Conference Volume | 5th Symposium for Research in Protected Areas | 10 to 12 June 2013, Mittersill | pages 607 - 614

Impact of dams, dam removal and dam-related river engineering structures on sediment connectivity and channel morphology of the Fugnitz and the Kaja Rivers

Nationalparks Austria Science Award 2013

Ronald E. Poeppl[1], Saskia D. Keesstra[2], Margreth Keiler[3], Tom Coulthard[4], Thomas Glade[1]

[1] Department of Geography and Regional Research, University of Vienna, Austria
[2] Soil Physics and Land Management Group, Wageningen University, the Netherlands
[3] Institute of Geography, University of Bern, Switzerland
[4] Department of Geography, University of Hull, United Kingdom

Abstract

In terms of changing flow and sediment regimes of rivers, dams are often regarded as the most dominant form of human impact on fluvial systems. Dams can decrease the flux of water and sediments leading to channel changes such as upstream aggradation and downstream degradation. The opposite effects occur when dams are removed. Channel degradation often requires further intervention in terms of river bed and bank protection works. The situation evolves more complex in river systems that are impacted by a series of dams due to feedback processes between the different system compartments.A number of studies have recently investigated geomorphic systems using connectivity approaches to improve the understanding of geomorphic system response to change. This paper presents a case study investigating the impact of dam construction, dam removal and dam-related river bed and bank protection measures on the sediment connectivity and channel morphology of the Fugnitz and the Kaja Rivers using a combination of DEM analyses, field surveys and landscape evolution modelling. For both river systems the results revealed low sediment connectivity accompanied by a fine river bed sediment facies in river sections upstream of active dams and of removed dams with protection measures. Contrarily, high sediment connectivity which was accompanied by a coarse river bed sediment facies was observed in river sections either located downstream of active dams or of removed dams with upstream protection. In terms of channel changes, significant channel degradation was examined at locations downstream of active dams and of removed dams. Channel bed and bank protection measures prevent erosion and channel slope recovery after dam removal. Landscape evolution modeling revealed a complex geomorphic response to dam construction and dam removal as sediment output rates and therefore geomorphic processes have been shown to act in a non-linear manner. These insights are deemed to have major implications for river management and conservation, as quality and state of riverine habitats are determined by channel morphology and river bed sediment composition.

Keywords

Dams, sediment connectivity, river engineering, channel morphology, river recovery

Introduction

The construction of dams has a major influence on the flow and sediment regimes of rivers as they significantly reduce the downstream flux of water and sediments (i.e. sediment connectivity) which further involves geomorphic channel changes (e.g. upstream aggradation and downstream degradation). In contrast, dam removals generally show the opposite effects. Channel degradation often requires further intervention in terms of river bed and bank protection works. This potentially induces further (unintended) geomorphic channel changes and/or may prevent from river recovery. However, the situation gets more complex in river systems that are impacted by a series of dams due to emerging feedback processes. A number of studies have recently investigated how connectivity approaches can be used to understand complex environmental systems in order to provide a better understanding of geomorphic system response to changes (e.g. Brierley et al. 2006; Poeppl et al. 2012).Furthermore, connectivity assessments are of major importance for river management and conservation, especially in protected areas, since sediment connectivity further determines the downstream transfer and residence times of nutrients and pollutants as well as the geomorphic channel conditions and therefore the state and quality of riverine habitats. In this paper, we present a case study in which we investigated the impact of dam construction, dam removal and dam-related river bed and bank protection measures on sediment connectivity and channel morphology of two rivers impacted by multiple dams.

Study area

The rivers Fugnitz and Kaja are located in the Northeast of Austria (Fig. 1a). Both rivers are mixed-load single-thread perennial streams that enter the Thaya River within the boundaries of the Thayatal National Park (Fig. 1b).

The region of the Fugnitz River (29.7 km; 138.4 km^2 catchment area) and the Kaja River (10.7 km; 21.3 km^2 catchment area) is characterized by a humid temperate climate (POEPPL et al. 2012).

