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Riverscape – sediment dynamics and connectivity

Practice-oriented research in hydraulic engineering and ecology

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Riverscape – sediment dynamics and connectivity

Practice-oriented research in hydraulic engineering and ecology

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Abstracts

Riverscapes are a diverse habitat mosaic of patches ranging from wet to dry that are shaped by the hydro- and morphodynamic characteristics of the river. Sediment dynamics and connectivity are therefore two key elements influencing the flood protection and ecological functions in river restoration efforts. The interdisciplinary research project 'Riverscape – sediment dynamics and connectivity' links hydraulic engineering and ecology to evaluate measures fostering sediment dynamics and to explore functional riverscape habitats. This publication comprises a summary of the main research findings of the project, supplemented by perspectives from researchers and practitioners who were not directly involved in the project.

Keywords:
clogging, ecological function, flood protection, interdisciplinary research, refugia, river habitat, riparian species, river restoration

Flusslandschaften bilden ein vielfältiges Habitatmosaik von feuchten zu trockenen Standorten, die durch die hydro- und morphodynamischen Eigenschaften des Flusses geprägt sind. Sedimentdynamik und Vernetzung sind daher zwei Schlüsselelemente, die den Hochwasserschutz und die ökologischen Funktionen bei Massnahmen zur Fliessgewässerrevitalisierung beeinflussen. Das interdisziplinäre Forschungsprojekt «Lebensraum Gewässer – Sedimentdynamik und Vernetzung» verbindet Wasserbau und Ökologie miteinander, um Massnahmen zur Förderung der Sedimentdynamik zu beurteilen und funktionale Lebensräume in Flusslandschaften zu erforschen. Diese Publikation fasst die wichtigsten Forschungsergebnisse zusammen und ergänzt diese durch Beiträge von Forschenden und Fachleuten aus der Praxis, die nicht direkt am Projekt beteiligt waren.

Stichwörter:
Kolmation, ökologische Funktion, Hochwasserschutz, interdisziplinäre Forschung, Refugien, Lebensraum Fliessgewässer, auenbewohnende Arten, Fliessgewässerrevitalisierung

Les milieux fluviaux constituent une mosaïque d'habitats variés, allant des habitats très humides à d'autres complètement secs, qui se forment en fonction des caractéristiques hydrodynamiques et morphodynamiques des cours d'eau. Ainsi, la dynamique sédimentaire et la connectivité sont deux éléments influant sur la protection contre les crues et les fonctions écologiques dans les efforts de revitalisation des cours d'eau. Le projet de recherche interdisciplinaire « Milieux fluviaux – dynamique sédimentaire et connectivité » fait le pont entre l'aménagement et l'écologie des cours d'eau afin d'évaluer les mesures favorisant la dynamique sédimentaire et d'explorer les habitats fonctionnels des milieux fluviaux. La présente publication contient un résumé des principaux résultats de ce projet ainsi que des interprétations complémentaires de la part de chercheurs et de praticiens qui n'ont pas directement participé au projet.

Mots-clés :
colmatage, fonction écologique, protection contre les crues, recherche interdisciplinaire, refuges, habitat fluvial, espèces riveraines, revitalisation des cours d'eau

I paesaggi fluviali sono caratterizzati da un mosaico di habitat diversi, da umidi ad aridi, plasmati dalle peculiarità idrodinamiche e morfodinamiche del corso d'acqua. La dinamica dei sedimenti e la connettività sono quindi due elementi chiave per la protezione contro le piene e le funzioni ecologiche negli sforzi di rivitalizzazione dei corsi d'acqua. Il progetto di ricerca interdisciplinare «Paesaggi fluviali – dinamica dei sedimenti e connettività» unisce la sistemazione e l'ecologia dei corsi d'acqua al fine di valutare le misure che favoriscono la dinamica dei sedimenti ed esplorare gli habitat funzionali dei paesaggi fluviali. La presente pubblicazione comprende una sintesi dei principali risultati del progetto, integrata dai punti di vista di ricercatori e professionisti del settore non direttamente coinvolti nel progetto.

Parole chiave:
colmatazione, funzioni ecologiche, protezione contro le piene, ricerca interdisciplinare, rifugio, ambienti fluviali, specie riparie, rivitalizzazione dei corsi d'acqua

Foreword

Near-natural watercourses are among the most species-rich habitats in Switzerland. They form a mosaic of sites ranging from wet to dry, which are constantly changing as a result of varying discharge conditions and sediment dynamics. They form a corridor that also includes gravel banks, floodplain forests and ponds. The connectivity of these habitats allows the preservation and development of biodiversity.

In Switzerland today, many watercourses are no longer close to their natural state. Most rivers and streams are constricted and their discharge and sediment balance have been altered. Biodiversity in riverscapes has decreased considerably. Additionally, climate change causes increased water temperatures and more extreme runoff conditions. Severe floods and increasingly frequent low water levels during drought pose a threat to humans and their infrastructures. To improve this situation in the long term, flood protection and restoration measures must be harmonized. This requires close collaboration between different disciplines.

The interdisciplinary research project 'Riverscape – sediment dynamics and connectivity' combines the two topics of hydraulic engineering and ecology. Researchers from these two disciplines have worked together to establish fundamental principles and propose solutions for the restoration of sediment dynamics and habitat connectivity. The most important results relevant to practice are presented in this publication. It is intended in particular for experts from the public administration and the private sector.

The research project 'Riverscape – sediment dynamics and connectivity' was a joint project of the FOEN and the research institutes Eawag, EPFL, ETH Zurich and WSL, which also involved experts from practice – from cantonal administrations, private offices and non-governmental organizations.

The FOEN would like to thank all participants for their valuable collaboration and the representatives from the cantonal administrations and the private sector for their dedicated support.

Katrin Schneeberger, Director
Federal Office for the Environment (FOEN)

Introduction

Sabine Fink, Anna Belser, Giovanni De Cesare, Christoph Scheidegger, Christine Weber and David Vetsch

Hydrological and hydraulic processes, such as sediment transport, affect aquatic, amphibian and terrestrial organisms and their habitats, far beyond the main channel of a river. This area, the so-called 'riverscape', includes a high diversity of riparian habitats, which can vary in space and time depending on the water discharge and sediment dynamics. The animals and plants adapted to life in riverscapes benefit from the changing environment. Specifically, sediment dynamics can provide nutrients, promote reproduction, and both create and temporarily alter habitats.

In near-natural riverscapes, the large area connecting land and water provides sufficient space to mitigate flood hazards. In altered riverscapes, however, human infrastructures and agricultural land are affected by events that exceed the design discharge, and protection measures and residual risk management are therefore necessary. To link flood protection and ecological functions in riverscapes, an understanding of the degree of connectivity is of utmost importance. Near-natural rivers are connected to their surroundings in multiple dimensions: longitudinally from the source to the mouth, laterally from the water to (and including) the shores, and vertically from the surface water to the groundwater. Sediment dynamics affect connectivity in all of these dimensions, and the processes involved range from the catchment to the patch scale.

In ecologically connected riverscapes, species can find refuge in areas where the impact of extreme events (e.g. floods and droughts) is reduced. Functional connectivity also promotes biodiversity, even in small areas, as it interlinks habitats and makes it possible for organisms to disperse or colonize new areas. The recolonization of riverscape habitats is a key process, as the dispersal of riparian species is possible over large distances along functional waterways. Strategic planning for restoration and conservation at the catchment scale benefits from a holistic perspective. Models can help to project the potential for species to reach habitats within riverscapes after years or decades, also under changing climatic and morphological conditions (see Chapter 1; Fink and Scheidegger 2023). Furthermore, aquatic and terrestrial species in riverscapes depend on specific habitats to establish, grow and reproduce. The formation of these habitats in particular locations is shaped by climatic and hydrological factors at the catchment scale and by hydrodynamic factors at the local scale (see Chapter 2; van Rooijen *et al.* 2023).

In near-natural riverscapes, the water and land are well connected, including food webs where insects emerging from the water serve as nutritious food for terrestrial predators (e.g. spiders and birds; see Chapter 3; Kowarik and Robinson 2023). Functional lateral connectivity between aquatic and terrestrial habitats may also be important for the prevention of natural hazards, e.g. flood water diversion. Riverscapes with sufficient space for water retention are able to reduce high water peaks and thus mitigate flood impacts downstream. In the case of a major flood event, lateral diversion structures divert flood water but also affect the sediment transport in the main channel (see Chapter 4; Frei *et al.* 2023). Because regular flooding is important for floodplain vegetation, the construction of lateral diversion structures may also be an effective ecological measure.

During small and large flood events, riverscape species seek shelter in refugia, which are aquatic or terrestrial habitats where the impact of high discharge and sediment mobilization is reduced (see Chapter 5; Rachelly *et al.* 2023). The mosaic of habitats within near-natural riverscapes creates an abundance of refugia, with sediment supply being a prerequisite for refuge provision and function. Additionally, the deposition of fine sediment on floodplains during floods is important for the formation of terrestrial riparian habitats such as species-rich floodplain forests. This process is highly dependent on the structure within the habitat, for example, shrubs and grass-like vegetation promote sediment deposition. Further, knowledge about the deposition characteristics of fine sediment in compound channels is crucial for flood protection in regulated rivers (see Chapter 6; Conde *et al.* 2023).

Suspended sediment may also be deposited in the river substrate, with fine particles being retained in the pore space, leading to clogging (also referred to as colmation) and hence reducing porosity and water exchange (see Chapter 7; Dubuis *et al.* 2023). With increasing discharge, declogging occurs as a result of increasing bedload mobilization and a resuspension of fine sediment. It is important to understand the factors responsible for clogging, as this process hinders nutrient fluxes and prevents free circulation of well-oxygenated water. The latter is of major importance for the development of the eggs of substrate-spawning fish, such as brown trout. Further, the type and size of sediment in the river substrate have an impact on the spatial distribution of brown trout, depending on the age and sex of the individual fish (see Chapter 8; Takatsu *et al.* 2023).

The establishment of near-natural sediment dynamics is key to enhancing the ecological function of river substrate. Impaired sediment continuity can be mitigated by sediment augmentation. The optimal approach to bedload restoration measures varies depending on the desired goal, e.g. improving fish spawning habitat, promoting riverbed structures, or enhancing channel dynamics (see Chapter 9; Mörtl *et al.* 2023). For all measures, the ideal timing, quality and quantity of the added substrate are highly dependent on the flood protection objectives and on the ecological characteristics of the aquatic and terrestrial species or habitat affected by the augmentation (e.g. fish and vegetation in the river reach).

This publication is the result of an interactive process involving the researchers working on the project and the advisory board consisting of practitioners from private consultancies, NGOs, and cantonal and federal administrations. It summarizes the main findings of the project phase 2017–2021 (see Box 1) and includes perspectives from researchers or practitioners who were not directly involved in the project (see the 'In practice' box in each chapter). More information about the programme 'Hydraulic engineering and ecology' and the projects can be found on the website *www.rivermanagement.ch*, which also includes links to previous reports and scientific publications.

Box 1: Research programme 'Hydraulic engineering and ecology'

The Federal Waters Protection Act (WPA, 1991) and the Waters Protection Ordinance (WPO, 1998) ask for functional rivers in near-natural riverscapes while maintaining flood protection. Since 2011, a national restoration strategy has been implemented to fulfill this mission. With foresight, the Federal Office for the Environment (FOEN) launched the interdisciplinary research programme 'Hydraulic engineering and ecology' 20 years ago, together with the research institutes VAW (ETH Zurich), PL-LCH (EPFL), Eawag and WSL. The aim of this programme is to develop scientific principles and practice-oriented solutions for dealing with watercourses and to process them in a way that is suitable for implementation. Researchers from various disciplines and experts from practice participate in the programme. The results are intended to contribute to the implementation of the Federal Waters Protection Act and the Hydraulic Engineering Act (1991) and are available to practitioners in the form of scientific and technical articles, manuals, reports and fact sheets.

'Riverscape – sediment dynamics and connectivity' was the fourth multi-year research project in the 'Hydraulic engineering and ecology' programme, following 'Rhone-Thur', 'Integral river management' and 'Sediment and habitat dynamics'. It comprised two main research topics, both focusing on flood protection and ecology in medium-sized rivers: (i) sediment dynamics and (ii) longitudinal, lateral and vertical connectivity. A detailed description of the research project with its specific foci, subprojects and research questions can be found in Vetsch *et al.* (2018) and Fink *et al.* (2018).

Important practice-related products of the research programme that have been generated so far include:

- Handbook for evaluating rehabilitation projects in rivers and streams (Woolsey *et al.* 2005)
- Integrales Gewässermanagement – Erkenntnisse aus dem Rhone-Thur-Projekt (Rohde 2005) [in German]
- Synthesebericht Schwall/Sunk (Meile *et al.* 2005) [in German]
- Wasserbauprojekte gemeinsam planen. Handbuch für die Partizipation und Entscheidungsfindung bei Wasserbauprojekten (Hostmann *et al.* 2005) [in German and French]
- Merkblatt-Sammlung Wasserbau und Ökologie. Erkenntnisse aus dem Projekt Integrales Flussgebietsmanagement (FOEN 2012) [in German, French and Italian]
- Merkblatt-Sammlung Wasserbau und Ökologie. Geschiebe- und Habitatsdynamik (FOEN 2017a) [in German, French and Italian]

1 Strategic planning for restoration and conservation

River restoration projects need to meet many ecological and societal needs. Strategic planning can help to prioritize project goals at both the cantonal and the local scale. This chapter focuses on methods for restoration planning based on models and genetic analyses of various organism groups, which make it possible to reconstruct past and project future colonization processes along rivers. The planning tools discussed here help to determine if currently protected areas are sufficient for the long-term conservation of riparian species.

Sabine Fink and Christoph Scheidegger

1.1 Challenges for conservation and restoration planning

River restoration planning is challenging, as the development of terrestrial and aquatic habitats, as well as the colonization of these habitats by species, depends on connectivity along rivers (Fig. 1). This has been acknowledged in the Swiss Biodiversity Strategy, which emphasizes an exchange of individuals and genes (FOEN 2017b) via a functioning ecological infrastructure that forms a network of sites. Protected areas, such as Emerald areas or Biotopes of National Importance, as well as sites with limited human activity, such as game reserves, are important nodes in these networks. These nodes can provide various types of habitat for species, e.g. sanctuaries enabling short-term persistence or providing temporary shelter, or refugia supporting long-term survival despite changing environmental conditions (see Chapter 5; Rachelly *et al.* 2023).

To understand such networks of habitats and the processes which help to maintain the links between nodes in these networks, it is necessary to have spatially explicit data on current and predicted species occurrences and habitat distributions, as well as species dispersal abilities. While data defining the broad ecological niche is available for many species at the national scale, regional information on the presence of target species can vary considerably in availability and quality. Extensive field studies mapping all presence points of a species in Switzerland are not feasible. Nonetheless, to ensure effective planning, spatially explicit data at a large scale is necessary.

1.2 Why use models for restoration planning?

Ecological models make it possible to fill information gaps regarding the distribution of species. Based on existing species records, this approach helps planners to understand the correlation between ecological factors and species presence,

Figure 1

Diverse riparian habitat along the Moesa river in the Mesolcina valley (GR). The connectivity of open gravel banks between densely vegetated areas along rivers can be investigated using field studies, genetic analyses and simulations of dispersal between habitats.

Photo: S. Fink

reproduction and dispersal (see Box 2 on ecological models and Chapter 2; van Rooijen *et al.* 2023), and it can be applied to project species distributions in space and time. This type of ecological model can also be used to assess the most important factors determining suitable habitats for a species, and can enable projections to other areas based on their environmental conditions, without data on the actual presence of the species in those areas. The applied statistical procedures assume that core processes that define the distribution of a species depend on ecological conditions, including both biotic and abiotic factors.

