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The geomorphic legacy of small dams—An Austrian study

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ABSTRACT

Dams represent one of the most dominant forms of human impact upon fluvial systems during the Anthropocene, as they disrupt the downstream transfer of water and sediments. Removing dams restores river continuity and channel morphology. Both dam construction and dam removal induce geomorphic channel responses that often require the installation of channel protection structures. Although such measures are well-established in river engineering, little is known about their interactions or legacy effects on river sediment dynamics, channel morphology and riverine habitats. This study investigated the legacy effects of small dams and their removal on bed sediment and channel morphology in two small mixed-load streams in Austria using field mapping and DEM-based geomorphometric channel analyses. At active dams, results showed increases in channel slope (1.76–13.88%) and depth (0.1–2 m) as well as in dominant bed sediment grain size. At some dam removal sites without channel protection structures, we observed balanced channel slope conditions and decreases in channel depth (0.5–1.9 m) as well as homogeneous bed sediment textures. At sites exhibiting channel engineering, bed and bank protection structures inhibited geomorphic response to dam removal, thereby preserving dam-induced channel conditions. However, at numerous locations geomorphic responses to dams and their removal were observed to be more complex as they are governed by dam interactions and feedback processes that are further influenced by the proximity of other dams and related hydro-geomorphic conditions.

1. Introduction

Dams represent one of the most dominant forms of human impact upon fluvial systems (Grant, 2012) and are seen as being one of the greatest modifications to the fluvial landscape during the Anthropocene (Skalak et al., 2013). They disrupt the downstream transfer of water and sediments (i.e. water and sediment connectivity), thereby inducing a range of geomorphic responses including aggradation and siltation upstream and enhanced flow variability and degradation downstream (Wohl, 2004; Petts and Gurnell, 2005; McCluney et al., 2014). These effects are further accompanied by textural channel bed adjustments (change in grain sizes), especially in mixed-load rivers (Grant et al., 2003; Grant, 2012), including the formation of bed armouring downstream (Williams and Wolman, 1984; Vericat et al., 2006; Schmidt and Wilcock, 2008).

More than 800,000 dams have been constructed world wide to provide services such as drinking water supplies, hydropower production, irrigation and flood control (Friedl and Wüest, 2002). A total of 48,000 dams are classified as large dams, defined as being dams over 15 m high and/or exhibiting a reservoir exceeding 3 million m^3 (cf. International Commission on Large Dams (ICOLD)). The great majority of dams are lower than 15 m in height. In the fields of fluvial geomorphology and river management, most attention is given to large dams (Graf, 2005), while the effects of small dams have often been overlooked. Recently, however, some case studies on small dams have highlighted their importance in shaping fluvial landscapes. Walter and Merritts (2008), for example, found that base-level changes induced by the construction of small mill-dams were the primary cause of fluvial aggradation and degradation in the eastern United States. Furthermore, Tullos et al. (2014) detected significant disturbances related to sediment pulses in the near-downstream reaches in two streams where small dams had been removed. Ecological recovery

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from these disturbances occurred within the year following removal of the dam, whereas geomorphic disturbance persisted for two years following dam-removal (Tullos et al., 2014).

Downstream effects of dams – such as river bed and bank erosion – often require the installation of protective measures (Gregory, 2006) such as downstream channel bed and bank protection structures, especially when infrastructure is threatened. These protective measures potentially inhibit “natural” geomorphic dynamics and adjustments. Upstream effects of dams, such as sediment infilling of reservoirs, require dredging, or in some cases complete dam removal. Dam removal can also result in numerous detrimental geomorphic impacts (e.g. erosion of reservoir sediments; Doyle et al., 2003; Cantelli et al., 2004) which may require additional interventions, for example the installation of bed and bank protection structures upstream of the former dam site to prevent channel erosion. Although channel protection measures are well-established in river engineering, less is known about their legacy effects on river sediment dynamics and channel morphology. We hypothesize that the presence of channel bed and bank protection measures inhibits the long-term geomorphic response to dam removal. Rather, these measures preserve dam-induced channel and bed sediment conditions.

Hydromorphological alterations due to dam construction have resulted in the alteration of flow and sediment regimes and riverine habitats (e.g. textural bed adjustments), thereby severely reducing the diversity of riverine biota (Poff et al., 2007). Evaluating the effects of river engineering on fluvial processes and river morphology has therefore become increasingly important to river management during recent decades (Skalak et al., 2013). Evaluating the impacts of in-stream structures on geomorphic dynamics along European rivers as part of river restoration efforts has further evolved as a legal requirement under the European Water Framework Directive (EU, 2000), and is one of the major issues in river basin management plans, such as in the Danube River Basin (ICPDR, 2009). One measure to restore river continuity and channel morphology which has become increasingly popular in recent decades is dam removal (Bushaw-Newton et al., 2002; Wildman and MacBroom, 2005; Burroughs et al., 2009; Kibler et al., 2011; Tullos et al., 2014). The commonly-held view of geomorphic river recovery after dam removal is that the channel will again incise and remove the sediment accumulated in the reservoir, and in this way restore pre-dam conditions (Poff and Hart, 2002). However, many restoration projects have failed (Wohl et al., 2005) due to incomplete pre-assessments or basic concepts that neglect the role of legacy effects (Doyle et al., 2005) and feedback mechanisms (cf. Bednarek, 2001), as well as the effects of complex geomorphic system response to change (Schumm, 1973; Pizzuto, 2002). Geomorphic adjustments to dams and their removal are myriad and complex, as they further depend on watershed, climate and dam characteristics (Pizzuto, 2002; Fassnacht et al., 2003; Cheng and Granata, 2007; Skalak et al., 2013). The situation gets even more complex in systems which are impacted by multiple dams as well as by channel protection structures, due to the interactions which occur, and feedback processes. We hypothesize that within a series of dams, the geomorphic response to dam removal is influenced by the proximity of other dams and related hydro-geomorphic conditions.

Skalak et al. (2013) proposed a conceptual model of how interacting dams might affect river geomorphology, resulting in distinct and recognizable morphologic sequences in alluvial rivers which they termed “inter-dam sequence”, further performing a case study in the Upper Missouri River. They identified five unique geomorphic gradational reaches (Fig. 1), two of which are controlled solely by the upstream dam (termed “Dam Proximal” and “Dam-Attenuating”) and three of which are controlled by the dam interaction (termed “River-Dominated Transitional”, “Reservoir-Dominated Transitional” and “Reservoir”.

Using the knowledge gaps identified above as a starting point, we investigated the legacy effects of small dams, their removal and channel protection structures on bed sediment and channel morphology in two small mixed-load streams in Austria, highlighting the role of complex interactions between geomorphic channel processes and engineering activities. In addition, we tested the conceptual model by Skalak et al. (2013) showing how interacting dams might affect river geomorphology in a selected river section impacted by a series of small dams. Finally, we discussed the implications for river restoration and freshwater ecology.

