Morphological Response of Channelized, Sinuous Gravel-Bed Rivers to Sediment Replenishment

C. Rachelly¹, F. Friedl², R. M. Boes¹, and V. Weitbrecht¹

¹Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland, ²Hunziker Betatech AG, Winterthur, Switzerland

Abstract  Anthropogenic alterations of sediment supply and transport processes may impact the ecological state of riverscapes and threaten infrastructure along the river. Sediment replenishment is one restoration method that is employed in channels impacted by sediment deficit. We performed flume experiments to investigate the channel bed response of a channelized, sinuous gravel-bed river to periodic and episodic sediment replenishment. The grain size distribution of the replenished material, flow discharge, and sediment supply level were varied in long-term steady-state experiments. In addition, the channel routing of a single sediment pulse was investigated. The long-term channel response included intensified sediment relocation and transversal bed leveling. Sediment supply level and flow discharge thereby exerted the strongest control over channel response, whereas the influence of the grain size distribution of the replenished material was minor. A simple habitat analysis using grayling as example species revealed that replenished sediment retained within the channel and thus providing episodically renewed clean gravel patches may increase spawning habitat availability. However, the general shortage of shallow habitats for grayling fry and juveniles in channelized rivers persisted regardless of sediment replenishment. Overall, the experiments illustrate that sediment replenishment may provide valuable habitats within a channelized river. Accompanying measures such as channel widening and the careful consideration of other remaining stressors are strongly recommended to increase restoration benefits further.

Plain Language Summary  Humans interfere with many aspects of river systems, typically to protect populations from floods, exploit gravel and sand for construction, or produce hydropower. One common consequence thereof is that the amount of sediment transported in our rivers may be significantly reduced. However, sufficient sediment transport is of substantial importance to river ecosystem health. There are, for example, some fish species that lay their eggs in a pit that they dig into gravel. But the bed of a river with a sediment deficit consists of cobbles and boulders that are too large for fish to move, and their reproduction may thus be impaired. In addition, a sediment deficit may also damage flood protection structures. To restore the sediment transport in a river to some degree, gravel of suitable size can be deposited in the river channel. We used a laboratory model to conduct systematic tests on how the artificially added gravel is distributed along the downstream reach during subsequent flood events. We found that this practice may provide some benefits to riverine biota, but its success will be diminished if other human pressures on the river system remain unrestored.

1. Introduction  
A natural sediment regime and the associated eco-morphodynamic processes are widely understood to be vital parts of the riverscape (Wohl et al., 2015). Sediment supply and transport regulate morphodynamic processes on different spatial and temporal scales (Church & Ferguson, 2015). However, many river systems worldwide have been heavily modified, and a common consequence thereof is an imbalance between the sediment input into a river and its transport capacity. While land-use changes such as deforestation may increase sediment input due to reduced soil erosion resistance (e.g., Madej et al., 2009), many river engineering measures have decreased sediment supply and conveyance compared to natural conditions (Kondolf, 1997). Extensive river channelization, in many countries completed mainly during the 19th century, led to a disconnection of the main channel from its floodplain and, therefore, from an extensive source of sediment (e.g., Hohensinner et al., 2011; Petts et al., 1989; Scorpio et al., 2018; Surian & Rinaldi, 2003). The construction of dams, sediment retention basins, and gravel extraction sites in the past century has...
interrupted longitudinal sediment conveyance and intensified the detrimental impacts on many river systems further (Heckmann et al., 2017; Kondolf, 1997).

If sediment supply to a river reach is considerably lower than its long-term average transport capacity, the consequences become apparent on various spatial scales (Kondolf, 1997). The lack of sediment transported during high flows may decrease morphodynamic activity and lead to impoverished channel morphology. Excess shear stress may result in channel incision and decoupling from the adjacent floodplain (e.g., Brousse et al., 2020a; Kondolf, 1997; Rollet et al., 2014), as well as the formation of a coarse armor layer (e.g., Dietrich et al., 1989; Kondolf, 1997; Nelson et al., 2009). Because the armor layer will only be eroded during relatively rare extreme floods, fine material may clog the interstitial spaces (e.g., Dietrich et al., 1989). These morphodynamic effects propagate to riparian fauna and flora with strong feedback, such as the encroachment and subsequent stabilization of river bars (e.g., Bertoldi et al., 2014). Ecological consequences include the loss of residential habitats, lack of refuge habitats during disturbance events, or interrupted successional development of riparian plants.

Measures aimed at restoring sediment transport were incorporated in progressive water protection legislation, such as the Swiss Waters Protection Act (WPA) and Waters Protection Ordinance (WPO), revised in 2011. The goals of sediment transport restoration may range from the local establishment of specific fish habitat (e.g., Zeh & Dönni, 1994) to the reach-scale or catchment-scale, geomorphic goal of restoring sediment transport as an ecosystem function (e.g., Brousse et al., 2020b; Pauli et al., 2018). The restoration activity can be mainly economically motivated, e.g., to prevent structural damage caused by bed incision (e.g., Brousse et al., 2020a; Frings et al., 2014; Klösch et al., 2011; Welber et al., 2020), or may have a more pronounced ecological focus, e.g., to reactivate the natural morphodynamic processes and increase topographic heterogeneity (e.g., Gaeuman et al., 2017; Pauli et al., 2018; Stähly et al., 2019). A wide range of structural, operational, and replenishment measures are applied to restore sediment transport, including gravel deposition or injection to the channel (Arnaud et al., 2017; Battisacco et al., 2016; Brousse et al., 2020a; Bunte, 2004; Friedl et al., 2018; Frings et al., 2014; Harvey et al., 2005; Ock et al., 2013; Schälchli et al., 2010), inducement of bank erosion (Friedl, 2017; Klösch et al., 2011), sediment flushing and bypassing from upstream of a dam (Boes, 2015; Sumi, 2017), or dam removal (O’Connor et al., 2015; Ritchie et al., 2018).

While the focus of structural and operational restoration efforts lies primarily on the sedimentation management of reservoirs (Kondolf et al., 2014), sediment replenishment (or gravel augmentation) in the form of gravel deposits or induced bank erosion may also be implemented far downstream of a dam, in reaches that are particularly affected by sediment deficit (e.g., Klösch et al., 2011). The sediment used for replenishment can come from different sources, such as the topset deposits of a reservoir delta, gravel pits, the floodplain, or river banks (Bunte, 2004; Harvey et al., 2005; Kondolf, 1997). To support the creation of specific habitats, such as spawning habitats, the grain size distribution used in sediment replenishment is usually restricted to suitable grain sizes (i.e., fine to medium gravel; see Kondolf & Wolman, 1993; Riedl & Peter, 2013). Below run-of-river hydropower plants, replenished sediment is exposed to near-natural hydrological conditions, whereas below a storage or diversion hydropower plant, the hydrological regime may be strongly altered. In the latter case, it may be beneficial to combine sediment replenishment with artificial floods (e.g., Brousse et al., 2020a; Gaeuman et al., 2017; Stähly et al., 2019).

As the boundary conditions and objectives of sediment replenishment vary widely, the definition of explicit goals and knowledge about the impact of the replenished sediment are prerequisites for an informed choice of replenishment technique (Harvey et al., 2005). However, our ability to predict the interaction of a specific sediment replenishment regime with a river’s topography and bed surface texture remains limited. Not only is sediment transport a highly dynamic and episodic process (Wohl et al., 2015), but many river systems are simultaneously impacted by multiple stressors (e.g., Brousse et al., 2020b; Schinegger et al., 2012). If restoration planning does not comprehensively address all detrimental impacts on a river system, remaining stressors may diminish the effectiveness of any single measure (e.g., Bond & Lake, 2003). Sediment replenishment in rivers with fixed banks is one example of a setting with remaining stressors (i.e., the stabilization of channel planform and width).

