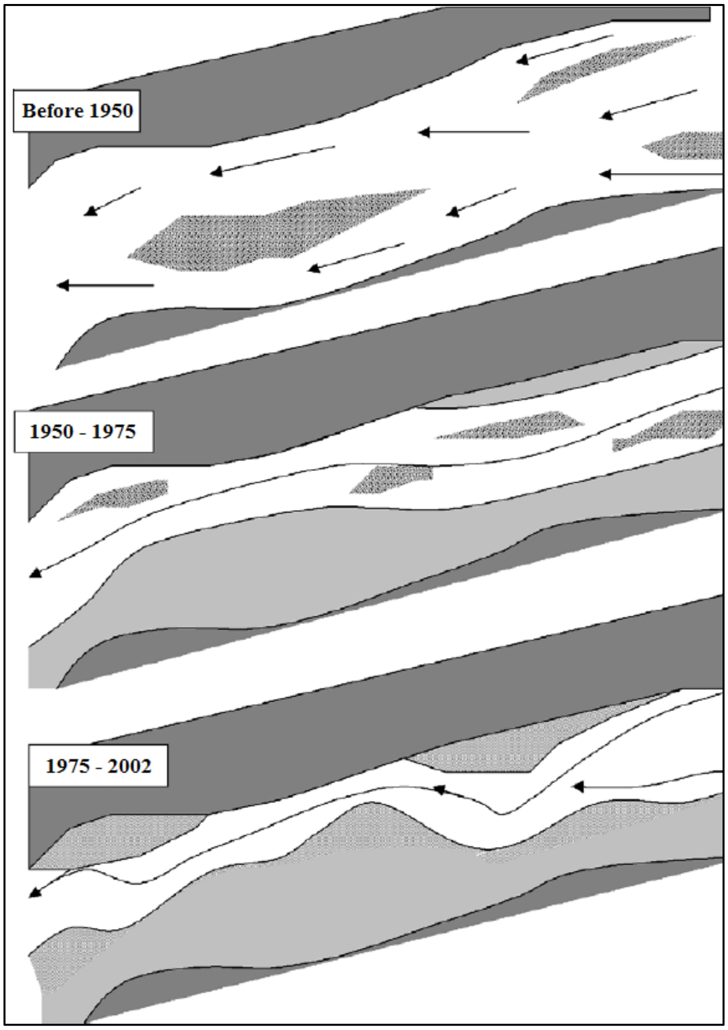


Fig. 23: Geomorphic channel changes of the Dragonja River from 1950 to 2002 derived from geomorphological mapping of the area. Prior to reforestation (before 1950), the river was braiding at some sites. From 1950 to 1975, the river incised and formed a terrace around 1.5 m above the current river level. From 1975 to 2002, incision continued, and the river started to meander along the old riverbed. (Source: Poeppl et al. 2012a, A.1, p. 154)

6.2 Lateral buffering and the role of riparian vegetation cover

6.2.1 Conceptual model on lateral buffering with special consideration of riparian vegetation cover

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A.2)

A reduction of sediment connectivity between hillslopes and the river channel is often related to the presence of topographical features inherent in the landscape that can act as sediment stores and sinks along sediment transport pathways (see Brunsden and Thornes 1979, Phillips 1992, Harvey 2002, Michaelides and Wainwright 2002, Hooke 2003). Apart from such topographical features, lateral sediment connectivity is also reduced by vegetation cover, as vegetation increases the hydraulic roughness and infiltration rates (from plot- to catchment scale: e.g. Le Bissonnais et al. 2004; on plot- to mesoscale: e.g. Borin et al. 2005, Deletic 2006) resulting in a reduction of transport capacity leading to sediment deposition (Wu et al. 1999, Wilson et al. 2005) and sediment trapping (Dabney et al. 1995, Meyer et al. 1995, Leguédois et al. 2008, Keesstra 2007, Keesstra et al. 2009a). Furthermore, sediment trapping is likely to occur in the backwater areas of tree belts, and micro-terraces form due to sedimentation processes (e.g. Leguédois et al. 2008). These features are assumed to emerge from biogeomorphic processes and further act as disconnectors between the different landscape compartments, especially in low-relief areas like valley floors.

Overland flow is the basic requirement for sediment connectivity between the hillslopes and the river channels (see Fig. 24). When sediment particles are entrained within the upland area/hillslope zone at location A1, they are routed along overland flow pathways until reaching location B1. Here, sediment particles can be deposited in the valley floor zone if the transport capacity changes due to an abrupt decrease of slope angle in relation to the presence of surface morphology breaklines. If overland flow is sufficient to overcome these breaklines, sediment can be routed further along the overland flow pathways within the valley floor zone or sediments will accumulate at location A2. Sediments can be remobilized and transported further during a later overland flow event until they meet the river channel zone. If sediment is mobilized at location A2 in valley floor zone, it is transported until transport capacity declines due to resisting forces and sediment is deposited. Sediment is either deposited in the riparian zone (location B2), or transported further to the river channel zone, where the material is temporally stored or transported downstream (location B3).

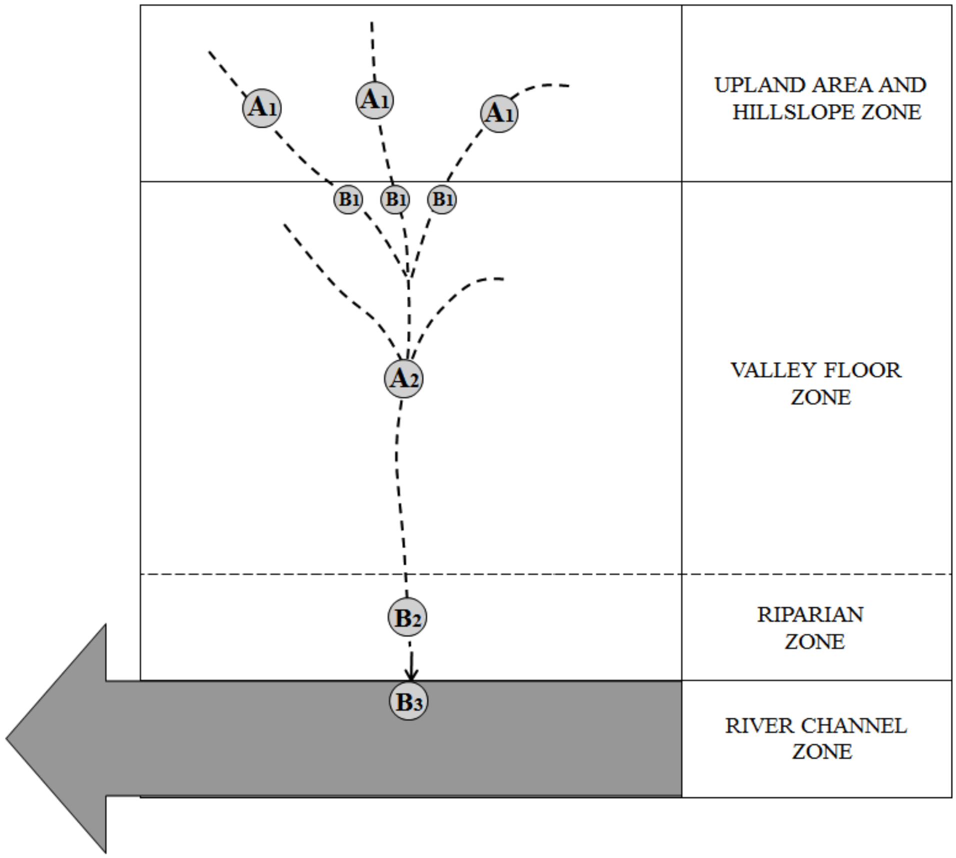


Fig. 24: Conceptual model of sediment entrainment, transport and accumulation processes along hillslope to channel overland flow pathways. Dashed arrows show potential overland flow pathways. The grey shaded arrow symbolizes the river channel. A1 and A2 in grey shaded circles show locations of potential sediment mobilization due to soil erosion processes, whereas B1, B2, and B3 indicate potential locations of sediment deposition or remobilization. (Source: Poeppl et al. 2012b, A.2, p. 171)

The type of process (erosion, transport, accumulation) and the location where the respective process occurs in at catchment depends on a range of factors that govern sediment generation and sediment transport processes. Erosion rates in the catchment are influenced by factors including rainfall pattern, lithology, soil type, topography, land use/land cover and management practices and sediment transport by water requires the presence of overland flow pathways. Sediment transport capacity and hence lateral sediment connectivity is governed by slope angle, surface roughness and the availability/amount of water. In general, transport capacity increases with slope angle and flow accumulation and is further affected by slope profile curvature. Sediment transport capacity is also influenced by surface roughness and soil infiltration capacity as physical and biological thresholds have to be exceeded (Puigdefabregas et al. 1999, Cammeraat 2002, Croke et al. 2005). As infiltration rates and/or hydraulic roughness are increased in vegetated zones, sediment transport capacity is expected to decrease in the riparian zones due to the presence of dense vegetation. Sediment deposition is therefore assumed to be related to the type of riparian land use and vegetation cover. A decrease in sediment transport capacity is further expected to be related to sediment trapping which occurs in the backwater reaches of tree roots, trunks and depositional features called root dams that emerge from biogeomorphic processes in forested riparian zones. It is assumed that dam-like geomorphic features called root dams form parallel to the stream channel as they emerge polygenetically from biogeomorphic processes due to a variety of reasons which are hypothesized below:

- Surface roots of trees and shrubs have a soil-binding function (Rawnsley 1991) that protects the underlying material from erosion. In contrast, adjacent agricultural areas with fewer surface roots exhibits a higher potential for erosion and loss of material which leads to elevation differences between protected and unprotected surfaces.
- Natural levees preferably form in forested riparian zones due to the decreased transport capacity caused by trees leading to a high reduction of transport capacity which induces sediment deposition. Thus, the occurrence of flood events can also be a major factor for enhancing the establishment of root dams.
- Surface tree roots and trunks of trees and shrubs act as natural obstacles to overland flow and sediment. Surface tree roots and trunks induce backwater areas and cause flow separation which alters the hydraulic conditions and influences the sediment transport capacity of overland flow. Moreover, infiltration rates of forest soils are comparatively high due to soil loosening caused by root action (e.g. Carmean 1957). These factors lead to a reduction of sediment transport capacity followed by sediment accumulation in front of tree roots and trunks at location A which is conceptualized in Fig. 25 (stage 1, see Fig. 25a). It is hypothesized that dense treelines lead to synergistic flow and sedimentation processes between close tree roots and trunks. In a following flow event, sediments that reach location A are diverted by the previously accumulated forms (stage 2, see Fig. 25b) and are further routed to neighbouring tree roots (see Fig. 25, locations B) where they accumulate. Moreover, accumulation is expected to occur adjacent to the accumulation forms at location A caused by a reduction of transport capacity in the lateral reaches of overland flow pathways when the water level drops. After root dams have fully established they are assumed to act as local natural barriers to sediment flow as they hinder sediments from entering the river channel zone (stage 3, see Fig. 25c).

Based on the hitherto outlined assumptions, sediment connectivity is hypothesized to be lower in forested than in non-vegetated or grassland riparian zones.

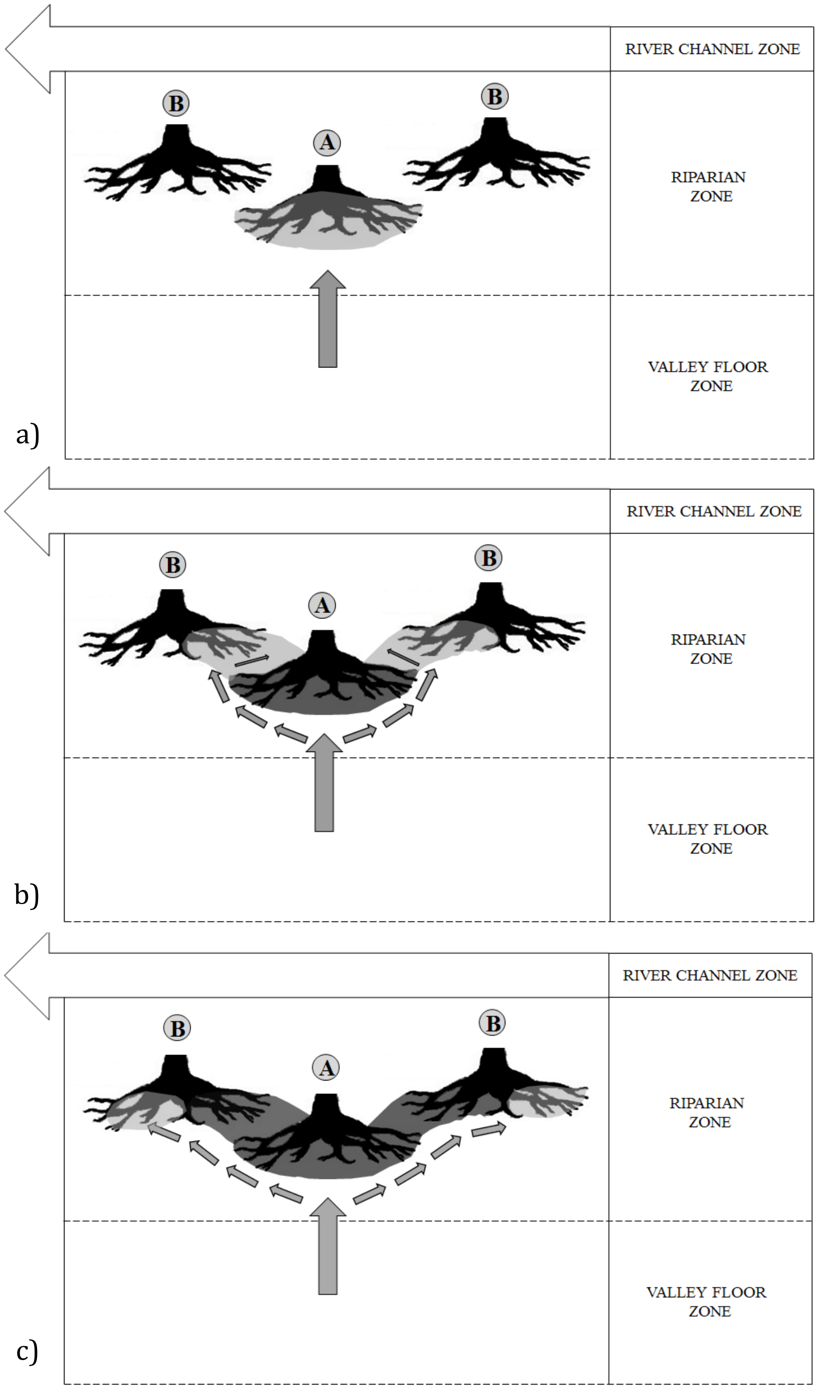


Fig. 25: Conceptual model showing the influence of damming processes along overland flow pathways in riparian zones on the establishment of root dams (angled view). Black shapes symbolize roots and trunks of trees which are protruding above the soil surface (subsurface roots are not shown here). Grey shaded arrows indicate the routing of oncoming sediment via overland flow pathways. Locations where accumulation processes occur are indicated by letters A and B. Light grey shaded shapes delineate newly deposited material, whereas dark grey shaded areas symbolize sediments that have accumulated during a preceding event. (Source: Poeppl et al. 2012b, A.2, p. 174-175)

6.2.2 Testing the conceptual model on lateral buffering with special consideration of riparian vegetation cover

Case study 5 - The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A.2)

i) Lateral sediment connectivity

The evaluation of the overland flow pathway model results showed that the lateral sediment connectivity in the observed system is strongly influenced by flow accumulation ("Flo_AL"), slope angle ("Slo_AL") and profile curvature ("Cur_AL") whereas only small differences in flow length values ("Len_AL") indicated no significant influence on lateral sediment connectivity (see Table 8):

Table 8: Results of the evaluation of overland flow pathway modelling showing the ratios between the mean values of explanatory variables ("Len_AL", "Flo_AL", "Slo_AL", "Cur_AL") of verified modelled overland flow pathways ("field_yes") and the modelled overland flow pathways where no related features were observed in the field ("field_no") (Source: Poeppl et al. 2012b, A.2, p. 184)

	field_yes : field_no
Len_AL	1.05
Flo_AL	1.87
Slo_AL	1.59
Cur_AL	2.03

The effects of riparian vegetation on diffuse lateral sediment connectivity assessed using PCA and a logistic regression model revealed three significant findings as follows (see also Tables 9 and 10):

- Lateral sediment connectivity decreases with an increasing proportion of forest vegetation (i.e. indicated by a high probability of sediment connectivity with high proportions of riparian grassland in the riparian zone "Per_GL") and the occurrence of root dams ("Rod")

- High slope angles in riparian grassland areas compared to those in adjacent agricultural areas increase the lateral sediment connectivity due to an abrupt increase of sediment transport capacity ("Dif_Slo_GL")
- Farm tracks located in the valley floor zone ("Fat") that run parallel to the river channel contribute to a disconnection between the valley floor zone and riparian zone

Table 9: Results of the logistic regression modelling scenario 1 (backward elimination method); model performance resulted in a Nagelkerke R^2 of 0.417 (Nagelkerke 1991) and an Omnibus test significance of $p < 0.05$. It was observed that 75.9% of the observations were assigned correctly. (Source: Poeppl et al. 2012b, A.2, p. 186)

Explanatory variables	Regression coefficient B1	Standard error	Wald	df	Sig.	Exp(B)
Dif_Slo_GL	**.671**	.497	1.826	1	**.177**	1.957
Fat	**-1.199**	.551	4.734	1	**.030**	.302
Rod	**-20.821**	13243.806	.000	1	**.999**	.000

Table 10: Results of the logistic regression modelling scenario 2 (backward elimination method); model performance resulted in a Nagelkerke R^2 of 0.523 (Nagelkerke 1991), and an Omnibus test significance of $p < 0.05$. Within this scenario, 83.3 % of the observations were assigned correctly. (Source: Poeppl et al. 2012b, A.2, p. 186)

Explanatory variables	Regression coefficient B2	Standard error	Wald	df	Sig.	Exp(B)
Fat	**-2.683**	.592	20.564	1	**.000**	.068
Rod	**-3.921**	1.090	12.939	1	**.000**	.020
Per_GL	**.330**	.085	14.910	1	**.000**	1.390

ii) Biogeomorphic processes

In the conducted geomorphic field surveys, 16 forest segments (= 59.3 %) of the total 27 riparian forest segments exhibited the presence of root dams which were shown to occur parallel of the river banks, both bilaterally and unilaterally (Fig. 26).

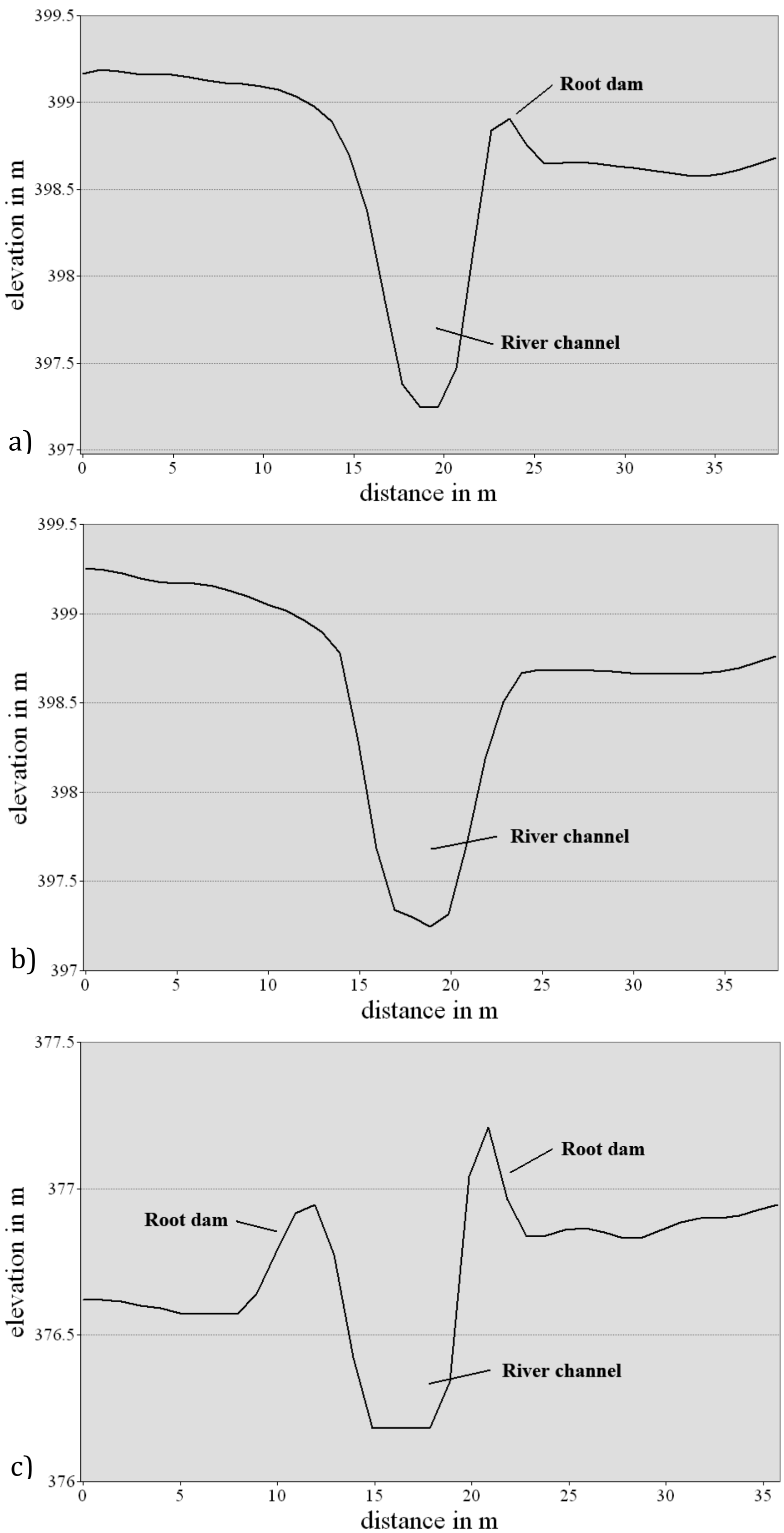


Fig. 26: Valley floor cross sections showing a) unilateral root dam occurrence along the right river bank; b) no root dam present (location next to cross section a); c) bilateral root dam occurrence (Source: Poeppl et al. 2012b, A2, p. 187-188)

Cross tabulations and Fisher´s exact test identified farm tracks ("Fat") as being the only significant factor ($p < 0.05$) that influences the establishment of root dams (see Table 11):

Table 11: Cross-tabulations for presence/absence of root dams and farm tracks (Source: Poeppl et al. 2012b, A.2, p. 188)

Factors		**Rod**		Total
		absent	present	
Fat	absent	6	16	22
	present	5	0	5
Total		11	16	27

The results presented in Table 11 indicate that the presence of "Fat" reduces the development of root dams which is most likely related to the disconnecting effects of farm tracks that prevent sediment of agricultural source areas from reaching the riparian zones. Nevertheless, the low number of observations (27) as well as the applied methodology is insufficient to derive general statements on the development of root dams. Thus, further research is required to investigate the influence of biogeomorphic processes on the establishment of root dams. Other factors to consider include: historical land use, species specific root morphology, tree density and age, frequency of flooding and human disturbance.

6.3 Connectivity between the human and the fluvial system and its implications for landscape change

6.3.1 Conceptual model on dam-induced connectivity between the fluvial system and the human system and its implications for landscape change

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms.* (Source: Poeppl et al. 2012c, A.3)

Human impact on the fluvial system due to dam construction induces geomorphic channel responses such as aggradation in the reservoirs and upstream reaches affected by backwater (e.g. Kondolf 1997, Fang and Rodi 2003, Heppner and Loague 2008) and downstream degradation (see Fig. 27a) (e.g. Taylor 1978, Al-Taiee 1990, Grant et al. 2003, Graf 2006, Gumiere et al. 2010, Thothong et al. 2011; Poeppl et al. 2012a, A.1). Contrarily, dam removal is also generally accompanied by geomorphic responses such as upstream degradation and downstream aggradation (e.g. Wildman and MacBroom 2005, Burroughs et al. 2009) as the river seeks for balanced slope conditions (see Fig. 27b).

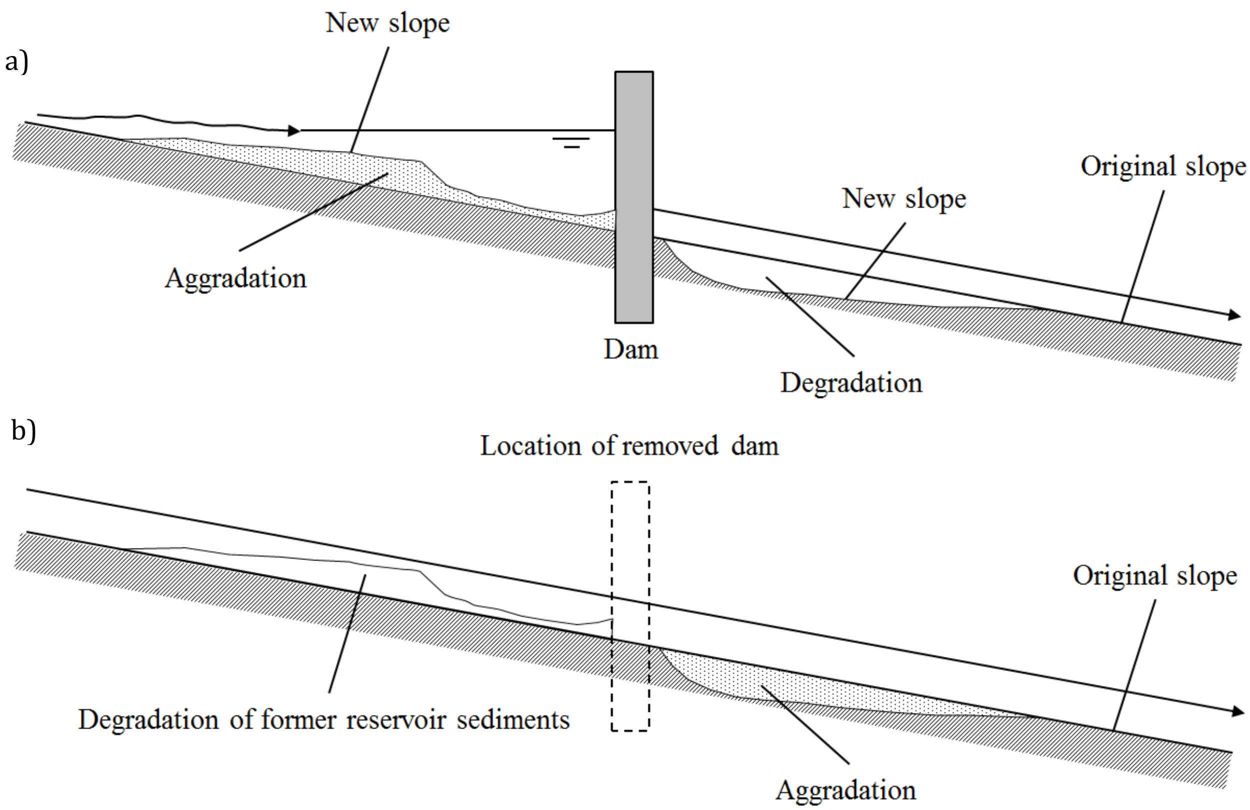


Fig. 27: Aggradation, degradation and related changes of the river slope at a dam: a) dam construction, after Gordon et al. (2004), b) dam removal. River flow direction is indicated by black arrows. (Source: Poeppl et al. 2012c, A.3, p. 198)

As conceptualised above, dam construction leads to geomorphic responses. These responses may have unintended side effects for the human system such as channel downstream that lead to losses in infrastructure (e.g. agricultural land, roads and buildings). Such potential losses call for human responses in terms of river management activities such as the installation of structural river engineering works. Structural river engineering is generally accompanied by channel straightening, a clearance of riparian vegetation cover (e.g. Brierley and Fryirs 2005) and land use and land cover change in the surrounding areas (e.g. Ouyang et al. 2010). Since upstream effects of dams such as sedimentation is often underestimated, sediment infilling of reservoirs causes human responses in terms of reservoir excavation or dam removal. Geomorphic channel responses to dam removal such as upstream degradation induce further human responses in terms of river bed and bank protection works. Moreover, dam removal is followed by land use and land cover change in and adjacent to the areas of the former reservoir. Dam construction is therefore assumed to have led to an interconnection of the human system and the fluvial system by triggering a series of process-response feedback loops between them (Fig. 28). These interactions are assumed to influence landscape changes in fluvial environments that manifest themselves in changing landscape metrics (i.e. land use and land cover changes, river planform geometry, and clearance of riparian vegetation).

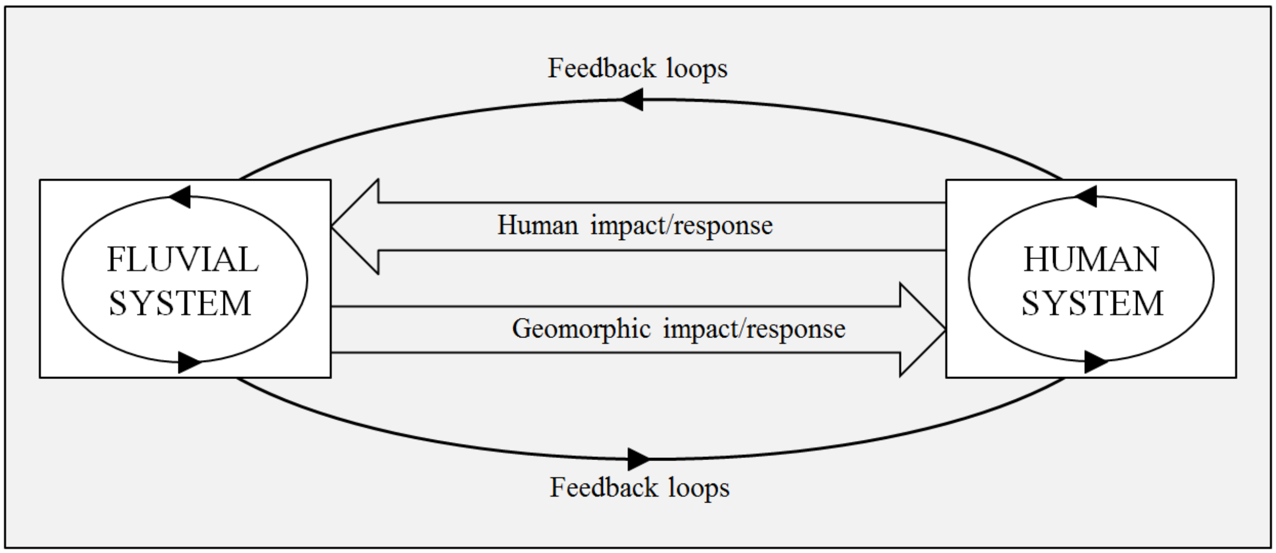


Fig. 28: Human-induced interconnection of the fluvial system and the human system, resulting in a human-landscape system via a series of feedback loops. Besides feedback loops that potentially occur in fluvial as well as in human systems (indicated by circles with arrows), feedback loops are observed as a series of human-induced geomorphic and human responses. (Source: Poeppl et al. 2012c, A.3, p. 199)

6.3.2 Testing the conceptual model on dam-induced connectivity between the fluvial system and the human system and its implications for landscape change

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms*. (Source: Poeppl et al. 2012c, A.3)

Case study 6 - Dam-induced landscape change and the role of human-landscape interactions – a reach-scale case study

1) Landscape evolution modelling with CAESAR

a) 3-dam-scenario of 1823 (dam construction)

The 184-year-scenario was the best fitting time-period scenario exhibiting the smallest mean elevation difference in meters (-0.88/-1.2) compared to the elevation data of 2010 (see Table 12). The output DEM of the 184-year-scenario showed reasonable results and was therefore used as input DEM for the 1-dam-scenario (dam removal) modelling.

Table 12: Model validation of the 3-dam-scenario (dam construction) outputs. (Source: Poeppl et al. 2012c, A.3, p. 211)

	Mean elevation difference in m	
Time-span scenario	**Reservoir: dam1**	**Reservoir: dam3**
184ys	-0.88	-1.2
151ys	-1.12	-1.22
129ys	-1.33	-1.24
41ys	-2.68	-1.37

Fig. 29 shows the modelled elevation differences in meters of the 184year-3-dam modelling scenario, while a quantification of geomorphic changes in the river channels and reservoirs due to dam constructions is presented for each river segment in Table 13. In all segments upstream of dams, sediment net deposition occurred, while in all segments downstream of dams net erosion was observed. A total of 248,247 m^3 of sediment was deposited along the whole river reach, with the highest amount recorded in segment 2 just upstream of dam 1 (85%), while 31,907 m^3 of sediment were eroded in total revealing the highest erosion rates occurring in segment 5, downstream of dam 2 (52.8%). More sediment was deposited than eroded between dams 1 and 2 (38.8%) as well as between dams 2 and 3 (20.8%) indicating that a significant amount of sediment which was eroded downstream of dams 1 and 2 was deposited in the subsequent reservoirs and the adjacent upstream reaches. This implies that a significant amount of material is transported across the dam crests of upstream dams which is then deposited in the subsequent reservoirs as well as in the adjacent upstream river reaches.

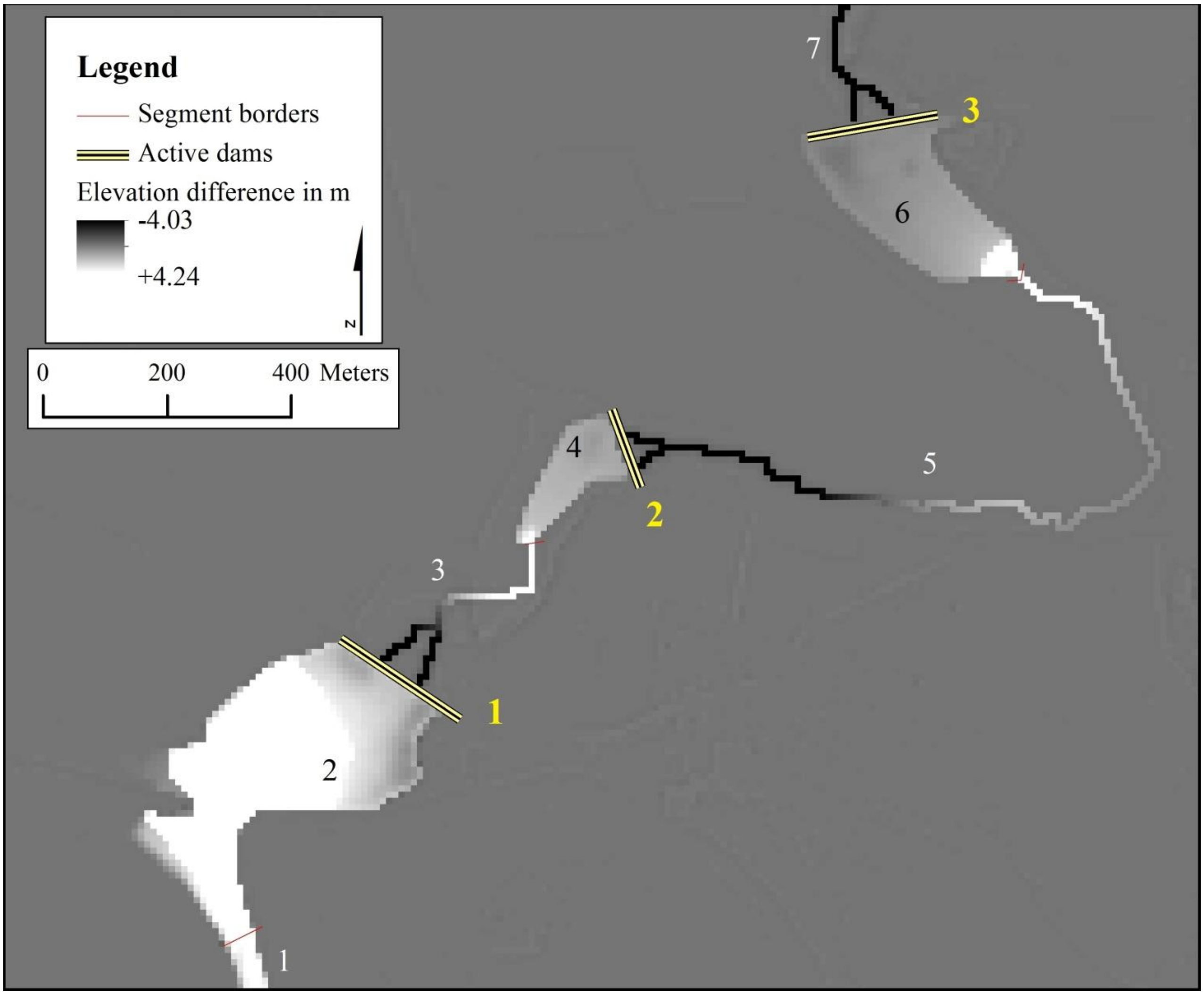


Fig. 29: Model output (elevation difference in m) of the 184year-3-dam modelling scenario (dam construction); river segments are numbered in black or white, active dams are labelled in yellow. (Source: Poeppl et al. 2012c, A.3, p. 213)

Table 13: Quantification of geomorphic changes in the river channels and reservoirs due to dam constructions for the 184year-3-dam modelling scenario (dam construction); Bold lines indicate presence and location of active dams. (Source: Poeppl et al. 2012c, A.3, p. 213-214)

	Erosion (sediment volume difference in m³ (% of total))	**Deposition (sediment volume difference in m³ (% of total))**	**Difference deposition/erosion (sediment volume difference in m³)**
Seg. 1	-	6,111 (2.5)	6,111
Seg. 2	-	208,423 (85)	208,423

Seg. 3	5,765 (18.1)	3,141 (1.3)	2,624
Seg. 4	-	6,284 (2.5)	6,284
Subtotal (in m^3)	5,765	9,425	3,660 (38.8%)
Seg. 5	16,858 (52.8)	8,041 (3.3)	8,817
Seg. 6	-	13,247 (5.4)	13,247
Subtotal (in m^3)	16,858	21,288	4,430 (20.8%)
Seg. 7	9,284 (29.1)	-	9,284
Total (in m^3)	31,907	245,247	213,340

b) 1-dam-scenario of 2010 (dam removal)

In Fig. 30 the model results are displayed showing the geomorphic effects of dam removals, while a quantification of geomorphic changes in the river channels and reservoirs due to dam removal for each river segment is presented in Table 14. In all segments located downstream of removed dams net deposition occurred, while in the abandoned reservoir of dam 1 (segments 1 and 2) net erosion was observed. In the abandoned reservoir of dam 3 slight net deposition was modelled due to continuous backward infilling after a period of erosion. A total of 91,790 m^3 of sediment was eroded along the whole river reach, exhibiting the highest amounts in segment 2 upstream of removed dam 1 (57.3%), followed by segment 5 (35.7%) downstream of active dam 2. Along the entire river reach, 70,422 m^3 of sediment were deposited in total, with highest deposition rates modelled for segment 4 (49.2%), followed by segment 7 (31.9%) and segment 3 upstream of segment 4 (15%), while only 3.9% were deposited in segment 6. Upstream of the removed dam 1, 23.4% more sediment was eroded than deposited upstream of the active dam 2. This implies that a significant amount of sediment input from upstream is transported across the crest of dam 2.

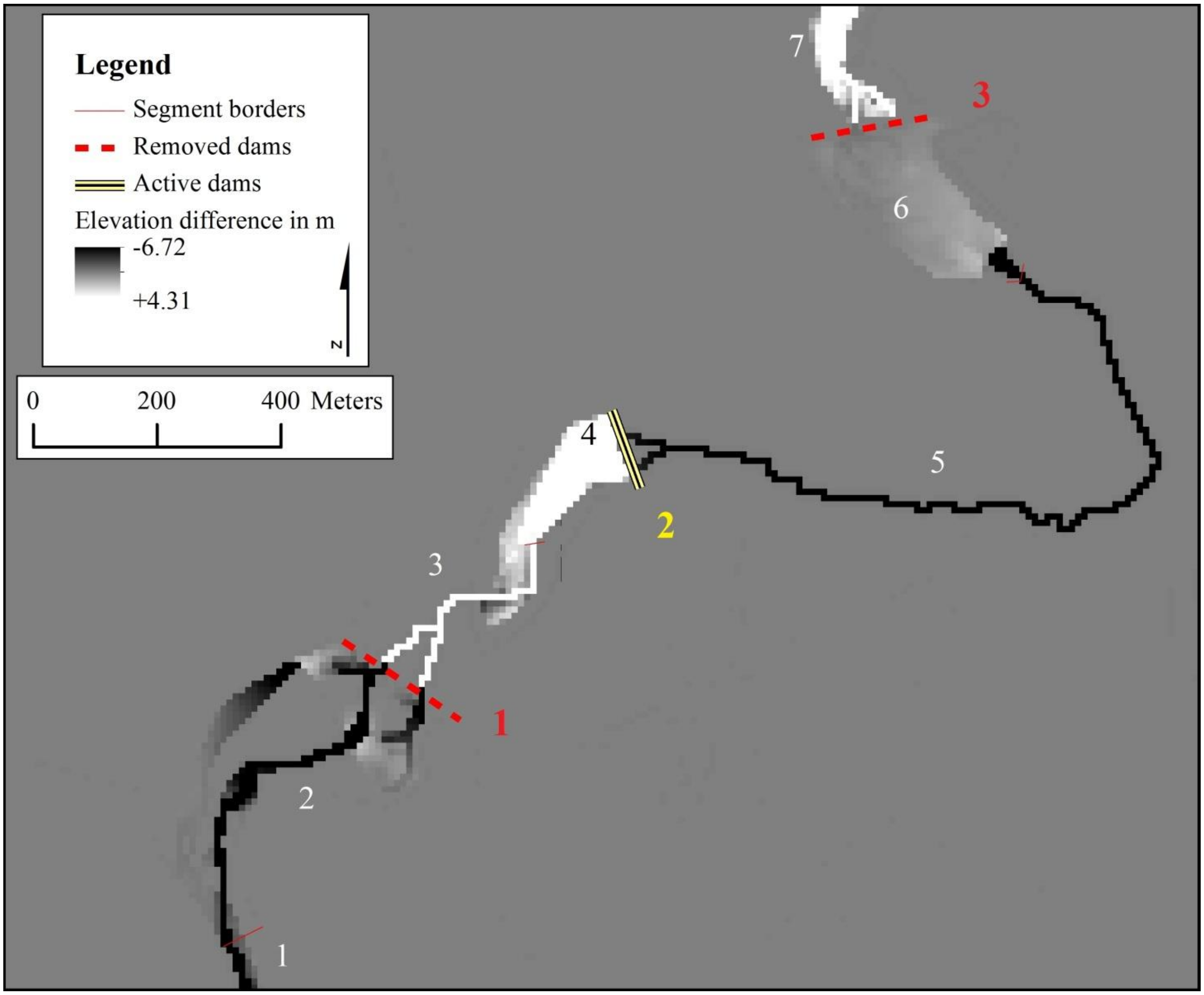


Fig. 30: Model output (elevation difference in m) of the 44year-1-dam-modelling-scenario (dam removal); river segments are numbered in black or white, active dams are labelled in yellow, removed dams in red. (Source: Poeppl et al. 2012c, A.3, p. 215)

Table 14: Quantification of geomorphic changes in the river channels and reservoirs due to dam removals for the 44year-1-dam modelling scenario (dam removal); Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. (Source: Poeppl et al. 2012c, A.3, p. 215-216)

	Erosion (sediment volume difference in m^3 (% of total))	**Deposition (sediment volume difference in m^3 (% of total))**	**Difference deposition/erosion (sediment volume difference in m^3)**
Seg. 1	6,440 (7.0)	-	6,440
Seg. 2	52,583 (57.3)	-	52,583

Seg. 3	-	10,547 (15.0)	10,547
Seg. 4	-	34,676 (49.2)	34,676
Subtotal (in m^3)	59,023	45,223	13,800 (23.4%)
Seg. 5	32,767 (35.7)	-	32,767
Seg. 6	-	2,724 (3.9)	2,724
Seg. 7	-	22,475 (31.9)	22,475
Subtotal (in m^3)	32,767	25,199	7,568 (23.1%)
Total (in m^3)	91,790	70,422	21,368

2) GIS-based mapping and geo-statistical analyses

The results exhibited significant alterations of river channel planform geometry, land use and land cover, and riparian woodland vegetation between the 3-dam-scenario of 1823 (see Fig. 31) and the 1-dam-scenario of 2010 (see Fig. 32).