2. Study area

The adjoining catchments of the Fugnitz and Kaja Rivers are located in northeast Austria on the border with the Czech Republic (Fig. 2). Both rivers are mixed-load single-thread perennial wadable streams that enter the Thaya River, which delineates the border between Austria and the Czech Republic before draining into the Morava River, a tributary to the Danube River. The Fugnitz River has a total length of 29.7 km and a catchment area of 138.4 km^2, while the 10.7 km long Kaja River drains a 21.3 km^2 watershed.

The region is characterized by a humid temperate climate with a mean annual temperature of ~8 °C and mean annual precipitation rates of ~500–600 mm, with maxima between April and September which is also reflected in the river runoff regimes that are further influenced by snowmelt processes (Fig. 3). The last high magnitude (100-year) flood event occurred along the Fugnitz River in June 2006, caused by a local thunderstorm cell (Thayatal Nationalpark, 2010).

The upper and middle reaches of both rivers have low river gradients, low slope angles, no bedrock steps and wide open valleys (see Fig. 2). The lithology consists of mica granite, mica gneiss and mica shale which are superimposed with Tertiary brackish-maritime sediments (clay to coarse gravel) and Quaternary loess (silt, fine sand) (GBA, 2008a, 2008b).

The area is predominantly used as cropland, mainly for growing cereals and rape (data source: AMA Austria, 2010). Lateral sediment input from adjacent hillslopes is mainly governed by soil erosion processes driven by water (cf. Poeppl et al., 2012). The lower reaches show high river gradients including bedrock steps, high slope angles, V-shaped valleys or V-shaped valleys with alluvial fills and bedrock mainly composed of mica granite, mica gneiss and mica shale (GBA, 2008a, 2008b). Here, land use and land cover are dominated by forests and woodland and lateral sediment input from adjacent hillslopes is dominated by mass wasting processes (e.g. rockfalls). Extensive land cover changes in the upper and middle reaches date back to the 13th century, when Bavarian settlement resulted in extensive deforestation and agricultural activities. Thereafter, no comparable land use or land cover changes took place in the catchments.

The Fugnitz and Kaja Rivers have both been impacted by multiple dams, which were built as overflow earth dams between 1425 (Knittler, 2005) and 1823 (see also Fig. 2). They range from three to six metres in height, with small storage capacity reservoirs mainly used for fish-farming purposes (Poeppl, 2010). At present, three dams are still active along the Kaja River, while all other dams had been removed before 1911 (see Figs. 2 and 4) due to a rapid loss in importance of the pond farming economy (Knittler, 2005). Along the Fugnitz River, four active weir dams are present, which were built as mill dams or for water diversion and extraction for the supply of water to fish ponds adjacent to the main river course (Fig. 5). Except for Fugnitz Dam 11 and Kaja Dams 12 and 13, all

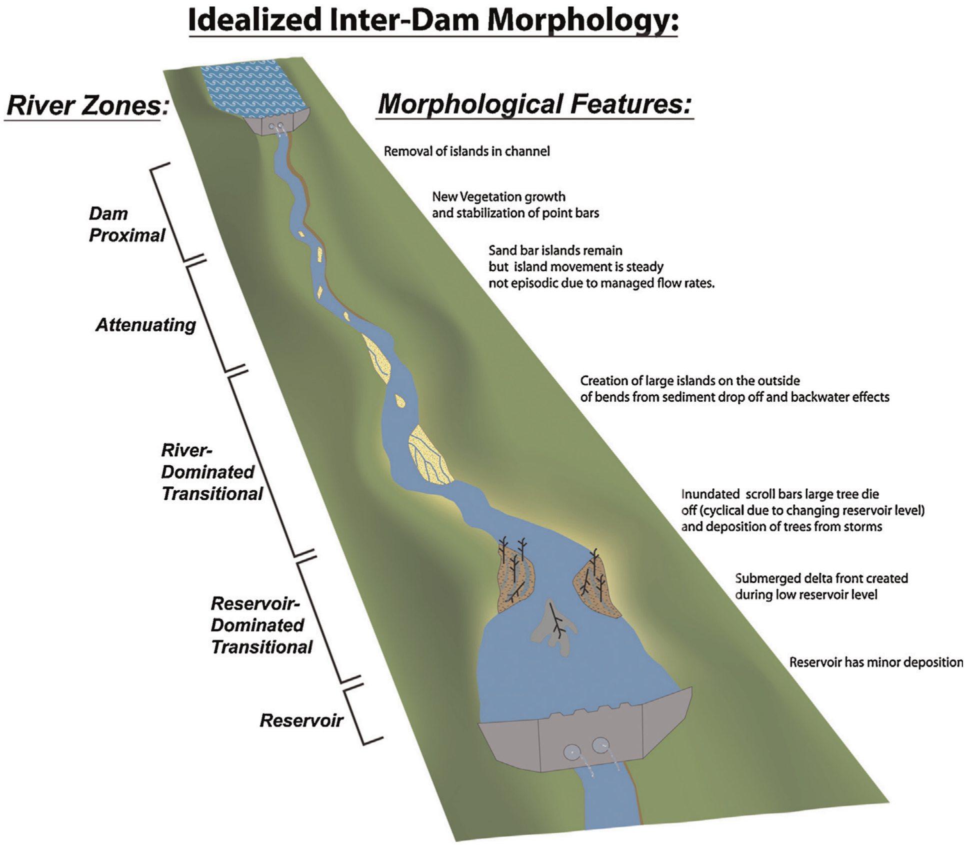

Fig. 1. Conceptual model of channel morphology that results from dam interaction along a river reach (taken from Skalak et al., 2013). Removal of islands occurs just below the dam in the Dam Proximal Zone (bed degradation and bank erosion are also likely). The eroded sediment may be locally deposited in new islands and sand bars downstream. These sand bars and islands are stable in the Dam Attenuating Zones but erosion and deposition are likely less episodic due to the controlled releases from the dam. In the transitional reaches all sediment that has not been locally deposited will accumulate here. This results in large distributary islands and deposition of large wood. Finally, in the downstream reservoir, the historic channel is completely submerged.
Reproduced from Skalak et al. (Anthropocene volume 2).

dams are located in the upper or middle river reaches of the systems. Notable tributaries in terms of water sediment delivery enter the Fugnitz River directly upstream of Dam 9, while none are present in the Kaja River system (see also Fig. 2) (Poeppl, 2010).

