9 Sediment continuity and augmentation measures

Impaired sediment transport can have numerous adverse impacts on the eco-morphodynamics of the riverscape. If well designed, sediment augmentation measures present a promising mitigation approach at different scales. This chapter focuses on flume experiments conducted to investigate the influence of sediment augmentation on morphological bed structures and the persistence of emerging bedforms. It also includes information about design criteria and outcome evaluation methods.

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9.1 Interrupted sediment continuity

From source to delta, rivers transport sediment along their course. In situations where natural sediment sources exist and the undisturbed discharge varies with flood events and seasons, a continuous process of erosion and deposition shapes the planform and bed morphology of the river. This natural dynamic is vital for a diverse riverine habitat space (FOEN 2017a).

In regulated rivers, the natural sediment regime is often disturbed by (i) an impaired discharge regime, (ii) increased transport capacity resulting from channelization or (iii) reduced bedload availability. An impaired discharge regime mainly comes from the regulation of flow for energy production (residual flow and hydropeaking) or flood protection. It reduces peak discharges required for major bedload mobilization events. Channelization, as part of historical river modification, increases transport capacity and causes riverbed incision and progressive flattening of the channel slope. Bedload availability can be reduced by riverbank protection or alluvial sediment extraction. The longitudinal continuity of sediment transport can be interrupted by sediment traps or hydraulic structures, such as run-of-river plants and dams with large reservoirs, and can lead to a complete depletion of bedload in the downstream reach.

As the mitigation of the negative impacts of hydropower on the bedload regime plays a key role in the 2009 revised Swiss water legislation (Federal Waters Protection Act (WPA, 1991), Art. 43a), this first section focuses on the impact of reservoirs on sediment continuity.

9.1.1 Impact of reservoirs

Interrupted sediment continuity resulting from reservoirs can have direct and indirect impacts upstream, downstream and at the reservoir itself (Fig. 52). At the upstream entrance of large reservoirs, bedload material accumulates as a result of reduced flow velocities. This can lead to riverbed aggradation and, in some cases, an increased risk of flooding. Inside large reservoirs, suspended fine sediment is transported closer to the dam, before slowly settling and leading to progressive filling of the reservoir. Reservoir sedimentation endangers the sustainable use of hydropower (Schleiss *et al.* 2010), for example by reducing the storage capacity or blocking outlets. Downstream of large reservoirs, the deficit in bedload material, combined with an unnatural flow regime, can lead to degradation of the eco-morphodynamics of the tailwater section. Under continuously low discharge, the smaller grain fractions of the riverbed erode, leaving behind a layer of coarse, immobile sediment (armour layer; Kondolf 1997). Over time, suspended fine sediment settles into the open pore space, resulting in clogging (see Chapter 7; Dubuis *et al.* 2023; Chapter 8; Takatsu *et al.* 2023). Clogging and armouring lead to a reduction in spawning habitat for gravel-spawning fish, degradation of macroinvertebrate habitat, and impaired hyporheic flow (Schälchli 1992). Under high discharges, the armour layer can break up and release fine sediment from the subsurface layer. With a deficit in bedload material, the riverbed risks permanent erosion (riverbed incision). In the long term, reduced hydromorphological dynamics lead to an impoverishment of the aquatic and riparian habitat space.

Figure 52

Sediment-related issues in regulated rivers, regarding discontinuity and morphological changes. Sediment discontinuity: (1) accumulation of sediment, (2) trapping of coarse sediment, (3) trapping of fine sediment, (4) trapping of organic matter, (6) deficit of bedload, and (9) surplus of suspended fine sediment. Morphological changes: (1) riverbed aggradation, (5) reservoir sedimentation, (6) development of static bed armour, (7) riverbed incision, (8) loss of morphological dynamics, and (9) clogging of pore spaces.

