A conceptual connectivity framework for understanding geomorphic change in human-impacted fluvial systems

Ronald E. Poeppl a,⁎, Saskia D. Keesstra b, Jerry Maroulis b,c

a Department of Geography and Regional Research, University of Vienna, Universitätsstraße 7, A-1010 Vienna, Austria
b Soil Physics and Land Management Group, Wageningen University, Drovenendaalsesteeg 4, 6708PB Wageningen, The Netherlands
b International Centre for Applied Climate Sciences, Institute for Agriculture and the Environment, University of Southern Queensland, Toowoomba, Queensland 4350, Australia

Abstract

Human-induced landscape change is difficult to predict due to the complexity inherent in both geomorphic and social systems as well as due to the coupling relationships between them. To better understand system complexity and system response to changing inputs, “connectivity thinking” has become an important recent paradigm within various disciplines including ecology and geomorphology. With the presented conceptual connectivity framework on geomorphic change in human-impacted fluvial systems a cautionary note is flagged regarding the need (i) to include and to systematically conceptualise the role of different types of human agency in altering connectivity relationships in geomorphic systems and (ii) to integrate notions of human-environment interactions to connectivity concepts in geomorphology to better explain causes and trajectories of landscape change. Geomorphic response of fluvial systems to human disturbance is shown to be determined by system-specific boundary conditions (incl. system history, related legacy effects and lag times); vegetation dynamics and human-induced functional relationships (i.e. feedback mechanisms) between the different spatial dimensions of connectivity. It is further demonstrated how changes in social systems can trigger a process-response feedback loop between social and geomorphic systems that further governs the trajectory of landscape change in coupled human-geomorphic systems.

1. Introduction

“Connectivity thinking” and related concepts have a long history in geographical research (e.g. in geomorphology (e.g. Chorley and Kennedy, 1971; Brunsden and Thornes, 1979), or in terms of human-environment interactions (e.g. Barrows, 1923)). The earliest documented statement of connectivity in a geomorphological context can be found in Chorley and Kennedy (1971) where connectivity is 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 first introduced by Brunsden and Thornes (1979) and Brunsden (1993, 2001) and extended by Harvey (1997, 2002) to explain landscape sensitivity and geomorphic change. 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; with capacity dependent on path density of the process and strength of the coupling between system components.

Especially since the beginning of the 21st century, connectivity research experienced a surge within various disciplines including ecology (Kindlmann and Burel, 2008), hydrology and geomorphology (e.g. Brierley et al., 2006; Bracken et al., 2013, 2015), in developing new or adapting already existing concepts on connectivity to better understand system complexity and system response to change within their respective discipline. Geomorphologists began to extend connectivity thinking by incorporating connectivity concepts from other disciplines, especially ecology and hydrology (cf. Bracken and Croke, 2007), to describe linkages between sediment source areas and the corresponding sinks in catchment systems (e.g. Croke et al., 2005; Brierley et al., 2006; Fryirs et al., 2007; Turnbull et al., 2008; Wainwright et al., 2011; Fryirs, 2013; Bracken et al., 2015) which further resulted in a differentiation between three types of connectivity: “Sediment connectivity”, i.e. the potential for sediments to move through geomorphic systems (Hooke, 2003), being governed by the physical coupling of landforms (i.e. “landscape connectivity”) and by the passage of the transporting medium from one part of the landscape to another (e.g. via water, “hydrological connectivity”).

Considerations of sediment connectivity in geomorphology are mainly based on thinking about sediment transfer between different stores or zones within a given system placing an emphasis on the distribution of sediment stores and sinks reflecting and influencing the
routes, travel distances and pathways of sediment movement within catchment systems (e.g. between channel reaches (Hooke, 2003); or between hillslopes and channels (Harvey, 2012); see Bracken et al. (2015). Bracken et al. (2015) further pointed out that a shift from thinking about sediment transfer between different stores to a continuum-based approach can be observed trying to understand pathways, routes and scales of movement of sediment that has been directly influenced by the progressive development of the concept of hydrological connectivity. Lexartza-Artza and Wainwright (2009, 2011), for example, underlined the importance of understanding the conditions for runoff generation and transmission to produce key information regarding sediment transfer in catchment systems.

Ecologists had already been using the concept of connectivity as a critical property in the persistence of spatially structured populations (Metzger and Décamps, 1997). In this context, hydrological connectivity has been defined by Pringle (2001) as being the water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle. This definition also reflects Chorley and Kennedy’s (1971) definition of connectivity (see above). Furthermore, hydrological connectivity, especially in the hydrological sciences, has been a dynamic area of research in the last decade, resulting in a novel framework for understanding runoff and run on (Bracken and Crone, 2007; Ali and Roy, 2009), see Bracken et al. (2013), further influencing recent concepts on sediment connectivity in geomorphology (e.g. Lexartza-Artza and Wainwright, 2009, 2011; Bracken et al., 2015).

Landscape connectivity has been defined in an ecological context as being “the degree to which a landscape facilitates or impedes the movement of individuals” (Taylor et al., 1993). In this context, important landscape characteristics include shape, size and location of different features in the landscape (Brooks, 2003). These considerations are also reflected in the coupling concept within the sensitivity concept of Brunsden and Thornes (1979; see above) which therefore can be seen as an early – if not the first – systematic consideration of landscape connectivity in a geomorphological context. At a later stage, Brierley et al. (2006) proposed a connectivity framework in which they characterized different forms of landscape connectivity based on the position of geomorphic processes in a catchment. Based on Ward’s (1989) conceptual model on the four-dimensional nature of lotic ecosystems (including notions of human-geomorphic interactions based on resilience theory) to develop a conceptual connectivity framework, (including notions of human-geomorphic interactions based on resilience theory) to develop a conceptual connectivity framework, the degree to which any limiting factor (i.e. termed buffers, barriers and blankets) constrains the efficiency of sediment transfer relationships.