Box 2: Ecological models

Ecological models are based on target species information, which can be obtained from the Swiss Information Centre for Species (*www.infospecies.ch*) or from field studies (Fig. 2). For target species which have been investigated in a Red List project, the detailed presence and absence data for various sites in Switzerland provides a solid basis for modelling.

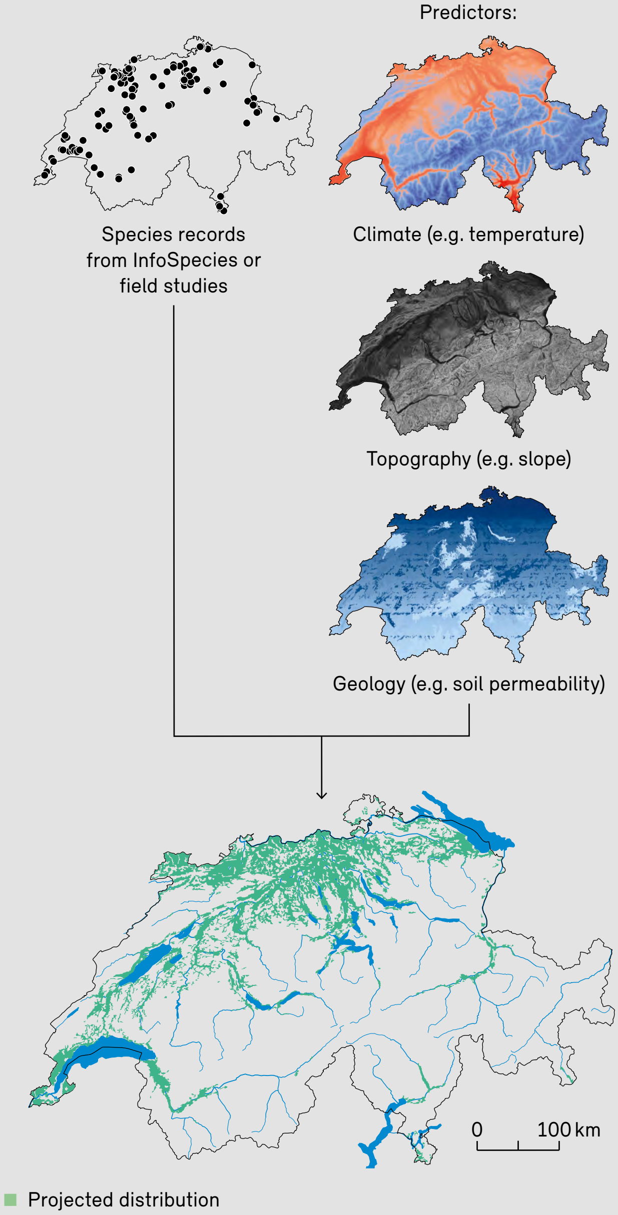
Every model needs a suitable set of predictors (environmental variables used to predict an event, situation or other variables). In the examples presented in this chapter, climatic, geological and topographic predictor data have been chosen to represent the species niche.

For plants, average temperature during the growing season and terrain slope (a proxy for incoming radiation) might be important factors, while for fungi, average annual temperature and precipitation might be the main factors to consider. Georeferenced environmental data is available at the national scale.

Modelling algorithms are available as open source packages in the free software environment R (*https://cran.r-project.org*). Many books on habitat modelling are available (e.g. Guisan *et al.* 2017). Habitat suitability maps can be transformed by applying a threshold to predicted species distribution maps.

Figure 2

Ecological models link species records (top left) and predictor layers (top right) in a statistical approach to map the projected distribution of a species (below).



Source: WSL

Figure 3

(a) Morchella semilibera was identified using a method in which fungi with a riverine affinity are detected as typical riparian species. (b) Based on species records (black dots), species presence (green areas) was projected in currently protected areas (areas outlined in red), but more frequently in currently unprotected areas along the Aare river in the canton of Bern.

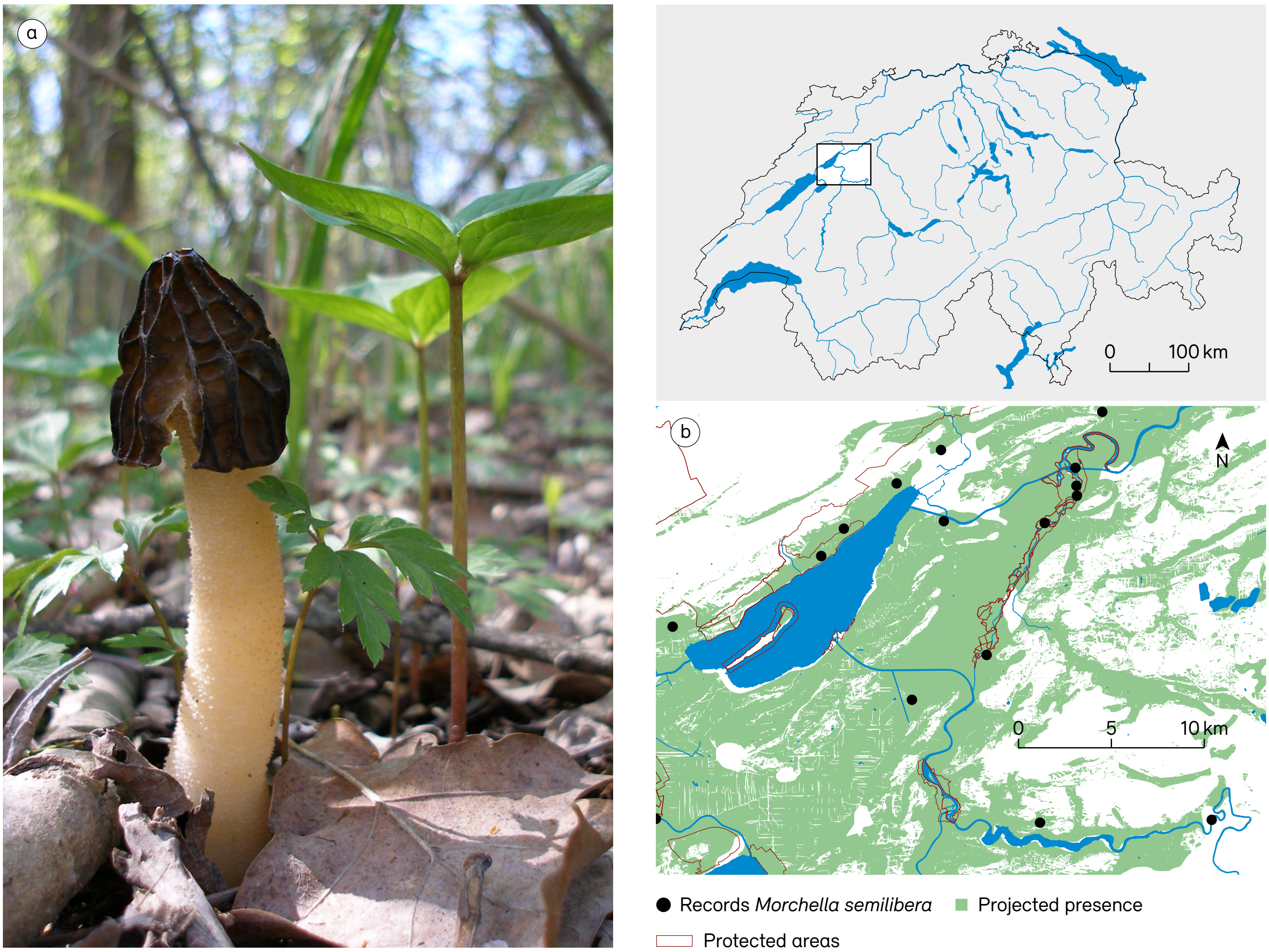


Photo: A. Gross, Figures: WSL

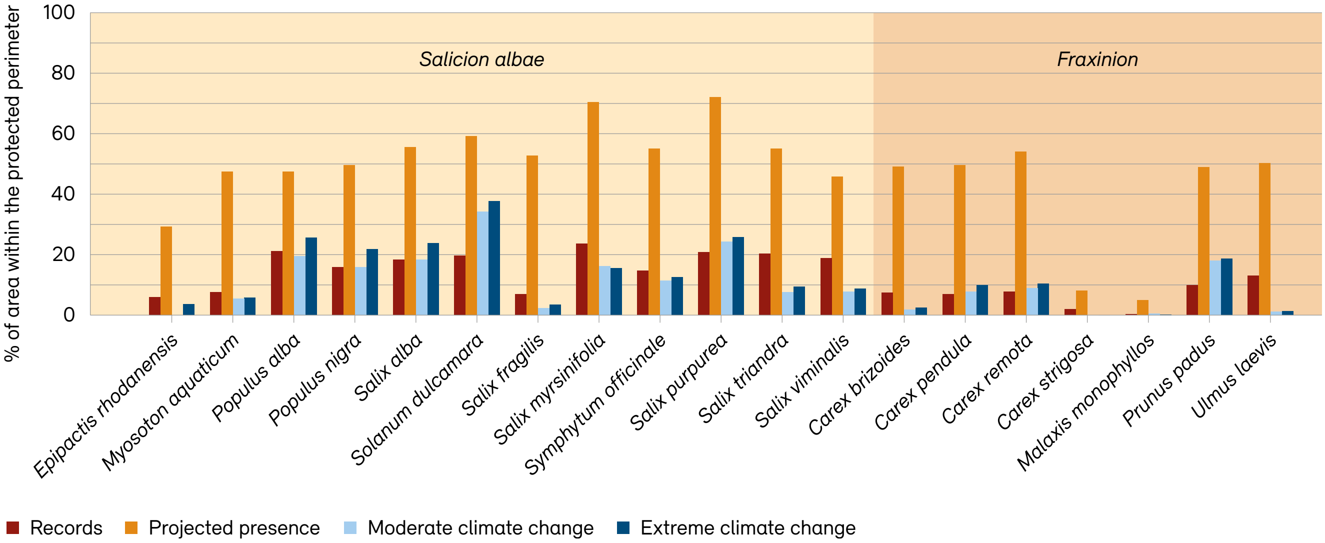
1.3 Application of ecological modelling in planning projects: example using fungi

Restoration projects mainly focus on a few groups of species of flora and fauna, and rarely consider other organisms such as fungi. Fungi occur in many habitats within the mosaic of floodplains; they play important roles in ecosystem processes, such as the decomposition of organic matter, and they can, as mycorrhizae, form a symbiosis with plants. Despite these important functions, fungi are underrepresented in planning guidelines. Fungi are important contributors to biodiversity in floodplain forests and other ecosystems, but they are difficult to track due to the limited seasonal visibility of their fruiting bodies. Data on fungal species presence is thus scarce in many regions of interest. Ecological models based on species records collected across Switzerland by a large community of volunteer mycologists can help us to overcome these limitations.

A list of typical riparian fungi occurring in Switzerland does not exist. In a recent study, spatial information from individual records was therefore used to identify species with a large

Figure 4

Floodplain forest species of the Salicion albae and Fraxinion plant communities have all been recorded within Floodplains of National Importance (red). The area within the floodplain perimeter which is projected to be suitable under current conditions is generally large (orange). Under both moderate (light blue) and extreme (dark blue) climate change scenarios, considerably fewer cells are forecasted for species' presence in the future (2084–2093).



Source: WSL

number of occurrences close to rivers (Fink *et al.* 2021). The resulting list of abundant species with high riparian affinity was evaluated with the help of data from the literature on their ecology, e.g. by identifying host tree species that are also typical of riparian habitats or soil substrates (e.g. sand) that are necessary for the species' growth. One of the typical species identified was *Morchella semilibera*, a saprobic species frequently found on turf or humus and associated with riparian plants. An ecological model was then used to project suitable habitats for this species along rivers (Fig. 3).

A network of connected habitats for riparian species should include existing areas with high biodiversity. The role of Swiss habitats that are currently protected (e.g. Floodplains of National Importance, Emerald habitats) was assessed by comparing the amount of suitable habitat within the protected perimeter to the amount of suitable habitat outside the protected areas. The models projected considerably more suitable habitat for fungi in unprotected compared with currently protected areas, which underlines the importance of including currently unprotected areas in conservation plans for riparian fungi (Fig. 3). The potential role of these candidate areas for species conservation should also be considered for other organisms within the same habitat (see the guild system, FOEN 2021a). Additionally, considering these areas could help to compensate for competing interests between species with opposing needs within already protected areas (Jöhl *et al.* 2020).

1.4 Restoration planning: temporal and spatial scales

Dynamic riparian areas frequently undergo changes, and populations of species may become extinct locally as a result of erosion (e.g. pioneer vegetation), flooding (e.g. macrozoobenthos), or habitat drying (e.g. small ponds along rivers for amphibians). Given their adaptation to dynamic habitats, specialized species can also benefit from dynamics such as repeated floods, which help them to outcompete less-adapted species. Hydrodynamic events will likely become more intense as climate change progresses, with more extreme floods and longer subsequent dry periods (Pistocchi and Castellarin 2012; FOEN 2021b). This is an important aspect to consider for the conservation planning of riparian habitats.

Figure 5

*(a) The lichen Coniocarpon cinnabarinum and (b) a comparison of the number of records of this species on individual trees in human-impacted (blue) and near-natural (green) floodplain forests in two habitat plots (A, B) along the Töss river (ZH) in 2018. The difference between the natural and human-impacted sites was significant in both plots (** p<0.01, *** p<0.001).*

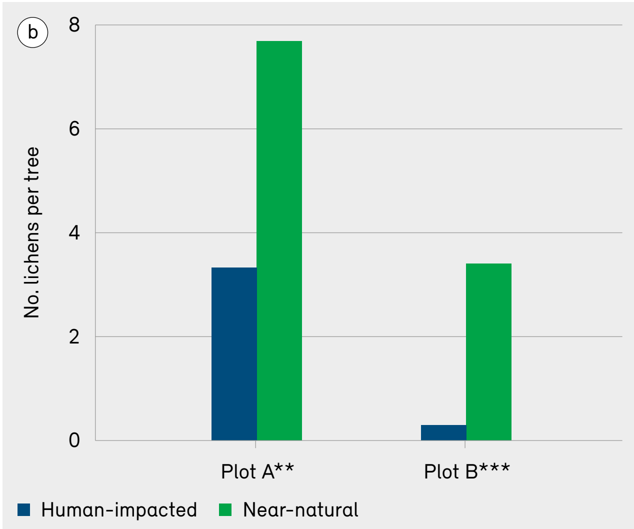


Figure adapted from Streit (2018), Photo: C. Scheidegger

The modelling approach enables us to project the fate of riparian systems under various climate scenarios. Although the results are subject to many uncertainties, they help us to visualize the extent of changes in available habitat or projected species distributions based on the magnitude of environmental fluctuations, e.g. in precipitation or temperature. This is pertinent information, as temperature changes affect multiple habitats and species. For example, terrestrial plant species are impacted by warmer, drier conditions during their growing season and aquatic fauna face reduced available habitat area with increasing water temperature.

Ecological model projections to future climate conditions that include simulations of the spread of species from current sites to currently unoccupied but suitable habitats support investigations of spatial and temporal networks. This has been demonstrated for floodplain forest plants, which form important communities along rivers: plants of the *Salicion albae* (softwood) vegetation type stabilize gravel banks against erosion, and *Fraxinion* (hardwood) forests are important for flood retention. These habitats harbour many threatened species, but are frequently at risk of fragmentation due to the limited space in riverscapes. The loss of habitat and species is predicted to accelerate under climate change, with species projected to find less suitable habitat area even within currently protected Floodplains of National Importance (Fig. 4). Therefore, management strategies to prevent accelerated loss (e.g. enhancement of water and sediment availability) must be considered now to ensure the survival of these plant communities in the future. Additionally, restoration projects should ensure sufficient space for floodplain forest establishment.