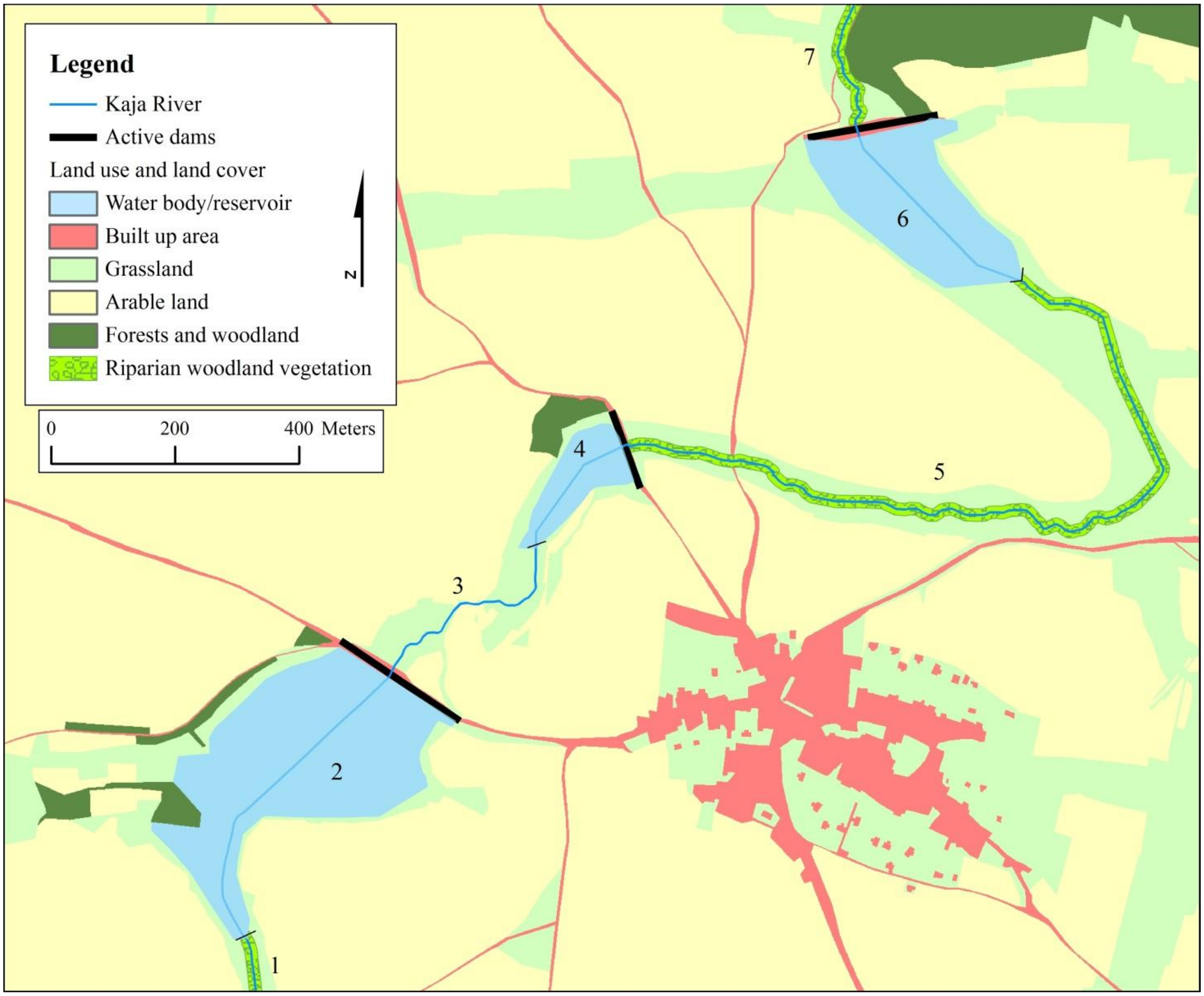


Fig. 31: 3-dam-scenario of 1823 showing land use and land cover conditions 1823 including information on river channel planform and the presence of riparian woodland vegetation and dams. River segments are numbered according to flow direction. (Source: Poeppl et al. 2012c, A.3, p. 208)

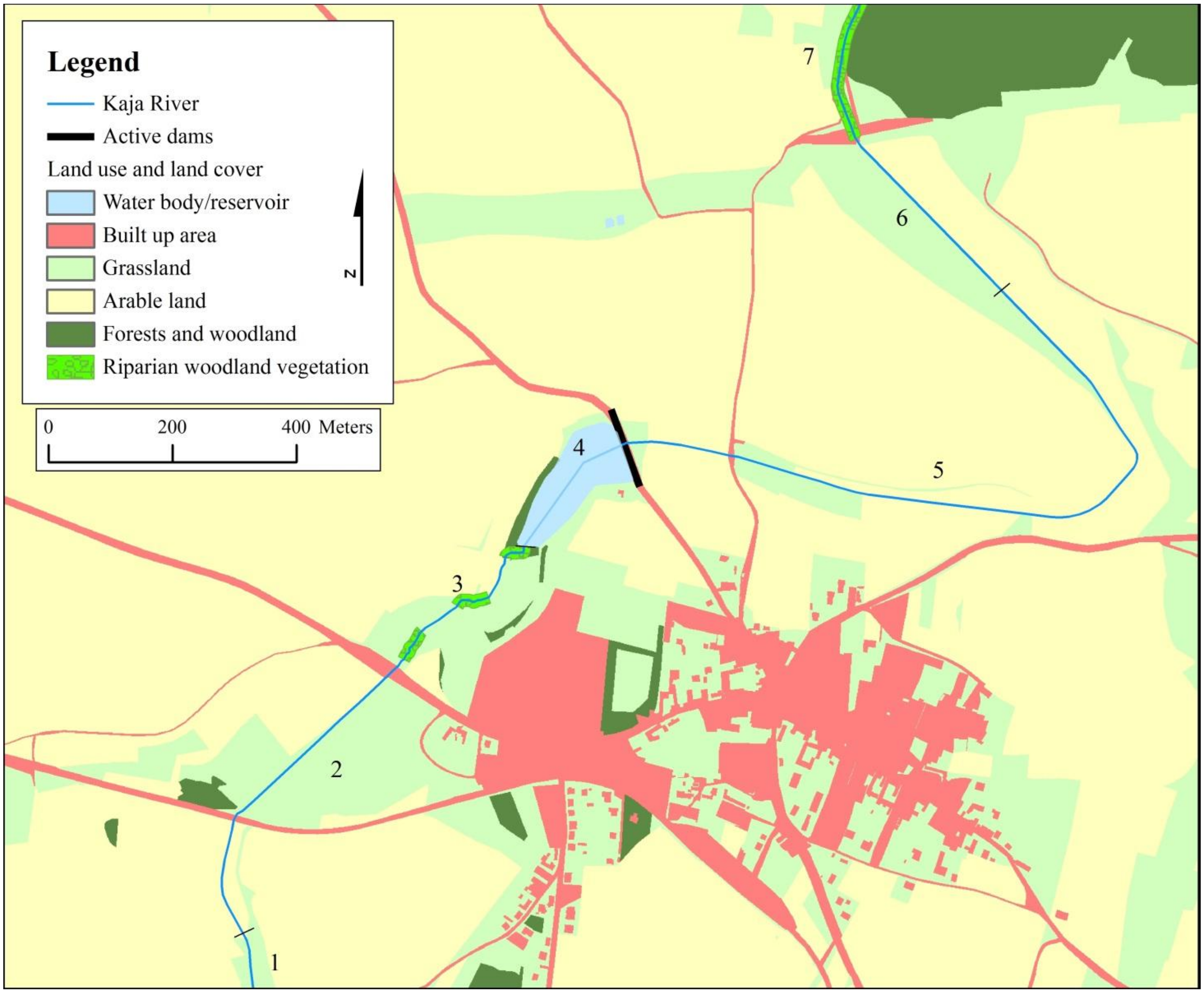


Fig. 32: 1-dam-scenario of 2010 showing land use and land cover conditions 2010 including information on river channel planform and the presence of riparian woodland vegetation and dams. River segments are numbered according to flow direction. (Source: Poeppl et al. 2012c, A.3, p. 209)

a) River channel planform geometry

Downstream of recent or former dam crests (= upstream of a recent or former reservoir) channel length and channel sinuosity decreased (i.e. segments 1, 3, 5, 7), while no changes were observed in segments 2, 4, 6 located in a recent or former reservoir (see Figs. 31 and 32; Tables 15 and 16). These results reveal channel straightening in river reaches where river bed degradation has been modelled and suggests the presence of river engineering works (i.e. downstream of active dams and upstream of abandoned dams).

Table 15: River channel lengths and changes in river channel length between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. (Source: Poeppl et al. 2012c, A.3, p. 209)

Length in m (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	3410.2	152.8	549.2	371.1	231.9	1379.2	369.9	356.1
2010	3177.9 (-6.8)	149.1 (-2.4)	549.2 (0)	322.2 (-13.2)	231.9 (0)	1224.0 (-11.3)	369.9 (0)	331.7 (-6.9)

Table 16: River channel sinuosity and river sinuosity changes between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. (Source: Poeppl et al. 2012c, A.3, p. 210)

Sinuosity (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	1.724	1.007	1.125	1.204	1.058	1.995	1.028	1.195
2010	1.604 (-7.0)	1.005 (-0.2)	1.125 (0)	1.103 (-8.3)	1.058 (0)	1.860 (-6.8)	1.028 (0)	1.111 (-7.1)

b) Land use and land cover

Significant land use and land cover changes occurred within a streamside buffer area of 25 m (see Figs. 31 and 32; Table 17): water bodies decreased by 25% due to dam removal, arable lands strongly increased (+41%), grasslands decreased by 19%, and built up as well as forested and woodland areas slightly increased (+1%). A significant shift from grassland to arable land use occurred in the downstream reaches of the active dam in 2010 (i.e. segment 5). Only minor changes took place downstream of removed dams (i.e. segments 3, 7). These results imply a relationship between river channel straightening and land use/land cover changes.

Table 17: Land use and land cover conditions and changes between 1823 and 2010, calculated for the total study area ("TSA") and the total streamside buffer area ("B 25", "Total") as well as for the streamside buffer area of each river segment ("B 25", "Seg."). Land use and land cover categories ("LU/LC") are abbreviated as follows: "WB" (Water bodies), "BA" (Built up areas), "GL" (Grassland), "AL" (Arable land), "FW" (Forests and woodland). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. (Source: Poeppl et al. 2012c, A.3, p. 210)

		Land use/land cover 1823 in %					**Land use/land cover 2010 in % (change in % 1823 - 2010)**				
	LU/LC	WB	BA	GL	AL	FW	WB	BA	GL	AL	FW

TSA	**Total**	4	4	16	72	4	1 (-3)	8 (+4)	16 (0)	71 (-1)	4 (0)
B 25	**Total**	32	2	60	4	2	7 (-25)	3 (+1)	41 (-19)	45 (+41)	3 (+1)
	Seg. 1	0	0	97	3	0	0 (0)	0 (0)	90 (-7)	10 (+7)	0 (0)
	Seg. 2	94	2	4	0	0	0 (-94)	5 (+3)	46 (+42)	48 (+48)	1 (+1)
	Seg. 3	0	3	73	24	0	0 (0)	3 (0)	70 (-3)	20 (-4)	6 (+6)
	Seg. 4	92	3	5	0	0	92 (0)	3 (0)	0 (-5)	0	5 (+5)
	Seg. 5	0	1	95	4	0	0 (0)	1 (0)	26 (-69)	73 (+69)	0 (0)
	Seg. 6	93	3	4	0	0	0 (0)	4 (+1)	51 (+47)	45 (+45)	0 (0)
	Seg. 7	0	6	72	1	21	0 (0)	11 (+5)	64 (-8)	5 (+4)	20 (-1)

c) Riparian woodland vegetation

A decrease of riparian woodland vegetation from 51% to 15% in the total river reach was observed (see Table 18), with especially high rates of decrease in the river segment located downstream of dam 2 in 2010 (i.e. segment 5). No clearance took place in river segments downstream of abandoned dams (i.e. segments 3, 7) and no woodland vegetation was detected in segments located in former reservoir areas (i.e. segments 2, 6), while 47 % has (re)established in segment 3 (= downstream of an abandoned dam).

Table 18: Proportions and changes of riparian woodland vegetation ("RWV") between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. (Source: Poeppl et al. 2012c, A.3, p. 211)

RWV in % (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	51	100	0	0	0	100	0	100
2010	15 (-36)	0 (-100)	0 (0)	47 (+47)	0 (0)	0 (-100)	0 (0)	100 (0)

3) Field surveys

River bed and bank protection works were surveyed along each river channel line segment in the field, since these structures are generally built to mitigate unintended dam-induced geomorphic effects and are assumed to be indicators for human responses to geomorphic processes. If detected in the downstream reaches of active dams or in abandoned reservoirs, the presence of these structures was related to channel degradation either induced by dam construction or removal.

In 82% of the total river reach river bed and/or bank protection measures have been installed (see Table 19). In all river segments except segments 4 (= active reservoir area) and 3 river bed and/or bank protection structures were surveyed. In every segment where erosion processes were modelled in the course of CAESAR modelling - either induced by dam construction or dam removal - human responses in terms of river bed and bank engineering were observed, with the only exception of segment 6 (see Table 19). In the river reaches where river engineering structures were installed, significant land use changes in floodplain areas of regulated river reaches, channel straightening, clearance of riparian woodland vegetation as well as dam-induced channel degradation were observed (see above). Therefore, a dam-induced interconnection of the human system and the fluvial system is deduced characterized by a series of dam-induced geomorphic and human responses which were shown to influence landscape changes in the fluvial environment.

Table 19: Proportions of the occurrence of river bed and bank protection structures ("RBBP") 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. River bed and/or bank protection works were related to dam-induced erosion processes which were examined in the course of landscape evolution modelling (indicated by an "X"). (Source: Poeppl et al. 2012c, A.3, p.217)

	Total	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
RBBP in %	82	100	100	0	0	100	100	100
Net erosion due to dam construction or removal		X	X			X		X

7. Discussion and conclusions

At the beginning of this thesis three hypotheses have been outlined:

I) Linking concepts of sediment connectivity to principles of channel processes contributes to a better understanding of geomorphic channel response to dam construction and changes of land use and land cover
II) Lateral buffering is strongly influenced by riparian vegetation cover type and biogeomorphic processes
III) Dam construction induces geomorphic channel changes that trigger a series of process-response feedback loops between the human and the fluvial system

Based on these hypotheses, two overarching objectives have been formulated which can be summarized as follows: (1) Developing a conceptual model for each hypothesis, (2) testing the model assumptions by performing and evaluating case studies in small human-impacted fluvial systems. From each hypothesis explicit objectives and research questions have issued which directed the course of this study. In this chapter, the results are discussed for each hypothesis and research question in order of their appearance in this thesis. As the developed conceptual models as well as the performed case studies are related to former concepts and approaches on connectivity (see chapters 2 and 3), the results will be discussed in the light of their reflections.

7.1 Linking sediment connectivity concepts to principles of channel processes – an advance for predicting fluvio-geomorphic responses to dam construction and land use change?

Hypothesis I: Linking concepts of sediment connectivity to principles of channel processes contributes to a better understanding of geomorphic channel response to dam construction and changes of land use and land cover

Two objectives issued from hypothesis I:

1) To develop a conceptual model that links human-induced sediment connectivity changes in fluvial systems with geomorphic channel processes
2) To test the various model assumptions by performing and evaluating case studies in small fluvial systems that are affected by dams and land use/land cover changes

7.1.1 *Conceptual model linking human-induced changes of sediment connectivity with geomorphic channel processes*

Reference: Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012): The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*. (Source: Poeppl et al. 2012a, A1)

Referring to research question *Ia*, impacts of direct and indirect human interventions on the three spatial dimensions of sediment connectivity in fluvial systems have been verbally and graphically conceptualized and causally linked to an equilibrium concept of geomorphic channel processes by Lane (1955). It has been shown that an increase in sediment connectivity on each spatial dimension of sediment connectivity (i.e. longitudinal, lateral and vertical) leads to channel aggradation, whereas a decrease leads to channel degradation. The conceptual model has been extended based on research question *Ib.* It has been conceptualized that after human-induced changes of sediment connectivity, self-regulatory properties of the system can lead to a recovery of the original connectivity conditions as a function of vegetation regrowth and geomorphic events. Lateral sediment connectivity has been assumed to recover after deforestation due to self-regulatory properties that are related to vegetation regrowth. A recovery of longitudinal sediment connectivity has been assumed to be related to geomorphic processes and events that lead to sediment infilling due to cumulative impoundment aggradation or dam failure due to erosion processes - both lead to a reconnection of up- and downstream channel reaches. The model assumptions were tested by performing and evaluating four case studies in small fluvial systems impacted by dams and land use/land cover changes related to research question *Ic.*

7.1.2 *Testing the conceptual model that links human-induced changes of sediment connectivity with geomorphic channel processes*

(1) Dam construction

Case study 1 - The effects of the Sagteich dam on the longitudinal and vertical sediment connectivity of the Kaja River, Austria

The objective of case study 1 was to detect the reach-scale effects of dams on longitudinal and vertical sediment connectivity. To investigate this, a variety of types of sediment analysis methods were used. Sediment samples were collected both upstream and downstream of the Sagteich dam and were then compared in order to determine the extent of dam-induced longitudinal sediment dis-connectivity. The results revealed that the dam inhibits longitudinal bedload connectivity and causes a grain size- selective reduction of longitudinal suspended sediment connectivity exhibiting a trap efficiency for suspended load of approximately 70%. (Source: Poeppl et al. 2012a, A.1)

The measured trap efficiency of the reservoir for suspended load is similar to the values examined by Toniolo and Schultz (2005) who performed laboratory experiments on trap efficiency for fine sediments calculating trap efficiencies ranging from 68% to 88% depending on the experimental design. During medium storms, Butcher et al. (1992) observed trap efficiencies at two reservoirs in the southern Pennines (UK) to be between 65% and 74%.

The results of this case study further indicated that downstream degradation occurred as a result of dam-induced sediment dis-connectivity in longitudinal direction. Furthermore, a decrease of vertical sediment connectivity due to dam-induced bed armouring downstream of the dam was observed. (Source: Poeppl et al. 2012a, A.1) Similar instances of bed degradation and armouring downstream of dams have been reported in literature (e.g. Williams and Wolman 1984, Xu 1990, Brandt 2000). Nevertheless, the reworking of old alluvia and reservoir sediments of a removed dam which were noted to still be stored in the downstream reaches prevented from a total lack of river bedload. (Source: Poeppl et al. 2012a, A.1) Instances of extensive reworking of materials from valley floors after disturbance have often been highlighted to be the dominant component of the post-disturbance budget (e.g. Erskine 1993, Rutherford 1996, Wasson et al. 1998, Doyle et al. 1999, Fryirs and Brierley 1999). Furthermore, it has been stated by several authors that the reworking of alluvial sediment stores has major implications for the geomorphic river conditions while strongly influencing the patterns and rates of river recovery (Brookes 1992, 1995; Downs and Gregory 1993, Newson 1994, Sear 1996, Bartley and Rutherford 1999).

The findings of case study 1 fit the general assumption of the developed conceptual model denoting that a decrease of longitudinal sediment connectivity leads to downstream channel degradation (P > SS → D). Referring to the coupling concept of Brunsden and Thornes (1979), the observed system can be characterized as being decoupled by dam installation inducing a reach-to-reach decoupling (Harvey 2002). Referring to Fryirs et al. (2007a), the observed dam acts as a barrier it disrupts sediment movement along the channel and further disconnects areas from the primary sediment conveyor belt which reduces the effective catchment area by decreasing the contributing area for sediment.

The results have also shown that the different spatial dimensions of sediment connectivity within fluvial systems are interrelated, meaning that a change of sediment connectivity in one spatial dimension can lead to a change in another. In this specific case, dam-induced decrease of longitudinal sediment connectivity induced a reduction of vertical sediment connectivity by causing bed armouring downstream further acting as a blanket while protecting the underlying sediments from reworking. Fryirs et al. (2007a).

The results have further exhibited that geomorphic adjustments within river systems are highly site-specific, since they further depend on the individual system history – in this case related to downstream sediment storage induced by a formerly existent dam which has prevented from a total exhaust of river bed sediments. These findings are in the line with the assumptions of the developed conceptual model denoting that geomorphic adjustments within river systems further depend on factors such as boundary conditions and the individual system history.

Case study 2 - Check dams and longitudinal sediment connectivity - examples from the Gimbach catchment, Austria

Case study 2 dealt with check dam-induced changes of longitudinal sediment connectivity, related geomorphic channel changes and the importance of self-regulatory system properties for system recovery in a steep mountain stream. Geomorphic channel processes occurring in a series of check dams have been verbally and graphically conceptualized. The assumptions were underpinned by presenting real-world examples from the Gimbach catchment. It has been shown that if the ratio between the length and height of a series of check dams is not properly chosen, scour develops downstream at the lowest check dam (P > SS → D) which results in the destabilisation of the foundation of this structure. As a result of scouring, the channel became reconnected in longitudinal direction. Furthermore, the results exhibited that reconnection can be further caused by aggradation processes (P < SS → A) which depend on the river's sediment load. Given enough sediment load, the deposition area within the impoundment will be filled to the height of the dam crest leading to a reconnection in longitudinal direction. (Source: Poeppl et al. 2012a, A.1)

The results of this case study fit the general assumption of the conceptual model assuming that a decrease of longitudinal sediment connectivity leads to downstream channel degradation (P > SS → D) and upstream channel aggradation (P < SS → A). The findings further revealed that self-regulatory system properties can lead to a recovery of sediment connectivity as a function of geomorphic processes and events – in this case due to sediment infilling or dam failure which both led to a reconnection of the upstream and downstream channel reaches. Likewise, other investigations have shown that check dam construction can destabilize the foundations of other check dams in the downstream reaches (e.g. Liu 1983). Similarly to the investigated dam in case study 1, the observed system can be characterized as being decoupled (Brunsden and Thornes 1979) by dams which function as barriers that disrupt sediment movement along the channel (Fryirs et al. 2007a). However, construction type as well as impoundment storage capacities strongly differ from that of embankment dams. These differences determine the effective temporal timescale of dis-connectivity (Harvey 2002) as well as the recovery time of the system. Effective timescales of dis-connectivity and thus recovery time is system-specific, as they are further determined by a range factors that govern sediment supply to the river channel and by the frequency and magnitude of geomorphic events (e.g. the climatic environment, channel-hillslope coupling). A comparative assessment on erosion and sediment yield in mountain regions of the world conducted by Dedkov and Moszherin (1992) indicated that erosion and sediment yield of mountain rivers strongly depend on climate and runoff, landscape character, relief, recent tectonic activity and underlying lithology. Moreover, the nature of hillslope-channel coupling is a key determinant of the effectiveness of downstream sediment transfer and sediment yield within a catchment (Phillips 1989, 1995; Harvey 1992). Fryirs and Brierley (1999) analyzed sedimentation rates in farm dams of a lowland river in SE-Australia. Their results clearly showed that although much material was eroded on hillslopes, most of this material has been stored on-slope without reaching the river channels. Conversely, Fort et al. (2010) noted a strong impact of hillslope-channel coupling on valley bottom and river morphology in the Nepal Himalayas.

(2) Land use change

Case study 3 - The effects of dirt roads on lateral connectivity in the Barranco de las lenas catchment, NE Spain

The specific of aim of case study 3 was to investigate the influence of human impacts on the lateral connectivity and gully development through the building of roads on lateral connectivity applying DEM-based flowpath analyses in a GIS-environment. Flowpath analyses were performed for two scenarios, one with and one without the presence of the dirt road. These two scenarios were then compared to identify the influence of the dirt road on lateral connectivity. In order to investigate geomorphic channel changes after road-induced alterations of lateral connectivity, the development of the gully channel was continuously monitored in the field. The results showed that the construction of a dirt road leads to a clear interruption of flow from the headcut catchment towards the gully causing a reduction of lateral connectivity that leads to reduced gully activity and a reduced gully headcut retreat. (Source: Poeppl et al. 2012a, A.1)

Therefore, land use change in terms of road construction has altered the delivery pathways within the catchment which has led to a total disconnection of the headcut catchment resulting in a decrease of the effective catchment area and reduced gully activity. In this case, the road diverted the catchment into two individual catchments by introducing a drainage line between them where all of the water and sediment arriving from the headcut catchment is diverted and drained into the neighbouring catchments. After road construction neither water nor sediment reached the gully from the former headcut catchment and the gully development significantly decreased. Therefore, not lateral sediment connectivity, but the catchment area decreased as flow was routed to neighbouring catchments. In a strict sense, this case study is not eligible to test the model assumptions. However, the fact that gully development significantly decreased implies that the general assumption of the developed conceptual model denoting channel degradation with decreasing lateral sediment connectivity is valid. This is justified by the assumption that if only lateral sediment connectivity decreased, the water from the headcut catchment would still reach the gully channel hence causing channel degradation due to an increase of stream power (P > SS → D) (see also case study 4).

Similar results on the effects of roads on lateral sediment connectivity have been reported by Croke et al. (2005) who investigated sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. The results of Croke et al.

(2005) have shown that only 11 of 218 surveyed road drains were predicted to deliver runoff to a stream which underlines the potential disconnecting effects of road construction. Nyssen et al. (2002) who studied the impact of road building on gully erosion risk in the Northern Ethiopian Highlands showed that road construction induced a diversion of concentrated runoff to other catchments and an increase of catchment size.

Case study 4 - Investigations on lateral sediment connectivity in the Dragonja catchment, SW Slovenia

The objective of case study 4 was to investigate the effects of natural reforestation due to land abandonment on lateral sediment connectivity, to relate these to geomorphic channel changes and to identify the role of self-regulatory system properties for system recovery. To investigate this, case study results which were obtained by applying hydrological analyses, sediment budget analyses, geomorphological mapping and different field and laboratory methods published by Keesstra et al. (2007) and Keesstra et al. (2009a, 2009b) were interpreted in the context of the newly developed conceptual model. The results have shown that reforestation after land abandonment has led to a significant decrease of lateral sediment connectivity accompanied by geomorphic channel changes through incision and narrowing. These findings meet the general assumptions of the developed conceptual model denoting that a decrease of lateral sediment connectivity due to reforestation leads to channel degradation (P > SS → D). Furthermore, self-regulatory system properties have been shown to lead to a recovery of lateral sediment connectivity as a function of vegetation regrowth. (Source: Poeppl et al. 2012a, A.1)
The assumptions of the presented conceptual model on the role of self-regulatory system properties as being a function of vegetation regrowth are only valid for landscapes where no land degradation occurred, since degraded soil conditions would not allow for a full re-establishment of the original vegetation cover. Therefore, system history plays an important role for system recovery. Climate is also another important factor governing soil erosion and lateral sediment input to a river and thus geomorphic channel response to land use change as well as determines vegetation recovery and hence recovery potential and recovery time of the system. Based on data from small watersheds in the United States Langbein and Schumm (1958) have shown that sediment yield is directly related to climate and vegetation cover. The data of Dedkov and Moszherin (1992) who did a comparative assessment on erosion and sediment yield in mountain regions of the world exhibited that the greatest erosion occurs in the glacial, subnival and in the Mediterranean zones due to the limited protection of their soils by vegetation. In contrast, in

forested zones little slope erosion has been recorded. These results are in line with the findings of case study 4.

Subsuming, the results for hypothesis I show that linking sediment connectivity concepts to principles of channel processes also considering the importance of self-regulatory system properties helps to explain geomorphic channel responses to human impacts in terms of dam construction and changes of land use and land cover. The applied Lane Balance as a stand-alone is very simplistic and there are serious limitations regarding the questions of when and where geomorphic changes will occur (Simon and Castro 2003). But it was shown when the Lane Balance is linked to connectivity assessments, locations of geomorphic channel changes can be delineated more precisely.

The case study results fit the general assumptions of the developed conceptual model denoting that geomorphic response change is strongly influenced by human-induced changes of sediment connectivity at different spatial dimensions. Dam construction has been shown to interrupt the longitudinal sediment connectivity leading to upstream aggradation and downstream degradation. Dam-induced downstream degradation has been further shown to decrease vertical sediment connectivity due to the establishment of bed armouring. Land use changes due to land abandonment and reforestation has decreased lateral sediment connectivity which has resulted in channel degradation. The results further confirmed the model assumption that self-regulatory system properties lead to a recovery of sediment connectivity delineating geomorphic channel processes and vegetation as being the driving factors of change. Recovery of longitudinal sediment connectivity has been shown to be related to geomorphic responses to dam construction such as cumulative aggradation of the impoundments or downstream degradation which both led to a reconnection of the upstream and downstream reaches within a series of check dams (case study 2). The results of case study 4 revealed that self-regulatory system properties resulted in the recovery of lateral sediment connectivity conditions as a function of vegetation recovery after catchment reforestation due to abandonment.

The discussion of the case study results have however revealed that system-specific properties which are related to individual boundary conditions such as climate and the individual system history are further important factors of influence and that rates and type of geomorphic channel responses to human-induced changes of sediment connectivity are thus highly variable and system-specific. Therefore, it is concluded that in a comprehensive assessment of geomorphic channel responses to dam construction and land use changes, system-specific boundary conditions as well as the individual system history need to be considered.

7.2 Which processes and factors govern lateral buffering and which role does the type of riparian vegetation cover play?

Hypothesis II: Lateral buffering is strongly influenced by riparian vegetation cover type and biogeomorphic processes

Two objectives originated from hypothesis II:

1) To develop a conceptual model by considering the processes and factors that govern lateral sediment connectivity and buffering in an agricultural catchment with special focus on the influence of riparian vegetation cover
2) To test the model assumptions by performing a case study in a small agricultural catchment

7.2.1 Conceptual model on lateral buffering with special consideration of riparian vegetation cover

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A2)

Referring to research question *IIa,* the different processes and factors that potentially influence the lateral sediment connectivity between the hillslopes and the river channels have been verbally and graphically conceptualized. Special consideration has been given to the role of riparian vegetation cover and biogeomorphic processes in governing lateral buffering. The basic model assumption has been that lateral sediment connectivity between agricultural areas and the river channel mainly depends on the presence of overland flow pathways and is primarily governed by slope angle, slope curvature, surface roughness and the availability/amount of water. Surface roughness and sediment transport capacity has been noted to be preferably reduced in riparian zones due to a high vegetation density and the strength of lateral buffering which has been expected to be related to the respective riparian land use and vegetation cover type. In forested riparian zones, increased lateral buffering has been assumed to be related to sediment trapping that occurs in the backwater reaches of tree roots and trunks, and due to the establishment of depositional features called root dams that have been hypothesized to emerge from biogeomorphic processes in forested riparian zones. Thus, sediment connectivity has been expected to be lower in forested than in non-vegetated or grassland riparian zones.

7.2.2 *Testing the conceptual model on lateral buffering with special consideration of riparian vegetation cover*

Case study 5 - The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment

Reference: Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T. (in press, 2012): The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A, Physical Geography*. (Source: Poeppl et al. 2012b, A2)

The objective of case study 5 was to assess the influence of different types of riparian vegetation cover on diffuse lateral sediment connectivity between agricultural areas on valley floors and the river channel. Furthermore, the case study aimed at identifying the influence of biogeomorphic processes on the development of dam-like features running parallel to the river channel and their role in governing lateral buffering. The results indicated that lateral sediment connectivity is strongly influenced by the amount of water available to transport sediments, slope angle and profile curvature. Lateral buffering has been shown to be governed by the type of riparian vegetation cover and the presence of farm tracks and root dams. Flow pathways featuring riparian forest vegetation and root dams exhibited the strongest lateral buffering efficiency. (Source: Poeppl et al. 2012b, A2)

The results of the performed case study meet the assumptions of the developed conceptual model in all respects. However, it has to be mentioned that the riparian woodland vegetation was accompanied by herbaceous undergrowth in many cases which may have enhanced lateral buffer capacity. Similar results have been obtained by Lee et al. (2003) where a multispecies switchgrass-woody buffer exhibited the highest trapping efficiency (97%) for the incoming sediment. Very high trapping efficiencies in forested riparian zones have been further reported by Cooper et al. (1987) and Lowrance et al. (1995). Leguédois et al. (2008) investigated sediment trapping by tree belts and observed the establishment of depositional features in the backwater areas of trees which were also the locations of highest trapping efficiency. Lowrance et al. (1995) noted that buffer zones are most effective in first and lower order streams because of the greater potential for interaction between upland runoff and the riparian zone and that as stream order increases, buffering capacity is generally reduced. This implies that the establishment of depositional features that emerge from biogeomorphic processes which have been investigated in case study 5 (small catchment) might not be applicable to larger river systems. Therefore, the model assumptions have to be further tested in larger river systems and in other geographic environments. Moreover, a more detailed assessment considering factors such as species specific root morphology, historical land use, tree age and density etc. is required to unravel the influence of biogeomorphic processes on the establishment of root dams.

Subsuming, the results for hypothesis II have shown that lateral sediment connectivity is strongly influenced by topography determining the hillslope runoff potential (slope angle, slope curvature) and the potential contributing area (flow accumulation). The results further revealed that lateral buffering is influenced by the type of riparian vegetation cover and related depositional features that emerge from biogeomorphic processes in forested riparian zones and by anthropogenic structures (farm tracks) that run parallel to the river channel. Since riparian vegetation cover (including related biogemorphic processes and forms) and anthropogenic structures strongly influence lateral buffering and hence lateral sediment connectivity, it is concluded that these factors need to be considered in comprehensive connectivity assessments.

7.3 Does the installation of dams induce interactions between the human and the fluvial system?

Hypothesis III: Dam construction induces geomorphic channel changes that trigger a series of process-response feedback loops between the human and the fluvial system

Two objectives issued from hypothesis III:

1) To develop a model that conceptualises dam-induced connectivity between the fluvial system and the human system and to identify possible implication for landscape change in fluvial environments (see 7.3.1)
2) To test the model assumptions by undertaking a case study in a small dam-impacted fluvial system (see 7.3.2)

7.3.1 Conceptual model on dam-induced connectivity between the fluvial system and the human system and its implications for landscape change

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms*. (Source: Poeppl et al. 2012c, A.3)

Dam-induced process-response feedback loops that exist between the human system (human responses) and the fluvial system (geomorphic responses) have been verbally and graphically conceptualized. In consideration of research question *IIIa,* it has been generalized that dam construction induces geomorphic channel responses which result in upstream aggradation and downstream degradation. In consideration of research question *IIIb,* it has been conceptualized that dam-induced geomorphic responses have undesirable outcomes on the human system that call for the following human interventions (human responses): installation of river bed and bank protection structures downstream of dams to prevent from channel degradation and related loss of human infrastructure such as agricultural land, roads and buildings; dam removal due to sediment infilling of reservoirs as sediment loads are often understated. In consideration of research question *IIIc,* dam removal has been identified to be accompanied by further geomorphic responses in terms of upstream degradation and downstream aggradation. Geomorphic responses to dam removal have been expected to further induce human responses through structural engineering of the river channel upstream of dams. Based on these assumptions, it has been inferred that dam construction triggers a series of process-response feedback loops between the human system and the fluvial system. It has been further conceptualized that structural river engineering involves channel straightening and clearance of riparian vegetation cover as well as land use and land cover changes in areas adjacent to the river. Thus, it has been hypothesized that the aforementioned process-response feedback loops manifest in changing landscape metrics in the fluvial environment and can therefore be used as indicators for human-landscape interactions (research question *IIId).*

7.3.2 Testing the conceptual model on dam-induced connectivity between the fluvial system and the human system and its possible implications for landscape change

Case study 6 - Dam-induced landscape change and the role of human-landscape interactions – a reach-scale case study

Reference: Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study (subm., 2012). *Earth Surface Processes and Landforms*. (Source: Poeppl et al. 2012c, A.3)

The objectives of case study 6 were to assess landscape changes in terms of land use/land cover and river planform geometry in a dam-impacted river reach between two points in time, and to relate these changes to dam-induced geomorphic channel changes considering aspects of dam-induced interactions between the fluvial and the human system. The objectives were met by applying a combination of GIS-based mapping techniques, geo-statistical analyses, numerical landscape evolution modeling with CAESAR and field surveys in a dam-impacted river reach of the Kaja River. The results of CAESAR modelling have shown that dam construction leads to geomorphic responses in terms of upstream aggradation and downstream degradation, while dam removal has been shown to have the opposite effects. The findings of the field surveys revealed the presence of river engineering structures in river reaches in which channel degradation - either induced by dam construction or dam removal - has been modelled. Since the presence of river engineering structures has been related to the the locations of channel degradation, it has been deduced that dam-induced geomorphic effects triggered a human response in terms of structural river engineering. GIS-based mapping techniques and geo-statistical analyses exhibited significant landscape changes in the fluvial environments in terms of channel straightening, land use and land cover and a clearance of riparian woodland vegetation. Occurrence and location of these landscape changes have been related to the presence of dam-induced geomorphic channel changes and the presence of river engineering structures. (Source: Poeppl et al. 2012c, A.3)

It is therefore concluded that human impact on fluvial systems in terms of dam construction led to an interconnection of the fluvial system and the human system by triggering a series of process-response feedback loops between them which further influenced landscape changes in the fluvial environment. Referring to Chorley and Kennedy (1971), the observed system can be regarded as a control system, identifying dam locations as ‘valves’ where intelligence intervenes to produce operational changes. It was further shown that human intervention can lead to unintended geomorphic side-effects which call for further human interventions that may result in a complex system of interactions. Urban (2002) identified the importance of feedback loops between geomorphic and socio-cultural contexts for landscape change and his findings are in line with the feedback loops between geomorphic and human processes identified in this thesis. It has to be stated that within the methodology applied in case study 6 socio-cultural motivations for human responses were only deduced from modelled and observed landscape changes between two points in time by using indicators rather than investigating them empirically. Thus, landscape change in the observed system may also be related to further factors such as technological trends towards river engineering. These trends are related to tendencies in the eighteenth and nineteenth century when river engineering works became wide-spread and large scale in Western Europe, mainly utilized to reclaim more agricultural land and to control floods (Takahasi 2009). Moreover, different economic trends can lead to land use changes including dam removals and related reservoir abandonment. In the case of the Kaja River which has been investigated in this case study, these potential trends include a decreased need for fish or a declined economic profitability of fish farming. In order to get a holistic picture on the influence of human-landscape interactions on landscape changes, the applied methodology therefore needs to be extended by including a comprehensive investigation of the socio-cultural divers of landscape change.

8. Synopsis

In the present thesis, human impacts on fluvial systems and associated landscape changes in fluvial environments have been observed by investigating (1) sediment connectivity relationships within fluvial systems and (2) connectivity relationships between the human system and the fluvial system. The following hypotheses have been formulated which further guided the course of this study:

Ad 1) Sediment connectivity relationships within fluvial systems

I) Linking concepts of sediment connectivity to principles of channel processes contributes to a better understanding of geomorphic channel response to dam construction and changes of land use and land cover

II) Dam construction induces geomorphic channel changes that trigger a series of process-response feedback loops between the human and the fluvial system

Ad 2) Connectivity relationships between the human system and the fluvial system

III) Lateral buffering is strongly influenced by riparian vegetation cover type and biogeomorphic processes

For each of the hypotheses outlined above, conceptual models have been developed and model assumptions were tested by performing and evaluating case studies. Apart from the fact that these models have to be further elaborated as well as tested in different geographical environments, these individual concepts need to be synthesized to come up with a more holistic conceptual model that allows for a comprehensive observation of connectivity relationships in human-impacted fluvial systems. The use of such a model is considered to contribute to a better understanding of the processes and factors that govern human-induced landscape changes in fluvial environments. Based on these considerations, the individual models are verbally and graphically linked to each other taking a broader perspective. For this, the factors and processes that govern sediment connectivity in fluvial systems will be outlined and related to geomorphic channel processes. Potential factors and processes inherent in human systems that potentially govern human modifications of fluvial systems will be identified. The fluvio-geomorphic effects of human impacts on fluvial systems as well as the implications of fluvio-geomorphic processes for the human system will be addressed. Lastly, the role of connectivity relationships between the human and the fluvial system in governing landscape changes in fluvial environments will be identified.

The potential for sediment transfer from one zone or location to another is determined by a range of factors that influence sediment transport capacity of which overland flow is the basic requirement for sediment connectivity (e.g. Poeppl et al. 2012b, A.2). Overland flow is governed by factors that determine runon and runoff processes. The major external control of overland flow processes is the climate which determines the amount of water reaching the land surface (see Fig. 33). Internal controls of overland flow are geology, topography, soils and vegetation. Geology and topography are mainly defined by tectonics and determine the delivery pathways of water and sediments to a river. Quantity and size of sediments that are potentially transported from the catchment areas to the river channels is governed by the soil conditions and factors that determine rates of soil erosion. Geomorphic processes in river channels are mainly defined by the ratios of sediment supply and stream power. Changes in all of the factors mentioned above may lead to a change of sediment connectivity on the different spatial dimensions and therefore to geomorphic channel changes, since they alter the ratios between stream power (P) and sediment supply (SS) (see Fig. 33).

As already highlighted in chapter 1, the reasons for human impacts fluvial systems are manifold, ranging from different types of land use to river engineering. Moreover, these rationales are ever-changing as the human processes and factors that govern them are subject to change. Human systems are governed by social factors and processes that shape the way humans act. These include the human population (e.g. population distribution and density), social organization, values, knowledge and technology that altogether influence human behaviour and the repertoire of human actions (Marten 2001, Urban 2002) (see Fig. 33).

Human impacts on fluvial systems can affect the internal factors of fluvial systems and the relationships that exist between them as well as the different spatial dimensions of sediment connectivity. Human-induced alterations of sediment connectivity have been shown to lead to geomorphic channel responses that may affect the human system. When the human system gets compromised (e.g. erosion, sedimentation of reservoirs), further intervention is necessary (e.g. river bank and bed protection, dam removal) which induces further geomorphic and human responses. Finally, a process-response feedback loop interconnecting the human and the fluvial system has established which results in the emergence of a coupled human-landscape system (see Fig. 33) that drives landscape change in fluvial environments.

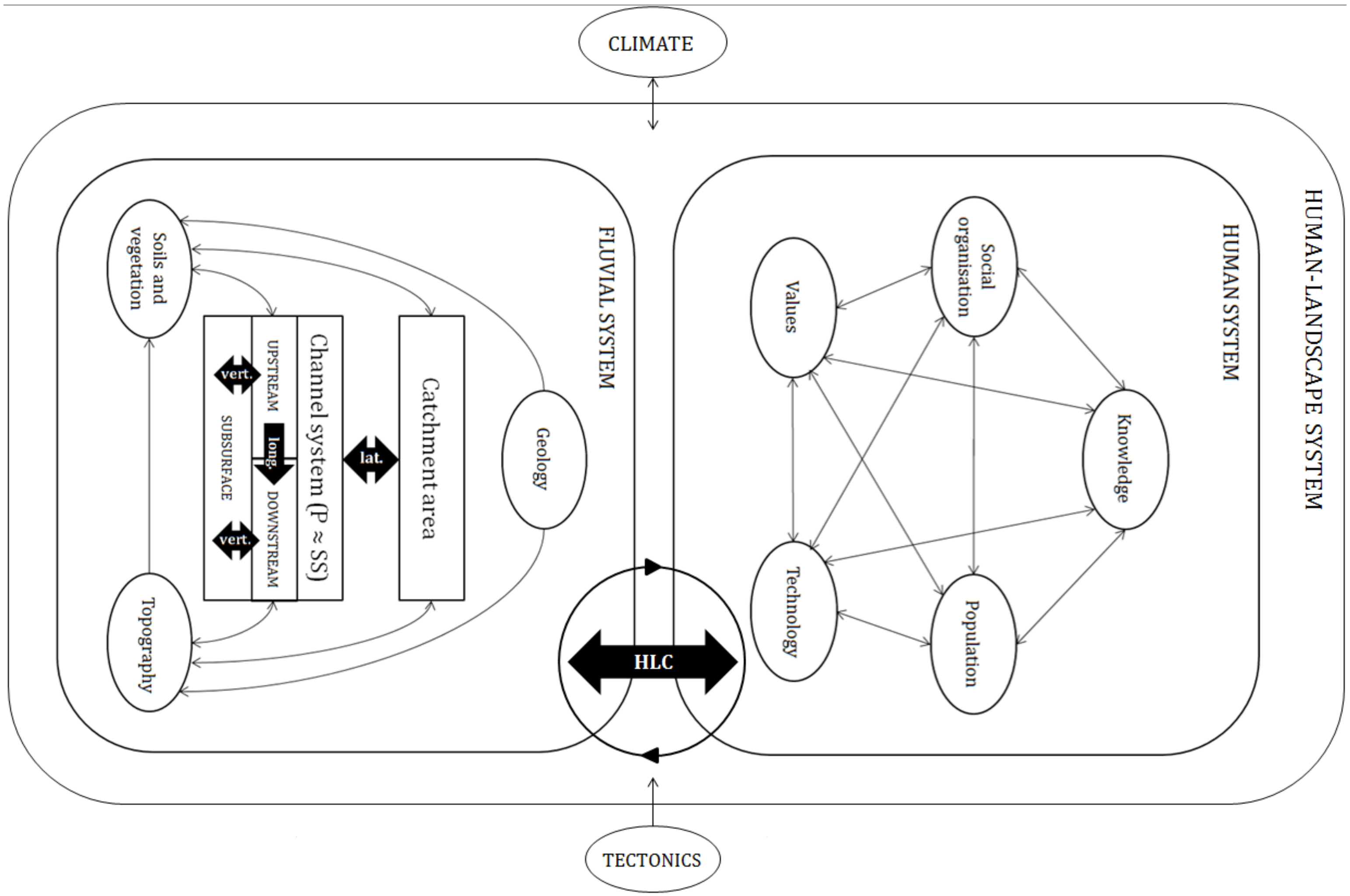


Fig. 33: Linking the conceptual models on connectivity. Relationships between factors and system compartments are indicated by slight arrows. Connectivity relationships are identified as bold arrows: (HLC)…human-landscape connectivity, (lat.)…lateral sediment connectivity, (long.)…longitudinal sediment connectivity, (vert.)…vertical sediment connectivity). Geomorphic state of the river channel system is indicated by the Lane Balance (Lane 1955): (SS)…sediment supply, (P)…stream power. Process-response-feedback loops between the human and the fluvial system are indicated by a circled arrow. Figure adapted from Marten (2001, Fig. 1.1) and Charlton (2008, Fig. 2.2).

References

Aitken, S.C., 1992. Person-environment theories in contemporary perceptual and behavioural geography II: The influence of ecological, environmental learning, societal/structural, transactional and transformational theories. Progress in Human Geography 16 (4), 553–62.

Al-Taiee, T.M., 1990. The influence of a dam on the downstream degradation of a river bed: case study of the Tigris River. Hydrology in Mountainous Regions. II – Artificial Reservoirs, Water and Slopes (Proceedings of two Lausanne Symposia, August 1990). IAHS Publ. no. 194, 1990.

Andrews, E.D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97, 1012– 1023.

Antrop, M., 2003. The role of cultural values in modern landscapes. The Flemish example. In: Palang, H., Fry, G. (eds.), Landscape Interfaces: Cultural Heritage in Changing Landscapes. Kluwer Academic Publishers, 91–108.

Arrow, K., Bolin,B., Costanza, P., Dasgupta, R., Folke, C., Holling, C.S., Jansson, B.-O., Levin, S., MŠler, K.-G., Perrings, C., Pimente, D., 1995. Economic growth, carrying capacity, and the environment. Science 268, 520–521.

Auzet, A.V., Boiffin, J., Papy, F., Ludwig, B., Maucorp, J., 1993. Rill erosion as a function of the characteristics of cultivated catchments in the north of France. Catena 20, 41–62.

Bartley, R., Rutherfurd, I., 1999. The recovery of geomorphic complexity in disturbed streams: using migrating sand slugs as a model. In: Rutherfurd, I., Bartley, R., Eds., Proceedings of the Second Australian Stream Management Conference, Adelaide 1, 39–44.

Bastian, O., 2001. Landscape Ecology – towards a unified discipline? Landscape Ecology 16 (8), 757–766.

Belisle, M., 2005. Measuring landscape connectivity: the challenge of behavioural landscape ecology. Ecology 86, 1988–1995.

Bennett, D., McGinnis, D., 2007. Coupled and complex: Human-environment interaction in the Greater Yellowstone Ecosystem, USA. Geoforum 39, 833-845.

Bergkamp, G., Cammeraat, L.H., Mertinez-Fernandez, J., 1996. Water movement and vegetation patterns on shrubland and an abandoned field in two desertification threatened areas in Spain. Earth Surface Processes and Landforms 21, 1073–1090.

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Poesen, J., 2000. Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. Geomorphology 32(1–2), 69–82.

Beyer, H. L., 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools (accessed 10 September 2010).

Boell, A., 1997. Wildbach- und Hangverbau, Berichte der Eidgenoessischen Forschungsanstalt fuer Wald, Schnee und Landschaft, 343, 123.

Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., Soriano-Soto, M.D., Tiemessen, I.R., 1998. Spatial and short-term temporal variations in runoff, soil aggregation and other soil properties along a Mediterranean climatological gradient. Catena 33, 123–138.

Borin, M., Vianello, M., Morari, F., Zanin, G., 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. Agricultural Ecosystems and Environment 105, 101-114.

Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena 75, 268-277.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrological Processes 21, 1749-1763.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena 40, 375-401.

Brierley, G.J., Fryirs, K.A., Outhet, D., Massey, C., 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22, 91–122.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and river management. Applications of the river styles framework. Blackwell Publishing.

Brierley, G., Fryirs, K., Jain, V., 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38(2), 165-174.

Brierley, G.J., Reid, H.E., Fryirs, K.A., Trahan, N. 2010. What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. Science of the Total Environment 408, 2025-2033.

Brookes, A., 1992. Recovery and restoration of some engineered British River channels. In: Boon, P.J., Calow, P., Petts, G.E., Eds., River Conservation and Management. Wiley, Chichester, 337–352.

Brookes, A., 1994. River channel change. In: Calow, P., Petts, G.E. (eds.) The River Handbook; Hydrological and Ecological Principles. Blackwell Science, Oxford, UK, 55–75.

Brookes, A., 1995. River channel restoration: theory and practice. In: Gurnell, A., Petts, G.E. ŽEds.., Changing River Channels. Wiley, Chichester, 369–388.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers, NS 4, 463-484.

Brunsden, D., 1993. Barriers to geomorphological change. In: Thomas, D.S.G., Allison, R.J. (eds.) Landscape Sensitivity. Wiley, 7–12.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. Catena 42, 99-123.

Bubenzer, O., Riemer, H. (2007): Holocene Climatic Change and Human Settlement between the Central Sahara and the Nile Valley - Archaeological and Geomorphological Results. - Geoarchaeology 22, 607-620.

Bull, L.J., Kirkby, M.J., Shannon, J., Hooke, J.M., 2000. The variation in estimated discharge in relation to the location of storm cells in SE Spain. Catena 38, 191–209.

Burel, F.A., Baudry, J., 2003. Landscape ecology. Concepts, Methods and Applications. Science Publishers Inc., Enfield.

Burroughs, B.A., Hayes, D.B., Klomp, K.D., Hansen, J.F., Mistak, J., 2009. Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan. United States. Geomorphology 110, 96-107.

Butcher, D.P., Claydon, J., Labadz, J.C., Pattinson, V.A., Potter, A.W.R., White, P., 1992. Reservoir sedimentation and colour problems in southern Pennine reservoirs. Journal of the Institute of Water and Environmental Management 6, 418-431.

Cammeraat, L.H., 2002. A review of two strongly contrasting geomorphological systems within the context of scale. Earth Surface Processes and Landforms 27, 1201-1222.

Carmean, W.H., 1957. The structure of forest soils. The Ohio Journal of Science 57(3), 164-168.

Charlton, R., 2008. Fundamentals of fluvial geomorphology. Routledge, London.

Chiverell, R.C., Foster, G.C., Marshall, P., Harvey, A.M., Thomas, G.S.P., 2009. Coupling relationships: Hillslope-fluvial linkages in the Hodder catchment, NW England. Geomorphology 109, 222-235.

Chorley, R.J., Kennedy, B.A., 1971. Physical Geography: A systems approach. Prentice Hall International Inc., London, UK.

Connor, T.B., 1986. The impact and economic effects of soil conservation practice on river aggradation. In Drainage Basin Sediment Delivery, TF Hadly (Ed.), IAHS Publication 159, 81-91.

Cooper, J.R., Gilliam, J.W., Daniels, R.B., Robarge, W.P., 1987. Riparian areas as filters for agricultural sediment. Soil Science Society of America Journal 51,(2), 416-420.

Cosgrove, D., 2003. Landscape: ecology and semiosis. In: Palang, H., Fry, G. (eds.): Landscape interfaces. Cultural heritage in changing landscapes. Landscape series 1. Dordrecht, 15–20.