In the last two decades connectivity further gained increasing importance in river and catchment management (incl. river restoration). For example, evaluating the effects of river engineering on connectivity and geomorphic dynamics along European rivers has evolved as a legal requirement under the European Water Framework Directive (EU, 2000). As a consequence, engineered rivers and their floodplains are increasingly being restored (e.g. Constantinescu et al., 2015; Magilligan et al., 2016), while also a shift from hard- to soft-engineering techniques can be observed (e.g. Moss and Monstad, 2008). However, many restoration projects have failed (Wohl et al., 2005) due to incomplete pre-assessments or basic concepts that neglect the role of complex geomorphic system response to change (Schumm, 1973; Pizzuto, 2002). This complexity is mainly related to the system-specific landscape history (Brierley, 2010) and associated legacy effects (Doyle et al., 2005), self-regulatory system properties incl. feedback processes (cf. Bednarek, 2001), interactions between processes and system components, and time-dependent changes that progressively alter the balance between forces and resistance to geomorphic change (Brunsden, 2002).

Humans, over thousands of years, have significantly altered geomorphic systems. These human impacts were mainly characterized by short-lived changes to their micro-environment rather than occurring on larger scales (Werner and McNamara, 2007). However, the scale of human impacts upon geomorphic systems such as fluvial systems is now considerably larger than at any point in our history with a multitude of either direct (e.g. dam construction) or indirect (e.g. land cover changes) (Goudie, 2006) impacts on their structure and function (Gregory, 2006). Simultaneously, increases in population and technology development have led to an increasing strength of interactions between humans and their natural environment resulting in regional or even global feedback loops due to strong and complex interdependencies between hydro-geomorphological, ecological, and human processes and functions (Werner and McNamara, 2007; Harden et al., 2014; Chin et al., 2014). Moreover, the increasing strength of interactions between human agency and landscape processes means that they “[…] can no longer meaningfully be treated separately, but rather only as an inter-weaved, coupled system” (Werner and McNamara, 2007; p. 394).

Research on coupled human-landscape systems has made good progress over the last 15 years: in socio-ecological contexts, e.g. Holling, 2001; Alberti et al., 2003; Walker et al., 2004; Folke, 2006; Matthews and Selman, 2006; Dearing et al., 2006; Liu et al., 2007; Harden et al., 2014; (adaptive) water and river management, e.g. Kondolf et al., 2003; Pahl-Wostl, 2007; Pahl-Wostl et al., 2007; and geomorphology, e.g. Werner and McNamara, 2007; Dearing, 2008; Chin et al., 2014. In particular, resilience has been increasingly used as a concept to understand social–ecological systems (e.g. Folke, 2006), further being applied to geomorphic (Phillips, 2009) and eco-geomorphological (Collins et al., 2012) systems. These concepts, which are focussing on feedback characteristics between open systems, are considered to provide valuable background for advancing research in coupled human-geomorphic systems (Chin et al., 2014). However, we are still facing a range of key challenges when investigating coupled human-landscape systems.

Although elaborated connectivity concepts, and approaches that use connectivity to explain complex geomorphic systems and geomorphic response to change emerged in the last decade, a range of key challenges and gaps still persist. These include (i) to systematically conceptualise the role of different types of human agency/disturbance in altering connectivity relationships in geomorphic systems and (ii) to integrate notions of human-environment interactions to connectivity concepts in geomorphology to better explain causes and trajectories of landscape change. These key challenges and gaps, which are elaborated in more detail in Section 2, are further forming the basis of discourse on the development of a revised conceptual connectivity framework dealing with causes and trajectories of geomorphic change in managed fluvial systems.

The aim of this paper is twofold. Firstly, we build upon earlier concepts and recent advances in geomorphology and landscape research (including notions of human-geomorphic interactions based on resilience theory) to develop a conceptual connectivity framework, underpinned by case study examples from literature to exemplify the causes and trajectories of geomorphic change in human-impacted fluvial systems (Section 3). Secondly, an overview of existing key tools to quantify connectivity in geomorphic and coupled human-geomorphic systems will be presented (Section 4), forming the second basis for Section 4 in which we will discuss the potential added value of our framework in the context of human-impact, connectivity and complexity research in fluvial geomorphology, further deriving some general implications for river and catchment management.

2. Key challenges and gaps

2.1. Disturbance and the role of human agency in geomorphological connectivity frameworks

Based on the frequency and magnitude concept of Wolman and Miller (1960); Brunsden and Thornes (1979) in their sensitivity concept
classified disturbance into pulsed and ramped types of inputs. Pulsed inputs are typically extreme and episodic events that are spatially and temporally restricted (e.g. low-frequency, high-magnitude flood events), while ramped input changes are sustained, resulting in permanent shifts in the controlling variables or boundary conditions. Brunsden and Thornes (1979) also stated that changes and fluctuations in environmental conditions, can be related to human activity such as land-use. In a revised version of the sensitivity concept, Brunsden (2001, p.99) stated that the likelihood of a given system to respond to any disturbance forces depends on “its structure, strength properties, transmission linkages, coupling efficiency, shock absorption capacity, complexity and resilience”. Similarly, Harvey (2001, p. 175) noted that “coupling behaviour conditions how the system responds to disturbance, and is therefore important in determining the geomorphic response to human-induced, climatically-induced or tectonically-induced environmental change”. Similar notions on the importance of landscape (dis)connectivity for the interpretation of landscape responses to human disturbance including management applications can also be found in the work of Brierley et al. (2006). However, in all these approaches no systematic information is provided on how different types of human activity induce and/or affect connectivity relationships and thus geomorphic sensitivity of geomorphic systems to (human-induced) change.