1.5 Habitat structure and shape

While models can help us to decide where conservation or restoration should be prioritized, additional information on the structure and shape of natural or near-natural habitats is necessary to maximize restoration and conservation success. Natural or restored floodplain forests provide habitat for highly specialized organisms such as lichens. The species aggregate *Coniocarpon cinnabarinum*, including the closely related *C. fallax*, grows on young ash trees (*Fraxinus excelsior*) and occurs mainly within floodplains. A study of the distribution of *C. cinnabarinum* along the

Figure 6

The genetic structure of Myricaria germanica populations along the Inn river and its tributaries suggests a connected habitat network. The proportions of genetic diversity assigned to three main clusters (orange, red, blue) are shown for each population. The diversity of two new populations (circles with a dashed outline) along the relocated Flaz tributary (brown line) is high. The assignment of plants in these two populations to the various clusters indicates the occurrence of water-mediated long-distance dispersal of seeds or plant parts downstream, as well as short-distance dispersal via wind or pollen.

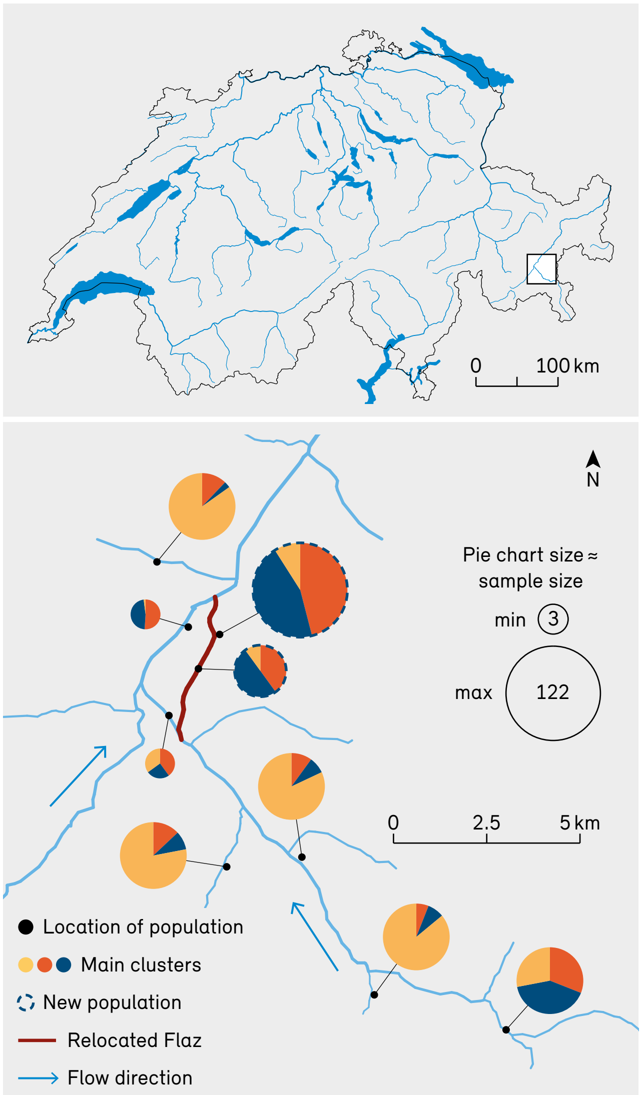


Figure adapted from Wöllner *et al.* (2021)

Töss river (ZH) showed that dynamic floodplain forests harbour more individuals than non-natural forests (Fig. 5; Streit 2018). For the presence of the *Coniocarpon* aggregate, the rare flooding of the floodplain forest is important for nutrient (see also Chapter 6; Conde *et al.* 2023) and light provision within the forest, as it causes the dieback of less-adapted understorey plants.

A study on lichens occurring on alder trees in the Albula catchment (GR) had the aim of identifying whether the shape of a grey alder floodplain forest influences lichen species diversity. For this purpose, floodplain patches about 60 m in both length and width were compared with hedge-shaped floodplains with lengths of up to 200 m but widths of only 10–20 m (Breitenmoser 2014). The mean number of lichen species per tree in the two floodplain types indicated that diversity is higher in floodplain patches, as they provide better connectivity in all directions between habitat trees and a better microclimate with higher humidity. This information is important for restoration planning, as it suggests that higher lichen diversity can be achieved in grey alder floodplains forests with more patch- than hedge-shaped habitats.

These examples demonstrate that not only habitat availability but also habitat shape is important to consider in restoration planning. This information on shape parameters, as well as on the structure within habitats (e.g. old or young trees, understorey presence or absence; for information on the importance of habitat structure for other species see Chapter 8; Takatsu *et al.* 2023), can be implemented in models, as done by Dymytrova *et al.* (2016) for lichens using information on forest stands.

1.6 Connectivity is crucial for successful restoration

The currently available riparian habitats are generally critically small, and connectivity between habitats therefore has to be ensured for species to spread among habitat patches. For sessile plants or species with a limited dispersal ability, such as wingless beetles, connectivity between habitats can only be maintained if the habitats are either spatially close or accessible by rare long-distance dispersal, e.g. by birds or water. Within a network of habitats along rivers, information on both habitat availability for and dispersal distances of target species with limited mobility is crucial for conservation efforts.

1.7 The use of genetic information to assess connectivity

Genetic analyses help us to indirectly assess the connectivity of populations of riparian species and especially immobile plants, as connected populations are genetically more similar than those that are not linked. Population genetics is also useful for understanding target species when dispersal vectors, such as water or birds, are difficult to track. Analysis of the genetic structure of populations within a network along rivers involves the assessment of the overall genetic diversity and the differentiation among populations. Such an analysis considers vegetative dispersal (when plant parts re-root in a new habitat), seed dispersal, and the contribution of pollen-mediated gene flow (e.g. by insects, which transport pollen to flowers on another plant individual).

Genetic analyses of populations of the German tamarisk (*Myricaria germanica*), a riparian shrub species growing on gravel banks and representative of pioneer vegetation, revealed a network of connected populations along the Inn river (GR) and its tributaries Flaz, Ova da Bernina and Ova da Morteratsch (Fig. 6; Wöllner *et al.* 2021). Even the relocation of the Flaz tributary near Samedan to the other side of the valley did not disrupt the connectivity of German tamarisk populations: the population that established along the relocated tributary contributed to the local genetic diversity.

Data on genetic relatedness between populations helps us to identify maximum possible dispersal distances along a river network. Examples of relocated rivers and information on dispersal events responsible for the colonization of the new habitat are especially informative. This data can be used in simulation studies to model connectivity, also in other river networks or habitats.

1.8 Riverscape restoration planning: aspects to consider when using models

The complexity of river restorations can be reduced in models to understand the major processes expected to influence the success of measures. By considering different scenarios, the impact of the changing climate, as well as limited dispersal, can be simulated. While most modelling frameworks for decision-making use a single target species, combinations of results on various species can help us to predict which habitats are most suitable for entire communities.

As ecological modelling is a statistical approach, some precautions have to be taken. Data needs to be verified before use, and model evaluations using statistical procedures are necessary. The ecological interpretation of modelling results requires expert knowledge because overestimations of habitat suitability are frequent, as not all factors can be considered in a model (e.g. microhabitats are not defined in this approach).

Ecological models have several advantages over e.g. single-site field studies. By understanding core processes related to habitats for target species, they make it possible to focus on regional instead of local planning, based on larger-scale projections. Data on many organisms can be combined and factors influencing the establishment of communities can be identified. Projections based on future scenarios can help us to adjust planning so that specialized species survive while less-adapted and invasive species remain at low densities, even under changing climate conditions and land use. Models therefore support strategic regional planning for successful species conservation and habitat restoration.

Box 3: In practice – Maximization of the potential for biotope and species protection

Erik Olbrecht, Office for Nature and Environment, GR

Restoration efforts are generally beneficial to biodiversity. However, the degree to which the improvement potential is realized depends to a large extent on the baseline survey and the definition of goals concerning biotope and species protection. It is crucial that these aspects are addressed at an early stage of the project, and that the planning of measures involving solutions to conflicting goals is conducted as a close collaboration between the project managers and the ecological expert.

Restoration projects are key elements of any ecological network. Riverscapes are often biodiversity hotspots and have important linking functions. In order to fulfil this critical function, it is essential that an ecological expert establishes the overarching regional and local objectives for the protection of biotopes and species at the beginning of the planning phase of a restoration project. This work results in a list of target species and target habitats (Table 1) and ideally also a distribution map indicating priority habitats and species that are closely linked to the project area. Additionally, conflicting goals within the planned measures for biotope and species protection should be specified and recommendations for prioritizations should be included.

In a next step, the project managers and the ecological expert work together in the early stages of the project (Preparation and Briefing or Concept Design) to evaluate the potential for improvement within the project perimeter and to find solutions to possible conflicts concerning objectives in biotope and species protection. In the Concept Design and Planning Application stages, the planning of restoration measures should be aligned as closely as possible with the target habitats and target species, including their connectivity requirements, and any conflicts between objectives should be resolved. Elements that are important in facilitating such a well-developed planning process are the specification of the objectives of biotope and species protection in the project planning documents and the development of concepts for visitor guidance and site maintenance, as well as a monitoring plan.

Table 1

Excerpt from a list of target species and target habitats for planning a restoration project. The habitat information is used by hydraulic engineers and ecologists for the collaborative planning of hydrological requirements and of morphological and ecological structures within the restoration site perimeter. Key additional information for implementation is listed in the column 'Measures'. Likewise, the target percentage of area of each habitat type within the project perimeter is an important tool for practitioners.

Target species			**Target habitat**		
English name	**Latin name**	**Number***	**Habitat**	**Measures**	**Target percentage of area within project perimeter**
Summer water starwort	*Callitriche cophocarpa*	1.2.2	Tributary/backwater with weak flow	· Hydrological dynamics must exist	20%
Eurasian water shrew	*Neomys fodiens*				
Common sandpiper	*Actitis hypoleucos*	3.2.1.0	Alluviums with gravel and no vegetation, no flooding in summer	· Hydrological dynamics must exist · Protection of species from disturbance by humans and dogs during breeding season	10%
Little ringed plover	*Charadrius dubius*				
Lesser centaury	*Centaurium pulchellum*	3.2.1.1	Alluviums with silt/fine material and pioneer vegetation	· Hydrological dynamics must exist · Protection of species from disturbance by humans and dogs during breeding season	20%
Common sandpiper	*Actitis hypoleucos*				
Little ringed plover	*Charadrius dubius*				
Eurasian water shrew	*Neomys fodiens*	6.1.3	Dynamic grey alder floodplain forest	· Periodically high water levels required · Structurally complex forests used as hunting areas, standing dead wood	30%
Alpine long-eared bat	*Plecotus macrobullaris*				

*compare to Delarze and Gonseth (2015)

2 Riparian eco-hydrodynamic habitat modelling

The availability of habitats for riparian plant species depends on climatic features and soil properties, as well as local river hydro-morphological conditions. To predict suitable habitats for the German tamarisk (Myricaria germanica), a species typical of riparian gravel banks, a large-scale ecological model was linked with a two-dimensional hydrodynamic model. This chapter includes a description of the modelling workflow, together with an application along the Moesa river (GR).

Erik van Rooijen, Davide Vanzo, David Vetsch, Annunziato Siviglia and Sabine Fink

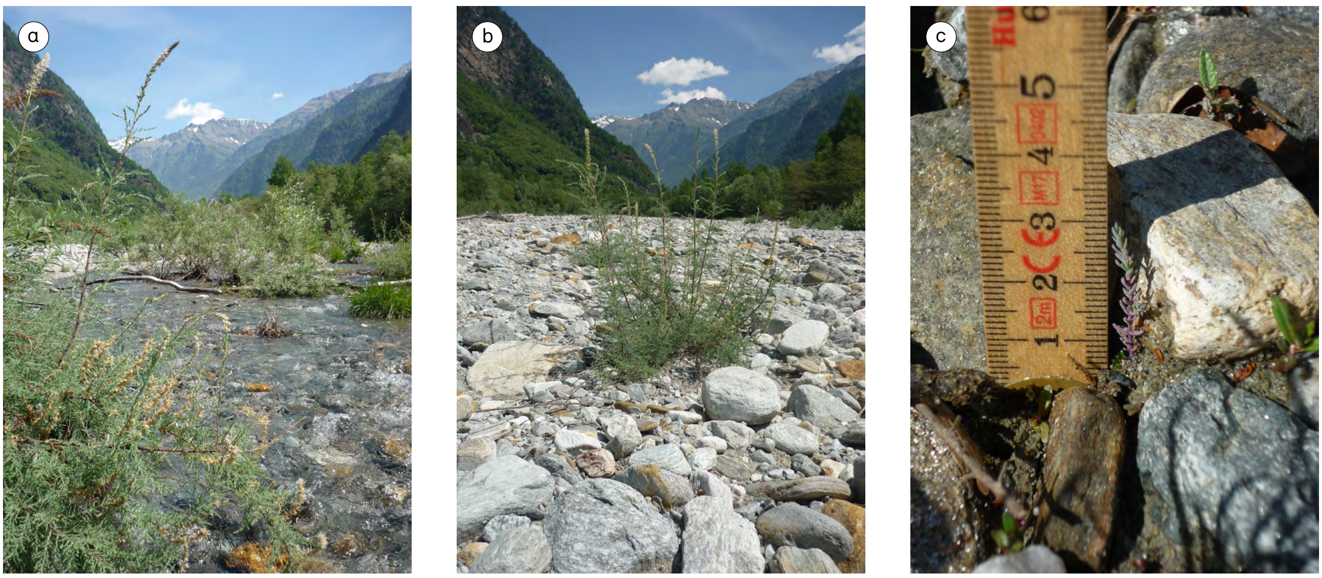
2.1 Habitat modelling in riverscapes

Riverscapes are composed of a variety of landforms, which host different habitats for terrestrial, aquatic and amphibian species. A habitat results from particular physical and biotic factors and represents a suitable location that supports the establishment, survival and reproduction of a species (Fig. 7).

The identification and quantification of habitats is crucial for the management of riverscapes. The amount and variety of habitat are linked to the biodiversity and ecological resilience of a given environment (see Chapter 5; Rachelly *et al.* 2023). Habitat analysis has practical applications for river managers, for example for evaluating the consequences of changes in environmental conditions, such as the hydrological regime (e.g. natural floods) or climate variables (e.g. temperature increase), on target plant or animal species. Examples of river habitat analysis outcomes are the identification and quantification of suitable areas for seed establishment or for fish spawning. Such results provide quantitative support to river

Figure 7

The highly dynamic riverscape along the Moesa river close to Cabbiolo (GR) harbours adult German tamarisk (Myricaria germanica) plants (a) in partially wetted areas (plant with flowers in the foreground), which also survive during dry periods. (b) Adult plants survive on gravel banks, and (c) seedlings establish on wet, sandy soil.



Photos: WSL

management decisions, such as the selection of the best spots for species conservation using the artificial sowing of seeds of an endangered plant species, or the design of more effective releases of stocked fish.

Environmental models (see Chapter 1; Fink and Scheidegger 2023) are informative, simplified representations of real-world components. They help us to understand the core elements of complex processes and can be applied at various spatial scales, from local to global. Habitat models have been applied in multiple contexts, for instance to assess the distribution of butterfly species (Maggini 2011) and the vulnerability of bird species (Maggini *et al.* 2014) in Switzerland. In the fluvial setting, models are often used to quantify fish habitats (e.g. MesoHABSIM; Parasiewicz 2011) but also vegetation succession in riverscapes (CASiMiR vegetation; Ecohydraulic Engineering GmbH 2019).