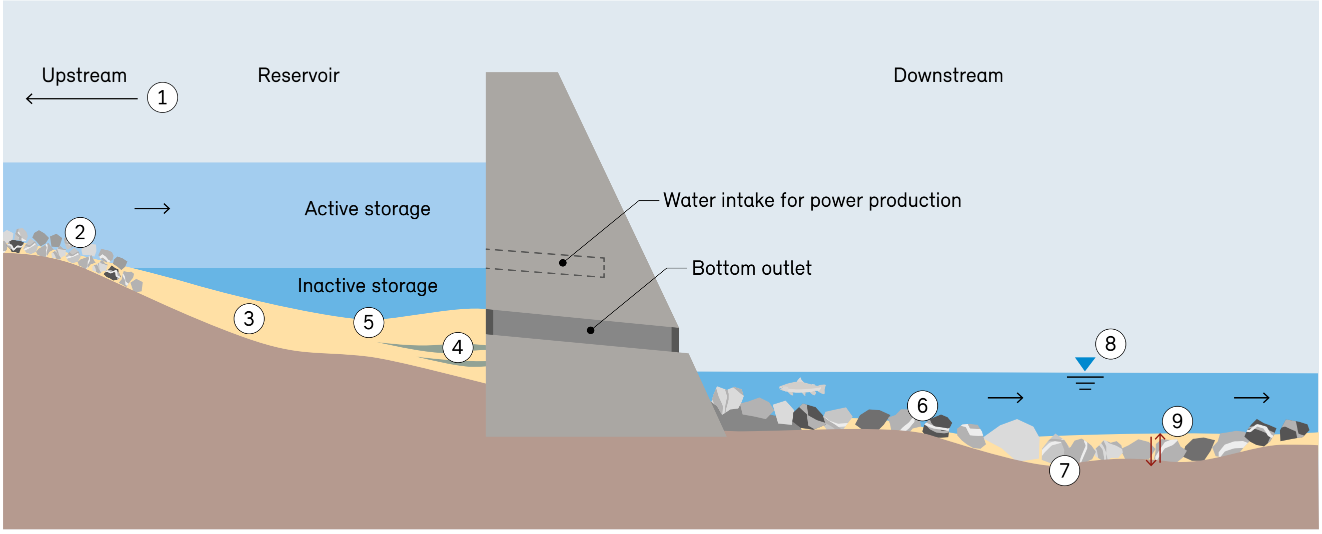


Figure adapted from Mörtl *et al.* (2020)

9.2 Sediment augmentation measures

9.2.1 Description and application

Sediment augmentation describes the artificial supply of sediment to a river. Sediment augmentation measures include the direct placement of sediment in the form of artificial banks or other morphological structures inside the river. Another option is the upstream supply of sediment by the creation of erodible deposits inside the channel or along the channel bank, which are designed to be mobilized during flood events. Instead of a one-time placement, sediment can also be supplied continuously during a flood, for example with the help of a conveyer belt or a natural chute. Sediment augmentation can also be performed indirectly through induced riverbank erosion, for example with guiding structures or the removal of bank protection.

9.2.2 Legal framework

In Swiss legislation, river rehabilitation is distinguished into river restoration, hydropower mitigation, and residual flow rehabilitation. Restoration is intended to restore the natural functions of watercourses by counteracting former human interference with channel morphology by means of civil engineering. Hydropower mitigation involves re-establishing the longitudinal connectivity for fish migration, mitigating hydropeaking effects, and rehabilitating a disturbed sediment regime.

If it is neither feasible nor proportionate to re-establish sediment continuity for an existing structure, sediment augmentation measures can be implemented for downstream sediment regime rehabilitation (Schälchli and Kirchhofer 2012). Sediment augmentation can also be applied in the context of river restoration projects. It can be part of the restoration measure itself (e.g. creation of spawning habitat, enrichment of structural diversity), can promote the functioning of a restoration measure (e.g. dynamic river widening), or can mitigate a restoration measure's secondary effects (downstream bedload deficit as a consequence of river-widening work).

