EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **44**, 433–448 (2019)

Published online 25 November 2018 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.4505

In situ measurements of fine sediment infiltration (FSI) in gravel-bed rivers with a hydropeaking flow regime

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Received 18 December 2017; Revised 31 August 2018; Accepted 10 September 2018

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ABSTRACT: The overpresence of fine sediment and fine sediment infiltration (FSI) in the aquatic environment of rivers are of increasing importance due to their limiting effects on habitat quality and use. The habitats of both macroinvertebrates and fish, especially spawning sites, can be negatively affected. More recently, hydropeaking has been mentioned as a driving factor in fine sediment dynamics and FSI in gravel-bed rivers. The primary aim of the present study was to quantify FSI in the vertical stratigraphy of alpine rivers with hydropeaking flow regimes in order to identify possible differences in FSI between the permanently wetted area (during base and peak flows) and the so-called dewatering areas, which are only inundated during peak flows. Moreover, we assessed whether the discharge ratio between base and peak flow is able to explain the magnitude of FSI. To address these aims, freeze-core samples were taken in eight different alpine river catchments. The results showed significant differences in the vertical stratification of FSI between the permanently wetted area during base flow and the dewatering sites. Surface clogging occurred only in the dewatering areas, with decreasing percentages of fine sediments associated with increasing core depths. In contrast, permanently wetted areas contained little or no fine sediment concentrations on the surface of the river bed. Furthermore, no statistical relationship was observed between the magnitude of hydropeaking and the sampled FSI rate. A repeated survey of FSI in the gravel matrix revealed the importance of de-clogging caused by flooding and the importance of FSI in the aquatic environment, especially in the initial stages of riparian vegetation establishment. © 2018 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: hydropeaking; fine sediments infiltration; clogging; sediment management; hydropower; alpine rivers

Introduction

Fine sediments (or 'fines') are frequently described as particles < 2 mm in size, and the inter-gravel deposition of such particles is known as fine sediment infiltration (FSI) (Cordone and Kelley, 1961; Einstein, 1968; Beschta and Jackson, 1979; Evans and Wilcox, 2013). In fisheries literature, however, grain sizes less than 6 mm are frequently used for labelling fines (Burton, 2005) or in the field of hyporheic research very small grain sizes are determined as fines, e.g. < 62.5 μm (Phillips and Walling, 1999). In this article, however, the threshold diameter of fines was set at 2 mm which is also at the cutoff between sand and gravel. The accumulation of fines on or within the gravel matrix of gravel-bed rivers can clog the bed surface and pore space (Frostick *et al.*, 1984; Schälchli, 1992). Land use properties and changes (Allen, 2004) as well as geological (Walling, 2005) and hydrological catchment scale characteristics such as flood disturbances, flood frequency, and daily glacier melt-off magnitude (Smith and Smith, 1980; Millner and Petts, 1994), have been identified as drivers of FSI and the clogging of surface and subsurface layers of the river bed. This accumulation can have a limiting effect on habitat use by aquatic biota (Waters, 1995; Wood and Armitage, 1997; Kemp *et al.*, 2011). In particular, macroinvertebrate (Crosa *et al.*, 2010) and fish habitats, especially spawning sites (Sutherland *et al.*, 2002; Hauer *et al.*, 2013; Pulg *et al.*, 2013), can be affected.

For FSI, two different modes must be distinguished depending on particle size; silt by advection and gravity, sand by gravity sedimentation. Moreover, Sear *et al.* (2008) distinguish between (a) gravity induced FSI, (b) fine sediment accumulation (due to ongoing infiltration over a certain time period), and (c) the deposition of fines on the gravel bed surface. Research has shown that the sedimentation rate can be increased by the advection of fines resulting from turbulence along rough bed materials (Leeder, 1983; Cuthbertson, 2001); however, gravitational processes remain the dominant factor in determining sedimentation rates (Richards, 1982; Knighton, 1998).

The morphological scale used to assess dynamic infiltration rates varies from individual spawning sites to meso-unit riffle–pool sequences (Huettel *et al.*, 1996; Sear *et al.*, 2008). For meso-units, the grain size distribution (GSD) characteristics of a gravel matrix must be related to local river morphology and morphological heterogeneity, which in turn significantly affects the hydraulic characteristics of the river bed's interstitial spaces (Zimmerman and Lapointe, 2005). Diplas and Parker (1992) and Packman et al. (1997) have noted that differences in the bathymetric topography of a river bed surface (longitudinal heterogeneity) lead to differences in the pressure gradient, which underlines the variability of fine sediment accumulation in relation to meso-scale morphological features. However, it must be remarked that studies of fine sediment accumulation at both meso- or micro-scales yield outcomes that strongly depend on the method used to quantify sedimentation in the field. Pits (Frostick *et al.*, 1984) and infiltration cans (Lisle, 1989) are typically used to take periodic *in situ* measurements and allow for the onsite quantification of fine sediment accumulation over a specific time period. On the other hand, freeze-core samples (Rood and Church, 1994; Evans and Wilcox, 2013) enable a detailed analysis of the vertical sediment composition of a river bed's surface, including the quantification of infiltrated fines. Some researchers have combined both methods to improve their analysis (Lisle, 1989; Schindler Wilhaber *et al.*, 2012).

FSI occurs as a result of natural sediment and morphological dynamics in most river systems (Smith and Smith, 1980). However, man-made changes may increase or decrease a river's (fine) sediment load, and increases result in primarily negative impacts on the aquatic ecology therein. For example, the installation of a hydropower system may significantly alter the (fine) sediment regime of a river based on the storage of water and the capture of sediments behind dams; this results in profound downstream changes to the natural patterns of flow regime and sediment transport (Poff and Hart, 2002). Fine sediment yields may be particularly impacted, as fines are often trapped in reservoirs and then artificially released during one controlled flush event, which can lead to variability in meso-scale deposition patterns and significant alterations to bedload transport rates (Wohl and Cenderelli, 2010). Possible ecological consequences of reservoir flushes include significant decreases in the downstream diversity and abundance of fish (Buermann *et al.*, 1995) and macroinvertebrates (Rabeni *et al.*, 2005). However, some species of benthic organisms have been shown to recover from these flushes within several weeks (Gray and Ward, 1982) or months (Crosa *et al.*, 2010).

More recently, the impact of hydropeaking has been suggested as a possible factor governing changes to the fine sediment composition of surface and subsurface layers of gravel-bed rivers (Schälchli *et al.*, 2002; Anselmetti *et al.*, 2007; Gailiuis and Kriauciuniene, 2009). Hydropeaking – the abrupt, artificial increase and reduction of discharge and corresponding water levels – is characterized by steep rising and falling hydrograph limbs (up to several cm min^{-1}, Hauer *et al.*, 2017) and is based on reservoir operations on energy demand occurring as one or several peaks per day, often exhibiting weekly periodicity (Moog, 1993; Charmasson and Zinke, 2011). Various legal directives in European states have established requirements for the ratio between base (Q_{base}) and peak flow (Q_{peak}) (e.g. Q_{base} = 30 $m^3\ s^{-1}$/Q_{peak} = 45 $m^3\ s^{-1}$; Q_{base}/Q_{peak} = 1:1.5, Swiss Water Protection Ordinance (WPO)) on the assumption that the higher the discharge ratio, the greater the negative impacts. These negative ecological impacts are generally related to stranding and drift of fish and macroinvertebrates (Moog, 1993; Bragg *et al.,* 2005). However, in addition to the direct impacts of fluctuating flows on biota (stranding or drift), changes to characteristics of the physical environment, including fine sediment dynamics, also may occur.

For example, it is proposed that changing discharge rates impact the infiltration rate of fine sediments in alpine gravel-bed rivers (Schälchli *et al.*, 2002). The magnitude of the deposits and changes in the infiltration processes result from alterations to sediment transport driven by the dynamics of peak and off-peak flows (hydropeaking). Previous studies have noted that during base flow following peak-events, transported sediments are deposited, which may result in the clogging of the gravel bed matrix (Schälchli *et al.*, 2002); on the other hand, during peak flows, sediments are partially re-suspended, which causes higher erosion and water turbidity (Anselmetti *et al.*, 2007; Wang *et al.*, 2013). Hydropeaking studies often distinguish between 'outer' and 'inner' river bed clogging, depending on whether the sediment is deposited on the surface gravel layer or within the interstitial spaces of the gravel bed (Schälchli *et al.*, 2002). Negative ecological impacts of clogging in reaches affected by hydropeaking include the reduction or elimination of refugia zones for macroinvertebrates (inner clogging) (Bruno *et al.*, 2009; Pulg *et al.*, 2013) or limited access to suitable substrate habitats (outer clogging) (Jones *et al.*, 2011). At spawning sites, the deposition of fines increases embryo mortality by filling inter-gravel pores and decreasing water circulation (reducing oxygen supply) (Lisle and Lewis, 1992; Rubin *et al.*, 1996; Kondolf, 2000; Greig *et al.*, 2005, 2007). Although various physical processes related to fine sediment deposition at the surface and in subsurface layers have been investigated (see Sear *et al.*, 2008 and Schälchli *et al.*, 2002), FSI and surface deposition have yet to be analyzed quantitatively in relation to hydropeaking.

A fundamentally open question is related to the effect of peaking flow on FSI, in comparison with the condition in which the same river would be found in the absence of peaking flow regulation. Answering such question has the intrinsic challenge of being able to sample the same river system subject to two markedly different flow regimes, which is essentially impossible. In this paper we aim to make a first step to answering such broad question by presenting a set of field observations on FSI in several sites characterized by hydropeaking. Specifically, we aimed to test two main research hypotheses, which we formulated referring to the few existing studies on this topic (Schälchli *et al.*, 2002). First, that fine sediment infiltration varies between permanently wetted and dewatering sites, which are only inundated during peak flows; second, that there is a positive correlation between the amount of FSI in the gravel matrix and a measure of the hydropeaking intensity, i.e. the discharge ratio of base to peak flow.

To test the two hypotheses, freeze-core samples of different hydropeaking rivers in the Alps were analyzed. For studies on the first hypothesis, samples were taken from the Alpine Rhine ('Alpenrhein') River, which forms part of the border between Austria/Switzerland and Liechtenstein/Switzerland, respectively. Moreover, to address the second hypothesis, 14 hydropeaking reaches in Austria were investigated. In addition, the Lech River (Austria) was sampled to analyze and establish a baseline for fine sediment accumulation rates in a sedimentologically undisturbed reference alpine braided gravel-bed river.