Costa, J.E., 1987. A comparison of the largest rainfall–runoff foods in the United States and the People's Republic of China and the world. Journal of Hydrology 96, 101–115.

Coulthard, T.J., Lewin, J., Macklin, M.G., 2005. Modelling differential catchment response to environmental change. Geomorphology 69, 222-241.

Croke, J., Mockler, S., Fogarty, P., Takken, I., 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. Geomorphology 68, 257–268.

Cullinan, V.I., Thomas, J.M., 1992. A comparison of quantitative methods for examining landscape pattern and scale. Landscape Ecology 7, 211-227.

Dabney, S.M., Meyer, L.D., Harmon, W.C., Alonso, C.V., Foster, G.R., 1995. Depositional patterns of sediment trapped by grass hedges. Transactions of the American Society of Agricultural Engineers 38(6), 1719–1729.

Deadman, M.L., Al-Sa'di, A.M., Al-Mahmuli, I., Al-Maqbali, Y.M., Al-Subhi, R., Al-Kiyoomi, K., Al-Hasani, H., Thacker, J.R.M., 2002. Management of Pythium aphanidermatum in greenhouse cucumber production in the Sultanate of Oman. In: the BCPC Conference: Pests And Diseases. Brighton, UK. pp. 171–176.

Dedkov, A.P., Moszherin, V.I., 1992. Erosion and sediment yield in mountain regions of the world. In: Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992), IAHS Publ. no. 209, 1992.

Deletic, A., 2006. Performance of grass filters used for stormwater treatment—a field and modelling study. Journal of Hydrology 317, 261–275.

Downs, P.W., Gregory, K.J., 1993. The sensitivity of river channels in the landscape system. In: Landscape Sensitivity, Thomas, D.S.G., Allison, R.J. (eds.), 15–30. New York: John Wiley and Sons.

Doyle, C., Nanson, G., Perrens, S., 1999. A geomorphic study into the effects and remedies of European influences on the Nambucca River catchment: lessons for gravel-bed river management in coastal southeastern Australia. In: Rutherfurd, I., Bartley, R., Eds., Proceedings of the Second Australian Stream Management Conference, Adelaide 1, 219–224.

Doyle, M.W., Stanley, E.H., Orr, C.H., Selle, A.R., Sethi, S.A., Harbor, J.M., 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. Geomorphology 71, 227-244.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266, 753-762.

Erskine, W.D., 1993. Erosion and deposition produced by a catastrophic flood on the Genoa River, Victoria. Australian Journal of Soil and Water Conservation 64, 35–43.

European Environment Agency, 2009. Water resources across Europe confronting water scarcity and drought. EEA Report No 2/2009. European Environment Agency, Copenhagen, Denmark. Retrieved from www.eea.europa.eu/publications/water-resources-across-europe (accessed 13 September 2010).

Fang, H.W., Rodi, W. 2003. Three-dimensional calculations of flow and suspended sediment transport in the neighborhood of the dam for the Three Gorges Project (TGP) reservoir in the Yangtze River. Journal of Hydraulic Engineering 41, 379–394.

Farina, A., 2000. Principles and methods in landscape ecology. Springer, Dordrecht, 412 pp.

Forman, R.T.T, Godron, M., 1986. Landscape ecology. John Wiley and Sons, New York, 640 pp.

Fort, M., Cossart, E., Arnaud-Fassetta, G., 2010. Hillslope-channel coupling in the Nepal Himalayas and threat to man-made structures: The middle Kali Gandaki valley. Geomorphology 124, 178-199.

Fitzjohn, C., Ternan, J.L., Williams, A.G., 1998. Soil moisture variability in a semi-arid gully catchment: implications for runoff and erosion control. Catena 32, 55–70.

Fryirs, K., Brierley, G.J., 1999. Slope–channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement. Catena 35, 41–63.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007a. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena 70, 49-67.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Spencer, J., 2007b. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. Geomorphology 84, 297-316.

Fuchs, S., 2009. Susceptibility versus resilience to mountain hazards in Austria – Paradigms of vulnerability revisited, Natural Hazards and Earth System Sciences 9, 337-352.

Fuller, I.C., Marden, M., 2011. Slope-channel coupling in steepland terrain: A field-based conceptual model from the Tarndale gully and fan, Waipaoa catchment, New Zealand. Geomorphology 128, 105-115.

Gábris, G., Kertész, Á., Zámbó, L., 2003. Land use change and gully formation over the last 200 years in a hilly catchment, Catena 50, 151-164.

Geist, H.J., Lambin, E.E., 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience 52(2), 143-150.

Gergel, S.E., Turner, M.G., Miller, J.R., Melack, JM., Stanley, E.H. 2002. Landscape indicators of human impacts to riverine systems. Aquatic Sciences 64, 118-128.

Gilvear, D.J., Winterbottom, S.J., 1992. Channel changes and flood events since 1783 on the regukated river Tay, Scotland: implications for flood hazard management. Regulated Rivers 7, 272-260.

Gimblett, H.R., 2005. Modelling Human-Landscape Interactions in Spatially Complex Settings: Where are we and where are we going? Paper presented at the MODSIM 2005, International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, 11–20.

Godfrey, A.E., Everitt, B.L., Duque, J.F.M., 2008. Episodic sediment delivery and landscape connectivity in the Mancos Shale badlands and Fremont River system, Utah, USA. Geomorphology 102, 242-251.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J., Nathan, R.J., 2004. Stream Hydrology: An Introduction for Ecologists. John Wiley & Sons, Chichester.

Gordon, E., Meentemeyer, R.K., 2006. Effects of dam operation and land use on stream channel morphology and riparian vegetation. Geomorphology 82, 412-429.

Goudie, A.S., 1986. The integration of human and physical geography. Transactions of the Institute of British Geographers 11, 454–58.

Govers, G., 1991. Rill erosion on arable land in central Belgium—rates, controls and predictability. Catena 18, 133–155.

Govers, G., Takken, I., Helming, K., 2000. Soil roughness and overland flow. Agronomie 20, 131–146.

Graf, W.L., 1977. The rate law in fluvial geomorphology. American Journal of Science 277, 178-191.

Graf, W.L., 2003. Dam Removal Research: Status and Prospects. Heinz Center for Science. Economics and the Environment, Washington, DC.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79, 336-360.

Grams, P.E., Schmidt, J.C., 2002. Streamflow regulation and multilevel floodplain formation: channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. Geomorphology 44, 337-360.
Grant, G.E., Schmidt, J.C., Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. Water Science and Application 7, 209-225.

GRASS Development Team, 2008. Geographic Resources Analysis Support System (GRASS) Software. Open Source Geospatial Foundation Project. http://grass.osgeo.org.

Gregory, K. J., 1985. The nature of physical geography. London: Edward Arnold.

Gregory, K.J., 2000. The Changing Nature of Physical Geography. Arnold, London.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172-191.

Gumiere, S.J., Le Bissonnais, Y., Raclot, D., Cheviron, B., 2010. Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: a review. Earth Surface Processes and Landforms 36, 3-19.

Haff, P.K., 2003. In: Wilcock, P.R., Iverson, R.M. (eds.), Neogeomorphology, prediction and the anthropic landscape. Prediction in Geomorphology: Geophysical Monograph, vol. 135. American

Hart, M.G., 1986. Geomorphology: Pure and applied. London: Allen and Unwin.

Haines-Young, R., Chopping, M., 1996. Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. Progress in Physical Geography 20, 418–445.

Haines-Young, R., 2000. Sustainable development and sustainable landscapes: defining a new paradigm for landscape ecology. Fennia 178, 7–14.

Harvey, A.M., 1992. Process interactions, temporal scales and the development of hillslope gully systems: Howgill Fells, Northwest England. Geomorphology 5, 323–344.

Harvey, A.M., 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. Catena 42, 225–250.

Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. Geomorphology 44, 175-201.

Harvey, A.M., 2007. Differential recovery from the effects of a 100-year storm: Significance of long-term hillslope-channel coupling; Howgill Fells, northwest England. Geomorphology 84, 192-208.

Helming, K., Römkens, M.J.M., Prasad, S.N., 1998. Surface roughness related processes of runoff and soil loss: a flume study. Journal of the Soil Science Society of America 62, 243–250.

Heppner, C.S., Loague, K., 2008. A dam problem: simulated upstream impacts for a Searsville-like watershed. Ecohydrology 1, 408-424.

Holdaway, S., Fanning, P., Rhodes, E., 2008. Challenging intensification: human-environment interactions in the Holocene geoarchaeological record from western New South Wales, Australia.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390-405.

Holub, M., Fuchs, S, 2009. Mitigating mountain hazards in Austria – Legislation, risk transfer, and awareness building, Natural Hazards and Earth System Sciences 9, 523-537.

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

Hooke, R., 2000. On the history of humans as geomorphic agents. Geology (Boulder) 28(9), 843–846.

ITGE, 1998. Instituto Tecnológico Geominero de España: Mapa Geológico de España, 1:50,000, Hoja 383, Memoria, Madrid, 47 pp.

Imeson, A.C., Verstraten, J.M., van Mulligan, E.J., Sevink, J., 1992. The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. Catena 19, 345–361.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO, Rome.

James, L.A., Marcus, W.A., 2006. The human role in changing fluvial systems: Retrospect, inventory and prospect. Geomorphology 79, 152-171.

Jessel, B., 2006. Elements, characteristics and character—information functions of landscapes in terms of indicators. Ecology Indicators 6 (1), 153–167.

Kasai, M., Marutani, T., Reid, L.M., Trustrum, N.A., 2001. Estimation of temporally averaged sediment delivery ratio using aggradational terraces in headwater catchments of the Waipaoa River, North Island, New Zealand. Earth Surface Processes and Landforms 26, 1–16.

Kasai, M., Brierley, G.J., Page, M.J., Maturani, T., Trustrum, N.A., 2005. Impacts of land use change on patterns of sediment flux in Weraamaia catchment, New Zealand. Catena 64, 27-60.

Keesstra, S., Huissteden, J.v., Vandenberghe, J., Van Dam, O., de Gier, J., Pleizier, I.D., 2005. Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes. Geomorphology 69, 191-207.

Keesstra, S.D., 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. Earth Surface Processes and Landforms 32(1), 49-65.

Keesstra, S.D., van Dam, O., Verstraeten, G., van Huissteden, J., 2009a. Changing sediment generation due to natural reforestation in the Dragonja catchment, SW Slovenia. Catena 78, 60-71.

Keesstra, S.D., Bruijnzeel, L.A., van Huissteden, J., 2009b. Constructing a sediment budget in a meso-scale catchment using a variety of methods: the Dragonja catchment, SW Slovenia. Earth Surface Processes and Landforms 32(1), 49-65.

Kimberly, A.W., Gardner, R.H., Turner, M.G., 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos 78, 151–169.

Kirkby, M.J., Bracken, L.J., Reaney, S., 2002. The influence of landuse, soils and topography on the delivery of hillslope runoff to channels in SE Spain. Earth Surface Landforms and Processes 27, 1459–1473.

Knighton, A.D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environmental Management 21(4), 533-551.

Kondolf, G.M., Piégay, H., Landon, N., 2002. Channel response to increased and decreased bedload supply from land-use change: between two catchments. Geomorphology 45, 35– 51.

Kondolf, G.M., Montgomery, D.R., Piégay, H. & Schmitt, L., 2003. Geomorphic classification of rivers and streams. In: G.M.Kondolf & H. Piégay (eds.) Tools in Fluvial Geomorphology, John Wiley & Sons, Chichester, UK.

Kondolf, G.M., Boulton, A. J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P., Nakamura, K., 2006. Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11(2), 5.

Lagasse, P.F., 1981. Geomorphic response of the Rio Grande to dam construction. New Mexico Geological Society, Special Publication 10, 27–41.

Lambin, E.F., Baulies, X., Bockstael, N., Fischer, G., Krug, T., Leemans, R., Moran, E.F., Rindfuss, R.R., Sato, Y., Skole, D., Turner, B.L. II, Vogel, C., 1999. Land-use and land-cover change (LUCC): Implementation strategy. IGBP Report 48, IHDP Report 10, Stockholm, Bonn.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Xiubin, L., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skanes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C., Jianchu, X., 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change 11, 261-269.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of the American Society of Civil Engineers 81, 1–17.

Langbein, W.B., Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. Transactions of the American Geophysical Union 39, 1976-1984.

Lasanta, T., Garcia-Ruiz, J.M., Perez-Rontome, C., Sancho-Marcen, C., 2000. Runoff and sediment yield in a semi-arid environment: the effect of land management after farmland abandonment. Catena 38, 265–278.

Lawson, J.M., 1925. Effect of Rio Grande storage on river erosion and deposition. Engineering News Record, 327–334.

Le, Q.B., Park, S.J., Vlek, P.L.G., Cremers, A.B., 2008. Land-Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. I. Structure and theoretical specification.

Le Bissonnais, Y., Lecomte, V., Cerdan, O., 2004. Grass strip effects on runoff and soil loss. Agronomie 24, 129–136.

Leach, M., Mearns, R., 1996. The lie of the land: challenging received wisdom on the African environment, Oxford: James Currey.

Lee, K.H., Isenhart, T.M., Schultz, R.C., 2003. Sediment and nutrient removal in an established multi-species riparian buffer. Journal of Soil and Water Conservation 58, 1-8.

Leguédois, S., Ellis, T.W., Hairsine, P.B., Tongway, D.J., 2008. Sediment trapping by a tree belt: processes and consequences for sediment delivery. Hydrological Processes 22, 3523-3534.

Lent, L., Holleyman, C., Lawrence, M., Jones, C., 1999. In: Ewing, l., Magoon, O.T., Robertson, S. (eds.), Sand Rights '99: Bringing Back the Beaches. ASCE, Virginia, 19–33.

Lenton, T.M., Schellnhuber, H.J., Szathmary, E., 2004. Climbing the co-evolutionary ladder. Nature 431, 913.

Leopold, L.B., 1972. River channel change with time: an example. Bulletin of the Geological Survey of America 84(6), 1845-1860.

Leser, H., 1991. Landschaftsökologie. Ansatz, Modelle, Methodik, Anwendung. UTB, Stuttgart.

Lexartza-Artza, I., Wainwright, J., 2011. Making conncetions: changing sediment sources and sinks in an upland catchment. Earth Surface Processes and Landforms 36, 1090-1104.

Liu, C.M., 1983. Impact of check dams on steep mountain channels in northeastern Taiwan. In: Soil Erosion and Conservation (ed. By S.A. El-Swaifi et al.), 540-548. Soil Conservation Society of America.

Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W., Todd, A.H., 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environmental Management 21(5), 687-712.

Madej, M.A., Ozaki, V., 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21, 911-927.

Magliocca, N.R., 2008. Induced coupling: an approach to modeling and managing complex human-landscape interactions. Systems Research and Behavioral Science 25(5), 655-662.

Marten, G.G., 2001. Human Ecology – Basic Concepts for Sustainable Development. Earthscan publications, pp. 256.

Marzolff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. Earth Surface Processes and Landforms 36(12), 1604-1623.

Meyer, W.B., Turner, B.L. III (eds.), 1994. Changes in Land Use and Land Cover: a Global Perspective. Cambridge University Press, Cambridge.

Meyer, L.D., Dabney, S.M., Harmon, W.C., 1995. Sediment-trapping effectiveness of stiff-grass hedges. Transactions of the ASAE 38, 809-815.

Michaelides, K., Wainwright, J., 2002. Modelling the effects of hillslope–channel coupling on catchment hydrological response. Earth Surface Processes and Landforms 27, 1441–1457.

Michaelides, K., Chappell, A., 2009. Connectivity as a concept for characterising hydrological behaviour', Hydrological Processes, 23, 517-522.

Miller, D.J., Benda, L.E., 2000. Effects of punctuated sediment supply on valley-floor landforms and sediment transport. Geological Society of America Bulletin 112, 1814–1824.

Murray, A.B., Lazarus, E., Ashton, A., Baas, A., Coco, G., Coulthard, T., Fonstad, M., Haff, P., McNamara, D., Paola, C., Pelletier, J. & Reinhardt, L., 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. Geomorphology 103(3): 496–505.

NASA, 1988. Earth System Science: a closer view. Report of the Earth Systems Sciences Committee, Advisory Council. Washington, DC: National Aeronautics and Space Administration.

Naveh, Z., 1994. Interactions of landscapes and cultures. Landscape and Urban Planning 32, 43-54.

Newson, M.D., 1994. Sustainable integrated development and the basin sediment system: guidance from fluvial geomorphology. In: Kirkby, C., White, W.R., Eds., Integrated River Basin Development. Wiley, Chichester, 1–10.

Nicholas, A.P., 2005. Cellular modeling in fluvial geomorphology. Earth Surface Processes and Landforms 30, 645-649.

Nicolau, J.M., Sole, A., Puidefabregas, J., Gutierrez, L., 1996. Effects of soil and vegetation on runoff along a catena in semi-arid Spain. Geomorphology 15, 297–309.

Nyssen, J., Poesen, J., Meoyersons, J., Luyten, E., Veyret-Picot, M., Deckers, J., Haile, M., Govers, G., 2002. Earth Surface Processes and Landforms 27, 1267-1283.

Orbock Miller, S., Ritter, D.F., Kochel, R.C., Miller, J.R., 1993. Fluvial responses to land-use changes and climatic variations within the Drury Creek watershed, southern Illinois. Geomorphology 6, 309– 329.

Ouyang, W., Hao, F.H., Zhao, C., Lin, C., 2010. Vegetation response to 30 years hydropower cascade exploitation in upper stream of Yellow River. Communications in Nonlinear Science and Numerical Simulation 15, 1928–1941.

Pacific Coast Federation of Fishermen's Associations, 2012. Dams and salmon. Why dams must go! http://www.pcffa.org/dams.htm (accessed 10 May 2012).

Park, C.C., 1977. Man-induced changes in stream channel capacity. In: Gregory, K.J. (ed.) River Channel Changes. Wiley, Chichester, UK, 121–144.

Park, C.C., 1981. Man, river systems and environmental impacts. Progress in Physical Geography 5, 1–31.

Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Progress in Physical Geography 3, 329– 362.

Petts, G.E., 1989. Perspectives for ecological management of regulated rivers. In: Gore, J.A. and Petts, G.E. (eds.) Alternatives in Regulated River Management. CRC Press, USA, 3–24.

Phillips, J.D., 1989. Hillslope and channel sediment delivery and impacts of soil erosion on water resources. Sediment and the Environment. IAHS Publ. no. 184, 183–190.

Phillips, J.D., 1992. Delivery of upper-basin sediment to the lower Neuse River, North Carolina, USA. Earth Surface Processes and Landforms 17, 699–709.

Phillips, J.D., 1995. Decoupling of sediment sources in large river basins. Effects of scale on interpretation of sediment and water quality. IAHS Publ. no. 226, 11–16.

Phillips, J.D., 2009. Changes, perturbations, and responses in geomorphic systems. Progress in Physical Geography 33(1), 17-30.

Pitlick, J., 1994. Relation between peak flow, precipitation, and physiography for five mountainous regions in western USA. Journal of Hydrology 53, 219–240.

Poeppl, R.E., 2010. Die Fluvialmorphologie der Fugnitz und des Kajabaches. Eine vergleichende Analyse ausgewaehlter Flussabschnitte unter besonderer Beruecksichtigung anthropogener Effekte. Final project report, National Park Thayatal, Austria, 95 pp. incl. DVD- Rom.

Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T., 2012a (acc., 2012). The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. Geomorphology.

Poeppl, R. E., Keiler, M., Elverfeldt, K.v., Zweimüller, I., and Glade, T., 2012b (in press, 2012). The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. Geografiska Annaler, Series A, Physical Geography.

Poeppl, R. E., Keiler, M., Coulthard, T.J. Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study, 2012c (subm., 2012). Earth Surface Processes and Landforms.

Poesen, J., 1984. The influence of slope gradient on infiltration rate and Hortonian overland flow volume. Zeitschrift für Geomorphologie Supplement Band 49, 117–131.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91-133.

Potthoff, K., 2007. Landscape change as an interface for different approaches in landscape research. Erdkunde 61, 54-71.

Puigdefabregas, J., Sole, A., Gutierrez, L., Del Barrio, G., Boer, M., 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain. Earth-Science Reviews 48 (1–2), 39–70.

Rawnsley, J., 1991. Trees and Soil Stabilization. Environmental Conservation 18, 371-371.

Rhoads, B.L., Thorne, C.E., 1994. Contemporary perspectives on Physical Geography with emphasis on geomorphology. Geographical Review 84(1), 90-101.

Roetzel, R., Fuchs, G., Ahl, A., Schubert, G., Slapansky, P., 2008. Erläuterungen zur Geologischen Karte 1:50,000, Blatt 8 Geras. Geologische Bundesanstalt Österreich.

Rutherfurd, I., 1996. Sand slugs in South East Australia streams: origins, distribution and management. In: Rutherfurd, I., Walker, M., Eds., Proceedings of the First National Conference on Stream Management in Australia, Merrijig, 19–23 February 1996. Cooperative Research Centre for Catchment Hydrology, Monash University.

Schick, A.P., 1988. Hydrologic aspects of floods in extreme arid environments. In: Baker, V.R., Kochel, R.C., Patton, P.C. (eds) Flood Geomorphology, Wiley New York, 189–203.

Schnitter, N.J., 1994. A history of dams. Rotterdam: Balkema.

Schoorl, J.M., Veldkamp, A., Bouma, J., 2002. Modelling water and soil redistribution in a dynamic landscape context. Soil Science Society of America Journal 66, 1610-1619.

Schumm, S.A., 1969. River metamorphosis. Proceedings of the American Society of Civil Engineers. Journal of the Hydraulics Division 95, 255–273.

Schumm, S.A., 1991. To interpret the Earth: Ten ways to be wrong. New York: Cambridge University Press.

Schumm, S.A., 2005. River variability and complexity. Cambridge university press.

Sear, D.A., 1996. The sediment system and channel stability. In: Brookes, A., Shields Jr., F.D., (eds.), River Channel Restoration: Guiding Principles for Sustainable Projects. Wiley, Chichester, 149–177.

Seeger, M., I. Marzolff, and J.B. Ries (2009), Identification of gully-development processes in semi-arid NE-Spain, Z. Geomorph. N. F. 53(4), 417–431.

Selman, P., 2006. Planning at the Landscape Scale. Routledge, Oxon.

Shafroth, P.B., Stromberg, J.C., Patten, D.T., 2001. Riparian vegetation response to altered disturbance and stress regimes. Ecological Applications 12(1), 107-123.

Sidorchuk, A., 2005. Stochastic components in the gully erosion modelling, Catena 63(2-3), 299.

Simon, A., Castro, J., 2003. Measurement and Analysis of Alluvial Channel Form. In: Kondolf, M., Piegay, H. (eds.) Tools in Fluvial Geomorphology. John Wiley and Sons. England.

Singer, M.J., Le Bissonnais, Y.L., 1998. Importance of surface sealing in the erosion of some soils from a Mediterranean climate. Geomorphology 24, 79–85.

Slaymaker, O., Spencer, T., 1998. Physical geography and global environmental change. Addison Wesley Longman, Singapore.

Slaymaker, O., Spencer, T., Dadson, S., 2009. Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction. In: Slaymaker, O., Spencer, T., Embleton-Hamann, C (eds.). Geomorphology and Global Environmental Change. Cambridge University Press.

Smith, M.D., Wilen, J.E., 2003. Economic impacts of marine reserves: the importance of spatial behavior. Journal of Environmental Economics and Management 46, 183–206.

Strahler, A.N., 1956. The nature of induced erosion and aggradation. In: Thomas, W.L. (ed.), Man's Role in Changing the Face of the Earth. University of Chicago Press, Chicago, 621–638.

Stanley, E.H., Luebke, M.A., Doyle, M.W., Marshall. D.W., 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. Journal of the North Americal Benthological Society 21(1), 172-187.

Swanwick, C., 2004. The assessment of countryside and landscape character in England: an overview. In: Bishop, K., Philipps, A. (Eds.), Countryside Planning. New Approaches to Management and Conservation. Earthscan, London, 109–124.

Takahasi, Y., 2009. Characteristics of River Systems. In: Dooge, J.C.I. (ed.), Fresh Surface Water. Encyclopedia of Life Support Systems. United Nations Educational, Scientific and Cultural Organization, pp. 289-299.

Taylor, K.V., 1978. Erosion downstream from dams. In: Chadwick, W.L. (eds.), Environmental Effects of Large Dams. American Society of Civil Engineers, New York, 165–186.

Thothong, W., Huon, S., Janeau, J.-L., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., Parkpian, P., 2011. Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand. Agriculture, Ecosystems and Environment 140 (3-4), 521-533.

Thornes, J.B., 1976. Semi-arid erosional systems: case studies from Spain. Geographical Papers No. 7, London School of Economics.

Tischendorf, L., Fahrig, L., 2000. How should we measure landscape connectivity? Landscape Ecology 15, 633–641.

Tress, B.A., Tress, G., 2001. Begriff, Theorie und System der Landschaft. Ein transdisziplinärer Ansatz zur Landschaftsforschung. Naturschutz und Landschaftsplanung 33 (2–3), 52–58.

Trimble, S.W., 1983. A sediment budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853-1977. American Journal of Science 283, 454-474.

Trimble, S.W., 1992. Preface. In: The American environment: Interpretations of past geographies, Dilsaver, L.M., Colten, C.E. (eds.). Totowa, NJ: Rowman and Littlefield, xv–xxii.

Turnbull, L., Wainwright, J., Brazier, R.E., 2008. A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. Ecohydrology 1, 23–34.

Turner, M.G., O'Neill, R.V., Gardner, R.H., Milne, B.T., 1989. Effects of changing spatial scale on the analysis of landscape pattern. Landscape Ecology 3, 153-162.

Turner, B.L. II, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B., 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge Univ. Press, Cambridge, 732 pp.

Uezu, A., Metzger, J.P., Vielliard, J.M.E., 2005. Effects of structural and functional connectivity and patch size on the abundance of seven Atlantic forest bird species. Biological Conservation 123, 507–519.

Urban, M.A., 2002. Conceptualizing anthropogenic change in fluvial systems: drainage development on the upper Embarras River, Illinois. The Professional Geographer 54(2), 204-217.

Van Eetvelde, V., Antrop, M., 2009. Indicators for assessing changing landscape character of cultural landscapes in Flanders (Belgium). Land Use Policy 26, 901-910.

Van Oost, K., Govers, G., Desmet, P.J.J., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecology 15, 577-589.

Verburg, P.H. and Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecology 24(9), 1167-1181.

Wainwright, J., 2006. Degrees of separation: Hillslope-channel coupling and the limits of palaeohydrological reconstruction. Catena 66, 93-106.

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., Brazier, R.E., 2011. Linking environmental régimes, space and time: Interpretations of structural and functional connectivity. Geomorphology 126, 387-404.

Ward, J.V., 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8(1), 2-8.

Wasson, R.J., Mazari, R.K., Starr, B., Clifton, G., 1998. The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. Geomorphology 24, 291–308.

Werner, B.T., McNamara, D.E., 2007. Dynamics of coupled human-landscape systems. Geomorphology 91 (3-4), 393–407.

Wiens, J.A., 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47, 501-515.

Wilcock, P.R., Barta, A.F., Shea, C.C., 1996. Observations of flow and sediment entrainment on a large gravel-bed river, Water Resources Research 32, 2897-2910.

Wilcox, B., Wood, M., Tromble, J., 1998. Factors influencing infiltrability of semi-arid mountain slopes. Journal of Rangeland Management 41, 197–206.

Wildman, L.A.S., MacBroom, J.G., 2005. The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City Dam removals. Geomorphology 71, 245-262.

Williams, G.P., 1978. The case of the shrinking channels—the North Platte and Platte Rivers in Nebraska. U.S. Geological Survey Circular, vol. 781. U.S.Government Printing Office, Washington, DC.

Williams, G.P., Wolman, M.G., 1984. Downstream Effects of Dams on Alluvial Rivers. U.S. Geological Survey Professional Paper 1286. U.S. Government Printing Office, Washington, DC.

Wilkinson, B.H., McElroy, B.J., 2007. The impact of humans on continental erosion and sedimentation. Geological Society of America Bulletin 119, 140-156.

Wilson, C.A.M.E., Stoesser, T., Bates, P.D. 2005. Modelling of open channel flow through vegetation. In Computational Fluid Dynamics: Applications in Environmental Hydraulics. Bates P.D., Lane S.N., Ferguson R.I. (eds.), John Wiley and Sons: Chichester, UK.

With, K.A., Gardner, R.H., Turner, M.G., 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos 78, 151–169.

With, K.A., King, A.W., 1997. The use and misuse of neutral landscape models in ecology. Oikos 79, 219–229.

Wolman, M. G., 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union 35(6), 951–956.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68, 54–74.

Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A, 385–395.

Wootton, J.T., Parker, M.S., Power, M.E., 1996. Effects of disturbance on river food webs. Science 273, 1558-1561.

Wu, F.C., Shen, H.W., Chou, Y.J., 1999. Variation of roughness coefficients for unsubmerged and submerged vegetation. Journal of Hydraulic Engineering 9, 934–942.

Xu, J.X., 1990. An experimental study of complex response in river channel adjustment downstream from a reservoir. Earth Surface Processes and Landforms 15, 43–53.

Zhao, Q., Shiliang, L. Denk, L., Dong, S., Cong, Wang, Yang, Z., Yang, J., 2012. Landscape change and hydrologic alteration associated with dam construction. International Journal of Earth Observation and Geoinformation 16, 17-26.

Zonneveld, I.S., 1995. Land ecology. An introduction to landscape ecology as a base for land evaluation, land management and conservation. SPB Academic Publishing, Amsterdam.

A. Articles

A.1 The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments

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Article title

The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments

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Abstract

Studying sediment connectivity offers the possibility to improve our understanding of how physical linkages govern geomorphic processes. Connectivity assessments provide a basis to identify transmission linkages and coupling efficiency in fluvial systems and therefore sensitive parts of the landscape. Connectivity assessments can also be used to estimate geomorphic responses to external forcing such as human impacts and to evaluate trajectories of future geomorphic change. However, due to the inherent complexity of landscape relationships that are related to self-regulatory properties of the system, geomorphic response to human disturbance is often difficult to predict. Previous research has already addressed the potential of connectivity concepts and assessments to analyze geomorphic responses to human impacts implicitly or explicitly and few case studies have already shown the effects of human activities on sediment connectivity and the geomorphic consequences. However, a theoretical and conceptual foundation focusing on the processes and factors that govern human-induced sediment (dis)connectivity in fluvial systems which also relates connectivity to fluvio-geomorphic processes is still missing. Moreover, further case study derived knowledge is needed to understand the processes and factors involved. This paper provides a conceptual basis on human-induced changes of sediment connectivity and their geomorphic consequences in fluvial systems. First, human-induced changes of sediment connectivity are conceptualized and related to fluvio-geomorphic reponse. Second, the conceptual model is expanded by integrating the factors of time and self-regulatory processes. The model assumptions are underpinned by presenting case studies from small to meso-scale catchments which are further interpreted and discussed within the context of the developed concept.

Keywords

Sediment connectivity, human impact, fluvial systems, geomorphic response, small to meso-scale catchments

1. Introduction

Sediment connectivity is defined by Hooke (2003, p.79) as "the potential for a specific (sediment) particle to move through the system". Studying sediment connectivity in geomorphic systems offers the possibility to improve our understanding of how physical linkages govern geomorphic processes (Van Oost et al., 2000; Keesstra, 2007; Wainwright et al., 2011) and provides knowledge on factors that determine landscape sensitivity such as coupling efficiency and transmission linkages (Brunsden, 2001). Connectivity generally operates in longitudinal, lateral, vertical dimensions and over time (Fryirs et al., 2007). According to Brierley et al. (2006) *longitudinal linkages* such as upstream-downstream and tributary- main-stem relationships drive the transfer of flow and sediments through the system and *lateral linkages* describe channel-floodplain and slope-channel relationships that govern the supply of materials to the channels. *Vertical linkages* refer to surface-subsurface interactions of water, sediment and nutrients. A general distinction is made between structural and functional connectivity. Structural connectivity describes the extent to which landscape compartments are physically linked to one another (Tischendorf and Fahrig, 2000; Turnbull et al., 2008). Functional connectivity refers to processes that result from interactions between multiple structural characteristics of the system (Kimberley et al., 1997; With et al., 1997; Belisle, 2005; Turnbull et al., 2008). In terms of sediment transfer, structural connectivity is mainly governed by the magnitude of flow events (Brunsden and Thornes, 1979; Harvey, 2002; Brierley et al., 2006, Wainwright et al., 2011). Linkages operate at a range of spatial scales and can be either connected (coupled) or disconnected (decoupled) over differing timescales (Brunsden and Thornes, 1979; Harvey, 2002). Various types of landforms, i.e. buffers, barriers, blankets and boosters can disrupt or enhance longitudinal, lateral and vertical linkages (Brierley et al., 2006). According to Fryirs et al. (2007) buffers are landforms that prevent sediments from entering the channels, barriers can disrupt sediment movement along the channel, while blankets are features that protect other landforms from reworking. On the contrary, reaches such as gorges act as boosters for sediment conveyance (Brierley et al., 2006).

Besides different landforms, human interventions can also disrupt or enhance longitudinal, lateral and vertical connectivity. At present, most fluvial systems have been affected by human interventions such as dam installations or land use changes. These impacts potentially alter flow and sediment dynamics (e.g. Kondolf et al., 2006) and pathways (Michaelides and Chappell, 2009) leading to significant geomorphic changes. Connectivity is a key determinant of the influence and persistence of impacts upon geomorphic river condition for any given site (Brierley et al., 2010) whether considered in terms of human-landscape interactions or interactions within the landscape itself (Brierley et al., 2006; de Vente et al., 2006; Fryirs et al., 2007; García-Ruiz and Lana-Renault, 2011). Effective description and explanation of connectivity relationships provides a basis to identify transmission linkages and coupling efficiency in fluvial systems and therefore sensitive parts of the landscape (Brunsden, 2001; Brierley et al., 2006). Thus, connectivity assessments can also be used to estimate geomorphic responses to external forcing such as human impacts and to evaluate trajectories of future geomorphic change determined by the propagation of these effects (cf. Harvey, 2007). However, due to the inherent complexity of landscape relationships that are related to self-regulatory properties of the system, geomorphic response to human disturbance is often difficult to predict since each regime also sets in motion time-dependent changes that progressively alter the balances between forces and resistances (Brunsden, 2002). In previous papers the potential benefit of (dis)connectivity concepts and assessments to analyze geomorphic responses to human disturbance have already been addressed implicitly or explicitly (e.g. Harvey, 2002; Brierley et al., 2006; Fryirs et al., 2007; Lexartza and Wainwright, 2009). Furthermore, few case studies have already shown the effects of human activities on sediment connectivity and the geomorphic consequences (e.g. Fryirs and Brierley, 1999; Kasai et al., 2005; Keesstra et al., 2005;

Borselli et al., 2008; Seeger et al., 2009; Lexartza-Artza and Wainwright, 2011; Wainwright et al., 2011; Poeppl et al., 2012). However, a theoretical and conceptual foundation that deals with the processes and factors that govern human-induced sediment (dis)connectivity in fluvial systems and relates the role of humans as sediment (dis)connectors to fluvio-geomorphic consequences is still missing. Moreover, further case study derived knowledge is needed to understand the processes and factors involved. The application of such a concept is further considered to be a useful tool for river managers to estimating future trajectories of human-induced geomorphic changes.

In consideration of the research gaps identified above, the main objective of this paper is to provide a conceptual basis on human-induced changes of sediment connectivity and their geomorphic consequences in fluvial systems. Firstly (i), human-induced changes of sediment connectivity are conceptualized and related to fluvio-geomorphic consequences (section 2. (i)). Secondly (ii), the conceptual model is expanded by integrating the factors of time and self-regulatory processes (section 2. (ii)). The reflections are underpinned by presenting case studies from small to meso-scale catchments (section 3) which are interpreted and discussed within the context of the developed concept (section 4).

2. Conceptual model

(i) Human-induced changes of sediment connectivity and geomorphic response

A general distinction between direct and indirect human impacts on fluvial systems can be made. *Direct human impacts* take place within the river channels due to direct removal/addition of sediments or by hindering or forcing the movement of water and sediments. These are modifications to the channel bed and/or banks which have typically taken the form of resource development activities such as water supply, power generation, gravel extraction or structural engineering works to mitigate unintended fluvio-geomorphic effects (e.g. flooding, channel bed incision; Brierley and Fryirs, 2005). *Indirect human impacts* occur in the catchment apart from the river channels themselves but also modify discharge and sediment load of the river. These include land use changes, the alteration of vegetation cover or water withdrawals.

The geomorphic state of a river system is governed by two critical elements, namely the stream power available to transport sediments, and the sediment supply which both can be altered by human impacts. Assigning a dynamic equilibrium (Chorley and Kennedy, 1971), a balance between these elements exists which has been described by Lane (1955) with the following equation that is further used in the conceptual model to link human-induced changes of sediment connectivity with geomorphic channel changes:

$$Stream\ power\ P\ (Qw\ \times S)\ \propto Sediment\ supply\ SS\ (Qs\ \times\ D50) \qquad (1)$$

Qw…stream discharge, S…stream slope, Qs…sediment load, D_{50}…median grain size of the sediment load

The Lane equation is commonly used to estimate geomorphic river response to changes. If the stream power is exactly sufficient to transport the sediment load, both sides of the scale are in balance and no net erosion and deposition takes place. An imbalance, however, leads to geomorphic channel changes. If stream power exceeds sediment supply, channel degradation takes place due to excess energy and erosive power:

- Stream power P > Sediment supply SS → Degradation D

In the case of sediment supply exceeding the ability of a river to transport these sediments, aggradation takes place and causes net deposition in the respective river reach:

- Stream power P < Sediment supply SS → Aggradation A

There are natural fluctuations in the balance of any of the factors involved, e.g. flood events, slope failures or debris jams, causing changes in the system. However, also human impacts are potentially unbalancing the ratios between stream power (P) and sediment supply (SS) which leads to degradation (D) and aggradation (A) processes in the affected river reaches. Imbalances can be caused by human impacts that induce changes on different spatial dimensions of sediment connectivity (Fig. 1). A decrease in *longitudinal sediment connectivity* is caused by direct human impacts that hinder sediments to move downstream such as the installation of a dam (see Fig. 1a). A dam induces sediment retention and accumulation upstream (P < SS → A) and degradation processes downstream (P > SS → D) as it unbalances the ratios between stream power (P) and sediment supply (SS) (e.g. Williams and Wolman, 1984; Grant et al., 2003; see also sections 3.1 and 3.4). Contrarily, an increase of longitudinal sediment connectivity followed by upstream degradation (P > SS → D) and downstream accumulation (P < SS → A) is caused by human impacts that force the propagation of water and sediments downstream such as the flushing of reservoirs or dam removals (e.g. Wildman and MacBroom, 2005; Burroughs et al., 2009). *Lateral sediment connectivity* is increased by indirect human impacts such as deforestation in the catchment which causes augmentation of lateral sediment input to the river channels due to enhanced soil erosion rates (see Fig. 1b). This leads to channel aggradation as a result of sediment supply exceeding stream power (P < SS → A; e.g. Connor, 1986; Miller and Benda, 2000; Kasai et al., 2005). Afforestation or reforestation shows the opposite effects (P < SS → A; e.g. Madej and Ozaki, 1996; Kasai et al., 2001; Keesstra, 2007; see also section 3.2). Alteration of lateral sediment connectivity can be further caused by human-induced changes of overland flow routing in the catchment such as by road building (e.g. Seeger et al., 2009; Poeppl et al., 2012; see also section 3.3), since the hydrological connectivity may be enlarged (increasing the catchments size due to catchment connection), reduced (cutting down flow paths) or re-directed (leading water flows towards different sites).
Vertical sediment connectivity is altered by direct human impacts that lead to an in- or decrease of sediment exchange between the channel subsurface and the channel itself (see Fig. 1c). This again unbalances the ratios between stream power (P) and sediment supply (SS) leading to channel degradation or aggradation. A decrease of vertical sediment connectivity can be caused by human-induced bed armouring either due to river bed protection works such as the installation of rock armour, or bed armouring and imbrication that typically occur downstream of a dam (e.g. Williams and Wolman, 1984; Xu, 1990; see also section 3.1). Bed armouring inhibits bed sediment entrainment and subsurface sediments to reach the channel which potentially causes channel degradation in unprotected channel reaches further downstream due to stream power exceeding sediment supply (P > SS → D). The opposite effects occur when natural channel bed armouring is destroyed by human activities such as gravel extraction from the river beds. Once the surface armour is broken, large volumes of readily moveable sediments are released potentially causing channel aggradation in the downstream reaches (P < SS → A).

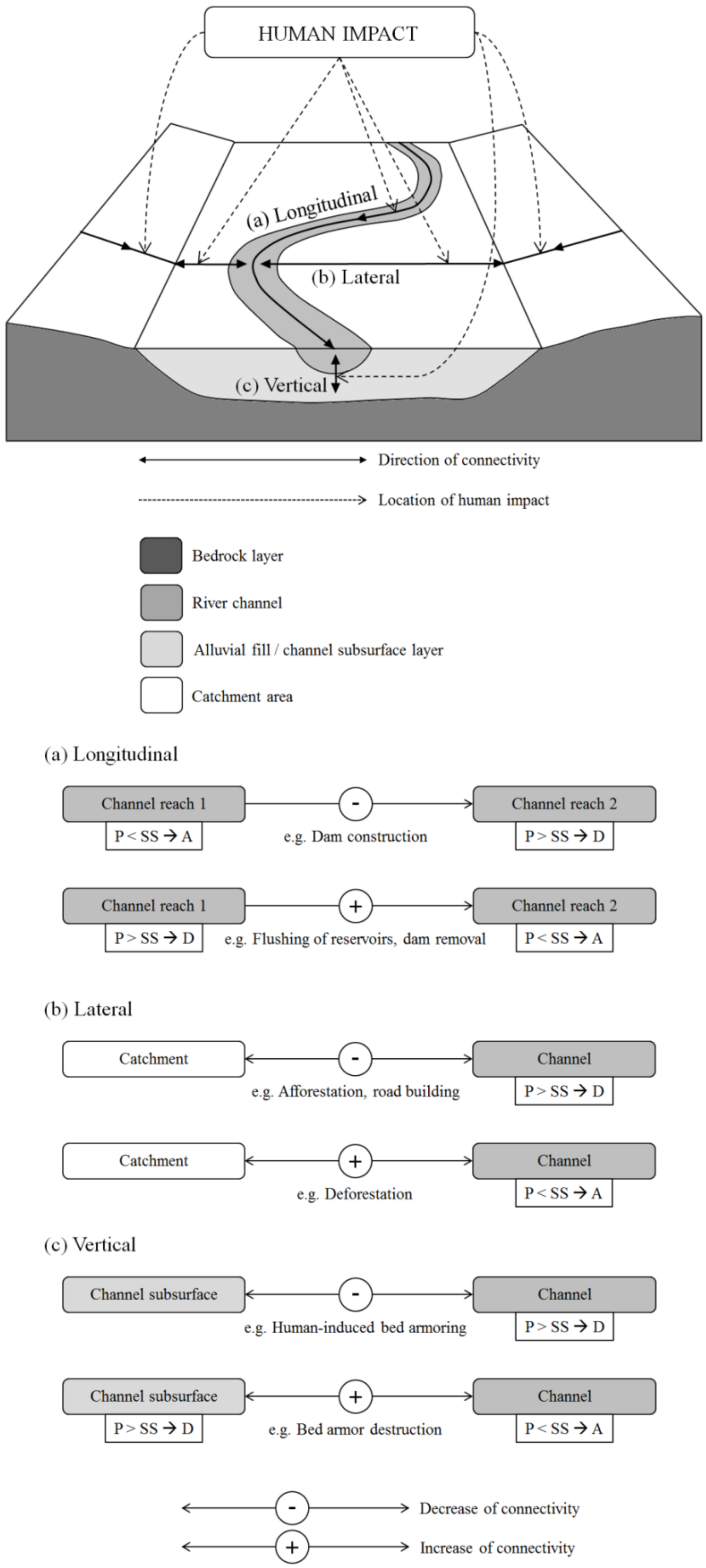

Fig. 1: Conceptual model on human-induced changes of sediment connectivity on different spatial dimensions. These changes cause an imbalance between stream power (P) and sediment supply (SS) which leads to degradation (D) and aggradation processes (A) in the channel

By means of the presented conceptualization it can be generalized that an increase in sediment connectivity leads to channel aggradation, whereas a decrease leads to channel degradation. However, the Lane balance is simplistic as geomorphic adjustments within river systems further depend on *boundary conditions* (e.g. channel substrate, riparian vegetation, valley confinement etc.), *climate, self-regulatory properties of the system* as well as the individual *system history*. Moreover, there are serious limitations regarding the questions of when and where geomorphic changes will occur (Simon and Castro, 2003). Geomorphic response to human-induced changes of sediment connectivity is therefore highly variable and can lead to spatially and temporally complex types of river adjustments (Bracken and Croke, 2007; Keesstra, 2007; Brierley et al., 2010).

(ii) The importance of time and self-regulatory system properties for sediment connectivity

After human-induced changes of sediment connectivity, self-regulatory properties of the system can lead to a full recovery of the original connectivity conditions as a function of *time* and *magnitude of geomorphic events*. With respect to direct human impacts, these properties include geomorphic processes and events that reduce the disconnecting efficiency of a river engineering structure such as a dam over time (i.e. recovery time) due to stepwise and continuous sediment infilling until a full reconnection between the up- and downstream channel reaches has established (Fig. 2). Continuous infilling occurs during mean and low flow conditions at which mainly fine sediments are accumulated in the dam impoundment. Stepwise infilling takes place during high magnitude events where large amounts of mainly coarse material are deposited. Geomorphic events can further lead to a dam failure which causes a flash flood accompanied by a short-duration increase of sediment connectivity and an instantaneous reconnection of up- and downstream channel reaches in longitudinal direction (Fig. 3).

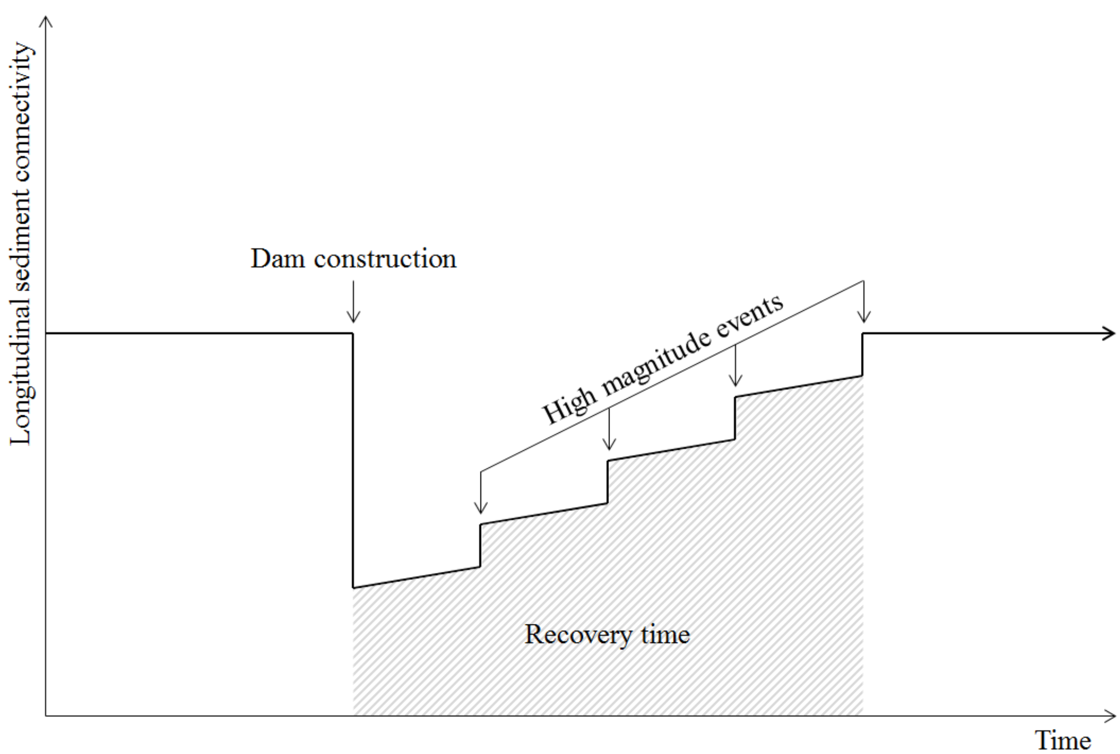

Fig. 2: Recovery of longitudinal sediment connectivity over time (i.e. recovery time) due to continuous and stepwise sediment infilling after dam construction. Continuous infilling occurs during mean and low flow conditions, while stepwise infilling takes place during high magnitude events.