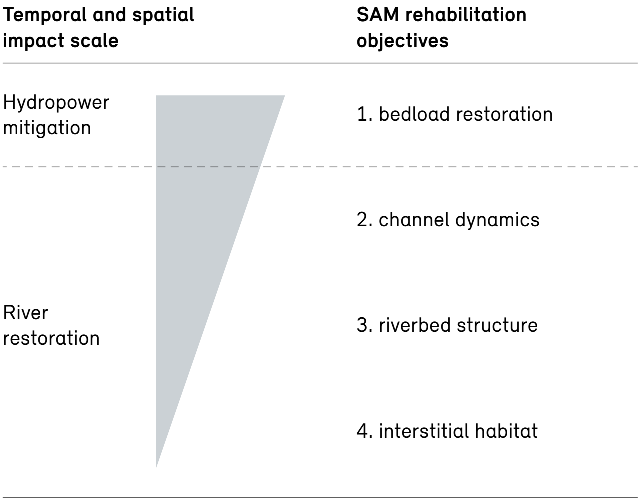
9.2.3 Case-specific design recommendations

All of the main objectives of sediment augmentation are related to improving the eco-morphodynamics at different spatial and temporal scales (Fig. 53; Mörtl and De Cesare 2021). For example, the aim of bedload restoration is to re-establish natural bedload transport, resulting in better morphological structures and dynamics anywhere in the river where conditions are favourable. It is designed for reach-wide, long-term improvement of eco-morphodynamics. If combined with other rehabilitation measures, like ecological flood regimes and sufficient space for the river corridor, it creates the prerequisite for natural evolution towards a sustainable reference state. An augmentation measure which focuses on spawning habitat restoration can produce positive, local effects in the short term. This measure can be applied in river sections with hydro-morphological restrictions, such as residual flow sections, but the positive impacts might be less persistent.

Bedload restoration
Sediment augmentation for bedload restoration is most commonly implemented upstream of a long, continuous river section with significant ecological potential and sufficiently strong hydro-morphological processes, to ensure continuous bedload transport. Design grain size distribution and volume should correspond to the bedload material and bedload deficit of the river (required transport volume) (Schälchli and Kirchhofer 2012). The material can originate from bedload traps, reservoirs or gravel pits, but should not contain a high content (>12–14%) of sediment smaller than fine gravel or organic matter, to avoid high turbidity and clogging (Kondolf 2000). Erodible deposits coupled with flood mobilization have proven to be a cost-efficient injection method (FOEN 2017a). An important placement criterion for efficient mobilization is channel morphology, which influences hydraulic parameters like transport capacity, discharge conditions and backwater curve. Other criteria, such as flood protection, infrastructure and accessibility, might impose further restrictions (FOEN 2017a). The selected timeframe should be outside the spawning period and ideally before the seasonal peak runoff. Where sediment transport has been disturbed over several decades, and depending on the ratio of supplied volume to annual bedload deficit, yearly repetition of the measure may be required. Spatial restrictions regarding sediment supply can also make repetition every 2–3 years a cost-efficient alternative.

Figure 53

Sediment augmentation measure (SAM) rehabilitation objectives at different temporal and spatial impact scales.



Source: EPFL

Promoting channel dynamics
With sufficient aggradation in the active channel, sediment supply rates can become a driving factor for lateral mobility (Rachelly *et al.* 2018). Sediment augmentation can therefore be used to promote channel dynamics, for example in dynamic channel widening efforts. When the river is given enough space, e.g. by removing bank protection, supplying artificial sediment can increase bank erosion rates and thus enhance lateral connectivity. The supplied sediment can be composed of a natural sediment mix. High peak discharge events are required to trigger the hydro-morphological processes for significant channel dynamics.

Enhancing riverbed structure
The longitudinal riverbed structure in natural gravel rivers of the Swiss midlands is characterized by a sequence of pools, runs and riffles. Where bedload transport and channel dynamics are highly impaired, e.g. in residual flow sections, sediment augmentation with erodible deposits can enhance the structural diversity of local river sections (Schroff *et al.* 2021). Direct placement of sediment can also be used to create desired bedforms. Rachelly *et al.* (2021) suggest that, for channelized, sinuous gravel bed rivers, morphological activity mainly depends on the sediment supply rate and discharge, while the impact of small changes in the grain size distribution of the supplied material on the channel response is minor. The frequency of repetition should depend on the morphological response of the river system.