Both rivers have been impacted by multiple dams which were built as overflow dams between 1425 AD and 1782 AD (KNITTLER 2005). They range from three to six meters in height with a rather small storage capacity and are or were mainly used for fish farming purposes (POEPPL 2010). In 2013, three dams are still active along the Kaja River, while all others had been removed (Fig. 1b). Five weir dams are currently present along the Fugnitz River. These were built as mill dams or for water diversion and extraction for the water supply of fish ponds. Some sections of the upper and middle reaches have been engineered by installing river bed and bank protection measures which are still present in the systems. In the middle reaches of the Kaja River a river section has been impacted by three active dams which were built before 1782 AD (Fig. 1c). Two of them had been removed between 1823 AD and 1966 AD.

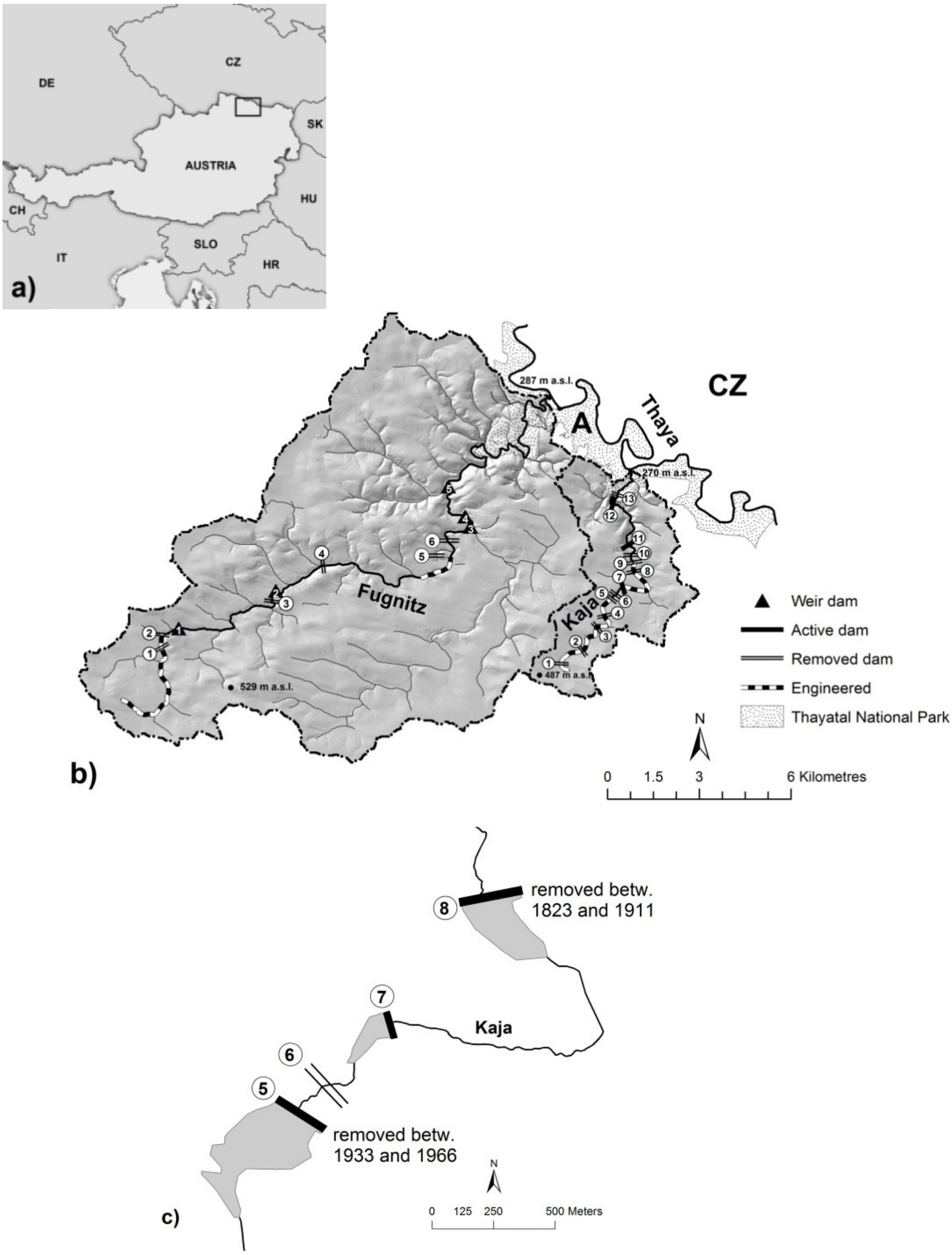


Figure 1; Study area; a) Location of the study area. b) Fugnitz and Kaja River with type and location of dams and river engineering structures. Data source: Provincial Government of Lower Austria, 2010. c) Study area for the modelling approach:situation in 1823 (derived from historical cadastral maps of the "Land register of Francis I" 1823)

Methods

Sediment connectivity is defined as the "potential for a specific particle to move through the system" (HOOKE 2003) which is mainly determined by local stream power. As for a given amount of sediment and discharge the most dominant factor in determining stream power is channel slope. Changes of channel slope are therefore seen as changes of sediment connectivity. In order to assess (changes of) channel slope, longitudinal river profiles were compiled for both rivers based on elevation information derived from a DEM in ArcGIS 10.0 (ESRI 2010).

Sedimentary river bed deposits distinct in grain size and/or sedimentary structure were mapped (= facies mapping) and information on the sediment facies was used as a proxy for stream power and hence sediment connectivity. The grain size categories were determined visually referring to WENTWORTH (1922): 0) no sediment (bedrock or engineered), 1) boulders (> 256 mm), 2) cobbles (64 - 256 mm), 3) gravels (2 - 64mm), 4) sands (0.63 - 2 mm), and 5) fines (< 0.63 mm). Furthermore, backwater area outreaches upstream of active dams were surveyed