We examined the topographic response of a channelized river downstream of a sediment barrier (e.g., a dam) and subject to sediment replenishment in a series of flume experiments. We thereby assumed that
the barrier does not decrease the flood peaks of morphologically active floods. The experimental conditions correspond to replenishment techniques with limited sediment quantities such as gravel deposits in the channel. More comprehensive measures such as dam removal were not treated. Furthermore, the study is concerned with situations where the removal of bank protection to increase channel width is not feasible, and significant bed aggradation following sediment replenishment cannot be tolerated due to increased flood hazards.

We addressed the following research questions considering both the long-term and short-term effects of sediment replenishment under variable boundary conditions:

1. Does sediment replenishment lead to changes in channel bed topography? We hypothesize that while some transversal bed leveling may occur due to thalweg filling (Zunka et al., 2015), the main topographic characteristics of the channel will not be affected.

2. Does sediment replenishment result in intensified sediment relocation activity, i.e., deposition of replenished sediment or erosion of the bed material? We hypothesize that sediment relocation zones expand with increasing sediment supply rates (Dietrich et al., 1989; Nelson et al., 2009). The resulting clean gravel zones may improve the ecological conditions by providing critical habitats to riverine biota.

2. Methods
2.1. Experimental Setup

The laboratory experiments were designed to represent typical channelized gravel-bed rivers in the Swiss Plateau region (Figure 1a), and geometrical, hydrological, and sedimentological parameters were chosen accordingly. The planform is sinuous, the banks are fully protected by riprap, and the bed consists of mobile alluvial material. A Froude scale factor of $\lambda = 50$ is assumed when comparing laboratory results to field conditions; however, the laboratory setup does not represent a specific river reach. The experiments were conducted at a longitudinal bed slope of $\sim 0.003$, and a stable bar-pool morphology developed within the fixed banks. In all tested configurations, the ratio of bed width to flow depth $b/h$ and flow depth to median grain size diameter $h/d_{50}$ calculated for a corresponding rectangular cross-section were $b/h = 10–24$ and $h/d_{50} = 25–93$, respectively. These values indicate a morphology in the transition zone between bar formation, plane bed, and meandering (Ahmari & Da Silva, 2011). Bar modes $m$ after Crosato and Mosselman (2009) varied between 0.47 and 0.94 except for one configuration with $m = 1.12$. The bar modes $m < 1$ show that alternate bars would not likely be present in a straight channel of the same dimensions. Therefore, the observed bar-pool morphology was mainly forced by the river planform (e.g., Crosato & Mosselman, 2020).

The experiments were conducted in a flume of 31.6 m length and 4 m width at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. A river planform with four consecutive bends and a straight section was constructed within the flume (Figures 1b and 1c). The sinuosity index after Wolman et al. (1964) was 1.06 for the entire channel and 1.12 for the region of interest (ROI) only (Figure 1c). The centerline length was 33.5 m, and the width of the initial flat bed 0.8 m. While the bed material was mobile, the banks were fixed to represent typical conditions in channelized rivers (Figure 2). A riprap texture was imprinted into the cement coating to approximate bank roughness. The bank slope was set to 1:1 (V:H) in the outer bend, 1:3 in the inner bend, and 2:3 in the straight section.

The flume is equipped with pumps that can circulate up to 400 l/s, and the inflow discharge was measured by a magnetic inductive discharge meter (MID) at an accuracy of ±0.5% (i.e., ±0.2 l/s for the maximum...
A stilling basin at the flume inlet ensured an even inflow into the channel. The water level in the outlet reservoir was controlled with an ultrasonic distance sensor (UDS) linked to a gate valve to maintain the downstream boundary condition. Eight UDS positioned on the centerline measured water levels at an accuracy of ±1% (i.e., ±0.005 m for the lowest water level in this study) and a sampling rate of 1 Hz (Figures 1b and 1c).

Dry bed topography was recorded with the terrestrial laser scanner (TLS) Leica ScanStation P15 (Friedl et al., 2017) with a mean registration error of ±0.001 m. Two scans recorded at different positions were merged to cover the entire flume (Figure 1c). When a run was interrupted to record bed topography, the flume was drained and filled slowly to prevent sediment displacement. Time-averaged UDS values recorded at the end of each run were used to match water table elevations with consecutive topography records.

Three sediment mixtures were used, representing bed material (S1), coarse replenished sediment (S2), and fine replenished sediment (S3) (Figure 3). Truncation of the grain size distributions at 0.25 mm prevents cohesive effects at laboratory scale. The grain size distribution S1 represents a poorly sorted gravel-bed river with a limited percentage of sand (∼30%). In accordance with sediment replenishment practice, the mixtures S2 (coarse) and S3 (fine) have a finer grain size distribution than the bed material S1. Insights regarding the maximum suitable grain size can be gained from observations of brown trout redds in Swiss rivers that have been shown to rarely occupy substrates larger than 0.064 m (Riedl & Peter, 2013). Assuming a scale factor of λ = 50, the upscaled $d_{90}$ values used here are 0.11 m (S2) and 0.07 m (S3). Note that the specific upper grain size limit for replenishment material may vary depending on river characteristics, fish communities, and restoration goals.

Dry sediment was supplied to the flow directly after the inlet via a calibrated conveyor belt at an accuracy of ±5% (i.e., ±3.3 g/min for the lowest supply rate in this study). All sediment was transported as bed-load. A submerged filtering basket suspended from load cells collected the sediment at the flume outlet (Figure 1b) and continuously monitored the output rate at a sampling rate of 1 Hz and an accuracy of ±5%. Sediment was not recirculated.

2.2. Test Procedure

The test procedure was set up to represent the typical sequence of channel adjustment exhibited by channelized rivers with a sediment barrier (e.g., a dam) and includes the phases (A) predam condition with transport-limited bed-load transport, (B) sediment deficit and armoring due to upstream dam construction, and (C) sediment replenishment at different supply levels (SL) (sensu Sklar et al., 2009; see Table 1 for all configurations). In all scenarios, flow was subcritical with Froude numbers between 0.62 and 0.80 and flow Reynolds numbers indicating fully turbulent flow ($R_R > 10^5$, with $R_R = \text{hydraulic radius [m]}, \nu = \text{flow velocity [m/s]},$ and $\nu = \text{kinematic viscosity [m}^2$/s$)$).

During the predam phase A, the initially flat bed (mixture S1) was transformed into a bar-pool morphology. Mixture S1 was supplied at a rate of 5.2 g/s, which corresponds to 650 kg/s if upscaled with a Froude scale factor of $\lambda = 50$. This rate was determined based on the transport capacity after Wong and Parker (2006) for a straight channel of the same dimensions and further adjusted during preliminary tests. The experiments were then performed at a longitudinal slope of $\sim 0.003$. The steady discharge $Q_s$ corresponded to the discharge necessary to break up the maximally coarse armor layer of the bed surface (mixture S1). The grain discharge in this study). A stilling basin at the flume inlet ensured an even inflow into the channel. The water level in the outlet reservoir was controlled with an ultrasonic distance sensor (UDS) linked to a gate valve to maintain the downstream boundary condition. Eight UDS positioned on the centerline measured water levels at an accuracy of ±1% (i.e., ±0.005 m for the lowest water level in this study) and a sampling rate of 1 Hz (Figures 1b and 1c).