Creating interstitial (spawning) habitat
When the direct creation of spawning habitat is the main objective of sediment augmentation, the design needs to be adapted accordingly. The characteristic grain size should be selected according to the spawning substrate requirements of the dominant or target fish species (see Chapter 7; Dubuis *et al.* 2023; Chapter 8; Takatsu *et al.* 2023), while also considering the naturally occurring substrate of the river type. For example, the preferred grain size for brown trout (*Salmo trutta*) is 2–5 cm (Breitenstein and Kirchhofer 2010). The supply volume can be estimated based on the volume of missing spawning substrate, while the placement should respect target species preferences in terms of flow velocity, flow depth and spawning depth. With the direct placement of sediment, ideal bedforms like spawning riffles can be created (Pulg *et al.* 2013). An indirect supply from erodible deposits can also be designed, requiring only small flood events because spawning grain size is usually small. The planning requires special attention regarding the expected transport and deposition processes. If correctly designed, sufficient transport of spawning substrate to the potential spawning grounds can be ensured. As with any sediment augmentation measure, impacts on flood protection and groundwater balance must be assessed and minimized. Annual repetition might be required to ensure long-term changes supporting successful reproduction. The ideal time for the creation of spawning habitat by gravel augmentation is late summer to autumn, between the reproduction periods of cyprinid and salmonid species (Breitenstein and Kirchhofer 2010). The optimal frequency of a measure depends on deposit erosion and the state of clogging.

9.3 Process fundamentals

9.3.1 Physical experiment

In the framework of the research project ‘Sediment and Habitat Dynamics’, advances have been made in the design optimization of sediment augmentation measures, by investigating typical erosion, transport and deposition patterns (Friedl *et al.* 2017). In the following section we describe a follow-up flume experiment conducted to investigate the influence of morphological bed structures and the persistence of emerging bedforms.

Experiment description
A straight channel with a length of 34 m and varying slope was constructed at the Platform PL-LCH at EPFL (Figs 54, 55). The channel has a trapezoidal cross section and two sections of different bed width. The upstream section contains fixed bed material and has a uniform channel width of 0.5 m. In the downstream section, the channel widens to a maximum of 0.75 m and contains mobile material. The fixed bed material consists of a coarse sediment mixture (grain size 4–16 mm), to represent an armoured riverbed, and is red in colour. The bed mixture was selected based on preliminary scan tests to represent a hydraulic roughness of K_{ST} = 34 $m^{1/3}$ s^{-1}. The mobile bed material in the wider section has a finer grain size distribution (4–8 mm). The augmented sediment consists of different mixtures and is placed in four deposits in alternating geometry (Fig. 55b) according to Battisacco *et al.* (2016). The total augmented volume (0.21 m^3) corresponds to 100% transport capacity of the simulated,