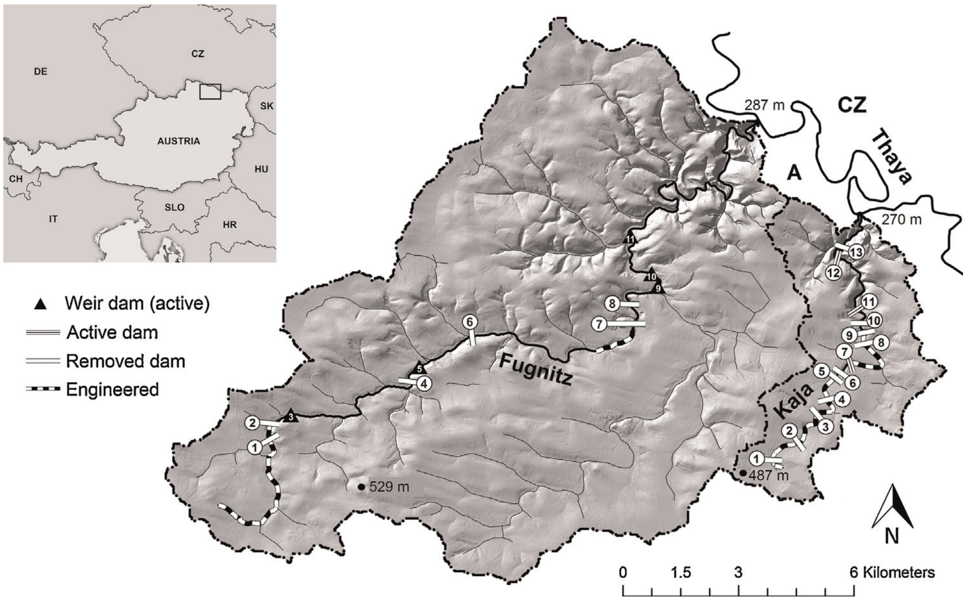

Fig. 2. Fugnitz and Kaja River catchments with types and locations of dams and channel engineering structures. Dam numbering increases from upstream to downstream. Data source (DEM with 1 m × 1 m resolution, river network and watershed delineation): Provincial Government of Lower Austria, 2010.

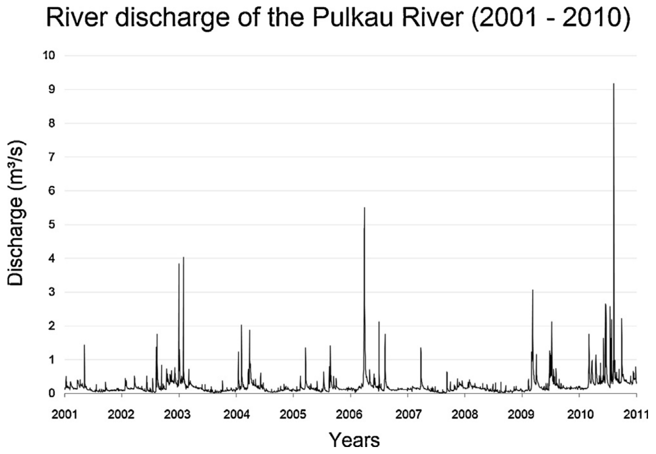

Fig. 3. Discharge data of the Pulkau River between 2001 and 2011. The Pulkau River catchment has a size of 87.6 km^2 (location of the gauging station), neighbours the Kaja and Fugnitz River catchments in the South and shows comparable physiographic conditions.
Data source: Hydrographic Service of Lower Austria, 2001–2011.

In the early 1970s, in the course of regulation works the local authorities installed river bed and bank protection structures in the upper and middle reaches to prevent lateral erosion and channel incision (Fig. 6). In the upstream river reaches, these channel-protection measures are mainly made of concrete chutes (Fig. 6A), in some cases combined with the installation of camp-shedding, while in the middle and lower reaches rip raps, in some cases combined with concrete chutes, have been used for channel protection (Fig. 6B). Rip raps were built of boulders, in most cases filled with concrete. Camp-sheddings are made of piles and boards along the river banks. Concrete chutes prevent channel-bed erosion, while rip raps and camp-shedding serve as very effective measures against lateral erosion and channel migration. As both rivers exhibit very similar physiographical characteristics, observations along both rivers were combined to collect a more comprehensive and representative dataset.

3. Methods

3.1. Assessment of river engineering structures and bed sediment

We mapped the locations of active and removed dams from a hillshade from an airborne LiDAR DEM with 1 m × 1 m resolution, which was obtained between late November 2007 and early April 2008 during low flow conditions (data source: Provincial Government of Lower Austria, 2014). The results were cross-checked with geological maps at a scale of 1:50,000 containing information on the presence of dam features (GBA, 2008a, 2008b) as well as by ground-truthing during extensive field surveys in May 2010 during low flow conditions. During these field surveys, we also mapped different types of river engineering structures: active weir dams, removed weir dams, and river bed and bank protection structures.

In order to determine channel bed sediment conditions, facies mapping (i.e. mapping of the top stratum of the streambed on the basis of visually-obtained surface particle size (Kondolf et al., 2003)) was applied. The term “facies” generally refers to sedimentary deposits that are distinct in grain size and/or sedimentary structure representing depositional environments (Pettijohn, 1975). Facies maps are useful as descriptors of current channel conditions, as baseline data against which to measure future change, or as a basis for comparing sediment conditions along channels and channel reaches (Kondolf et al., 2003). In the course of the field surveys, six different bed sediment categories were visually determined according to the dominant sediment grain size (cf. Wentworth, 1922; see Table 1), further relating changes in bed sediments to the presence and type of river engineering structure.

3.2. Assessment of channel morphology

In order to assess the geomorphic effects of dams, dam removals and dam-related river engineering structures on channel morphology, we developed and analysed longitudinal and cross-sectional channel profiles:

Fig. 4. Dam section along the Kaja River (flow direction from South to North): Dam 11 is still active, while Dams 8–10 have been removed (see also Fig. 1B). River sections upstream of Dams 8 and 9 are engineered. The former reservoir area upstream of Dam 8 is still clearly visible in the field (dashed line). Data source (DEM with 1 m × 1 m resolution, aerial photograph with 0.25 m × 0.25 m resolution): Provincial Government of Lower Austria, 2010.

We created *longitudinal profiles* based on elevation information derived from the non-filled airborne LiDAR DEM with 1 m × 1 m resolution. The main river channels were manually digitized as polyline layers in ArcGIS 10 (ESRI, 2010) and further converted into raster data containing elevation information from the DEM. Afterwards, we converted each single cell of the raster data into point data. Point data information on elevation was then plotted to create longitudinal profiles of the main river channels. The channel slope was calculated for channel sections 50 m up- and downstream of the dam in order to identify changes in channel slope.

Channel cross sections were digitally compiled 20 m upstream of the reservoir inlet and 20 m downstream of the dam toes based on non-filled airborne LiDAR DEM with 1 m × 1 m resolution using the "Path Profile/LOS Tool" in Global Mapper 10 (Blue Marble Geographics, 2009). In the case of active dams, the upstream profile was taken in river reaches unaffected by backwater. The channel cross-sections were geomorphometrically analysed based on the DEM according to their maximal channel depths, widths and cross-sectional areas, assuming a bankfull stage. Finally, we have related upstream to downstream changes in channel slope and channel depths to the presence and type of river engineering structure and considered as a proxy for channel incision and aggradation.

LiDAR data in fluvio-geomorphic studies are subject to limitations, e.g. as near-infrared (NIR, 1064 nm) laser pulses emitted by most LiDAR systems are strongly absorbed by water and therefore fail to provide topographic information from deeply-submerged areas of the channel (Reusser and Bierman, 2007; Notebaert et al., 2009). However, LiDAR data can be used to derive channel bed morphology of small streams with low water levels (<2 m) (James et al., 2007; Cavalli et al., 2008; for technical details refer to Kinzel et al., 2007; Hilldale and Raff, 2008; Allouis et al., 2010).