Study Reaches

Eight rivers were studied in the present work (Figure 1). The primary focus of this research was on the Alpenrhein, which originates in Switzerland at the confluence of the Vorderrhein and Hinterrhein (N46°49′24″E9°24′27″) (Figure 1). The Alpenrhein is 86 km long and discharges into Lake Constance (N47°30′42″ E9°39′31″; catchment size = 6123 km^2); the bed elevation changes from 599 m.a.sl. to 396 m.a.sl. (average bed slope = 0.0014). The river is subject to high annual suspended (Müller and Förster, 1968) and bedload transport rates (with annual sediment transport volume of 10 000 m^3 to 70 000 m^3, Zarn, 2001); nevertheless, ongoing bed incision has occurred (Zarn, 2008). It has a combined glacial, nival, and pluvial hydrologic regime with distinctive peak flows occurring in June (Zarn, 2001). Detailed information on the Alpenrhein catchment can be found in Uehlinger *et al.* (2009).

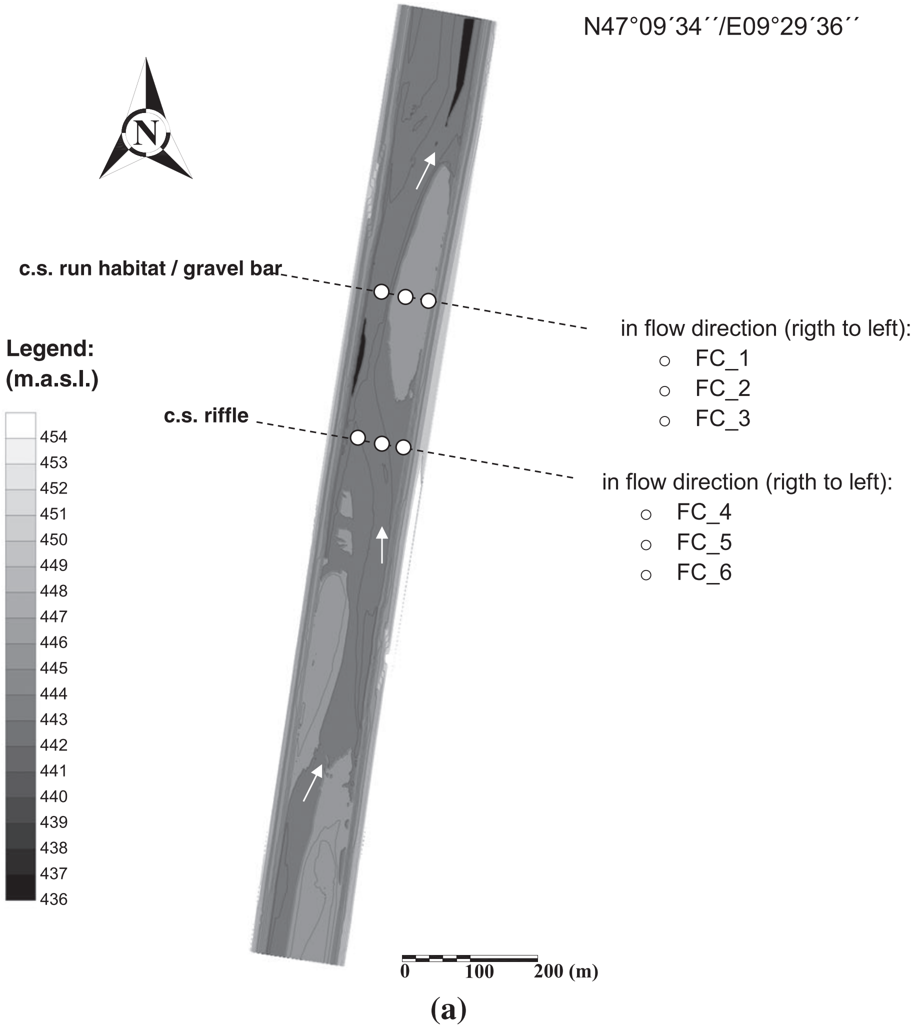
Hydropeaking along the Alpenrhein River is related to turbine operations at the Reichenau power plant (installed capacity 18 Megawatt (MW)). To investigate the effects of this process, we studied a 1416 m long channelized reach (no bank erosion possible) near Buchs (Figure 2(a)). This reach is located approximately 45 km downstream of the hydropower plant Reichenau and characterized by dynamic, alternating gravel bars (Adami *et al.*, 2016). The variability of hydropeaking ratios (Q_{base}/Q_{peak}) in the investigated reach depends on the seasonal variations in base flow, and are presented in Table I. The characteristic discharges are calculated on the analysis of a discharge time series at gauging station Bad Ragaz (HO3602), for the period 31.03.2005 to 31.12.2012. The results exhibit high variability in base flow over the hydrological year. Exemplarily, $Q_{50\%}$ varies from 57.4 m^3 s^{-1} in winter to 157.8 m^3 s^{-1} in summer with corresponding changes in hydropeaking ratios Q_{base}/Q_{peak} from 1:3 to 1:7, respectively with variable rates of changes from Δwater surface elevation = 1 cm min^{-1} to 4 cm min^{-1} (Pfaundler and Keusen, 2007). Main fine sediment sources are found south and east of the Vorder and Alpenrhein river between Vals (catchment Glenner) and the so called Rätikon (south of the Schesaplana) in the form of 'Bündner Schists' and Flysch producing high amounts of suspended and wash load at the investigated study site (Schälchli *et al.*, 2001). Catchments with high numbers of 'Bündner schists' and flysch are the Glenner River, the Rabiusa River, the Nolla River, the Plessur River, the Landquart River and the Tamina River. The operational scheme of the HP Reichenau, however, allows the gates to open giving high flows and thus suspended and wash load sediments especially are transported downstream, with only minor impacts due to the hydropower facility. Bedload sources are found in the (i) alluvial deposits of the Alpenrhein valley with limited opportunities for side erosion and (ii) due to some major tributaries (e.g. Landquart River N46°58′07″/E9°33′01″).

In addition to the investigations along the Alpenrhein, six Austrian rivers (13 reaches) (Figure 1) with run-off patterns altered by hydropeaking were analyzed (Table II). Most of the Austrian study sites are characterized by plane-bed and riffle–pool morphologies (Figure 2(b), Table II). These sites are located along 4451 m of the Drau River (reach 1) and 256 m of the Enns River (reach 2) and have a nival and/or glacial hydrological regime (Table II). These hydropeaked rivers are situated wholly within the alpine areas of the Austrian provinces of Vorarlberg (Ill River, Bregenzerach River), Tyrol (Inn River, Ziller River), Carinthia (Drau River) and Styria (Enns River) (Figure 1) (review in Hauer *et al.*, 2014). This study also included a hydrologically undisturbed reference site, the Lech River, which has not been subjected to hydropeaking (Figure 1). The Lech River (study reach located upstream of the Johannes Bridge; 47°25′52″/10°35′45″) is one of the last remaining braided river systems in the European Alps and is characterized by high annual sediment loads (Walling, 1999) with an average sediment transport volume of 50 000 m^{3}a^{-1}(Bauer, 1979) and a moderate nival run-off regime (Mader *et al.*, 1996). The selected study site along the Lech River drains a catchment approximately 1012.2 km^2 (Lechaschau gauge station). Detailed morphological and hydrological data for the selected study reaches are presented in Table II.

Methods

To address the aims of the present study and test the two primary hypotheses, various methodological approaches were used. Freeze-core sampling was carried out at 15 sites

Figure 1. Central European map featuring the various investigated rivers (n = 8) and study reaches for fine sediment infiltration (n =15).



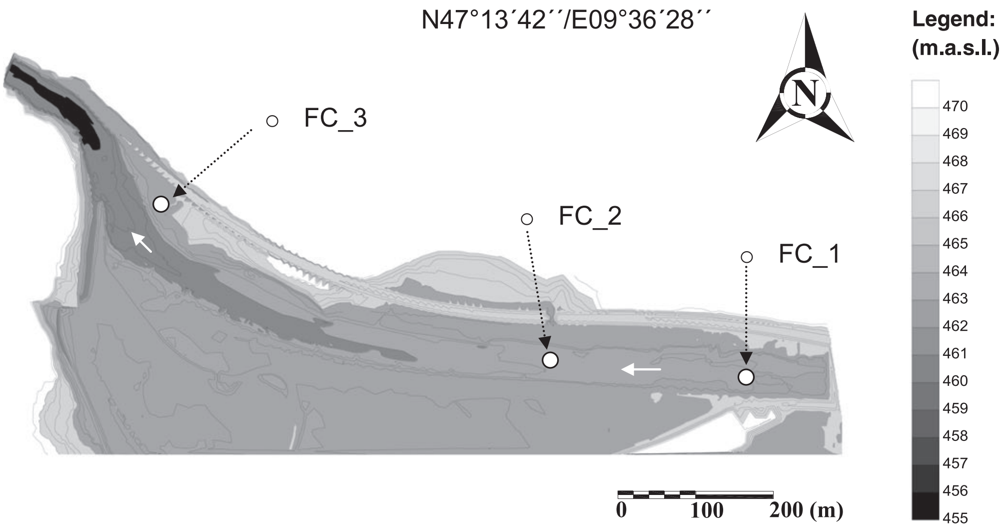


Figure 2. (a) Digital terrain model of the study reach Buchs (Alpenrhein River). Points of stratified (cross-sectional based) freeze-core samples in bar and riffle habitats are highlighted (white dots) (b) Digital terrain model of the study reach Ill_2 (Ill River). Points of random freeze-core samples in the investigated section are highlighted (white dots); flow direction indicated by white arrows; FC = freeze-core; flow direction indicated by white arrows; c.s. = cross-section; FC = freeze-core.

in 2013, and it was repeated three times at the Alpenrhein site over a 1 year period to determine possible seasonal fluctuations in fine sediment infiltration related to the annual flow regime (e.g. snow-melt induced high flows). We took samples from both the permanently wetted areas (including the winter base flow line) and the dewatering areas, which are periodically inundated during hydropeaking. Moreover, volumetric surface material sampling of deposited materials (USGS-sampling standard, Bunte and Abt, 2001) have been done in dewatering areas at the Alpenrhein site. All samples were dried and sieved in a laboratory to determine grain size distributions.