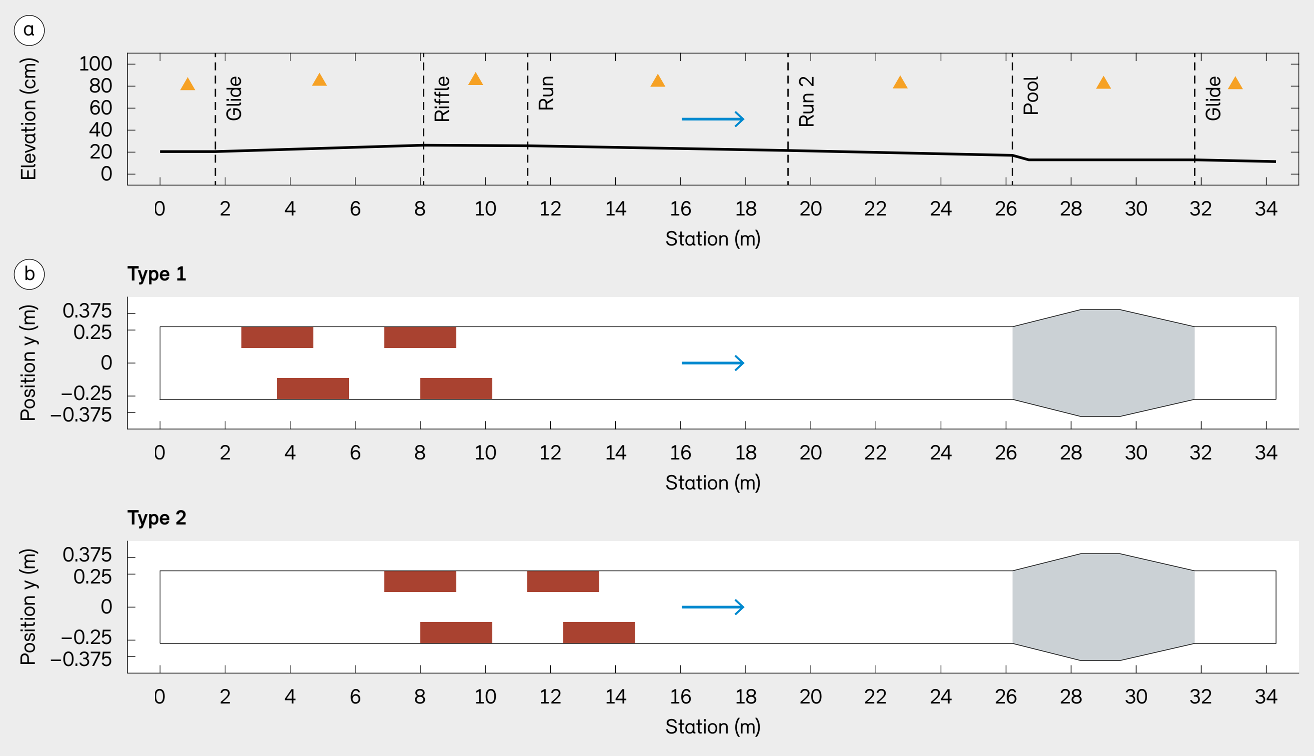
Figure 54

Photo of a morphological channel with erodible deposits at the Platform PL-LCH at EPFL.

Photo: C. Mörtl, © PL-LCH

Figure 55

(a) Longitudinal profile of the artificial channel, showing the sections of different represented riverbed structures and the position of water level sensors (yellow triangles). (b) Top view of the channel bed, showing the two placement positions of deposits (red squares) and the erodible bed area (grey surface) within the widened cross-section.



Source: EPFL

morphogenic flood events (HQ_2, 8 h) for the average channel slope. The slope of the channel is separated into different linear sections, each representing a different riverbed structure (Fig. 55a), according to the definitions in the FOEN outcome evaluation of river restoration projects (Weber *et al.* 2019). The sequence of represented bed structures was identified at the Sarine river residual flow reach in the canton of Fribourg (Schroff *et al.* 2021), downstream of the 2016 sediment augmentation (Stähly *et al.* 2020).

The goal of the experiment was to find optimal design criteria for sediment augmentation with erodible deposits to enhance riverbed structure (Section 9.2.3).

Bed structures

Changing the slope and cross section creates different hydraulic conditions along the channel. An increase in bed level creates an impoundment upstream (glide), where near-bed velocities and bed shear stresses, required for sediment mobilization, are considerably reduced. As the bed level rises (riffle), the water depth decreases and the flow starts to accelerate, due to the decreased cross-sectional area of the flow. For the same high-peak discharge, sediment deposits placed at the riffle are eroded and transported out of the deposit zone at a significantly higher rate (89% of augmented volume; Fig. 55b, Type 2) than deposits placed in the upstream glide section (46%; Fig. 55b, Type 1).

With increasing slope downstream of the riffle (run, slope 5.5‰), velocities and bed shear stresses increase further. Sediment transport and deposition in the run section depend on the magnitude, shape and duration of the flood hydrograph. In the rising limb of a symmetric hydrograph, strong deposition occurs along a stretch corresponding to 10 channel widths (Fig. 56). Alternating deposits with a high blocking ratio (proportion of wetted cross-sectional area blocked by deposit, 1/3 in this case) induce a strong deflection of the flow and the deposition front towards one side of the river. With the falling limb, new bedforms manifest at a distance of 10–20 channel widths from the deposit zone in the steeper slope (run 2, 7.0‰).