in order to delineate their influence on sediment connectivity. A fine sediment facies is interpreted to reflect low stream power and hence low sediment connectivity, while the opposite accounts for a coarse sediment facies. Changes of channel slope and sediment facies were then related to the presence of (removed) dams and dam-related river bed and bank protection measures.

In order to delineate geomorphic channel responses to dams, dam removal and dam-related river bed and bank protection measures, we compared channel cross-sections up- and downstream of the dams. The channel cross sections were digitally compiled 20 m up- and downstream of the dam toes based on a the DEM using the Path Profile/LOS Tool in Global Mapper 10 (Blue Marble Geographics 2009). The channel cross-sections were morphometrically analyzed according to their maximal channel widths, depths and cross-sectional areas assuming a bankfull discharge. Differences between up- and downstream reaches were calculated and interpreted according to the presence of dams and river bed and bank protection measures.

The CAESAR-Lisflood 1.2 landscape evolution model was used to simulate the effects of dam construction and dam removal on channel morphology (incl. sediment budgeting) and sediment input/output rates (sediment connectivity) for a specific reach of the Kaja River (see study area, Fig. 1c). CAESAR-Lisflood 1.2 (freely available via *http://www.coulthard.org.uk/CAESAR.html*) is a new hydrodynamic version of the CAESAR model developed by COULTHARD (1999) and COULTHARD et al. (2007). CAESAR is a cellular model that allows the simulation of geomorphic processes (erosion and deposition) as well as the calculation of sediment input/output rates for different grain sizes at fine-resolution temporal and spatial scales. Two scenarios, each over an experimental time period of 1000 years were modelled: 1) presence of 3 active dams (see also Fig. 1c), 2) removal of all dams after scenario 1. For this, the DEM was adapted to the physiographic settings of 1823. Water and sediment input arriving from the catchment area upstream the studied river reach were simulated using hourly rainfall data over a period of 10 years (data source: Hydrographischer Dienst Niederösterreich 2001-2010). Sediment particle size data were obtained from river bed sediment samples and soil samples in spring 2010 (POEPPL 2010).