Fig. 5. Weir dam (Dam 9) along the Fugnitz River (refer to Fig. 1B) used for water diversion and extraction for the supply of water to the fish ponds separate from the main river course (not visible here); (A) photograph taken upstream of the dam wall (see controllable outlet on the left hand side of the dam wall; flow direction from left to right); (B) photograph taken downstream of the dam wall.

In order to be able to test the conceptual model by Skalak et al. (2013), we applied further field mapping in two active inter-dam sequences along the Kaja River (i.e. between Dams 7 and 11 (impacted by river engineering and dam removal) and between Dams 11 and 13). For this, we delineated the following features: sediment bars (vegetated and non-vegetated) including information on channel bed sediments derived by facies mapping (Kondolf et al., 2003; see also Section 3.1), presence of large woody debris and bank erosion. It is assumed that vegetated sediment bars reflect higher sediment bar age and stability (Hickin, 1984; Gurnell et al., 2001), while we further hypothesize that large woody debris reduces sediment transport capacity, further inducing sediment accumulation as well as bed scouring, flow diversion and bank erosion downstream (Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Curran and Wohl, 2003; Hicks et al., 2007; Gurnell, 2012). The obtained data have been interpreted to test the conceptual model by Skalak et al. (2013) of how interacting dams might affect river geomorphology for a selected river section impacted by a series of small dams. For this, we roughly divided the river sequences into different zones determined by distance to the dam as well as of bed sediment grain sizes, reflecting the influence of backwater effects using the terminology as presented by Skalak et al. (2013) (see also Fig. 1): Dam Proximal, Attenuating, River-Dominated Transitional, Reservoir-Dominated Transitional and Reservoir.

4. Results

In the following sections detailed results on the impact of dams, their removal as well as the effects of channel-protection structures on channel bed sediments (Section 4.1) and on channel morphology (Section 4.2) are shown, while a summarizing overview of the results is provided in Table 2.

Fig. 6. Channel protection structures: (A) Concrete chutes along the Kaja River downstream of Dam 7 (refer to Fig. 2B); (B) Rip raps (partially covered by grass) along the Fugnitz River upstream of Dam 7 (refer to Fig. 2B).

Table 1
Bed sediment grain size categories determined in the course of facies mapping (cf. Wentworth, 1922).

Category	Description	Dominant grain size in mm
0	No sediment (bedrock or concrete bed)	–
I	Boulders	>256
II	Cobbles	64–256
III	Gravels	2–64
IV	Sands	0.63–2
V	Fines	<0.63

4.1. River engineering structures and bed sediments

Along the Fugnitz River, we identified five active weir dams and six removed dams (Figs. 2 and 7A), while the Kaja River has three active dams, ten removed dams and no weir dams (Figs. 1 and 7B), resulting in a total of 24 observations (Table 3). Five different types of river engineering categories were classified for the observed systems: see Table 3. One notable tributary in terms of water and sediment delivery, potentially influencing bed sediment and channel morphology exists along the Fugnitz River upstream of Dam 9. Due to the low number of observations per river engineering category, statistical analyses of site-specific variables were omitted.

We observed “bed sediment coarsening”, i.e. an increase of at least one grain size category between the upstream and downstream river sections adjacent to dam locations, at 14 sites in total. At ten sites we detected no change, while none of the observations exhibited the opposite effect (i.e. “bed sediment fining”) (Fig. 7A and B, Table 2). At no location of tributary inflow a visible shift in bed sediment was observed.

4.2. Channel morphology

4.2.1. Longitudinal profiles

At 18 locations we observed an upstream to downstream increase in channel slope, while at four sites no significant change (i.e. within a range of +–0.5%) was detected. Two observations exhibited a decrease in channel slope between the upstream and downstream channel reaches (see Tables 4 and 2, Fig. 7A and B).

Table 2
Summarizing overview of the results (see also Tables 2–4): bed sediment texture and channel morphology characteristics of the Fugnitz (FUG) and Kaja (KAJ) Rivers per engineering category upstream (“Up”) and downstream (“Down”) of dam locations. “No_change” denotes no change in bed sediment, channel slope (i.e. within a range of +–0.5%) and channel depth (i.e. within a range of +–0.5 m); “*” denotes the presence of a tributary upstream.

	Dam#	Channel protection		Bed sediment			Channel slope			Channel depth		
		Up	Down	Finer_down	Coarser_down	No_change	Flatter_down	Steeper_down	No_change	Shallower_down	Deeper_down	No_change
Category A	FUG 3				X			X			X	
	FUG 5				X			X				X
	FUG 9*				X			X			X	
	FUG 10				X			X			X	
	FUG 11					X		X			X	
Category B	KAJ 7		X		X			X		–	–	–
	KAJ 11		X		X			X				X
	KAJ 12		X		X			X			X	
Category C	FUG 4					X			X	X		
	FUG 6					X			X			X
	FUG 8				X				X	X		
	KAJ 6					X		X		–	–	–
	KAJ 10					X	X					X
	KAJ 13				X			X				X
Category D	FUG 1	X	X			X			X			X
	KAJ 1	X	X			X		X				X
	KAJ 2	X	X		X			X				X
	KAJ 3	X	X		X		X					X
	KAJ 4	X	X			X		X				X
	KAJ 8	X	X		X			X				X
Category E	FUG 2	X			X			X				X
	FUG 7	X			X			X			X	
	KAJ 5	X				X		X		–	–	–
	KAJ 9	X				X		X			X	
n		10	9		14	10	2	18	4	2	7	12

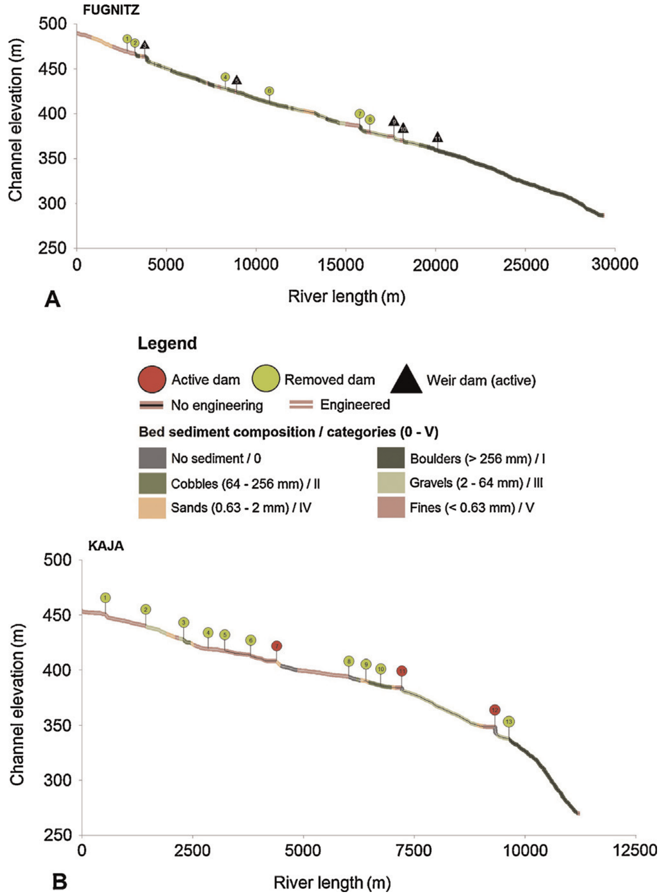

Fig. 7. Longitudinal profile, river engineering and bed sediment of the (A) Fugnitz River and (B) Kaja River.