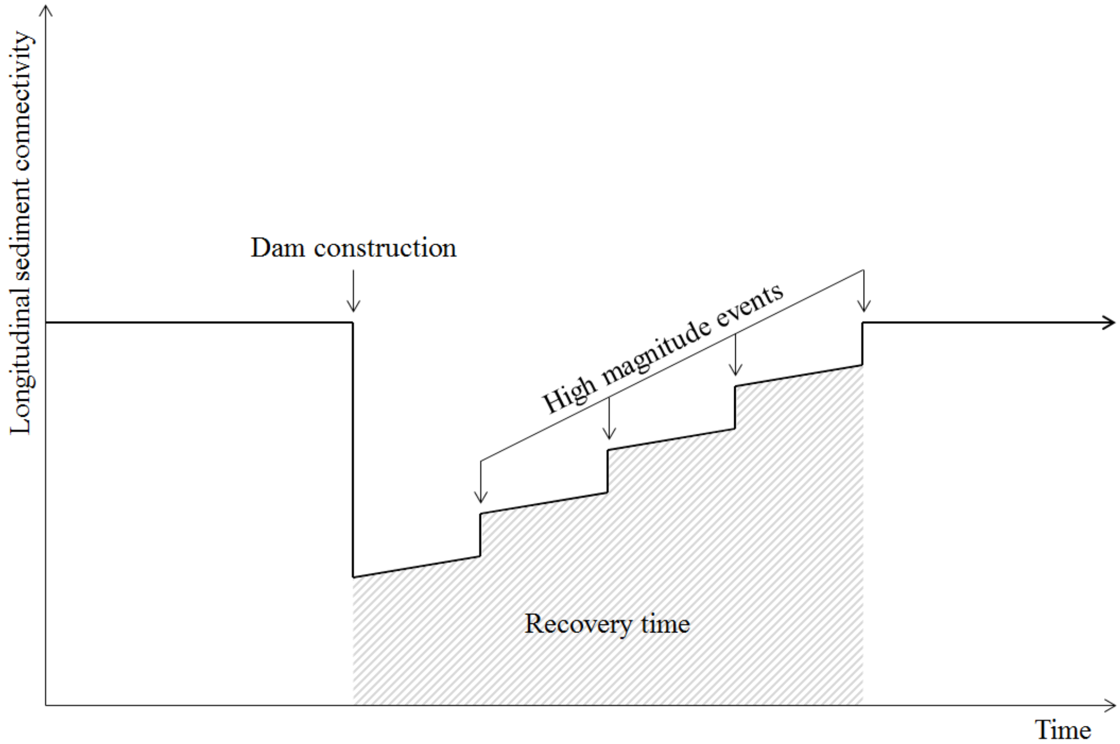

Fig. 3: Recovery of longitudinal sediment connectivity over time (i.e. recovery time) due to continuous and stepwise sediment infilling after dam construction. Continuous infilling occurs during mean and low flow conditions, while stepwise infilling takes place during high magnitude events. Dam failure leads to an instantaneous reconnection of up- and downstream channel reaches and causes a flash flood which is accompanied by a short-duration increase of sediment connectivity.

After human-induced alterations of lateral sediment connectivity in terms of land use changes, self-regulatory properties of the system that are related to *vegetation growth* can also lead to a full recovery of the original connectivity conditions as a function of *time* (see Fig. 4). Human impact due to deforestation causes a significant increase of lateral sediment connectivity. After human interference, assuming that no further impact occurs, vegetation succession takes place until vegetation cover has re-established and the connectivity conditions have recovered (i.e. recovery time). Similar effects are anticipated when catchments are reforested. However, if deforestation is followed by agriculturalization, a new equilibrium system state in terms of lateral sediment connectivity may establish (i.e. post-impact equilibrium).

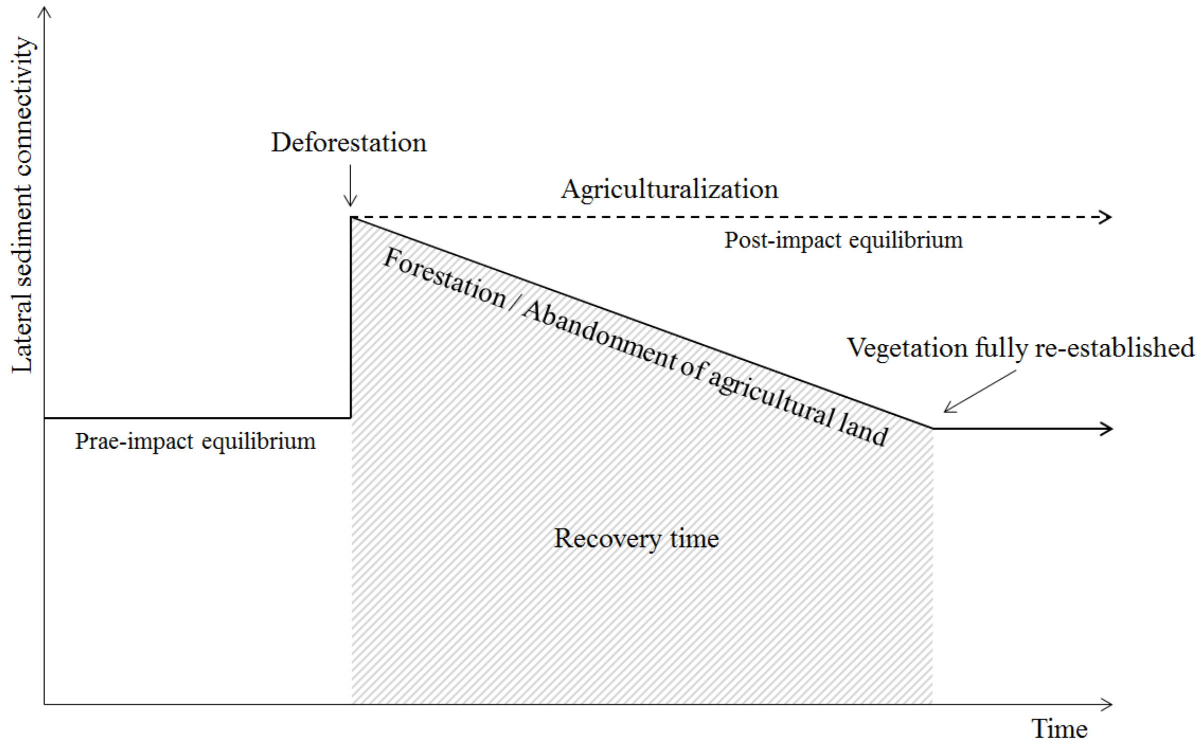

Fig. 4: Recovery of lateral sediment connectivity after deforestation. Vegetation succession takes place until vegetation cover has potentially fully re-established and connectivity conditions are recovered (i.e. recovery time). If deforestation is followed by agriculturalization, a new equilibrium system state in terms of lateral sediment connectivity establishes (i.e. post-impact equilibrium).

3. Case studies

Four case studies on small- to meso-scale catchments in Europe are presented to underpin the conceptual model assumptions (1) Kaja catchment, Austria; 2) Dragonja catchment, Slovenia; 3) Barranco de las lenas, Spain; 4) Gimbach catchment, Austria). Case study locations are given in Fig. 5, while an overview of catchment name, size and location, investigated spatial dimension of sediment connectivity, type and temporal scale of human impact, spatial scale of observation and geographic environment is given in Tab. 1.

Fig. 5: Case study locations. 1) Kaja catchment, Austria. 2) Dragonja catchment, Slovenia. 3) Barranco de las Lenas, Spain. 4) Gimbach catchment, Austria.

Tab. 1: Overview of the presented case studies providing information on catchment name, size and location, investigated spatial dimension of sediment connectivity, type and temporal scale of human impact, spatial scale of observation and geographic environment

Case study No.	Catchment name, size, location	Investigated spatial dimension of connectivity	Type of human impact	Temporal scale of human impact	Spatial scale of observation	Geographic environment
1	Kaja, 21.3 km², Austria	Longitudinal, vertical	Embankment dams	> 220 years	Reach scale	Temperate climate, low mountain range
2	Dragonja, 91 km², Slovenia	Lateral	Reforestation due to abandonment	50 years	Catchment scale	Sub-Mediterranean hills

3	Barranco de las Lenas, 51.3 ha, Spain	Lateral	Road building	50 years	Catchment scale	Semi-arid climate, continental Mediterranean basin
4	Gimbach, 2.8 ha, Austria	Longitudinal	Check dams	120 years	Reach scale	Temperate climate, high mountain range

3.1 Case study 1 - The effects of embankment dams on the longitudinal and vertical sediment connectivity of the Kaja River, Austria

The aim of this case study is to detect the reach-scale effects of embankment dams on longitudinal and vertical sediment connectivity by applying different types of sediment analyses. The study site is located in the Kaja catchment in the northern part of Austria (see Fig. 5). The Kaja River has a length of app. 10.7 km, is situated in a low mountain range with temperate climate and can be regarded as a mixed-load river (see also Tab. 1). The main river course is impacted by a series of dams which were built for extensive fish farming purposes (Poeppl, 2010). Data presented was collected in river reaches up- and downstream of an active embankment dam (see also Fig. 6). The dam itself is an overflow dam with a height of about 7 m that was built before 1782 AD. An inactive embankment dam is located app. 200 meters downstream which has resulted in the retention of river sediments. The majority of sediments are still stored in the former impoundment area and are now overlain by fine alluvial deposits (see also Fig. 6).

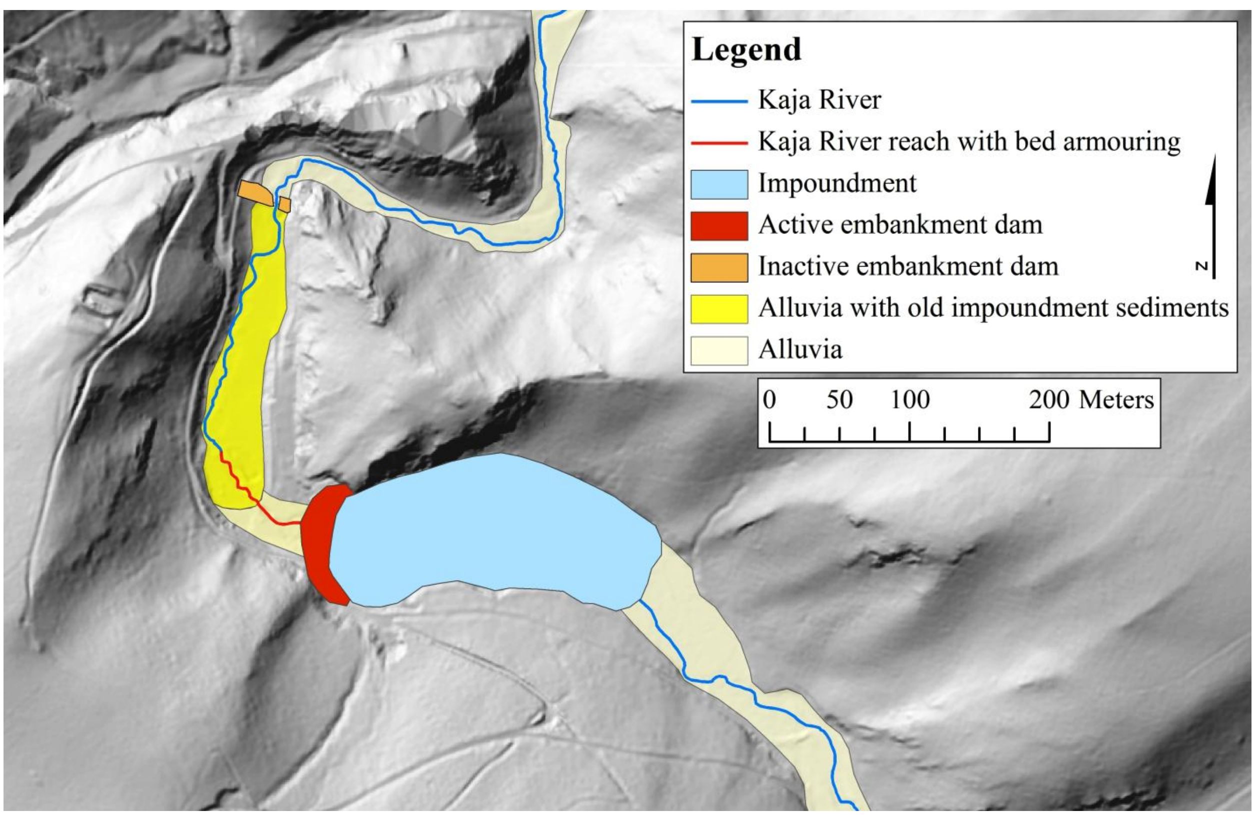

Fig. 6: Study area settings. Data source of the hillshade-DTM (1 m x 1 m resolution): Provincial State Government of Lower Austria, 2010.

In order to delineate dam-induced longitudinal sediment dis-connectivity, sediment analyses were conducted in May 2011. Gravel bar sediment composition was analysed by performing Wolman pebble counts during low flow conditions in river reaches app. 200 m up- and downstream of the active dam. Suspended load samples were taken after a heavy rainfall event on the dam crest as well as in upstream reaches which were unaffected by backwater and grain size classes were analysed in the lab. In order to survey bed armouring which is seen as an indicator for decreased vertical sediment connectivity typically occurring downstream of a dam, facies mapping was performed during low-flow conditions (for a detailed method description refer to Kondolf et al., 2003).
The results of the Wolman pebble counts demonstrated that the grain size distribution of the upstream gravel bars significantly differs from that of the downstream bars (see Fig. 7). These findings indicate dam-induced bedload retention and sediment disconnectivity in longitudinal direction. As old alluvia and old reservoir sediments are stored in the downstream reaches they prevent the total lack of river bedload (see Fig. 6). Total suspended sediment load is reduced by the dam by more than 70%. Silt fractions are retained and clay fractions are observed to be transported through the impoundment crossing the dam crest (see Fig. 8). Hence, the dam causes a grain size-selective reduction of longitudinal suspended sediment connectivity. Facies mapping showed the delineation of river bed armouring directly downstream of the dam (see Fig. 6). It is interpreted that the observed bed armouring downstream of the dam is related to degradation processes caused by a dam-induced unbalance of stream power and sediment supply which further infers a decrease in vertical sediment connectivity.

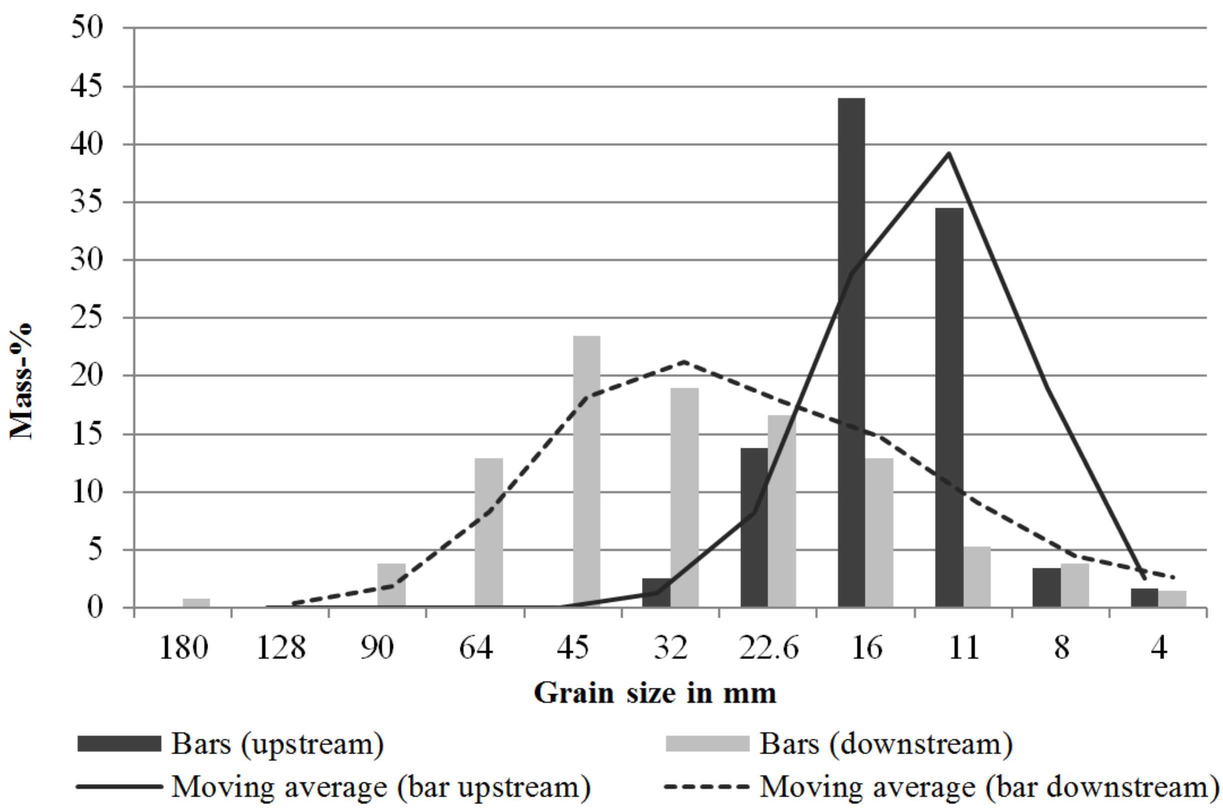

Fig. 7: Results of the Wolman pebble counts

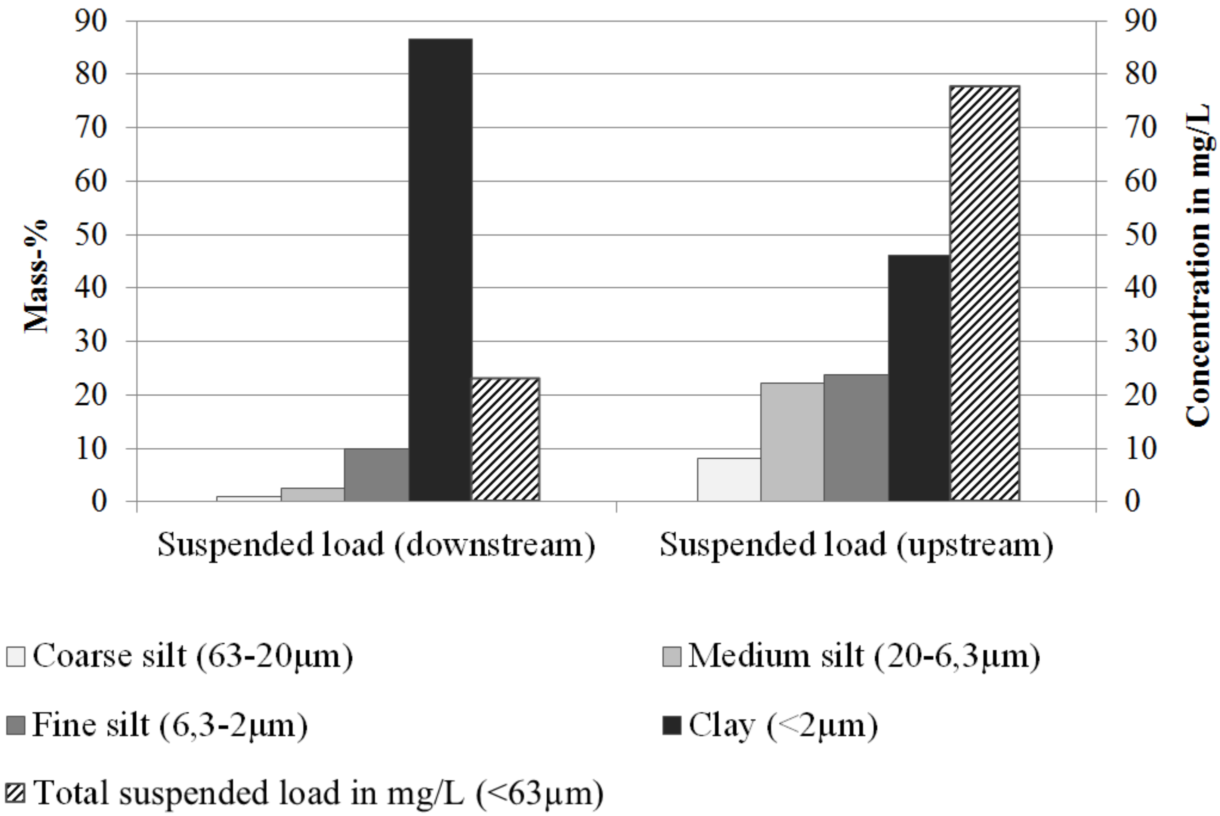

Fig. 8: Results of suspended sediment load samples

3.2 Case study 2 - Investigations on lateral sediment connectivity in the Dragonja catchment, SW Slovenia

The aim of this case study is to assess the effects of reforestation on lateral connectivity and geomorphic channel changes in a meso-scale river using hydrological analysis, geomorphological mapping and sediment budget analyses by applying a variety of field and laboratory methods (Keesstra, 2007; Keesstra et al., 2009a, 2009b). The study was conducted in the Dragonja catchment which is located in southwestern Slovenia (see Fig. 5, Tab. 1) and has experienced an increase in forest cover of more than 60%. The increase in forest is most evident on the steep slopes adjacent to the river channel which used to be cultivated on small terraces. The abandoned fields changed first into grass field and then into a full grown forest over a period of 30 years.

Significant changes in lateral sediment connectivity accompanied by geomorphic channel changes are a result of reforestation and to land abandonment. The dense vegetation cover, now covering the slopes in between the sediment source area, i.e. the fields on the hill crests and the river have caused a 90% decrease of sediment influx into the channel. Furthermore, the water influx decreased due to the higher water demand of the trees compared to the agricultural fields. However, the change in water discharge was not as big as the changed sediment influx and therefore the river water was depleted from sediment which changed the ratio of stream power and sediment supply, leading to the formation of “hungry waters” (Kondolf, 1997) that caused river channel incision.

The incision exhibits two phases. In the first phase, incision took place after the large-scale abandonment of agricultural fields, which caused a change in vegetation cover and became bare. Bare fields, susceptible to erosion, were quickly invaded by pioneer herb and grass species. In this phase, the water discharge had not changed much, but the sediment flux diminished significantly causing channel incision at a depth of approximately 2 m (see Figs. 9, 10). The second phase occurred about 30 years after the initial abandonment. Over this time a full grown forest has developed on the former fields. These forests had a higher water demand and caused a lower discharge in all periods of the year (Keesstra, 2007). Both, peak flow and base flow discharge was lowered. Lower peak flow is the result of the higher interception and infiltration caused by the larger leaf area of the forest and better soil structure due to higher root density and litter layers. Lower base flow is also the result of higher water demand of the trees compared to the former field crops. Lower peak flow also affected the gravel bars in the river which began to stabilize becoming overgrown by pioneer vegetation contributing to further stabilization of gravel bars. As a result, these bars now start to function as the floodplain area and the river starts to meander through its now oversized channel bed and incises additional 0.5 m (see also Fig. 9, 10).

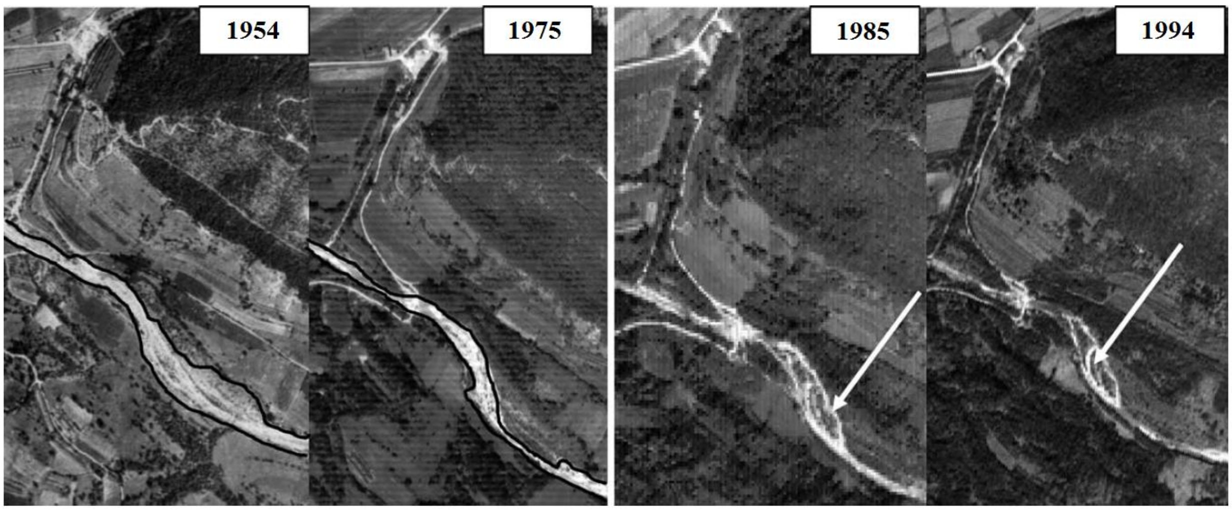

Fig. 9: Geomorphic channel changes of the Dragonja River. The narrowing and incising of the river is clearly visible on aerial photographs taken from the area just upstream from the confluence of the Dragonja River and its major tributary, the Rokava River. Channel narrowing is delineated by black borders, while channel incision is indicated by white arrows. From left to right, the photographs were taken in 1954, 1975, 1985 and 1994 (after Keesstra et al. 2005).

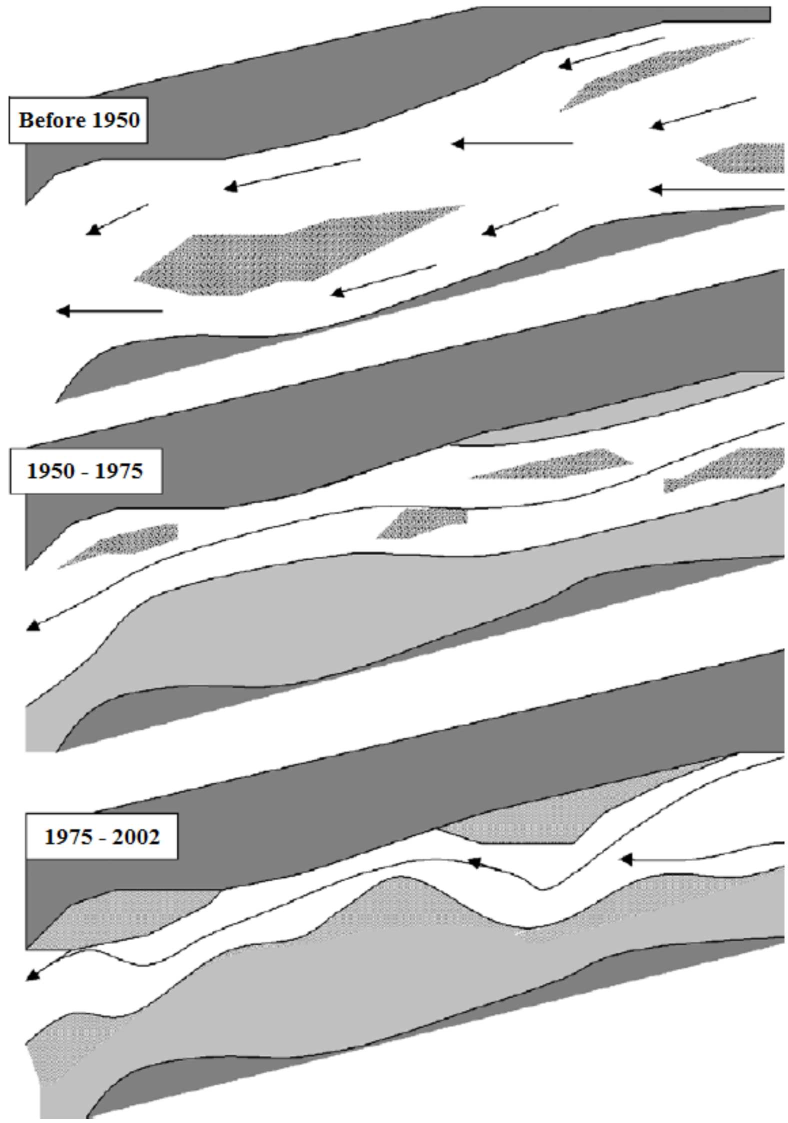

Fig. 10: Geomorphic channel changes of the Dragonja River from 1950 to 2002 derived from geomorphological mapping. Before the reforestation (before 1950), the riverbed was braiding at some places. From 1950 to 1975, the river incised and formed a terrace at 1.5 m above the current river level. From 1975 to 2002, incision continued, while the river started to meander within the old riverbed (after Keesstra et al., 2005).

3.3 Case study 3 - The effects of dirt roads on lateral connectivity in the Barranco de las lenas catchment, NE Spain

The aim of this case study is to assess the effects of road building on lateral connectivity and gully development using GIS-based flowpath analyses. Gully development is a phenomenon of high spatio-temporal variability (Fitzjohn et al., 1998; Gábris et al., 2003) and pronounced non-linearity (Sidorchuk, 2005). As gully-growth is mainly driven by headcut retreat, the supply of concentrated overland-flow is crucial for gully development. In semi-arid climate overland-flow is generally reduced to low frequency and high magnitude events because the hydrological connectivity of the supplying catchment is subject to large rainfall variations and the relationship between the mid-term volume loss on gully headcuts and the catchments size have been identified (Marzolff et al., 2011) and catchments size has been shown to regulate the water supply to the headcut. Human modification of the flowpaths within the catchment is therefore assumed to have a clear effect on the gully development, since the hydrological connectivity may be enlarged (increasing the catchments size), reduced (cutting down flow paths) or re-directed (leading water flows towards different sites).

The gully case study site is situated within the Central Ebro Depression in the Huerva valley south of Zaragoza, at the footslopes of the "Plana de Zaragoza". The lithology of the gully catchment is dominated by Miocene gypsum, marl and clay series with interbedded limestone and sandstone (ITGE, 1998). The bank type gully (Poesen et al., 2003) is deeply incised into Holocene alluvial deposits which reach up to 20 m thickness. The incised alluvial fill reaches 1.5 – 3 m at the Barranco de las Lenas headcut and is built upon an underlay of massive gypsum banks outcropping at the bottom of the gully. The average annual temperature in the Central Ebro Basin arises up to 15° C and the average annual rainfall reaches 280 mm in this semi-arid climate. The mapped gully catchment covers about 31 ha and is only weakly covered with vegetation. The catchment is crossed by an unpaved road and a bike trail upwards of the gully incision. Close to the gully headcut, remnants of old agricultural terraces cause a stepped surface with almost horizontal areas. The steep slopes of the gully headcut catchment show evidence of intensive sheet wash processes, but are also incised by deep rills. Sedimentation close to the gully headcut can be observed which indicates reduced lateral connectivity. Along the dirt road, almost perpendicular to the hillslope, a clear incision has developed, directly leading to the depositional area described above (Seeger et al., 2009).

Flowpath analyses using a DEM with 1 m horizontal resolution show the influence of the dirt road on flow routing within the catchment when introducing the linear feature option into the generation algorithm of the DEM. The dirt road was incised 50 cm with a width of 3 m by using the r.carve function of GRASS-GIS (GRASS Development Team, 2008). Without the dirt road, flow accumulates mainly at the gully-headcut (Fig. 11a). The effect of the human intervention in the catchment is shown in the modified DEM as the dirt road lead to a clear interruption of flow from the headcut catchment towards the gully (Fig. 11b). This results in the reduction of lateral hydrological connectivity that leads to the reduced activity of the gully headcut and to reduced gully activity.

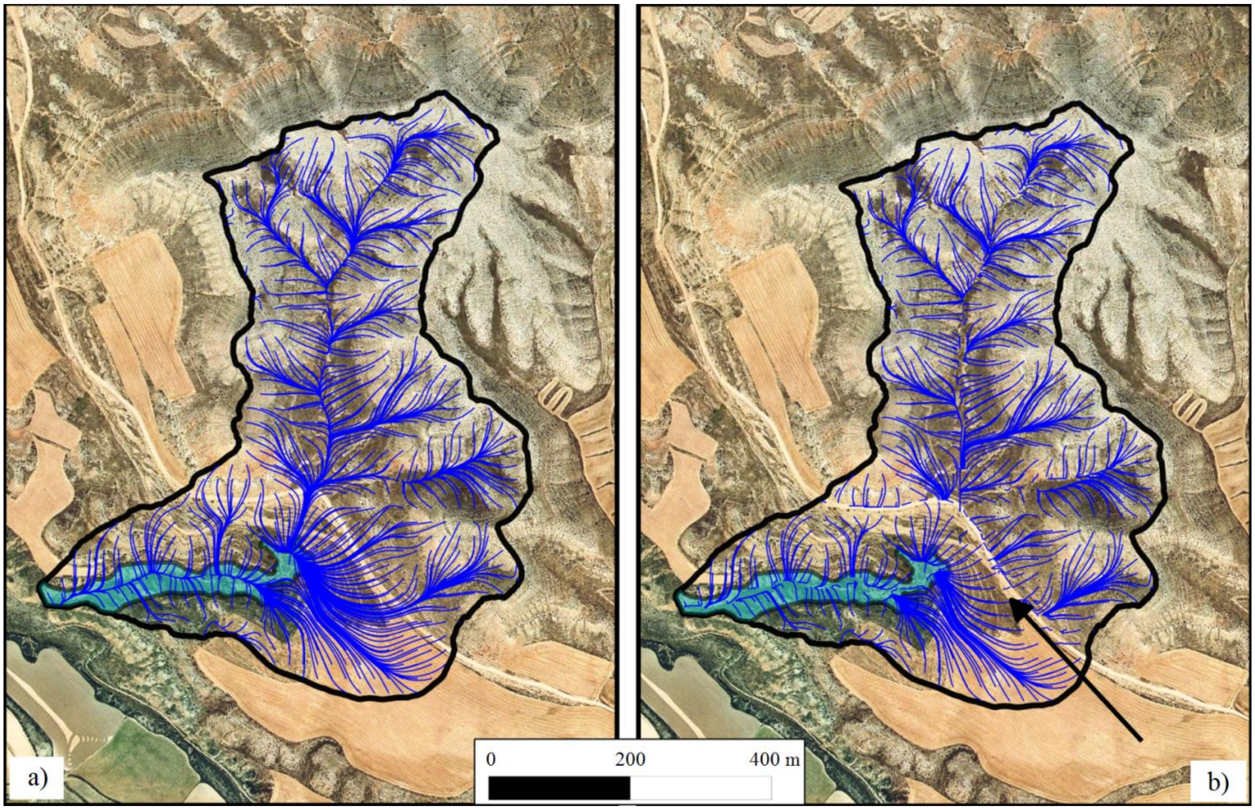

Fig. 11: Flowpath analysis of the catchment of the Barranco de las Lenas gully. a) flowpaths of hydrological consistent DEM, b) with incision of the dirt road (3 m width, 0.5 m depth). The black arrow marks the generalized flow interruption by the modeled dirt road. Dark blue lines indicate modeled flow lines; light blue polygons indicate gully boundaries and black polygons indicate boundaries of the total gully catchment.

3.4 Case study 4 - Check dams and longitudinal sediment connectivity - examples from the Gimbach catchment, Austria

This case study deals with the effects of check dams on longitudinal sediment connectivity and geomorphic channel response. Extreme events in steep mountain streams are characterised by multiple geomorphic process patterns such as those involving sudden morphological changes of the channel bed due to intense local erosion or deposition and remobilisation of bedload in individual channel reaches. In order to mitigate hazards in these areas, technical mitigation concepts are implemented. These include technical structures along channel systems and channel tracks and in the deposition area (Holub and Fuchs, 2009). In steep mountain streams, a series of check dams can be implemented along the longitudinal axis of the channel in order to support the upstream bank slopes, supporting the deposition of material in the channel bed and stabilising the channel bed preventing vertical erosion. The overarching principle is that every check dam in this series protects the foundation of the upstream one from scouring, and a deposition area with a modified channel gradient φ' compared to the original steeper channel gradient φ is built up (see Fig. 12). As such, the series of check dams is targeted at a bedload equilibrium by preventing further vertical erosion of the channel bed. A result of this technical mitigation measure, bedload and flood discharge become longitudinally disconnected and the original complex interaction between erosion and deposition that include the remobilisation of sediment during periods of high discharge is prevented until the local erosion basis given by the height of the overflow section of every individual check dam.

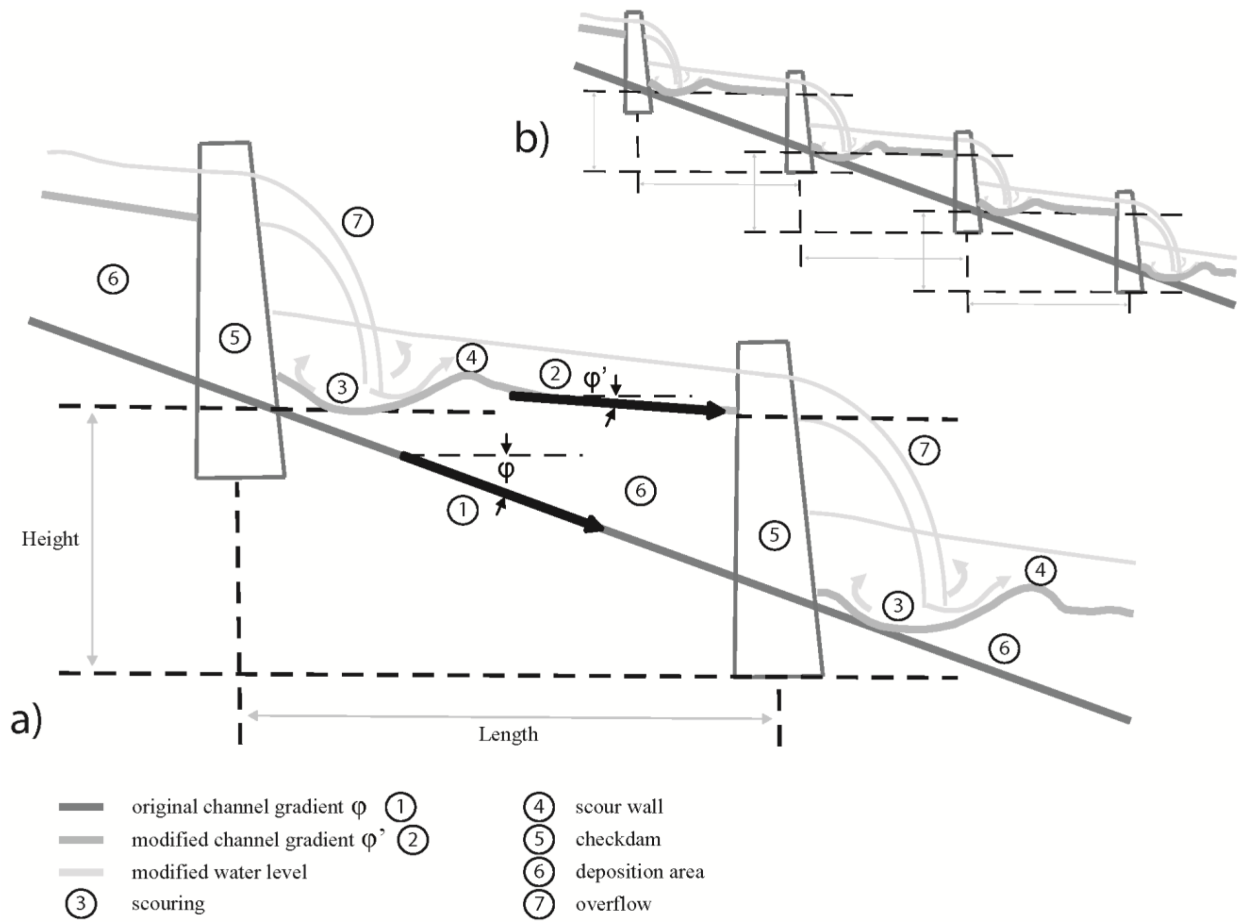

Fig. 12: Schematic cross-section of a check dam series. a) Between two check dams (5) the original channel gradient (1, φ) is modified (2, φ') due to the overall amount of material deposited on the upstream side (6) of each check dam. The development of scour (3) and a scour well (4) is created due to energy dissipation resulting from dam overflow (7). Both the amount of material deposited and development of scour affects the height and the length of the check dam series (5). b) The overall reduction of the channel gradient due to the implementation of a check dam series (modified from Boell, 1997).

Structural mitigation inevitably has its limitations (Fuchs, 2009). If the ratio between the length and height of a series of check dams is not properly chosen, the scour developing over time at the lowest check dam will result in a destabilisation of the foundation of this structure. As a result, the check dam will be scoured or bypassed, and the channel will become reconnected in longitudinal direction due to an increase in sediment available for transportation in combination with an increased channel gradient (Fig. 13). Erosive processes can be intensified which may result in the destabilisation of other check dams leading to an increase in longitudinal sediment connectivity.

Fig. 13: Scouring of a check dam in the Gimbach catchment (2.8 ha), Austria, due to suboptimal localization and subsequent reconnection within the channel system. The check dam in this figure was constructed in the 1900s (the exact year of construction is unknown). In 2010, the height of the scour is approximately 2 m. Photograph courtesy of Fuchs, 2010

Reconnection can be further caused by the aggradation of a check dam series (Fig. 14). Aggradation is dependent on the volume of discharge and the amount of sediment available during the transport process and given enough sediment and optimal transport capacity after the construction of a check dam series, the deposition area will be filled to the height of the dam crest. On the upstream side, the channel gradient will be adjusted to an angle that has a maximum angle equal to the modified channel gradient ((2) in Fig. 12). If the optimal distance between two subsequent check dams is not met, scouring will occur leading to a destabilisation of the entire chain of structural protection and therefore to a reconnection over time (Fig. 14).

Fig. 14: Longitudinal reconnection due to aggradation processes in a check dam series. (Gimbach torrent, Austria, courtesy of Fuchs, 2010)

4. Discussion and conclusions

(i) Human-induced changes of sediment connectivity and geomorphic response

The four case studies presented in this paper established that direct and indirect human impacts alter sediment connectivity on different spatial dimensions creating an imbalance in stream power and sediment supply ratios. This contributes to degradation and aggradation processes in river channels. A decrease in the *longitudinal sediment connectivity* due to dam construction and associated geomorphic consequences was revealed in case studies 1 and 4. Case study 4 presents a decrease of longitudinal sediment connectivity that caused local downstream degradation and upstream aggradation processes in a series of check dams. Similar geomorphic effects were observed in case study 1. The construction of an embankment dam caused sediment retention and accumulation upstream ($P < SS \rightarrow A$) which lead to channel degradation in terms of bed armouring downstream ($P > SS \rightarrow D$). As bed armouring further causes a decrease of *vertical sediment connectivity*, it can be interpreted that the different spatial dimensions of sediment connectivity are interconnected, meaning that a change in one spatial dimension induces a change in another. In case study 1, a decrease of sediment connectivity due to the presence of dams in longitudinal direction also caused a decrease in vertical direction (bed armouring) The results further revealed that geomorphic response to human impact is also strongly influenced by *system history* as the presence of old alluvia and old reservoir sediments stored in the downstream reaches prevented the total lack of river bedload.

In the case studies 2 and 3, human-induced alterations of *lateral sediment connectivity* were shown to cause geomorphic changes in the river channel. Case study 2 revealed the profound effects of land use change (natural reforestation due to land abandonment) on lateral sediment connectivity. The reforestation on the steep hillslopes not only changed the erosivity of the hillslopes themselves, resulting in lower sediment generation, but also the forests prohibited sediment generated on the hill tops to reach the river channel. The decreased lateral sediment connectivity also altered the sediment dynamics of the river by changing the ratio between stream power and sediment supply which caused geomorphic response in terms of riverbed incision (P > SS → D). As the channel incision showed two phases which were mainly related to the water demand of different types and stages of vegetation cover, results further suggest that human impacts can lead to temporally complex changes of connectivity and river adjustments. Case study 3 shows that the presence of a road changes the routing of overland flow pathways which decreases the lateral hydrological connectivity and affects the amount of water and sediment reaching the gully and in this case, inhibited further gully development. Since in semi-arid environments overland-flow is generally reduced to low frequency and high magnitude events and the hydrological connectivity of the supplying catchment is therefore subject to large variations depending on the rainfall volume, *climate* plays a major role in determining (dis)connectivity and geomorphic processes in semi-arid gully catchments.

It was demonstrated that human interventions alter the physical linkages and geomorphic processes within fluvial systems and that the presented connectivity model that links human-induced sediment (dis)connectivity in fluvial systems to fluvio-geomorphic consequences is useful to qualitatively estimate geomorphic responses to human impacts. The equation used (i.e. Lane Balance; Lane, 1955) provides an indication of the major ways in which channel morphology might change but used alone lacks predictive power because of uncertainty associated with a particular environment (Gregory, 2006) and *self-regulatory properties of fluvial systems*. In order to examine the sensitivity of a given landscape to human interference and to predict future trajectories of fluvio-geomorphic change, quantitative approaches need to be applied. The spectrum of methods used to quantitatively assess sediment connectivity ranges from field-based empirical techniques (e.g. Hooke, 2003) to GIS-oriented (e.g. Poeppl et al., 2012) and numerical modelling approaches (e.g. Wainwright and Mulligan, 2004). Additionally, connectivity can be quantified by using statistical connectivity functions (e.g. Western et al., 2001) and connectivity indices (e.g. Borselli et al., 2008).

(ii) The importance of time and self-regulatory system properties for sediment connectivity

The recovery of sediment connectivity due to self-regulatory system properties was clearly shown in the case studies 2 and 4. Case study 4 dealt with the effects of geomorphic processes and events on reducing the disconnecting efficiency of check dams over time as a function of *geomorphic event magnitude*. On the one hand, sediment infilling of the check dam (P < SS → A) lead to a full reconnection between the up- and downstream channel reaches over time (i.e. recovery time) and on the other hand, as the distance between two subsequent check dams had not been appropriately chosen, dam failure due to scouring occurred and caused an instantaneous reconnection of up- and downstream channel reaches in longitudinal direction. It was shown in case study 2 that after human-induced alterations of lateral sediment connectivity in terms of land use changes, self-regulatory properties of the system that are related to *vegetation growth* lead to a recovery of the connectivity conditions with *time* (i.e. recovery time). The decrease of lateral connectivity was shown to be highly dependent on the water demand of different types and development stages of vegetation cover. As two phases of channel incision were observed, these findings suggest a non-linear decrease of lateral connectivity that is strongly influenced by the factor of vegetation. However, the assumptions of the presented conceptual model are only valid for landscapes where no land degradation such as due to soil erosion processes occurred, since the resulting soil conditions would not allow for a full re-establishment of the vegetation cover. It is therefore expected that after human disturbance a new lateral sediment connectivity equilibrium system state establishes according to the post-degradation vegetation cover conditions and that therefore sediment connectivity conditions in human-impacted fluvial systems are strongly minted by the individual *system history*.

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References

Belisle, M., 2005. Measuring landscape connectivity: the challenge of behavioural landscape ecology. Ecology 86, 1988–1995.

Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena 75, 268-277.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrological Processes 21(13), 1749-1763.

Brierley, G., Reid, H., Fryirs, K., Trahan, N., 2010. What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. Science of the Total Environment 408(9), 2025-2033.

Brierley, G., Fryirs, K., Jain, V., 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38.2, 165-174.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management. Blackwell.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers NS4, 463–484.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. Catena 42, 99-123.

Brunsden, D., 2002. Geomorphological roulette for engineers and planners: some insights into an old game. Quaternary Journal of Engineering Geology and Hydrogeology 35, 101-142.

Burroughs, B.A., Hayes, D.B., Klomp. K.D., Hansen, J.F., Moitak, J., 2009. Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States. Geomorphology 110, 96-107.

Chorley, R.J., Kennedy, B.A., 1971. Physical Geography: A Systems Approach. Prentice Hall International Inc., London, UK.

Connor, T.B., 1986. The impact and economic effects of soil conservation practice on river aggradation. In Drainage Basin Sediment Delivery, TF Hadly (Ed.), IAHS Publication No. 159, 81-91.

De Vente, J., Poesen, J., Bazzoffi, P., Rompaey, A.V., Verstraeten, G., 2006. Predicting catchment sediment yield in Mediterranean environments: the importance of sediment sources and connectivity in Italian drainage basins. Earth Surface Processes and Landforms 31(8), 1017-1034.

Fitzjohn, C., Ternan, J.L., Williams, A.G., 1998. Soil moisture variability in a semi-arid gully catchment: implications for runoff and erosion control, Catena 32(1), 55.

Fryirs, K., Brierley, G.J., 1999. Slope-channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement. Catena 35, 41–63

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena 70(1), 49-67.