Results and discussion

Impact of dams, dam removal and dam-related river engineering structures

The Fugnitz River has an overall channel slope of 0.068 ‰ and generally shows a nearly straight longitudinal profile in the upper and middle reaches and slight convexity in the lower reaches before entering the deeply-incised Thaya River (Fig. 2a; see also Fig. 1b). However, a multiplicity of knickpoints is present, mainly related to the presence of weir dams (e.g. weir dams 1 and 3) as well as to the presence of removed dams in river sections exhibiting upstream engineering (e.g. dams 2 and 5). The Kaja River has an overall channel slope of 0.172 ‰ and shows a very diverse longitudinal profile with alternating concave and convex sections in the upper reaches and convex steeply sloping lower reaches before entering the deeply incised Thaya River (Fig. 2b; see also Fig. 1b).

Sediment facies mapping resulted in the delineation of 50 river sections along the Fugnitz River showing all types of grain size categories except category 0 (Fig. 2a). The channel slope of the different river sections varies between 0.009 ‰ (section 5) and 0.264 ‰ (section 4). All river sections with low channel slope values showed a sediment facies of either category 5 or 4 which indicates low sediment connectivity (see Fig. 2a). Contrarily, all river sections with high channel slope values exhibited a sediment facies of category 1 indicating high sediment connectivity. All river sections within the coarsest sediment facies class 1 and high channel slope values are located downstream of either active dams or removed dams with upstream engineering. Whereas all sections exhibiting a fine sediment facies (i.e. grain size category 5 or 4) and low channel slope values are located upstream of active dams, within their backwater reaches, removed dams with upstream bed and bank protection measures, or at the river mouth.

Following the results of sediment facies mapping, 24 river sections were delineated along the Kaja River showing all types of grain size categories (Fig. 2b). The channel slope of the different river sections varies between 0.007 ‰ (section 16) and 1.118 ‰ (section 21,). Three river sections with the highest channel slope values exhibited a sediment facies of either category 0 or 1 which indicates high sediment connectivity. However, one river section within the range of the highest channel slope values (i.e. section 7) showed a sediment facies of 4 indicating low sediment connectivity which might be caused by the backwater effect of dam 7. All river sections within the range of low channel slope values exhibited a sediment facies of category 5 or 4 which indicates low sediment connectivity. All river sections within the coarsest sediment facies class 1 and high channel slope values are located downstream of either active dams or removed dams with upstream engineering. Whereas all sections exhibiting a fine sediment facies and low channel slope values are located upstream of active dams, within their backwater reaches, removed dams with upstream bed and bank protection, or at the river mouth.