Dry bed topography was recorded with the terrestrial laser scanner (TLS) Leica ScanStation P15 (Friedl et al., 2017) with a mean registration error of ±0.001 m. Two scans recorded at different positions were merged to cover the entire flume (Figure 1c). When a run was interrupted to record bed topography, the flume was drained and filled slowly to prevent sediment displacement. Time-averaged UDS values recorded at the end of each run were used to match water table elevations with consecutive topography records.

Three sediment mixtures were used, representing bed material (S1), coarse replenished sediment (S2), and fine replenished sediment (S3) (Figure 3). Truncation of the grain size distributions at 0.25 mm prevents cohesive effects at laboratory scale. The grain size distribution S1 represents a poorly sorted gravel-bed river with a limited percentage of sand (∼30%). In accordance with sediment replenishment practice, the mixtures S2 (coarse) and S3 (fine) have a finer grain size distribution than the bed material S1. Insights regarding the maximum suitable grain size can be gained from observations of brown trout redds in Swiss rivers that have been shown to rarely occupy substrates larger than 0.064 m (Riedl & Peter, 2013). Assuming a scale factor of $\lambda = 50$, the upscaled $d_{90}$ values used here are 0.11 m (S2) and 0.07 m (S3). Note that the specific upper grain size limit for replenishment material may vary depending on river characteristics, fish communities, and restoration goals.

Dry sediment was supplied to the flow directly after the inlet via a calibrated conveyor belt at an accuracy of ±5% (i.e., ±3.3 g/min for the lowest supply rate in this study). All sediment was transported as bed-load. A submerged filtering basket suspended from load cells collected the sediment at the flume outlet (Figure 1b) and continuously monitored the output rate at a sampling rate of 1 Hz and an accuracy of ±5%. Sediment was not recirculated.

2.2. Test Procedure

The test procedure was set up to represent the typical sequence of channel adjustment exhibited by channelized rivers with a sediment barrier (e.g., a dam) and includes the phases (A) predam condition with transport-limited bed-load transport, (B) sediment deficit and armoring due to upstream dam construction, and (C) sediment replenishment at different supply levels (SL) (sensu Sklar et al., 2009; see Table 1 for all configurations). In all scenarios, flow was subcritical with Froude numbers between 0.62 and 0.80 and flow Reynolds numbers indicating fully turbulent flow ($R_R > 10^5$, with $R_R = \text{hydraulic radius [m]}, \nu = \text{flow velocity [m/s]},$ and $\nu = \text{kinematic viscosity [m}^2$/s$)$).
size distribution of this armor layer was determined after Gessler (1965), and its critical bed shear stress, and thus critical discharge for armor layer mobilization, was estimated after Günter (1971). Assuming \( \lambda = 50 \) and comparing the resulting upscaled discharge of 684 m\(^3\)/s to typical rivers in the Swiss Plateau region, we can estimate that \( Q_A \) roughly corresponds to a flood event with a return period of \(~5–20\) years and thus represents the long-term morphological development of these rivers. The calculated dimensionless bed shear stress for the median grain size \( \theta_{50,S1} \) was higher than, e.g., the average \( \theta_{50} \) of 0.068 reported for gravel-bed rivers in Colorado during 100-year floods (Andrews, 1984). However, the value complies with the general rule that the bed shear stress in gravel-bed rivers rarely exceeds two to three times the critical value of \( \theta_c \approx 0.03–0.06 \). Considering that this study refers to channelized rivers with compact cross-sections, elevated bed shear stress values may be expected.

The following phase B represented the interruption of sediment transport by a transverse structure, such as a dam. Hence, no sediment was supplied to the flume while the discharge was held constant at 0.8 \( Q_A \) to winnow the bed surface and obtain an armor layer of maximal stability without breaking it up. Phases A and B were back to back to form a complete cycle. Table 1 shows the test program with the long-term series 1–4 and the single pulse series 5.
and B were repeated prior to phase C of every test series to reproduce the initial bed topography and texture (Table 1).

Phase C represented different sediment replenishment regimes. For the long-term series 1–4, either one of the replenishment mixtures (S2, S3) was continuously supplied to the flume at a constant rate while a steady discharge of $0.3Q_A (LQ)$, $0.51Q_A (MQ)$, or $0.73Q_A (HQ)$ was applied (Table 1). The maximum supply level of 100% was individually defined for each combination of replenishment mixture and hydraulic conditions, and roughly corresponded to the transport capacity. Some series were started without sediment supply to validate the stability of the armor layer at lower flows and resulting higher local energy head differences. The sediment supply rate was then raised incrementally in all series until the respective maximum supply rate was reached. As sediment replenishment is not typically timed to coincide with extreme flood events, the upscaled discharges ($\lambda = 50$) applied in phase C roughly correspond to flood events with return periods of 1–2 years. Accordingly, the bed shear stresses computed for the bed material S1 were close to the critical dimensionless bed shear stress (Table 1).

Except for runs 5_C_const and 5_C_var, all runs were continued until a sediment equilibrium was reached, which was defined as the difference between sediment input and output rate falling below 5% for at least 1 h. This equilibrium approach was chosen to represent a future steady state of a river after decades of repeated sediment replenishment in relatively short intervals (e.g., annual renewal of gravel deposits), as shown to be an appropriate simplification (Elgueta-Astaburuaga and Hassan, 2017).

In contrast, the goal of series 5 was to record the routing of a single gravel deposit through the river reach and observe how much sediment of a single pulse is retained. Run 5_C_const corresponded to run 1_C_4 with LQ and fine sediment (S3; Table 1), except sediment input at 4.5 g/s was stopped after a volume of 0.028 m$^3$ had been supplied (i.e., after 150 min). The added volume corresponded to a typical gravel deposit of 3,500 m$^3$ in a Swiss lowland river if $\lambda = 50$ is assumed (Friedl, 2017). Every 75 min, the run was interrupted, and the topography was scanned to closely track the advance of the sediment pulse. Run 5_C_const was terminated after nine intervals of 75 min when no significant change in bed topography was detected anymore. After the last interval, the remaining replenished material was carefully flushed without damaging the armor layer developed during run 5_B.

Run 5_C_var then repeated the procedure of adding a total sediment volume of 0.028 m$^3$ to the flume, but a series of identical hydrographs with a peak flow of LQ (0.3Q_A) replaced the steady conditions. The flow hydrograph was designed to match the cumulated transport capacity of one steady interval in run 5_C_const. For the sake of simplicity, the transport capacity was assumed to increase linearly between the initiation of transport, visually determined to be at $\sim 7 \text{ l/s}$, and 4.5 g/s at the maximum discharge of 11.5 l/s. The slope of the ascending and descending leg of the hydrograph with a broad peak was $5.4 \times 10^{-3} \text{ l/s}^2$ and $-0.9 \times 10^{-3} \text{ l/s}^2$, respectively. This approach resulted in an interval length of 121 min. Analogous to 5_C_const, sediment supply was arranged during the first two intervals of 5_C_var, and the run was terminated after nine intervals.