The first geomorphological landscape connectivity framework in which notions on different types of human disturbance on sediment flux have been addressed explicitly can be found in Fryirs et al. (2007; see also Fryirs, 2013) in which the impact of human disturbance upon sediment flux is framed in terms of alterations to the operation of landforms that impede sediment transfer within catchments. However, besides some general considerations about the effects of human-induced land cover changes and the construction of dams on lateral and longitudinal connectivity in catchment systems, no systematic conceptualisation on the role of different human agencies in altering connectivity relationships in catchment systems, is evident. Considering the multiplicity of human impacts upon catchment systems, and assuming a complex relationship between the different spheres of connectivity within these systems, yet a more systematic conceptualization of the role of human disturbance in altering connectivity relationships in catchment systems is deemed essential for understanding the role of human agency in altering catchment-scale sediment fluxes and geomorphic response to change.

In their conceptual model on hydrological connectivity Bracken and Croke (2007) defined five components of hydrological connectivity affecting the conditions for runoff generation and transmission further influencing sediment connectivity in catchment systems: (1) climate, (2) hillslope runoff potential, (3) landscape position (4) delivery pathway and (5) lateral buffering. Within each of these components they named a number of factors which influence hydrological connectivity including the potential impacts of human agency such as land management (e.g. ploughing, road construction) in altering hillslope runoff potential and delivery pathways. Lexartza-Arta and Wainwright (2009) presented practical guidelines for assessing connectivity in the field including anthropogenic influences such as water and catchment management. They further stressed the need to consider dynamic aspects of connectivity that emerge from interactions and feedback loops between structural and functional connectivity and the role of self-regulation in providing a better understanding of system complexity (for hydrological connectivity: Bracken and Croke, 2007; Lexartza-Arta and Wainwright, 2009; Wainwright et al., 2011; for sediment connectivity: Bracken et al., 2015). However, these frameworks do not provide systematic information on the role of different types of human agency in altering/inducing functional relationships between different spatial dimensions of connectivity in geomorphic systems, which are yet hypothesized to further influence the trajectory of geomorphic change.

2.2. Human-environment interactions in geomorphology and the role of connectivity

In a socio-ecological context, research on human-environment interactions has received considerable attention in recent literature (e.g. Holling, 2001; Alberti et al., 2003; Walker et al., 2004; Folke, 2006; Matthews and Selman, 2006; Dearing et al., 2006; Liu et al., 2007). Many of these approaches are based on complex adaptive systems and resilience theory. According to Holling (2001) there are three properties that shape the adaptive cycle and the future state of a system (whether at the scale of the cell or the biosphere, the individual or the culture), which are wealth, controllability, and adaptive capacity. Holling (2001, p. 394) stated that the “internal controllability of a system; that is, the degree of connectedness between internal controlling variables and processes, a measure that reflects the degree of flexibility or rigidity of such controls, such as their sensitivity or not to perturbation”. In terms of human-environmental systems this implies that the sensitivity of both sub-systems, i.e. the environmental and human/social system, and the sensitivity of coupled human-environmental systems are governed by the strength of connectivity relationships.

Various approaches have been used to couple human behaviour with geomorphic processes, ranging from conceptual frameworks (e.g. Urban, 2002; Kondolf et al., 2003; Chin et al., 2014) to field-based (e.g. Dearing, 2008) and modelling approaches (e.g. Werner and McNamara, 2007; for a detailed review refer to Zvollef and An, 2014). Yet, we are still facing enormous knowledge gaps in quantifying full impact-feedback loops within geomorphic systems involving significant human interactions, such as in the economic evaluation of changed landscapes (Chin et al., 2014). General key problems are mainly related to the lack of effective communication and collaboration among multiple communities, integrative concepts, common metrics, integrating disparate data types, and new ways to synthesise and scale up research results from local case studies to broader large scale theories and models (Harden et al., 2014). For geomorphologists, Chin et al. (2014) identified general key questions and challenges in investigating coupled relationships in human-landscape systems related to varying spatial and temporal scales for the processes involved, data gaps, linking impacts and responses, and a lack of integrative tools and interdisciplinary collaboration. They mainly argue that development of new geomorphic principles and theoretical frameworks on potential feedbacks between physical and human processes within a common conceptual framework for human-landscape systems is required. It is further argued here, that the existing conceptual frameworks on coupled “human-geomorphic systems” disregard the importance of type and location of human impact upon geomorphic systems, further neglecting the role of connectivity relationships governing the systems’ sensitivity and resilience to change.