Fuchs, S., 2009. Susceptibility versus resilience to mountain hazards in Austria – Paradigms of vulnerability revisited, Natural Hazards and Earth System Sciences 9, 337-352.

Gábris, G., Kertész, Á., Zámbó, L., 2003. Land use change and gully formation over the last 200 years in a hilly catchment, Catena 50, 151-164.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region - A review. Agriculture, Ecosystems and Environment 140 (3-4), 317-338.

Grant, G.E., Schmidt, J.C., Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. Water Science and Application 7, 209-225.

GRASS Development Team, 2008. Geographic Resources Analysis Support System (GRASS) Software. Open Source Geospatial Foundation Project. http://grass.osgeo.org.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172-191.

Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. Geomorphology 44, 175– 201.

Harvey, A.M., 2007. Geomorphic instability and change – Introduction: Implications of temporal and spatial scales. Geomorphology 84, 153-158.

Holub, M., Fuchs, S, 2009. Mitigating mountain hazards in Austria – Legislation, risk transfer, and awareness building, Natural Hazards and Earth System Sciences 9, 523-537.

ITGE, 1998. Instituto Tecnológico Geominero de España: Mapa Geológico de España, 1:50,000, Hoja 383, Memoria. Madrid. 47 p.

Kasai, M., Marutani, T., Reid, L.M., Trustrum, N.A., 2001. Estimation of temporally averaged sediment delivery ratio using aggradational terraces in headwater catchments of the Waipaoa River, North Island, New Zealand. Earth Surface Processes and Landforms 26, 1–16.

Kasai, M., Brierley, G.J., Page, M.J., Maturani, T., Trustrum, N.A., 2005. Impacts of land use change on patterns of sediment flux in Weraamaia catchment, New Zealand. Catena 64, 27-60.

Keesstra, S., Huissteden, J.v., Vandenberghe, J., Van Dam, O., de Gier, J., Pleizier, I.D., 2005. Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes. Geomorphology 69, 191-207.

Keesstra, S.D., 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. Earth Surface Processes and Landforms 32(1), 49-65.

Keesstra, S.D., van Dam, O., Verstraeten, G., van Huissteden, J., 2009a. Changing sediment generation due to natural reforestation in the Dragonja catchment, SW Slovenia. Catena 78, 60-71.

Keesstra, S.D., Bruijnzeel, L.A., van Huissteden, J., 2009b. Constructing a sediment budget in a meso-scale catchment using a variety of methods: the Dragonja catchment, SW Slovenia. Earth Surface Processes and Landforms 32(1), 49-65.

Kimberly, A.W., Gardner, R.H., Turner, M.G., 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos 78, 151–169.

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environmental Management 21(4), 533-551.

Kondolf, G.M., Montgomery, D.R., Piégay, H. & Schmitt, L., 2003. Geomorphic classification of rivers and streams. Tools in Fluvial Geomorphology (eds. G.M.Kondolf & H. Piégay), John Wiley & Sons, Chichester, UK.

Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Huber, H., Koljonen, S., Louhi, P.. Nakamura, K., 2006. process- based rcological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11(2), 5.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering, American Society of Civil Engineering, Proceedings, 81, paper 745, 1-17.

Lexartza-Artza, I., Wainwright, J., 2009. Hydrological connectivity: linking concepts with practical implications. Catena 79, 146–152.

Lexartza-Artza, I., Wainwright, J., 2011. Making connections: changing sediment sources and sinks in an upland catchment. Earth Surface Processes and Landforms 36, 10-1104.

Madej, M.A. and V. Ozaki, 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21, 911-927.

Marzolff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. Earth Surface Processes and Landforms 36(12), 1604-1623.

Marzolff, I., Ries, J.B., 2007. Gully erosion monitoring in semi-arid landscapes, Zeitschrift fuer Geomorphologie 51, 405-425.

Michaelides, K., Chappell, A., 2009. Connectivity as a concept for characterising hydrological behaviour. Hydrological Processes 23(3), 517-522.

Miller, D.J., Benda, L.E., 2000. Effects of punctuated sediment supply on valley-floor landforms and sediment transport. Geological Society of America Bulletin 112 (2000), 1814–1824.

Poeppl, R.E., Keiler, M., Elverfeldt, K.v., Zweimueller, I., and Glade, T. (acc. 2012). The influence of riparian vegetation cover on lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment. Geografiska Annaler, Series A.

Poeppl, R.E., 2010. Die Fluvialmorphologie der Fugnitz und des Kajabaches. Eine vergleichende Analyse ausgewaehlter Flussabschnitte unter besonderer Beruecksichtigung anthropogener Effekte. Final project report, National Park Thayatal, Austria, 95 pp. incl. DVD- Rom.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs, Catena 50, 91-133.

Seeger, M., I. Marzolff, and J.B. Ries (2009), Identification of gully-development processes in semi-arid NE-Spain, Z. Geomorph. N. F. 53(4), 417–431.

Sidorchuk, A., 2005. Stochastic components in the gully erosion modelling, Catena 63(2-3), 299.

Simon, A., Castro, J., 2003. Measurement and Analysis of Alluvial Channel Form. in Kondolf, M. and H. Piegay., eds. Tools in Fluvial Geomorphology. John Wiley and Sons. England.

Tischendorf, L., Fahrig, L., 2000. How should we measure landscape connectivity? Landscape Ecology 15, 633–641.

Turnbull, L., Wainwright, J., Brazier, R.E., 2008. A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. Ecohydrology 1, 23–34.

Van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of change in landscape structure on soil erosion by water and tillage. Landscape Ecology 15 (6), 577-589.

Wainright, J., Mulligan, M., 2004. Pointers for the future, in Wainright, J., Mulligan, M., eds. Environmental modelling. Finding simplicity in complexity. Wiley, Chichester, 389–96.

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., Brazier, R.E., 2011. Linking environmental régimes, space and time: Interpretations of structural and functional connectivity. Geomorphology 126(3-4), 387-404.

Western, A.W., Bloeschl, G., Grayson, R.B., 2001. Toward capturing hydrologically significant connectivity in spatial patterns, Water Resources Research 37(1): 83-97.
Wildman, L.S., McBroom, J., 2005. The evolution of gravel bed channels after dam removal: case study of the Anaconda and Union City dam removals. Geomorphology 71, 245-262.
Williams, G.P., Wolman M.G., 1984. Downstream effects of dams on alluvial rivers. US Geological Survey Professional Paper 1286.
With, K.A., Gardner, R.H., Turner, M.G., 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos 78, 151–169.
Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68, 54–74.
Xu, J.X., 1990. An experimental study of complex response in river channel adjustment downstream from a reservoir. Earth Surface Processes and Landforms 15, 43–53.

A.2 The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment

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Article title

The influence of riparian vegetation cover on diffuse lateral sediment connectivity and biogeomorphic processes in a medium-sized agricultural catchment

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Abstract
Connectivity concepts are often used to describe the linkages between sediment sources and sinks within a catchment (Croke et al. 2005). In this respect, vegetation plays an important role as it influences surface roughness and the local capacity to store sediments and water. However, knowledge about the effects of riparian vegetation on lateral sediment connectivity as well as on the processes and factors that govern them is rare and presents an important research gap.
The main objectives of this paper are to assess the influence of riparian vegetation cover type on diffuse lateral sediment connectivity on valley floors and to investigate biogeomorphic processes acting in forested riparian zones of a medium-sized agricultural catchment. Governing processes and factors are assessed using GIS-based overland flow pathway modelling and geomorphic field surveys together with multivariate statistics (PCA, logistic regression modelling). The results reveal that diffuse lateral sediment connectivity is highly influenced by the respective type of riparian vegetation cover. Forested riparian zones significantly reduce sediment inputs and act as strong disconnectors between the catchment area and the river channel. Topographical features called root dams emerge from biogeomorphic processes in forested riparian zones and act as buffers that limit the connectivity as they hinder the sediment transport between landscape compartments.

Key words
lateral sediment connectivity, riparian vegetation, land use, biogeomorphic processes, root dams

1. Introduction

Concepts of connectivity are often used to describe the linkages between the sediment source areas and the corresponding sinks within a catchment (Croke et al. 2005). The term sediment connectivity is defined by Hooke (2003, p. 79) as the "transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system". Sediment connectivity occurs at a range of spatial scales and can be connected (coupled) or disconnected (decoupled) over differing timescales (Harvey 2002). Generally, connectivity operates within longitudinal, lateral and vertical dimensions (Ward 1989, Fryirs et al. 2007a). According to Brierley et al. (2006), longitudinal linkages are defined as upstream-downstream and tributary-main stem relationships, which drive the transfer of flow and sediments through the catchment. Lateral linkages, such as channel-floodplain and slope-channel relationships, govern the supply of materials to the channels. Vertical linkages refer to surface-subsurface interactions of water, sediment and nutrients.

Connectivity assessment is an important tool to estimate sediment conveyance and propagation through a system. Croke et al. (2005) distinguish between two types of connectivity: direct connectivity via new channels and diffuse connectivity where surface runoff and transported sediments reach the stream network via overland flow pathways. Sediment connectivity is further governed by frequency and magnitude characteristics (Wolman and Miller 1960) of sediment transport processes and the temporal evolution of vegetation, land use and management (Borselli et al. 2008). A greater understanding of the connectivity relationships between landscape compartments is crucial as it leads to an understanding of how (i.e. how fast and if at all) the observed systems react to external forcing (e.g. human interference). Nowadays, almost every catchment is affected by human interventions, such as land clearance and different types of agricultural practices. Deforestation, followed by agricultural land use, for example, generally leads to sediment mobilization as a result of increased soil erosion rates and increased transfer rates from sediment source areas to the river channel networks (e.g. Van Rompaey et al. 2002). In general, vegetation cover is most susceptible to human alterations (Brooks and Brierley 1997) and is one of the primary internal factors that determine the magnitude of erosion and sediment delivery to a river. Furthermore, vegetation plays an important role in governing lateral sediment connectivity as it influences surface roughness and the local capacity to store sediments and water (Puigdefabregas et al. 1999).

Large quantities of mobilized sediment may be deposited prior to reaching the stream channels. The specific sediment yield of a discrete catchment can therefore be significantly less than the rates of soil loss (Slattery et al. 2002, Raclot et al. 2009). Increased travel distances generally increase the opportunity for sediment deposition and lead to decreasing sediment delivery ratios with increasing catchment area (e.g. Boyce 1975, Williams 1977, Walling and Webb 1996, Lane and Richards 1997, Walling 1999). In some basins, the correlation of sediment yield and catchment area is even inverse or complex, since topographic thresholds play an important role for the initiation of different erosion processes (de Vente et al. 2007). A general decrease of sediment delivery with increasing catchment size is often related to the presence of sediment stores and sinks along the sediment transport pathways, which reduce sediment connectivity between landscape compartments (refer to Brunsden and Thornes 1979, Phillips 1992, Harvey 2002, Michaelides and Wainwright 2002, Hooke 2003). Topographical features, such as buffers, barriers and blankets act as landscape impediments, i.e. stores and sinks which are potentially limiting the connectivity as they hinder the sediment transport between landscape compartments (Fryirs et al. 2007a). Since increased travel distances generally increase the opportunity for sediment deposition (de Vente et al. 2007), agricultural areas that lie adjacent to the riparian zones are often considered as being the main sources of fine sediment input to the river channel due to soil erosion processes. De Vente and Poesen (2005) state that with increasing catchment size floodplains tend to substitute slopes as the direct source of sediment to the channels. Hence, agricultural source areas on valley floors should receive specific attention in terms of a lateral sediment connectivity assessment.

Disconnecting effects are further caused by different types of vegetation cover, as they are increasing the hydraulic roughness and infiltration rates (from plot- to catchment scale: e.g. Le Bissonnais et al. 2004; on plot- to mesoscale: e.g. Borin et al. 2005, Deletic 2006). This leads to sediment deposition as a result of reduced transport capacity (Wu *et al.* 1999, Wilson *et al.* 2005) and sediment trapping processes (Dabney et al. 1995, Meyer et al. 1995, Leguédois et al. 2008, Keesstra 2007, Keesstra et al. 2009). Tree belts, for example induce the development of micro-terraces due to sedimentation processes as well as sediment trapping in backwater deposits was observed (e.g. Leguédois et al. 2008). These features emerge from biogeomorphic processes and can further act as disconnectors between the different landscape compartments, especially in low-relief areas like floodplains including the riparian zones. Riparian zones are described by Green and

Haney (2011) as transitional boundaries between the stream and the terrestrial catchment. The capability of a riparian zone to buffer the sediment flux from agricultural areas to the channel network highly depends on its vegetation cover. Especially in small to medium-sized streams, forested riparian zones can significantly reduce sediment inputs (Osborne and Kovacic 1993). Hence, they potentially act as strong disconnectors between the river channel and the adjacent catchment areas. Nevertheless, in the field of geomorphology, preceding studies mainly dealt with catchment sediment fluxes and the importance of sediment connectivity in general, whilst the role of riparian vegetation was not assessed. Therefore, knowledge about the effects of riparian vegetation on lateral sediment connectivity as well as on the processes and factors that govern them is rare and presents an important research gap.

Generally, the spectrum of methods used to assess sediment connectivity ranges from field-based empirical techniques to GIS- and numerical modelling approaches. Additionally, connectivity can be quantified by using statistical connectivity functions (e.g. Western et al. 2001) and connectivity indices (e.g. Borselli et al. 2008). Potential effects of different types of land use and vegetation cover on sediment conveyance have already been considered in some empirical and experimental studies by Hayes et al. (1984), Cooper et al. (1987), Dillaha et al. (1988, 1989), Dabney et al. (1995), Daniels and Gilliam (1996), Mankin et al. (2007) and Leguédois et al. (2008). Numerical models for vegetated filter effects such as GRASSF, VSMOD, TRAVA have been developed (refer to Gumiere et al. (2011) for an overview) and catchment-scale erosion models for predicting area-specific sediment yield including the mitigating effects of vegetation cover on sediment transport such as EUROSEM, EMSS, WEPP, LISEM, SEMMED, LASCAM are used (cf. Gumiere et al. 2011). Few studies have, however, combined GIS- and field approaches in order to assess sediment connectivity and less have included the factor of vegetation cover (e.g. Borselli et al. 2008, Sandercock and Hooke 2011).

Based on the previous considerations and the detected research gaps, the main objectives of this paper are (i) to assess the influence riparian vegetation cover type on diffuse lateral sediment connectivity on valley floors, and (ii) to investigate biogeomorphic processes acting in forested riparian zones of a medium-sized agricultural catchment. In order to survey the governing processes and factors as well as the interrelated effects, GIS analyses and geomorphic field surveys were combined with multivariate statistics.

As described in the next section, the Fugnitz River catchment, like many river catchments of Austrian lowlands, is highly affected by agricultural land use. However, the upper and middle reaches of the Fugnitz River are lined with different types of riparian vegetation cover adjacent to agricultural areas. These features of the selected study area allow a comprehensive investigation of the effects of different types of riparian vegetation cover on lateral sediment connectivity as well as to assess the role of biogeomorphic processes. In section 3, a detailed outline of the conceptual background is given and the underlying assumptions and hypotheses for each of the study´s objectives are presented.

2. Study area

The Fugnitz catchment is located in the eastern part of the Bohemian Massif in Austria (see Fig. 1). It is characterized by a humid temperate climate with a mean annual temperature of 8.5°C and annual precipitation ranging from 500 mm to 600 mm with maxima between April and September. The Fugnitz River is a 29.7 km-long, mixed-load, single-thread perennial stream draining a watershed with a total area of 138.4 km^2. The maximum catchment elevation reaches 540.5 m a.s.l. and the outlet is at 286.4 m a.s.l. The drainage basin is characterized by a rather smooth topography with an average slope angle of 2.6° and maximum slope angles up to 32° (computed from a DEM with 10 m x 10 m; data source: provincial state government of Lower Austria 2009). The bedrock mainly consists of crystalline mica granite and mica shale, which are largely overlain by Quaternary Pleistocene loess layers (silt, fine sand) and, in some places, by Tertiary silts, clays and sands (brackish-maritime) (Roetzel et al. 2008). Prevalent soil types are Cambisols (IUSS Working Group WRB 2007). The land use/vegetation cover is very heterogeneous, exhibiting the following land use classes: agricultural land (56%), forests and woodland (34%), grassland (7%), and built up areas (3%) (see also Fig. 1).

The maximal slope angle occurring in agricultural land is 31%, with tillage practices being dominated by autumn ploughing, exhibiting bare ground during late autumn and early winter. Unfortunately, neither detailed data on the proportions of those agricultural areas that are subject to tillage, nor data on the proportions of bare ground during autumn/early winter is available. The main crops are cereals (summer barley, winter wheat, winter rye, and corn), rape, lucerne, milk thistle, and oil squash (data source: AMA Austria 2010). The riparian zones along the upper and middle reaches of the main river channel, which are adjacent to agricultural areas, are mainly covered by managed grassland and/or by discontinuous forests and woodland. The predominant tree species occurring in these riparian biotope types are: *Salix fragilis, Alnus glutinosa, Salix cinerea* and *Fraxinus excelsior* (UBA 1989).

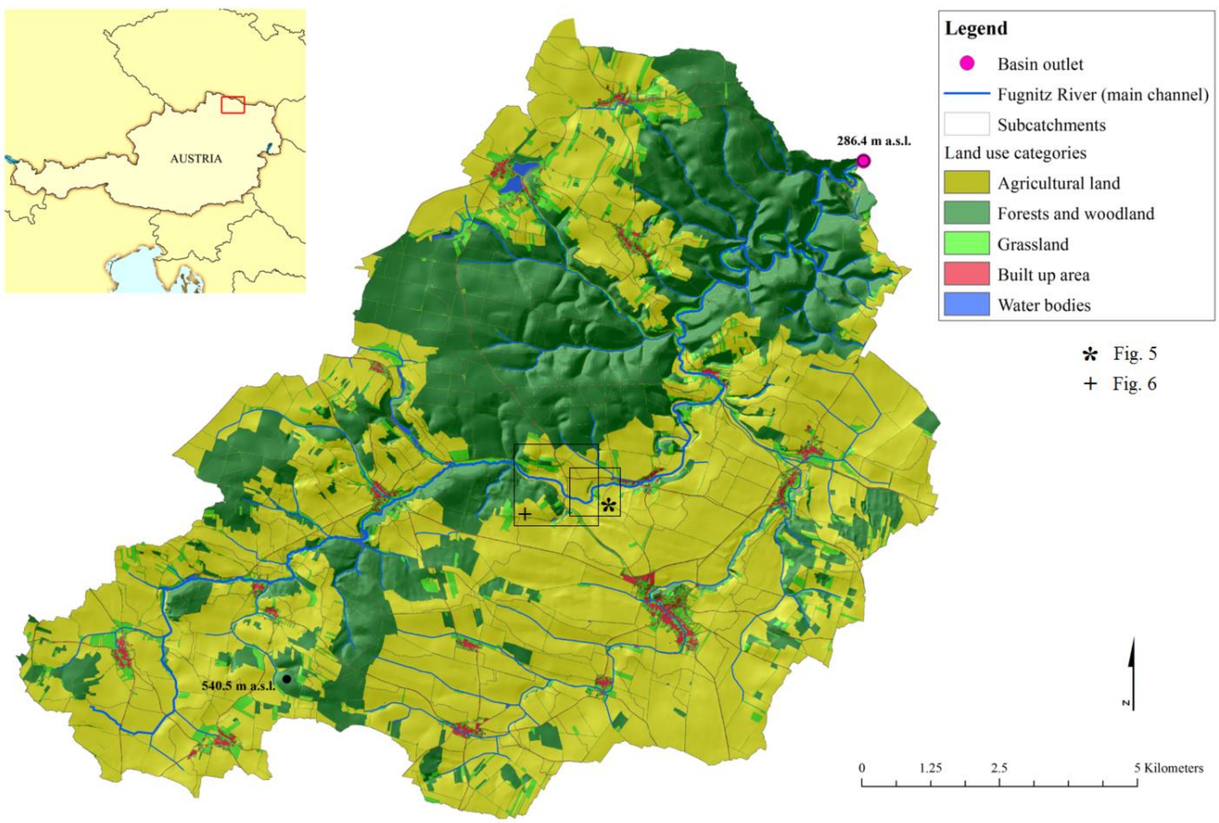


Fig. 1: Location and land use of the study area. Land use data has been derived by applying aerial photograph interpretations (data source: provincial state government of Lower Austria 2009). Catchment areas were delineated with Arc Hydro Tools 1.4 in ArcGIS 9.3 using a LiDAR-DTM with 1 m x 1 m resolution (data source: provincial state government of Lower Austria 2009). The course of the main river channel was digitized with a manual mapping procedure that interprets a DTM-derived hillshade.

3. Conceptual background

3.1 Study area zonation

To assess the influence of riparian vegetation cover type on diffuse lateral sediment connectivity on the valley floor (objective i), a medium-sized agricultural catchment was conceptually subdivided into different zones: upland area and hillslope, valley floor, riparian and streambed. This was done, firstly, to define criteria for delimiting the modelled overland flow pathways to the area of main research interest (i.e. valley floors), and, secondly, for further analyses of the pathways within the valley floor zone (see 4.1). The zonation of the catchment is based on the following general criteria: (1) slope angle thresholds related to surface morphology breaklines, and (2) changes in land use and vegetation cover:

The valley floor zone includes those catchment areas that are located between the upland area/hillslope zones and the streambed zone. The valley floor zone was delimited from the upland area/hillslope zone by a slope angle threshold of 2°. According to Fryirs et al. (2007b), who also used slope threshold analysis in GIS to analyse landscape (dis)connectivity in a similar environment, this value represents conditions under which off-slope sediment transport is likely to be promoted. The occurrence of river banks is again assumed to be related to slope angles > 2°. At locations where slope angles are below a threshold of 2° (i.e. the base of the river banks), the streambed zone was delimited from the valley floor zone. The riparian zone, which is the transitional zone between the streambed zone and its catchment, was distinguished from the valley floor zone by a change in vegetation cover (i.e. from agricultural land use to the presence of trees/shrubs and/or grasses). Information on land use and vegetation cover was obtained in the course of the land use mapping procedure (see 4.1).

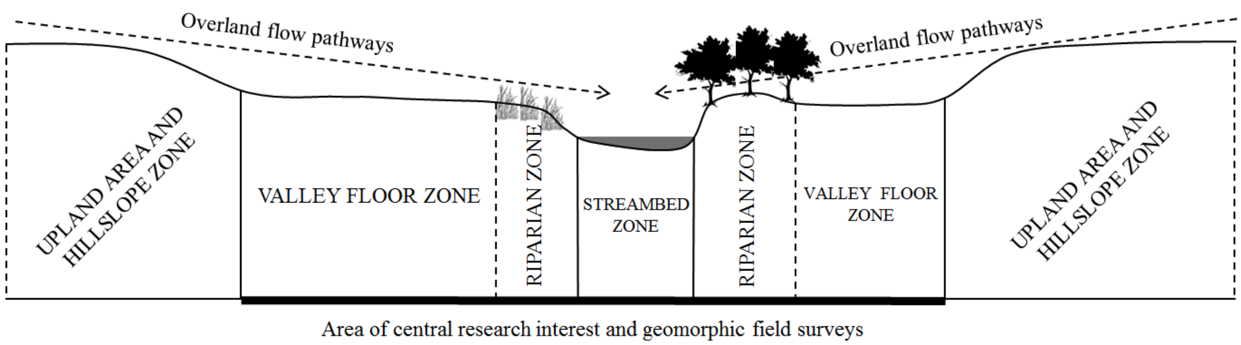
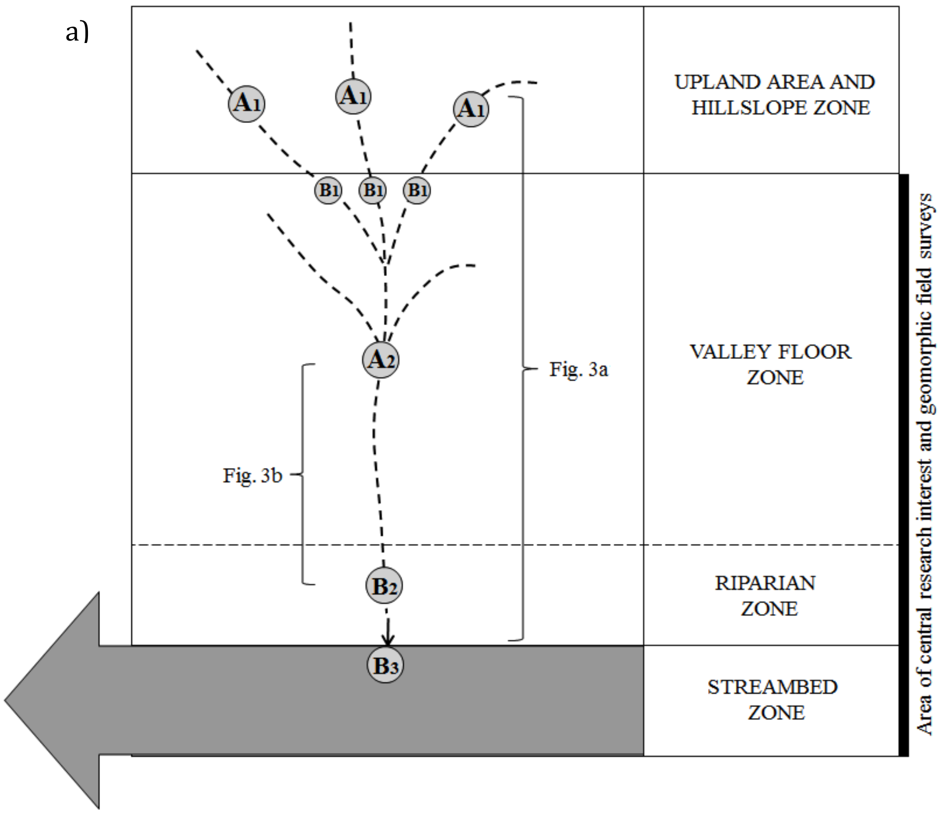


Fig. 2: Zonation of the study area. Dashed arrows indicate overland flow pathways that potentially connect the different study area zones. The area of central research interest and geomorphic field surveys is shown by the bold black line. *Root dams* are present in the forested riparian zones (see 3.3).

3.2 Lateral sediment connectivity

Hydrologic overland flow connectivity is the basic requirement for sediment connectivity between the different zones of the study area (see Fig. 3a). If sediment particles are mobilized within the upland area/hillslope zone at location A1, they are potentially routed via overland flow pathways to location B1 in the valley floor zone. Here, sediment particles can be deposited if the transport capacity changes abruptly, e.g. due to the presence of a surface morphology breakline and a related decrease of slope angle. If overland flow is sufficient to overcome these breaklines, sediment can be routed further along the overland flow pathways within the valley floor zone or sediments will accumulate. Sediments can be remobilized and transported further in the course of a later overland flow event until they meet the streambed zone. If sediment is mobilized at location A2 within the valley floor zone, the sediment is transported until transport capacity declines due to resisting forces. The material is then either deposited at location B2 (riparian zone), or transported further until it reaches the river streambed zone, where the material is temporally stored or transported downstream (location B3).

a)



b)

c)

Fig. 3: a) Conceptual model of sediment entrainment, transport and accumulation. Dashed arrows show potential overland flow pathways. The grey shaded arrow symbolizes the river channel. A1 and A2 in grey shaded circles show locations of potential sediment mobilization due to soil erosion processes, whereas B1, B2, and B3 indicate potential locations of sediment deposition or remobilization. Curly brackets localise the areas of extent of Fig. 3b) and Fig. 3c) which show real-life events from the study area. The bold black line at the bottom right hand side of Fig. 3a) indicates the area of central research interest and geomorphic field surveys.

As illustrated above, erosivity, transport capacity of overland flow and erodibility determine the type of process (erosion, transport, accumulation) as well as the location of appearance. In order to assess the sediment connectivity between the agricultural source areas and the river channel, a range of factors that potentially govern sediment generation and sediment transport processes need to be considered:

a) Sediment source areas

In an arable field, soil erosion rates mainly depend on rainfall pattern, soil type, topography, crop system and management practices. These factors can be identified by using specialized models for soil erosion, such as USLE and RUSLE (Wischmeier and Smith 1978, USDA-SCS 1986). Additionally, soil erosion processes may be directly observed by using geomorphic field survey methods, which also can be used to validate the results of soil erosion models (ground truthing).

Initially, all agricultural areas within the valley floor zone of the study area are considered as potential sediment source areas, since in these areas increased erodibility due to open soil conditions is assumed. In contrast, erodibility of grassland and forest-covered areas is expected to be comparatively low and hence soil erosion to be negligible.

b) Sediment transport

In addition to sediment mobilization, the second basic requirement for potential sediment transport by water is the presence of overland flow pathways. Generally, sediment transport capacity depends on slope angle, surface roughness and the availability/amount of water. Water can be generated on the spot itself (valley floor zone) and/or upslope (upland area/hillslope zone) (Borselli et al. 2008). Transport capacity generally increases with slope angle and flow accumulation. Local flow accumulation, in turn, strongly depends on the rainfall intensity and the spatial distribution of rainfall events in a catchment. Slope profile curvature which displays the change of the gradient is another important factor which also has to be considered in the course of assessing potential water flow and sediment transport processes (e.g. Moore et al. 1993).

Furthermore, sediment transport capacity of water is influenced by surface roughness and soil infiltration capacity, since physically and biologically controlled thresholds have to be exceeded (Puigdefabregas et al. 1999, Cammeraat 2002, Croke et al. 2005).
The potential for sediment transport is expected to be reduced by the respective types of land use and vegetation cover along the overland flow pathways within the riparian zone since infiltration rates and/or hydraulic roughness increase which results in sediment deposition. A further decrease in sediment transport capacity can also be expected due to sediment trapping in the backwater reaches of tree roots and trunks, and due to the establishment of root dams in forested riparian zones (see 3.3). Based on these assumptions, sediment connectivity is hypothesized to be lower in forested areas than in agricultural and grassland areas. It is therefore assumed that, if flow accumulation and slope angle remain constant, sediment connectivity in forested and grassland areas declines with the length of the overland flow due to cumulative disconnecting effects of vegetation cover.
Apart from disconnecting effects of vegetation cover, the local surface morphology breaklines depict azonal occurrence patterns (e.g. related to field boundaries or building structures, such as farm tracks) that affect transport capacity within the valley floor zone as these features can lead to abrupt changes in transport capacity and hence sediment connectivity. These features are therefore also included in the present connectivity assessment, again by applying a slope threshold of 2°.
The following forms are assumed to be indicators of overland flow connectivity between the agricultural source areas and the river channel network. They are therefore used as indicators for sediment connectivity:

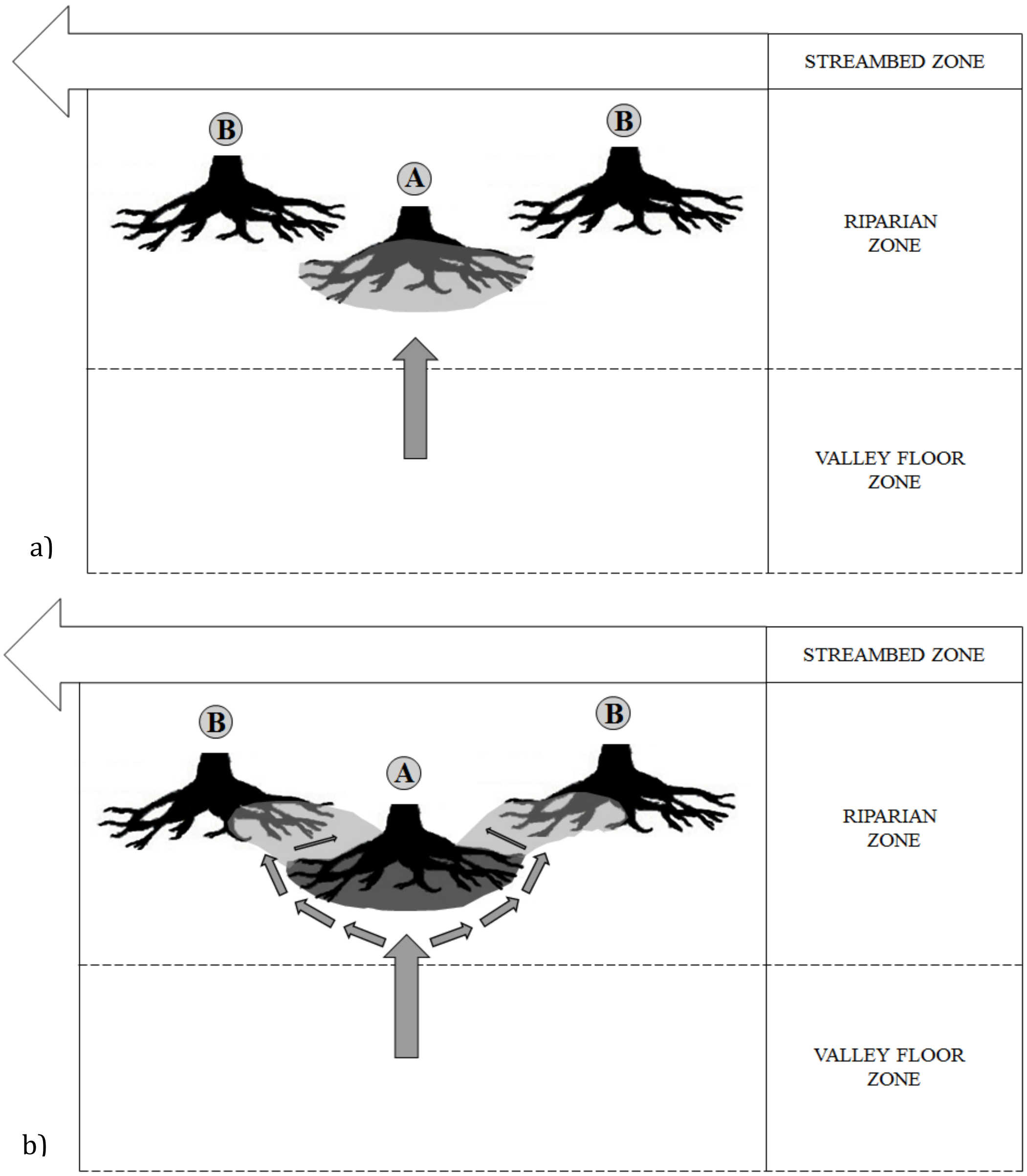
- Continuous rills (vegetated or non-vegetated) (see also Fig. 3b)
- Continuous indications of overland flow processes (sheet flow or concentrated flow): plants oriented in flow direction, siltation marks on vegetation (see also Fig. 3c)

3.3 Biogeomorphic processes

Dam-like geomorphic features called *root dams* potentially form parallel to the stream channel. It is hypothesized that these features emerge from biogeomorphic processes polygenetically (see also Fig. 2), since:

- Surface roots of trees and shrubs have a soil-binding function (Rawnsley 1991), and protect the underlying soil from potential soil erosion processes. In contrast, those areas within the valley floor zone without or with less surface roots exhibit a higher potential for soil loss. This leads to elevation differences between protected and unprotected surfaces.
- It is assumed that the formation of natural levees preferably occurs in forested riparian zones, as the presence of trees leads to higher a reduction of transport capacity and thus sediment deposition during flood events.
- The establishment of root dams may be caused by the presence of surface tree roots, trunks of trees and shrubs. These act as natural obstacles to overland flow and transported sediment arriving from adjacent agricultural areas. Surface tree roots and trunks are causing backwater areas and flow separation, thus altering the hydraulic conditions and consequently the sediment transport capacity of overland flow. Furthermore, infiltration rates of forest soils are comparatively high due to soil loosening caused by root action (e.g. Carmean 1957). These factors lead to a reduction of sediment transport capacity, especially in flat areas such as floodplains and sediment accumulation occurs in front of obstacles at location A (stage 1, see Fig. 4a). Hypothetically, dense treelines lead to synergistic flow and sedimentation processes between close tree roots and trunks. In a following flow event, sediments that reach location A are diverted by the previously accumulated forms at location A (stage 2, see Fig. 4b) and further routed to neighbouring tree roots (see Fig. 4b,

locations B), where accumulation takes place. Accumulation is also said to occur adjacent to the accumulation forms at location A (Fig. 4). This is expected to be caused by a reduction of transport capacity in the lateral reaches of the overland flow pathways when the water level drops. When root dams have fully established they are hypothesized to act as local natural barriers to sediment flow as they hinder subsequently arriving sediments to enter the streambed zone (stage 3, see Fig. 4c).



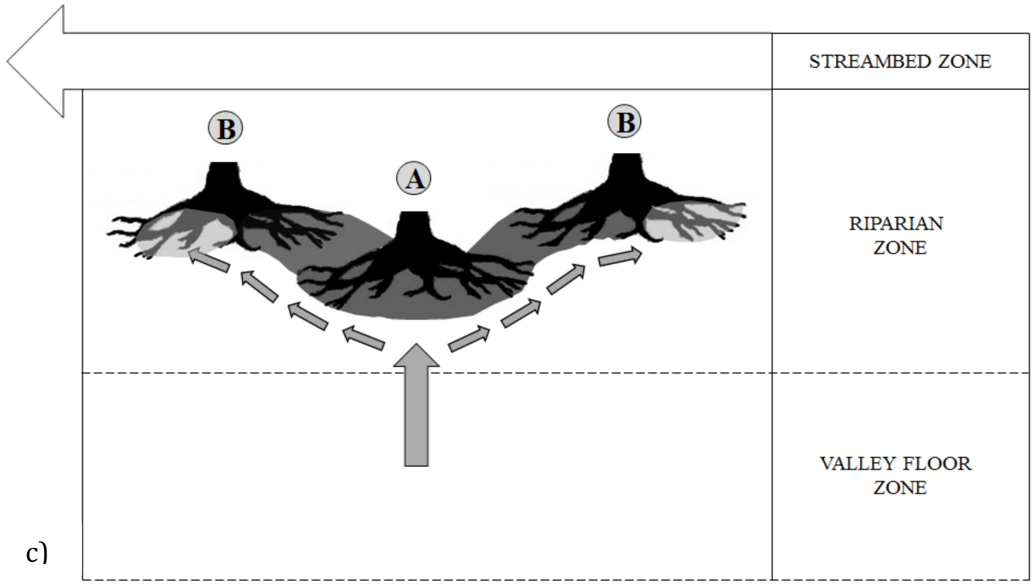


Fig. 4a, 4b, 4c: Conceptual model showing the influence of damming processes along overland flow pathways on the establishment of root dams (angled view). Black shapes symbolize roots and trunks of trees which are protruding above the soil surface (subsurface roots are not shown here). Grey shaded arrows indicate the routing of oncoming sediment via overland flow pathways. Locations where accumulation processes occur are indicated by letters A and B. Light grey shaded shapes delineate newly deposited material, whereas dark grey shaded areas symbolize sediments which have been accumulated during a preceding event. For specific study area location see Fig. 1.

4. Methods

This section gives a detailed description of the methods used for each objective and provides additional information on the underlying assumptions of each methodical step.

4.1 Lateral sediment connectivity

In order to assess the lateral sediment connectivity within the catchment, two key processes have to be assessed: sediment mobilization in source areas and sediment transport along the flow routes. Source areas are delineated using land use mapping, while sediment transport is assessed applying GIS analyses, geomorphic field surveys and statistical analyses. These methods are presented in detail below.

- **Land use mapping – Potential sediment source areas**

Land use mapping was conducted by using recent orthorectified aerial photographs with 25 cm x 25 cm resolution within ArcGIS (data source: provincial state government of Lower Austria 2009). The following land use classes were outlined for the whole catchment: agricultural land, grassland, forests and woodland (incl. shrubland) and built up areas. Land use mapping was verified using field surveys conducted during the geomorphic field survey (see below). In order to estimate the land use conditions of the valley floor zone, percentages of each land use class within a bilateral streamside buffer range of 100 m were calculated in ArcGIS for areas exhibiting slope angles below 2° (see also criteria for valley floor subdivision in chapter 3.1). For this, raster data containing information on land use were clipped on the extent of a bilateral streamside buffer range of 100 m. The same was done with a slope raster dataset which was calculated with Spatial Analysts Tool in

ArcGIS using a DTM with 1 m x 1 m resolution. The clipped slope raster data was then reclassified by assigning pixels with slope angles > 2° the value “0” and pixels with slope angles < 2° the value “1”. Subsequently, both datasets were multiplied by each other which resulted in a raster dataset only containing land use information for pixels with slope angles < 2° within a bilateral buffer range of 100 m.

- **Overland flow pathway modelling – Sediment transport**

The aim of these GIS analyses is to obtain a simple model of sediment routing within the valley floor zone based on the criteria defined in chapter 3.1. The modelled flow routes (represented as polylines) were required to exhibit the following characteristics, i.e. they have to:

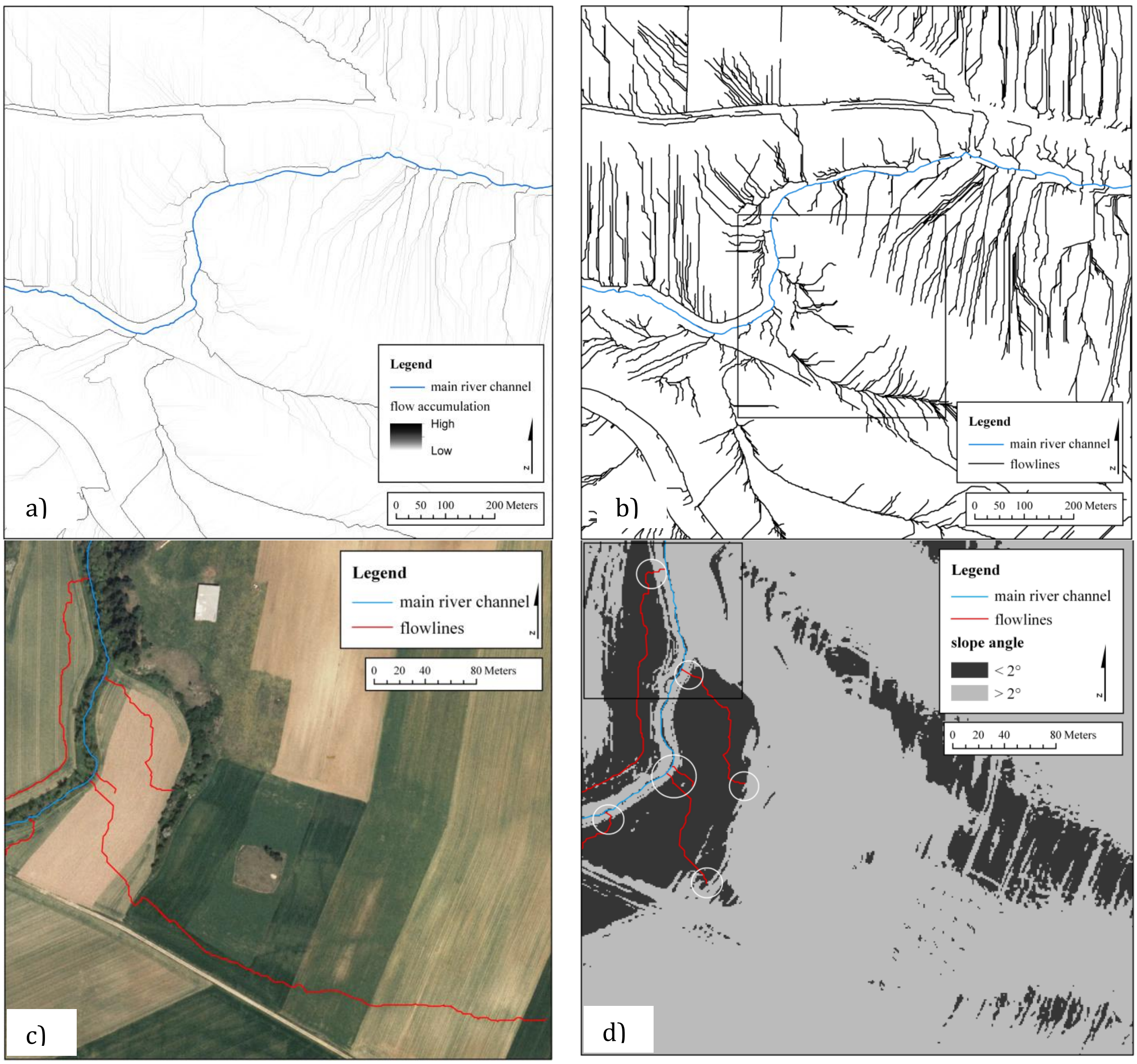
- originate in agricultural areas of the valley floor zone (see also Fig. 5c)
- end in front of surface morphology breaklines (see also Fig. 5d)
- end at the border of the streambed zone (see also Fig. 5e)
- consist of a single line per vegetation cover type, including information on segment length (measured in metres) (see also Fig. 5e)

The analyses are conducted in ArcGIS 9.3 using a LiDAR-DTM with 1 m x 1 m resolution. The river channel network of the study area is integrated into the calculation process by burning the river channel network into the DTM by subtracting 10 m from the filled DTM along the river channel network. This was done to prevent from mis-routings during the overland flow pathway modelling (see below) that can result from errors in the DTM along the channel network. The river channel network itself is digitized with a manual mapping procedure that interprets a DTM-derived hillshade. The result is corrected according to aerial photograph interpretations and field surveys.
In order to model *overland flow pathways*, the flow accumulation is calculated (Fig. 5a). The GIS command “Flow Accumulation” creates a raster grid of accumulated flow into each cell. It is considered to be a proxy for the potential amount of water for each grid cell within the catchment. A hydrological “correction” was required for processing. Single cells of the DTM surrounded by higher elevation cells were therefore filled using the “Fill Sinks” tool, while “real” depressions (sinks) were assumed to stay mainly unmodified. When the modelled flow reaches sediment sinks, the flow routing will stop after entering the sink area.
To drop cells with low flow accumulation values, the modelled Flow Accumulation grid is reclassified to a grid that only contains values above the mean. The output raster grid was then converted into polyline format (Fig. 5b). In order to extract the overland flow pathways, the longest line features crossing the last agricultural area within the valley floor zone was extracted and merged manually. All other segments were deleted, which resulted in a single line segment from the last agricultural area to the main river channel crossing the riparian zone (Fig. 5c). Finally, line segments were cut according to the criteria described above. Information on slope thresholds was obtained by calculating a slope derivate of the DTM and by reclassifying the resulting raster grid. This reclassification is again based on a 2° slope threshold, and all values beneath/above this threshold were set to 0 and 1, respectively. When a line segment crosses a slope threshold of 2°, the respective upline segment was manually cut and deleted (Fig. 5d). Where a change in vegetation cover along a line segment occurs, the line segment was cut. This led to the conversion of a single line to a polyline feature (Fig. 5e). Furthermore, for each line segment the segment length was calculated.
To obtain information on the factors that potentially influence lateral sediment connectivity, the “Line Raster Intersection Statistics Tool” provided by Hawth´s Analysis Tools for ArcGIS (Beyer 2004) was used. This application calculates the length of each line that falls within a raster cell and a statistical summary is created based on these segments (i.e. length weighted mean, minimum

values, maximum values, standard deviation). It is assumed that the following factors influence sediment transport and thus sediment connectivity:

- Slope angle in degrees
- Profile curvature
- Flow accumulation

Consequently, these factors were created as raster layers for the whole catchment and used for this statistical analysis. After processing, the values were stored in the attribute table of the polyline layer for further statistical analyses.



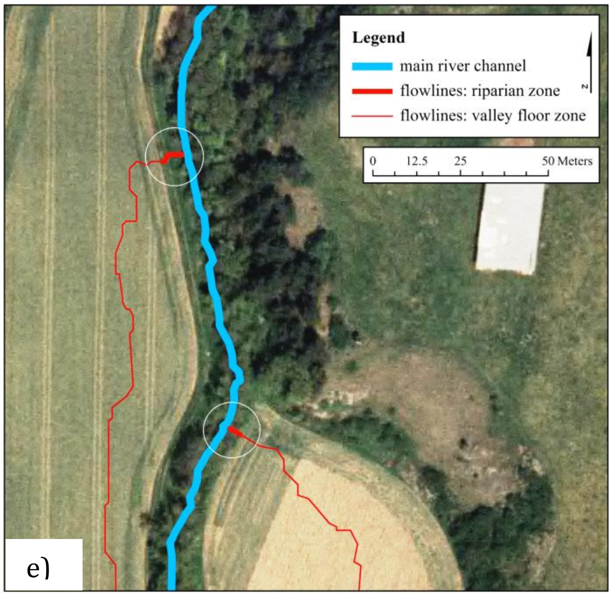


Fig. 5: Delineation of overland flow pathways with ArcGIS: a) Calculation of Flow Accumulation; b) conversion of Flow Accumulation raster grid into polyline format; c) extraction of the longest flowlines that cross the last agricultural area within the valley floor zone before they confluence the main river channel. All other segments were deleted, resulting in a single line segment from the last agricultural area to the main river channel, also crossing the riparian zone; d) cutting of line segments crossing a slope threshold of 2°: the respective upline segment was cut and deleted (locations are indicated by white circles); e) cutting of line segments according to changes in vegetation cover (locations are indicated by white circles). For specific study area location see Fig. 1.