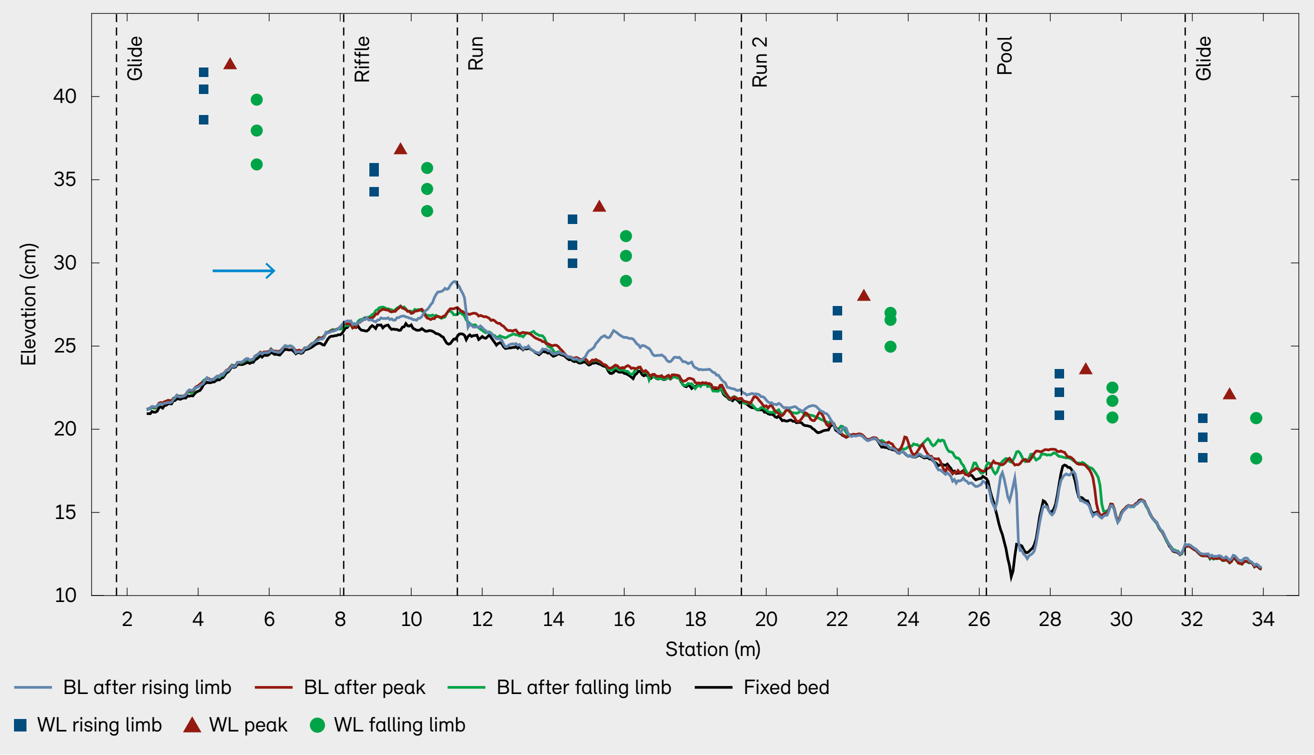
In a typical sequence in a gravel bed river, pools are formed downstream of runs. They act as sediment retention basins, which store and send out waves of sediment sporadically and are thought to be a major contributor to sediment pulse releases (Dhont and Ancey 2018). In the laboratory experiment, most of the mobilized material was deposited in the pool after the first and the second successive flood event (63% and 73%). In each case, a neglectable percentage was transferred or released farther downstream. On the contrary, at the Sarine residual flow section, tracers in deposited sediment revealed considerable transport across and deposition downstream of a large pool (Stähly *et al.* 2020). This suggests that micro-morphological features, bank roughness and hydraulic heterogeneities, such as secondary currents, can significantly enhance transport across pools in a single flood event. Nevertheless, pools downstream of sediment augmentation measures (< 20 channel widths) reduce the impact length until sediment from repeated augmentation or natural supply fills up the pool sufficiently to trigger a new sediment pulse.

Persistence of bedforms

The persistence of newly created bedforms from erodible deposits was evaluated in tests with successive flood events with identical hydrographs. After two flood events, the percentage of cover of the armour layer (8.3%) was significantly reduced compared with the cover after a single flood event (22.5%) (Fig. 57). Except for a large part of the most upstream deposit, all deposits were eroded and

Figure 56

Longitudinal channel profile, with bed level (BL) and water level (WL) records at different stages (rising limb, peak, falling limb) of a symmetric hydrograph. BL records represent the mean bed level elevation of a longitudinal strip 18 cm wide (offset between deposits) along the centre axis of the channel.