### 2.3. Data Analysis

The high-resolution laser scan data obtained after every run allowed the close observation of morphological changes, such as adjustments of the longitudinal and transversal slope, as well as erosion and deposition patterns. The unstructured point cloud with a measurement accuracy of $\pm 0.001 \text{ m}$ was interpolated onto a $0.01 \times 0.01 \text{ m}$ grid to obtain a digital elevation model (DEM). The linearly propagated error of the DEMs of difference (DoDs) is $\pm 0.0014 \text{ m}$ and lies between the dimensionless bed shear stress ($\lambda = 50$) applied in phase C roughly correspond to flood events with return periods of 1–2 years. Accordingly, the bed shear stresses computed for the bed material S1 were close to the critical dimensionless bed shear stress (Table 1).

The unstructured point cloud with a measurement accuracy of $\pm 0.001 \text{ m}$ was interpolated onto a $0.01 \times 0.01 \text{ m}$ grid to obtain a digital elevation model (DEM). The linearly propagated error of the DEMs of difference (DoDs) is $\pm 0.0014 \text{ m}$ and lies between the dimensionless bed shear stress ($\lambda = 50$) applied in phase C roughly correspond to flood events with return periods of 1–2 years. Accordingly, the bed shear stresses computed for the bed material S1 were close to the critical dimensionless bed shear stress (Table 1).

Along the channel, 620 cross-sections (CS) perpendicular to the centerline were extracted from the DEMs. Their longitudinal spacing on the centerline is 0.05 m, and their transversal point spacing is 0.01 m. CS 136–341 correspond to the region of interest (ROI), which covers 10.15 m along the centerline and contains two bar-pool units (Figure 1c). Most topographical analyses were only performed within the ROI, as the water table elevation in the outlet basin may have influenced the sediment transport in the last few meters of the flume.
The thalweg was defined as the minimum elevation in each CS, and its path was smoothed with a moving average over 10 CS. The average longitudinal bed slope along the centerline $S_m$ was determined as a linear fit of the average bed elevation in each CS within the width of the initial flat bed of 0.8 m. Because deposition zones can extend beyond this width, this procedure introduces a slight bias toward scouring.

To assess alterations of the transversal bed slope, the normalized change in bed relief index $\Delta BRI^*$ ($-$) was calculated for every CS

$$\Delta BRI^* = \frac{BRI_C^* - BRI_B^*}{BRI_B^*}$$  \hspace{1cm} (1)$$

with the normalized bed relief index (Liébault et al., 2013) after phase B $BRI_B^*$ ($-$), and after phase C $BRI_C^*$ ($-$) defined as

$$BRI^* = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (z_i - \bar{z})^2}$$  \hspace{1cm} (2)$$

with the $i$th bed elevation $z_i$ (m) in a CS of $n$ points, the mean bed elevation $\bar{z}$ (m) of the CS, and the bed width $b$ (m) of the CS. Thus, the $BRI^*$ corresponds to the standard deviation of bed elevations normalized with the bed width in a specific CS (Liébault et al., 2013).

In series 5, the single sediment pulse was tracked by continuous visual observation of the pulse front and frequent laser scans. The downstream-cumulative elevation differences (CED) calculated from these repeated scans visualize the relative importance of translation and dispersion for the transport of a single sediment pulse (cf. Sklar et al., 2009, Figure 1). Here, the 95th percentile of the bed elevation difference in each CS between the topography after phase B and after the respective phase C was summed up along the centerline and normalized with the maximum CED of the respective series. The CED curve of a purely translational pulse will travel downstream without changing its shape, while the upstream end of the CED curve of a purely dispersive pulse will remain in place, and the rest of the curve will flatten over time (cf. Sklar et al., 2009, Figure 1).

3. Results

3.1. Phases A and B: Initial Bed

The initial flat bed was constructed with a slope of 0.0017 (see supporting information for measured slope values of all runs). During phase A, a bar-pool morphology with point bars after the apex of every bend and corresponding scours on the opposite side of the channel developed (Figure 4a). Just upstream of the flume outlet, an elongated scour formed along the left bank of the straight section. The longitudinal slope adjusted to the sediment supply rate and increased to 0.0030–0.0034 (all phases A). Continuous measurements of the sediment input and output are presented in supporting information. The average normalized bed relief index in the ROI after all phases A was $BRI_A^* = 0.034 \pm 0.016 \; (\pm \sigma)$.

During phase B, the topography that developed during phase A remained stable (Figure 4b) with an average slope of 0.0030–0.0033 (all phases B). Along the entire channel length, the bed underwent a slight average net erosion of $-0.003 \pm 0.003 \; m \; (\pm \sigma)$ due to the winnowing of fine grains (Figure 4c). This degraded bed with an average $BRI_B^*$ of 0.034 $\pm$ 0.015 $\pm \sigma$ in the ROI represented the state of a channelized river with a substantial sediment deficit prior to any sediment replenishment measures in phase C.

3.2. Phase C of Series 1 to 4: Steady-State Replenishment

The steady-state runs in phase C of series 1–4 represent the long-term effects of repeated sediment replenishment. The added sediment mixtures S2 and S3 are finer than the bed material S1 (Figure 3) and were added at variable supply rates under three different hydraulic conditions (LQ, MQ, HQ; Table 1). The bed relief index ($BRI^*$) in the ROI generally decreased for increasing sediment supply levels, indicating that the
transversal slope tended to decrease, and the overall bed topography was leveled. The effect was strongest for series 1 with LQ and S3 with a median $\Delta BRI = -0.38$ after 1_C_4. The thalweg was filled with sediment, and the bed underwent extensive aggradation. In phases 2_C and 3_C, the transversal leveling was weaker with a median $\Delta BRI = -0.10$ and -0.14 after 2_C_5 and 3_C_5, respectively. With a median $\Delta BRI = -0.04$ after 4_C_5, the observed bed relief change for series 4 was negligible (see supporting information for all $\Delta BRI$ of series 1–4).

Figure 5 compares the effect of different sediment supply levels on the bed topography using the example of series 2 (see supporting information for flume-length DoD plots of all series). Run 2_C_1 with 0% sediment supply reaffirmed that the initial topography was stable (Figure 5a). At low relative sediment supply levels, the deposition was limited to the bar apexes, whereas the lateral bar zones were subject to erosion (Figures 5b and 5c). As the supply level increased to 75% and 100%, the deposition zones expanded toward the thalweg, and the erosion zones elongated toward the bar tails (Figures 5d and 5e). Higher sediment...
supply levels thus increased the active transport zone (i.e., the proportion of the bed where sediment relocation occurs). This tendency was replicated in all long-term series (see supporting information), but the balance between erosion and deposition zones varied. Note that the presence of erosion zones (Figures 5b–5e) indicates that the armor layer was mobilized, even though phase 2_C was run with lower discharges than phases 2_A and 2_B (Table 1). The longitudinal bed slope of 0.0030 after 2_C_5 was more or less stable compared to 0.0033 after phase 2_B (see supporting information).