Table I. Seasonal hydropeaking variability at the Alpenrhein River, reach Buchs. Data based on gauging station Bad Ragaz; dates of the representative peaking events are listed in the table, discharge Q is presented in $m^3\ s^{-1}$

Scenario	$Q_{25\%}$ winter	$Q_{50\%}$ winter	$Q_{75\%}$ winter	$Q_{25\%}$ spring	$Q_{50\%}$ spring.	$Q_{75\%}$ spring
Date:	9.1.2006	27.1.2010	17.12.2007	23.3.2006	10.5.2011	26.4.2006
Q_{base}	50.1	57.4	68.6	76.7	105.0	155.5
Q_{peak}	200.4	171.4	237.5	199.4	202.6	270.2
ΔQ_{max}	150.3	114.0	168.9	122.7	97.6	119.8
Q_{base}/Q_{peak}	4.0	3.0	3.5	2.6	1.9	1.7
Szenario	**$Q_{25\%}$ summer**	**$Q_{50\%}$ summer**	**$Q_{75\%}$ summer**	**$Q_{25\%}$ autumn**	**$Q_{50\%}$ autumn**	**$Q_{75\%}$ autumn**
Datum:	21.8.2008	15.7.2009	14.8.2010	14.11.2005	22.10.2007	3.9.2008
Q_{base}	127.9	157.8	219.6	69.2	88.7	111.5
Q_{peak}	269.1	274.4	326.7	221.2	247.9	237.5
ΔQ_{max}	141.3	116.6	107.1	152.0	159.2	126.0
Q_{base}/Q_{peak}	2.1	1.7	1.5	3.2	2.8	2.1

Table II. Description of the selected study reaches (*n* = 15) based on morphological, hydrological and sedimentological characteristics

No	site	Q_L ($m^3\ s^{-1}$)	peak_flow ($m^3\ s^{-1}$)	D_{bf} (m)	W_{bf} (m)	slope (-)	length (m)	bed_min (m.a.sl)	Morph. (-)	D_{50} (mm)	nb.-FC (-)
1	Buchs (n = 54)	20.0	120	6.7	115.6	0.0015	1415.8	437.16	RP	33.7	n = 4 (PA) n = 2 (DA)
2	Ill_1* (*n*=45)	4.50	2 × 34 [1)] 2 × 8 [1)]	6.3	53.6	0.0042	429.0	441.12	plane	27.1	n = 3 (PA) *n* = 0 (DA)
3	Ill_2 (*n*=63)	15.10	2 × 34 [1)] 2 × 8 [1)]	3.9	64.1	0.0042	1191.0	456.24	plane	25.4	n = 2 (PA) n = 1 (DA)
4	Ill_3 (*n*=41)	13.99	2 × 34 [1)]	4.3	53.0	0.0036	369.0	471.21	plane	26.6	n = 1 (PA) n = 2 (DA)
5	B. Ach_1 (*n*=40)	1.30	38 [1)]	5.1	91.5	0.0008	716.2	409.91	RP	20.2	n = 3 (PA) n = 0 (DA)
6	Inn_1 (*n*=51)	33.00	85 [2)] + 48 [2)]	5.1	97.0	0.0024	1409.5	612.25	plane	29.5	n = 2 (PA) n = 1 (DA)
7	Inn_2 (*n*=61)	33.00	85 [2)] + 48 [2)]	6.1	147.6	0.0022	2424.9	617.59	RP	49.1	n = 3 (PA) n = 0 (DA)
8	Inn_3 (*n*=44)	29.00	85 [2)]	5.7	84.4	0.0045	1846.1	654.71	RP	28.8	n = 2 (PA) n = 0 (DA)
9	Inn_4** (*n*=57)	6.30	92 [4)] + 54 [3)]	4.9	93.8	0.0031	1949.0	716.93	RP	21.9	n = 3 (PA) n = 0 (DA)
10	Drau_1 (*n*=58)	26.70	110 [3)]	5.1	96.2	0.0017	4451.5	528.13	RP	39.8	n = 4 (PA) n = 1 (DA)
11	Ziller_1 (*n*=19)	8.90	6 × 15 [3)] + 28 [3)]	5.2	57.4	0.0043	281.9	535.65	plane	17.6	n = 2 (PA) n = 1 (DA)
12	Ziller_2 (*n*=15)	3.90	6 × 15 [3)]	3.4	49.3	0.0054	257.2	584.56	plane	25.1	n = 3 (PA) n = 0 (DA)
13	Enns_1 (*n*=23)	12.94	34[3)] + 9 [3)]	3.7	43.8	0.0021	341.0	646.64	RP	31.5	n = 3 (PA) n = 0 (DA)
14	Enns_2 (*n*=20)	12.44	34[3)]	3.5	35.1	0.0017	256.1	657.69	plane	29.2	n = 2 (PA) n = 1 (DA)
15	Lech (*n* = 31)	1.83	(-)	2.6	259.5	0.0057	1864.8	888.96	RP	18.7	n = 1 (PA) n = 2 (DA)

[a]RP = riffle-pool morphology; plane according to Montgomery and Buffington [1997]
*Residual flow unit; minimum legal discharge 4.5 $m^3\ s^{-1}$/peak flow due to differences in recorded discharge minus 43 $m^3\ s^{-1}$ weir intake
**Residual flow unit; minimum legal discharge 1 $m^3\ s^{-1}$/Landeck-Perjen gauging station used for Q_L and Q_M/peak flow usually not occurring due to storage in backwater of HPP Imst.
(n=19) total number of cross-sections within a reach (e.g. 19 for Ziller_1).
[1)]Illwerke_vkw[I)]
[2)]TIWAG
[3)]Verbund_VHP
[4)]Engadiner Kraftwerke (Switzerland)
Q_L = mean annual low-flow, peak_flow = operating peaking mode of one or more turbines, D_{bf} = bankfull depth, W_{bf} = bankfull width, slope = average bed slope of the selected reach, length = total reach length used for modeling, bed_min = minimum bed elevation within the study reach, morph. = morphological characteristics, D_{50} = median grain size diameter at exposed gravel bars, nb.-FC = number of freeze cores, PA = permanent wetted area, DA = dewatering area.

Volumetric sampling of fines on the gravel bars

To determine the grain size distribution (GSD) of deposited fines on the surface of Alpenrhein River gravel bars, which are prone to erosion during peak flows and lead to increased turbidity (compare Hall *et al.*, 2015), volumetric sediment samples were taken. Sampling occurred in dewatering areas immediately along the shoreline and in areas containing an initial riparian forest stage (Figure 3). Sample volumes were determined using the three sample mass criteria presented by Church (1987). This analysis allowed comparison of surface-deposited materials with the infiltrated materials in the permanently wetted areas and dewatering areas as identified in the freeze-core sampling. It was aimed to determine whether the grain size distribution of the deposited fines on the surface of the gravel bars was similar to that of FSI at the various sites or if the sampled sediments within the inter-gravel matrix were different. The comparisons of volumetric surface deposits and FSI were carried out only for the Alpenrhein reach, which is characterized by high suspended load transport (compare Zarn, 2001) and thus significant deposition of fines in dewatering areas (Figure 3).

FSI in surface and subsurface layers of the gravel bed by freeze-core sampling

In general, freeze-core samplers are used to collect all particles that freeze to one or several hollow rods driven into a stream bed. Samples extend from the surface layer to the subsurface layer and maintain the stratification of the bed sediments (Bunte and Abt, 2001). Single-tube freeze-core samplers were used in the present study, following various fine sediment studies (Petts, 1988). The single-tube method was applied in both the dewatering (partially dry) areas as well as the permanently wetted river bed. A floating platform was used to sample the Alpenrhein reach and various Austrian sites (e.g. Drau River, Inn River) where deep water (> 3 m) was present. A high-grade steel pointed hollow rod with a 4.5 cm inner diameter was applied at all sample sites (Alpenrhein and Austrian rivers). The rod was driven 0.5 m, 0.75 m or 1 m into the river bed, depending on the size of the bed material size and silting conditions. A striking weight of 30 kg was used to drive the rod into the river bed. Liquid nitrogen (–196°C) was used to freeze the surface and subsurface bed material. An average volume of 40 L per core was applied over a 30 to 45 minute freezing period. Depending on the duration of the freezing process, cores with an average diameter of 30 cm were obtained.

For the present study, the stratification of deposited/sorted sediments and the quantification of fines were determined by analyzing vertical layers 10 cm and 20 cm deep, depending on the core length. It was aimed to collect core lengths of at least 1 m; however, in some cases the coarseness of the material or intensity of the clogged gravel matrix made this impossible, and samples of only 0.5 m or 0.75 m were obtained. Each discrete sediment layer was dried and sieved to quantify the percentage of fines (i) < 0.125 mm, (ii) < 0.5 mm and (iii) < 2 mm. Square-hole sieves were used to separate out 0.125 mm – 256 mm sediments following a 0.5 ϕ gradation. However, given that the investigated river sites varied in gradient and catchment scale geology (Table II), large bed particles within the freeze cores varied. It is possible that this skewed the grain size distributions, especially if large samples were absent (Church *et al*., 1987; Rood and Church, 1994). Hence, particles larger than 32 mm were eliminated from further testing (e.g. comparison of fine content between different samples), as suggested by Adams and Beschta (1980) and Evans and Wilcox (2013).

In total, 62 freeze-cores were taken and analyzed. Eighteen freeze-cores were taken along the Buchs study reach on the Alpenrhein River (six in winter 2013, six in summer 2013 and six in autumn 2013) (Figure 2(a)). Forty-one freeze-cores were taken at the various Austrian hydropeaking study sites, with a clear differentiation between (1) permanently wetted areas (wetted during low base-flow conditions) and (2) dewatering areas (wetted during peak flow and dry during base flow). The Austrian hydropeaking sites were sampled randomly, while the Alpenrhein reach was sampled following a stratified cross-section approach (Figure 2(a)). The reason for the different approaches was based on the morphological heterogeneity of the various Austrian sites (compare sites in Table III) and the aim to consider reach scale variations with reduced numbers of samples. The results of the random approach, however, may be biased compared with the stratified approach.

However, along some of the heavily regulated river reaches in Austria (*n* =7) (Table II), particularly those that lacked gravel bar features, only the permanently wetted areas could be sampled. Three freeze-core samples (two in wetted areas and one at a dry gravel bar site) were taken from the Lech River (Table II) in order to compare the FSI along hydropeaking sites with those of at least one site unaltered by anthropogenic activities.