- **Geomorphic field surveys – Sediment transport**

To assess overland flow pathways and to validate the model performance (ground truthing), geomorphic field surveys were applied. The geomorphic field surveys were conducted after a daily rainfall event of 37 mm which occurred in autumn 2010 and constituted approximately 7% of the annual precipitation. This rainfall event occurred during a time of sparse crop cover in agricultural areas due to preceding harvesting which was expected to promote overland flow processes. Surveys were carried out along both sides of the river channel within the valley floor zone at locations where overland flow pathways were modelled. Locations with contradictory results were also recorded, i.e. where indicators for overland flow processes were observed in the field (criteria are described in chapter 3.2b), but where no flow pathways have been modelled. The lengths of overland flow pathway per vegetation cover within the riparian zone were measured with a measuring tape. Plough direction and root damming were included in the geomorphic field survey process, since they are assumed to influence lateral sediment connectivity. Plough lines running perpendicular to the flow direction of the main river channel are expected to enhance sediment connectivity, whereas contour ploughing lines are assumed to have the opposite effect. Root dams were surveyed, since they are regarded as major disconnecting features due to related damming processes (see 4.3). The presence of farm tracks running parallel to the river channel were also considered as they are assumed to lower sediment transport capacity due to damming effects or surface flattening. Tab.1 shows the detailed check list for the geomorphic field survey procedure:

Tab. 1: Geomorphic field survey check list

Location No.:	Survey date:
Modelled overland flow pathway?	☐ Yes ☐ No
RIPARIAN ZONE	

Overland flow pathways	□ **No overland flow pathways**
□ Rill	
□ Marks of overland flow processes	
□ **Root damming**	
Vegetation cover	
Vegetation Type	*Segment length in m*
□ Grassland (GL)	
□ Forested land and/or shrubland (FL)	
VALLEY FLOOR ZONE	
Overland flow pathways	□ **No overland flow pathways**
□ Rill	
□ Indications of overland flow processes	
Plough Direction □ parallel	□ perpendicular
□ **Presence of farm tracks**	

For very short segment lengths (e.g. 1 m) with more than one type of vegetation (i.e. grassland (GL) and forested land (incl. shrubland, FL) observed in riparian zones, the values for riparian overland flow pathways segments from Line Raster Intersection Statistics (i.e. information on slope angle, profile curvature, flow accumulation) were not differentiated further. In such cases, it was assumed that consistent conditions for the whole segment within the riparian zone occurred while assigning the values of the whole segment to each single segment per vegetation cover. Nevertheless, information on segment lengths per vegetation cover was considered in the course of the statistical analyses (logistic regression) (see next section).

- **Statistical analyses – Sediment transport**

In order to investigate the influence of riparian vegetation cover type on sediment connectivity, as well as to examine the explanatory power of the potential factors of influence, *logistic regression modelling* was applied. Logistic regression allows the prediction of the probability of an event to occur (p). In our case probabilities higher than 0.5 are taken as an indicator for sediment connectivity, probabilities below 0.5 indicate the contrary. The dependent variable (in our case the lateral sediment connectivity) is binary (yes=1, no=0).
Binary and numerical parameters for each line segment which had been examined in the course of GIS analyses and/or geomorphic field surveys were chosen as explanatory variables Tab. 2 presents a list of the explanatory variables which were used for logistic regression modelling, introduces their abbreviations and provides information on type of input data.

Tab. 2: Explanatory variables for PCA-analysis and logistic regression modelling including abbreviations and type of input data. All numerical values were log2-transformed. According to the type of land use and vegetation cover along each line segment, abbreviations were extended by adding "AL" for agricultural land, "GL" for grassland, and "FL" for forested land including shrubland.

Explanatory variable	**Abbreviation**	**Type of input data**
Percentage of riparian vegetation (GL/FL)	Per	Numerical
Cumulative flow length for all segments within the riparian zone in m	CumLen	Numerical
Flow length in m (AL)	Len	Numerical
Slope angle in ° (mean)	Slo	Numerical
Profile curvature (mean)	Cur	Numerical
Flow accumulation (mean)	Flo	Numerical
Difference in slope angle, profile curvature and	Dif_Slo, Dif_Cur, Dif_Flo	Numerical

flow accumulation between valley floor zone and riparian zone (= mean of valley floor zone – mean of riparian zone, 3 variables), see also *Scenario 1*		
Root dams: 0 (no root dam present), 1 (root dam present)	Rod	Binary
Plough direction: 0 (parallel to the flow direction of the main river channel), 1 (perpendicular to the flow direction of the main river channel)	Plo	Binary
Farm tracks: 0 (no farm tracks present), 1 (farm tracks present)	Fat	Binary

A principal component analysis (*PCA)* was performed as some of the explanatory variables were highly correlated. This was done to avoid collinearity problems and PCA-components were used as uncorrelated explanatory variables for the logistic regression model. The scree-criterion was used to select the number of PCA-factors extracted and a varimax-rotation was applied to ensure easy interpretation of the factors.
In order to determine the variables with the highest explanatory power for sediment connectivity, *logistic regression* (dependent variable = presence of sediment connectivity), backward elimination of explanatory variables was applied and all explanatory variables were initially included. Subsequently, the variable that contributes the least to explain the response variable is removed at each step (= "backward elimination"). Positive regression coefficients indicate a predicted increase in probability for sediment connectivity if the explanatory variable increases. The opposite holds true for negative regression coefficients.
As 37 of 91 observations of overland flow pathways were not modelled and only examined in the field, they lacked information on slope angle, slope profile curvature, flow accumulation and flow length along agricultural areas adjacent to the riparian zone. Nevertheless, data on "Per", "CumLen", "Rod", "Plo" and "Fat" for segments within the riparian zone were available because these features had been examined during the geomorphic field surveys. Thus, two different logistic modelling scenarios were calculated followed by a comparison of the results aiming to perform a statistically representative analysis for each explanatory variable:

Scenario 1: The five axes from the PCA and the three binary variables "Plo", "Fat", and "Rod" were used as explanatory variables. Observations without numerical information on explanatory variables (i.e. observations of overland flow pathways, which had not been modelled, but examined in the field) were excluded from the analysis.

Scenario 2: All observations with explanatory variables, which had been examined in the field, were integrated into the logistic regression model (i.e. "Per", "CumLen", "Rod", "Plo", and "Fat").

4.2 Biogeomorphic processes

During *geomorphic field surveys* (see Tab. 1), root dams were examined in the field. The survey was carried out along the modelled overland flow pathways within forested areas of the riparian zone. The delineation of root dams was conducted in the field based on the following criteria:

- Presence of overland flow pathways within the valley floor zone
- Absence of overland flow pathways within the riparian zone
- Riparian zone lies higher than the adjacent areas of the valley floor zone

Differences in elevation between the riparian zone and the adjacent areas within the valley floor zone were examined visually and by walking in the field. To visualize root dams, valley floor cross-sections have been drawn using the 3D Analyst Tool in ArcGIS 9.3 using a DTM with 1 m x 1 m

resolution. For this procedure, a non-filled DTM was used, in order to make sure that no filling of real sinks had taken place in the course of the "Fill Sinks" processing.
To delineate potential factors of influence for the establishment of root dams, a *statistical analysis* using cross-tabulations and Fisher´s exact test was performed to relate overland transport pathway segments exhibiting forest cover to the binary explanatory variables (see Tab. 2).

5. Results and discussion

5.1. Lateral sediment connectivity

- **Land use mapping – Potential sediment source areas**

The land use/vegetation cover of the total catchment is very heterogeneous, exhibiting the following land use classes: agricultural land (56%), forests and woodland (34%), grassland (7%), and built up areas (3%) (see also Fig. 6). The valley floor located in the upper and middle reaches are dominated by agricultural areas (64 %) (potential sediment source areas) and the following land use classes: forests and woodland (5%), grassland (27%), and built up areas (4%). It is noted that 73% of these river reaches are lined bilaterally (93%) or unilaterally (7%) by forests and woodland, while 27% showed no forest and woodland cover. Riparian zones without forest and woodland cover are almost exclusively covered by grassland with only sporadic occurrence of agricultural or built up areas directly adjacent to the river channel.

- **Overland flow pathway modelling– Sediment transport**

The overland flow pathway model identified 164 overland flow pathways that meet the needs of the following criteria: they originate in agricultural areas in the valley floor zone, cross the riparian zone, end in front of surface morphology breaklines and end at the border of the streambed zone. Fig. 6 shows a part of the model output and Tab. 3 shows a summary of all modelled overland flow pathways segments per land use and riparian vegetation cover within the valley floor zone. A total of 89 riparian segments exhibited grassland vegetation (mean segment length of 5.4 m), while 75 segments showed forest and woodland cover (mean segment length of 5.7 m).

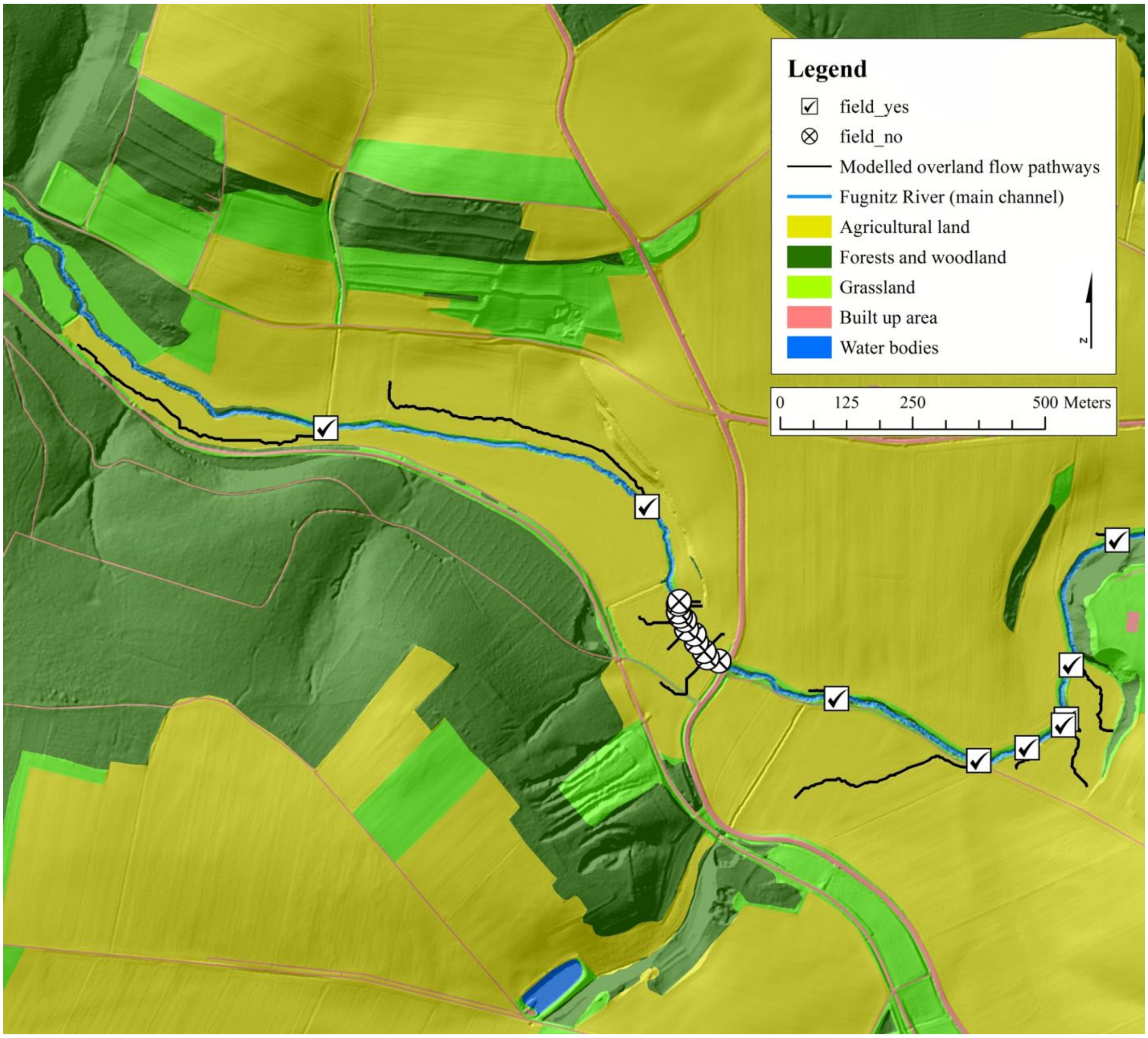


Fig. 6: Overland flow pathway modelling output; field-verified modelled overland flow pathways are indicated by "field_yes"; modelled overland flow pathways where no related features had been observed in the field are designated by "field_no".

Tab. 3: Summary of all modelled overland flow pathway segments per land use and riparian vegetation cover

	Agricultural areas	Riparian forests and woodland	Riparian grassland
Mean segment length in m	89.7	5.7	5.4
Min. segment length in m	3.9	2.0	1.4
Max. segment length in m	778.2	14.6	86.4
Stdev: segment length in m	113.7	2.7	10.4
Number of segments	164	75	89

- **Geomorphic field surveys – Sediment transport**

A total of 91 overland flow pathways were surveyed in the field. These meet the following criteria: continuous rills (vegetated or non-vegetated), continuous indications of overland flow processes (sheet flow or concentrated flow). At 45 locations sediment connectivity between the agricultural areas and the river channel was found. A total of 54 out of 164 modelled overland flow pathways could be verified in the field, while in 37 locations, overland flow pathways were detected where no flow pathways had been modelled. In Tab. 4 the results of the geomorphic field surveys are presented, while Tab. 5 shows a summary of all observed overland flow pathways segments per vegetation cover within the riparian zone. A total of 80 riparian segments exhibited grassland vegetation (mean segment length of 3.7 m), while 26 segments showed forest and woodland cover (mean segment length of 2.4 m).

Tab. 4: Summary of the geomorphic field survey results

Parameter	**No. of observations**
VALLEY FLOOR ZONE	
Overland flow pathway present	91
Overland flow pathway present, overland flow pathway modelled	54
Overland flow pathway present, no overland flow pathway modelled	37
Sediment connectivity between agricultural source area and river channel present	45
Farm track present	29
No farm track present	62
Plough direction: parallel	54
Plough direction: perpendicular	37
RIPARIAN ZONE	
Agricultural land only	3
Forests and woodland (incl. shrubland) only	8
Grassland only	62
Mixture: forests and woodland (incl. shrubland), grassland	18
Root dams present	16
No root dams present	11

Tab. 5: Summary of observed overland flow pathway segments per riparian vegetation cover type

	Riparian forests and woodland	Riparian grassland
Mean segment length in m	2.4	3.7
Min. segment length in m	1	1
Max. segment length in m	6	32
Stdev: segment length in m	1.6	4.3
Number of segments	26	80

- **Validation of overland flow pathway modelling**

A total of 54 out of 164 modelled overland flow pathways could be verified in the field which indicates a model overestimation of 303.7%. A total of 59.3% of all overland flow pathways detected in the field were assigned correctly by the model. At 37 locations overland flow pathways were detected where no flow pathways had been modelled which leads to a model underestimation of 41.7% (see also Fig. 8). In order to gain information for potential improvement of the model performance, causes of model over- and underestimations are discussed in the following sections.

The applied overland flow pathway modelling approach provides information on potential pathways of overland flow. However, the occurrence and site at which overland flow takes place in reality further depends on factors that have not been considered in this study which may lead to model over- or underestimations. These factors include rainfall intensity, rainfall distribution patterns, differences in soil infiltration capacity, micro-relief, and subsurface drainage. Although the applied approach takes into account the amount of water from upland/hillslope zones that potentially reaches the valley floor zone (flow accumulation), other factors governing flow generation and overland flow processes in the upland/hillslope zones are not considered. For a

comprehensive lateral sediment connectivity assessment it might thus be of added value to extend the present approach to the hillslope/upland area zones as well as to include the explanatory factors mentioned above.
In order to estimate factors relevant to the overland flow pathway modelling that are potentially influencing model overestimation, a statistical analysis was performed. For segments with agricultural land use "AL", the ratios of mean values "Len", "Flo", "Slo", and "Cur" were calculated for field-verified observations ("field_yes"). These were divided by mean values where no flow pathways could be verified in the field ("field_no") (see Tab. 6):

Tab. 6: Results of the statistical analysis showing the ratios between the mean values of explanatory variables ("Len_AL", "Flo_AL", "Slo_AL", "Cur_AL") of verified modelled overland flow pathways ("field_yes") and the modelled overland flow pathways where no related features were observed in the field ("field_no")

	field_yes : field_no
Len_AL	1.05
Flo_AL	1.87
Slo_AL	1.59
Cur_AL	2.03

The ratios presented in Tab. 3 indicate that the mean values of the explanatory variables "Flo_AL", "Slo_AL", and "Cur_AL" are significantly higher in field-verified modelled overland flow pathways ("field_yes") than in modelled overland flow pathways where no related features had been observed in the field ("field_no"). On the one hand, these results suggest that these factors are influencing lateral sediment connectivity. On the other hand, they imply that a possible reason for model overestimation is the use of too high threshold values for the explanatory variables. In order to estimate possible threshold values for the present data (*threshold analysis*), the lowest values of explanatory variables for "field_yes" have been evaluated. An explanation of these variables is given below:

- "Flo_AL": "Flo_AL" is the only factor, where a threshold value was principally assumed, because only modelled Flow Accumulation values above the mean (> 586) have been considered in the modelling procedure (see 4.1). The lowest value of "Flo_AL" for "field_yes" was 779, while the average value of "field_yes" was 36820. Hence, only a small difference between the lowest value of "Flo" for "field_yes" and the threshold of Flow Accumulation values above the mean, suggest that other factors than "Flo_AL" are preferably governing the model overestimation.
- "Slo_AL": The lowest value of "Slo_AL" for "field_yes" was 0.31°, which suggests a lower mean slope angle threshold of roughly 0.3° within the study area.
- "Cur_AL": No "field_yes" observation showed "Cur_AL"-values below -0.57, indicating a lower mean profile curvature threshold of about -0.6.

Another reason for model overestimation involves the use of the DTM "Fill Sinks" tool. If real depressions are filled, the flow routing might not stop in existing sink areas, but can be modelled further downslope until potentially reaching the streambed zone. This may occur in transition areas between the valley floor zone and forested riparian zone areas where the presence of small-scale real sinks due to the establishment of root dams and filling of real sinks is highly probable. The same effects are expected to occur at the boundaries of agricultural source areas and farm tracks, where a filling of small-scale real sinks may also take place.
Model underestimations can generally occur at locations where the flow along the overland flow pathways is sufficient to overcome the surface morphology breaklines. This may also depend on conditions in the upland/hillslope zones that are enhancing flow generation and overland flow

processes and determines the amount of water reaching the valley floor zone which is then available for sediment transport (e.g. high local rainfall intensity, low soil infiltration capacity, and subsurface drainage). Furthermore, model underestimation can be caused by errors in the DTM which potentially lead to flow misroutings. Another reason for model underestimation could be related to the choice of flow direction algorithm. Flow direction algorithms generally have been categorized into two types: single-direction and multiple-direction. A single-direction algorithm transfers the flow from the center cell to one downslope neighbor, while multiple-direction algorithms are able to partition flow to multiple downslope neighbors (Erskine et al. 2006). The Flow Direction tool in ArcGIS 9.3 uses a single-direction algorithm based on the D8 (eight flow directions) method that assigns flow from each pixel to one of its eight neighbours in the direction with steepest downward slope (Jenson and Dominigue 1988). Great relative differences between single- and multiple-direction algorithms have been observed by Erskine et al. (2006) especially in divergent areas such as ridges and side slopes using high-resolution DEMs. Moreover, model underestimation could be due to a non-consideration of factors influencing the potential for soil loss, such as the soil erodibility factor, which has not been integrated in the present study due to a lack of data.

- **Statistical analyses**

In the course of the *PCA*, 5 factors were extracted, explaining 77.7% of the variability in the data. The factors are in order of decreasing importance “Dif_Slo_GL” (principal component (PC) 1, influenced mainly by the percentage contribution of grass land and the difference in slope between agricultural land and buffer zone), “Flo_AL” (PC2, influenced by characteristics of the agricultural land, e.g. its width, its flow accumulation and its slope (negatively)) , “Cur” (PC3, mainly affected by the curvature of the arable land and the difference in curvature between arable land and buffer zone), “CumLen” (PC4, affected by the total width of the buffer zone), and “Dif_Flo” (PC5, affected by the difference in flow accumulation between arable land and buffer zone), respectively (see Tab. 7). All 5 PCs were used as explanatory variables in the logistic modelling procedure.

Tab. 7: Factor loadings of the 5 PCA-factors. Bold numbers indicate the strongest correlations between PC-scores and variable values; values were log2-transformed All factors were used as explanatory variables in the logistic regression model.

Variables	**Dif_Slo_GL**	**Flo_AL**	**Cur**	**CumLen**	**Dif_Flo**
Per_FL	**-.759**	-.042	.094	.498	.063
Per_GL	**.878**	.026	-.047	-.002	.067
CumLen	-.085	-.044	-.001	**.964**	.016
Flo_AL	.439	**.650**	.005	.000	.314
Slo_ AL	.096	**-.769**	-.337	-.162	.246
Cur _AL	.039	.126	**.819**	-.115	.254
Dif_Cur_AL	.017	-.061	**.833**	.122	-.172
Dif_Slo_AL	**.687**	-.058	.197	.021	-.276
Dif_Flo_AL	-.131	-.119	.044	.034	**.910**
Len_AL	-.074	**.819**	-.145	-.185	-.094

Logistic regression modeling: Scenario 1

In scenario1, the five axes from the PCA and the three binary variables plough direction, farm tracks, and root dams were used as explanatory variables. The general model performance resulted in a Nagelkerke R^2 of 0.417 (Nagelkerke 1991) and an Omnibus test significance of $p < 0.05$. It was observed that 75.9% of the observations were assigned correctly. The following explanatory variables remained after backward elimination: “Dif_Slo_GL”, “Fat”, “Rod” (see Tab. 8).

Tab. 8: Results of the logistic regression scenario 1 (backward elimination method)

Explanatory variables	Regression coefficient B_1	Standard error	Wald	df	Sig.	Exp(B)
Dif_Slo_GL	**.671**	.497	1.826	1	**.177**	1.957
Fat	**-1.199**	.551	4.734	1	**.030**	.302
Rod	**-20.821**	13243.806	.000	1	**.999**	.000

Logistic regression modelling: Scenario 2

In Scenario 2 all observations with explanatory variables, which had been examined in the field, were integrated into the logistic regression model (i.e. "Per", "CumLen", "Rod", "Plo", and "Fat"). Within this scenario, 83.3 % of the observations were assigned correctly, showing a Nagelkerke R^2 of 0.523 (Nagelkerke 1991), and an Omnibus test significance of $p < 0.05$. The following explanatory variables remained after backward elimination: "Fat", "Rod", and "Per_GL" (see Tab. 9).

Tab. 9: Results of the backward elimination for logistic regression scenario 2

Explanatory variables	Regression coefficient B_2	Standard error	Wald	df	Sig.	Exp(B)
Fat	**-2.683**	.592	20.564	1	**.000**	.068
Rod	**-3.921**	1.090	12.939	1	**.000**	.020
Per_GL	**.330**	.085	14.910	1	**.000**	1.390

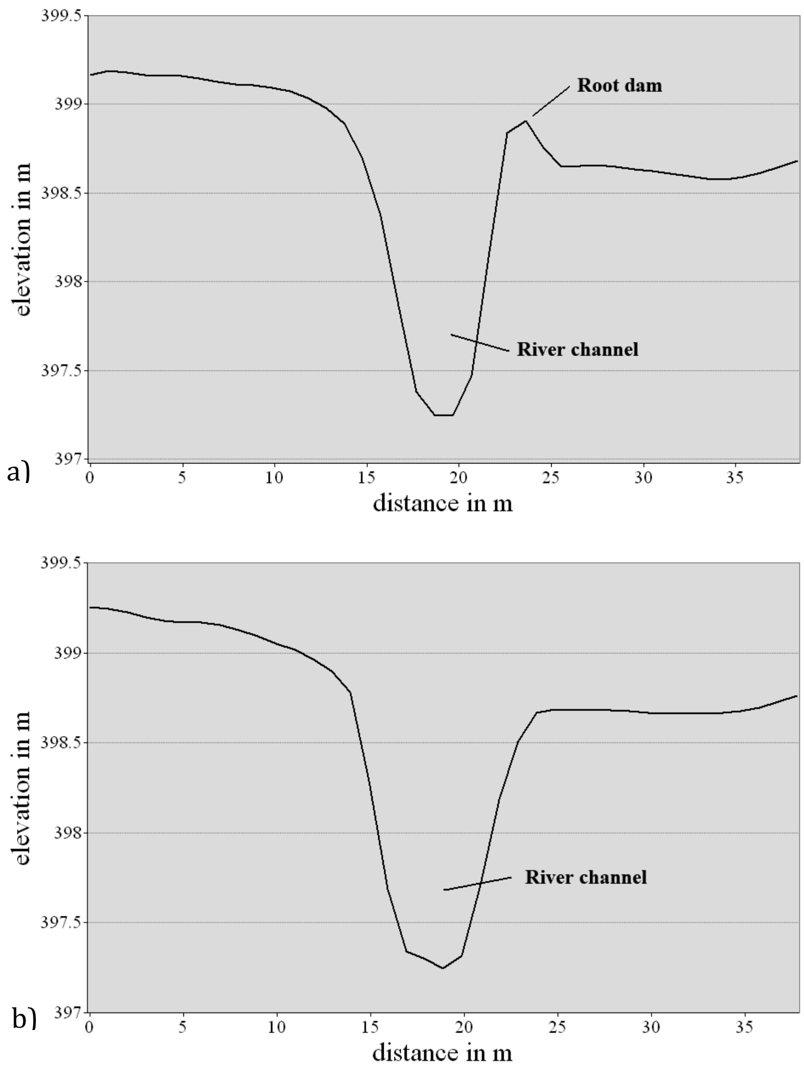
Scenario 1 and scenario 2 produced very similar results. The results of both model scenarios suggest that the occurrence of root dams ("Rod") has strong disconnecting effects on lateral sediment connectivity (B_1 (scenario 1) = -20.821, B_2 (scenario 2) = -3.921). In the first scenario the covariate "Rod" is not significant due to a very large standard error of the regression coefficient which is probably a combined effect of a smaller number of observations and "Rod" being a binary variable. However, the fact that it is retained in the final regression solution shows its strong effect in scenario 1 (together with the large absolute values of the regression coefficient B1). Hence, the presence of root dams is interpreted as having a high potential to dam sediments which are delivered from adjacent agricultural areas and thus preventing them from entering the stream. In both scenarios the presence of farm tracks within the valley floor zone ("Fat") leads to a disconnection between the valley floor zone and the riparian zone (B_1 = -1.199, B_2 = -2.683). Damming processes are expected to be related to the presence of farm tracks running parallel to the river channel since elevation differences and real sinks occur between the farm tracks and adjacent agricultural source areas. As the farm tracks within the valley floors of the study area are very flat features, deposition preferably takes place there. However, given enough transport capacity these features might further act as conduits for sediment transport redirecting water and sediment towards locations where material potentially enters the channel network. It should be further mentioned that only farm tracks were considered in the course of overland flow pathway modelling where a slope angle threshold of 2° had been reached. Nevertheless, a significant decrease of slope angle and hence transport capacity also occurs below a slope angle of 2°. Thus, including a lower slope angle threshold to improve the validity of overland flow pathway model is necessary (see also 5.1).

Results of scenario 1 indicate that high differences in slope angle between the valley floor zone and the percentage of riparian zone covered by grassland ("Dif_Slo_GL") lead to an increase of sediment connectivity (B_1 = 0.671). In the study area, grassland segments within the riparian zones exhibit much higher mean slope angle values (10°) than agricultural segments (0.9°). This strong increase of slope angle is related to an abrupt increase of sediment transport capacity and hence sediment connectivity. The results of the PCA (see Tab. 4) suggest that the explanatory variable "Dif_Slo_GL" is positively correlated with the variable "Per_GL". An increase of sediment connectivity with increasing proportions of grassland within the riparian zones can therefore be derived. This relationship is also reflected by the results of scenario 2, revealing that sediment connectivity generally increases with increasing proportions of grassland in riparian zones “Per_GL” (B_2 = 0.330). Since high proportions of “Per_GL” are always related to low proportions of “Per_FL”, it can be stated that sediment connectivity decreases with “Per_FL”. Furthermore, proportions of forested areas within riparian zones (“Per_FL”) are shown to be negatively correlated with “Dif_Slo_GL” (see Tab. 4). This again implies a decrease of sediment connectivity with increasing proportions of riparian forest vegetation.

5.2 Biogeomorphic processes

- **Biogeomorphic field surveys**

Overall, 27 riparian forest segments were examined in the course of the geomorphic field surveys. In 16 forest segments (= 59.3%) root dams were present. The field surveys further revealed that root dams occur discontinuously along the river banks, both bilaterally and unilaterally, which is visualized in Fig. 7:



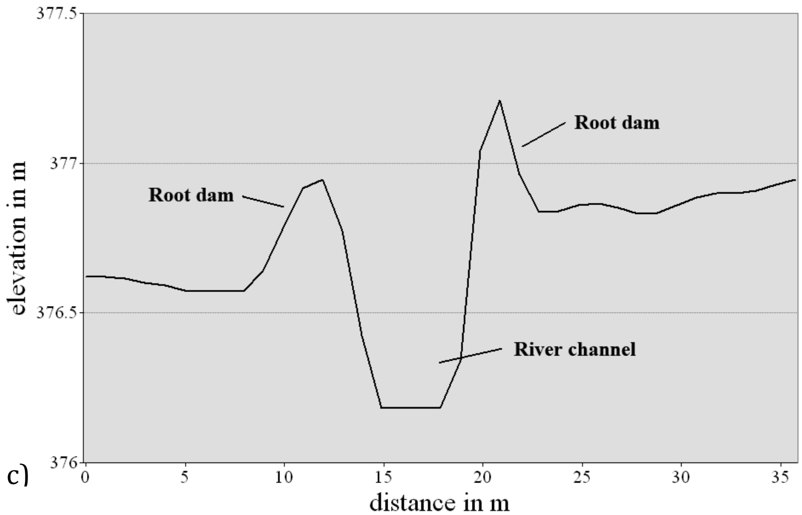


Fig. 7: Valley floor cross sections; a) unilateral root dam occurrence along the right river bank; b) no root dam present (location next to cross section a); c) bilateral root dam occurrence

- **Statistical analyses**

Statistical analysis using cross tabulations and Fisher´s exact test resulted in the delineation of "Fat" (Farm Tracks) being the only significant factor ($p < 0.05$) potentially influencing the establishment of root dams (see Tab. 10).

Tab. 10: Cross-tabulations for presence/absence of root dams and farm tracks

Factors		**Rod**		Total
		absent	present	
Fat	absent	6	16	22
	present	5	0	5
Total		11	16	27

The results presented in Tab. 6 suggest that the presence of "Fat" reduces the development of root dams. This is most likely related to the disconnecting effects of farm tracks that prevent sediment of agricultural source areas from reaching the riparian zones (see also 5.2). However, neither the methodology nor the low number of observations (27) is sufficient to derive general statements. Further research is required to unravel the influence of biogeomorphic processes on the establishment of root dams. A more detailed assessment considering factors such as species specific root morphology, historical land use, tree age and density, frequency of floods, human disturbance is necessary.

6. Summary of results

The use of an overland flow pathway model and threshold analysis produced results that showed that the lateral sediment connectivity is strongly influenced by flow accumulation, slope angle and profile curvature and the assessment of biogeomorphic processes in forested riparian zones indicated that the presence of farm tracks adjacent to the riparian zones reduce the development of root dams. These results support the hypothesis that root dam establishment is driven by sediment supply from agricultural land, as farm tracks seem to re-direct sediment flow away from the river.

The effects of riparian vegetation on diffuse *lateral sediment connectivity* assessed using PCA and a logistic regression model produced for three significant findings:

- Lateral sediment connectivity decreases with an increasing proportion of forest vegetation in the riparian zone and the occurrence of root dams.
- High slope angles in riparian grassland areas compared to those in adjacent agricultural areas increase the lateral sediment connectivity due to an abrupt increase of sediment transport capacity.
- Farm tracks located in the valley floor zone contribute to a disconnection between the valley floor zone and riparian zone.

7. Conclusions

With respect to the two objectives of this study, i.e. (i) to assess the influence of riparian vegetation cover type on diffuse lateral sediment connectivity on valley floors, and (ii) to investigate biogeomorphic processes acting in forested riparian zones of a medium-sized agricultural catchment, the following conclusions are drawn:

- Forested riparian zones significantly reduce sediment inputs and act as strong disconnectors between the agricultural source areas and the river channel.
- Root dams are topographical features which are acting as buffers that limit the sediment connectivity as they hinder the sediment transport between the catchment areas and the river channel.
- Root dams emerge from biogeomorphic processes which are driven by factors including the sediment supply from agricultural land.

It is important to note that vegetation plays an important role in governing lateral sediment connectivity due to its local capacity to store sediments. Furthermore, topographical features emerging from biogeomorphic processes act as stores and sinks which limit the lateral connectivity as they hamper the sediment transport between landscape compartments. Riparian zones therefore require specific attention with regards to connectivity research, connectivity assessment and river management. Since knowledge about the role of riparian vegetation is rare and presents an important gap in connectivity research, this contribution is a step forwards to grasp the effects of riparian vegetation on lateral sediment connectivity as well as to understand the processes and factors that govern them.

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References

Beyer, H. L., 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Borin, M., Vianello, M., Morari, F. and Zanin, G., 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. Agricultural Ecosystems and Environment, 105: 101-114.

Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena 75: 268-277.

Boyce, R.C., 1975. Sediment routing with sediment delivery ratios. Present and Prospective Technology for Predicting Sediment Yield and Sources, Publ. ARS-S-40. U.S. Department of Agriculture, Washington, D.C., pp. 61-65.

Brierley, G., Fryirs, K. and Jain, V., 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38.2: 165-174.

Brooks, A.P. and Brierley, G.J., 1997. Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926. Geomorphology 18: 291–304.

Brunsden, D. and Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers NS4: 463–484.

Cammeraat, E.L.H., 2002. A review of two strongly contrasting geomorphological systems within the context of scale. Earth Surface Processes and Landforms 27 (11): 1201–1222. Carmean, W.H., 1957. The structure of forest soils. The Ohio Journal of Science 57(3): 164-168.

Cooper, J.R., Gilliam, J.W., Daniels, R.B. and Robarge, W.P., 1987. Riparian areas as filters for agricultural sediment. Soil Science Society of America Journal 51(2): 416–420.

Croke, J., Mockler, S., Fogarty, P., Takken, I., 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. Geomorphology 68: 257–268.

Dabney, S.M., Meyer, L.D., Harmon, W.C., Alonso, C.V. and Foster, G.R., 1995. Depositional patterns of sediment trapped by grass hedges. Transactions of the American Society of Agricultural Engineers 38(6): 1719–1729.

Daniels, R.B. and Gilliam, J.W., 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60(1): 246–251.
Deletic, A., 2006. Performance of grass filters used for stormwater treatment—a field and modelling study. Journal of Hydrology 317: 261–275.
De Vente, J., Poesen, J., Arabkhedri, M., Verstraeten, G., 2007. The sediment delivery problem revisited. Progress in Physical Geography 31(2): 155-178.
De Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth-Science Reviews 71: 95–125.
Dillaha, T.A., Reneau, R.B., Mostaghimi, S. and Lee, D., 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the American Society of Agricultural Engineers 32(2): 513–519.
Dillaha, T.A., Sherrard, J.H., Lee, D.S.M. and Shanholtz, V.O., 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. Journal of Water Pollution Control Federation 60: 1231–1238.
Erskine, R.H., Green, T.R., Ramirez, J.A., MacDonald, L.H., 2006. Comparison of grid-based algorithms for computing upslope contributing area. Water Resources Research, 42, W09416, doi: 10.1029/2005WR004648.
Fryirs, K.A., Brierley, G.J., Preston, N.J. and Kasai, W., 2007a. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. Catena 70: 49-67.
Fryirs, K.A., Brierley, G.J., Preston, N.J. and Spencer, J., 2007b. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. Geomorphology 84: 297-316.
Green, C.H., Haney, R., 2011. Riparian Zones. Sera-17, Best Management Practices Factsheet.
Gumiere, S.J., Le Bissonnais, Y., Raclot, D. and Cheviron, B., 2011. Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: A review. Earth Surface Processes and Landforms 36: 3-19.
Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. Geomorphology 44: 175– 201.
Hayes, J.C., Barfield, B.L. and Barnhisel, R.I., 1984. Performance of grass filters under laboratory and field conditions. Transactions of the American Society of Agricultural Engineers 27: 1321–1331.
Hooke, J.M., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. Geomorphology 56: 79–94.
IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO, Rome.
Jenson, S. K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation models, Photogramm. Eng. Remote Sens. 54, 1593– 1600.
Keesstra, S.D., van Dam, O., Verstraeten, G. and van Huissteden, J., 2009. Changing sediment generation due to natural reforestation in the Dragonja catchment, SW Slovenia. Catena 78: 60-71.
Keesstra, S.D., 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. Earth Surface Processes and Landforms 32(1): 49-65.
Lane, S.N. and Richards, K.S., 1997: Linking river channel form and process: time, space and causality revisited. Earth Surface Processes and Landforms 22: 249–260.
Le Bissonnais, Y., Lecomte, V., Cerdan, O., 2004. Grass strip effects on runoff and soil loss. Agronomie 24: 129–136.
Leguédois, S., Ellis, T.W., Hairsine, P.B. and Tongway, D.J., 2008. Sediment trapping by a tree belt: processes and consequences for sediment delivery. Hydrological Processes 22: 3523-3534.

Mankin, K.R., Ngandu, D.M., Barden, C.J., Hutchinson, S.L. and Geyer, W.A., 2007. Grass-shrub riparian buffer removal of sediment, phosphorus, and nitrogen from simulated runoff. Journal of the American Water Resources Association 43(5): 1108-1116.

Meyer, L.D., Dabney, S.M. and Harmon, W.C., 1995. Sediment-trapping effectiveness of stiff-grass hedges. Transactions of the ASAE 38: 809-815.

Michaelides, K. and Wainwright, J., 2002. Modelling the effects of hillslope–channel coupling on catchment hydrological response. Earth Surface Processes and Landforms 27: 1441–1457.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A., 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57: 443–452.

Nagelkerke, N., 1991. A Note on a General Definition of the Coefficient of Determination. Biometrika 78 (3): 691–692

Osborne, L.L., Kovacic, D.A., 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29: 243-258.

Phillips, J.D., 1992. Delivery of upper-basin sediment to the lower Neuse River, North Carolina, USA. Earth Surface Processes and Landforms 17: 699–709.

Puigdefabregas, J., Sole, A., Gutierrez, L., Del Barrio, G., Boer, M., 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain. Earth-Science Reviews 48 (1–2): 39–70.

Raclot, D., Le Bissonnais, Y., Louchart, X., Andrieux, P., Mossa, R. and Voltz, M., 2009. Soil tillage and scale effect on erosion from fields to catchment in a Mediterranean vineyard area. Agric. Ecosyst. Environ. 134: 201–210.

Rawnsley, J., 1991. Trees and Soil Stabilization. Environmental Conservation 18: 371-371.

Roetzel, R., Fuchs, G., Ahl, A., Schubert, G., Slapansky, Peter, 2008. Erläuterungen zur Geologischen Karte 1:50,000, Blatt 8 Geras. Geologische Bundesanstalt Österreich.

Sandercock, P.J., Hooke, J.M., 2011. Vegetation effects on sediment connectivity and processes in an ephemeral channel in SE Spain. Journal of Arid Environments 75: 239-254.

Slattery, M.C., Gares, P.A., Phillips, D., 2002. Slope-channel linkage and sediment delivery on North Caroline Coastal Plain Cropland. Earth Surface Processes and Landforms 27:1377–1387.

UBA, 1989. Biotoptypen in Österreich. Vorarbeiten zu einem Katalog. Umweltbundesamt Wien.

USDA-SCS, Soil Conservation Service, 1986. National Engineering Handbook—Sect. 4, Hydrology. Washington D.C.

Van Rompaey, A.J.J., Govers, G., Puttemans, C., 2002. Modeling land use changes and their impact on soil erosion and sediment supply to rivers. Earth Surface Processes and Landforms 27: 481-494.

Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia 410: 223-240.

Walling, D.E., Webb, B.W., 1996. Erosion and sediment yield: a global overview. Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996). IAHS Publ. no. 236, 1996.

Ward, J.V., 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8, 2–8.

Western, A.W., Bloeschl, G., Grayson, R.B., 2001. Toward capturing hydrologically significant connectivity in spatial patterns, Water Resources Research 37 (1): 83-97.

Williams, J.R., 1977. Sediment delivery ratios determined with sediment and runoff models. Erosion and Solid Matter Transport in Inland Waters. IAHS-AISH publication 122: 168–179.

Wilson, C.A.M.E., Stoesser, T. and Bates, P.D. 2005. Modelling of open channel flow through vegetation. In Computational Fluid Dynamics: Applications in Environmental Hydraulics.

Bates P.D., Lane S.N., Ferguson R.I. (eds.), John Wiley and Sons: Chichester, UK. Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses – a guide to conservation planning. USDA Handbook 537. U.S. Department of Agriculture.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68: 54–74.

Wu, F.C., Shen, H.W., Chou, Y.J., 1999. Variation of roughness coefficients for unsubmerged and submerged vegetation. Journal of Hydraulic Engineering 9: 934–942.

A.3 Dam-induced landscape change and the role of human-landscape interactions – a-reach-scale case study

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The publication was initiated, designed and solely written by Ronald E. Poeppl. Margreth Keiler accompanied the development of the conceptual model and the writing with scientific exchange, discussions and constructive feedback. Tom Coulthard was responsible for the CAESAR model setup and supervised the whole modelling process.

Article title

Dam-induced landscape change and the role of human-landscape interactions - a reach-scale case study

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Abstract

Dams significantly impact riverine processes, since they alter the hydrological regime and disrupt the longitudinal sediment connectivity which induces geomorphic channel changes in the affected river reaches. These geomorphic consequences often call for river management activities such as the installation of structural engineering works or dam removals which induce further geomorphic responses that may again call for further human intervention. Such human responses are generally accompanied by landscape changes such as channel straightening and a related removal of riparian vegetation as well as by land use changes in the surrounding areas. This paper investigates interactions and feedbacks between the human system and the fluvial system and derives potential causes for landscape change by applying a combination of GIS-based mapping techniques, geo-statistical analyses, landscape evolution modeling with CAESAR and field surveys. The study is conducted in a river reach of the Kaja River which is located in the Northeast of Austria and has been affected by a series of dams. The results of the CAESAR landscape evolution modelling exhibited that dam construction caused significant geomorphic channel changes in terms of downstream channel degradation and upstream aggradation. Field surveys revealed that river bed and bank engineering works were installed along all river reaches affected by dam-induced channel degradation. GIS-based mapping and geostatistical analyses resulted in the delineation of significant landscape changes in the fluvial environment and were shown to be related to a dam-induced interconnection of the human and the fluvial system.

Key words

Human impact, fluvial systems, dams, landscape change, human-landscape interactions

Introduction

For more than 5,000 years, dams have been constructed for a wide variety of purposes (Kondolf, 1997) including water supply, flood and debris control, hydropower production, or fish farming. The rate of dam construction increased dramatically after 1945 and each year more than 200 large dams are constructed (Gregory, 1995). Dams significantly impact riverine processes, since they alter the hydrological regime and disrupt the longitudinal sediment connectivity (e.g. Fryirs et al., 2007; Poeppl et al., 2012). Thus, dams are considered to have the most significant impact on rivers and concerns about the effects of dam construction have recently increased with the rising number of dams (Tockner and Stanford, 2002; Dudgeon, 2005). The most common geomorphic responses to dam construction are aggradation in the reservoirs and upstream river reaches as well as degradation downstream (e.g. Leopold, 1973; Petts, 1979; Mahmood, 1987; Kondolf, 1997; Poeppl et al., 2012). These geomorphic responses are mostly classified as negative effects from a human perspective and thus call for river management activities such as structural engineering works to inhibit downstream degradation or reservoir excavation to prevent from sediment infilling.

However, if dams no longer fulfil their intended purpose and socio-economic benefits no longer outweigh the negative impacts they cause, dams are removed (Burroughs et al., 2009). Dam removal again alters flow and sediment dynamics of a river and thus induces geomorphic responses (e.g. Wohl and Cenderelli, 2000; Bushaw-Newton et al., 2002; Stanley et al., 2002; Wildman and MacBroom, 2005; Burroughs et al., 2009) which may again call for further river management activities. Hence, both, dam construction as well as the removal of dams potentially lead to geomorphic channel changes. Besides the geomorphic effects which occur within the river channels, structural engineering works which are generally accompanied by channel straightening and clearance of riparian vegetation (Brierley and Fryirs, 2005) lead to significant landscape changes in fluvial environments. Furthermore, the most obvious impacts of dams on the landscape are associated with land use and land cover in the surrounding areas of a river (Ouyang et al., 2010). Therefore, since dams significantly impact the landscape system as well as the human system, assessing and evaluating dam-induced landscape changes is of great scientific and social importance.

Human impact on landscape systems is now larger than at any point in history, so that modifications of the landscape exceed natural processes (for global perspective Hooke, 2000; Wilkinson and McElroy, 2006; for a local and regional perspective Keiler, 2004; Keiler et al., 2006) and geomorphic response to human impacts on fluvial systems is complex in space and time (Petts and Gurnell, 2005). Unintended or unconsidered effects due to intervention in the fluvial system such as erosion downstream of dams require repeated intervention by river engineering structures such as canalizations and river bed and bank protection (Gregory, 2006). In turn, these structures cause further intended and unintended effects (Schumm, 2005) and the chain of interactions could lead to undesirable feedbacks. Previous approaches to analyse the drivers of landscape change have been increasingly criticized for being too simplistic (e.g. Leach and Mearns, 1996; Lambin et al., 2001; Geist and Lambin, 2002). They must be rather matched by enhanced understanding of the causes of change (Committee in Global Change Research, 1999) and it is further argued that human activities and landscape change should be viewed together as a co-evolutionary and adaptive process (Holling, 2001; Lenton et al., 2004). However, research questions on the interlinkages between fluvial systems and human systems have not sufficiently been studied so far (Gregory, 2006; James and Marcus, 2006). Since social as well as natural processes are often driven by system interactions, system behaviour cannot be understood by analysing system components in isolation (Bennett and McGinnis, 2007). There is a need to appraise notions of connectivity considered in terms of human-landscape interactions (Brierley et al. 2006) and therefore approaches which focus on interactions and feedbacks between the human and the landscape system are needed to untangle potential reasons of landscape change.

The chosen unit of study is that of the landscape. The term “landscape” should be understood in the context of this paper as “an intermediate scale region, comprising landforms and landform assemblages, ecosystems and anthropogenically modified land” (Slaymaker et al., 2009, p.1). Landscape changes are often assessed by using landscape indicators (e.g. Gergel et al., 2002). Landscape indicators generally quantify the amount and arrangement of land cover, human-altered land, and the physical structure of landforms and landform assemblages (e.g. Meyer and Turner, 1994). This paper focuses on landscape changes in terms of land use and land cover, riparian vegetation and river channel morphology. These parameters are further very important measures for physical and biological integrity of surface waters which are therefore also considered in the Water Framework Directive of the European Union. Different methods for assessing such landscape changes exist, ranging from remote sensing techniques (e.g. interpretation of aerial photographs, satellite images and airborne laser-scans), interpretation of historical maps, field surveys (e.g. mapping techniques), to numerical models (e.g. landscape evolution models). Although often used separately, these methods have been rarely combined in order to investigate landscape changes in fluvial environments.

Based on the outlined considerations, this paper focuses on the detected research gaps, i.e. to investigate interactions and feedbacks between the human system and the fluvial system and to derive potential reasons for landscape change by using a combination of different methods. The main objectives of the present study are (i) to compare a dam-impacted river reach regarding land use/land cover and river planform geometry at two points in time, (ii) to model dam-induced geomorphic channel changes and to relate them to aspects of dam-induced interactions between the fluvial and the human system between these points in time. This is met by applying a combination of GIS-based mapping techniques, geo-statistical analyses, numerical landscape evolution modeling and field surveys. The following section gives a detailed outline of the conceptual background and presents the underlying assumptions and hypotheses for each of the study´s objectives.