3. Conceptual connectivity framework for understanding geomorphic change in managed fluvial systems

Building upon earlier connectivity concepts and recent advances in geomorphology and landscape research, we intend to develop a conceptual connectivity framework that helps to account for the causes and trajectories of geomorphic change in human-impacted fluvial systems. To achieve this, initially, (1) a systematic outline of common human impacts on rivers (i.e. river engineering) and catchments (i.e. land cover change and land management practices) considering their effects on on-site (1) longitudinal, lateral and vertical connectivity conditions is presented in Section 3.1. In this context, connectivity in fluvial systems is defined as being the potential for a sediment particle to move through catchment systems (incl. all sub-systems) under the influence of water. Furthermore, according to the classification of different types of disturbance (Brunsden and Thornes, 1979) differentiation is also made between ramped and pulsed human disturbance (Table 1). (2) The relationship between connectivity, sensitivity and resilience and the
role of system-intrinsic self-regulatory processes in governing the trajectories of geomorphic response to different types of anthropogenic disturbance (incl. their off-site effects) is conceptualized in Section 3.2. (3) A conceptual framework on coupled “human-geomorphic systems” will then be developed highlighting the importance of connectivity relationships in governing systems’ sensitivity and resilience to change (Section 3.3). In this context connectivity in social and coupled human-geomorphic systems is understood as being the general degree of connectedness or interactions between system compartments, and/or factors and processes that influence them. The presented conceptual models will be additionally underpinned by case study examples from literature exemplifying human-induced connectivity changes and their geomorphic implications in human-impacted fluvial systems.

3.1. Human impact on connectivity in fluvial systems (1)

Connectivity in fluvial systems is operating at longitudinal, lateral, and vertical spatial dimensions (Ward, 1989; Fryirs et al., 2007), governed by a complex interplay of “natural” factors such as climate, tectonics, geology, topography, soils and vegetation (for an extensive review see Bracken and Croke, 2007; Fig. 1). Human activities directly affect connectivity by land cover changes and different land use practices altering sediment delivery from hillslopes and floodplains to the channel system (i.e. lateral connectivity), or by actions in the river channels influencing sediment exchange between the channel and the channel subsurface (i.e. vertical connectivity) or sediment transport (i.e. longitudinal connectivity; see Fig. 1).

Different types of river engineering have been shown to affect longitudinal connectivity. Dams represent one of the most dominant features affecting longitudinal connectivity as they interrupt the transfer of water and sediments from headwater source areas (Pettis and Gurnell, 2005). Although, dam construction works had been reported to increase sediment yields by >50% (Nilsson, 1976), once closed dams and the reservoirs they impound had been shown to act as effective sediment sinks (Grimshaw and Lewin, 1980). The degree of longitudinal disconnectivity is determined by the trap efficiency of the dam. For example, research on three reservoirs in central Missouri (USA) has shown that dam trap efficiency ranges from 33% to 99% during individual storms, further being governed by the detention time of storm runoff, dam characteristics and by factors governing particle size (Raush and Heinemann, 1975). Results of Poeppl (2012) who analysed suspended sediment samples directly up- and downstream of a 6 m high overflow dam in a small mixed-load river in Austria, for example revealed a grain-size-selective reduction of longitudinal connectivity (Fig. 2): nearly all silt is retained, while clay is transported through the impoundment and across the dam crest. Similarly, flow diversion and abstraction at dam locations can also lead to a significant decrease of flow magnitude and hence longitudinal connectivity (cf. Kingsford, 2000). Contrarily, when dams are removed or reservoirs are flushed (e.g. Wen Shen, 1999) or when river channels are cleared of woody debris (e.g. Pégay and Gurnell, 1997; Brooks et al., 2004) longitudinal connectivity and sediment flux is increased (cf. Hart et al., 2002).

Channelization and meander cut-offs associated with the installation of bed and bank protection structures involves channel straightening which may further affect longitudinal connectivity. If channel straightening results in an increase in channel slope (e.g. Brooker, 1985) and/or there is the presence of channel bed and bank protection measures, which reduce hydraulic roughness (Arcement and Schneider, 1989), then stream power and thus longitudinal connectivity is locally increased. Bed protection structures further cause a decline of vertical connectivity (Boulton et al., 1993; for an extensive review on exchange processes between rivers and groundwater see Brune and Gonser, 1997).

Anthropogenic sediment addition or removal in river channels may also affect longitudinal and/or vertical connectivity. For example, sediment addition to river channels can lead to a clogging of the river bed which reduces vertical connectivity (Schalchli, 1992) or to the development of sediment slugs reducing longitudinal connectivity (Nicholas et al., 1995). Contrarily, sediment removal from gravel bed channels may locally increase vertical connectivity due to bed armour removal which – if present – has been shown to reduce the exchange of matter between the water body and the bed subsurface (Prudic et al., 2007).

Channel embankments (including road embankments) and levees are permanent features that locally disrupt lateral connectivity as they prevent sediments from entering the channel system (Poeppl et al., 2012; Marchmalu et al., 2015). Furthermore, a variety of human activities in catchments, mainly related to land cover changes and land management, can significantly affect lateral connectivity. For instance, deforestation may lead to an increase of surface runoff and the generation of new overland flow pathways such as rills and gullies (Pierson et al., 2001; Li et al., 2007) and thus enhances lateral connectivity, while afforestation has been shown to reduce lateral connectivity (Sorriso-Valvo et al., 1995; Keestra, 2007).