Source: EPFL

at least partly mobilized in the two flood events. Bedform persistence was highest in the close vicinity of the original deposit positions (<5 channel widths). Longitudinal bedforms near the banks were more persistent than transverse bedforms in the channel centre. The flume results suggest that sediment should be resupplied after every major morphogenic flood event (~HQ_2), if the objective is to enhance riverbed structure on a static armour layer in the near downstream reach (<20 channel widths). The volume of the deposits should be resupplied up to 100% of the corresponding transport capacity. Flow events with a smaller peak discharge were found to show little impact on newly created bedforms.

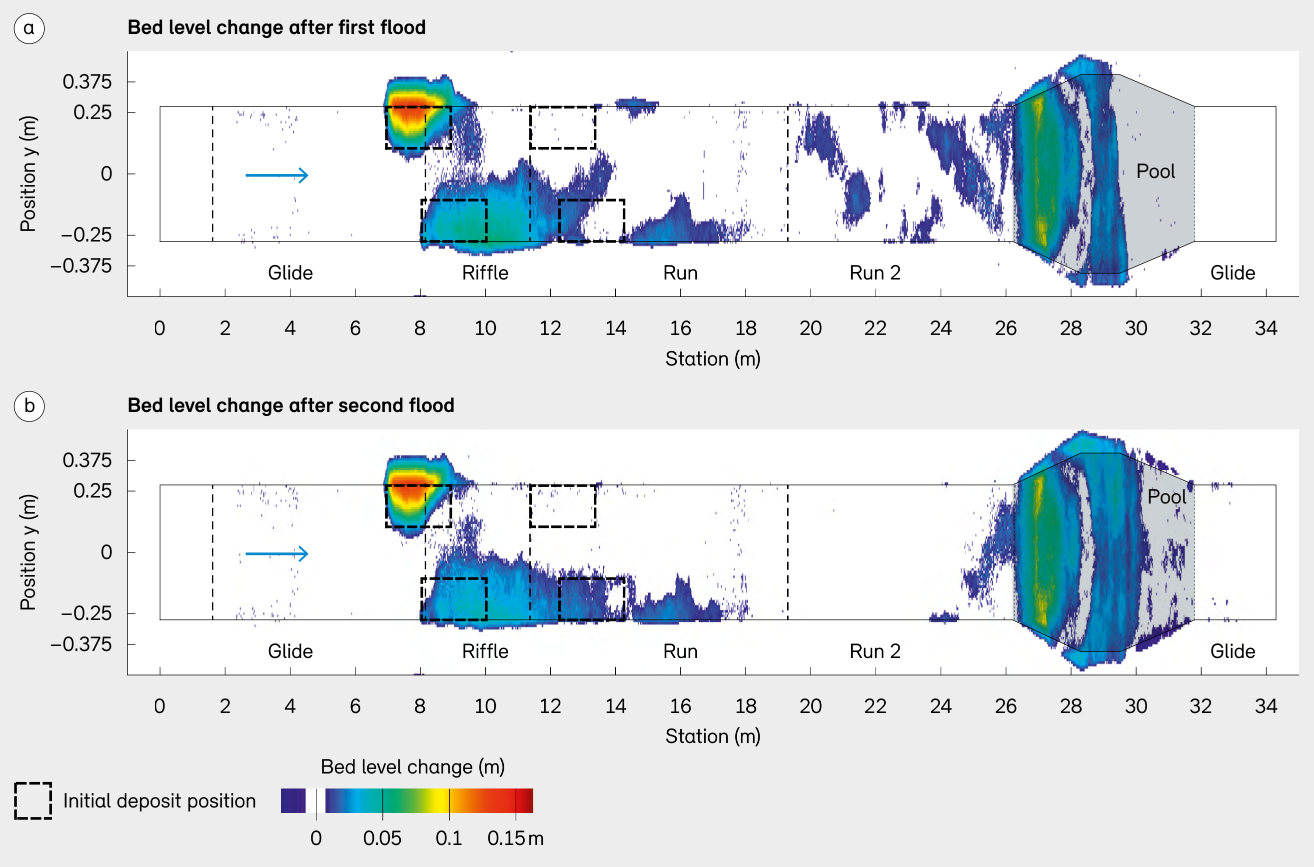
9.4 Outcome evaluation

For an objective-oriented outcome evaluation of sediment augmentation measures, several standardized assessment methods are available. The use of guidelines and standardized methods ensures comparability and facilitates inter-project learning. The choice of appropriate methods depends on the context of the measure but also on the rehabilitation objectives. In Switzerland, outcome evaluations are necessary for measures implemented in the context of sediment regime rehabilitation, as well as for river restoration projects (Waters Protection Ordinance [WPO], 1998, Art 42c, Art. 49).