To identify the influence of flow discharge and grain size distribution of the replenished material, Figure 6 cross-compares runs 1_C_4 to 4_C_5 (i.e., after reaching an equilibrium with a supply level of 100%; see supporting information for cross-comparisons at lower supply levels). Figures 6b and 6c show series 2 and 3, which were both operated at MQ (0.51Q_A), but fine sediment (S3) was supplied in series 2, and coarse sediment (S2) was supplied in series 3. Both series show deposition at bar apexes and in the thalweg as well as lateral erosion of the bars toward their tails. Similar patterns are also apparent for series 4 with HQ (0.73Q_A) and coarse sediment S2 (Figure 6d), but the lateral bar erosion is more pronounced. Also, the zone of sediment relocation (i.e., either erosion or deposition) covered almost the entire bed after 4_C_5. The extensive erosion zones indicate that a significant portion of the armor layer developed during phase 4_B was eroded. While series 2–4 resulted in similar general outcomes, series 1 with LQ (0.3Q_A) and fine sediment S3 showed predominant deposition throughout the flume (Figure 6a). The deposition thickness was largest along the thalweg and at the bar apexes, and no erosional zones occurred. The longitudinal slope change remained negligible for series 2 and 3, with a slight reduction to 0.0030 after 2_C_5 and 3_C_5. In contrast, the longitudinal slope decreased more significantly to 0.0027 after 4_C_5. The extensive deposition in series 1 caused a more substantial reduction of the average bed slope to 0.0024 after 1_C_2 and a return to 0.0028 after 1_C_4 due to net aggradation (see supporting information for all slope measurements).

Figures 7a and 7b summarize the results of the long-term series 1–4 and show the prevalence of erosion and deposition zones in the ROI in relation to the sediment supply level. Series 2–4 show similar tendencies with generally comparable extents of erosion and deposition zones. In series 1 with LQ and fine replenishment material (S3), however, deposition was predominant, and no extensive erosion zones were present. Figure 7c adds up erosion and deposition zones to total sediment relocation area. All four series roughly follow a linear trend with increasing relocation area for increasing sediment supply level and a maximum relative relocation area of 50–80% of the total bed area in the ROI at a sediment supply level of 100%.

The distribution and thickness of the erosion and deposition zones for a supply level of 100% are shown in Figures 7d–7g as histograms of relative erosion and deposition area. Note that the deposition thickness and erosion depth are normalized with $d_{50}$ of the replenishment material and $d_{90}$ of the bed material, respectively. This normalization was chosen to represent the relevance of the bed armor layer for erosion processes and, in contrast, the relevance of the replenishment material for deposition processes. Series 2 and 3 show a similar pattern of prevailing deposition, with...
the maximum deposition thickness being slightly larger for series 2 with replenishment material S3, and the deposition area being slightly greater for series 3 with the replenishment material S2 (Figures 7e and 7f). Figure 7g displays an inverse tendency with prevailing erosion for series 4 with HQ. Overall, erosion and deposition were fairly balanced for series 2–4, and the maximum erosion depth and deposition thickness reached \(\sim 10d_{50,S1} (0.04 \text{ m})\) and 40–80\(d_{50} (0.036–0.04 \text{ m})\), respectively. In contrast, deposition prevailed in series 1 and reached a maximum thickness of almost 120\(d_{50,S3} (0.06 \text{ m})\) (Figure 7d).

To evaluate potential ecological benefits connected to the topographical changes and sediment relocation activity reported here, an analysis of suitable fish habitats was performed using the grayling as example species. The grayling is a typical endangered rheophile fish of Swiss lowland rivers and prefers flow depths of 0–2.35 m for spawning habitats, 0.1–0.3 m for fry habitats, and 0.1–0.6 m for juvenile habitats (Kirchhofer et al., 2006, pp. 14–15). The UDS point measurements at eight locations (Figure 1c) were linearly interpolated and extrapolated across the entire bed area to assess the spatial distribution of flow depths. To obtain meaningful results, these flow depths measured during small flood events (\(LQ, MQ, HQ\)) were reduced to correspond to a long-term mean annual discharge (7.9 l/s at laboratory scale) via a simple uniform flow calculation. These values were subsequently upscaled assuming \(\lambda = 50\). Figure 8 presents the resulting flow depth distribution for series 1–4 at a sediment supply level of 15%–25% (Figures 8a–8d) and a sediment supply level of 100% (Figures 8e–8h). Assuming that areas where sediment relocation occurred are more valuable than stable, potentially clogged areas, the analysis distinguishes between the wetted area where the bed was stable (light gray) and the wetted area where sediment relocation occurred (dark gray). Combined with flow depth preferences, the proportion of potentially suitable flow depths with and without sediment relocation can be quantified. Merely the maximum preference flow depths for graylings were considered (i.e., 2.35 m for spawning, 0.3 m for fry, and 0.6 m for juveniles).

This analysis implies that long-term sediment replenishment at a high sediment supply rate (\(SL = 100\%\)) can provide a relative bed area of 30%–36% with fresh gravel (deposition of replenished sediment or erosion of the armor layer) and suitable flow depths for spawning (Figures 8f–8h). The value is even higher for run 1_C_4 (62%, Figure 8a), but this scenario results in significant net aggradation and may cause flood safety issues. In contrast, lower sediment supply rates of 15%–25% SL result in 14%–19% relative bed area with suitable flow depths and sediment relocation (Figures 8a–8d). This reduction in potentially suitable spawning area is mainly caused by the lower sediment relocation activity observed for lower sediment supply rates (cf. Figure 7c). For all series, the habitat areas suitable for fry and juveniles remain limited due to the general shortage of shallow regions in a channelized river.

### 3.3. Phase C of Series 5: Single Pulse

In series 5_C_const and 5_C_var, a single sediment pulse was transported with steady discharge and a series of hydrographs, respectively (Table 1). Continuous visual observation of the pulse front and frequent laser scans revealed that replenished sediment was mainly transported along the thalweg (see supporting information for DoD plots). Figure 9 shows the downstream-cumulative elevation differences (CED) for...
series 5_C_const and 5_C_var, normalized with the maximum CED during the respective series. The sediment supply period in the first two intervals is clearly visible as counter-clockwise rotation of the CED curves (arrow 1 in Figure 9). The maximum CED occurred during the third or fourth interval when the largest fraction of the replenished sediment was within the ROI. In the fourth interval, the CED curve begins to be shifted to the right, which is a sign of downstream translation, and it is simultaneously rotated clockwise, indicating dispersion (arrow 2 in Figure 9). During the last three to four intervals of each series, the CED curves stabilize, showing no further changes in the bed elevation levels. A significant portion of the replenished material remained in the channel until the end of each series. The translation seems to occur slightly faster and stronger for series 5_C_var, but no significant difference in the overall process can be observed.

4. Discussion

The goal of this study was to examine the long-term and short-term response of a channelized, sinuous river to sediment replenishment with regard to topographic change and sediment relocation. Most tests were performed as equilibrium tests to represent the long-term channel response to small, frequently renewed sediment deposits (sensu Elgueta-Astaburuaga & Hassan, 2017). Sediment supply level, flow discharge, and grain size distribution of the replenished material were varied to identify the most relevant parameters.
Long-Term Channel Response to Sediment Replenishment

The general bar-pool morphology with point bars in the inner bends remained stable throughout all experiments, as was to be expected due to the forced nature of the point bars and the nonerodible banks (Eaton & Church, 2009; Vonwiller, 2017; Welber et al., 2020). This indicates that sediment replenishment cannot meet primarily geomorphic goals in the setting studied here (i.e., the expectation that an increase in sediment transport would substantially increase morphodynamic activity such as the growth and erosion of bars). These processes have certainly been observed, e.g., after dam removals or massive landslides, when braiding and channel migration strongly intensified in the downstream reach (e.g., Nelson & Dubé, 2016; Ritchie et al., 2018). However, if the instantaneous sediment supply is not as abundant and the channel banks are nonerodible, the morphological impoverishment can generally not be reversed.