Land management activities such as contour ploughing decrease lateral connectivity by preventing the input of eroded soils from agricultural field to the channel systems, while perpendicular ploughing has been shown to enhance lateral connectivity (Kirkby et al., 2002; Poeppl et al., 2012). Land levelling (filling), in response to rill and gully formation, decreases overland flow, water erosion (Liu et al., 2013) and thus lateral connectivity, while the construction of ditches in agricultural areas (Dunn and Mackay, 1996) as well as subsurface drainage (Skaggs et al., 1994) have been shown to have the opposite effects. Furthermore, road construction and urbanization also increase lateral connectivity as they act as efficient overland flow pathways collecting and routing storm runoff to the river channel systems (Booth and Jackson, 1997; Croke and Mockler, 2001; Wemple and Jones, 2003).

3.2. Geomorphic response to human disturbance: connectivity, sensitivity, resilience and self-regulation (2)

Geomorphic response to human disturbance depends on a multiplicity of factors including type, location and duration of impact (e.g. pulsed vs. ramped), system-specific boundary conditions, connectivity and self-regulatory system properties (incl. system-intrinsic feedback...
processes; cf. Brunsden, 2002). Connectivity relationships in geomorphic systems further determine sensitivity and resilience of the system to change (cf. Brunsden and Thornes, 1979; Harvey, 2007; Lexartza-Arta and Wainwright, 2009; Fig. 3). Geomorphic systems with low connectivity are less sensitive and thus more resilient to disturbance as the propagation of the effects of change is limited. This relationship, for example, has been shown in the work of Fryirs and Brierley (1999) and Harvey (2001) where in some settings, slopes and channels are disconnected with materials mobilised on slopes re-stored on slopes or in fans at the base of slopes. An example of channel-hillslope (dis-)connectivity is shown in Fig. 4. The temporal characteristics of connectivity relationships are further governed by the magnitude and frequency of threshold-exceeding disturbance events required to breach or create (dis-)connecting landscape features switching on and off certain parts of catchments over certain timeframes (Harvey, 2001; Fryirs et al., 2007). As a consequence, connectivity in geomorphic systems changes over time – either due to natural processes and/or anthropogenic factors – altering or inducing process-form relationships (e.g. via feedback processes) that determine geomorphic change (Turnbull et al., 2008; Wainwright et al., 2011; Bracken et al., 2015).

Dams, for example can be seen as ramped human disturbances permanently decreasing longitudinal connectivity until the dam is removed which further results in channel erosion in the downstream river reaches due to a lack of sediments (Kondolf, 1997). However, geomorphic response to dam construction has been shown to be complex in space and time as being determined by the system-specific boundary conditions (incl. system history) and self-regulatory system properties related to feedback processes. As shown by Williams and Wolman (1984) geomorphic changes following dam construction can be rapid in semi-arid regions (i.e. up to 1 m of bed erosion per year), while elsewhere (e.g. along the Peace River below the Bennett Dam, Canada) morphological adjustment has been shown to be of the order of millennia as a result of the small magnitude of bed material transport (Church, 1995). Contrarily, stable bars of coarse sediments had been observed at major tributary confluences along regulated rivers (Graf, 1980). Moreover, accelerated rates of sedimentation had been observed where regulation had reduced tributary base-levels during floods, causing tributary degradation at the junctions (e.g. Makkaveyev, 1972; Kellerhals and Grill, 1973; see Petts and Gurnell, 2005) as a consequence of emerging feedback processes between the main river and its downstream tributaries. Additionally, geomorphic response to dam construction as well as their removal have been shown to be influenced by emerging feedback processes in multi-dam systems (Skalak et al., 2013), further being governed by the proximity of other dams, channel

**Fig. 1.** Human impact on connectivity in fluvial systems at the three spatial dimensions. (Adapted from Poeppl, 2012)

**Fig. 2.** Grain-size-selective reduction of longitudinal suspended sediment connectivity caused by a 6 m high overflow dam located in a mixed-load section of the Kaja River, Austria (adapted from Poeppl, 2012): nearly all silt is retained, while clay is transported through the impoundment and across the dam crest.
engineering and related legacy effects (Poeppl et al., 2015). The latter examples clearly show how dam-induced changes of longitudinal connectivity trigger off-site geomorphic feedback processes that further determine the trajectories of geomorphic response to human disturbance. Feedback processes are system-intrinsic self-regulatory properties: a negative feedback brings about an adjustment that counters or limits the initial change, while positive feedbacks are self-enhancing mechanisms that tend to cause instability within systems (for an overview on feedback relationships in geomorphology, see King, 1970; Murray et al., 2008; Chin et al., 2014). A simple scenario exemplifying dam-induced functional linkages between the different spatial dimensions of connectivity and different types of human disturbance (pulsed/ramped; exemplified left).

Pulsed human disturbances such as extensive deforestation can lead to an abrupt increase in lateral connectivity which is followed by a recovery phase (see also Fig. 3). Duration and type of recovery and related geomorphic effects further depend on system-specific boundary conditions (e.g. climate) and self-regulatory system properties related to vegetation dynamics. Vegetation and vegetation change significantly affects surface runoff and sediment dynamics on the hillslopes themselves further governing lateral sediment input rates to the channel systems (for a comprehensive review on vegetation-geomorphology linkages see Marsten, 2010). To underpin the complex relationship between vegetation dynamics, recovery of lateral connectivity and the trajectories of geomorphic change in channel systems we present a simple example, however quite common for temperate climates, showing the effects of catchment deforestation followed by natural vegetation recovery due to land abandonment on lateral connectivity and channel morphology in the Dragonja catchment, Slovenia.