Conceptual model

Dams and geomorphic response

The *construction of dams* alters the river morphology, and field observations of channel changes downstream of dams are documented for more than 85 years (e.g. Lawson, 1925). The installation of a dam generally causes geomorphic responses in terms of downstream channel degradation due to an excess of stream power and energy in the river (Kondolf, 1997) resulting from human-induced reduction of downstream sediment supply (e.g. Taylor, 1978; Al-Taiee, 1990; Grant et al., 2003; Graf, 2006; Gumiere et al., 2010; Thothong et al., 2011; Poeppl et al., 2012). Observations indicate that after dam closure the erosional front migrates downstream from the dam (Wang et al., 2007). Lagasse (1994) reported that geomorphic changes from shrinkage to channel planform geometry have resulted from dam construction. Upstream, the bed load and all or part of the suspended load is deposited within the reservoir as well as in the upstream river reaches which are affected by backwater (e.g. Kondolf, 1997; Fang and Rodi, 2003; Heppner and Loague, 2008). As a long-term effect, shallowing of reservoirs caused by continuous retention of material supplied by the river has been observed (Lajczak, 1996). Consequently, both processes upstream aggradation and downstream degradation result in a change of the river slope (see Fig. 1a). Currently, a growing number of dams exists that no longer fulfill their intended purpose of providing social and economic benefits (Burroughs et al*.,* 2009), since in many instances rates of sedimentation were underestimated and dam removal is necessary. *Dam removal* is again accompanied by geomorphic consequences such as degradation of former reservoir sediments upstream and downstream channel aggradation (e.g. Wildman and MacBroom, 2005; Burroughs et al., 2009) as the river seeks for balanced slope conditions (see Fig. 1b).

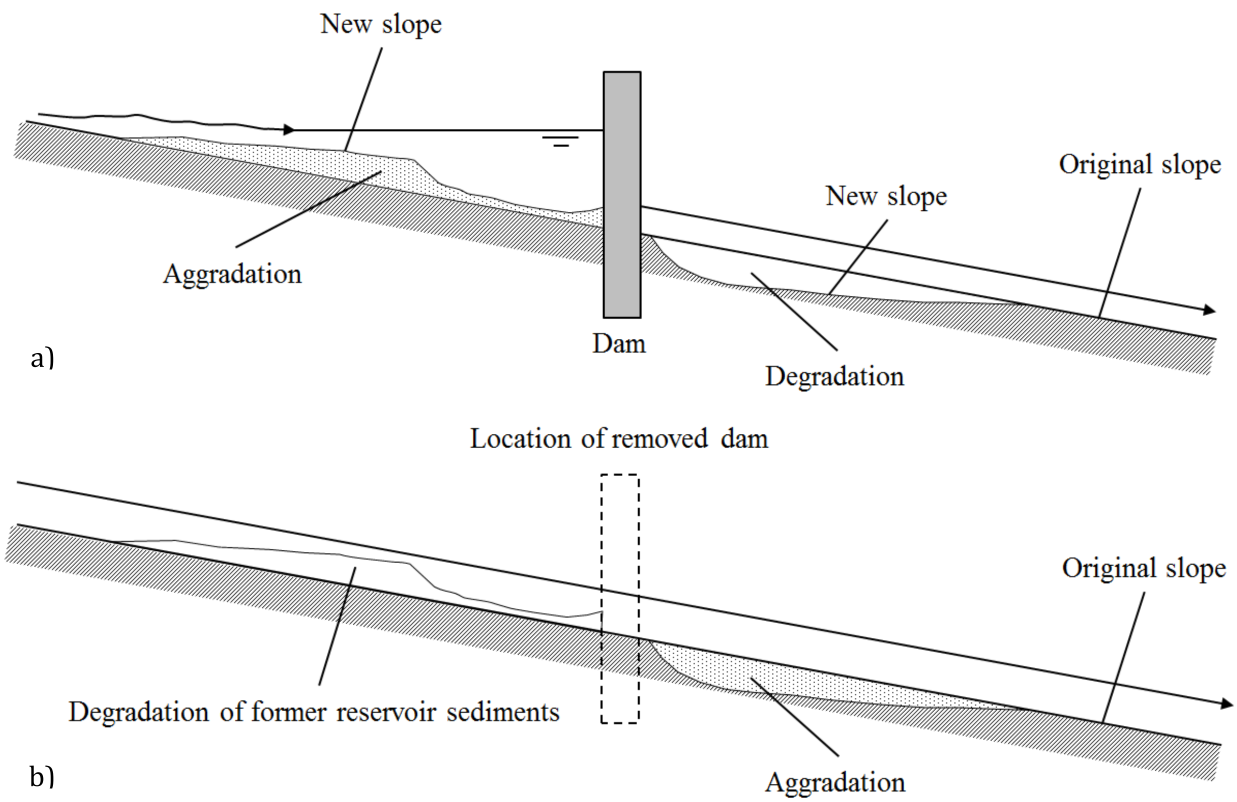

Fig. 1: Aggradation, degradation and related changes of the river slope at a dam: a) dam construction, after Gordon et al. (2004), b) dam removal. River flow direction is indicated by black arrows.

Dam-induced interactions between the human system and the fluvial system

As conceptualized in chapter 2.1, *human impact* on fluvial systems in form of a dam causes *geomorphic responses*. Geomorphic responses include river bed aggradation/degradation, channel narrowing/widening and river planform geometry changes. These geomorphic responses often have undesirable side effects for the human system, especially when human resources and infrastructures are affected. In the downstream reaches, these side effects often lead to *human responses*, as they call for river management activities such as structural river engineering works which are utilized to mitigate river bed and bank degradation downstream of a dam. The installation of such mitigation measures is generally accompanied by landscape changes associated with land use and land cover changes in the surrounding areas (e.g. Ouyang et al., 2010), channel straightening and a clearance of riparian vegetation cover (e.g. Brierley and Fryirs, 2005). Upstream effects are related to sediment infilling causing human responses in terms of reservoir excavation or dam removal. Dam removal is generally associated with land use and land cover changes in and adjacent to the areas of the former reservoir. Furthermore, dam removal leads to *geomorphic responses* which may have negative effects on the human system such as upstream degradation, which again call for *human responses* in terms of river bed and bank protection works. It is therefore hypothesized that human impact on fluvial systems in terms of dam construction causes an interconnection of the human system and the fluvial system by triggering a series of process-response feedback loops between them which influence landscape changes in fluvial environments (see Fig. 2).

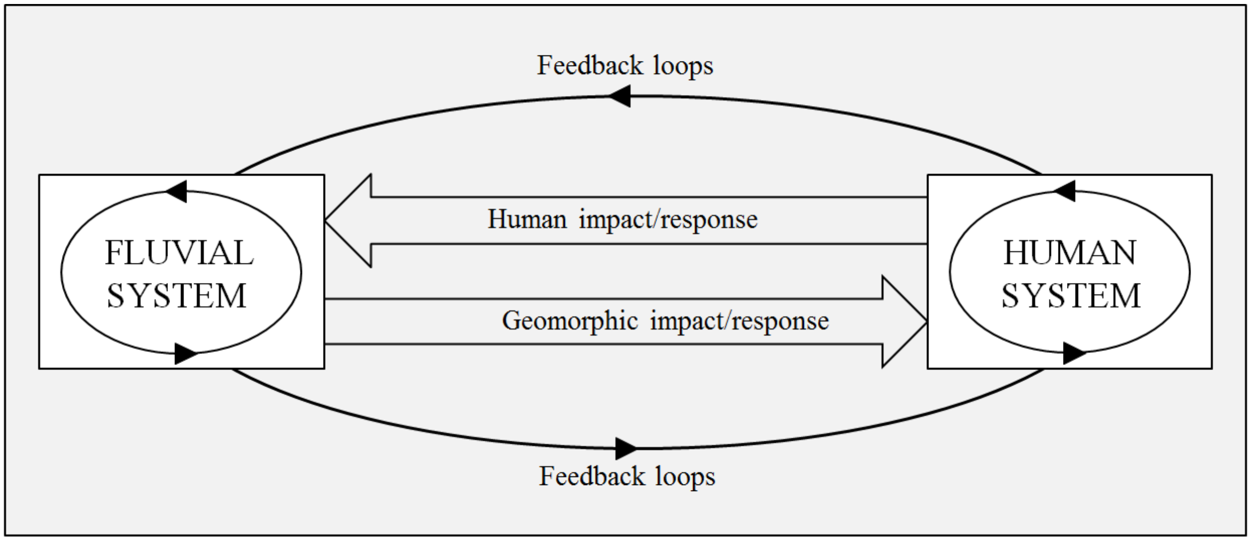

Fig. 2: Human-induced interconnection of the fluvial system and the human system, resulting in a human-landscape system via a series of feedback loops. Besides feedback loops that potentially occur in fluvial as well as in human systems (indicated by circles with arrows), feedback loops are observed as a series of human-induced geomorphic and human responses.

The outlined interrelations are accompanied by changes in the landscape which manifest themselves in the landscape metrics (i.e. changes in land use and land cover, river planform geometry, and clearance of riparian vegetation) which can be analysed and used as indicators for human-landscape interactions. Like many of the European rivers the Kaja River, studied in this paper, has been affected by a series of dams (see next section). However, the number of dams and hence the locations of impact changed over time. These features of the selected study area allow for a comprehensive investigation of human-induced historical landscape changes in a highly dam-impacted river reach.

Study area

The Kaja watershed is located in the Northeast of Austria at the border to the Czech Republic in Europe (see Fig. 3). The Kaja River is a 10.7-km-long mixed-load single-thread perennial stream which drains a 21.3 km^2 watershed in total. Annual precipitation is between 400 mm and 500 mm with maximum rates from April to September. The elevation of the drainage basin ranges from 327 m a.s.l. to 487 m a.s.l. and can be subdivided morphologically, lithologically and in terms of land use/land cover into two units: (1) the upper and middle reaches have a low river gradient, low slope angles and wide open valleys with sides flaring out. Here, the bedrock mainly consists of mica granite which is superimposed by tertiary silts, clays and sands (brackish-maritime) and by quaternary loess layers (silt, fine sand). River bed sediments are generally composed of fine material (i.e. clays, silts, sands and fine gravels). The land-use is predominantly characterized by arable lands with partially occurring grassland, forested and built up areas. (2) The lower reaches show a high river gradient, high slope angles, V-shaped valleys or V-shaped valleys with alluvial fills and bedrock composed of mica shale, quartzite and mica granite. The river bed sediments primarily consist of coarse material (coarse gravels, stones and boulders). Land use and land cover are dominated by forests and woodland.
Along the Kaja River, 15 dams in total exist with the majority located in the middle reaches (see Fig. 3). This information was derived from topographic maps and cadastral plans (data source: BEV Austria 1823, 2010) as well as by interpreting aerial photographs and a hillshade of a digital

elevation model (DEM) with 1 m x 1 m resolution (data source: provincial state government of Lower Austria, 2010). The dams are overflow dams that range from 3 m to 6 m in height whose reservoirs have/had rather small storage capacities and were used for fish farming purposes (Poeppl, 2010). In 2010, four dams have been active, while the others had been removed. The study area is located in the middle reaches of the Kaja River near a human settlement. This river reach was impacted by three dams in 1823. In 2010, two of them are removed (see Fig. 4).

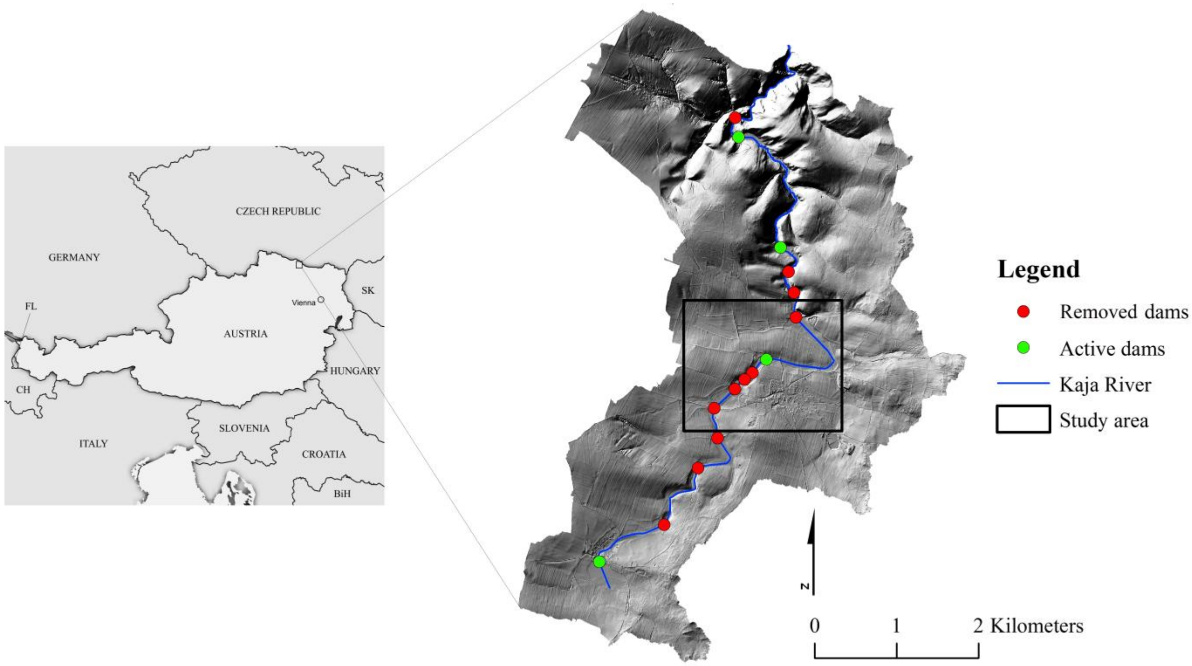

Fig. 3: Study area. a) Location of the Kaja watershed. b) Locations of abandoned and active dams along the Kaja River in 2010; study area extent is indicated by the black rectangle; data source (Digital Terrain Model (DEM) hillshade with 1 m x 1 m resolution): provincial state government of Lower Austria, 2010

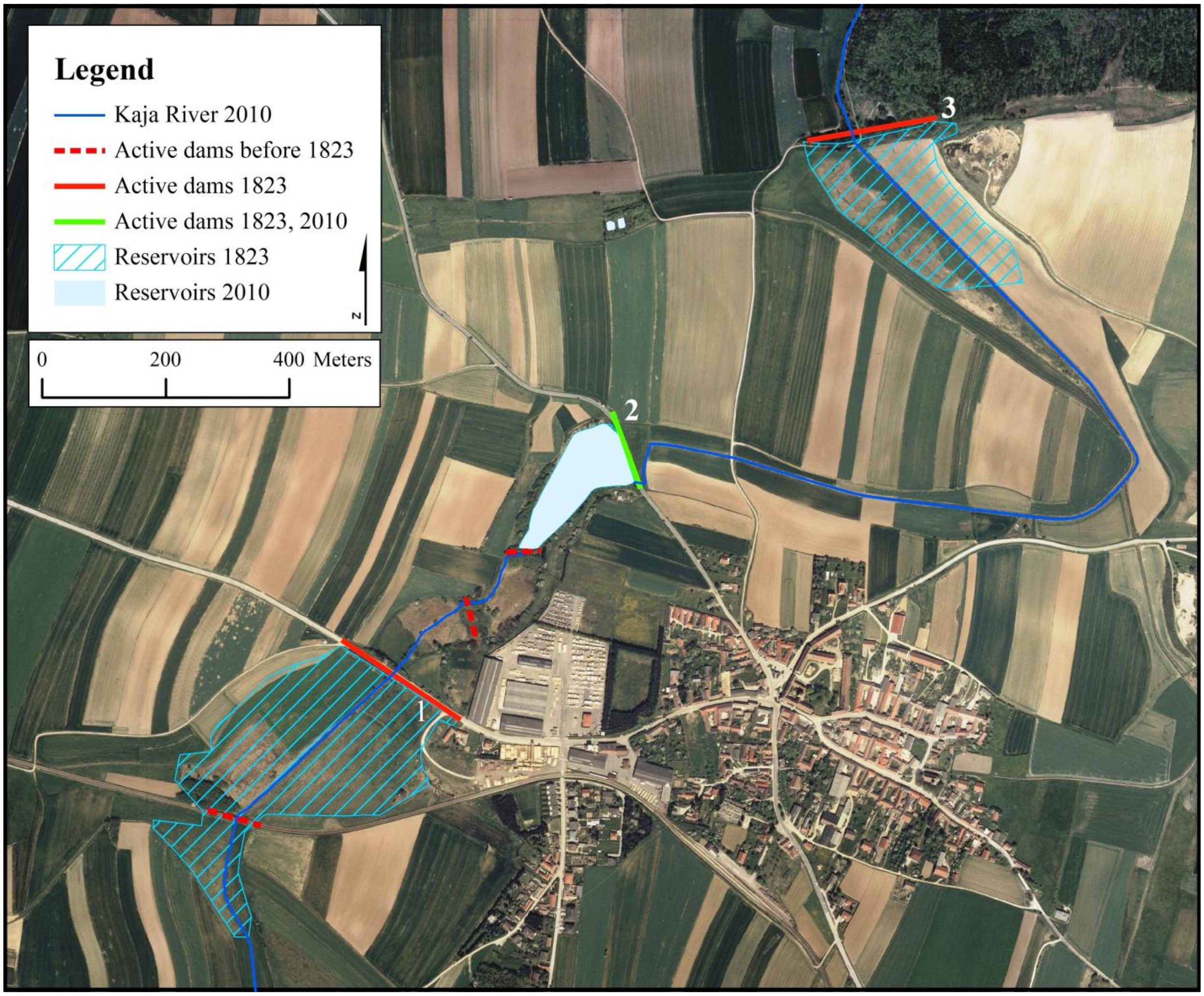

Fig. 4: Study area extent showing active dams and reservoirs of 1823, 2010 and before 1823. Data source (aerial photographs): Provincial state government of Lower Austria 2010. Information on reservoir locations in 1823 have been derived from the "Land register of Francis I" 1823 (data source: BEV Austria, 2010). Numbering of dams in downstream direction.

Methods

GIS-based mapping and geo-statistical analyses

GIS-based mapping techniques and statistical analyses were used to compare the landscapes of 1823 and 2010. Changes in the following parameters are seen as indicators for dam-related landscape changes:

a) River channel planform
b) Land use and land cover
c) Riparian woodland vegetation

Information on these parameters was obtained by evaluating cadastral maps, aerial photographs and hillshades of a Digital Elevation Model (DEM) for the time slices where information on the presence/absence of dams has been available, i.e. (i) 3-dam-scenario of 1823, (ii) 1-dam-scenario of 2010:

(i) 3-dam-scenario of 1823

Data source was the cadastral map of the "Land register of Francis I" which is a comprehensive cartographical and statistical documentation of the natural, economic and social circumstances in the Habsburg monarchy in the first half of the 19th century ("Land register of Francis I" 1823, BEV Austria, 2010). The cadastral map with a scale of 1:1,440 provides information on land use and land cover on a parcel basis distinguishing between built up areas (incl. transport routes), forests and woodland, grassland, water bodies, arable land (incl. vineyards) and the presence of riparian woodland vegetation (indicated by lines of single trees). These maps were digitized and geo-referenced in ArcGIS. *River channel planform* was mapped while in reservoirs where no information on river channel planform was available, a straight channel planform was assumed. *Land use and land cover* were mapped and classified delineating the following categories: arable land, grassland, forests and woodland, built up areas and water bodies.

(ii) 1-dam-scenario of 2010

River channel planform geometry was mapped in ArcGIS by interpreting a hillshade of a DEM with a resolution of 1 m x 1 m (data source: Provincial state government of Lower Austria, 2010). The results were corrected by applying aerial photograph interpretations using RGB-orthophotos with a resolution of 0.25 m x 0.25 m (data source: Provincial state government of Lower Austria, 2010). In reservoirs where no information on river channel planform was available, again a straight channel planform was assumed. *Land use and land cover* was mapped on a parcel scale using a parcel map in polygon format (data source: Provincial state government of Lower Austria, 2010). Based on the criterion of largest proportion, one of the above mentioned land use/land cover categories were assigned to each parcel polygon. Information on land use and land cover as well as on the presence of *riparian woodland vegetation* was derived by applying RGB-orthophoto interpretations. For further statistical analyses, land use and land cover data were converted into raster format (see section b).

Geo-statistical analyses were performed to assess and quantify the changes of the parameters *river channel planform geometry, land use and land cover,* and *riparian woodland vegetation* between 1823 and 2010. In order to spatially relate these changes to the influence of dams, the river polylines were segmented by cutting them on dam crests as well as on locations where the river enters the reservoir. This leads to two different categories of river segments, i.e. they are located (1) in a recent or former reservoir or (2) downstream of a recent or former dam crest (= upstream of a recent or former reservoir).

a) River channel planform geometry

The following parameters of the polyline layers were calculated and compared as they are understood as indicators for dam-induced channel changes: *channel length, channel sinuosity*. A decrease of channel length and sinuosity is related to channel straightening expected being caused by river engineering and is assumed to be a response of the human system to unintended dam-induced geomorphic effects. Furthermore, as straight channel planform had been assumed and mapped in river segments of former reservoir areas, no (!) channel planform changes between 1823 and 2010 are seen as an indicator for dam-induced human responses in terms of bank and/or bed protection measures to mitigate potential upstream geomorphic effects after dam removal. This is based on the assumption that if no such measures would have been built, at least slight channel migration would have occurred. Therefore, the absence of planform changes has been related to the presence of river bank and/or bed protection measures.

Channel lengths were evaluated for the whole river reach as well as for each river segment by using the calculate geometry tool in ArcGIS and *channel sinuosity* was calculated by utilizing the Line

Metrics Tool of Hawth's Analysis Tools Extension for ArcGIS (Beyer, 2004). Hereby, for each line, sinuosity *(S)* is calculated as follows:

$$S = Lt / Lsf \quad (1)$$

whereby *Lt* is the total length of the line, and *Lsf* is the distance between the start and finish locations.

b) Land use and land cover

Land use and land cover changes were evaluated for the total study area as well as for each river channel segment within a streamside buffer area of 25 m in order to spatially relate changes of land use and land cover to the influence of dams. This was done by applying Zonal Statistics in ArcGIS. Streamside buffers of 25 m were created on both sides of the river channel segments which approximately correspond to the extent of the natural floodplain area (Poeppl, 2010).

c) Riparian woodland vegetation

River channel line segments were further cut based on the presence/absence of *riparian woodland vegetation* and proportions were calculated for the total river reach as well as for each segment. An absence of riparian woodland vegetation is seen as an indicator for human responses in terms of structural engineering works to unintended dam-induced channel changes, since installation of such measures is generally accompanied by a clearance of riparian woodland vegetation (Brierley and Fryirs, 2005).

Landscape evolution modelling with CAESAR

The CAESAR Lisflood 1.2 landscape evolution model (freely available via http://www.coulthard.org.uk/CAESAR.html) was used to test the general assumptions about geomorphic responses of the fluvial system to dam construction (i) and dam removal (ii). CAESAR-Lisflood is a new hydrodynamic version of the CAESAR model, developed by Coulthard (1999) and Coulthard et al. (2007). CAESAR is a cellular model which allows the modelling of fluvio-geomorphological processes at fine-resolution temporal and spatial scales. It has been applied to fluvial catchments all over the world over 10^0 – 10^4 timescales, e.g. in the UK (Coulthard et al., 2002; 2005; 2007), in meandering reaches (Coulthard and Van De Wiel, 2006) and braided systems (Coulthard et al., 2007). A full description of CAESAR can be found in Coulthard and Macklin (2003) and Van De Wiel et al. (2007).

CAESAR is a numerical two dimensional flow and sediment transport model that simulates the evolution of landforms which are subject to fluvial and diffuse erosion and mass transport processes. In CAESAR, landscapes are represented with a regular mesh of grid cells of uniform size based on a DEM and the elevation of these cells is changed during model iterations to represent erosion and deposition. CAESAR-Lisflood has four main components – a hydrological model, a hydraulic model, fluvial erosion and deposition, and slope processes. CAESAR-Lisflood can operate over a reach or catchment with water added at a point(s) or determined from rainfall with the built-in hydrological model based on the TOPMODEL algorithm (Beven and Kirkby, 1979). Surface flow is then routed using an adaptation of the Lisflood-ACC 2D flow model (Bates et al., 2010; Neal et al., 2011) that generates flow depths and velocities across the DEM. From this, fluvial sediment transport is simulated over multiple grain sizes with either the Einstein-Brown (Einstein, 1950) or the Wilcock and Crowe (2003) bedload transport formula. This interacts with an "active layer" system that allows suspended sediment, bed armouring, selective transport and the development of stratigraphy (Van De Wiel et al., 2007). Bedrock depth can also be integrated as a DEM on the same

dimensions as the surface DEM and the model incorporates a basic soil creep and landslide model for slope processes.
For a given study site CAESAR-Lisflood's data requirements are a *DEM* of the area of interest, either rainfall data (Catchment mode) or water discharges (Reach mode), sediment particle distribution as well as a bedrock depth DEM if required. CAESAR-Lisflood can generate water and sediment outputs at any time interval from the catchment exit as well as elevation, surface grainsize and flow parameters.
CAESAR-Lisflood was used to simulate two different scenarios, a 3-dam-scenario of 1823 (dam construction) and a 1-dam scenario of 2010 (dam removal). The following sections detail how the model was set up for both.

(i) 3-dam-scenario of 1823 (dam construction)

DEM. A DEM of the whole catchment with a grid cell size of 10 m of 2010 was produced by resampling a DEM with 1 m x 1 m resolution in ArcGIS (data source: provincial state government of Lower Austria 2010) in order to speed up model run time. The DEM of the whole catchment was clipped to two different extents: a) *Catchment DEM*: catchment area of the most upstream dam which has been calculated by using the Watershed Tool of the Spatial Analyst in ArcGIS 10; b) *River reach DEM*: study river reach (dam-impacted river reach). River channels were mapped interpreting RGB-orthophotos with a resolution of 0.25 m x 0.25 m (data source: Provincial state government of Lower Austria 2010) and burnt in the DEM by subtracting 1 m. Information on average river channel depth (1 m) was obtained during field work in spring 2010 by using scaled measuring sticks. The *river reach-DEM* was adapted to the physiographic settings of 1823 based on the information which was obtained and mapped from the cadastral maps of the "Land register of Francis I" (see also 4.1), i.e. river channel planform, presence of dams and reservoirs. For this, the river channels inherent in the DEM of 2010 were filled and flat floodplain areas were created by applying interpolation within the streamside buffer area of 25 m. Reservoirs were introduced into the DEM by subtracting 3 m from the 2010 DEM in the mapped reservoir areas of 1823, as this depth approximately corresponds to the original reservoir depths in the study area (Poeppl 2010). In order to produce a balanced river gradient along free flowing river reaches (i.e. river reaches up- and downstream of reservoirs) channel elevation between known points were interpolated. Dam parts were filled to the original dam height according to information on original dam heights obtained from neighbouring residual dam parts that are still present in the landscape and hence in the river reach DEM.
Discharge (m^3/s). Water and sediment discharge arriving from the catchment area upstream of dam 1 were simulated by using CAESAR-Lisflood in catchment mode for the area above the study reaches. The upstream catchment was driven by hourly rainfall data which were available for a period of 10 years (2001 – 2010; data source: Hydrographischer Dienst Niederösterreich) from a rain gauge located close to the study catchment. In accordance with previous CAESAR applications (e.g. Hancock 2012) the model was run for several years prior to the period to be simulated in order to 'spin up' the catchment. This process is required as when a DEM is first run it usually contain small errors and sharp breaks in slope that CAESAR-Lisflood will erode – in effect a form of internal adjustment. After this spin-up the model was run for different time periods according to information derived from historical maps on the time spans in which dam construction/removal took place (Table. 1):

Table 1: Time spans of dam construction/removal; * information derived from a historical aristocratic map of 1782 (data source: Mathias Waldstein, 2011)

	Dam 1	**Dam 2**	**Dam 3**
Period of construction	≥ 1782*	≥ 1782*	≥ 1782*
Period of removal	1933 - 1966	-	1823 - 1911

Based on the information presented in Table 1, CAESAR was run in catchment mode for calculating water and sediment discharge for the following time spans which were then used as input data for the dam-impacted river reach to model the geomorphic consequences of dam constructions:

- -184 years (1782 – 1966): scenario referring to the max. time of existence of Dam 1
- 151 years (1782 – 1933): scenario referring to the min. time of existence of Dam 1
- 129 years (1782 – 1911): scenario referring to the max. time of existence of Dam 3
- 41 years (1782 – 1823): scenario referring to the min. time of existence of Dam 3

The input points for the discharge input data were chosen at the most upstream part of the river reach DEM.

Bedrock depth DEM (i.e. a DEM that defines depths at which no (more) vertical erosion is modelled). A bedrock depth DEM which contained information on bedrock depth and dam height was created and integrated into the modelling procedure. For this, every pixel of the whole River reach DEM except at dam locations was lowered by 11 m in ArcGIS. This results in a layer that allows vertical erosion within each cell in the landscape until potentially reaching bedrock depth except at dam locations where flow and sediment is modelled across the dam crest which corresponds to the construction type of these overflow dams. Information on bedrock depth was derived from drilling data performed in alluvial deposits along the study area river reach (data source: Austromineral, 1981).

Sediment particle distribution. Sediment particle size data were obtained from river bed sediment samples and soil samples in spring 2010 (Poeppl, 2010) and then combined to represent the full range of sediment grain sizes present in the system. Core samples were taken from a sediment bar in a river reach which has been unaffected by backwater as well as from soils adjacent to the river channel. Particle size distributions were determined by using sieving and sedigraph analysis utilising a Micrometrics Sedigraph III and further classified into nine average particle sizes to fit the input requirements of CAESAR (see Table 2) of which the finest fraction represents sediments in suspension. For the finest fraction (suspended load) an average grain size of the soil samples of 20 microns was calculated and used as an input parameter. For the suspended sediments a fall velocity of 0.000327m/s was calculated according to Stokes' settling equation and used as input parameter within the sediment tab of CAESAR. The other fractions (bedload) were derived from the river bed sediment sample analyses (see also Table 2).

Table 2: River sediment particle size (% by mass) as input to CAESAR (Data source: Poeppl, 2010)

Size (mm)	**0.02 (suspended)**	**0.1315**	**0.415**	**1.315**	**3**	**6**	**12**	**23.75**	**60**
% by mass	30	2.4	8.1	16.8	17.1	16.7	6.9	1	1

The model results for the different time spans were validated based on the modeled amount of sediment accumulation within the reservoirs of dams 1 and 3 by comparing the calculated values with the DEM data of 2010. For this, elevation differences between the elevation output files ('elev') of each time span scenario and the DEM of 2010 file were calculated by subtraction using the Raster Calculator function in ArcGIS. Mean elevation difference in meters and number of pixels within each reservoir were calculated using the Zonal Statistics ++ Tool of Hawth's Analysis Tools Extension for

ArcGIS (Beyer, 2004). Based on this information, sediment volume difference in m^3 between each time span scenario and the DEM data of 2010 were calculated.
The model output DEM of the best fitting time-span scenario, i.e. the model output with the smallest mean elevation difference in meters and sediment volume difference in m^3 compared to the elevation data of 2010 was then used as river reach DEM for modelling the geomorphic consequences of dam removal in reach mode (see section ii). To calculate net sediment balance for the whole river reach, mean sediment input rates were compared with mean sediment output rates for each grain size class. In order to quantify geomorphic changes in the river channels and reservoirs due to dam constructions, the mean elevation difference and sediment volume difference in m^3 between the output DEM of the best fitting time-span scenario and the input DEM of 1823 were calculated for each river segment. For linear river segments (i.e. no reservoir or areal extension), the Line Raster Intersection Statistics Tool of Hawth's Analysis Tools Extension for ArcGIS (Beyer, 2004) was utilized, while for reservoir areas and areal extensions of the river channels the Zonal Statistics ++ Tool of Hawth's Analysis Tools Extension for ArcGIS (Beyer, 2004) was applied. Based on this information, sediment volume difference in m^3 between best fitting time-span scenario and the input DEM of 1823 were calculated.

(ii) 1-dam scenario of 2010 (dam removal)

River reach DEM. After model validation, dams 1 and 3 were removed from the best fitting elevation output file *'elev'* of the dam-construction scenario in ArcGIS according to the elevation information of the original DEM of 2010 and further used as the river reach DEM for dam-removal scenario modelling.
Bedrock depth DEM. The bedrock depth DEM of the dam construction scenario was adapted to the conditions of 2010 and dams 1 and 3 were removed in ArcGIS according to the elevation information of the original DEM of 2010 and used as the bedrock depth DEM for dam-removal scenario modelling.
Discharge (m^3/s). *Sediment particle distribution*. The same discharge input data, input locations and sediment particle distribution parameters were used for dam-removal scenario modelling as for the dam construction scenario.
To simulate general geomorphic consequences of dam removals in the study river reach, the model was run for a period of 44 years, since the last dam removal took place at the latest in year 1966 (see also Table 1). Since between 1823 and 2010 structural engineering works took place along most river reaches (see next chapter), quantitative model validation of dam-removal-induced geomorphic consequences was not possible. To calculate net sediment balance for the whole river reach, mean sediment input rates were compared with mean sediment output rates. In order to quantify geomorphic changes in the river channels and former reservoir areas due to dam removals, the mean elevation difference and sediment volume difference in m^3 between the output DEM scenario and the input DEM of the dam removal were calculated for each river segment applying the same method as described in (i).

Field surveys
Field surveys were performed in spring 2010 to assess the presence and spatial occurrence of *river engineering structures* within each river channel line segment. As river bed and bank protection works are generally built to mitigate unintended dam-induced geomorphic effects, they are seen as indicators for human responses to geomorphic system responses and for interactions between the human system and the fluvial system. If such measures had been detected in the downstream reaches of active dams or in abandoned reservoirs, they were related to dam-induced geomorphic effects.

Results and discussion

GIS-based mapping and geo-statistical analyses

GIS-based mapping applied to assess dam-induced landscape changes resulted in the examination of significant alterations of *river channel planform, land use and land cover,* and *riparian woodland vegetation* between the (i) 3-dam-scenario of 1823 (see Fig. 5) and the (ii) 1-dam-scenario of 2010 (see Fig. 6). The segmentation of river polylines intended to spatially relate changes of the parameters *river channel planform, land use and land cover, riparian woodland vegetation* between 1823 and 2010 to the influence of dams resulted in the delineation of 7 segments of two different types (see also Fig. 5, 6):

(1) Location in a recent or former reservoir: i.e. segments 2, 4, 6
(2) Location downstream of a recent or former dam crest (= upstream of a recent or former reservoir): i.e. segments 1, 3, 5, 7

The results of the geo-statistical analyses performed to quantify the changes of the parameters mentioned above and to relate them to the presence of dams are presented in the following sections (a) – c)).

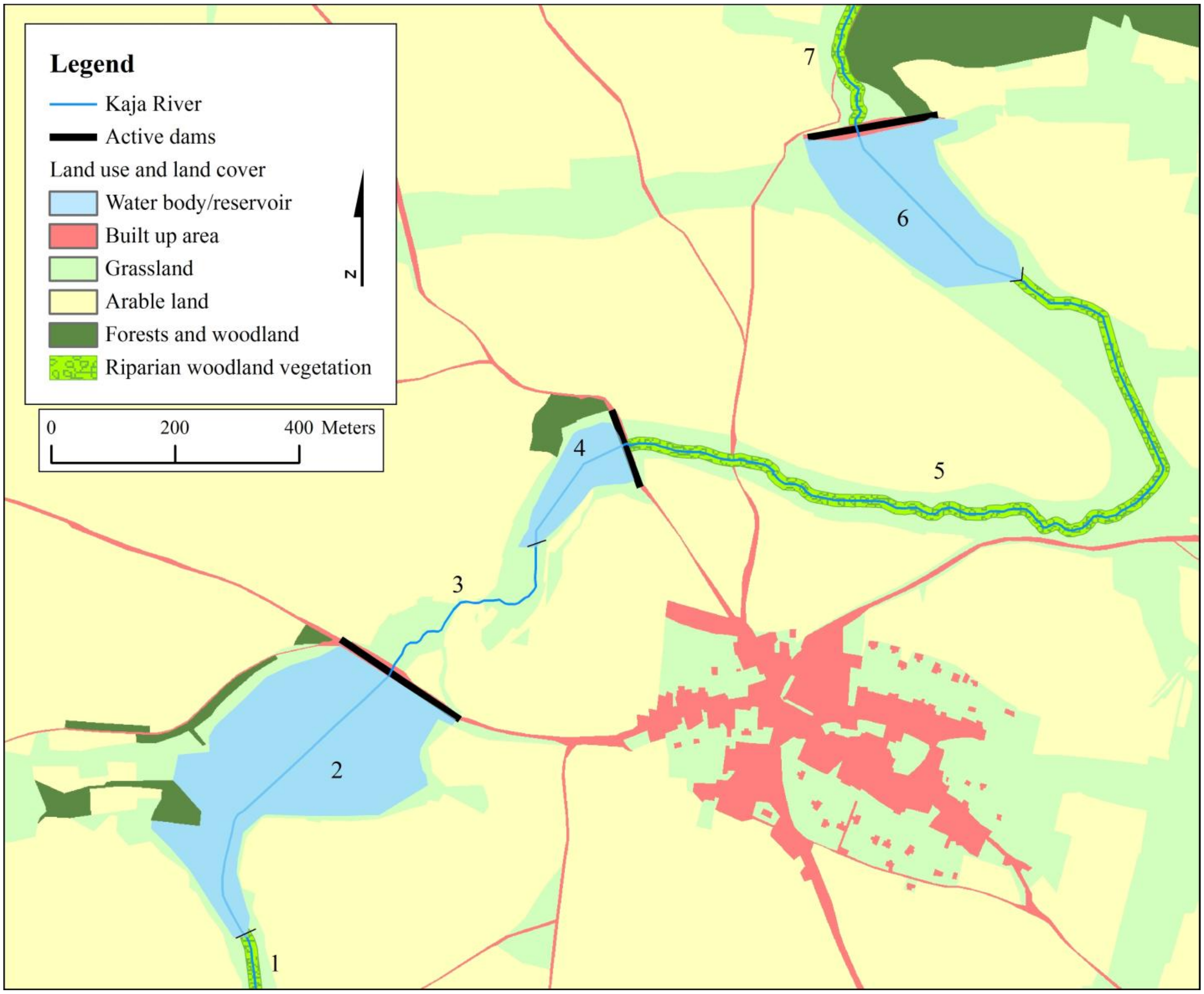

Fig. 5: 3-dam-scenario of 1823 showing land use and land cover conditions 1823 including information on river channel planform and the presence of riparian woodland vegetation and dams. River segments are numbered in flow direction.

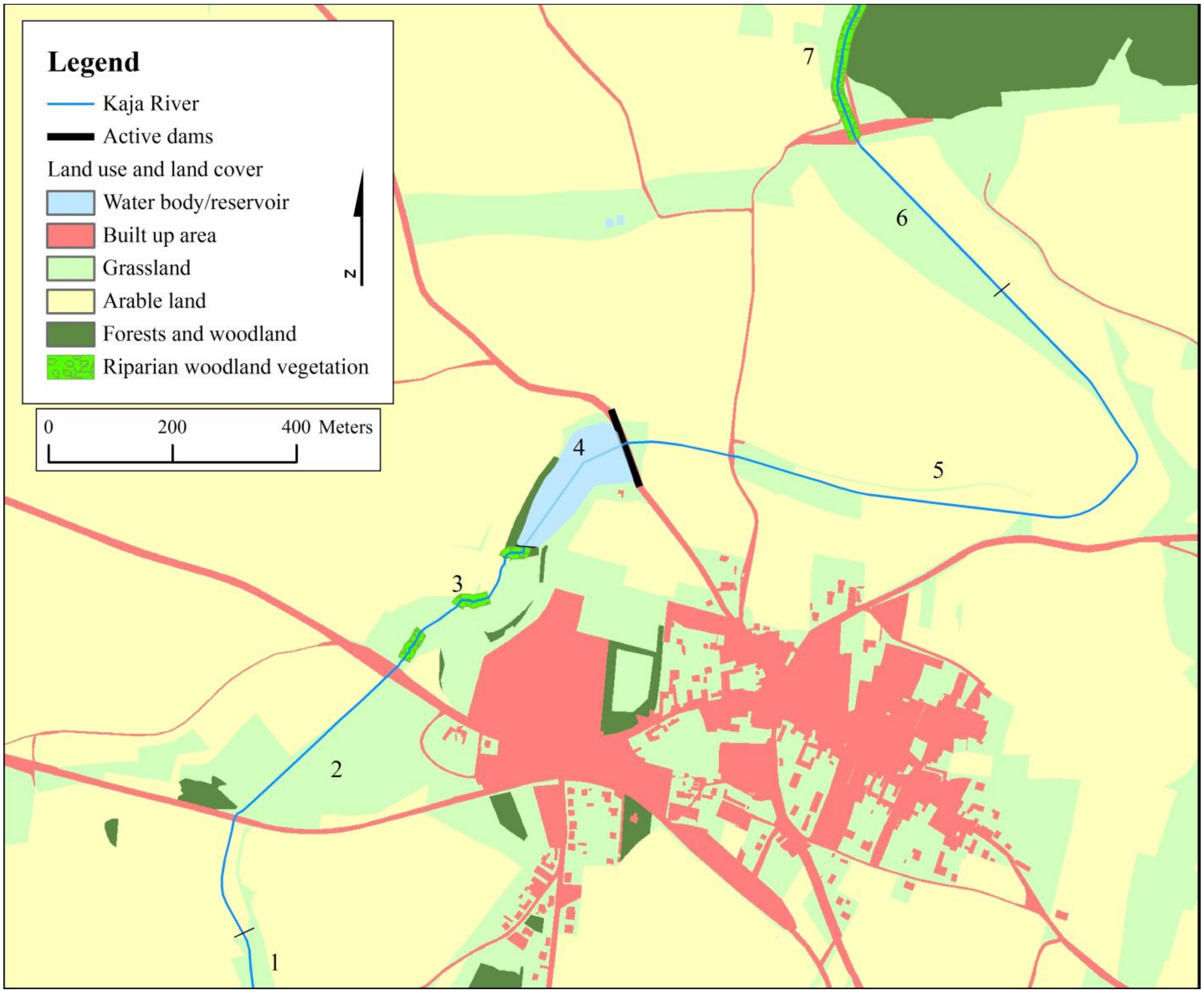

Fig. 6: 1-dam-scenario of 2010 showing land use and land cover conditions 2010 including information on river channel planform and the presence of riparian woodland vegetation and dams. River segments are numbered in flow direction.

a) River channel planform

Between 1823 and 2010, *channel length* and *channel sinuosity* decreased in segments located downstream of a recent or former dam crest (= upstream of a recent or former reservoir), i.e. segments 1, 3, 5, 7, while no changes were observed in segments located in a recent or former reservoir, i.e. segments 2, 4, 6 (see Table 3, 4). These findings reveal channel straightening and suggest the presence of river engineering works resulting from dam-induced human responses to unintended geomorphic responses such as channel degradation downstream of active dams and channel degradation upstream of abandoned dams.

Table 3: River channel lengths and river channel length changes between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams.

Length in m (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	3410.2	152.8	549.2	371.1	231.9	1379.2	369.9	356.1
2010	3177.9 (-6.8)	149.1 (-2.4)	549.2 (0)	322.2 (-13.2)	231.9 (0)	1224.0 (-11.3)	369.9 (0)	331.7 (-6.9)

Table 4: River channel sinuosity and river sinuosity changes between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams.

Sinuosity (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	1.724	1.007	1.125	1.204	1.058	1.995	1.028	1.195
2010	1.604 (-7.0)	1.005 (-0.2)	1.125 (0)	1.103 (-8.3)	1.058 (0)	1.860 (-6.8)	1.028 (0)	1.111 (-7.1)

b) Land use and land cover

Between 1823 and 2010, major land use and land cover changes occurred within the streamside buffer area of 25 m, while only minor changes took place in the total study area (see Table 5). Within the streamside buffer area, water bodies decreased by 25% due to dam removal, while arable lands strongly increased (+41%). Grasslands decreased by 19% and built up as well as forested and woodland areas slightly increased (+1%).

Besides the conversion of water bodies in areas of former reservoirs to mainly grasslands and arable lands (i.e. segments 2, 6), a significant shift from grassland to arable land use took place in the downstream reaches of the currently active dam (i.e. segment 5), whereas only minor changes occurred downstream of removed dams (i.e. segments 3, 7). As the streamside buffer area approximately corresponds to the extent of the natural floodplains which are subject to geomorphic change, it is interpreted that the presence of arable lands within these areas is made possible by the installation of river bed and/or bank protection structures.

Table 5: Land use and land cover conditions and changes between 1823 and 2010, calculated for the total study area ("TSA") and the total streamside buffer area ("B 25", "Total") as well as for the streamside buffer area of each river segment ("B 25", "Seg."). Land use and land cover categories ("LU/LC") are abbreviated as follows: "WB" (Water bodies), "BA" (Built up areas), "GL" (Grassland), "AL" (Arable land), and "FW" (Forests and woodland). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams.

		Land use/land cover 1823 in %					**Land use/land cover 2010 in % (change in % 1823 - 2010)**				
	LU/LC	WB	BA	GL	AL	FW	WB	BA	GL	AL	FW
TSA	**Total**	4	4	16	72	4	1 (-3)	8 (+4)	16 (0)	71 (-1)	4 (0)
B 25	**Total**	32	2	60	4	2	7 (-25)	3 (+1)	41 (-19)	45 (+41)	3 (+1)
	Seg. 1	0	0	97	3	0	0 (0)	0 (0)	90 (-7)	10 (+7)	0 (0)
	Seg. 2	94	2	4	0	0	0 (-94)	5 (+3)	46 (+42)	48 (+48)	1 (+1)
	Seg. 3	0	3	73	24	0	0 (0)	3 (0)	70 (-3)	20 (-4)	6 (+6)
	Seg. 4	92	3	5	0	0	92 (0)	3 (0)	0 (-5)	0	5 (+5)
	Seg. 5	0	1	95	4	0	0 (0)	1 (0)	26 (-69)	73 (+69)	0 (0)
	Seg. 6	93	3	4	0	0	0 (0)	4 (+1)	51 (+47)	45 (+45)	0 (0)
	Seg. 7	0	6	72	1	21	0 (0)	11 (+5)	64 (-8)	5 (+4)	20 (-1)

c) Riparian woodland vegetation

Riparian woodland vegetation decreased in the total river reach from 51% to 15%. Especially the river segment located downstream of the active dam in 2010 (i.e. segment 5) was affected by clearance of riparian woodland vegetation cover (see Table 6), while no clearance occurred in river segments downstream of abandoned dams (i.e. segments 3, 7). No woodland vegetation was present in segments located in former reservoir areas (i.e. segments 2, 6), while 47 % (re)established in segment 3 (= downstream of an abandoned dam). As the absence of riparian vegetation is seen as an indicator for the presence of structural engineering works, the findings suggest dam-induced human responses to unintended geomorphic responses such as channel degradation downstream of the active dams and channel degradation in abandoned reservoirs. Furthermore, as continued existence or re-establishment of riparian woodland vegetation only took place in segments where no significant agriculturalization occurred (i.e. segments 3, 7) (see also Table 5) an absence of river engineering structures and therefore no human response to dam-induced geomorphic effects is expected.

Table 6: Proportions and changes of riparian woodland vegetation ("RWV") between 1823 and 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams.

RWV in % (change in %)	**Total**	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
1823	51	100	0	0	0	100	0	100
2010	15 (-36)	0 (-100)	0 (0)	47 (+47)	0 (0)	0 (-100)	0 (0)	100 (0)

Landscape evolution modelling with CAESAR

(i) 3-dam-scenario of 1823 (dam construction)

The validation of the model outputs resulted in the delineation of the 184-year-scenario as being the best fitting time-span scenario, since exhibiting the smallest mean elevation difference in meters (-0.88/-1.2) and sediment volume difference in m^3 (-87,296/-59,880) compared to the elevation data of 2010 (see Table 7). The output DEM of the 184-year-scenario showed reasonable results and was therefore used as input DEM for the 1-dam-scneario (dam removal) model. However, it has to be stated that the modeled sediment accumulation in the reservoirs resulted in a mean elevation which is still significantly less than in the DEM of 2010. This may be due to many reasons ranging from underestimated water and sediment inputs or underestimated erosion and deposition rates during the modeling procedure to underestimated dam ages or post-dam (human-induced) sediment infilling of the abandoned reservoirs.