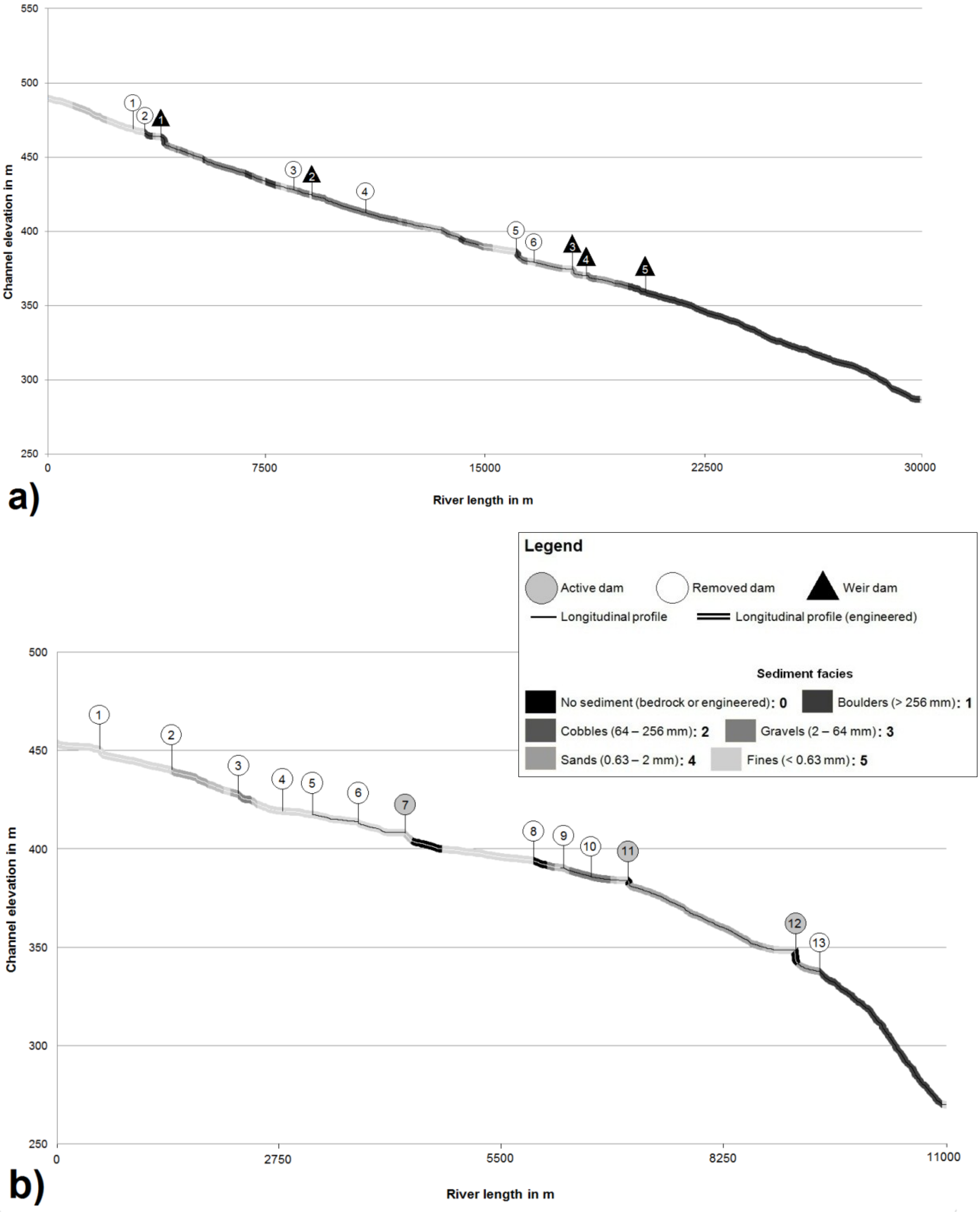
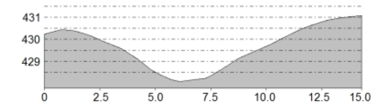
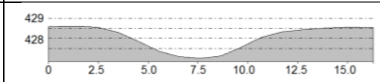
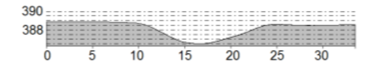
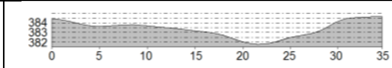
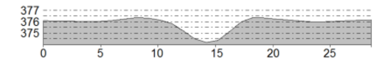
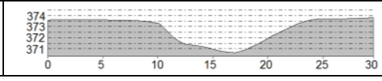


Figure 2 Longitudinal profile, river engineering and sediment facies along the rivers a) Fugnitz and b) Kaja.

Along the Fugnitz River, significant increases in cross-sectional channel areas, in channel depth and/or channel width between sections up- and downstream of dams were observed at locations of weir dams (e.g. W3; see Fig. 3a) as well as removed dams where the upstream sections have been engineered (e.g. D5; see Fig. 3a). These results indicate lateral and vertical channel erosion in non-engineered reaches downstream of active dams. Significant decreases in cross-sectional channel areas and in channel depth between sections up- and downstream of dams were examined at locations of removed dams without upstream engineering(e.g. D3; see Fig. 3a). Like in the Fugnitz case, significant increases in channel depth, channel width and cross-sectional channel areas between sections up- and downstream of dams were examined at locations of removed dams where the upstream sections exhibited engineering (e.g. D9; see Fig. 3b). Furthermore, significant increases in channel depth and cross-sectional channel area were detected at the location of an active dam without channel engineering (e.g. D12; see Fig. 3b).