The Dragonja catchment has seen an increase in forest cover of >60% from 1954 to 2002 most evident on the steep slopes adjacent to the river channel which were previously cultivated on small terraces before being abandoned in the 1950s–1960s. Abandoned fields initially reverted to grassland before returning to a fully forested state over 30 years. Due to natural reforestation, distinct nonlinear changes were observed in both the hydrological and sediment dynamics in the catchment (Fig. 8). The dense vegetation cover on the slopes between the source area, the fields on hill crests, and the river, decreased channel sediment influx by >90% (Keesstra, 2007). Furthermore, water influx decreased due to the trees’ higher water demand compared to
agricultural fields. However, relative changes in water discharge were not as large as sediment influx resulting in a nonlinear decrease of hydrological and sediment connectivity (see Fig. 8). As a consequence, river water was depleted of sediment causing channel incision (Keesstra, 2007). Channel incision occurred in two phases: firstly, incision occurred immediately post large-scale abandonment of agricultural fields. Bare fields, previously susceptible to erosion, were quickly invaded by pioneer species of herbs and grasses exhibiting a relatively low water demand (Keesstra et al., 2009). In this phase, the percentage of discharged rainfall (the rainfall-runoff ratio) and the resulting river discharge had not changed significantly, but sediment flux had, causing major channel incision of ~2 m (Fig. 9), while the second phase occurred ~30 years after initial land abandonment. Since 1975, a 30–35 year old stand of forest developed on the former fields. These forests have high water demand and therefore generate less runoff in all periods of the year (Keesstra, 2007), with both peak and base flows decreasing. The lower peak flow results from higher interception and infiltration due to the higher leaf area of the forest, improved soil structure, higher organic matter content, higher root density and thicker litter layers in the forest compared to the former cropped fields. Due to lower peak flows, gravel bars in the river have stabilized and are currently overgrown by pioneer vegetation that has further stabilized the bars (see Fig. 9). These bars function as the floodplain area – currently used for grazing – through which the undersized river meanders within the currently oversized channel bed, incising an additional 0.5 m since 1975 (Keesstra, 2007).

3.3. Connectivity in coupled human-geomorphic systems (3)

The causalities of management decisions and thus of type, locality and duration of human disturbance are strongly related to the sensitivity and resilience of social systems which is further governed by the degree of connectedness (incl. feedback processes) between internal controlling variables and processes (Holling, 2001). Social systems with low connectivity have weak control and thus low resilience/high sensitivity (i.e. high vulnerability) to disturbance (cf. Holling, 2001). In natural hazard research, resilience and vulnerability of populations to different types of natural (incl. hydro-geomorphic) hazards have been strongly influenced by different controlling variables that are further subject to spatial and temporal change (cf. Cutter and Finch, 2008).

Controlling variables of social systems include knowledge, technology, social organisation, population (e.g. density and locality) and values (e.g. economic) which are interrelated via feedback processes that further influence human behaviour and the repertoire of human actions (Marten, 2001; Urban, 2002; Fig. 10). The degree of connectivity between geomorphic and social systems (i.e. the strength of “human-
geomorphic connectivity") is therefore also strongly dependent on the strength of connectivity within both sub-systems (Fig. 11). Connectivity between geomorphic and social systems is characterized by the presence of process-response feedback loops which are triggered by different types of human disturbance (e.g. different types of river and catchment management) or (human-induced) geomorphic disturbance affecting the social system (see Fig. 11; for an overview on feedback relationships between social and geomorphic systems see Chin et al., 2014). Different types of river and catchment management decisions are governed by human needs (e.g. increasing food demand due to population increase) or technological changes (e.g. during industrialisation; see Fig. 10). Referring to fluvial systems, in the following we use two simple examples to demonstrate how changes in social systems can trigger a process-response feedback loop between social and geomorphic systems that further governs the trajectory of landscape change in coupled human-geomorphic systems.

Dams, for example, are man-made features constructed for different purposes to fulfill human needs such as hydropower generation, flood control or fish farming. Besides the direct effects of large reservoirs upon individuals and families who are forced to resettle or otherwise alter their livelihood patterns (McCully, 2001; Sneddon and Fox, 2008), dam construction induces geomorphic processes such as upstream channel aggradation and downstream erosion due to a change in longitudinal connectivity (cf. Kondolf, 1997). These geomorphic responses may also compromise values of the social system, e.g. reservoir sedimentation reduces dam efficiency while downstream erosion may reduce bank and slope stability further affecting infrastructure located in the vicinity of the river. As a consequence, further intervention such as dam excavation or removal or channel bank and/or bed protection measures may become necessary which in turn again induces further geomorphic responses. Dam removal, for example induces upstream erosion further affecting bank and slope stability (Williams and Wolman, 1984) where the installation of channel protection measures may become necessary. However, a major problem for river management is that the time scales relevant to human processes and institutions and related management decisions are often short compared to the time frames of geomorphic processes (Kondolf and Podolak, 2014) and lag times between forcing factors (e.g. dam removal) and system responses (Chin et al., 2014). Furthermore, legacy effects of past disturbances condition modern morphodynamics and alter the trajectories of geomorphic system responses (Liu et al., 2007; see Fig. 10).