In this chapter, we propose a habitat modelling workflow for the German tamarisk (*Myricaria germanica*), a red-listed shrub species (Fig. 7). This typical pioneer plant lives on gravel banks in the dynamic riverine zone, and has specific habitat requirements depending on the particular life stage. Climate, geology, topography and hydraulics are all important for the adult shrubs. For example, frequent sediment turnover is necessary for them to avoid being outcompeted by other pioneer species such as willows (*Salix* spp.). Adults start flowering after two years if the air temperature in late spring and summer is sufficiently high. Single flood events can lead to young plants being washed away or buried. Environmental conditions therefore need to remain favourable for several years for plants to become fully established.

The seeds of the German tamarisk germinate within 24–48 h on wet sandy soil, i.e. in areas that have been inundated recently. A favourable habitat for seedling establishment has two requirements: (i) the presence of adult plants during the seed dispersal season (May to September) to ensure seed production and (ii) high inundation frequencies in the surrounding areas to support seed germination.

2.2 Linking ecological and hydrodynamic models

To predict suitable habitat for riparian species in the dynamic riverine zone, we linked two models: (i) an ecological statistical model of German tamarisk distribution and (ii) a deterministic two-dimensional hydrodynamic model for the simulation of riverine local flow conditions (see Box 4). The ecological model predicts the habitat for the German tamarisk based on large-scale (i.e. regional) climatic, geological and topographic indicators (see Chapter 1; Fink and Scheidegger 2023). The main outcome is a spatially explicit map indicating the likelihood that the target species can establish and persist in different areas. To increase the accuracy of habitat prediction for the German tamarisk, which is highly dependent on local hydrodynamic conditions, at the local (reach) scale, we linked the ecological model with a deterministic, two-dimensional hydrodynamic model (see Box 4). The resulting workflow, with the main steps and required inputs, is shown in Figure 8.

2.2.1 Ecological modelling

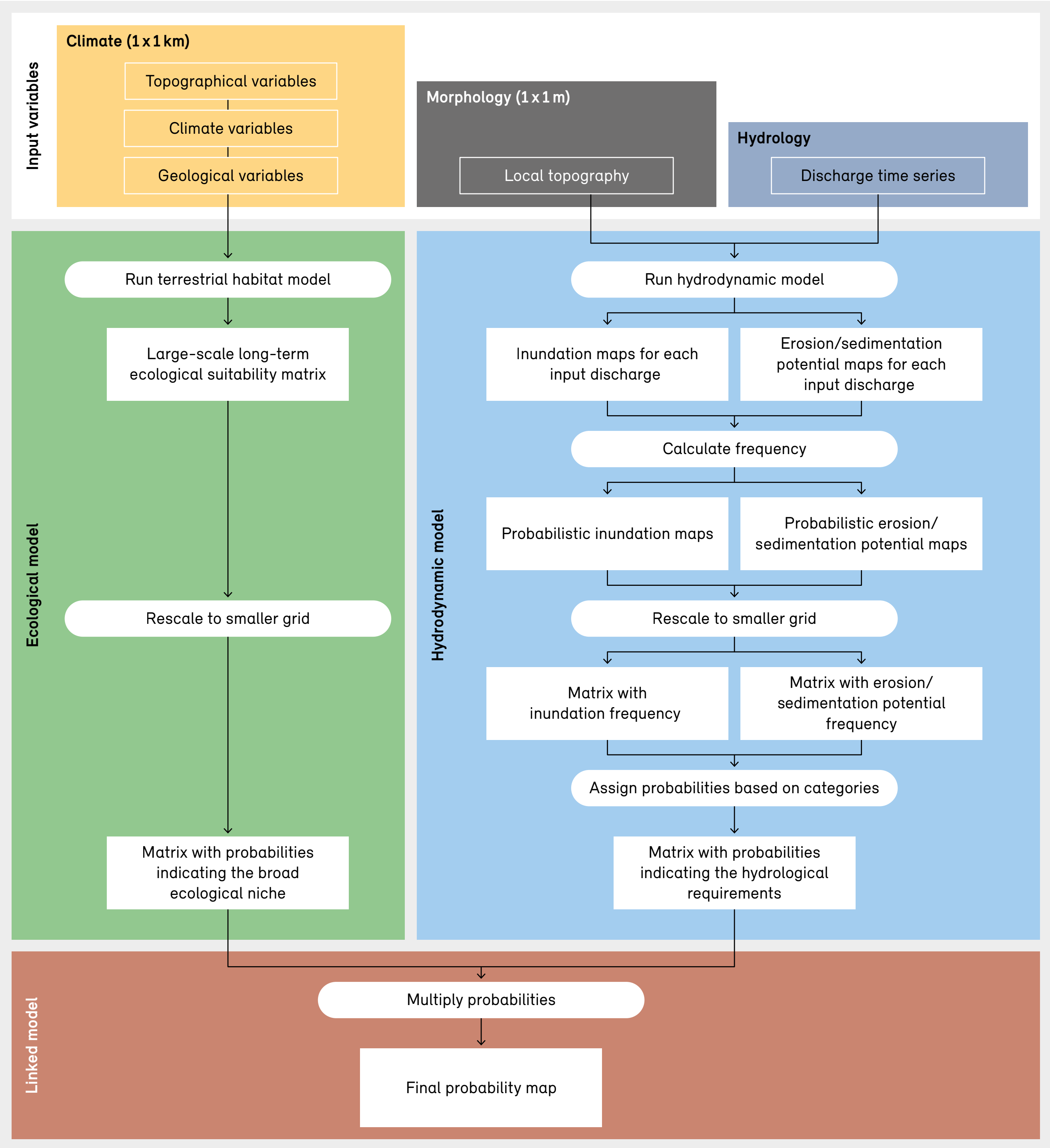
The ecological statistical habitat model for adult plants provided a large-scale habitat suitability matrix based on climatic, geological and topographic predictors. With this matrix, we could identify potentially suitable areas at a 1 × 1 km raster scale. The model used a long-term dataset covering all of Switzerland, and returned a long-term habitat suitability map for the predicted presence of German tamarisk (see Chapter 1; Fink and Scheidegger 2023).

Box 4: Hydrodynamic models

Hydrodynamic models solve a set of equations describing fluid dynamics in order to simulate water flow in rivers. In addition, hydro-morphodynamic models feature a solver to simulate the erosion and deposition of sediment along the river. Results of such simulations are the spatial distribution of flow depth and velocity, and, in the case of morphodynamic models, bed level. Hydrodynamic models require a set of input data; in this study we made use of a digital terrain model (DTM), a hydrological data series (i.e. discharge values), and an estimation of riverbed roughness. In the case of a morphodynamic simulation, extended information on sediment characteristics is needed. In Switzerland, discharge data is measured and available at many sites, whilst the remaining input data often needs to be collected ad hoc for each study site. For the hydrodynamic simulations of this study, we used BASEMENT (Vanzo *et al.* 2021), a freeware tool for the simulation of multiple river processes.

Figure 8

Workflow linking the ecological and hydrodynamic models. The results of both the ecological model and the hydrodynamic model are linked to obtain a probability map, predicting seedling habitat more accurately. The large coloured blocks represent the subsections of the methodology. The smaller rectangles represent datasets and the ovals represent actions.



Source: VAW, ETH Zurich /WSL

2.2.2 Hydrodynamic modelling

We set up and calibrated a two-dimensional hydrodynamic model of the study site (see Section 2.3) using the freeware BASEMENT (*https://basement.ethz.ch;* Vanzo *et al*. 2021). With the outputs of BASEMENT simulations, we generated inundation frequency maps. We then estimated areas prone to sediment erosion/deposition under different flow conditions. Further information on hydrodynamic modelling is given in Box 4.

2.2.3 Model linking

We linked the ecological and hydrodynamic models to realize a fine-scale prediction of suitable locations for German tamarisk seedling establishment, as this is the most vulnerable life stage, and successful establishment ensures local persistence. To predict seed dispersal and establishment, we used: (i) the adult habitat matrix from the ecological model, (ii) the inundation maps, and (iii) the erosion/deposition maps from the hydrodynamic model (Fig. 8). By multiplying probability rates for these three maps on a fine spatial scale (1 × 1 m raster as subsamples from the large raster; for details see Fig. 8), we produced probability maps that indicated the locations where German tamarisk is likely to establish as a seedling.

2.3 Case study: Moesa river

2.3.1 Site description and data collection

We tested the linked model on a small floodplain of the Moesa river, GR (Fig. 9). The reach is located near the village of Cabbiolo in an area where the river has never been channelized, but is confined by levees for flood protection. The floodplain is approximately 800 m long and the total width is between 100 and 200 m.

We monitored the site from the beginning of May to the end of September 2020. At the beginning of the study period few adult German tamarisks were present. During the study period, on 7 June and 29 August, two floods altered the river topography. We surveyed the site with a drone and digitalized the topography using Structure-from-Motion techniques (Agisoft 2020). The topography of the submerged areas was measured using handheld GPS devices.

Figure 9

Aerial image of the study site along the Moesa river, close to Cabbiolo (GR). The floodplain is confined by two lateral embankments. The white arrow represents the flow direction (from North to South) and the white rectangle represents the section of the site corresponding to the modelled results displayed in Figure 10.

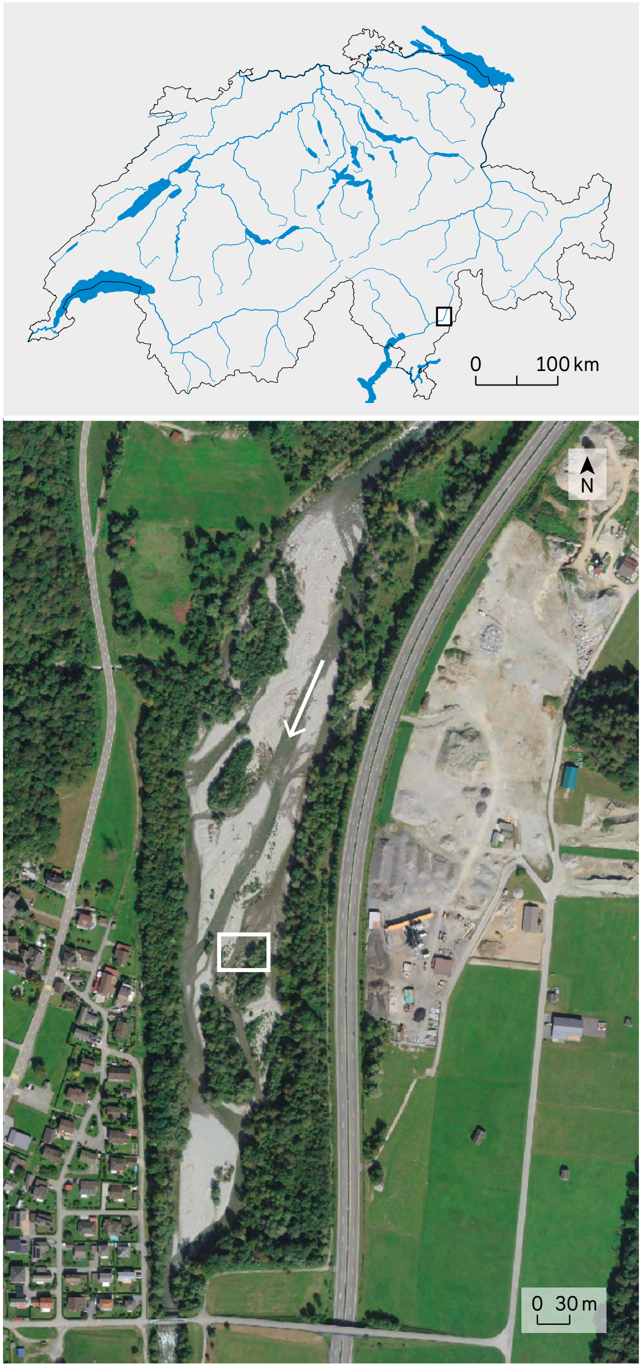


Photo: Swisstopo

The presence of German tamarisk was recorded every two weeks, covering the plant's reproductive phase from early flowering to late seed dispersal. The exact locations of the plants were measured using handheld GPS devices.

The ecological model was based on geological and climatological data for the period 1960–2016, with habitat availability modelled based on species records from the National Data and Information Center on the Swiss Flora, Infoflora (Fink *et al.* 2017; see also Chapter 1; Fink and Scheidegger 2023). The hydrological data was obtained from the Office for Nature and Environment (Amt für Natur und Umwelt) of Canton Grisons.

2.3.2 Evaluation of modelling results

For adult individuals, the level of detail of the large-scale ecological model alone was insufficient, as it did not indicate why some plants did not survive during the study period in 2020. The distribution of shrubs within the site suggests that erosion processes play an important role in determining the persistence of adult plants, but these factors were not implemented in the ecological model. Therefore, we checked if the additional information from the hydrodynamic model allowed us to predict the survival of German tamarisk.

The hydrodynamic model used discharge data from the study period and high-resolution river topography information to assess potential gravel erosion at a smaller spatial scale. Continuous erosion of gravel in early May resulted in the loss of adult plants in areas which were indeed predicted to be subject to gravel erosion and sedimentation by the hydrodynamic model. By linking the ecological model and the hydrodynamic model, the predicted habitat changes reflected the fate of the adult individuals accurately.

The linked model was mainly used to predict the locations where the successful establishment of German tamarisk seedlings is possible. While the ecological model was important for predicting the habitat of adult individuals, the inundation, erosion and sedimentation areas within the two-week periods during the flowering phase were used to predict where seed germination is likely to occur. The linked information from the ecological and hydrodynamic models made it possible to detect the general pattern of suitable seedling habitat at a small spatial scale, as established seedlings were indeed observed in some of the regions predicted by the linked model (Fig. 10).

2.3.3 Benefits of the linked model

The main benefit of the linked model is that the identification of potentially suitable areas for seed germination is possible at a finer spatial scale. Such areas are very important for the recolonization and persistence of German tamarisk. The higher accuracy of the linked model enables the prioritization of locations along the floodplain for local species promotion or targeted management actions, such as competitor (or invasive) plant removal.

The use of tools that support a high level of detail (e.g. 2D river modelling tools) and the increasing availability of high-resolution datasets from remote sensing represent a consolidated trend in practice and academia. The proposed linked model fits with this trend by exploiting the benefits of combining modelling tools with various spatial and temporal scales.

2.3.4 Limitations of the linked model

While the linked model was useful for detecting adult and seedling habitat for the target species, it involves greater modelling complexity. This is due to the difference in spatial scale (large for the ecological model and small for the hydrodynamic model) and thus the need for re-adjustment (rescaling, see Fig. 8). Additionally, the linked model does not consider all the environmental processes that a species is exposed to. The model can be further refined, for example by accounting for interactions between sediment dynamics and plants (e.g. Caponi and Siviglia 2018). Furthermore, the proposed workflow (Fig. 8) requires the use of a series of tools (e.g. BASEMENT) and some scripting skills for data elaboration (e.g. in R or Python), as it is not implemented in a single bundled tool. Nevertheless, the workflow can be fully reproduced with freeware tools.