a) Fugnitz River

Dam no.	Upstream cross-section	Engineering	Downstream cross-section	Engineering
D3rem		no		no
D5rem		yes		no
W3act		no		no

b) Kaja River

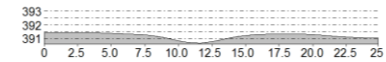
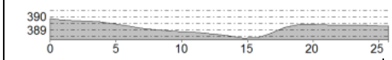
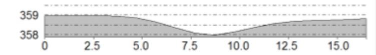
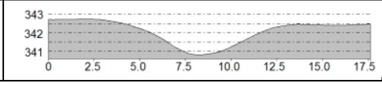
Dam no.	Upstream cross-section	Engineering	Downstream cross-section	Engineering
D9rem		yes		no
D12act		no		no

Figure 3 Selected channel cross-sections and the presence of river engineering structures ("Engineering") up- and downstream of dams along a) the Fugnitz River and b) the Kaja River. Dams are numbered from source to mouth ("Dam no.") referring to Fig. 1b. Active dams are referenced with "act", removed dams with "rem". Profile labeling is in meters.

Reach-scale modellingon the effects of dam construction and dam removal

1) Dam construction scenario

After dam construction, modelled sediment output rates (= sediment connectivity) declined for all grain size classes, but then increased with time due to an infilling of the reservoirs (Fig. 4a, 4b, 4c) indicating a recovery of sediment connectivity due to aggradation processes. The suspended sediment output rates showed a continuous increase with time (Fig. 4b), while a stepwise increase after infilling of all reservoirs was observed for bedload sediments (Fig. 4c). Simulation of channel changes due to dam construction exhibited aggradation in the reservoirs as well as in the upstream reaches affected by backwater, while channel degradation was observed in the downstream reaches. Sediment budgeting showed a net balance of plus 542,200 m³ indicating high sediment deposition rates due to dam construction. Nevertheless, after infilling of all reservoirs, sediment output outweighs sediment input which suggests increased channel erosion rates downstream of the dams (Fig. 4d).