Walter and Merritts (2008), for example exhibited that gravel-bed streams in the mid-Atlantic piedmont region of the eastern US are actively incising into legacy sediment left when thousands of milldams were abandoned during the nineteenth century due to the adoption of steam engines (i.e. a change in technology; see Fig. 10). Increased sediment yields to downstream nearshore environments called for sediment-control efforts in river corridors thereby further influencing modern system response to dam removal. A similar example can be found in Poeppl et al. (2015) who investigated the geomorphic legacy effects of medieval dams in the Bohemian Massif, Austria. Along the 11.7 km long Kaja River, a small mixed-load low mountain range stream, 14 dams and reservoirs existed which had been built for extensive fish farming purposes. Due to reservoir sedimentation combined with a rapid loss in the importance of fish farming economy the majority of these dams had been removed which was followed by active incision into legacy reservoir sediments. Incision and lateral erosion further affected newly acquired agricultural fields in the vicinity of the river.
which called for the installation of channel protection measures (Fig. 12).

As shown in the examples above there is a need to integrate notions of connectivity in both, conceptual frameworks and empirical (including quantitative) approaches in order to better understand resilience/sensitivity and thus causes and trajectories of human-geomorphic systems to change. However, quantification of connectivity – either within geomorphic or social systems or between them – is a difficult task due to the complexity inherent in these systems. As quantification of connectivity in these systems strongly depends on the specific research question and thus the respective temporal and spatial scale of study, the applied techniques and therefore also the respective key tools are highly variable (see Section 4).

4. Key tools to quantify connectivity in geomorphic and coupled human-geomorphic systems: an overview

In a geomorphological context, techniques to measure connectivity can range from single-event small-scale measurements (cf. Cerdan et al., 2010) to multi-annual large-scale monitoring (e.g. Verstraeten et al., 2003). Besides deriving connectivity from measuring structure and fluxes in the field, advances in index development (e.g. Cavalli et al., 2013) and modelling approaches (e.g. Baartman et al., 2013) have been made over the past years. Connectivity indices mainly use a combination of topography and vegetation characteristics to determine connectivity (e.g. Borselli et al., 2008; Cavalli et al., 2013). Indices are static representations of structural connectivity, which are useful for
determining areas of high and low structural connectivity within the study areas. Based on GIS analyses, Borselli et al. (2008) developed a connectivity index (IC) reflecting the potential for each cell within a catchment system to receive sediments from other parts of the landscape and governed by catchment surface, slope gradient and type of land use. However, because indices are static, they do not provide information about fluxes and thus functional connectivity. Different types of models (e.g. cellular automata, statistical models), on the

---

**Fig. 10.** Conceptual model of human-geomorphic connectivity determined by the presence of process-response feedback loops (bold black arrows) between fluvial and social systems which are triggered by human disturbances (e.g. different types of river and catchment management) or (human-induced) geomorphic disturbances/responses affecting the social system.

---

**Fig. 11.** Conceptual model on the relationships between connectivity, sensitivity and resilience in social and geomorphic systems as further being governed by system-intrinsic self-regulatory properties associated to positive and negative feedback processes as well as being connected via human and geomorphic disturbance.
The impact of the economy on the landscape through damage events and slowly varying changes to the landscape, i.e. the landscape on the economy through the effect of repeated fast-scale for the future, i.e. the economic and political model; 3. The impact of the as well as revenues and pro

2. The state of the economy within that landmass using variables asso-
coupled landmass (as in a river

5. Discussion and conclusions

5.1. Human impact on connectivity in fluvial systems (1)

The proposed framework on human impact on connectivity in fluvial systems conceptualizes the on-site effects of common human impacts (i.e. pulsed or ramped types; Brunsden and Thornes, 1979) on different spatial dimensions of connectivity in fluvial systems (Ward, 1989; Brierley et al., 2006; Fryirs et al., 2007). With this, a systematic basis for a more detailed conceptualization of complex geomorphic response to human disturbance is provided. Complex geomorphic response is conceptualized as being governed by connectivity relationships and thus sensitivity, resilience as well as by system-intrinsic self-regulatory pro-

5.2. Geomorphic response to human disturbance: connectivity, sensitivity, resilience and self-regulation (2)

Considerations on the sensitivity and resilience of geomorphic sys-
tems to change (Brunsden and Thornes, 1979; Brunsden, 2001; Harvey, 2001) and recent advances in hydrological and sediment connectivity re-
search (e.g. Bracken and Croke, 2007; Lexartza-Artza and Wainwright, 2009; Wainwright et al., 2011; Bracken et al., 2015), have led to the de-
velopment of a conceptual model in which we provide information on the role of different types of human agency in altering/inducing functional-
relationships between the different spatial dimensions of connectivity in fluvial systems. These relationships and self-regulatory system proper-
ties associated with feedback processes and vegetation dynamics are further conceptualized to determine the spatio-temporal trajectories of geomorphic response (incl. off-site effects) to different types of human disturbance.

It has been shown that the geomorphic response to ramped distur-
bance (dam construction) is being governed by strong functional link-
ages between the different spatial dimensions of connectivity and emerging feedback mechanisms. Furthermore, geomorphic response to dam construction and removal has been shown to be complex in
other hand, do provide information on (potential) fluxes and can be powerful tools in determining how structural connectivity relates to sediment transport (e.g. Mueller et al., 2007; Poepl et al., 2012; Heckmann and Schwanghart, 2013; Baartman et al., 2013). Baartman et al. (2013), for example, used a landscape evolution model called LAPSUS to simulate sediment connectivity of different landscape types, relating feedback mechanisms between erosion and deposition to landscape complexity.