While channels without lateral restriction will adjust their sinuosity, and thus their channel gradient, in response to changing sediment supply (Eaton & Church, 2004; Nelson & Dubé, 2016), this process is unavailable to channels with nonerodible banks (Eaton & Church, 2009). In confined rivers, alterations in bed texture (i.e., bed fining) will be the quickest and most relevant reaction to increased sediment supply (e.g., Facchini, 2017).

Nevertheless, sediment replenishment may induce topographic changes within the boundaries of a particular morphology. In the conditions studied here, a general trend toward transversal leveling was observed (cf. Zunka et al., 2015). However, the bed relief always remained more pronounced than, e.g., the BRI* = 0.001–0.01 reported by Liébault et al. (2013) for braided rivers, which can be attributed to channelization.

Figure 8. The flow depth distribution and ratios of suitable habitat area with and without sediment relocation to total bed area \(A/A_{\max}\) in the region of interest (ROI) for grayling spawning, fry, and juveniles for runs (a) 1_C_1, (b) 2_C_2, (c) 3_C_1, and (d) 4_C_2 with sediment supply rates of 15%–25% as well as runs (e) 1_C_4, (f) 2_C_5, (g) 3_C_5, and (h) 4_C_5 with a sediment supply rate of 100%. The flow depths measured during the phase C experiments were adjusted to correspond to a long-term mean annual discharge and upscaled assuming Froude scaling with a scale factor of \(\lambda = 50\). Light gray bars to the left of the respective thresholds show the ratio of potentially suitable flow depths while dark gray bars represent zones where both flow depth is suitable and sediment relocation occurred. The percentage of suitable area relative to the total ROI area is calculated for the total wetted area as well as only for the wetted area with sediment relocation (value in brackets).
Furthermore, sediment relocation, i.e., local deposition of replenished sediment and erosion of the armor layer, was intensified. The grain size distribution of the replenished sediment thereby exerted limited control over the erosion and deposition patterns in the channel, as indicated by the comparison of series 2 and 3. While substantial variations in the ratio of pulse to bed material grain sizes have been shown to influence the propagation dynamics of sediment pulses significantly (e.g., Cui et al., 2003), the range of grain sizes studied here was likely too narrow to induce distinctly different channel responses. In contrast, discharge magnitude and thus bed shear stress seem to control the channel response much more directly. Three discharges were tested, and the outcomes ranged from predominant net aggradation to intensive bed reworking with extended erosional zones. When aggregating deposition and erosion to relocation, the differences become less significant, indicating that discharge primarily influences the balance of erosion vs. deposition.

The variation of the third parameter (i.e., increasing sediment supply rate) resulted in a roughly linear expansion of the sediment relocation area and a transversal leveling of the channel bed. Welber et al. (2020) observed a similar relation between sediment supply and deposition area in a semialluvial channel of comparable sinuosity. Similar to the results reported here, no full coverage of the bed was achieved; instead, the cover fraction reached 80%–85% for three supply rates close to the transport capacity.

Except for series 1 (lowest discharge), the stable armor layer developed during phase B was partly mobilized. The deposition of fine material patches on a stable armor layer may locally increase the near-bed velocity due to the reduced grain roughness. This leads to locally increased bed shear stresses that may erode an armor layer developed under high hydraulic stress (e.g., Hohermuth & Weitbrecht, 2018; Miwa & Parker, 2017; Venditti et al., 2010). The bed shear stress values $\bar{\tau}_{50}$ calculated for the scenarios studied here reflect this process. When determined for the bed material, $\bar{\tau}_{50,S1}$ for all phases C is smaller than for phases A and B, and thus the armor layer remains stable (cf. Table 1). However, with the addition of finer material (either S2 or S3), higher $\bar{\tau}_{50,S2,S3}$ values result than during phases A and B, thus potentially mobilizing the armor layer. This process may be beneficial to sediment replenishment, as it reduces the replenishment volume necessary to achieve a certain degree of sediment relocation and obtain clean, unclogged sediment patches (Harvey et al., 2005). Regarding laboratory experiments, it can be concluded that fixed-bed experiments are of limited value to comprehensively study the effects of sediment replenishment on an alluvial bed (cf. Battisacco et al., 2016; Friedl, 2017). However, adding sediment to a laboratory flume with a fixed bed may be appropriate to study replenishment in semialluvial channels (Welber et al., 2020).
The potential ecological benefits of long-term sediment replenishment were assessed with a simple habitat analysis based on suitable flow depths for different life stages of the example species grayling. The results imply that sediment replenishment may increase the availability of potential spawning habitats, especially for high supply rates of the replenished sediment. However, the positive impacts on fry and juveniles that require shallow flow depths are likely to be marginal without further measures to increase structural variability. Due to the underlying bathymetry and the compact cross-section of channelized rivers, the occurrence of shallow flow depths is generally limited, and the shape of flow depth distributions is mostly preserved in response to varying discharge.

There are several limitations to this fish habitat analysis; for instance, flow velocities were not explicitly considered. Also, the connectivity and specific location of suitable areas were not analyzed, and microhabitats such as crevices in the riprap were not taken into account. Nonetheless, the approach of connecting hydraulic conditions to sediment relocation processes may serve as a valuable instrument to assess the potential ecological benefits of sediment replenishment. Examples of local positive effects of gravel deposits on grayling reproduction in Swiss lowland rivers have been reported indicating that sediment replenishment may alleviate the general shortage of spawning grounds to some extent (see Abegg et al., 2013, Chapter 8; Schälchli et al., 2010).

### 4.2. Short-Term Channel Response to Sediment Replenishment

The main goal of series 5 was to track a single sediment pulse through the river reach. Whether translation or dispersion is the dominant transport process may be of importance in the context of sediment replenishment planning (cf. Sklar et al., 2009). If dispersion is dominant, the replenished sediment will remain in a limited river reach for a longer time, maximizing the temporal impact of the replenishment but limiting its spatial impact. The opposite is true for translation-dominated transport, maximizing the river length affected by the sediment replenishment but limiting the duration for which the replenished sediment is beneficial to any river reach. Therefore, the trade-off between dispersion and translation is one between the temporal and spatial impact of a sediment pulse (e.g., Cui et al., 2003; Harvey et al., 2005). Both extremes have potential disadvantages. If replenished sediment does not move at all, it may become clogged and armored over time, and its positive impact is temporally limited (e.g., Zeh & Dönni, 1994). By contrast, if sediment is routed through a river reach too quickly, it may not provide the stability necessary to, e.g., act as spawning habitat, and the deposit may have to be renewed more regularly. The optimal balance between the two processes depends on the restoration goal and the boundary conditions of the river system (e.g., Sklar et al., 2009). The two single pulse experiments reported in this study do not provide a comprehensive insight into achieving this balance because only one scenario was studied. The results suggest that a sediment pulse is partly retained in the sinuous reach during small flood events (return period 1–2 years), mostly independent of the temporal discharge variation. However, larger flood events would presumably flush the replenished sediment out of the reach. Even larger flood events may induce erosion of the armor layer and cause a destructive rearrangement of the entire bed.