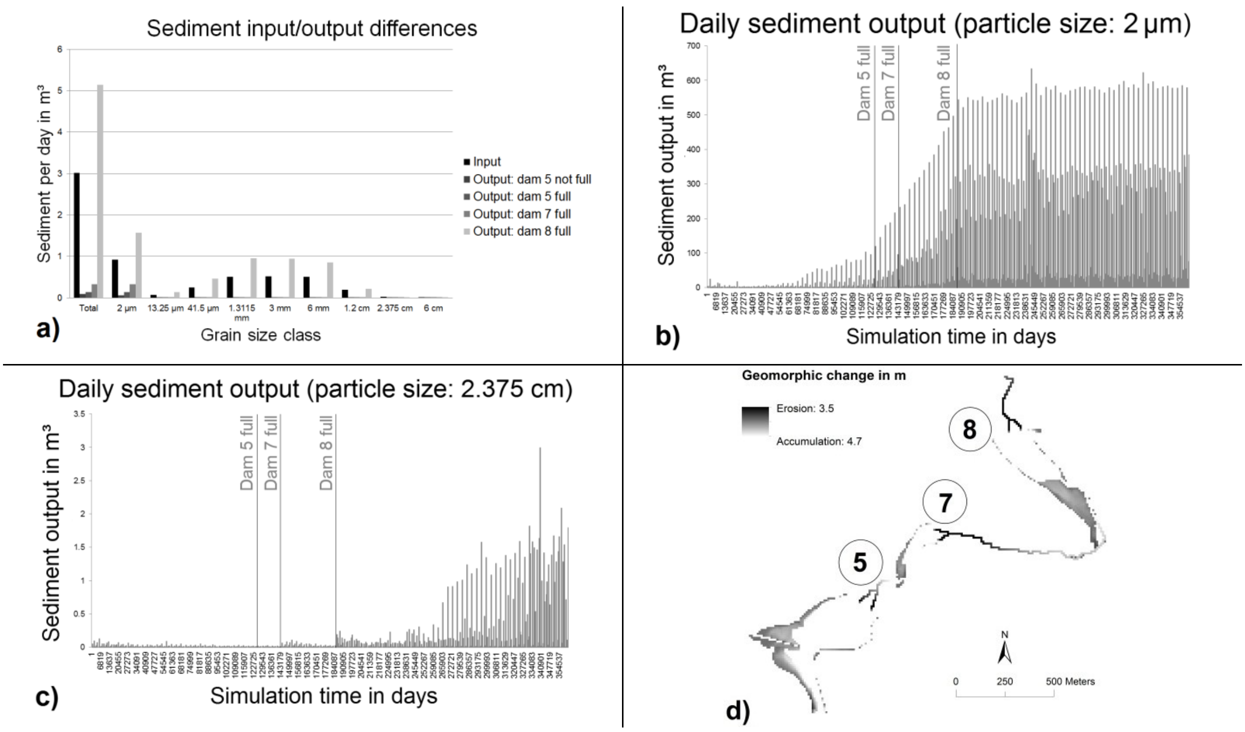


Figure 4: Modelling results for the dam construction scenario (examples): sediment outputs for a) all grain size classes, b) suspended sediments, c) bedload sediments; d) geomorphic channel changes

2) Dam removal scenario
After the removal of all dams, modelled sediment output rates outweighed sediment input rates (Fig. 5a, 5b, 5c) indicating a phase of high erosion rates removing most of the sediment volume which was accumulated during the dam construction scenario. This is also reflected by the results of the simulated channel changes after dam removal (Fig. 5d) exhibiting high erosion rates especially in the former reservoir areas as well as by the sediment budget calculations which resulted in a net balance of minus 529,700 m³ of sediment. However, 12,500 m³ of sediment are still stored in the system which shows that not all deposited sediment has been eroded after dam removal. It is interpreted that after a phase of high erosion rates the establishment of bed armoring prevented from further bed erosion processes. This assumption is also strengthened by sediment output rates that equal sediment input rates after the phase of erosion which indicates a system in equilibrium (see Fig. 5b, 5c).

Conclusions

Dams and dam removal significantly alter the sediment connectivity and sediment dynamics of river systems which results in geomorphic channel changes (e.g. channel degradation downstream of dams). Channel degradation calls for further intervention in terms of river bed and bank protection measures. However, the installation of such mitigation measures has been shown to prevent from channel slope recovery and therefore from recovery of sediment connectivity along the river channels. Based on our modelling results, we further conclude that geomorphic response to dam construction and dam removal can be complex in space and timeas sediment output rates and therefore geomorphic processes have been shown to act in a non-linear manner. These insights have also major implications for river management and conservation, as quality and state of riverine habitats are determined by channel morphology and river bed sediment composition (e.g. spawning grounds for fish, macrozoobenthos community structure).