2.3.5 Extendibility to other case studies and species

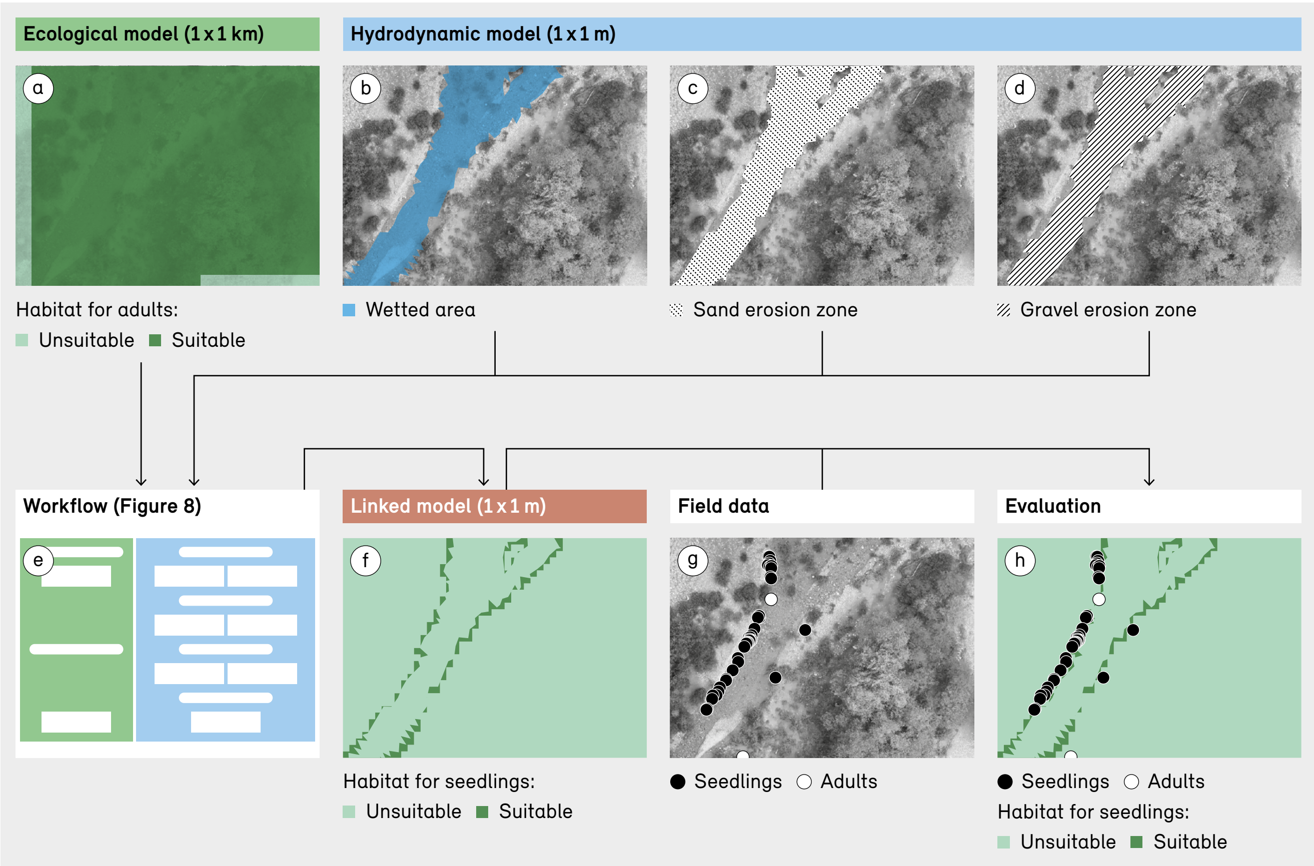
The linked model can be adapted to other river sites and other species. In particular, there are no limitations with respect to the type or size of river reach, provided that the 2D modelling approach is valid. By using BASEMENT, all types of flow conditions (i.e. both sub- and supercritical) can be reproduced; hence, both lowland and alpine reaches can be investigated.

To apply the linked model at other river sites, both the ecological model and the hydrodynamic model are required. The ecological model is executed at the national scale and available information for the German tamarisk can be used for other sites in Switzerland (Fink *et al.* 2017). The workload required for the hydrodynamic model depends on the availability of a high-quality digital terrain model (DTM), which can be time-consuming to generate from scratch. Considering the workload, we recommend using this approach in specific reaches of interest (order of kilometres) but not on a national scale.

Since the German tamarisk is an indicator species for pioneer vegetation in floodplain areas (Delarze and Gonseth 2015), the outcome presented here can also be used to infer habitat for species with similar niches (e.g. the willow *Salix daphnoides*) or non-plant species in the same habitat (e.g. the moth *Istrianis myricariella).* The methodology could also be adapted to model other types of motile species, such as fish or riparian terrestrial beetles or spiders (Box 5, see also Chapter 3; Kowarik and Robinson 2023). In this case, the ecological model step would need to be adapted to reflect the target species, and the hydrodynamic model would need to quantify the hydraulic parameters that are important for these species.

Figure 10

Evaluation of the linked model with field data on German tamarisk adults and seedlings in a section of the floodplain near Cabbiolo, GR (aerial image from winter 2020). Seedlings were present in areas identified as suitable in the ecological model (dark green area in panel a), close to the modelled inundation lines (blue area in panel b), and outside the modelled erosion and deposition zones (c: sand, d: gravel). Following the workflow to link the two models (e), the combined probability matrix (f) narrows down the locations suitable for seedling establishment (dark green areas in panels f and h) and matches the field data (g) as shown in the evaluation (h).



Source: VAW, ETH Zurich /WSL

2.4 Use in practice

The linked model is a useful tool for assessing the potential for local conservation of target species via natural rejuvenation and local growth. The red-listed German tamarisk tends to be outcompeted by more common and faster-growing willows, which render light conditions too shady for this slower-growing species. For the German tamarisk, rejuvenation along inundation lines where competition is low is crucial, and it helps this species to persist despite the co-occurrence of neophytes like the invasive summer lilac (*Buddleja davidii*; Mörz 2017). The probability map of seedling habitat facilitates the investigation of the potential for rejuvenation at sites which are impacted by hydropower. Further, it can be applied to validate restoration success by comparing the predicted habitat potential of restored areas with observations of established seedlings.

Under climate change, floods are expected to become more frequent and occur in different periods than they do currently. More accurate predictions and a deeper understanding of processes are crucial for river managers to deal with future environmental changes. With the linked model, it is possible to forecast future habitat conditions while considering changes in temperature, precipitation and discharge, leading to an improved understanding of the fate of species in a changing world.

Box 5: In practice – An application perspective on habitat modelling

Mauro Carolli, Research Scientist at SINTEF (Norway)

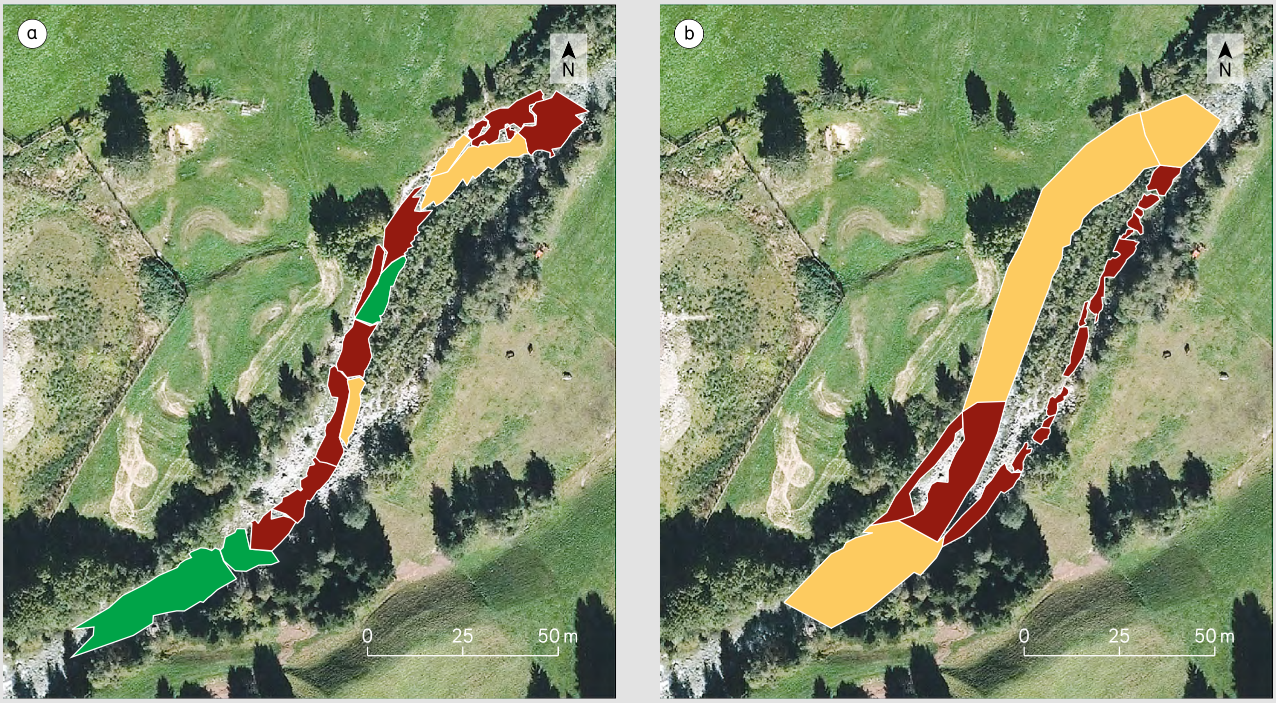
Habitat modelling can be extremely useful for assisting practitioners and decision-makers in the management of river systems. We applied habitat modelling to quantify environmental flows downstream of water abstractions for human activities (e.g. hydropower production). Minimum flows are typically defined using only hydrological relationships within the catchment, while with habitat modelling ecological aspects can be considered as well. In 2015, guidelines from the EU suggested the implementation of habitat modelling methods to define ecological flows for the Water Framework Directive.

In pilot case studies in the Italian Alps, we used the MesoHABSIM method (Parasiewicz 2011) to define environmental flows from a more ecological perspective, in line with the EU guidelines. We mapped habitat at different streamflow rates to build a habitat-discharge curve and assess habitat quality for the two main local species, the brown trout (*Salmo trutta,* Fig. 11) and the marble trout (*Salmo trutta marmoratus*). We simulated different amounts of water withdrawal for human use, and we transformed the streamflow data series into habitat series, which we used to identify the ecological flow thresholds below which habitat quality rapidly decreases. Habitat quality is assessed at the reach scale (10–1000 m) in the field, but hydrodynamic modelling can assist in extending habitat assessments to a larger spatial scale, if relevant (sub-catchment or catchment). The transformation of the streamflow data series into habitat series can also be computed at different time scales, depending on the resolution of the input data. Doing so helps us to assess the ecological effects of phenomena that might affect the river community from sub-daily (e.g. hydropeaking) to weekly or monthly (e.g. extreme droughts) scales.

The habitat modelling concept directly relates hydrology and water management to the biotic communities in rivers. In addition, this concept can be extended in order to quantify other ecosystem services, when a relationship between streamflow (or other hydraulic variables) and water use can be established. An example is the quantification of river suitability for recreational navigation (rafting, kayaking) downstream of hydropower plants under different flow conditions. Overall, the habitat modelling concept is a powerful tool for river management, and it holds huge potential for the analysis of possible trade-offs and synergies among different river uses and biotic communities.

Figure 11

Habitat suitability for adult brown trout (Salmo trutta) at river discharge rates (Q) of (a) 1.15 $m^3\ s^{-1}$ and (b) 3.95 $m^3\ s^{-1}$. Vermigliana creek, Vermiglio (IT).



Adult brown trout, Q = 1.15 $m^3\ s^{-1}$

Optimal Suitable Unsuitable

Adult brown trout, Q = 3.95 $m^3\ s^{-1}$

Optimal Suitable Unsuitable

Source: Courtesy of Prof. G. Zolezzi (DICAM, University of Trento, Italy)

3 Aquatic-terrestrial resource fluxes

This chapter focuses on how rivers and their surrounding landscapes are closely linked, and how resource fluxes between these systems are important for maintaining aquatic and terrestrial biodiversity. It includes a discussion of the export of biomass and specific nutrients, so-called omega-3 PUFAs, as a crucial ecosystem service provided by healthy aquatic systems. Management and restoration projects should take into account this lateral connectivity to improve the success of restoration measures.

Carmen Kowarik and Christopher T. Robinson

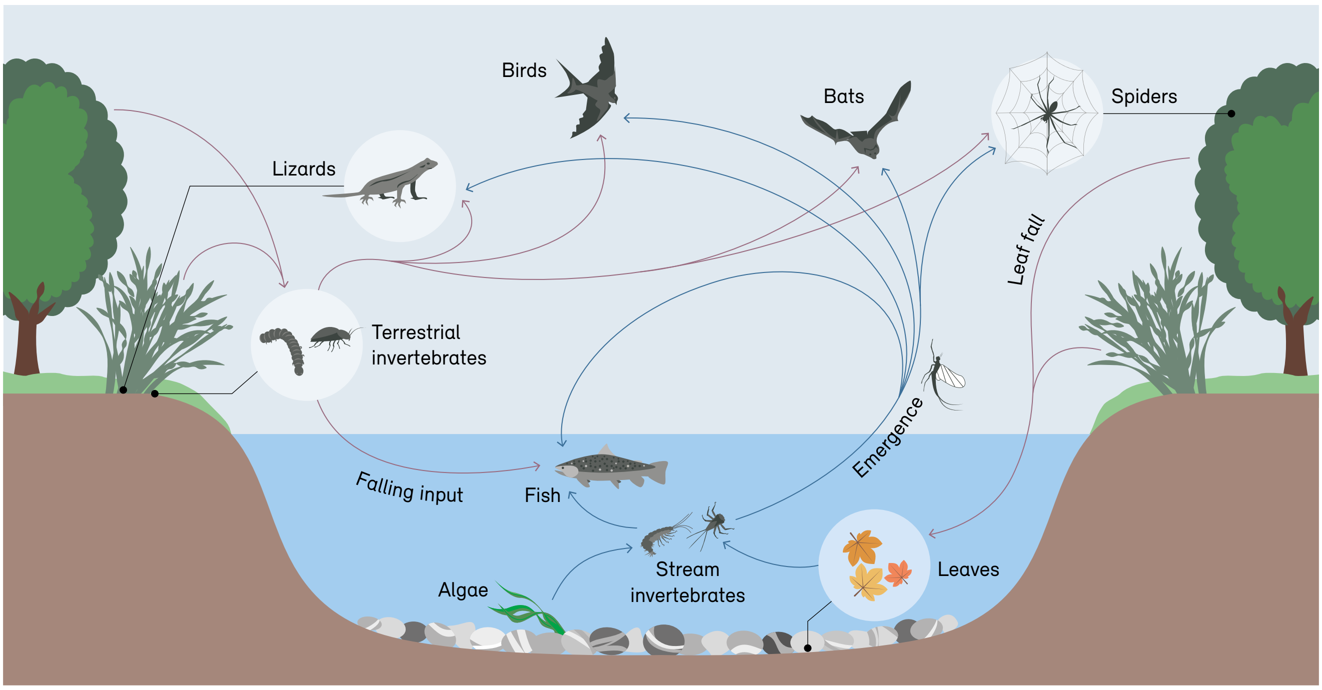
Rivers and the adjacent floodplains and riparian areas are interactive, open units connected along multiple pathways (Baxter *et al.* 2005). Here, we take a closer look into cross-boundary resource fluxes that involve, in this context, the exchange of organic resources (biomass and nutrients) between adjacent aquatic and terrestrial ecosystems (Fig. 12). Resource fluxes occur in both directions, e.g. via leaf litter input into streams and the emergence of aquatic insects into terrestrial systems, creating what Baxter *et al.* (2005) call a 'tangled web'. Such cross-boundary fluxes can play crucial roles in sustaining recipient systems.

3.1 Importance of cross-boundary fluxes from aquatic to terrestrial systems

The present chapter focuses on resource subsidies from aquatic to adjacent terrestrial ecosystems. Aquatic-derived resources provide an additional food source for riparian predators such as spiders, e.g. in the form of emerging aquatic insects. Many aquatic insects have life histories in which the larval stage is aquatic and the adult reproductive stage is terrestrial. The timing of aquatic subsidies reflects the life histories of local assemblages and leads to seasonal resource pulses. Aquatic insect emergence, especial-

Figure 12

Schematic of cross-boundary resource fluxes between a stream and the surrounding landscape.