Seal formation

The sampled vertical stratigraphy of FSI at the Alpenrhein site was also tested for potential seal formation (driving freeze-core probes into the bed can disrupt seals). Seal formation is described as a dynamic process in which deposition of larger grains among the pores near the surface of the gravel bed occurs, thus blocking possible sediment infiltration deeper into the gravel matrix and creating a so called seal (Lisle, 1989; Leonardson, 2010). Seal formation has frequently been

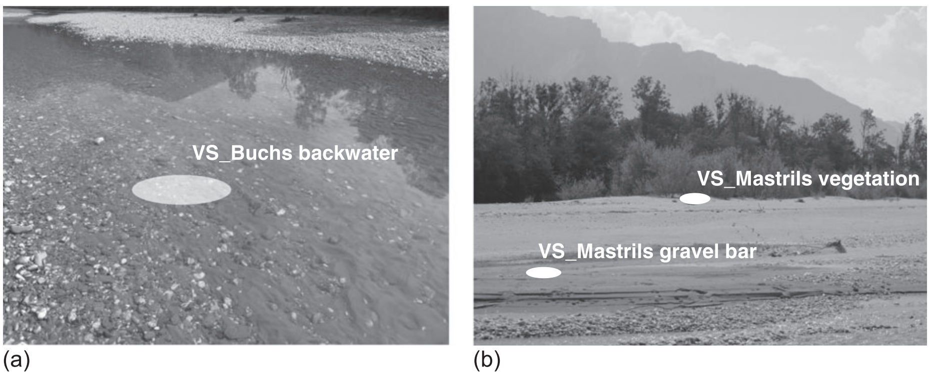


Figure 3. Fine sediment deposits at submerged and non-submerged gravel bars at the Alpenrhein; sampling points are indicated in white for (a) Buchs (downstream view) and (b) Mastrils (upstream view); VS = volumetric sample.

Table III. Testing for statistical significant differences ($P < 0.05$) of means in FSI distributions (< 0.125 mm, < 0.5 mm, < 2 mm) in different vertical layers (0–10 cm; 10–20 cm; 20–30 cm) for the two different groups of samples; permanent wetted (n = 35) and dewatering zones (n = 7)

Tested data		mean (%)	S.D. (%)	Levene's test F	Levene's test Sig.	probability Sig. (2 tailed)
< 0.125 (0-–10 cm)	PA	0.61	0.44	50.126	<0.001	0.022
	DA	3.89	2.81			
< 0.5 (0–10 cm)	PA	4.17	3.51	16.12	<0.001	0.047
	DA	12.52	8.87			
< 2 (0–10 cm)	PA	12.90	9.03	0.36	0.850	0.034
	DA	21.35	10.59			
< 0.125 (10–20 cm)	PA	1.06	0.49	4.72	0.036	0.001
	DA	3.01	0.97			
< 0.5 (10– 20 cm)	PA	7.65	4.58	0.301	0.587	0.032
	DA	11.70	3.24			
< 2 (10–20 cm)	PA	21.11	9.31	0.434	0.514	0.064
	DA	28.07	5.13			
< 0.125 (20–40 cm)	PA	1.44	0.69	0.068	0.796	0.487
	DA	1.64	0.76			
< 0.5 (20–40 cm)	PA	9.58	4.07	0.185	0.669	0.799
	DA	9.16	3.67			
< 2 (20–40 cm)	PA	25.71	11.44	0.385	0.539	0.930
	DA	26.10	5.04			

PA =permanent wetted area; DA = dewatering area; SD = standard deviation;

identified using field data (Lisle, 1989; Acornley and Sear, 1999), and Gibson *et al.* (2010) have suggested the following relationship to describe the seal formation process based on physical laboratory studies:

$$d_{15}\ \text{substrate}/d_{85}\ \text{infiltrating sand} < 12\text{–}14 \quad (1)$$

Analyses of possible seal formations were conducted for both the permanently wetted and dewatering areas. Seal formation was calculated using the volumetric sediment samples (n = 4) from the gravel bar surface (Figure 2(a)), along with characteristic grain sizes (d_{85} infiltrating sand) and the grain size distribution of the surface layer (0–10 cm of vertical depth) for gravel bar areas exposed to dewatering due to hydropeaking (d_{15} substrate) at the Buchs site (n= 2).

Hydropeaking and sediment transport analysis

For the study site at the Alpenrhein River, streamflow data were obtained from a gauge station (Bad Ragaz) close to the investigated reach (22.9 km downstream). Analysis of long-term recorded streamflow data was also performed for the Austrian sites (n = 16) (ehyd, 2013), allowing computation of the discharge ratio between base and peak flows (e.g. 1:5) during the freeze-core sampling field campaign (20 January 2011 to 31 March 2011).

For hydraulic analysis of studies on suspended load and bedload movement of fine sediments the one-dimensional hydrodynamic-numerical model HEC-RAS was applied. The bathymetry for the selected cross-sections for modelling (n = 54) was based on a 200 463 point grid, derived from interpolated multibeam-echo-sounding and LiDAR data (total length of modelling stretch = 1416 m) (see Figure 2(a)). Mean distance between the cross-sections was 26.7 m (SD: 7.0 m). Moreover, point density varied according to bathymetric heterogeneity in the various cross-sections between 62 points and 438 points. The calibrated model (Manning n for high flows = 0.037) was applied for analysis of the highest recorded discharges in the study period (01.01.2013–30.01.2013; gauge station Bad Ragaz) and for two representative peak-flow scenarios from Table I; to differentiate between grain sizes which have been transported as (i) bedload, (ii) suspended load or (iii) wash load. For this analysis the work of Komar (1980) has been used. He summarized criteria to distinguish between the various forms of sediment transport (n = 3). The analysis was based on a comparison of the grain settling velocities tending to move them towards the bottom with the upward component of the turbulent eddy velocities (Bagnold, 1966). This approach leads to the ratio

$$\frac{w_S}{u_*} = k \quad (2)$$

where w_S is the settling velocity (m s^{-1}) of the cutoff grain size between bedload and suspension, and u_* is the so-called frictional velocity. Here, w_S is given by

$$w_S = \sqrt{\frac{4}{3} \cdot \left(\frac{\rho_P}{\rho_F} - 1\right) \cdot \frac{g \cdot d}{C_D}} \quad (3)$$

where ρ_P is density of the particle (kg m^{-3}), ρ_F is the density of the fluid, g is the acceleration due to gravity (m s^{-2}), d is the grain size diameter (m), C_D is the drag coefficient 0.44; and u_* is given by

$$u_* = \left(\frac{\tau}{\rho}\right)^{0.5} \quad (4)$$

where τ is the shear stress (N m^{-2}) between the flowing water and bottom and ρ is the water density (1000 kg m^{-3}).

In the presented study the proposed intermediate k = 1.25 value of Komar (1980) was used for the differentiation between bedload and suspended transport. Moreover, to distinguish between suspended and wash load the threshold k = 0.13 (Stevens and Charles, 1972) was applied. The two selected hydropeaking scenarios for the hydrodynamic-numerical analysis were representative of the lowest and highest peak flow event (Table I), to show the full range of possible fine sediment dynamics due to hydropower operation.

Statistical analysis

Simple linear regression models using the least squares approach were used to derive possible predictive models concerning discharge ratios and fine sediment infiltration (< 0.125 mm, < 0.5 mm and < 2 mm). The SPSS15 statistical software was used to analyze a modelled data set of x (discharge ratios) and y values (FSI) (Equation (5)).

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots\ldots b_ix_i \quad (5)$$

where Y = dependent variable, x = independent variable, b_0 = intercept value (the value of Y when x = 0), b_i = unknown parameters, and i = number of parameters used in the linear regression analysis.

In addition, two regression models were applied to investigate the possible relationships between dependent (e.g. FSI) and independent variables, respectively (discharge ratio of base to peak flow). Both the exponential function (Equation (6)) and the logarithmic function (Equation (7)) have been frequently used in geomorphological research (Hack, 1973) and are written as follows:

$$Y = ae^{bx} \quad (6)$$

$$y = a\ln x + b \quad (7)$$

where Y is the dependent variable, x the independent variable, and a and b are coefficients that are independently determined for each test.

Significance testing was applied to the various freeze-core samples to determine if any significant differences in FSI exist between the permanently wetted and dewatering areas (testing of hypothesis 1). A Student's t-test of two independent samples was selected as the testing procedure to analyze the data after they were checked for normal distributions using a Shapiro–Wilk normality test (Shapiro and Wilk, 1965) and for homogeneity of variances using a Levene's-test (Levene, 1960). In cases where heterogeneous variances occurred, a Welch-test for two independent samples was applied. For all statistical tests, such as the homogeneity of variances and probability of differences in fine sediment infiltration, the level of significance was set at α=0.05.

Results

Volumetric fine sediment samples on gravel bars

The volumetric sample results for Alpenrhein gravel bar surface deposits are presented in Figure 4. The samples were collected from dewatering areas (Buchs and Mastrils gravel bar), permanently wetted areas during base flow (backwater of Mastrils gravel bar) and gravel bars on which vegetation was in the early stages of succession (Figure 3). The results indicate that deposited fine sediments dominate the grain size from d = 0.1 mm to d = 0.5 mm. d_{90} was calculated at 0.45 mm for sample A (Buchs), 0.58 mm for sample B (Mastrils backwater), 0.65 mm for sample C (Mastrils gravel bar) and 0.21 mm for sample D (Mastrils vegetation). Hence, for the Mastrils reach, the permanently wetted area and the backwater site consisted of grain sizes (d_{90}) coarser than 0.5 mm (Figure 4). The dewatering sites and those in the earliest stage of vegetative growth contained finer grain sizes. However, given the sieving method used to determine the percentage of fine sediments in the dried samples, measurements were limited to a threshold grain size < 0.063 mm. Sample D (Mastrils vegetation) in particular, which was taken from the top of a gravel bar (area of vegetation succession), had a sample volume in which 11.2% of sediments were finer than 0.063 mm.