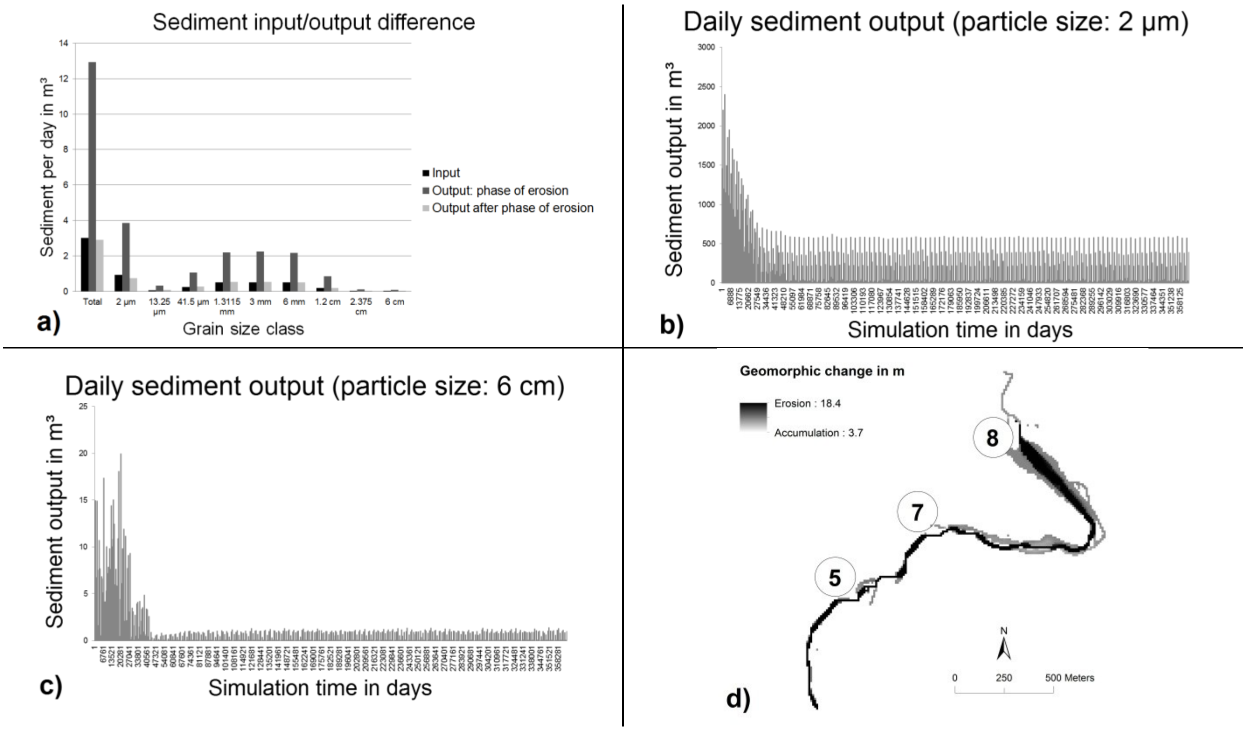


Figure 5: Modelling results for the dam removal scenario: sediment outputs for a) all grain size classes, b) suspended sediments (example), c) bedload sediments (example); d) geomorphic channel changes

References

Blue Marble Geographics 2009. Global Mapper Version 10, Blue Marble Geographics, Hallowell, Maine, USA

BRIERLEY, G., FRYIRS, K., VIKRANT, J. 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38(2): 165-174

COULTHARD, T.J., HICKS, D.M., VAN DE WIEL, M.J. 2007. Cellular modelling of river catchments and reaches: advantages, limitations and prospects. Geomorphology 90: 192–207

COULTHARD, T.J. 1999. Modelling upland catchment response to Holocene environmental change.PhD Thesis, School of Geography, University of Leeds, 181 pp.

ESRI 2010. ArcGIS for Desktop Version 10.0, Environmental Systems Research Institute, Redlands, California, USA

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

KNITTLER, H. 2005. Teiche als Konjunkturbarometer? Das Beispiel Niederösterreich. In: Water management in medieval rural economy. Les usages de l'eau en milieurural au MoyenÂge (= Ruralia V): 208-221

POEPPL, R.E., KEILER, M., ELVERFELDT, K.V., ZWEIMUELLER, I., GLADE, T. 2012. The influence of riparian vegetation cover on diffuse lateral connectivity and biogeomorphic processes in a medium-sized agricultural catchment, Austria. Geografiska Annaler, Series A, Physical Geography, 94: 511-529

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, 95pp. incl. DVD-Rom

WENTWORTH, C.K. 1922. A scale of grade and class terms for clastic sediments.Journal of Geology 30: 377-392

Contact

Ronald E. Poeppl
ronald.poeppl@univie.ac.at

Thomas Glade
thomas.glade@univie.ac.at

Department of Geography and Regional Research
University of Vienna
Universitätsstraße 7
1010 Vienna
Austria

Saskia D. Keesstra
saskia.keesstra@wur.nl

Soil Physics and Land Management Group
Wageningen University
Costerweg 50
6701-BH Wageningen
The Netherlands

Margreth Keiler
margreth.keiler@giub.unibe.ch

Institute of Geography
University of Bern
Hallerstrasse 12
3012 Bern
Switzerland

Tom Coulthard
T.Coulthard@hull.ac.at

Department of Geography
University of Hull
Cottingham Road
Hull, HU6 7RX
United Kingdom