Table 7: Model validation of the 3-dam-scenario (dam construction) outputs

	Mean elevation difference in m/sediment volume difference in m^3	
Time-span scenario	**Reservoir: dam1**	**Reservoir: dam3**
184ys	-0.88 / -87,296	-1.2 / -59,880
151ys	-1.12 / -111,104	-1.22 / -60,878
129ys	-1.33 / -131,936	-1.24 / -61,876
41ys	-2.68 / -265,856	-1.37 / -67,365

The calculation of net sediment balance of the 184year-3-dam modelling scenario exhibited that only 5% of the total amount of input sediments exited the system. This implies a net sediment loss of 95% along the whole river reach and all grain sizes fractions except the finest (suspended) and coarsest were retained to a similar extent of app. 96 - 97% (see Table 8). Less retention of suspended sediments is interpreted to be related to a continuous transport of a distinct amount across the dam crests. Less retention rates of the coarsest sediments could be related to erosion and detachment of coarse sediment from the river bed occurring downstream of dam 3 just before exiting the system (see Fig. 7).

Table 8: Net sediment balance of the 184year-3-dam-scenario (dam construction) in total and for each particle size

Particle grain size in mm	**0.02 (suspended)**	**0.1315**	**0.415**	**1.315**	**3**	**6**	**12**	**23.75**	**60**	**Total**
Input-output difference in %	-91.2	-97.4	-97.4	-97.4	-97.3	-97.1	-96.8	-96.1	-87	-95

Fig. 7 shows the modelled elevation differences in meters of the 184year-3-dam modelling scenario, and a quantification of geomorphic changes in the river channels and reservoirs due to dam constructions for each river segment is presented in Table 9. In all segments upstream of dams, sediment net deposition occurred, while in all segments downstream of dams net erosion was observed which confirmed our overall assumption about geomorphic responses to dam construction (see also Fig. 1a). Deposition in the reservoirs showed the pattern of a fan or delta which evolved in downstream direction over time. Along the whole river reach, 248,247 m^3 of sediment were deposited with the highest amount in segment 2 upstream of dam 1 (85%). Since this dam is the first within a series of three dams, it thus retained most of the sediment entering the system. 31,907 m^3 of sediment were eroded in total. Highest erosion rates were modelled for segment 5 downstream of dam 2 (52.8%). This high value compared to segment 3 (18.1%) is interpreted to be caused by a bigger distance to upstream effects of subsequent dams which thus allows for erosion over a longer channel distance. More sediment was deposited than eroded between dam 1 and 2 (38.8%) as well as between 2 and 3 (20.8%). This indicates that most of the sediments eroded downstream of dams 1 and 2 are deposited in the subsequent reservoirs and the adjacent upstream reaches. However, this also implies a significant amount of sediment input from upstream and that material is transported across the crests of upstream dams which is then deposited in the subsequent reservoirs and the adjacent upstream river reaches.

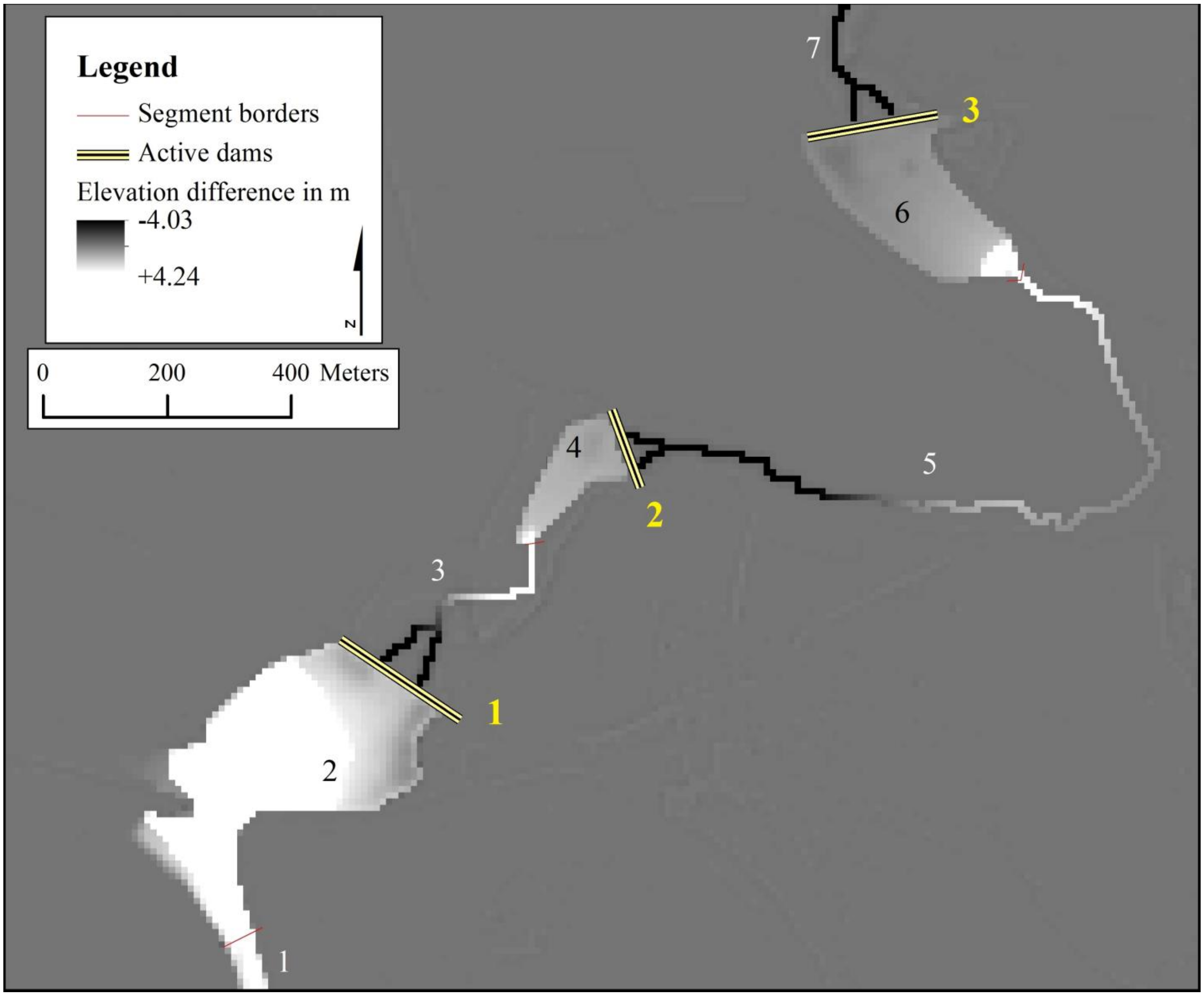

Fig. 7: Model output (elevation difference in m) of the 184year-3-dam modelling scenario (dam construction); river segments are numbered in black or white, active dams are labelled in yellow

Table 9: Quantification of geomorphic changes in the river channels and reservoirs due to dam constructions for the 184year-3-dam modelling scenario (dam construction); bold lines indicate presence and location of active dams.

	Erosion (mean elevation difference in m/ sediment volume difference in m^3 (% of total))	**Deposition (mean elevation difference in m/ sediment volume difference in m^3 (% of total))**	**Difference deposition/erosion (mean elevation difference in m/ sediment volume difference in m^3)**
Seg. 1	-	1.61 / 6,111 (2.5)	1.61 / 6,111
Seg. 2	-	2.02 / 208,423 (85)	2.02 / 208,423
Seg. 3	1.37 / 5,765 (18.1)	1.08 / 3,141 (1.3)	0.29 / 2,624
Seg. 4	-	0.42 / 6,284 (2.5)	0.42 / 6,284
Subtotal (in m^3)	5,765	9,425	3,660 (38.8%)
Seg. 5	2.7 / 16,858 (52.8)	0.44 / 8,041 (3.3)	2.26 / 8,817
Seg. 6	-	0.29 / 13,247 (5.4)	0.29 / 13,247
Subtotal (in m^3)	16,858	21,288	4,430 (20.8%)

Seg. 7	1.87 / 9,284 (29.1)	-	1.87 / 9,284
Total (in m^3)	31,907	245,247	213,340

(ii) 1-dam scenario of 2010 (dam removal)

The calculation of net sediment balance of the 44year-1-dam modelling scenario exhibited that 99.1% of the total amount of input sediments exited the system which implies a net loss of sediment along the whole river reach of 0.9%. All grain sizes fractions except the finest (suspended) were retained by a similar extent of app. 96 - 99%. 66% more amount of suspended sediment exited than entered the system. This may be due to high deposition rates in segment 7 where most coarse sediments were deposited before exiting the system, while the suspended sediments were potentially transported across this depositional area (see Fig. 8).

Table 10: Net sediment balance of the 44year-1-dam-scenario (dam removal) in total and for each particle size

Particle grain size in mm	**0.02 (suspended)**	**0.1315**	**0.415**	**1.315**	**3**	**6**	**12**	**23.75**	**60**	**Total in m^3**
Input-output difference in %	+66.1	-95.4	-95.7	-96.1	-96.6	-97.6	-98.9	-97.6	-97.1	-0.9

Fig. 8 shows the modelled elevation differences in meters of the 44year-1-dam modelling scenario, and a quantification of geomorphic changes in the river channels and reservoirs due to dam removal for each river segment is presented in Table 11. In all segments downstream of removed dams net deposition was observed which confirmed our overall assumption in terms of geomorphic responses to dam removal (see also Fig. 1b). Nevertheless, in the abandoned reservoir of dam 1 (segments 1 and 2) net erosion occurred while in the abandoned reservoir of dam 3 slight net deposition was observed. Along the whole river reach 91,790 m^3 of sediment were eroded with the highest amount in segment 2 upstream of removed dam 1 (57.3%), followed by segment 5 (35.7%) downstream of active dam 2. Extensive headward erosion in segment 5 is further interpreted to have caused net deposition in the abandoned reservoir of dam 3 (segment 6) instead of net erosion with time due to upstream sediment input from this river reach. 70,422 m^3 of sediment were deposited within the whole river reach in total. Highest deposition rates were modelled for segment 4 upstream of the still active dam 2 (49.2%) followed by segment 7 (31.9%) downstream of removed dam 3 and segment 3 upstream of segment 4 (15%), while only 3.9% were deposited in segment 6 (former reservoir of dam 3). 23.4% more sediment was eroded upstream of removed dam 1 than deposited upstream of the active dam 2 which implies that a significant amount of sediment input from upstream is transported across the dam crest potentially enhanced by the total infilling of segments 3 and 4.

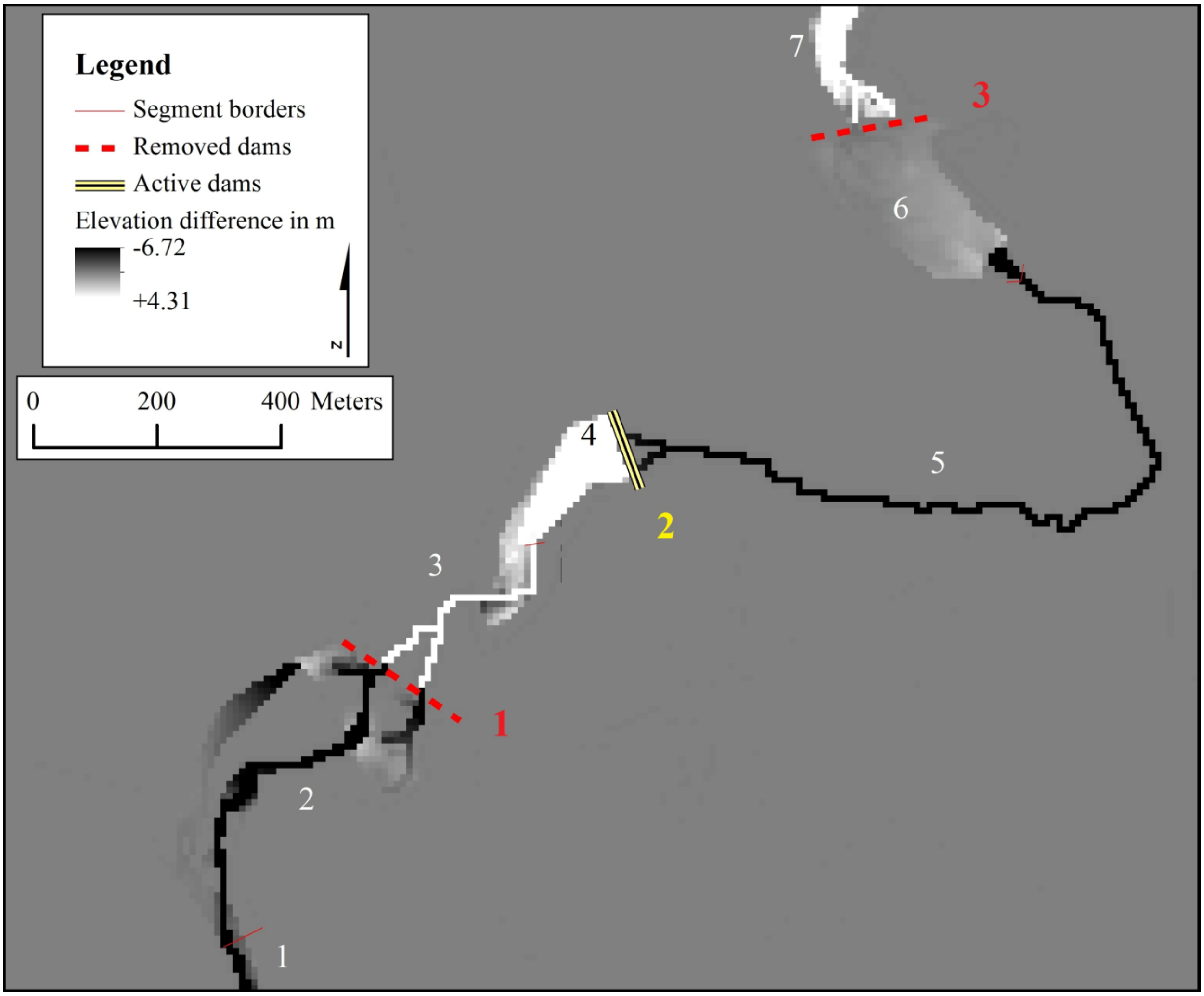

Fig. 8: Model output (elevation difference in m) of the 44year-1-dam-modelling-scenario (dam removal); river segments are numbered in black or white, active dams are labelled in yellow, removed dams in red

Table 11: Quantification of geomorphic changes in the river channels and reservoirs due to dam removals for the 44year-1-dam modelling scenario (dam removal); bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams.

	Erosion (mean elevation difference in m/ sediment volume difference in m³ (% of total))	**Deposition (mean elevation difference in m/ sediment volume difference in m³ (% of total))**	**Difference deposition/erosion (mean elevation difference in m/ sediment volume difference in m³)**
Seg. 1	2.01 / 6,440 (7.0)	-	2.01 / 6,440
Seg. 2	0.53 / 52,583 (57.3)	-	0.53 / 52,583
Seg. 3	-	0.66 / 10,547 (15.0)	0.66 / 10,547
Seg. 4	-	1.16 / 34,676 (49.2)	1.16 / 34,676
Subtotal (in m³)	59,023	45,223	13,800 (23.4%)
Seg. 5	1.03 / 32,767 (35.7)	-	1.03 / 32,767
Seg. 6	-	0.06 / 2,724 (3.9)	0.06 / 2,724
Seg. 7	-	1.81 / 22,475 (31.9)	1.81 / 22,475
Subtotal	32,767	25,199	7,568 (23.1%)

(in m^3)			
Total (in m^3)	91,790	70,422	21,368

Field surveys

The results of the field surveys revealed that 82% of the total river reach were engineered by installing river bed and/or bank protection measures (see Fig. 9, Table 12), including all segments except segments 4 (= active reservoir area) and 3. Since segment 3 was the only one where no agriculturalization occurred (see also Table 4), it is interpreted that no engineering was necessary in these reaches since no infrastructures were present that would have needed protection. However, segment 7 had been engineered although dam removal as well as no agriculturalization took place. A possible reason could be that river engineering structures were already installed before the dam was removed. In all segments except segment 7, the installation of river bed and/or bank protection measures was accompanied by riparian woodland vegetation clearance. Possible reasons for the presence of riparian woodland vegetation in segment 7 are that the installation of river engineering structures was not accompanied by clearance at all or that a re-establishment of riparian woodland vegetation after clearance has made possible since no significant agriculturalization occurred in the floodplains. In order to test these hypotheses, further investigations such as tree ring analysis for age determination of riparian woodland vegetation need to be performed. In Table 12 river bed and/or bank protection works were related to dam-induced erosion processes which were examined in the course of landscape evolution modelling. Except in segment 6, in every segment where erosion processes were modelled, either induced by dam construction or dam removal, human responses in terms of river bed and bank engineering were observed in the field.

Fig. 9: River reaches with bed and/or bank protection structures in 2010 including information on the presence of dams and reservoirs in 1823 and 2010. River segments are numbered in flow direction. Data source (aerial photographs): Provincial state government of Lower Austria 2010. Information on reservoir locations in 1823 has been derived from the "Land register of Francis I" 1823 (data source: BEV Austria, 2010).

Table 12: Proportions of the occurrence of river bed and bank protection structures ("RBBP") 2010, calculated for the total river reach ("Total") and for each river segment ("Seg."). Bold lines indicate presence and location of an active dam, while dashed lines refer to abandoned dams. River bed and/or bank protection works were related to dam-induced erosion processes which were examined in the course of landscape evolution modelling (indicated by an "X").

	Total	**Seg. 1**	**Seg. 2**	**Seg. 3**	**Seg. 4**	**Seg. 5**	**Seg. 6**	**Seg. 7**
RBBP in %	82	100	100	0	0	100	100	100
Net erosion due to dam construction or removal		X	X			X		X

Synopsis and conclusions

The present work focussed on the investigation of interactions and feedbacks between the human system and the fluvial system and derived potential reasons for landscape change by applying a combination of GIS-based mapping techniques, geo-statistical analyses, numerical landscape evolution modeling and field surveys. The aims of this study were (i) to compare a dam-impacted river reach regarding land use/land cover and river planform geometry at two points in time, (ii) to model dam-induced geomorphic channel changes considering and to relate them to aspects of dam-induced interactions between the fluvial and the human system between these points in time. It was hypothesized and conceptualized that human impact on fluvial systems in terms of dam construction leads to an interconnection of the human system and the fluvial system by triggering a series of process-response feedback loops between them which influence landscape changes in fluvial environments.

The results of the CAESAR landscape evolution modelling indicated that dam construction caused significant geomorphic channel responses in terms of downstream channel degradation and upstream aggradation along the whole study reach. Most aggradation occurred upstream of dams 1 and 3 which led to a shallowing of these reservoirs and their backwater reaches due to continuous retention of sediment supplied by the river. Since the reservoirs in the study area were used for fish farming it is interpreted that due to shallowing these reservoirs did not fulfill their intended purpose of providing social and economic benefits anymore which further induced human response in terms of dam removal. The results of the field surveys revealed that river bed and bank engineering works were installed along all river reaches downstream of dams. Therefore, these mitigation measures are interpreted to be related to river degradation downstream to prevent from negative effects on human infrastructure. After dam removal, further geomorphic channel responses have been modelled with CAESAR exhibiting degradation upstream and aggradation downstream of the removed dams. Field surveys revealed that river bed and bank engineering works were installed along river reaches upstream of the removed dams which are thus interpreted to be related to river degradation induced by dam removal utilized to mitigate from negative effects on human infrastructure (e.g. loss of arable land).

GIS-based mapping and geostatistical analyses exhibited significant landscape changes in the fluvial environment between 1823 and 2010 which were related to dam-induced geomorphic channel changes and the associated human responses. In the river reaches where river engineering structures were installed channel straightening, clearance of riparian woodland vegetation as well as significant land use changes were observed in the floodplain areas of regulated river reaches. Therefore, we conclude that in the investigated system dam construction led to an interconnection of the human system and the fluvial system by triggering feedback loops between them. These feedback loops have been characterized by a series of dam-induced geomorphic and human responses which were shown to influence landscape changes in the fluvial environment. We further conclude that these results underline the notion that causes of landscape change cannot be fully understood by analysing human and landscape systems in isolation and that therefore approaches which focus on interactions and feedbacks between them.

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References

Al-Taiee TM. 1990. The influence of a dam on the downstream degradation of a river bed: case study of the Tigris River. Hydrology in Mountainous Regions, II – Artificial Reservoirs, Water and Slopes (Proceedings of two Lausanne Symposia, August 1990). IAHS Publ. no. 194, 1990

Austromineral 1981. Kaolinpropektion im Raum Retz, N.Ö. Endbericht 1981 über Durchführung von Kernbohrungen und abschließende Projektbeurteilung, Bohrung Niederfladnitz 4/80. Unveröffentlichter Bericht für Bundesministerium Wissenschaft und Forschung, Land Niederösterreich, 108 pp.

Bates PD, Horritt MS, Fewtrell TJ. 2010. Simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology* **387**: 33–45

Bennett D, McGinnis D. 2007. Coupled and complex: Human-environment interaction in the Greater Yellowstone Ecosystem, USA. *Geoforum* **39**: 883-845
Beven K, Kirkby MJ. 1979. A physically based contributing area model of basin hydrology, *Hydrological Science Bulletin* **24**: 43–69

Beyer H.L. 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools

Brierley G, Fryirs K, Vikrant J. 2006. Landscape connectivity: the geographic basis of geomorphic applications. *Area* **38(2)**: 165-174

Brierley GJ, Fryirs KA. 2005. Geomorphology and River Management. Blackwell.

Burroughs BA, Hayes DB, Klomp KD, Hansen JF, Moitak J. 2009. Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States. *Geomorphology* **110**: 96-107

Bushaw-Newton KL, Egan J, Ashley JT, Johnson TE, Horwitz RJ, Keeley M, Lawrence J, Charles D, Gatenby C, Kreeger DA, Thomas RL, Velinsky DJ, Hart DD, Pizzuto JE, Thompson JR. 2002. An Integrative Approach Towards Understanding Ecological Responses to Dam Removal: The Manatawny Creek Study. *Journal of the American Water Resources Association* **38**: 1581-1599

Charlton R. 2008. Fundamentals of Fluvial Geomorphology. Routledge.

Committee on Global Change Research 1999. Global Environmental Change: Research Pathways for the Next Decade. National Academy Press, Washington, DC.

Coulthard TJ, Hicks DM, Van De Wiel MJ. 2007. Cellular modelling of river catchments and reaches: advantages, limitations and prospects. *Geomorphology* **90**: 192–207.

Coulthard TJ, Van de Wiel MJ. 2006. A cellular model of river meandering. *Earth Surface Processes and Landforms* **31**: 123–32

Coulthard TJ, Lewin J, Macklin MG. 2005. Modelling differential catchment response to environmental change. *Geomorphology* **69**: 222–41

Coulthard TJ, Macklin MG, Kirkby MJ. 2002: A cellular model of Holocene upland river basin and alluvial fan evolution. *Earth Surface Processes and Landforms* **27**: 269–88.

Coulthard TJ. 1999. Modelling upland catchment response to Holocene environmental change. PhD Thesis, School of Geography, University of Leeds, 181 pp.

Dudgeon D. 2005. River rehabilitation for conservation of fish biodiversity in monsoonal Asia. *Ecology and Society* **10**: 15. http://www.ecologyandsociety.org/vol10/iss2/art15/

Einstein HA. 1950. The bed-load function for sediment transportation in open channel flows. *USDA Soil Conservation Service Technical Bulletin* **1026**: 71.

Fang HW, Rodi W. 2003. Three-dimensional calculations of flow and suspended sediment transport in the neighborhood of the dam for the Three Gorges Project (TGP) reservoir in the Yangtze River. *Journal of Hydraulic Engineering* **41**: 379–394

Fassnacht H, McClure EM, Grant GE, Klingeman PC. 2003. Downstream effects of the Pelton-Round Butte hydroelectric project on bed load transport, channel morphology, and channel-bed texture, lower Deschutes River, Oregon. *Water Science and Application* **7**: 175–207

Fryirs KA, Brierley GJ, Preston NJ, Kasai M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena* **70(1)**: 49-67

Geist HJ, Lambin EF. 2001. What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational scale case study evidence. LUCC Report Series No. 4. University of Louvain, Louvainla- Neuve.

Gergel SE, Turner MG, Miller JR, Melack JM, Stanley EH. 2002. Landscape indicators of human impacts to riverine systems. *Aquatic Sciences* **64**: 118-128

Gordon ND, McMahon TA, Finlayson BL, Gippel CJ, Nathan RJ. 2004. Stream Hydrology: An Introduction for Ecologists. John Wiley & Sons, Chichester.

Grant GE, Schmidt JC, Lewis SL. 2003. A Geological Framework for Interpreting Downstream Effects of Dams on Rivers. *Water Science and Application* **7**: 209-225

Graf WL. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology* **79**: 336-360

Gregory KJ. 1995. Human activity and palaeohydrology. In: Gregory KJ, Starkel L, Baker VR (eds.): Global Continental Palaeohydrology. John Wiley & Sons, Chichester; 151–172

Gregory KJ. 2006. The human role in changing river channels. *Geomorphology* **79**: 172–191

Gumiere SJ, Le Bissonnais Y, Raclot D, Cheviron B. 2010. Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: a review. *Earth Surface Processes and Landforms* **36**: 3-19

Hancock GR, Coulthard TJ. 2012. Channel movement and erosion response to rainfall variability in southeast Australia. *Hydrological Processes* **26**: 663-673

Harrison A. 1950. Report on special investigation of bed sediment segregation in a degrading bed. *California Institute of Engineering Research Series* **33**: 1

Heppner CS, Loague K. 2008. A dam problem: simulated upstream impacts for a Searsville-like watershed. *Ecohydrology* **1**: 408-424

Holling CS. 2001: Understanding the complexity of economic, ecological and social systems. *Ecosystems* **4**: 390–405

Hooke RL. 2000. On the history of humans as geomorphic agents. *Geology* **28**: 843–846

James LA, Marcus WA. 2006. The human role in changing fluvial systems: Retrospect, inventory and prospect. *Geomorphology* **79 (3-4)**: 152–171

Keiler M. 2004. Development of the damage potential resulting from avalanche risk in the period 1950-2000, case study Galtür. *Natural Hazards and Earth System Sciences* **4 (2)**: 249–256

Keiler M, Sailer R, Jörg P, Weber C, Fuchs S, Zischg A, Sauermoser S. 2006. Avalanche risk assessment – a multi-temporal approach, results from Galtür, Austria. *Natural Hazards and Earth System Sciences* **6 (4)**: 637–651

Kondolf GM, Swanson ML. 1993. Channel adjustments to reservoir construction and instream gravel mining, Stony Creek, California. Environmental Geology and *Water Science* **21**: 256–269

Kondolf GM. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* **21(4)**: 533-551

Lagasse PF. 1994. Variable response of the Rio Grande to dam construction, In: Schumm SA, Winkley BR (eds.): The variability of large alluvial rivers, American Society of Civil Engineers Press, New York; 395–420

Lajczak A. 1996. Modeling the long-term course of non-flushed reservoir sedimentation and estimating the life of dams. *Earth Surface and Landforms* **21**: 1091–1107

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Xiubin L, Moran EF, Mortimore M, Ramakrishnan PS, Richards

JF, Skanes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Jianchu X. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* **11**: 261-269

Lawson LM. 1925. Effect of Rio Grande storage on river erosion and deposition. *Engineering News-Record* **95(10)**: 372–374

Leach M, Mearns R. (eds.) 1996. The lie of the land. Challenging received wisdoms on the African environment The International African Institute in association with James Currey, Oxford and Heinemann, Portsmouth.

Lenton, TM, Schellnhuber HJ, Szathmary E. 2004. Climbing the co-evolutionary ladder. *Nature* **431**: 913

Leopold LB. 1973. River channel change with time: an example. *Geological Society of America Bulletin* **84**: 1845–1860

Mahmood K. 1987. Reservoir sedimentation: Impact, extent, mitigation. World Bank Technical Report, vol. 71. Washington D.C.

Meyer WB, Turner BL (eds.) 1994. Changes in Land Use and Land Cover: a Global Perspective. Cambridge University Press, Cambridge, UK.

Neal JC, Schumann G, Fewtrell T, Budimir M, Bates PD, Mason D.C. 2011. Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK. *Journal of Flood Risk Management* **4(2)**: 88-95

Ouyang W, Hao FH, Zhao C, Lin C. 2010. Vegetation response to 30 years hydropower cascade exploitation in upper stream of Yellow River. *Communications in Nonlinear Science and Numerical Simulation* **15**: 1928–1941

Petts GE. 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography* **3**: 329–362

Petts G, Gurnell A. 2005. Dams and geomorphology: Research progress and future directions. *Geomorphology* **71**: 27–47

Poeppl RE. 2010. Die Fluvialmorphologie der Fugnitz und des Kajabaches. Eine vergleichende Analyse ausgewählter Flussabschnitte unter besonderer Berücksichtigung anthropogener Effekte. Project report, Thayatal National Park, Austria

Poeppl RE, Keesstra SD, Fuchs S, Seeger M, Bertsch R, Glade T. 2012 (acc.). The role of humans as sediment (dis)connectors in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology*.

Schumm SA. 2005. River Variability and Complexity. Cambridge University Press, Cambridge.

Slaymaker O, Spencer T, Dadson S. 2009. Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction. In: Slaymaker O, Spencer T, Embleton-Hamann C (eds.): Geomorphology and Global Environmental Change. Cambridge University Press.

Stanley EH, Luebke M, Doyle MW, Marshall DW. 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. *Journal of the North American Benthological Society* **21(1)**: 172-187

Taylor KV. 1978. Erosion downstream from dams. In: Chadwick, W.L. (eds.): Environmental Effects of Large Dams. American Society of Civil Engineers, New York; 165–186

Thothong W, Huon S, Janeau JL, Boonsaner A, de Rouw A, Planchon O, Bardoux G, Parkpian P. 2011. Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand. Agriculture, *Ecosystems and Environment* 140 **(3-4)**: 521-533

Tockner K, Stanford JA. 2002. Riverine flood plains: present state and future trends. *Environmental Conservation* **29**: 308–330

Van De Wiel MJ, Coulthard TJ, Macklin MG, Lewin J. 2007. Embedding reach-scale fluvial dynamics within the CAESAR cellular automaton landscape evolution model. *Geomorphology* **90**: 283–301

Wang Z, Wu B, Wang G. 2007. Fluvial Processes and morphological response on the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam. *Geomorphology* **91**: 65–79

Welsh KE, Dearing JA, Chiverrell RC, Coulthard TJ. 2009. Testing a cellular modelling approach to simulating late-Holocene sediment and water transfer from catchment to lake in the French Alps since 1826. *The Holocene* **19(5)**: 785-798

Wilcock PR, Crowe JC. 2003. Surface-based transport model for mixed-size sediment. *Journal of Hydraulic Engineering* **129**: 120–28

Wildman LS, McBroom J. 2005. The Evolution of Gravel Bed Channels After Dam Removal: Case Study of the Anaconda and Union City Dam Removals. *Geomorphology* **71**: 245-262

Wilkinson H, McElroy BJ. 2006. The impact of humans on continental erosion and sedimentation. *Geological Society of America Bulletin* **119**: 140–156

Wohl EE, Cenderelli DA. 2000. Sediment deposition and transport patterns following a reservoir sediment release. *Water Resources Research* **36**: 319–333

B. English and German summary

B.1 Summary

Human impacts on fluvial systems can be traced back over thousands of years, but have become more pronounced over the last century. River engineering and land use/land cover changes are regarded as being the most prominent forms of human disturbance in fluvial systems as they alter the flow and sediment regime of rivers. Investigations on human-induced landscape changes in fluvial environments can be conducted on assessing connectivity relationships within the fluvial system itself, but also by looking at the linkages that exist between the human and fluvial systems. Sediment connectivity approaches are increasingly used to describe the linkages between sediment sources and sinks within a catchment providing an opportunity for improving our understanding of how physical linkages govern geomorphic processes. Sediment connectivity operates on different spatial dimensions and is governed by a range of factors that determine overland flow processes and hence the potential of sediment transfer through the system. These include factors such as topography, soil conditions and vegetation cover. In terms of lateral sediment connectivity, riparian vegetation cover is recognized to play an important role in buffering the sediment fluxes from hillslopes to the channel network. Furthermore, approaches that consider connectivity in terms of human-landscape interactions are ever more recognized as being essential when it comes to examining causes for landscape change.

The research undertaken in this thesis is based on the identification of three main research gaps which are summarized in the following. (i) Although human impact on connectivity relationships in fluvial systems and the related fluvio-geomorphic consequences are considerable, no conceptual model has yet focused on the role of humans as (dis)connectors in fluvial systems. Furthermore, concepts of sediment connectivity had not been linked to principles of geomorphic channel processes to investigate the geomorphic effects of human-induced alterations of sediment connectivity in fluvial systems so far. (ii) The role of riparian vegetation had not been integrated in connectivity concepts so far and only rarely assessed in the context of sediment connectivity. (iii) Concepts and approaches that focused on connectivity relationships between the fluvial and the human system and their role in governing landscape changes in fluvial environments had been missing.

These challenges have been undertaken in this thesis through the development of a conceptual model for each research gap identified above addressing the following issues: (i) Human impacts on

sediment connectivity in fluvial systems and fluvio-geomorphic response; (ii) Lateral buffering and the role of riparian vegetation in agricultural catchments; (iii) Connectivity between the human and the fluvial system and its implications for landscape change. The assumptions of the newly developed conceptual models have been tested by conducting and evaluating case studies in small fluvial system impacted by agricultural land use or dams by applying a variety of methods including GIS analyses, numerical modelling, multivariate statistics, field surveys and sedimentological analyses. Lastly, the individual conceptual models have been linked to each other to develop a holistic conceptual model that allows for a more integrated understanding of connectivity relationships in human-impacted fluvial systems and the related landscape changes in fluvial environments.

The results of this thesis can be summarized for each issue as follows: (i) Linking sediment connectivity concepts to principles of channel processes helps to explain geomorphic channel responses to human impacts in terms of land use change and dam construction; (ii) Lateral buffering is governed by the type of riparian vegetation cover and related depositional features that emerge from biogeomorphic processes in forested riparian zones; (iii) Human impacts on fluvial systems in terms of dam construction leads to an interconnection of the fluvial system and the human system by triggering a series of process-response feedback loops between them which further influences landscape changes fluvial environments.

B.2 Zusammenfassung

Menschliche Eingriffe in fluviale Systeme lassen sich über Jahrtausende zurückverfolgen. Das Ausmaß des menschlichen Einflusses hat jedoch innerhalb des letzten Jahrhunderts dramatisch zugenommen. Etwa durch die Errichtung von immer mehr und immer größeren Staudämmen in den Gerinnen sowie durch gravierende Landnutzungsänderungen in den Einzugsgebieten verändert der Mensch Wasser- und Sedimenthaushalt der Flusssysteme und induziert dadurch Veränderungen in der Flusslandschaft. Die Rolle des Menschen in der Veränderung von Flusslandschaften kann auf Basis der Betrachtung von Konnektivitätsbeziehungen auf zweierlei Ebenen untersucht werden. Erstens, mittels Betrachtung des menschlichen Einflusses auf die Konnektivitätsbeziehungen innerhalb fluvialer Systeme und zweitens durch die Ermittlung human-induzierter Wechselbeziehungen zwischen Mensch und fluvialem System.

Die Geomorphologie untersucht verstärkt Sediment-Konnektivitätsverhältnisse in fluvialen Systemen, mit dem Ziel ein besseres fluvial-geomorphologisches Prozessverständnis zu erlangen. Grundvoraussetzung für Sediment-Konnektivität in fluvialen Systemen ist das Vorhandensein von Oberflächenabfluss, welcher durch eine Vielzahl von Einflussfaktoren wie zum Beispiel Klima, Relief, Bodenverhältnisse und Vegetationsbedeckung gesteuert wird. Die Ufervegetation nimmt im Kontext der Sediment-Konnektivität aufgrund ihres Potenzials den Sedimenteintrag in Fließgewässer signifikant abzupuffern eine besondere Bedeutung ein. Des Weiteren gibt es in der Landschaftsforschung immer mehr Ansätze, die die Ursachen für Landschaftsveränderungen auf Basis der Betrachtung von Mensch-Umwelt-Konnektivitätsbeziehungen zu erklären versuchen.

Im Rahmen der Recherchen zur vorliegenden Arbeit wurden drei Forschungslücken identifiziert: (i) Obwohl der menschliche Einfluss auf Sediment-Konnektivitätsbeziehungen in fluvialen Systemen sowie dessen fluvial-morphologischen Implikationen weitestgehend bekannt sind, gab es bis dato kein Modell, das den Einfluss des Menschen auf die Sediment-Konnektivitätsbeziehungen in fluvialen System konzeptualisiert und mit fluvial-morphologischen Prozessen in Beziehung setzte. (ii) Die Rolle der Ufervegetation wurde in konzeptionellen Modellen und Fallstudien zur Sediment-Konnektivität in fluvialen Systemen noch nicht ausreichend berücksichtigt. (iii) Es gab noch kein Modell sowie nur wenige Fallstudien, welche Landschaftsveränderungem im Kontext der Konnektivitätbeziehungen zwischen Mensch und fluvialem Systeme beleuchtet hätte.

Basierend auf den Forschungslücken wurden im Zuge dieser Dissertation drei konzeptionelle Modelle entwickelt, deren Annahmen des Weiteren mittels Durchführung mehrerer Fallstudien in anthropogen beeinflussten fluvialen Systemen unter Verwendung unterschiedlicher Methoden (z.B.

numerische Modellierung, GIS-gestützte Analysen, Sedimentanalysen, Kartierung im Gelände, multivariate Statistik) getestet wurden.

Die zentralen Ergebnisse der vorliegenden Arbeit lassen sich folgendermaßen zusammenfassen: (i) Die Anwendung eines Modells, welches den Einfluss des Menschen auf die Sediment-Konnektivitätsbeziehungen in fluvialen System konzeptualisiert und mit fluvial-morphologischen Prozessen in Beziehung setzt hilft bei der Abschätzung fluvial-morphologischer Systemantworten auf menschliche Einflüsse. (ii) Der laterale Sedimenteintrag von Ackerflächen in Fließgewässer ist maßgeblich durch die Art der Ufervegetation beeinflusst. (iii) Menschliche Eingriffe in Fließgewässer in Form der Errichtung von Dämmen sowie durch Landnutzungsänderungen induzieren Wechselwirkungen zwischen Mensch und fluvialem System in Form von Prozess-Reaktions-Feedbackschleifen, welche die Entwicklung von Flusslandschaften beeinflussen.

Eidesstattliche Erklärung

Hiermit erkläre ich, Ronald Erwin Pöppl, geboren am 22.01.1981 in Horn die vorliegende Dissertation selbständig angefertigt zu haben. Aus fremden Quellen direkt oder indirekt übernommenen Informationen und Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher weder in gleicher noch in ähnlicher Form einer anderen Prüfungsbehörde vorgelegt oder veröffentlicht.

Wien, Juli 2012 ______________________________

C. Curriculum vitae

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Professional career:

2010 – 2012	University assistant ("prae doc"), Physical Geography, Department of Geography and Regional Research, University of Vienna, Austria, ENGAGE working group (geomorphological systems and risk research)
2011 – 2012	Research project: Flood risk modeling and assessment in the Rhein Valley; funded by the Chamber of Commerce, Vorarlberg, Austria
2009 – 2012	Lecturer, Physical Geography, Department of Geography and Regional Research, University of Vienna, Austria
2008 – 2010	Research project: Human impacts on small fluvial systems: geomorphic effects, ecomorphology, Thayatal National Park, Austria; funded by the European Union
2008 – 2009	Research project: Improvement of the natural reproduction of the brown trout (*salmo trutta*) in the Thayatal National Park, Austria; funded by the Thayatal National Park

Education:

2008 – 2012	Ph.D. studies, Geography, University of Vienna, Department of Geography and Regional Research, Austria; Concentrations: Physical Geography, Fluvial Geomorphology; Dissertation: "Investigating the role of humans as

	(dis)connecting agents in fluvial systems - new concepts and applications for fluvial geomorphology and landscape research"
2007	Mag. rer. nat., Geography and Biology, University of Vienna (Austria) Concentrations: Physical Geography, Fluvial Geomorphology, Biogeography, Didactics; Diploma thesis: "Hydromorphology of the Thaya River within the boundaries of the Thayatal National Park with special consideration of fluvial geomorphology and the vegetation cover of fluvial islands"
2009	B.A., Jazz-instrumental, Conservatorium Vienna University, Austria

Further educational courses:

18.4. – 21.4.2011	Advances in River Science Seminar; Swansea, UK
31.1. – 4.2. 2011	Training course: university teaching; University of Vienna
2.11. – 3.11. 2010	Project management; focus: research projects; University of Vienna
21.11. – 25.11. 2010	4th International Seminar on Small Catchments dynamics: Connectivity in Time and Space; Netanya and Beer-Sheva, Israel
26.9. – 2.10. 2010	1st Mid-European Summer School on Geomorphology: Complex Response of Earth Surface Processes to Environmental Change; Heimbuchenthan, Germany
21.6. – 26.6. 2009	Mountains Risks Intensive Course; UNIL, EPFL, Quanterra Switzerland

Teaching:

2009– 2012	University of Vienna, Austria, Department of Geography: PS - Introduction to Geomorphology EX - Physiogeographical field trip: Fluvial Geomorphology UE – Exercises in vegetation geography PR – Field class in Physical Geography
2008 – 2010	Academic high school, BG 11, Geringer Gasse, Vienna, Austria; Subjects: Geography and Economics, Biology and Environmental Science
2007 – 2008	Academic high school, AKG, Vienna, Austria; Subjects: Biology and Environmental Science
2007 – 2008	Academic high school, BRG 1, Vienna, Austria; Subjects: Geography and Economics

Skills:

Languages:	English (fluent in spoken and written), German (fluent in spoken and written)
IT:	Microsoft Office, Endnote, E-Learning, Image processing
Methodical:	Physiogeographical laboratory and field methods, GIS, numerical modeling
Mobility:	Driving license, class B

Memberships:

Since 2010	European Geosciences Union (EGU)
Since 2010	American Geosciences Union (AGU)
Since 2010	Austrian Geographical Society (ÖGG)
Since 2010	Austrian Research Association on Geomorphology and Environmental Change (ÖGG)
Since 2011	Austrian Committee Danube Research – International Association for Danube Research (ÖK-IAD)

Prices and awards:

2008	Austria's National Parks Researcher's Award - Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria

Publications:

Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (acc., 2012). Humans as (dis)connecting agents in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. *Geomorphology.*

Poeppl, R.E., Keiler, M., Elverfeldt, K.v., Zweimueller, I., and Glade, T. (in press, 2012). The effects of riparian vegetation cover on lateral connectivity and biogeomorphic feedback processes in a medium-sized agricultural catchment. *Geografiska Annaler, Series A*, *Physical Geography.*

Poeppl, R.E., Keiler, M., Coulthard, T.J. (subm., 2012). Dam-induced landscape change and the role of human-landscape interactions – a reach-scale case study. *Earth Surface Processes and Landforms.*

Bertsch, R., Pöppl, R.E., Glade, T. (2012). Hochwassermodellierung im unteren Rheintal - Güterbahnhof Wolfurt: Datenaufbereitung und Hochwassermodellierung. Project report, Wien, 14 pp.

Bertsch, R., Pöppl, R.E., Glade, T. (2012). Hochwassermodellierung im unteren Rheintal - Güterbahnhof Wolfurt, Vergleichende Studie. Project report, Wien, 27 pp.

Poeppl, R.E., Bauer, B., Keiler, M. & Glade, T. (2011). Die Thaya im Nationalpark Thayatal – eine flussmorphologische Analyse auf verschiedenen räumlichen Skalenebenen. *Wissenschaftliche Mitteilungen aus dem Niederösterreichischen Landesmuseum* 21, 209-220.

Poeppl, R.E. (2011). Erfahrungsbericht aus der Arbeitswelt eines Universitätsassistenten (prae doc) und Doktoranden. *GEOGRAPHIEaktuell* 10 IV/2011: p. 8.

Poeppl, R.E. (2010). Die Fluvialmorphologie der Fugnitz und des Kajabaches. Eine vergleichende Analyse ausgewählter Flussabschnitte unter besonderer Berücksichtigung anthropogener Effekte. Project report, Thayatal National Park, Austria, 95 pp. incl. DVD-Rom

Poeppl, R.E., Übl, C. (2008). Die Hydrogeographie der Thaya innerhalb der Grenzen des „Nationalparks Thayatal“ unter besonderer Berücksichtigung der Flussmorphologie und der Inselvegetation. *Research in National Parks* 2007/2008, 93-94. Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria.

Poeppl, R.E. (2007). Die Hydrogeographie der Thaya innerhalb der Grenzen des „Nationalparks Thayatal“ unter besonderer Berücksichtigung der Flussmorphologie und der Inselvegetation. Unpublished diploma thesis (typescript), Department of Geography and Regional Research, University of Vienna, Austria; 124 pp. incl. CD- Rom

Presentations:

Poeppl, R.E., Keesstra, S.D., Fuchs, S., Seeger, M., Bertsch, R., Glade, T. (2012). Humans as (dis)connecting agents in fluvial systems: a conceptualization with case studies from small to meso-scale catchments. Oral presentation: *EGU* General Assembly 2012, Vienna, Austria; Geophysical Research Abstracts, Vol. 14, EGU2012-9265, 2012

Bertsch, R., Poeppl, R.E., Glade, T. (2012). Longitudinal sediment connectivity in a dammed river system using fine sediment analyses – a case study in the Kaja river, Lower Austria. Poster presentation: *EGU* General Assembly 2012, Vienna, Austria; Geophysical Research Abstracts, Vol. 14, EGU2012-13961, 2012

Poeppl, R.E., Glade, T. & Keiler, M. (2011). Humans as (dis)connecting agents in fluvial systems: geomorphic system response, sedimentological effects and possible implications for geomorphological system research. Oral Presentation: *Advances in River Science* 2011 Workshop, Swansea, UK

Poeppl, R.E., Keiler, M., Elverfeldt, K.v. & Glade, T. (2011). The effects of different land use patterns on sedimentological (dis)connectivity in small agricultural catchments. Oral Presentation: *EGU* General Assembly 2011, Vienna, Austria; Geophysical Research Abstracts, Vol. 13, EGU2011-4700, 2011

Poeppl, R.E., Glade, T. & Keiler, M. (2011). The role of humans as (dis)connectors in small fluvial systems: sedimentological effects and their implications. Poster Presentation: *EGU* General Assembly 2011, Vienna, Austria; Geophysical Research Abstracts, Vol. 13, EGU2011-4706-2, 2011

Poeppl, R.E. (2011). Vergleich von naturnahen und durch den Menschen beeinflussten Gewässerabschnitten an der Fugnitz: Landnutzung, Hochwasser und Gewässerstruktur". Oral presentation: 12. Nationalparkforum Thayatal, 10.11.2011, Nationalparkhaus Hardegg, Österreich

Poeppl, R.E., Keiler, M. & Glade, T. (2010). Geomorphic Response to agricultural Land Use in small fluvial Systems – The Role of Landscape Connectivity. Oral Presentation: *AGU* General Assembly 2010, San Francisco, USA

Keiler, M., Poeppl, R.E. (2010). A conceptual Model for coupled Human-Landscape Systems in Mountain Regions. Poster Presentation: *AGU* General Assembly 2010, San Francisco, USA

Poeppl, R.E., Keiler, M. & Glade, T. (2010). Human Impacts on fluvial Systems – Sediment Delivery, Storage and Landscape Connectivity in small Catchments. Poster Presentation: *IAG* 4th International Seminar on small Catchments Dynamics: Connectivity in Time and Space, Tel Aviv (Israel), November 2010

Poeppl, R.E., Keiler, M. & Glade, T. (2010). Impacts of Dams on the Geomorphodynamics of fluvial Systems – Complex System Response? Poster Presentation: *EGU* General Assembly 2010, Vienna, Austria; Geophysical Research Abstracts, Vol. 12, EGU2010-10621-2

Poeppl, R.E., Glade, T. & Keiler, M. (2010). Human Impacts on fluvial Systems – A Small-Catchment Case Study. Poster Presentation: *EGU* General Assembly 2010, Vienna, Austria; Geophysical Research Abstracts, Vol. 12, EGU2010-10715-1

Poeppl, R.E., Embleton-Hamann, C. (2010). Geomorphologie und globaler Umweltwandel. Die Bedeutung des Menschen. Presentation at the FDZ-Night 2010, University of Vienna, Austria.

Poeppl, R.E., Glade, T. & Bauer, B. (2009). Die Hydromorphologie der Fugnitz und des Kajabaches. Poster Presentation: Deutscher Geographentag 2009, Vienna, Austria