Source: Baxter *et al.* (2005)

ly in spring, provides an important supplement for riparian predators at a time when terrestrial resources are low in abundance. Various studies have shown that riparian predators, such as spiders and birds, are seasonally dependent on aquatic resource subsidies (Iwata *et al.* 2003; Paetzold *et al.* 2005; Burdon and Harding 2008).

Aquatic-derived resources not only represent an additional food source, but also contain an important nutrient in low supply in terrestrial ecosystems, the well-known omega-3 fatty acid EPA (Table 2). We find high concentrations of EPA in fish, making them a beneficial food source also for humans, and in other aquatic organisms like insects. In fact, aquatic ecosystems are considered a principal source of EPA (Hixson *et al.* 2015). EPA belongs to the group of

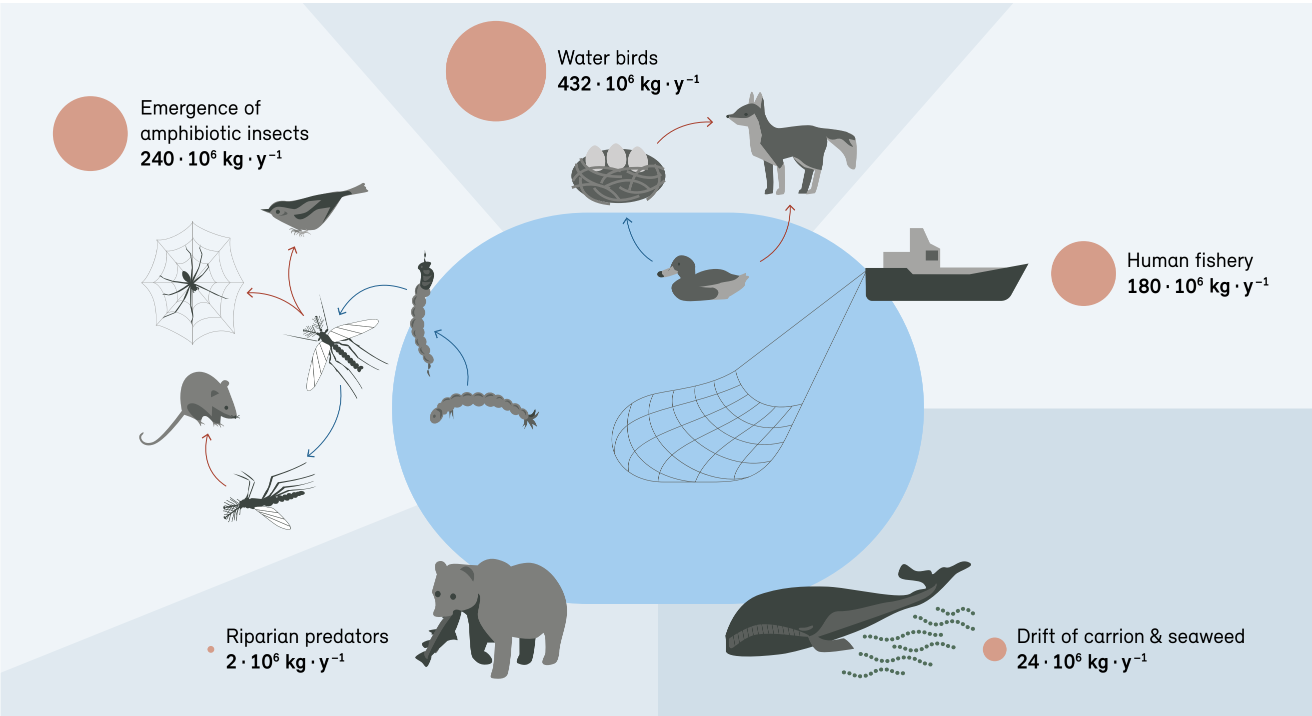
Table 2

Important omega-3 polyunsaturated fatty acids (PUFAs).

Abbreviation	Chemical formula	Name	Primary producers
ALA	C18:3n3	Alpha-linoleic acid	Produced by most algae and by some land plants, with especially high concentrations in some seeds and nuts (e.g. rapeseed, flaxseed, walnut)
SDA	C18:4n3	Stearidonic acid	Produced by many algae (e.g. many cryptophytes and some green algae) but by only a few higher plants (e.g. black currant and echium)
EPA	C20:5n3	Eicosapentaenoic acid	Produced by many algae (e.g. diatoms and cryptophytes) but not by higher plants (except some mosses); aquatic systems as principal source
DHA	C22:6n3	Docosahexaenoic acid	Produced mostly by marine algae (e.g. marine cryptophytes)

Figure 13

Estimated annual (y) export of EPA + DHA (see Table 2) via different pathways, illustrating the magnitude and importance of this ecosystem service provided by aquatic systems.



Source: Gladyshev *et al.* (2009)

polyunsaturated fatty acids (PUFAs; Table 2) that contain multiple double bonds, which only specific organism groups can produce. While several algal groups, e.g. diatoms, produce large amounts of EPA and it therefore accumulates in aquatic food chains, terrestrial plants, except for some mosses, completely lack this ability (Harwood 1996; Uttaro 2006; Hixson *et al.* 2015); this makes EPA-rich organisms (aquatic insects) a resource in high demand in terrestrial ecosystems. Preliminary estimates indicate that the quantity of PUFAs exported from aquatic systems can be substantial (Fig. 13), providing an important cross-boundary ecosystem service (Gladyshev *et al.* 2013).

But why are PUFAs so important? In animals, including humans, PUFAs are involved in many physiological processes. They are, for example, essential parts of our cell membranes, have important functions in our immune system, and play a role in signal transduction in the body (Stillwell and Wassall 2003; Stanley 2014; Schlotz *et al.* 2016). In short, PUFAs are essential for survival und need to be taken up with the diet. Although some organisms can convert other PUFAs to EPA, this process is generally inefficient, and EPA uptake via the diet is thus quite important. In support of this, studies on riparian predators have demonstrated, for example, a positive effect of aquatic-derived EPA fluxes on the development and breeding success of riparian birds, such as tree swallows (Twining *et al.* 2016, 2018), and on the immune system of riparian spiders (Fritz *et al.* 2017).

Humans have altered most aquatic ecosystems and especially rivers and streams, in both morphology and water chemistry, thereby causing the 'dark side of subsidies' via the cross-boundary transfer of micropollutants and heavy metals (Kraus 2019). Healthy freshwaters clearly sustain the positive side of cross-boundary resource fluxes to adjacent terrestrial systems as an ecosystem service. The extent to which human activities impact aquatic resource subsidies, in terms of both quantity and quality, remains unknown. Some 25% of Swiss running waterways are in a poor eco-morphological state. Specifically, over 100,000 artificial barriers blocking sediment movement occur on Swiss rivers, critically degrading streambed conditions for biota (FOEN 2018), and river shoreline length has been substantially reduced by straightening and shoreline fortifications. Emerging aquatic insect and insectivore bird abundance are positively correlated with shoreline length (Iwata *et al.* 2003), meaning that less natural river networks with a shorter shoreline may be associated with reduced PUFA transfer. By modifying both rivers and adjacent riparian zones, human activities and infrastructures clearly influence the distribution and amount of cross-boundary resource exchange and flux (Laeser *et al.* 2005; Paetzold *et al.* 2011).

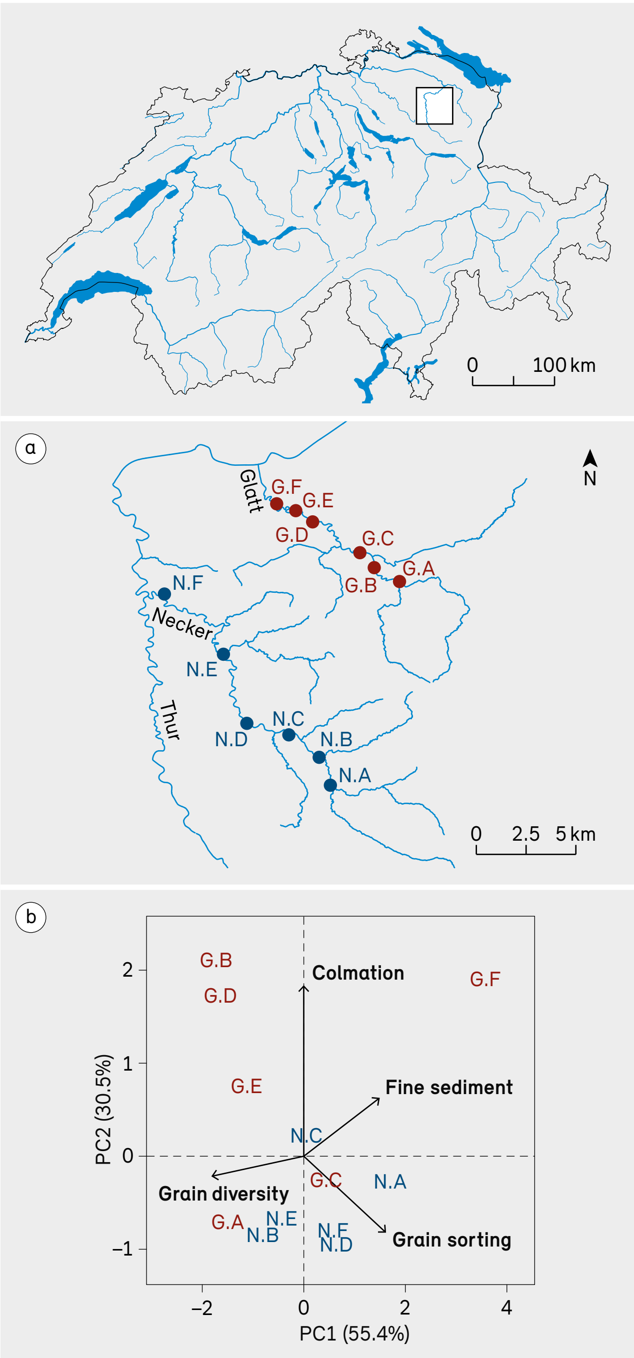
Despite the important ecological role of cross-boundary resource subsidies within the context of multi-dimensional riverscapes, they have been largely neglected in practical management. In future projects, restoration measures should therefore account for the lateral connectivity along rivers to incorporate cross-boundary resource fluxes.

3.2 Aquatic-terrestrial resource subsidy data from Switzerland

Here we present results about resource subsidies from aquatic to terrestrial systems along two contrasting rivers in Canton St Gallen (Fig. 14a). The Necker river (N) is a mostly unregulated river with a natural flow and sediment regime, whereas the adjacent Glatt river (G) is highly regulated, with multiple barriers that alter the flow and sediment regime. Land use also differs between the two catchments, with the Glatt having poorer water quality (higher nitrogen and phosphorus levels) than the Necker. We selected six sites along each river to assess aquatic resource subsidies to adjacent terrestrial ecosystems. We focused on emergent aquatic insects and the export of aquatic-derived PUFAs to two riparian predators (ground-dwelling and web-building spiders). Ground-dwelling spiders (ground spiders) are roaming predators in riparian areas, whereas web-building spiders (web spiders) are stationary predators, catching prey in their webs. Here, we address various aspects of resource subsidies along the two rivers.

Figure 14

(a) Map of sampling sites along the rivers Glatt (G) and Necker (N). (b) Principal component analysis (PCA) plot showing the difference in habitat properties between the two rivers. The axes represent dimensions 1 and 2 of the PCA, and the percentage of variance explained by each dimension is given. Sediment variables of colmation, grain (size) diversity, fine sediment (amount) and grain (size) sorting are represented as arrows.



Source: Eawag

3.2.1 How does regulation influence environmental gradients along river networks?

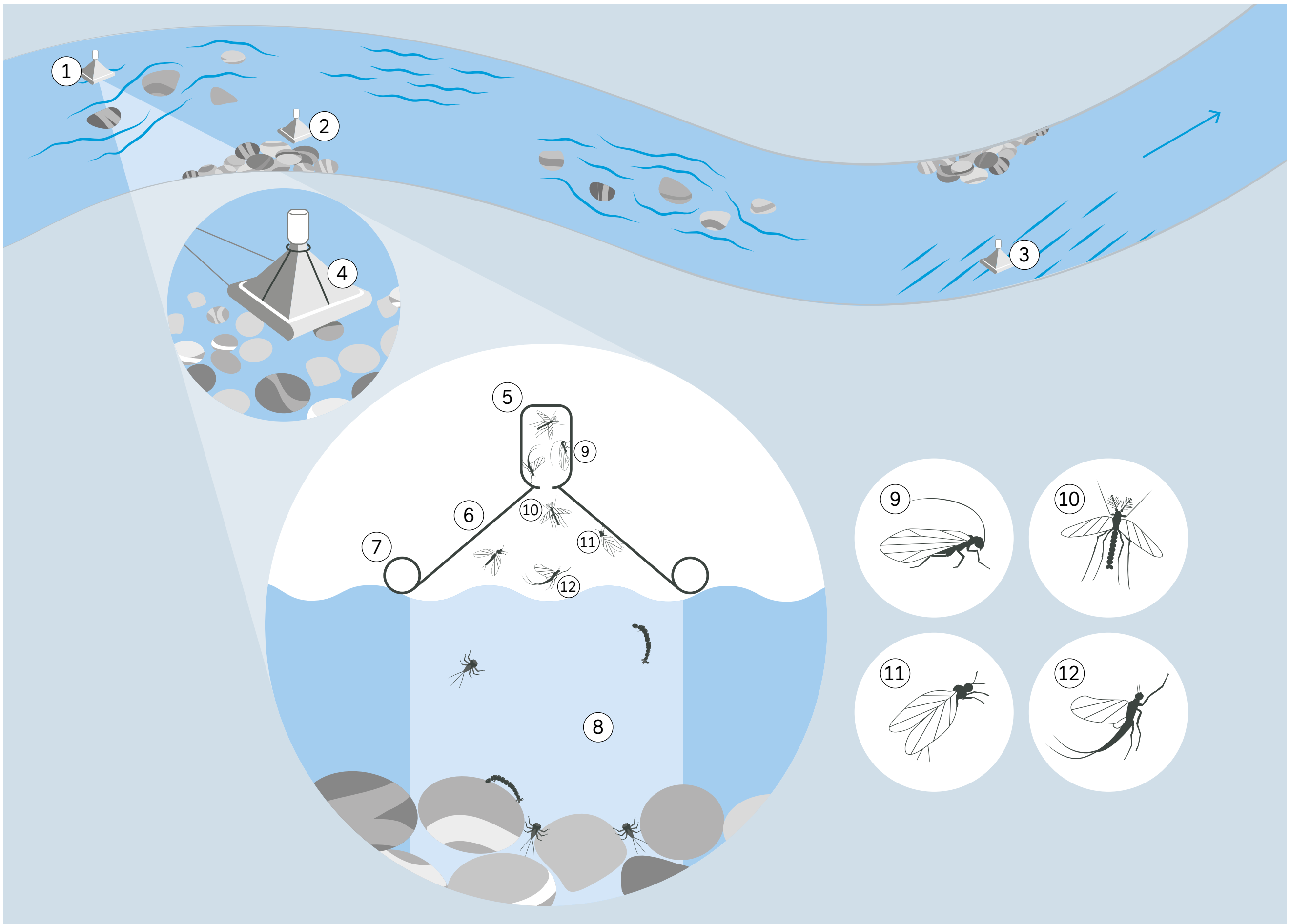
We evaluated various sediment characteristics, such as grain size distribution and internal colmation (see Chapter 7; Dubuis *et al.* 2023). We observed an increase in fine sediment and colmation at sites below structures (barriers) blocking bed movement. Along the Glatt river, the most upstream site (G.A) still had a natural sediment signature, but this changed rapidly downstream of the first structure (G.B). This change in habitat properties is shown in a principal component analysis (PCA) plot (Fig. 14b), where sites that are depicted close to each other have similar bed characteristics and arrows represent different reasons for a separation. G.A clusters with the more natural sites of the Necker river because it has less fine material, while G.B and the other Glatt sites are farther away because it has a higher degree of colmation.