FSI in surface and subsurface layers of the gravel bed

Figure 5 illustrates the grain size distributions of surface- and subsurface-layer truncated freeze-core samples for alternating gravel bars in Buchs on three different sampling dates. The

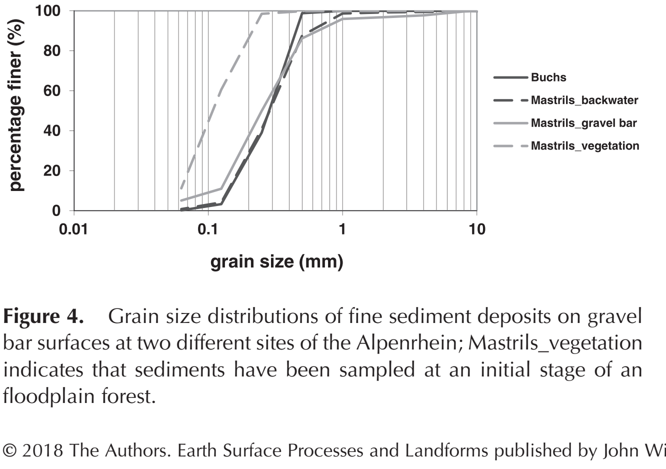


Figure 4. Grain size distributions of fine sediment deposits on gravel bar surfaces at two different sites of the Alpenrhein; Mastrils_vegetation indicates that sediments have been sampled at an initial stage of an floodplain forest.

results of the run/bar cross section (sampling points FC 1-3, Figure 2(a)) show two different FSI patterns very clearly. On the one hand, portions of the alternating gravel bars (bar 1 and bar 2) exhibit a continuous increase in fine sediment deposition on the surface layer (e.g. bar 1 (FC_1)) over the entire monitoring period (Figure 5), with a shift in the GSD from coarser to fine sediments. On the other hand, in areas where FSI was evident, particularly in the subsurface layer, a bimodal grain size distribution was apparent (Figure 5); e.g. samples dominated by sediments < 1 mm and > 10 mm (Figure 5(d)).

The FSI analysis and the comparison between samples (truncated at 32 mm) taken over a 1 year period allowed the quantification of existing FSI dynamics (different graphs in Figure 6). For the Buchs dewatering area sample (bar 1 and bar 2), FSI fluctuated perceptibly between the various sampling dates (Figure 6(a), 6(b)). For example, the FSI rate for d < 0.5 mm taken from the surface layer (0–10 cm) varied from 4.93% in the winter to 7.94% in the summer and 1.09% in the autumn (Figure 6(a)). However, this variation was also observed in the subsurface layer (Figure 6), indicating that fines are flushed out by high flows (509 m^3 s^{-1} between the summer and autumn sampling dates) as part of bedload transport erosion and related bar turnovers or probably migration processes. Changes in channel morphology (e.g. turnover of bars and channel) were closely correlated with changes in FSI in the surface and subsurface layers of sampling point 3 (run habitat), with the presence of fines < 2 mm increasing to more than 80% in autumn (tail of the upstream alternating gravel bar). In comparison, this sampling point contained almost no fines in winter or summer 2013 (Figure 6(f)).

The FSI dynamics and morphological changes are obvious in the riffle habitat (sampling points FC 4-6, Figure 2(a)) cross-section. In winter 2013, the riffle habitat was identified as a transient bed form between two alternating gravel bars (Figure 2(a), overview). During the winter sampling period, the GSDs for samples truncated at 32 mm varied across the three sampling points (0.5%–15.8% d < 0.5 mm). However, dynamic disturbances resulted in dynamic alterations to the GSDs and fine sediment concentrations at the various sampling points during the study period. Hence, clear variations in the GSD along the cross-section of the surface layer can be observed, with almost no fines apparent in the gravel matrix (1.1% for d < 0.5 mm) for the riffle sample (FC_5) located in the stream centerline over the entire monitoring period to sediment samples (FC_4 and FC_6) which exhibit a de-clogging in summer (FC_6: 15.8% down to 4.7% for d < 0.5 mm) and a re-deposition of the gravel matrix again in autumn (FC_6: 22.8% for d <0.5 mm) (Figure 6). This sampling result (Figure 6) underscores the process of sediment dynamics and related morphodynamics of alternating gravel bars in the study reach. The moderately high dynamic nature of FSI is also apparent at those sites with backwater characteristics, at least for one of the sampling dates (e.g. chute channels at alternating gravel bars, or downstream of an alternating gravel bar (Figure 5)). This site contained fine sediment deposits (d < 0.5 mm) more than 10 cm deep in the surface layer.

To answer the question of whether the erosion of deposited fines (Figure 4) and what kind of transport mode (bed or suspended load) is responsible for clogging the gravel matrix, we assessed the vertical stratigraphy results of different FSI classes (< 0.125 mm, < 0.5 mm < 2 mm) (Figure 6) in combination with hydrodynamic-numerical modelling. The results of the hydrodynamic-numerical modelling showed that for the highest recorded discharge in the monitoring period (Q = 509 m^3 s^{-1}) a mean of cross-sectional averaged flow velocity of 2.3 m s^{-1} (SD = 0.33 m s^{-1}) was calculated. Moreover, mean maximum water depth of 4.0 m (SD = 0.58 m) was modelled. This means according to the Komar (1980) criteria for the

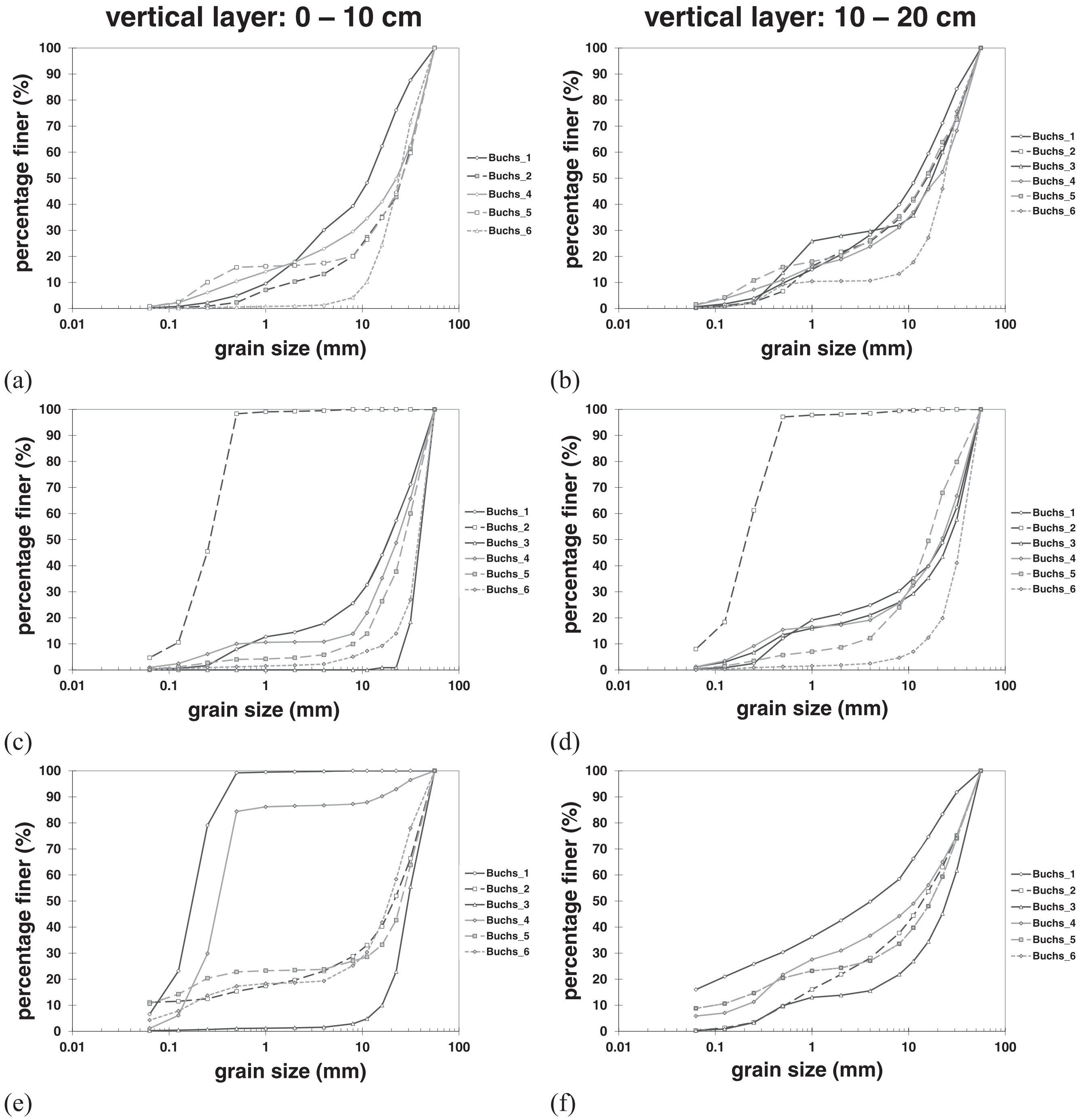


Figure 5. Grain size distribution of truncated freeze-core samples in Buchs for different vertical layers (0–10 cm and 10–20 cm depth) at three specific dates in winter = (a), (b); summer = (c), (d); and autumn (e), (f); note = due to a disturbed sediment sample no grain size distribution is presented for Buchs_3 for the vertical layer 0–10 cm.

various characteristic FSI grain sizes, that the k-value of 1.06 (d = 2 mm) was below the threshold for the consideration of bedload transport (k = 1.25). Thus, the fines described in Figure 4 are solely transported as suspended load in terms of an annual flooding (Q = 509 m^3 s^{-1}). The outcomes of the peak flow events (n =2), however, show that minor parts of the grain size distribution of the deposited fines are transported as bedload. Especially for the lowest peak-flow scenario (199.4 m^3 s^{-1}) the threshold between bedload and suspended load was calculated for d = 1.7 mm. For Q_{peak} = 326.7 m^3 s^{-1} the critical grain size was d = 2.2 mm. Thus, remobilized fines increase the river's turbidity (by both suspended and wash load) and are mainly responsible for FSI and potential clogging of the Alpenrhein gravel matrix with some minor contribution due to fine sediments transported as bedload.