The highest increase at a category A site existed at Fugnitz Dam 9, where a tributary enters the Fugnitz River directly upstream of the dam (Table 4).

4.2.2. Cross-sectional profiles

At 21 sites, we were able to perform an up-to-downstream comparison of channel cross-section dimensions, while at three locations wetlands instead of river channels were present (Tables 5 and 2). At seven locations, significant upstream to downstream increases in channel depth were identified, while the largest increase was observed at Fugnitz Dam 9, where a tributary enters the Fugnitz River directly upstream of the dam. At two locations, we detected an upstream to downstream decrease in channel depth, while seven sites exhibited no significant upstream to downstream changes (i.e. changes within a range of +/−0.5 m). In Fig. 8, one representative cross-sectional profile example for each engineering category (A–E) is presented.

4.2.3 Inter-dam sequences

Field mapping of the inter-dam sequence A affected by river engineering and dam removal along the Kaja River demonstrated a total absence of sediment bars in the Dam Proximal (DP) and Attenuating (AT) Zones, which are further impacted by channel engineering. In the River-Dominated Transitional Zones (RivDT), also impacted by engineering in the upper reaches, we observed eight non-vegetated sediment bars, of which five were directly related to woody debris jams. In the upper and lower reaches, bed sediment is dominated by fines (category V), no sediment (category 0) or sands (category IV), while bed sediment in the lower reach is characterized by cobbles (category II; Fig. 9A, Table 6). In the Reservoir-Dominated Transitional Zone (ResDT) we observed two non-vegetated sediment bars, of which one was directly related to woody debris jams. In this zone, bed sediment is dominated by sands. Along the inter-dam sequence B (no engineering), 16 vegetated and 16 non-vegetated sediment bars were observed in total, of which six vegetated and eight non-vegetated were directly related to woody debris jams (Fig. 9B). Sediment bars could be found in all zones except in the middle reaches of RivDT, as well as in the Res Zone. Bed sediment of the whole inter-dam sequence B is characterized by gravels (category II), except in the backwater reaches of Dam 12 (ResDT) where bed sediment is dominated by sands. We observed bank erosion to occur predominantly at locations of large woody debris jams, in combination with the occurrence of mostly non-vegetated sediment bars (Fig. 9, Table 6). For the Reservoir Zones (Res), unfortunately no sediment data were available.

5. Discussion

5.1. Bed sediments

River bed sediment depends on a number of factors, especially sediment source and stream power (Hooke, 2003; also refer to Einstein, 1950; Nordin et al., 1980; Van Rijn, 1984; Guyot et al., 1999; Wilcock and Crowe, 2003). Stream power is governed by several parameters, including channel slope, discharge and bed roughness (Bagnold, 1966). The overall influence of lithology, land use and hillslope processes (lateral sediment input), as well as channel slope conditions on bed sediment are reflected in our results showing abrupt coarsening from the upper and middle (i.e. Tertiary and Quaternary (loess) sediments, arable land, soil erosion processes, low river gradient) to the lower river reaches (i.e. crystalline rocks, forests and mass wasting processes (e.g. rock-falls), high river gradient). Except for the aforementioned regional factors influencing bed sediment, the results show that the presence of dams and channel protection structures significantly influence bed sediment texture in the observed mixed-load rivers (cf. Simon and Rinaldi, 2006).

At active overflow dams, the observed sediment coarsening between the upstream and downstream river sections is related to altered stream power conditions. Reduced stream power results in

Table 3
Overview of the five types of river engineering categories and their frequency of observation identified along the Fugnitz and Kaja Rivers; "*" denotes the presence of a tributary upstream.

Category	Type of river engineering	Fugnitz	Kaja	*n*
A	Active dams without channel protection	Dams 3, 5, 9*, 10, 11	–	5
B	Active dams with downstream channel protection	–	Dams 7, 11, 12	3
C	Removed dams without channel protection	Dams 4, 6, 8	Dams 6, 10, 13	6
D	Removed dams with up and downstream channel protection	Dam 1	Dams 1, 2, 3, 4, 8	6
E	Removed dams with upstream channel protection	Dams 2, 7	Dams 5, 9	4
∑				24

Table 4
Upstream to downstream differences in mean channel slope for river sections adjacent to dam locations of each river engineering category; "*" denotes the presence of a tributary upstream.

a) Fugnitz	Dam#	Upstream slope in %	Downstream slope in %	Difference in %
Category A	3	2.18	7.84	5.66
	5	0.46	2.22	1.76
	9*	0.4*	7.5*	7.1*
	10	0.02	2.78	2.76
	11	0.7	2.68	1.98
Category C	4	0.2	0.32	0.12
	6	1.22	0.74	-0.48
	8	0.32	0.34	0.02
Category D	1	1.1	1.1	0
Category E	2	0.4	2.24	1.84
	7	1.5	6.52	5.02

b) Kaja	Dam#	Upstream slope in %	Downstream slope in %	Difference in %
Category B	7	0.02	5.9	5.88
	11	0.002	6.9	6.9
	12	0.02	13.9	13.88
Category C	6	1.48	3.2	1.72
	10	1.2	0.6	-0.6
	13	0.78	3.04	2.26
Category D	1	0.68	8.42	7.74
	2	0.86	2.72	1.86
	3	4.44	1.22	-3.22
	4	0.18	0.76	0.58
	8	0.95	1.76	0.81
Category E	5	0.34	2.82	2.48
	9	0.14	0.9	0.76

the accumulation of fine sediments upstream, while increased stream power causes bed degradation, accompanied by erosion of fine sediments, downstream (Brandt, 2000; Petts and Gurnell, 2005; Keesstra et al., 2005). However, the opposite effect, i.e. bed sediment coarsening in river reaches upstream of dams (Wolman, 1955; Leopold, 1973; Jacobson and Coleman, 1986; Walter and Merritts, 2008), which is expected when dams are removed, was not observed at dam removal sites exhibiting channel bed and bank protection structures. These structures rather preserved pre-dam-removal channel slope and thus stream power conditions by preventing geomorphic channel adjustments after dam removal. Moreover, at two dam-removal sites without channel protection structures, the expected upstream bed sediment coarsening also failed to occur (i.e. Fugnitz Dam 8 and Kaja Dam 13). At these locations, channel cross-section analysis suggests potentially-ongoing upstream channel incision (Fugnitz Dam 8) as well as uncommon upstream channel widening (Kaja Dam 13; see Table 4; for explanation of upstream channel widening see next section). Both processes cause reworking and supply of underlying fine reservoir sediments to the channel system, thereby potentially causing bed sediment fining (Doyle et al., 2005).