3.2.2 How does stream degradation influence aquatic subsidies?

Flow regulation often causes habitat degradation in rivers, which typically translates to changes in the communities and abundances of macroinvertebrates in regulated waters relative to free-flowing watercourses. Consequently, the quality and quantity of resource subsidies transferred to adjacent riparian areas also differ. We compared insect biomass export along a bed degradation gradient in the Glatt and Necker rivers, using colmation as a proxy for bed degradation (see Fig. 15 for methods and Fig. 16 for results). No general decline in biomass export was observed with increasing colmation, but there was a change in community composition, with fewer emerging stoneflies in the Glatt than in the Necker river. While a peak in stonefly emergence in autumn, consisting of rather common stonefly species (*Leuctra* spp.), was visible to some extent at most sites along the Glatt river, the important peak in stonefly emergence in early spring was essentially missing along the Glatt river, with a low level of emergence occurring only at sites G.A and G.C (Fig. 16a). This early spring peak consisted of stonefly families that are more sensitive to environmental disturbances, such as an increased fine sediment load (Extence *et al.* 2013). This lack of stoneflies can have a large impact, as stoneflies express a different emergence behaviour than other aquatic insects, such as mayflies and caddisflies, which emerge in flight directly from the water column (Fig. 16b). In contrast, stoneflies crawl to shore before they emerge (Fig. 16c), thus representing an important cross-boundary pathway to ground-dwelling predators that is lost in streams without stoneflies (Fig. 17).

Figure 15

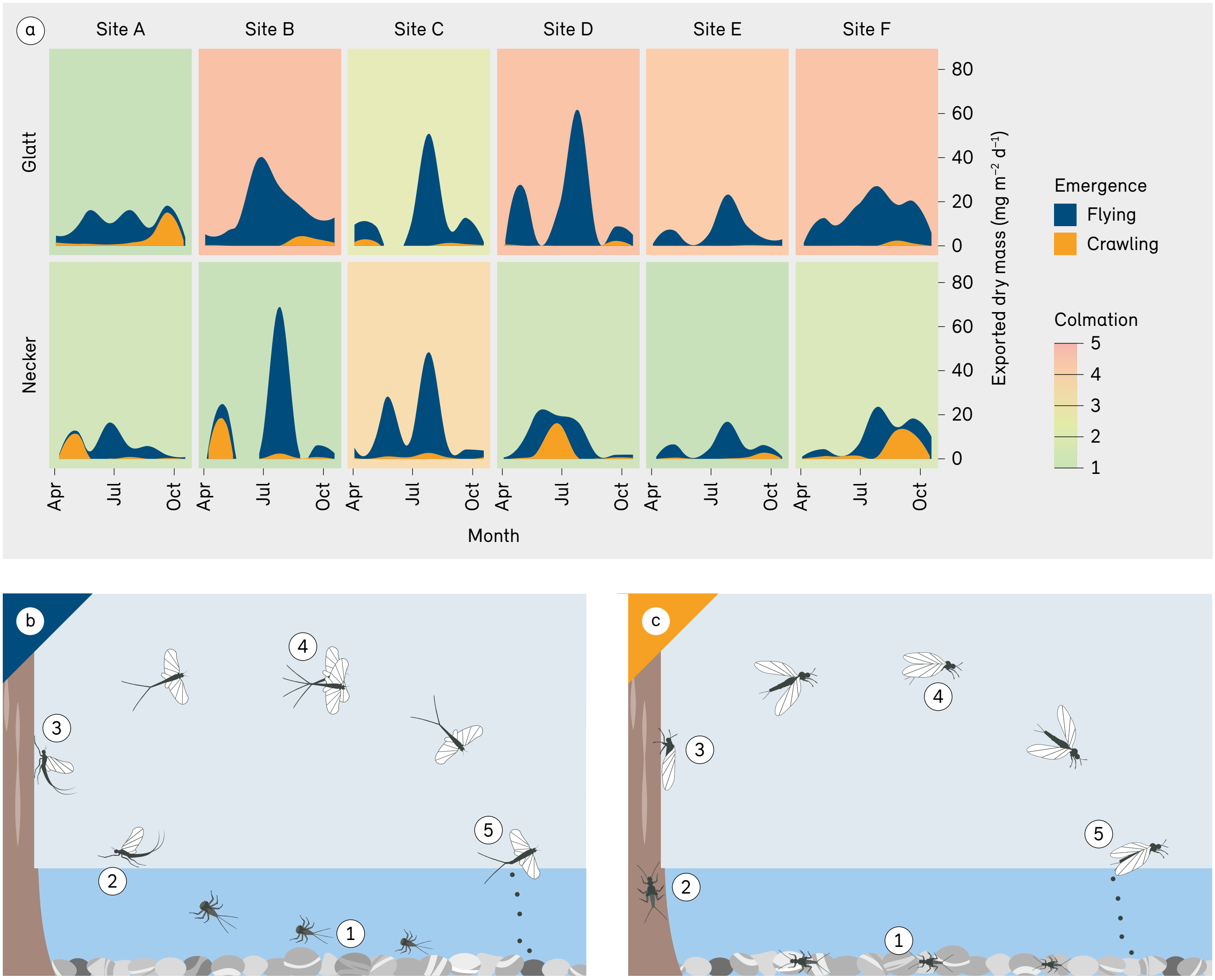
Method for estimating biomass export in the form of emergent aquatic insects. Three floating emergence traps were used per river reach (surface area 0.25 m²) to cover different habitat types: (1) riffle, (2) edge and (3) pool. (4) Emergence traps, consisting of (5) bottle for insect collection, (6) net cover (mesh size 100 µm), (7) styrofoam floaters, (8) area where emerging insects are collected. Collected insects (9) Trichoptera (caddisflies), (10) Diptera (midges), (11) Plecoptera (stoneflies), (12) Ephemeroptera (mayflies).



Source: Eawag

Figure 16

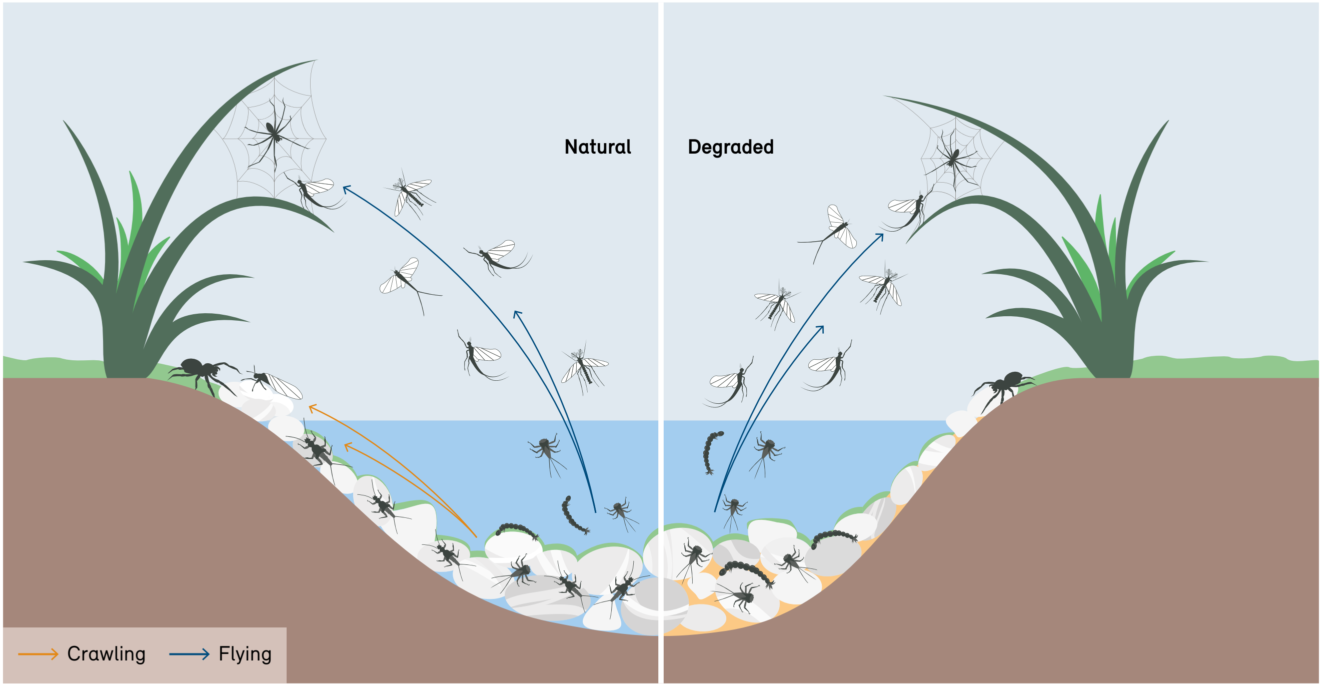
(a) Estimation of biomass export in the form of emergent crawling (e.g. stonefly) and flying (e.g. caddisfly, mayfly) aquatic insects along the Glatt river (top row) and the Necker river (bottom row). The sites (A–F) correspond to those shown on the map in Figure 14. (b and c) Illustration of the different emergence modes: (b) flying versus (c) crawling.



Source: (b) adapted from *http://www.delawareriverguide.net/insects/mayflycyc.html; (c) adapted from http://www.delawareriverguide.net/insects/stoneflycyc.html*

Figure 17

A potential consequence of stream degradation for the cross-ecosystem transfer of resource subsidies from aquatic ecosystems to riparian landscapes. The loss of stoneflies in degraded streams results in the loss of a resource pathway (yellow linkage) to adjacent riparian systems.



Source: Eawag

3.2.3 Do emergent insects transfer PUFAs and is there a difference between systems?

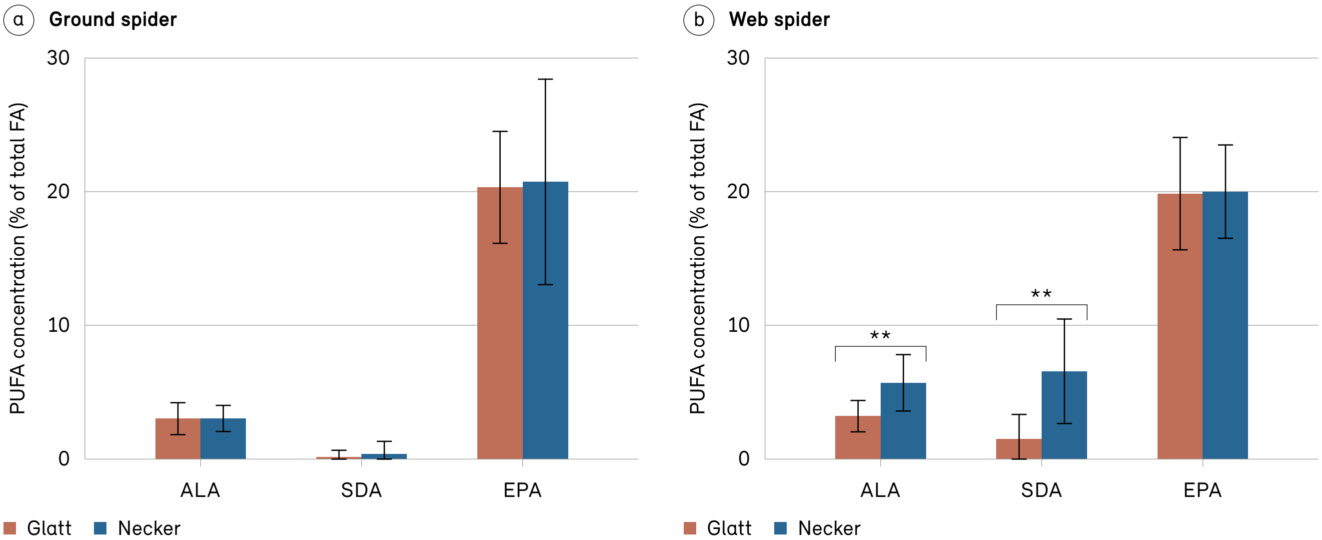
EPA and other PUFAs (i.e. ALA + SDA) predominantly found in aquatic environments were present in considerable concentrations in emergent insects (EPA: 15–25% of total fatty acids) and in riparian spiders along both the Glatt and the Necker river (Fig. 18). Web spiders and ground spiders had a similar ALA concentration (~4% of total fatty acids), and both had a very high EPA concentration (~15%) relative to other terrestrial organisms. SDA was higher in web spiders (1.4%) than in ground spiders (0.3%), indicating that predator type played a role in resource transfer.

We compared PUFA concentrations in riparian spiders between the two systems in spring. In ground spiders, we detected no significant differences. Web spiders, on the other hand, contained more SDA and ALA along the Necker river than along the Glatt river, although there was no significant difference in EPA concentration (Fig. 18). We also measured PUFA concentrations in emergent insects and periphyton scraped from rock surfaces and found similar patterns, especially for SDA. It appears that the difference between the systems already occurred at the base of the food chain, potentially because of different environmental conditions. We conclude that SDA production and transfer in particular were very limited along the Glatt river, while the nutritionally important EPA was transferred in comparable quantities.

A closer look at the EPA concentration in riparian spiders reveals some interesting patterns. First, the EPA concentration of riparian spiders was dependent on the distance from shore. At site N.F, where spiders were sampled at different distances from the shore, EPA concentration declined with increasing distance from the shore, with values already lower around 40–50 m from the channel, especially in ground spiders (Fig. 19a). Although differences were not significant due to relatively small sampling size, this pattern is in line with previous findings (Chari *et al.* 2020) and demonstrates that access to aquatic insects is important for EPA transfer and accumulation. Second, looking at seasonal changes, the EPA concentration in both spider types was highest in spring (Fig. 19b). This finding suggests that emergent aquatic insects are especially important for PUFA transfer into riparian zones in spring.

Figure 18

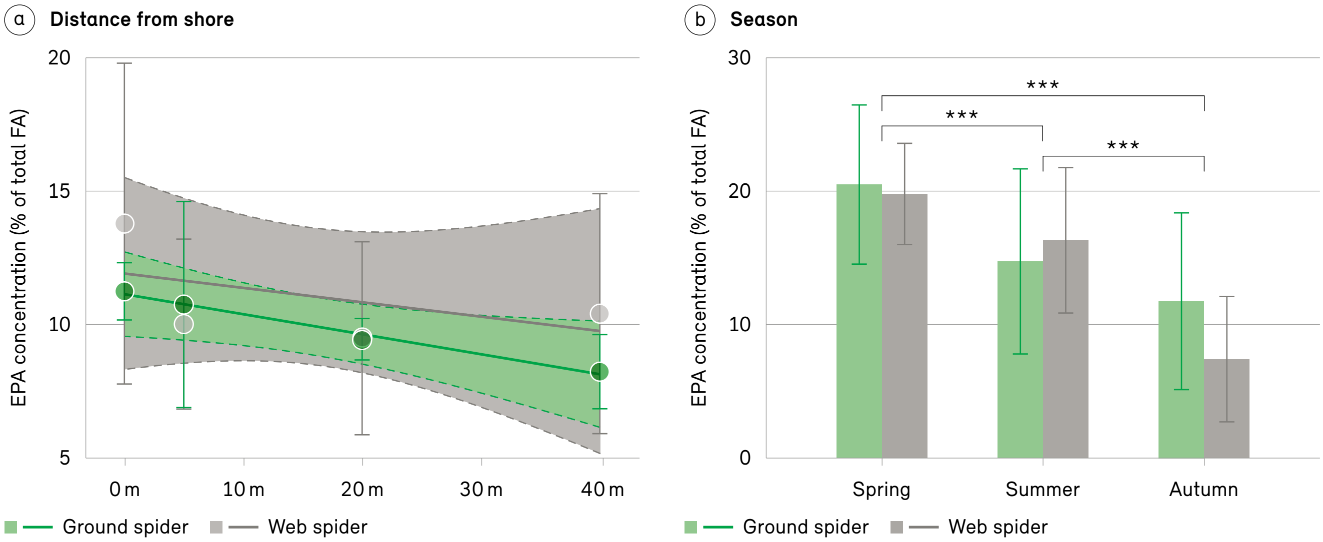
Mean (± SD) polyunsaturated fatty acid (PUFA: ALA, SDA and EPA; see Table 2) concentration, expressed as a percentage of the total fatty acid (FA) concentration in (a) riparian ground spiders and (b) web spiders in the Glatt and Necker rivers. Asterisks represent significant differences between the two river systems at p <0.01.