For the Austrian test sites (n = 14), FSI was quantified according to the vertical distribution and variability of sediment grain sizes in the river bed. In Figure 7, analyzed fines are quantified according to the variability in stratigraphic depth. The truncated sample analysis indicates that, in the permanent wetted areas (wetted during base flow), fine sediment concentrations were low to almost zero in the first sampled stratigraphic layer of the river bed (0 – 10 cm in depth), independently of the selected threshold (2 mm, 0.5 mm or 0.125 mm) (Figure 7). The rates of fines present in the permanently wetted sample sites varied from 2.26% in the Bregenzerach River to 40.8% in the Inn River for an applied threshold < 2 mm; for < 0.5 mm, rates varied from 0.34% in the Bregenzerach River to 13.8 % in the Inn River; and for < 0.125 mm, rates varied from 0% in the Ziller River to 1.21% in the Inn River. Statistical testing of the

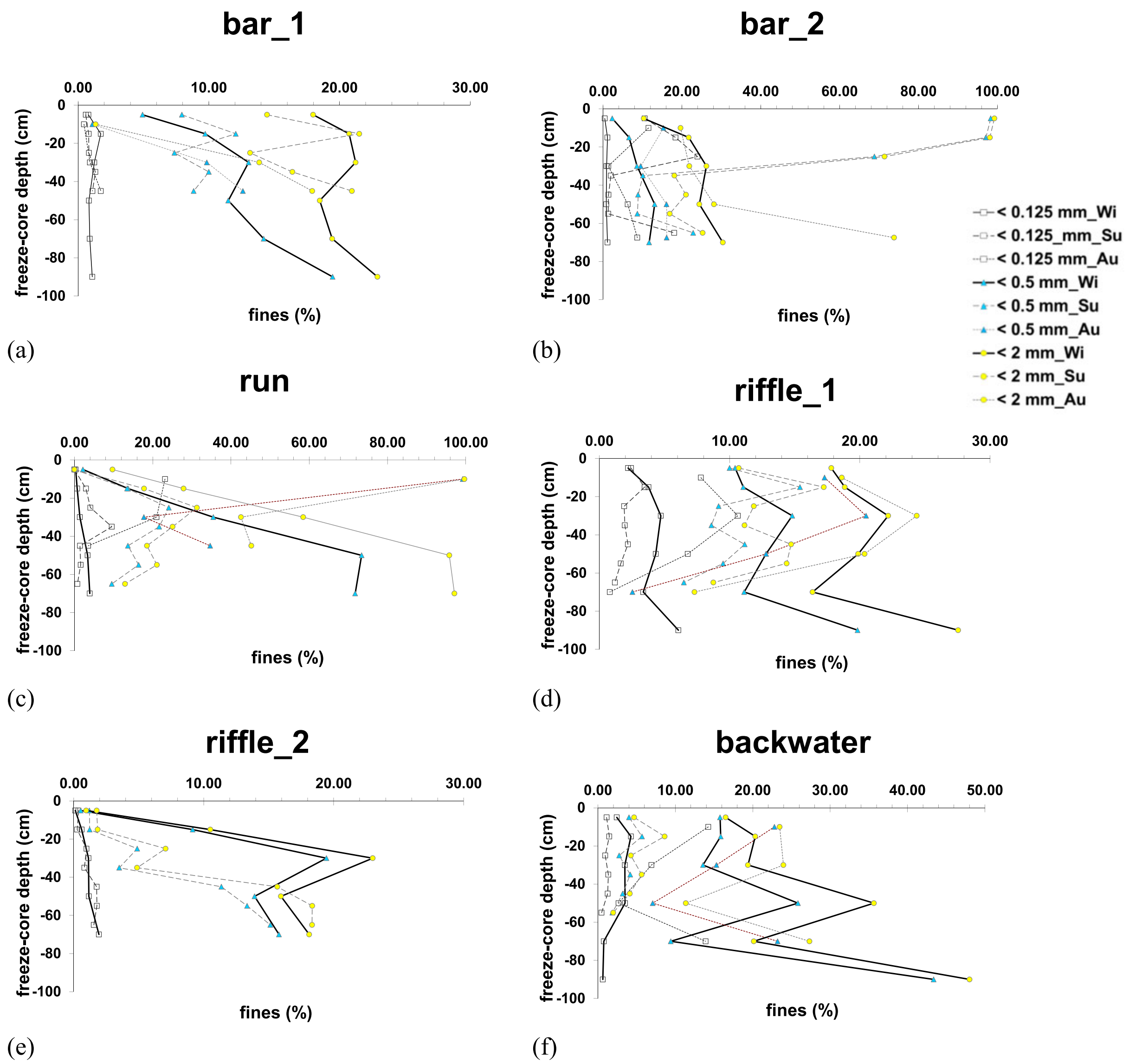


Figure 6. Quantification of FSI and FSI changes for six different sampling points (see Figure 2a) in the study reach of Buchs during the investigated period of 2013 (data based on truncated freeze-core samples); Wi = winter, Su = summer, Au = autumn; note: different scaling of y-axis for Figures (a) and (d). [Colour figure can be viewed at wileyonlinelibrary.com]

two sample location categories, permanently wetted area and dewatering area, showed that there are significant differences ($P < 0.05$) in FSI for the various thresholds of fine sediments (2 mm, 0.5 mm or 0.125 mm) (Table III), with dewatering areas holding more fine sediments compared with permanently wetted areas. Those significant differences were detected in the first (0–10 cm) and the second vertical layers (10–20 cm), except for when comparative testing of fine sediment infiltration < 2 mm in the subsurface layer of 10–20 cm was performed ($P = 0.064$). As sampling depth increased (20–40 cm layer), non-significant differences ($P > 0.05$) were identified, and a high probability of similarity between the different groups ($P = 0.487$ for < 0.125 mm, $P = 0.799$ for < 0.5 mm, and $P = 0.930$ for < 2 mm) was found (Table III).

Seal formation risk

The data from the Alpenrhein River were also used to calculate the possibility of seal formation, particularly in those areas where the samples showed a clear accumulation of fines in the surface layer and moderate decreases with sampling depth (e.g. dewatering areas) (Figure 5, Figure 6). The initial results of our seal formation analysis indicate that certain grain sizes (e.g. d_{85}) are characteristic of deposited fines at the Alpenrhein sites ($n = 4$) and the surface layer sediment samples of the gravel bars in the dewatering areas ($n = 2$); these results are presented in Table IV. Comparing the two sampling points at the alternating gravel bars in Buchs (FC_1 and FC_2) Figure 2(a) reveals that, for the sample point closest to the right bank (FC_1) a risk of seal formation exists. The relationship between d_{15} within the surface substrate and d_{85} of infiltrated sediments was calculated within the range of $d_{15}/d_{85} = 8.92$ and $d_{15}/d_{85} = 10.19$. These values are below the 12–14 threshold and thus within the range for seal formation. Sampling point 2 in the dewatering area, on the other hand, exhibits no risk of seal formation based on the collected data (d_{15}/d_{85} = 24.94–63.0). Sampling sites in which very fine materials are associated with the initial stages of Aue-forest growth are also outside the range of seal formation ($d_{15}/d_{85} = 22.53$).

Potential hydropeaking and reach-scale controls on FSI

The truncated sample data (Table II) were also analyzed to test the second hypothesis that the magnitude of the discharge ramping ratio (e.g. base flow/peak flow = 1:3) has an impact on the magnitude of FSI in the surface and subsurface layers. The results of the discharge ratio analysis are presented in

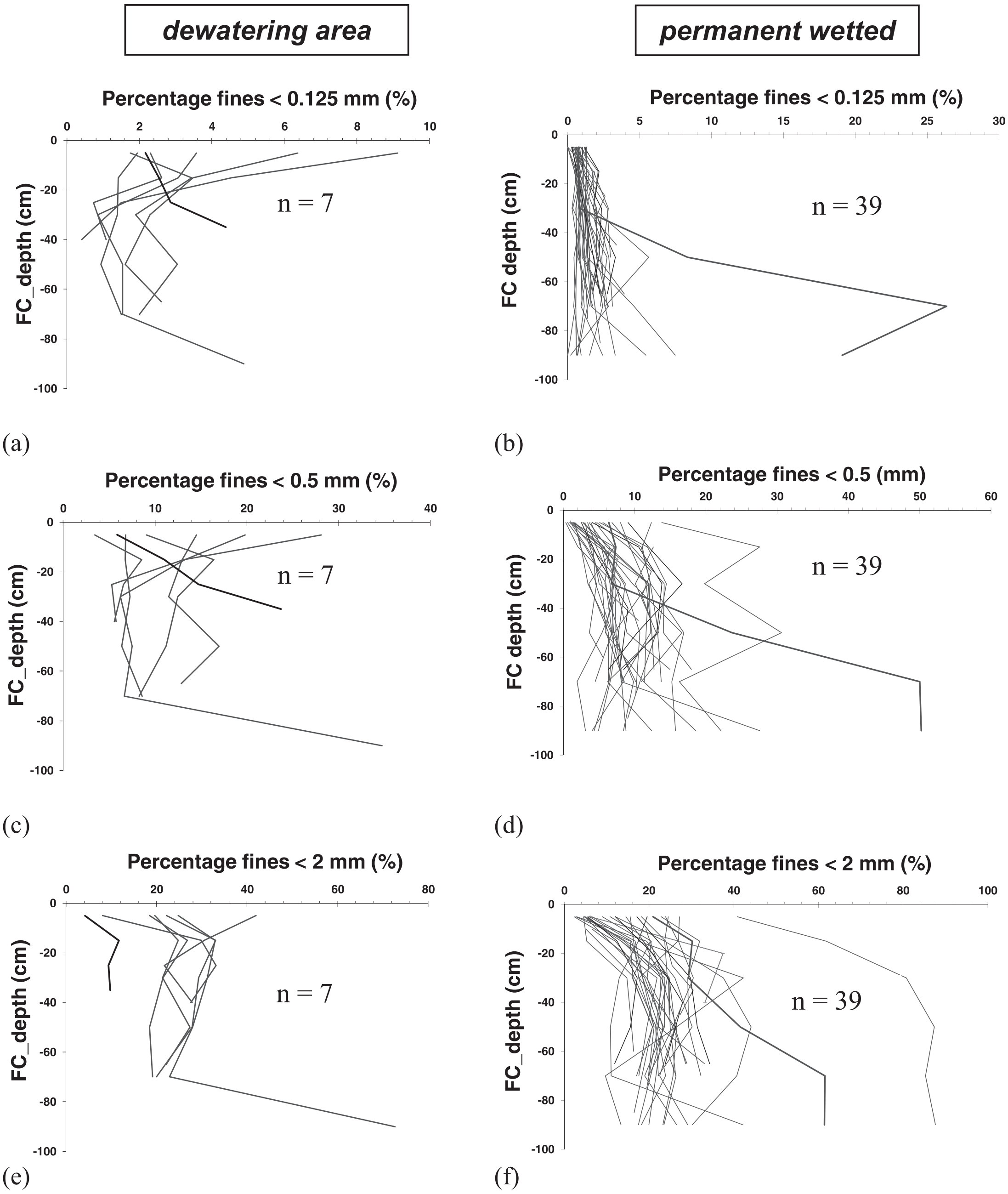


Figure 7. Variability in fine sediment infiltration concerning freeze-core depth in dewatering and permanent wetted areas of hydropeaking reaches in Austria using thresholds d < 0.125 mm (a, b), d < 0.5 mm (c, d) and d < 2 mm (e, f) (please note different scaling of x-axis).