5.2. Channel morphology

Characteristic geomorphic channel adjustments at active dam sites, i.e. upstream aggradation (Heppner and Loague, 2008) and downstream degradation (Grant et al., 2003) caused by dam-induced base-level changes, are clearly reflected by the observed channel slope values, increasing from upstream to downstream. The expected opposite effects when dams are removed, i.e. upstream channel incision (Schumm et al., 1984; Simon and Rinaldi, 2000) leading to balanced slope conditions, are also visible in our findings at three out of six dam removal sites which do not have any channel-protection structures (category C; i.e. Fugnitz Dams 4, 6 and 8). At dam removal sites of categories D and E, pre-dam-removal channel slope conditions have been preserved by the installation of channel protection structures as these structures inhibited geomorphic channel adjustments after dam removal.

The same phenomena as mentioned above are also demonstrated by the results of channel depth analyses for the category A, B, C, and E sites. A, B and E sites exhibited an up-to-downstream increase in channel depth indicating downstream incision. At category C sites we observed an up-to-downstream decrease in channel depth, indicating upstream incision after dam removal followed by the presence of a deeply incised channel in the upstream reaches (Wildman and MacBroom, 2005; Burroughs et al., 2009). However, at many other locations geomorphic responses to dams and their removal were more complex as they are governed by dam interactions and channel protection measures as well as related legacy effects on river sediment dynamics. At category D sites no up-to-downstream changes in channel depth were detected. This could have been the result by dredging activities prior to the installation of protection structures, as the practice of channelization sometimes involves lowering of the streambed by dredging (Simon and Rinaldi, 2006). Another factor potentially influencing present channel dimensions is the time-span of geomorphic response to dam construction and dam removal before the installation of channel protection structures. However, it needs to be stated here that although the exact dates of dam construction and dam removal are unknown, the long time periods between dam construction (1425–1823), dam removals (before 1911) and the installation of channel protection measures (early 1970's) suggest that in our case time (+60 years) as a limiting factor for geomorphic response to dam removal is somewhat negligible (Burroughs et al., 2009; Tullos et al., 2014). Furthermore, we observed complex geomorphic responses to dam removal at

Table 5
Cross-sectional channel profile parameters for each river engineering category; "*" denotes the presence of a tributary upstream.

a) Fugnitz	Dam#	Depth in m			Width in m (bankfull)			Area in m^2		
		Upstream	Downstream	Change	Upstream	Downstream	Change	Upstream	Downstream	Change
Category A	3	0.5	2.1	1.6	7	11	4	2	16.2	14.2
	5	2.1	1.7	−0.4	11	16	5	9.5	12.3	2.8
	9*	1.2	3.2	2	7	14	7	7.2	27.7	20.5
	10	1.8	3	1.2	10.5	15.5	5	14.2	27	12.8
	11	2	2.7	0.7	14.5	24	9.5	17.1	40.6	23.5
Category C	4	2.2	1.7	−0.5	9.7	10.5	0.8	11.3	9.2	−2.1
	6	1.7	1.9	0.2	10	10	0	9.6	10.4	0.8
	8	3.1	1.2	−1.9	23	14	−9	37.2	6.6	−30.6
Category D	1	1.3	1.3	0	8.5	10.5	2	5.4	5.5	0.1
Category E	2	0.7	0.9	0.2	5.8	8.5	2.7	2.5	4.3	1.8
	7	2.4	2.9	0.5	14	32	18	18.9	40.6	21.7

b) Kaja	Dam#	Depth in m			Width in m (bankfull)			Area in m^2		
		Upstream	Downstream	Change	Upstream	Downstream	Change	Upstream	Downstream	Change
Category B	7	Wetland	0.7	Wetland	Wetland	2.6	Wetland	Wetland	6.5	Wetland
	11	0.7	0.8	0.1	10	11	−1	3.1	3.4	0.3
	12	1	1.9	0.9	13.5	10	−3.5	5.2	9.3	4.1
Category C	6	Wetland	Wetland	Wetland	Wetland	Wetland	Wetland	Wetland	Wetland	Wetland
	10	1.2	1.5	0.3	11.5	13	1.5	7.4	11.2	3.8
	13	0.6	0.7	0.1	7	12	5	2	4.4	2.4
Category D	1	0.6	0.8	0.2	6	6	0	2	2.4	0.4
	2	0.9	0.9	0	7	7	0	3.3	3.1	-0.2
	3	2	1.8	−0.2	6.5	8	1.5	5.6	5.6	0
	4	0.5	0.6	0.1	4.5	5	0.5	1.3	1.8	0.5
	8	1	0.8	−0.2	7	6.5	−0.5	4.1	3.6	-0.5
Category E	5	0.8	Wetland	Wetland	5	Wetland	Wetland	2.3	Wetland	Wetland
	9	0.7	1.2	0.5	7.5	11.5	4	2.9	6.4	3.5

the category C sites of Kaja Dams 6 and 13, showing an up-to-downstream steepening which indicates a lack of geomorphic adjustments after dam removal. The observed lack of geomorphic adjustments at these locations could be related to their proximity to active dams and related backwater effects, as well as to the formation of channel bed armouring.

Several authors have reported the formation of bed armouring in gravel bed streams directly downstream of active dams, further limiting channel incision (Williams and Wolman, 1984; Vericat et al., 2006; Schmidt and Wilcock, 2008). Kaja Dam 6 is located within the backwater reaches of Kaja Dam 7, inhibiting upstream erosion after dam removal due to reduced stream power. Kaja Dam 13 is located directly downstream of Kaja Dam 12, where the formation of channel bed armouring was detected by Poeppl (2010). As bed armouring inhibits channel incision, bed armouring downstream of Kaja Dam 12 is further assumed to be the cause of the observed channel widening instead of the expected channel incision upstream of Kaja Dam 13. The results outlined clearly show the complexity of geomorphic responses to dam removal in systems impacted by multiple dams, as well as by channel protection structures due to interactions which occur and feedback processes that are further influenced by the proximity of other dams and related hydro-geomorphic conditions.

Mapping of channel morphology along the non-engineered inter-dam sequence of the Kaja River exhibited different results than those proposed in the conceptual model by Skalak et al. (2013). Removal of "islands" in the DP Zone did not occur directly downstream of the dam, while new vegetation growth and stabilisation of point bars, which are reflected in our data by the presence of vegetated sediment bars, seem to have taken place in the lower reach of this zone. This could be caused by dam-induced reduction of annual peak flows (Kondolf and Batalla, 2005). However, the presence of large woody debris jams seems to play a major role here in potentially limiting downstream degradation by lowering stream power and downstream connectivity, further inducing sediment retention and accumulation (Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Curran and Wohl, 2003; Hicks et al., 2007; Gurnell, 2012). This statement is supported by our data as many of the mapped sediment bars are directly related to the presence of large woody debris jams. In the AT Zone we observed numerous vegetated and non-vegetated sediment bars at large woody debris jams as well as at locations without large woody debris, which corresponds to the re-maintenance of "sand bars" in these premises as proposed in the conceptual model by Skalak et al. (2013). In the RivDT Zone, where the conceptual model of Skalak et al. (2013) proposes the creation of large "islands", we recorded numerous vegetated and non-vegetated sediment bars in the upper and lower reaches, while in the middle reaches these features were missing. This could be related to steeper channel slope and thus higher stream power conditions in the middle reaches of this zone (see knickpoint between Dams 11 and 12 in Fig. 2). As proposed by the conceptual model of Skalak et al. (2013), we observed dead and fallen trees as well as sediment bars in the backwater reaches of the dam in the ResDT Zone.