In 2019 a practice documentation was published by the FOEN, which describes a defined structure and standardised procedure for the outcome evaluation of river restoration

Figure 57

Top view of the change after (a) the first and after (b) the second successive flood event with identical hydrograph, following a single sediment augmentation measure. Dashed boxes indicate initial deposit positions.



Source: EPFL

projects (Weber *et al.* 2019). Similar documentation for sediment regime rehabilitation projects is under development and currently available in a draft version. The basic principle of the outcome evaluation described in both documents is a comparison of relevant characteristics of the affected river reach before and after rehabilitation.

Sediment regime rehabilitation

The primary objective of sediment regime rehabilitation is the re-establishment of typical, near-natural morphological structures and dynamics (Schälchli and Kirchhofer 2012). In the outcome evaluation of sediment regime rehabilitation measures, the recommended objective-oriented assessment is based on a set of six abiotic indicators (channel planform, extent of gravel bars, substrate composition, inner clogging, thalweg evolution, mean bed position evolution). The set can be complemented by biotic indicators, with a particular focus on the fish fauna. Additionally, the rehabilitation measure's effective impact on the reach's mean annual bedload budget should be estimated.

River restoration

The practice documentation for the outcome evaluation of river restoration projects comprises 22 indicators, assembled into 10 indicator sets (Weber *et al.* 2019). Each indicator set represents a typical restoration goal. Indicator set 1 (habitat diversity) comprises six eco-morphological indicators: riverbed structures, river bank structures, water depth, flow velocity, presence of cover, and substrate. Their assessment is the mandatory basis for the outcome evaluation of a restoration project (Weber *et al.* 2019). Beyond the mandatory indicator set 1, indicator set 2 (dynamics) is also highly relevant and can be an effective assessment tool for sediment augmentation measures. Its three indicators riverbed structure dynamics, river bank structure dynamics, and bed position evolution are directly linked to a properly functioning sediment regime. The suitability of the remaining abiotic and biotic indicator sets, such as indicator set 7 (fish), can be assessed on a case-by-case basis and depend on the stated rehabilitation objectives.

Box 12: In practice – Planning: objectives and key questions

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Five key questions are central to the planning of sediment continuity and augmentation measures: where, how and when should the sediment be deposited, and what quality and quantity of sediment should be used?

Definition of objectives

To answer these questions, a detailed analysis of the current situation regarding flood safety and ecology must be carried out. Subsequently, objectives are defined for the target condition after the application of sediment measures. These objectives might include achieving a near-equilibrium bedload balance, preventing scouring, and creating new habitats and spawning sites. As in restoration projects, target fish species must be determined, for which the optimal sediment regarding spawning substrate is selected.

Key questions

Where and how: during a flood event, existing constrictions within the channel should not be reduced even more by sediment deposits. Simultaneously, hydraulic structures, such as power plants, and other boundary conditions, such as pipelines and recreational use, must be considered when planning a gravel embankment. Once a suitable site has been found, accessibility to the river must be ensured, and no natural objects meriting protection should be compromised. During pouring, care must be taken to ensure an even and distributed addition of sediment to prevent overloading of the system. The location of the sediment deposition must be logistically manageable.

Quantity and quality: the amount of sediment necessary for a state of equilibrium is a function of the transport capacity and of the sediment available. Further, the quantity and quality of sediment might influence downstream turbidity. In general, a smaller but more regular addition of sediment is preferable. For reasons of sustainability, the sediment should be derived from the same catchment area.

When and how: aspects related to flood protection, aquatic fauna and vegetation must be considered when selecting the timing of sediment augmentation. Pilot studies can be used to gain experience with uncertainties and contingencies in order to determine the best possible timing. In the end, concerns relating to both flood safety and ecology are important, and an optimal balance must be found when planning sediment continuity and augmentation measures.