Figure 8. Statistical testing (linear regression or exponential models) indicated that there is no correlation between the magnitude of the discharge ratio (e.g. 1:3 or 1:10) and FSI, regardless of the threshold used to define fine sediments (d < 0.125 mm up to d < 2 mm). The correlation coefficient was $R^2 < 0.1$ for both the surface layer (0 – 10 cm depth) and the subsurface layer (10 – 20 cm). Thus, the tests of various freeze core samples from different river reaches with variable hydropeaking impacts failed to support the second hypothesis. FSI and its possible correlations with local bed slope (S) and bankfull depth (D_{bf}) were also tested using the data presented in Table II, with similar results. No correlation ($R^2 < 0.1$) was found between the bathymetric data and the relative distribution of fines (FSI) within the tested river reaches (*n* = 13).

Discussion

Some studies have connected the physical processes of a hydropeaking flow regime to the magnitude of FSI in alpine gravel-bed rivers (review in Schmutz *et al.*, 2015). However, the impacts of those physical processes on fine sediment distributions and dynamics were not investigated in the present study. Rather, the present study sought to define the characteristics of FSI in hydropeaked rivers. In particular, this study revealed significant differences between FSI in the permanently wetted areas and the dewatering zones supporting the first hypothesis.

The results showed that the highest proportion of FSI is found in the dewatering areas, especially in the surface and near surface layers. It is possible that this sedimentological characteristic may be related to the high frequency of flow pulses (often several times per day), which results in the erosion and deposition of fines in those areas of the gravel bars (compare with Brunke and Gonser, 1997; Brunke, 1999; Cui *et al.*, 2008). However, erosion and deposition rates in the studied rivers were maybe unbalanced in relation to the frequent peak flow events, and thus continuous accumulation of fines occurred. This was documented through an FSI analysis in the dewatering areas, where partial seal formation would be possible. In

Table IV. Characteristic grain sizes (d_{10}–d_{90}) of volumetric sediment samples of fine sediment deposits at gravel bars of the Alpenrhein River (VS) and the surface layer sediment composition determined by freeze-cores at exposed gravel bars in the study reach of Buchs (FC)

	VS_A	VS_B	VS_C	VS_D	FC_1	FC_2
d_{10} (mm)	0.14	0.14	0.11	0.06	2.16	6.49
d_{20} (mm)	0.17	0.17	0.15	0.07	7.65	16.63
d_{30} (mm)	0.21	0.20	0.18	0.08	14.37	27.53
d_{40} (mm)	0.25	0.25	0.21	0.09	23.31	36.92
d_{50} (mm)	0.28	0.29	0.25	0.11	48.36	48.31
d_{60} (mm)	0.32	0.33	0.30	0.12	59.41	58.41
d_{70} (mm)	0.36	0.39	0.37	0.15	64.22	91.78
d_{80} (mm)	0.40	0.45	0.44	0.18	71.86	101.73
d_{90} (mm)	0.45	0.58	0.65	0.21	80.42	112.77
d_{15} (mm)	0.16	0.16	0.14	0.07	4.28	11.97
d_{85} (mm)	0.42	0.47	0.48	0.19	75.17	106.01
d_m (mm)	0.30	0.39	0.48	0.13	41.93	56.06
U	2.24	2.38	2.72	2.00	27.45	9.00
Cc	0.97	0.90	0.91	0.87	1.61	2.00

VS = volumetric sampling; FC = freeze-cores; $U = \frac{d_{60}}{d_{10}}$ curvature; Cc = $Cc = \frac{d_{30}^2}{d_{10} \cdot d_{60}}$ irregularity.

general, seal formation has been observed in the field (Frostick *et al.*, 1984; Lisle, 1989; Acornley and Sear, 1999) as well as in laboratory studies (Gibson *et al.*, 2010). Interestingly, the measured increase in fine sediment storage in the surface or near surface layer along the Alpenrhein River failed to indicate a risk of seal formation using a deterministic formula (Gibson *et al.,* 2010) in several cases.

This discrepancy between measured and calculated FSI characteristics requires discussion to clarify how the dynamic components of gravel bar formation impact site characteristics. Here, a lack of dynamism (e.g. gravel bar turnover) is likely much more responsible for the risk of seal formation than turbidity or suspended sediment transport in general, especially in relation to hydropeaking. The results of the FSI dynamics analysis, which are presented in Figure 6, underline this point. Gravel bars that are re-shaped or turned-over by floods may accumulate finer fractions of transported bedloads or suspended loads over time, which reduces the d_{15} of aggraded sediments in the gravel matrix. These dynamic changes related to accumulation govern the threshold between the d_{15} of the surface substrate and d_{85} of the transported

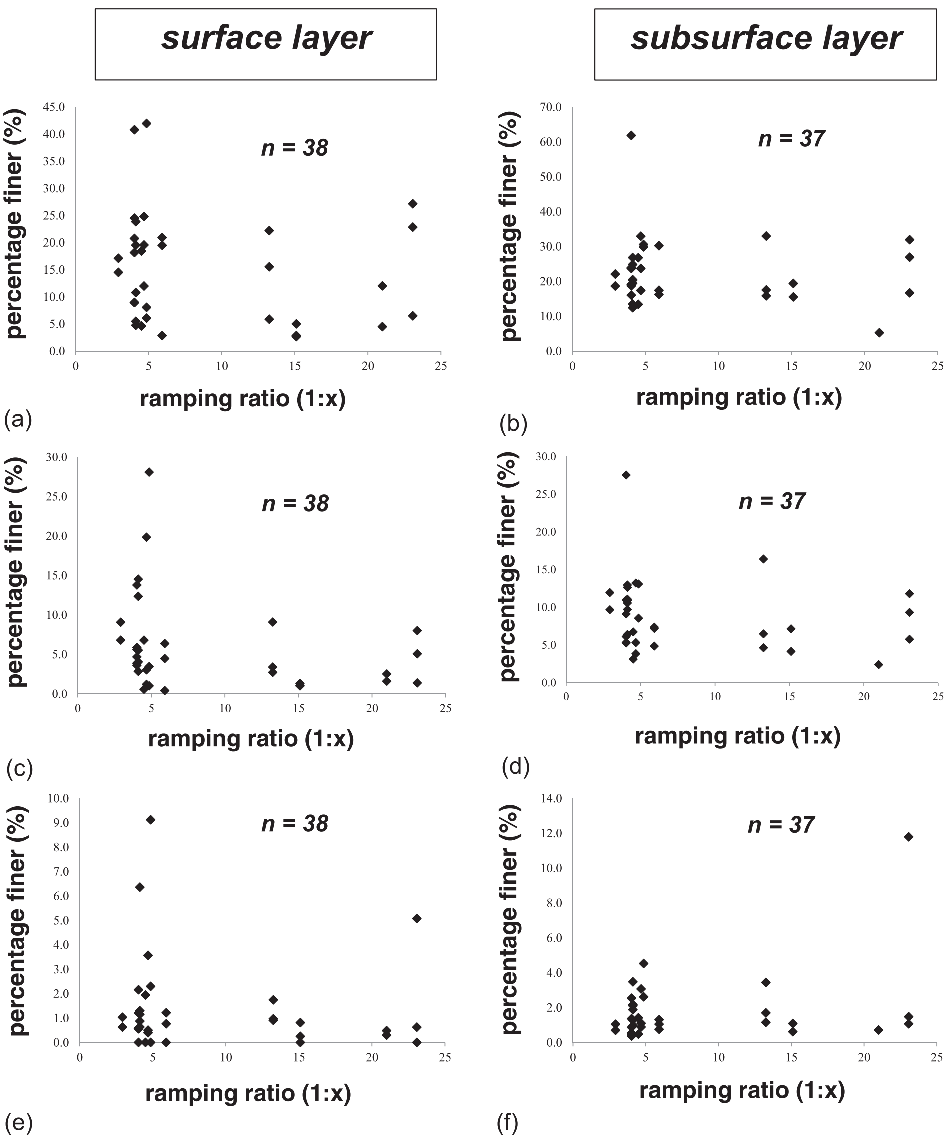


Figure 8. Fine sediment infiltration for trunced samples at 31.5 mm. Different thresholds for quantification have been applied (a,b < 2 mm; c,d < 0.5 mm; e,f < 0.125 mm) as well as the analysis of different vertical layers; Samples (a), (c) and (e) = 0–10 cm (surface layer); Samples (b), (d) and (f) = 10–20 cm (subsurface layer);

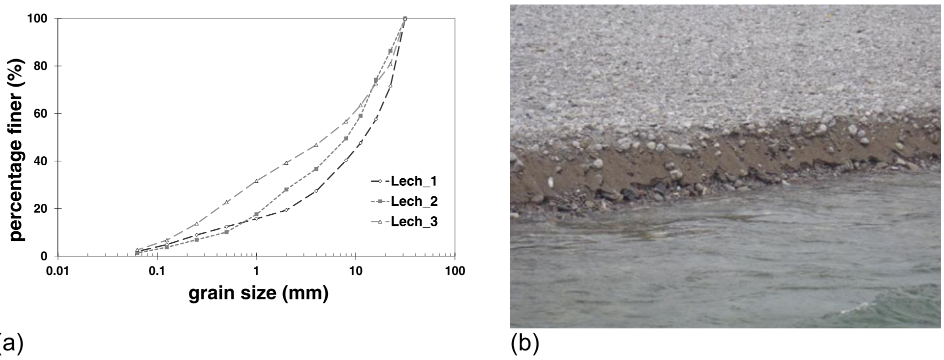
(deposited) fines used in seal formation formulas. In contrast, the second variable, the grain size of the eroded and transported suspended load (d_{85}), does not vary significantly within a river system. For the Alpenrhein samples analyzed using the Komar criteria (1980) in the present study (Figure 4), the grain sizes for possible suspended load transport varied but were apparently below d = 3 mm. Thus, the risk of seal formation in this alpine gravel-bed river will be determined by the period of time a gravel bar is static, the suspended sediment regime and the frequency of fine sediment deposits (fine sediment dynamics), which is quite high in hydropeaking reaches. Nevertheless, downstream fining as a natural sediment sorting process (Rice and Church, 2010) is responsible for the variability in gravel bar sediment characteristics (e.g. d_{15}) as well. These points are well supported by Wooster *et al.* (2008), who stated that the lack of seal formation is likely related to sediment transport, turnover and, hence, self-forming fluvial processes that mobilize substrate below the depth of typical infiltration.