Channel morphology and bed sediment of the engineered inter-dam sequence along the Kaja River were shown to be significantly impacted by the presence of channel bed and bank protection structures. Except in the lower reaches of the RivDT and ResDT Zones, no significant sediment dynamics and related landforms were detected. Similar to the non-engineered inter-dam sequence, we recorded numerous non-vegetated sediment bars in the non-

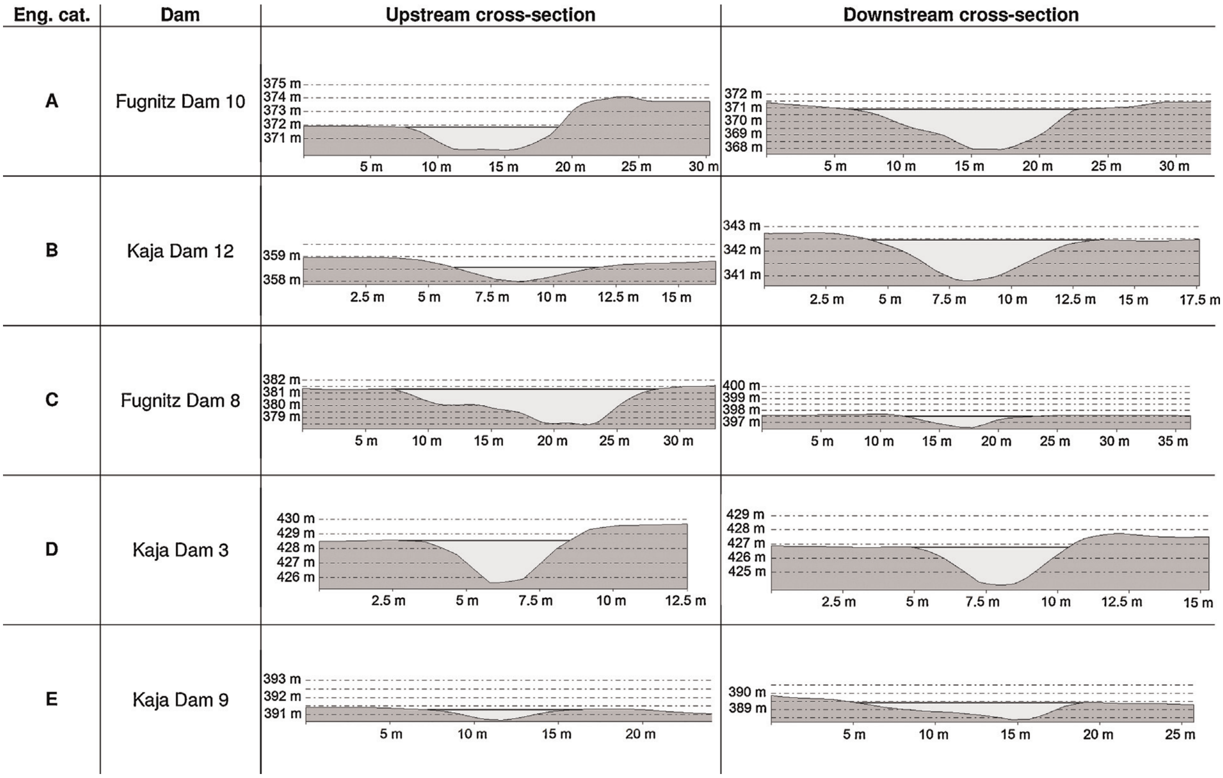

Fig. 8. Representative cross-sectional profiles for each engineering category (A–E): (A) upstream to downstream increase in channel cross-sectional dimension at active dams without channel protection; (B) upstream to downstream increase in channel cross-sectional dimension at active dams with downstream channel protection; (C) upstream to downstream decrease in channel cross-sectional dimension at removed dams without channel protection; (D) no upstream to downstream change in channel cross-sectional dimension at removed dams with up- and downstream channel protection; (E) upstream to downstream increase in channel cross-sectional dimension at removed dams with upstream channel protection.

engineered lower reaches of the RivDT Zone as well as in the ResDT Zone, of which the majority was related to the presence of large woody debris jams, while none of the sediment bars exhibited vegetation cover. Channels lacking sediment bars with vegetation cover indicate high sediment dynamics (Brierley and Fryirs, 2005; Wheaton et al., 2013). High rates of sediment availability and mobility could be related to increased sediment entrainment downstream of removed Dams 9 and 10, combined with an increase in channel slope angle and thus transport capacity related to the presence of a legacy knickpoint upstream of Dam 9 which has been preserved by channel engineering (see also Fig. 2). High sediment entrainment potential is also indicated by the high number of observed bank erosion features downstream of Dam 9 (see Fig. 8 and Table 6). To summarize our findings, at numerous locations our observations did not conform to all of the assumptions formulated in the conceptual model by Skalak et al. (2013), due to a number of factors determining river geomorphology on the local to reach scale, e.g. the presence of large woody debris jams, (legacy) knickpoints and channel engineering structures.

5.3. Implications for river restoration and freshwater ecology

The use of dams has far-reaching consequences on river ecosystem properties such as nutrient dynamics, composition, distribution and abundance of riparian vegetation, benthic algae, benthic invertebrates and fish (Thomson et al., 2005; Ellis and Jones, 2013). Therefore, dam removal as a river restoration measure might provide the basis for changes in the ecosystem structure and in the overall connectivity with adjacent stretches (Pizzuto, 2002; Feld et al., 2011). The commonly-held view of geomorphic river recovery after dam removal is that the channel will again incise into and remove the sediment accumulated in the reservoir, and in this way restore the former channel and bed sediment conditions (Poff and Hart, 2002). In general, the removal of dams produces beneficial effects for different aquatic organisms such as fish, benthic invertebrates and riparian vegetation, but the full ecological benefits can only be achieved if the re-establishment of the underlying geomorphic processes can be achieved to obtain the necessary habitat diversity (Doyle et al., 2005). While the short-term environmental effects of dam removal include changes in longitudinal connectivity, flow conditions in the impacted stretches, temperature regime and oxygen availability and turbidity conditions leading to rapid biological responses in primary production and ecosystem metabolism, full recovery (e.g. re-establishment of stable population of species in restored sections) would take much longer. It would depend on changes in bed sediments and the local habitat mosaic, which could take up to 80 years and depend largely on the effectiveness of the overall measures taken (Feld et al., 2011). Tullos et al. (2014), for example, have shown that ecological recovery after dam removal takes place in the year following dam removal, whereas signals of geomorphic disturbance persisted two years post dam-removal (Tullos et al., 2014). However, our study found that channel recovery in many reaches was impeded by the presence of protection measures on the banks and bed of the channel, and channel slope, depth, and width therefore remain in a pre-dam removal state which further impacts on transport competence and thus bed sediment conditions.