This finding links to the question of sustainability of different sediment replenishment methods. A case study in the channelized Old Rhine downstream of the Kembs Dam found that the effect of one-time sediment replenishment (deposited downstream of the dam) is often local and minor and that the river bed essentially returns to its prereplenishment state after the sediment pulse has passed through (Arnaud et al., 2017; Chardon et al., 2018; Staentzel et al., 2018). Sediment replenishment in the form of channel deposits can be characterized as an impulse response inducing an immediate, nonlinear channel response that is attenuated over time (cf. Ritchie et al., 2018). One-time sediment replenishments are therefore characterized by limited longevity (Bunte, 2004; Harvey et al., 2005). To sustain the benefits of sediment replenishment over the long term, the deposit has to be renewed regularly, thus resembling the step response of reestablished sediment continuity (cf. series 1–4). For example, removing gravel from topset deposits in a reservoir and reintroducing it immediately downstream of a dam may mimic the step response of dam removal to some degree (cf. Ritchie et al., 2018). Still, regular repetition of gravel addition is necessary to achieve sustainable downstream effects (Harvey et al., 2005). Furthermore, the entrainment of the sediment deposit requires some attention; otherwise, the transport capacity of a sediment-deficient reach cannot be adequately saturated. Deposits have to be optimally placed in the flow field and constructed in a
way that facilitates efficient erosion (e.g., Battisacco et al., 2016; Brousse et al., 2020a; Chardon et al., 2018; Friedl et al., 2018; Heckmann et al., 2017).

5. Conclusions

The experimental study presented here indicates that the long-term channel response of a sinuous, channelized gravel-bed river to repeated sediment replenishment is characterized by transversal bed leveling and intensified sediment relocation while the general bar-pool morphology remains stable. Two additional experiments with single sediment pulses showed how replenished sediment is partly retained in the reach as marginal depositions on the point bars. These freshly deposited gravel patches may deliver ecological benefits, e.g., as suitable spawning habitats or pioneer sites for riparian vegetation.

The spatial extent of sediment relocation zones and their division into erosion and deposition areas thereby mainly depend on sediment supply rate and flow discharge. These results illustrate the need for careful adaptation of a replenishment strategy to specific boundary conditions, especially the hydrological regime. Where sediment replenishment is combined with artificial floods, the magnitude and duration of the flood may be selected according to the replenishment strategy or vice versa (e.g., Brousse et al., 2020a; Stähly et al., 2019). However, when a river reach with near-natural hydrology is concerned, it is crucial to allow for some flexibility in the replenishment strategy accounting for the variable frequency and magnitude of naturally occurring flood events (e.g., Bunte, 2004).

The impact of the replenished material’s grain size distribution on the channel response is minor, which can be attributed to the relatively narrow range of tested grain sizes and to the supply of finer material onto a coarse armor layer. As this approach corresponds to general sediment replenishment practice, these outcomes suggest that the selection of the replenished material’s grain size distribution may be focused on biological criteria or availability rather than transport dynamics.

For practical applications, we recommend pursuing a combination of numerical modeling (e.g., Juez et al., 2016) and repeated monitoring of the channel response after flood events to adjust the replenishment strategy when necessary and to gain valuable insights on the degree of success (e.g., Arnaud et al., 2017; Brousse et al., 2020a, 2020b; Gaeuman et al., 2017). Furthermore, monitoring is essential to detect net aggradation due to sediment replenishment and ensure flood protection. If sediment replenishment is not only motivated by erosion control issues but also pursues ecological goals, the monitoring of biological metrics is indispensable to achieve a comprehensive analysis of the relevant parameters (Palmer et al., 2010).

As is true for any river restoration activity, its success may be diminished by remaining stressors acting on various temporal and spatial scales (Bond & Lake, 2003; Palmer et al., 2010; Schinegger et al., 2012). Although sediment replenishment contributes to restoring fluvial processes rather than only river form (Wohl et al., 2015), its effectiveness may be limited due to other factors such as alterations of the flow regime (e.g., Staentzel et al., 2018). Our study illustrates the benefits as well as the limitations of sediment replenishment in channelized rivers with regard to morphological changes and the longevity of the restoration effect. To more effectively promote a long-term change in bed topography and an increase in morphological variability, combining sediment replenishment with channel widening or remeandering is strongly recommended (e.g., Arnaud et al., 2017; Chardon et al., 2018; Brousse et al., 2020b). Vonwiller (2017) has evaluated the potential of channel widening to trigger morphological changes in selected Swiss lowland rivers. The application of the bar mode predictor m by Crosato and Mosselman (2009) showed many rivers to be close to a bar mode of 1, indicating the likely formation of alternate bars and more complex morphologies following river widening. We consider it crucial to acknowledge the interaction of river planform and sediment supply in any restoration strategy (Church & Ferguson, 2015), as sediment replenishment presumably leads to more substantial and sustained ecological benefits in nonchannelized rivers.

Notation

| Symbol | Definition |
|--------|------------|
| A      | Area (m²)  |
| A_{dep}| Deposition area (m²) |
| A_{er} | Erosion area (m²)    |
Acknowledgments
This study was initiated and cofinanced by the Swiss Federal Office for the Environment (FOEN) in the scope of developing management recommendations for sediment replenishment. During the first phase of the study, the channel planform and the test procedure were slightly different from those presented herein (Friedli, 2017). The experiments were later continued within the interdisciplinary research program Hydraulic engineering and ecology. The first author is financially supported by the Swiss Federal Office of Energy and the Regional Council of Freiburg i. Br. (in German).

Ahmari, H., & Da Silva, A. M. F. (2011). Regions of bars, meandering and braiding in da Silva and Yalin’s plan. Journal of Hydraulic Research, 49(6), 718–727. https://doi.org/10.1080/00221686.2011.614518

Andrews, E. D. (1984). Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geologcal Society of America Bulletin, 95(3), 371–378. https://doi.org/10.1130/0016-7606(1984)95(371:BEAHGO)2.0.CO;2

Arnaud, F., Piégay, H., Béal, D., Collery, P., Vaudor, L., & Rollet, A.-J. (2017). Monitoring gravel augmentation in a large regulated river: The case of the Saint-Sauveur dam in the Buëch River (Southern Alps, France). Ecological Management and Restoration, 18, 7167–7175. https://doi.org/10.1002/1468-0040.12561

Battisacco, E., Franca, M. J., & Schleiss, A. J. (2016). Sediment replenishment: Influence of the geometrical configuration on the morphological evolution of channel-bed. Earth Surface Processes and Landforms, 42, 2147–2166. https://doi.org/10.1002/esp.4161

Boes, R. M. (Ed.). (2015). Proceedings of the 1st International Workshop on Sediment Bypass Tunnels. Switzerland: Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich.