Moreover, the freeze-core results of the present study support the first hypothesis and clearly indicate that mapping subsurface clogging (inner clogging) cannot be performed using visual estimations along the shoreline, as has been proposed by Schälchli *et al.* (2002). There was a statistically significant difference between the FSI rate along the shoreline (dewatering areas) and the FSI in the permanently wetted area. Visually estimating the clogging along the shoreline may lead to an overestimation of the clogging and thus an overestimation of fine sediments' negative impacts on aquatic biota (e.g. macroinvertebrates). Nevertheless, the importance of areas near the shoreline for certain species and life stages must be considered, and thus additional focus on those areas might be appropriate from an ecological perspective.

In terms of the grain sizes of infiltrated fines, it is possible that major parts of the accumulated fines in the Alpenrhein are likely transported (re-mobilized) as a suspended load with grain sizes <2 mm according to the Komar-criteria (calculated for highest recorded flow of 509 $m^3 s^{-1}$). Nevertheless, a minor proportion of deposited fines, particularly those in the permanent wetted areas, are transported as a bedload (d ~ 1.5 mm) for hydropeaking events with low base flow rates. These observations support in some parts the findings of Lisle (1989), who stated in his work that the largest proportion of infiltrated sediment originated from the finest fraction of bedload material rather than from deposited suspended loads. Thus, in line with some physical laboratory studies which showed a clear correlation between suspended sediment concentrations and fine sediment infiltration (Carling, 1984), the assumption of the causal relationship that hydropeaking leads to increased suspended sediment transport and thus to the clogging of pore spaces (Schälchli *et al.*, 2002) is valid.

Furthermore, it is important to consider that the deposition and accumulation of fines on the gravel bar surface is a natural component of river system dynamics (Smith and Smith, 1980). The freeze-core samples taken from the Lech River in this study support this point. The truncated samples (threshold: d = 31.5 mm) revealed FSI within the range 2.9%–4.4% (d < 0.125 mm) for the surface layer and 3.7%–6.7% (d < 0.125 mm) for the subsurface layer (Figure 9(a) in periodically inundated areas (Figure 9(b)) according to an undisturbed hydrograph of all three sample sites. Especially, during site visits to the Alpenrhein River, fine sediment deposits and accumulations outside the area impacted by frequent flow fluctuations (hydropeaking) were observed to be important for the initiation and succession of vegetation, and thus supported the initial stages of riparian forest growth (Figure 3). In these parts of the river, loose gravel and sand are unable to retain water or moisture due to their high permeability; thus, gravel bars with a poor sorting coefficient generally contain only limited vegetation (McBride and Strahan, 1984). For riparian-specific plant species (e.g. willows), however, fine sediments provide the required moisture for seeds to grow (Gilvear and Willby, 2006; McBride and Strahan, 1984). The role of fine interstitial sediments in facilitating seedling establishment has also been addressed in Piegay *et al.* (2000) and Goodson *et al.* (2003). Thus, while FSI may lead to clogging and therefore have negative impacts on certain biota or biotic processes such as macroinvertebrates or the development of fish eggs, it may be an important component of riverine processes (vegetation dynamics) even in hydropeaked rivers, particularly if enough lateral space is given for the self-forming evolution of gravel bars and the non-linear dynamics of erosion and deposition of gravel and fine sediments that lead to variability in sediment disturbance rates.

In general, channel bars that are exposed to vegetation succession are controlled by a multitude of different boundary conditions, including the frequency, depth and duration of flooding; distance to the water table; and soil properties such as particle size and moisture content (Hupp and Osterkamp, 1985; Robertson and Augspurger, 1999; Lyon and Sagers, 2003). Hence, the negative impacts of FSI on the local aquatic ecology strongly depends on both a disturbed sediment regime (e.g. increased supply of fines and/or decrease of bedload) and a disturbed flow regime (reduction of large floods and thus of possible bed turnover) as well as on river training measures that determine the active river width (Hauer *et al.*, 2014) and thus limit lateral bar evolution, creating an anthropogenically disturbed fine sediment dynamics (erosion and accumulation).



(a) (b)

Figure 9. (a) Grain size distribution of the subsurface layer (vertical freeze-core depth = 10–20 cm) for trunced sediment samples (threshold d = 31.5 mm) at the Lech River (reference site) close to the shore line at low flow conditions (Q_L = 1.83 $m^3 s^{-1}$); (b) picture (downstream view) of the surface and subsurface layer of an eroded gravel bar at the Lech River (reference site Johannes bridge). [Colour figure can be viewed at wileyonlinelibrary.com]

As a result, the discussion of possible habitat mitigation in relation to fine sediment management in hydropeaked rivers must occur at the catchment scale, and it must include the impacts of sedimentological aspects such as fines on hydropower reservoir management and instream hydraulics and morphology (e.g. the space required for near-natural gravel bar evolution and fine sediment dynamics). Therefore, the magnitude of bedload transport, which is responsible for bar formation, must be investigated and evaluated in addition to suspended sediment transport and fine sediment dynamics.

In addition, the freeze-core results for the Inn River and the Ill River in the present study highlight the interaction between bedload deficits and the sustainable clogging of pore spaces due to FSI. Due to a heavily disturbed sediment continuum (torrent controls, check-dams) in the headwaters, the Ill River lacks bedload sediments (gravel supply), which results in river bed incision and consequently in the development of pavement layers (Parker *et al.*, 1982). In combination with stable bed surface conditions (e.g. no turnover during low recurrence interval flooding), the natural accumulation of fines (Jones *et al.*, 2011) increased to harmful rates in this river. This point is also supported by the findings of Frostick *et al.* (1984), who studied the infiltration of fine sediments into coarse-grained alluvial matrices. Such conditions may principally be found downstream of reservoirs, where mobilizing flows have been limited or removed by the hydrological alteration of the reservoir (Sear, 1993) and gravel and fines are deposited in the backwater of the reservoir.

These processes have also been examined in Sear *et al.* (2008), who studied spawning habitats and found that those streams with low stream power relative to the critical stream power of the surface layer are more sensitive to increases in fine sediment yields, resulting in the accumulation of fine sediments in the gravel matrix. These negative impacts are superimposed in cases of reservoir flushing and the release of a larger than normal proportion of fines to the downstream reach (Buermann *et al.*, 1995; Rabeni *et al.*, 2005). Evans and Wilcox (2013) also addressed the question of whether bed material is frequently mobilized and how observed fines are related to falling-limb deposition or if fine sediments have a multi-year residence and accumulation time in immobile beds. Thus, several research questions remain to be addressed in relation to the impact of multiple anthropogenic stressors on fine sediment dynamics.

Limits and uncertainties

For the examined relationship between discharge ratio and FSI, the high likely variability of FSI on a small scale should be noted. There is great variability in subsurface fines content (from a few percent to over 30%) within and between unregulated gravel-bed rivers. Much of this variation is correlated with the bed surface D_{50} (as controlled by slope and formative shear stress) and with differences in the suspended sediment regime between rivers. Although data on the suspended sediment regime were not available for this study, comparison of the D_{50} of the various sites (see Table II) indicated that 9 out of the 15 sites contained a D_{50} between 20 mm and 30 mm. These similarities in confounding variables across sites, however, should overcome the weakness in lack of comparability, underlining that the presented data are not just descriptive. The derived findings are valid for the studied river gradients from 0.0017 up to 0.0054. From a methodological point of view, Freeze-cores may have uncertainties concerning larger grain sizes (not frozen in an appropriate way to the rod). However almost no uncertainties are given for the quantification of very fine sediments of the derived samples.

Lisle (1989) underlined that the fine sediment fraction within depositional patterns strongly depends on transport mode, local hydraulics and self-forming processes, which are linked to the larger scale sediment regime and flood dynamics. Moreover, Rice and Church (1998) have also documented the variability of FSI for similar depositional settings. Hence, local and stochastic samples of fine sediment accumulations in permanently wetted and dewatering areas of hydropeaking river reaches may be biased in relation to other Austrian hydropeaking sites. Nevertheless, no relationship with the discharge ratio (e.g. Q_{base}/Q_{peak} = 1:3) could be found, even if the small scale variability and local scale disturbances and the quantity of fines in the gravel matrix are considered. Moreover, due to insufficient control on unregulated reference sites, the study design does not allow conclusions of peaking on FSI in comparison with the natural state of the same system without flow regulation.

Conclusions

Based on the findings of this study, it can be concluded that there are significant differences in FSI between permanently wetted areas and dewatering sites along alpine rivers impacted by artificial hydropeaking flow regimes. The flow hydrograph of the wetted area appears flushier than that of base flow areas and prone to FSI, especially since fine sediment concentration would tend to be higher at peak flows when gravel bars are inundated. In contrast to the high accumulation rates in the surface layer of dewatering sites, almost no fine sediment deposition occurred in the upper part of the gravel matrix of permanently wetted areas. Prolonged recession flow in the base area would tend to winnow fines from the bed. Thus, clogging of benthic habitats seems to be only a minor concern due to hydropeaking, as this process is generally restricted to specific areas.

However, the catchment sediment regime is a crucial factor in determining how dynamic a river bed is and, thus, how frequent disturbances are, which lead to a wash out of accumulated fines from the gravel matrix. This study also documented the potential importance of FSI and fine sediment deposits in the natural dynamics of a river system, especially in terms of supporting the initial stages of vegetation growth (e.g. riparian forests). Thus, in addition to the hydrological impacts of artificial flow fluctuations, the multiple pressure impacts such as changes in the catchment scale sediment regime and river regulation for flood protection should be considered in the management of hydropeaking rivers. Moreover, two other important management issues were identified. First, a possible visual assessment of FSI along the entire river should be restricted along the shoreline, as quantitative sampling data showed that there are significant differences between dewatering sites and the permanently wetted part during base flow. Second, the magnitude of the discharge ratio is not a limiting factor in relation to the rate of FSI in hydropeaking rivers.

Acknowledgements—The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation of Research, Technology and Development of Austria is gratefully acknowledged.

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