Improvement in longitudinal connectivity is expected to have immediate positive effects on the migration and mobility of adult fish and benthic invertebrates. However, limited changes in bed sediments and local channel morphology might curtail the successful re-establishment of riverine populations due to limited

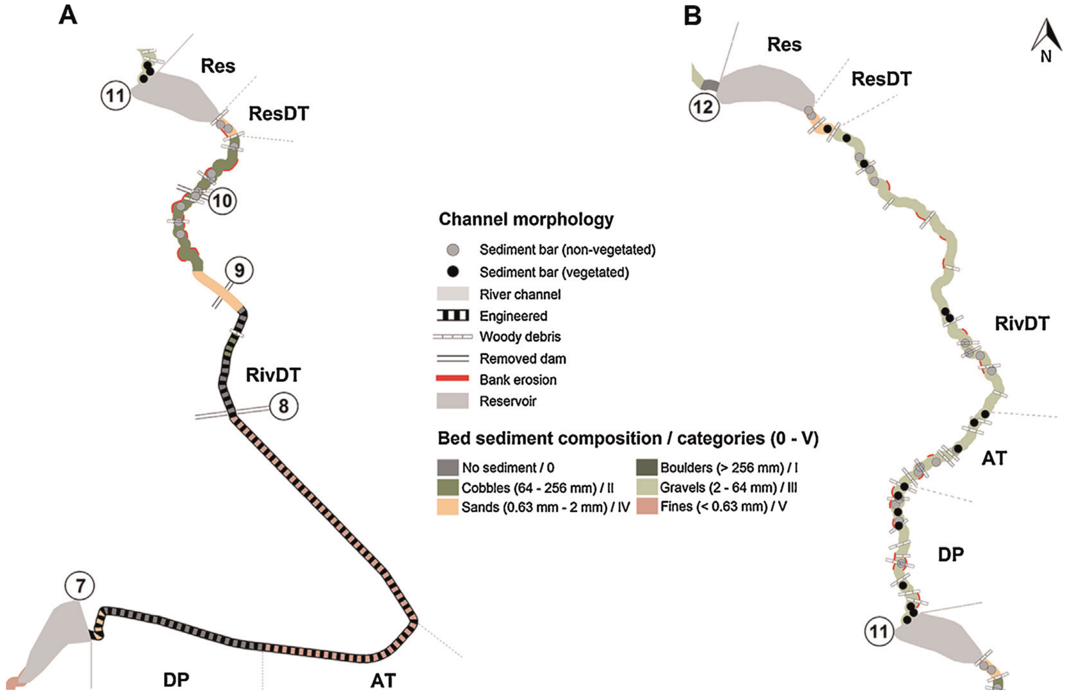

Fig. 9. Geomorphic conditions in two active inter-dam sequences along the Kaja River: (A) between Dams 7 and 11 (impacted by river engineering and dam removal), (B) between Dams 11 and 13 (without channel engineering and dam removal). The river has been roughly divided into different zones according to the terminology as presented in the conceptual model on channel morphology in inter-dam sections by Skalak et al. (2013) (see also Fig. 1):"DP" = " Dam Proximal", "AT" = "Attenuating", "RivDT" = River-Dominated Transitional", "ResDT" = "Reservoir-Dominated Transitional", "Res" = Reservoir.

habitat availability for all of their life stages in the restored and adjacent river reaches (Thomson et al., 2005). The results of this study underline – as also pointed out in Sear et al. (2009) and Kondolf et al. (2007) – that a more holistic way in approaching river restoration is needed, through the consideration of river management and engineering history, including placement of channel protection measures (Feld et al., 2011). These factors can be decisive in determining the extent to which the bed sediment and the channel morphology might change, and how this would impact the local community composition. Positive examples from the US have shown that sediment coarsening induced by low head dam removals led to immediate responses from the benthic communities (Stanley et al., 2002; Pollard and Reed, 2004).

The authors believe that the findings presented in this study are a step forward towards a better understanding of the complex interactions between geomorphic channel processes and engineering activities in fluvial systems during the Anthropocene. Considering the tremendous number of existing dams, as well as the increasing amount of dam removal taking place worldwide, the knowledge presented here is of global interest, further providing useful information on potential outcomes of river restoration efforts that are further determined by system-specific complex interactions and landscape histories.

6. Conclusions

In this paper, we investigated the legacy effects of small dams, their removal and channel protection structures on bed sediment and channel morphology in two small mixed-load streams in Austria, highlighting the role of complex interactions between geomorphic channel processes and engineering activities. Moreover, we tested a conceptual model as proposed by Skalak et al. (2013) on how interacting dams might affect river geomorphology in a selected river section impacted by a series of small dams. Additionally, the implications for river restoration and freshwater ecology were discussed.

Based on our findings we conclude that the upper and middle reaches of the observed river systems are highly impacted by multiple dams and related channel engineering structures and can be classified as Anthropocene Streams (Merritts et al., 2011). In the

Table 6

Geomorphic conditions in two active inter-dam sequences along the Kaja River: (A) between Dams 7 and 11 (impacted by river engineering and dam removal), (B) between Dams 11 and 13 (without channel engineering and dam removal). The river has been roughly divided into different zones according to the terminology as presented in the conceptual model on channel morphology in inter-dam sections by Skalak et al. (2013)(see also Fig. 1): "DP", " Dam Proximal", "AT", "Attenuating", "RivDT", River-dominated Transitional", "ResDT", " Reservoir-Dominated Transitional", "Res", Reservoir.

	Zone	Sediment bars (non-vegetated)	Sediment bars (vegetated)	Channel engineering	Large woody debris	Bank erosion
Sequence A (engineered)	DP	0	0	X	0	0
	AT	0	0	X	0	0
	RivDT	8	0	X	6	8
	ResDT	2	0	–	2	1
Sequence B (no engineering)	DP	4	8	–	9	6
	AT	3	3	–	6	2
	RivDT	7	4	–	9	6
	ResDT	2	1	–	2	0

observed systems, the geomorphic response to dam removal has been shown to be inhibited by the presence of channel bed and bank protection measures which preserve dam-induced channel and bed sediment conditions. The results outlined clearly show the complexity of geomorphic responses to dam removal in systems impacted by multiple dams as well as by channel protection structures, due to occurring interactions and feedback processes that are further influenced by the proximity of other dams and related hydro-geomorphic conditions. At numerous locations our observations do not conform to the conceptual model by Skalak et al. (2013), due to a number of factors determining river geomorphology on the local to reach scales, e.g. the presence of large woody debris jams, (legacy) knickpoints and channel engineering. Based on the discussion on potential implications for freshwater ecology, it is further concluded that the immediate response of stream biota to dam removal is linked to the improvement of upstream-downstream connectivity and local bed sediment composition and channel morphology, while in this case study the response might be more limited due to the legacy effects of former dams, as local habitat conditions (sediment composition) have not improved at all restored sites. The results of this study further highlight the need for assessments and basic concepts in fluvial geomorphology and river restoration that consider the role of system history, legacy effects, feedback mechanisms and interactions between dams and other engineering structures as well as the effects of complex geomorphic system responses to change.

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