Bond, N. R., & Lake, P. S. (2003). Local habitat restoration in streams: Constraints on the effectiveness of restoration for stream biota. Ecological Management and Restoration, 4(3), 193–198. https://doi.org/10.1046/j.1442-8903.2003.00156.x

Brousse, G., Arnaud-Fassetta, G., Liébault, F., Bertrand, M., Melun, G., Liore, R., et al. (2020a). Channel response to sediment replenishment in a large gravel-bed river: The case of the Saint-Sauveur dam in the Butch River (Southern Alps, France). River Research and Applications, 36(6), 880–893. https://doi.org/10.1002/rra.3527

Brousse, G., Liébault, F., Arnaud-Fassetta, G., Breilh, B., & Tacon, S. (2020b). Gravel replenishment and active-channel widening for braided-river restoration: The case of the Upper Drac River (France). Science of the Total Environment, 766, 142517. https://doi.org/10.1016/j.scitotenv.2020.142517

Bunte, K. (2004). State of the science review: Gravel mitigation and augmentation below hydropower dams: A geomorphological perspective (Tech. Rep.). Fort Collins, CO. Report submitted to the Systems Technologies Center, USDA Forest Service, Rocky Mountain Research Station. https://doi.org/10.13140/2.1.1094.3361

Chardon, V., Schmitt, L., Piégay, H., Arnaud, F., Serouliou, J., Houssier, J., & Clutier, A. (2018). Geomorphic effects of gravel augmentation on the Old Rhine River downstream from the Kembs dam (France, Germany). In E3s Web Conf., Proceedings of the 9th
Nelson, A., & Dubé, K. (2016). Channel response to an extreme flood and sediment pulse in a mixed bedrock and gravel-bed river. *Earth Surface Processes and Landforms, 41*(2), 178–195. https://doi.org/10.1002/esp.3843

Nelson, P. A., Venditti, J. G., Dietrich, W. E., Kirchner, J. W., Ikeda, H., Iseya, F., & Sklar, L. S. (2009). Response of bed surface patchiness to reductions in sediment supply. *Journal of Geophysical Research, 114*, F02005. https://doi.org/10.1029/2008JF001144

O’Connor, J. E., Duda, J. J., & Grant, G. E. (2015). 1000 dams down and counting. *Science, 348*(6234), 496–497. https://doi.org/10.1126/science.aau9204

Ock, G., Suni, T., & Takemen, Y. (2013). Sediment replenishment to downstream reaches below dams: Implementation perspectives. *Hydrological Research Letters, 7*(3), 54–59. https://doi.org/10.3178/hrl.7.54

Palmer, M. A., Menninger, H. L., & Bernhardt, E. (2010). River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? *Freshwater Biology, 55*, 205–222. https://doi.org/10.1111/j.1365-2427.2009.02372.x

Pauli, M., Hunzinger, L., & Hitz, O. (2018). More bed load in rivers. Achieving a sediment balance close to the natural state. *Journal of Applied Water Engineering and Research, 6*(4), 274–282. https://doi.org/10.1002/23249676.2018.1497554

Pettis, G. E., Müller, H., & Roux, A. L. (Eds.). (1989). *Historical change of large alluvial rivers: Western Europe*. Chichester: John Wiley & Sons Ltd.

Rachelly, C., Friedli, F., Boes, R. M., & Weitbrecht, V. (2021). Dataset for “Morphological response of channelized, sinuous gravel-bed rivers to sediment replenishment”. ETH Research Collection. https://doi.org/10.3929/ethz-b-000467163

Riedl, C., & Peter, A. (2013). Timing of brown trout spawning in Alpine rivers with special consideration of egg burial depth. *Ecology of Freshwater Fish, 22*(3), 384–397. https://doi.org/10.1111/eff.12033

Ritchie, A. C., Warrick, J. A., East, A. E., Magirl, C. S., Stevens, A. W., Bounty, J. A., et al. (2018). Morphodynamic evolution following sediment release from the world’s largest dam removal. *Scientific Reports, 8*(1), 13279. https://doi.org/10.1038/s41598-018-30817-8

Rollet, A. J., Piegay, H., Dufoir, S., Borneotte, G., & Persat, H. (2014). Assessment of consequences of sediment deficit on a gravel river bed downstream of dams in restoration perspectives: Application of a multicriteria, hierarchical and spatially explicit diagnosis. *River Research and Applications, 30*(8), 939–953. https://doi.org/10.1002/rra.2689

Schädellich, U., Breitenstein, M., & Kirchhofer, A. (2010). Kiesschütterungen zur Reaktivierung des Geschiebebehauls der Aare—Die kieslachenden Fische freut’s (Gravel deposits to restore the bed-load balance in the Aare River—The gravel-spawning fish are pleased). *Wasser, Energie, Luft, 102*(3), 209–213 (in German).

Schindegger, R., Trautwein, C., Melcher, A., & Schmutz, S. (2012). Multiple human pressures and their spatial patterns in European running waters. *Water and Environment Journal, 26*(2), 261–273. https://doi.org/10.1111/j.1747-6593.2011.00285.x

Scorpio, V., Zen, S., Bertoldi, W., Surian, N., Mastronunzio, M., Dai Prà, E., et al. (2018). Channelization of a large alpine river: What is left of its original morphodynamics? *Earth Surface Processes and Landforms, 43*, 1044–1062. https://doi.org/10.1002/esp.4301

Sklar, L. S., Fadde, J., Venditti, J. G., Nelson, P., Wydzga, M. A., Cui, Y., & Dietrich, W. E. (2009). Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams. *Water Resources Research, 45*, W08439. https://doi.org/10.1029/2008WR007346

Staenzel, C., Arnaud, F., Combroux, I., Schmitz, L., Trémolières, M., Grac, C., et al. (2018). How do instream flow increase and gravel augmentation impact biological communities in large rivers: A case study on the Upper Rhine River. *River Research and Applications, 34*(2), 153–164. https://doi.org/10.1002/rra.3217

Stähly, S., Franca, M. J., Robinson, C. T., & Schleiss, A. J. (2019). Sediment replenishment combined with an artificial flood improves river habitats downstream of a dam. *Scientific Reports, 9*(1), 5176. https://doi.org/10.1038/s41598-019-41575-6

Sumi, T. (Ed.). (2017). *Proceedings of the Second International Workshop on Sediment Bypass Tunnels*. Japan: University of Kyoto.

Surian, N., & Rinaldi, M. (2003). Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology, 50*(4), 307–326. https://doi.org/10.1016/S0169-555X(02)00219-2

Venditti, J. G., Dietrich, W. E., Nelson, P. A., Wydzga, M. A., Fadde, J., & Sklar, L. (2010). Mobilization of coarse surface layers in gravel-bedded rivers by finer gravel bed load. *Water Resources Research, 46*, W07506. https://doi.org/10.1029/2009WR008329

von Wilser, L. (2017). Numerical modeling of sediment replenishment in gravel-bed rivers. In R. M. Boes (Ed.), *VAW-Mitteilungen* (Vol. 246). Switzerland: Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich. https://doi.org/10.3929/ethz-b-000267914

Welber, M., Papangelakis, E., Ashmore, P., & McVicar, B. (2020). Experiments on restoring alluvial cover in straight and meandering rivers using gravel augmentation. *River Research and Applications, 36*, 1543–1558. https://doi.org/10.1002/rra.3699

Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C. (2015). The natural sediment regime in rivers: Broadening the foundation for ecosystem management. *BioScience, 65*(4), 358–371. https://doi.org/10.1093/biosci/biv002

Wolman, M. G., Miller, J. P., & Leopold, L. B. (1964). *Fluvial processes in geomorphology*. San Francisco: Freeman.

Wong, M., & Parker, G. (2006). Reanalysis and correction of bed-load relation of Meyer-Peter and Müller using their own database. *Journal of Hydraulic Engineering, 132*(11), 1159–1168. https://doi.org/10.1061/(asce)0733-9499(2006)132:11(1159)

Zeh, M., & Dönni, W. (1994). Restoration of spawning grounds for trout and grayling in the river High-Rhine. *Aquatic Science, 56*(1), 59–69. https://doi.org/10.1007/BF00877435

Zunka, J. P. P., Tullos, D. D., & Lancaster, S. T. (2015). Effects of sediment pulses on bed relief in bar-pool channels. *Earth Surface Processes and Landforms, 40*(8), 1017–1028. https://doi.org/10.1002/esp.3697