Integrative modelling tools for linking and quantifying geomorphic and human processes are also available (for an overview see Zvoleff and An (2014) or Chin et al. (2014)). These include agent-based and spatial simulation models such as provided by Werner and McNamara (2007) in which they used a cellular agent-based modelling approach to investigate the dynamics of coupled human-landscape systems along a single reach of the Mississippi River in New Orleans involving and linking the following factors (Fig. 13): 1. The state of the landscape with variables defined on a one-dimensional array of cells (for problems involving coastlines) or a two-dimensional array covering a tightly coupled landmass (as in a river floodplain), i.e. the landscape model; 2. The state of the economy within that landmass using variables asso-
ciated with those cells that specify supply, demand and price of product as well as revenues and profits for economic actors and their predictions for the future, i.e. the economic and political model; 3. The impact of the landscape on the economy through the effect of repeated fast-scale damage events and slowly varying changes to the landscape, i.e. the hazard model; 4. The impact of the economy on the landscape through the effect of economically driven alterations to the landscape to mitigate damage, i.e. the hazard mitigation model.

Although the approach of Werner and McNamara (2007) is seen as a major leap forward in modelling complex coupling relationships between geomorphic and social systems, it is argued here that the landscape model they used does not integrate notions of connectivity as: a) being restricted to a single part of a catchment system, and b) widely neglecting aspects of landscape evolution that govern the spatio-temporal dynamics of connect-
v. Note that a) could be overcome by adding static information on connectivity to each cell of the array as being provided by the calculation of connectivity indices across catchment systems (e.g. Borselli et al., 2008; Cavalli et al., 2013), while b) could be addressed by using a landscape evolu-
tion model (e.g. LAPSUS or CAESAR-Lisflood) instead of static representa-
tions of the landscape.

Fig. 12. Dam section along the Kaja River, Austria (flow direction from South to North; adapted from Poepl et al., 2015). \( r \) = removed dams, \( a \) = active dam. Note: Channel erosion at lowermost removed dam (no channel engineering) vs. no channel erosion at re-

removed dams upstream (engineered); former reservoir area upstream of the uppermost removed dam is still clearly visible (dashed line).
space and time as being determined by the system-specific boundary conditions (incl. system history, related legacy effects and lag times; Walter and Merritts, 2008; Brierley, 2010; Poeppl et al., 2015). Moreover, it has been further demonstrated that geomorphic response to land abandonment is complex in space and time and governed by the recovery time of the system after disturbance. This is itself strongly related to vegetation dynamics in influencing hydrological and sediment connectivity in a nonlinear way (Keesstra et al., 2009). These observations are further comparable with observations on the effects of reforestation on catchment systems as presented in Harden and Mathews (2002), Liebault et al. (2002) and Marston et al. (2003).

Returning to the key questions raised by Gregory (2006), our conceptual models (2) and (3) provide useful information to address questions about how and why causes and trajectories of change in fluvial systems occur. Our model (2) is in line with conceptual frameworks on connectivity in which system complexity and thus system response to change is conceptualized as being governed by structural and functional interdependencies (e.g. Lexartza-Arta and Wainwright, 2009; Wainwright et al., 2011; Bracken et al., 2015) and system-intrinsic self-regulatory mechanisms (e.g. King, 1970; Murray et al., 2008; Phillips, 2009; Chin et al., 2014). The proposed conceptual models (1) and (2) are considered to involve innovative potential in the context of human-impact research in fluvial geomorphology, in putting forward existing connectivity concepts and providing potentially valuable information for river and catchment management by: a) systematically addressing the role of different human agencies (i.e. external disturbance) in altering/inducing functional connectivity relationships, and b) further relating these to system-intrinsic mechanisms that govern the propagation (incl. off-site effects) and spatio-temporal trajectories of geomorphic change.

The proposed framework is not capable of providing generalized information on how much change occurs/how long will it take/how does it occur, when will it start and finish, and where will it occur as these parameters have been shown to be highly system-specific. Instead a cautionary note is flagged regarding the need to attain “catchment-specific knowledge of landscape character and behaviour, connectivity and evolution to provide a physical platform with which to engender effective river and catchment engagement (e.g. Brierley et al., 2002)” (Brierley et al., 2006; p. 166).

5.3. Connectivity in coupled “human-geomorphic systems” (3)

Based on fundamental concepts on resilience (e.g. Holling, 2001) and feedback relationships (e.g. Chin et al., 2014) in the context of coupled human-landscape systems research as well as based on our considerations as presented in (1) and (2), we developed a theoretical model conceptualizing connectivity between geomorphic and social systems. Connectivity between geomorphic and social systems is considered as being dependent on the connectivity, sensitivity and thus resilience of these systems to (human-induced) change. Connectivity between geomorphic and social systems has been further shown to be characterized by the presence of process-response feedback loops which are triggered by different types of human disturbance (e.g. different types of river and catchment management) or (human-induced) geomorphic disturbance affecting the social system. We used different examples from the literature to underpin our model assumptions and to further address the importance and surplus value of integrating notions of connectivity in both, conceptual frameworks and empirical (including quantitative) approaches in order to better understand resilience/sensitivity and thus


Kellerhals, R., Gill, D., 1973. Observations and potential downstream effects of large stor-
age projects in Northern Canada. Trans. 11th Int. Congr. on Large Dams, Madrid, Proc. 6 (1), 141–157.


Sorriso-Valvo, M., Bryan, R.B., Yair, A., Antonucci, L., 1995. Impact of afforestation on hydro-


Urban, M.A., 2002. Conceptualizing anthropogenic change in fluvial systems: drainage develop-
ment on the upper Embarras River, Illinois. Prof. Geogr. 54 (2), 204–217.