Source: Eawag

Figure 19

*(a) Mean (± SD) EPA concentration in riparian ground and web spiders (site N.F) at different distances from the river shore. The shaded areas represent 95% confidence intervals. (b) Seasonal differences in mean (± SD) EPA concentration in the two spider types, showing the importance of spring emergence. Asterisks represent significant differences between seasons (*** p <0.001).*

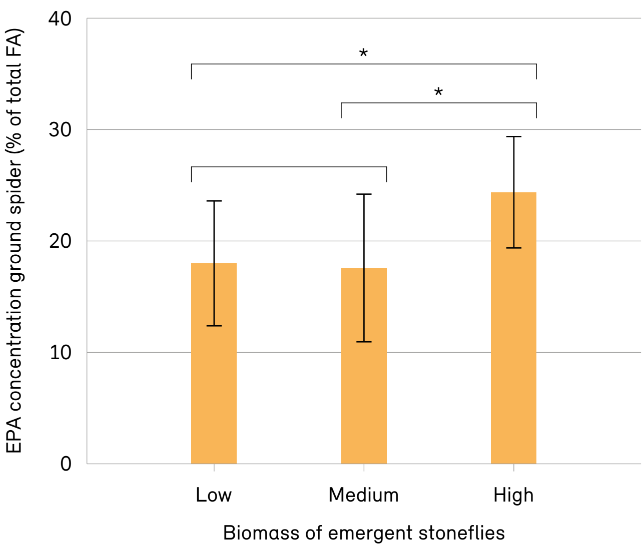


Source: Eawag

We found no significant difference in the total EPA export/transfer between the natural Necker river and the more degraded Glatt river. However, the difference in macroinvertebrate composition between streams, with reduced stonefly emergence in the Glatt (see Section 3.2.2), altered EPA availability for different kinds of riparian predators. While web spiders were largely unaffected, the EPA concentration in riparian ground spiders was lower in degraded sites with reduced stonefly emergence in spring (Fig. 20). As mentioned above, stoneflies have a specific 'emergence mode' involving crawling to shore. This behaviour makes them easy prey for ground-dwelling predators, while other insects that emerge by flight are much harder to catch. As the EPA concentration in ground spiders is linked with immune function (Fritz *et al.* 2017), less access to EPA, in this case resulting from reduced stonefly emergence, may have negative consequences on predator survival. Importantly, stonefly decline is a general problem in degraded streams; it weakens aquatic-terrestrial linkages, not only for riparian spiders but potentially also for other ground-dwelling riparian predators, such as lizards and beetles.

Figure 20

EPA concentration of riparian ground spiders in spring in relation to emergent stonefly biomass. Categories of stonefly biomass: low = dry mass <0.25 mg m^{-2} day^{-1}, medium ≤1 mg m^{-2} day^{-1}, high = dry mass >1 mg m^{-2} day^{-1}. Asterisks represent significant differences at $p < 0.05$.



Source: Eawag

3.3 Management implications

We show that both emergent aquatic insects and riparian spiders contain considerable concentrations of EPA and are thus a central link that promotes EPA transfer into terrestrial systems. Waterbodies, which provide aquatic subsidies, and riparian zones, which form the main habitat of riparian spiders, need to be in good ecological condition to sustain healthy populations. In riparian zones in particular, web spider density depends on riparian vegetation such as shrubs and trees (Laeser *et al.* 2005), and the PUFA concentration in spiders is higher if a riparian buffer zone is present (Ramberg *et al.* 2020). Conservation of the riverine zone, including a healthy watercourse, is therefore crucial for the maintenance of cross-boundary resource fluxes.

Research on Cross-boundary linkages provides a chance to inform and engage different stakeholders in riparian management projects, as suggested by Muehlbauer *et al.* (2019). Discussions of restoration projects should take a more holistic perspective, considering terrestrial and aquatic ecosystems in combination. For example, a bird conservation project might have low value if nearby waterbodies are in poor condition and cannot provide needed aquatic resource subsidies such as PUFAs. In this case, PUFA export should be considered a crucial ecosystem service. In this context, it is especially important to stop the general decline in stoneflies, which form a distinct export pathway easily accessible to ground-dwelling riparian predators. Stoneflies cannot live in streams with a poor ecological state, and thus this pathway and resource flux across ecosystem boundaries is lost in degraded riverscapes.

Box 6: In practice – Fostering key connections between a watercourse and its surrounding terrestrial area

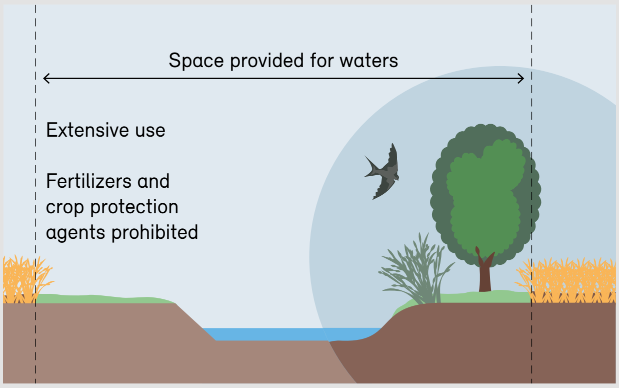
Vinzenz Maurer, Office for Water and Waste, Aquatic Ecology, BE

The Swiss Cantons and municipalities are currently defining the 'space provided for waters' in their spatial planning framework (Fig. 21). In this context, the space required for flood protection and for the protection of water bodies and aquatic organisms from agricultural pollution are important topics. However, most discussions revolve around the loss of usable agricultural land. The benefit that a near-natural shoreline can provide for the adjacent agricultural land is, in contrast, rarely discussed. Near-natural and heterogeneous banks harbour a diverse community of algae, aquatic plants and animals, which, as the presented study nicely demonstrates, produce important substances that are distributed far beyond the watercourses via emerging insects. This benefits not only the spiders studied here but also many other organisms, which in turn hunt for 'pests' in agricultural areas, thus benefitting humans.

We should seize the opportunity presented by this spatial planning definition and allow rivers to form diverse shorelines, create habitats for emerging insects, and grow richly structured shoreline vegetation with diverse habitats for spiders, birds and hedgehogs, which can benefit from aquatic insects as a food supply. Finally, we should appreciate the role that these organisms play in the natural pest control of crops.

Figure 21

An example of the 'space provided for waters', a widely used definition of the riverine zone by resource managers.



Source: AWA (2020)

4 Channel response to flood diversion into floodplains

Lateral diversion structures in rivers are common measures used to divert parts of the discharge during flood events. The lateral overflow reduces discharge and thus bedload transport capacity in the main channel, resulting in sediment deposition. In this chapter, interactions between lateral discharge and changes in bed level are discussed and illustrated using 1D and 2D modelling approaches, and recommendations for practical model applications are provided. Further, aspects of ecological flooding of retention areas are briefly discussed.

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4.1 Introduction

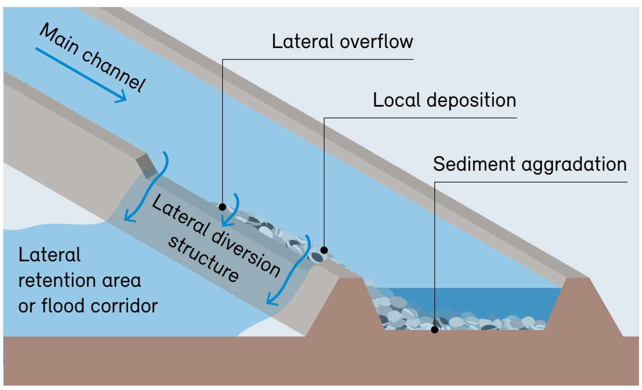
Lateral diversion structures in rivers, such as side weirs (lateral weirs) and overflow embankments, are common measures used to divert part of the discharge into a lateral retention area or into a flood corridor during major flood events. In this way, the inundation risk for downstream areas can be reduced. While both regulated and unregulated lateral diversion structures exist, most of them are unregulated in Switzerland (Bühlmann and Boes 2014).

Lateral overflow occurs as soon as the water level reaches the dam or weir crest. The crest height has to be designed according to hydrological and flood protection goals, and in Switzerland the protection objective is based on a risk assessment and determined based on the damage potential of the flood-prone area (FOEN 2005). The design overflow discharge is therefore a project-specific value. Lateral diversion structures are used in flood protection, both as part of the design concept and for system safety during extreme events (overload scenario). Lateral overflow is typically considered upstream from areas with high vulnerability, such as clustered settlements and industrial facilities, provided that appropriate retention areas are available or flood corridors can be used to convey the lateral overflow. Lateral overflow leads to discharge reduction and thus lower bedload transport capacity in the main channel. Consequently, local deposition near the lateral diversion structure and sediment aggradation in the downstream channel may occur (Fig. 22). The bed level increase may enlarge the lateral overflow considerably compared with a situation without bedload.

As the duration of the flood increases, the aggradation continues to expand towards the downstream main channel. During the falling limb of the flood wave, erosion occurs again where local deposition and sediment aggradation had occurred. However, the interaction between lateral overflow and changes in bedload dynamics in the river must not be neglected in the design of lateral diversion structures. Design guidelines for lateral diversion structures that do not consider sediment aggradation can be found in Bühlmann and Boes (2014), Giesecke *et al.* (2014) and Jäggi *et al.* (2015). To account for the effect of bed level increase on lateral overflow, Rosier (2007) conducted several flume experiments at the Platform PL-LCH at EPFL.

Figure 22

Lateral diversion structure with local bedload deposition and sediment aggradation due to lateral overflow during a flood event. Figure adapted from Rosier (2007).



Source: VAW, ETH Zurich

Numerical models commonly used in hydraulic engineering and for flood risk assessment, i.e. 1D and 2D models based on shallow-water equations, can be used as tools for the design of lateral diversion structures considering bed level changes. The simulation software BASEMENT (Vetsch *et al.* 2020) has been applied to analyse the interaction between lateral overflow and changes in bed level, using findings from flume experiments (Rosier 2007) to validate the results. In this chapter model capabilities and requirements are shown and recommendations are provided.

Another aspect that is rather novel in Switzerland is the use of lateral overflow to improve ecological conditions in retention areas in what has been termed 'ecological flooding' (see Box 7). In such a system, water is diverted into the retention areas not only during major but also during minor flood events. This may support the formation of dynamic floodplain biotopes. In Germany, ecological flooding has been successfully employed, for example at the Altenheim polder along the Rhine river, which has existed since 1987 (Pfarr *et al.* 2014).

4.2 Estimation of lateral overflow

4.2.1 Common approaches

Classical weir equations for discharge estimation assume that the flow approaches the weir perpendicular to the weir axis. In contrast, the flow approaches lateral diversion structures at an angle of <90°. Figure 23 shows the top and side views of a lateral diversion structure in a channel with subcritical flow conditions where the flow is diverted towards a lateral retention area or a flood corridor. All variables described below are depicted in Figure 23.

The water depth along the lateral diversion structure is increasing for subcritical (flow velocity < wave speed; Fig. 23b) and decreasing for supercritical (flow velocity > wave speed) conditions. Therefore, the lateral unit overflow for supercritical flow is distinctly smaller than for subcritical flow and almost impossible to predict (Jäggi *et al.* 2015). Lateral diversion structures are not recommended for supercritical flow (Hager 2010) and thus should only be considered in subcritical river reaches with an upstream Froude number $Fr_o = v_o/(g \cdot A/B_w)^{0.5}$ <0.75 (Hager 2010; Giesecke *et al.* 2014), where $v_o = Q_o/A$ = velocity of the approaching flow averaged over the cross-section, Q_o = upstream discharge, A = cross-sectional flow area, g = acceleration of gravity, and B_w = top width of the water surface. Several approaches for estimating the lateral overflow Q_D are available in the literature, and they are commonly based on the assumption of no energy loss over the lateral diversion structure.

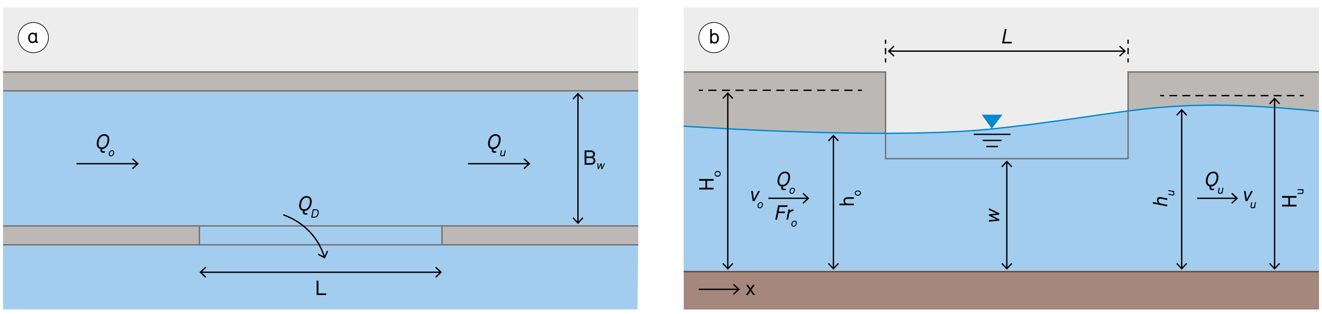
For the calculation of lateral overflow in a rectangular, horizontal channel with a lateral sharp crested weir, De Marchi (1934) proposed the equation:

$$\frac{dQ_D}{dx} = \frac{2}{3} \cdot C_M \cdot \sqrt{2g} \cdot (h_W - w)^{2/3} \qquad (1)$$

$\frac{dQ_D}{dx}$ rate of change in discharge along the lateral diversion structure [m³ (m⁻¹ s⁻¹)]

Figure 23

(a) Top view and (b) side view of a lateral diversion structure, showing the water profile under subcritical channel flow conditions. All variables are defined in the main text. Figure adapted from Bollrich 2013.



Source: VAW, ETH Zurich

C_M side weir discharge coefficient [-]

Q_D lateral overflow [$m^3 s^{-1}$]

$h_W = h_W(x)$ water depth along the lateral diversion structure [m]

w lateral diversion structure crest height [m]

g acceleration of gravity [$m s^{-2}$]

De Marchi's approach is based on the solution to a 1D dynamic equation for gradually varied flow with non-uniform discharge and non-constant water depth $h_W(x)$ along the structure (Di Bacco and Scorzini 2019). For lateral sharp-crested weirs in rectangular and trapezoidal channels under subcritical conditions, the discharge coefficient C_M can be determined according to the simplified approach of Hager (1987) (Eq. 2). There is little literature on side weir discharge coefficients for broad-crested (e.g. Ranga Raju 1979), round-crested (e.g. Izadinia and Heidarpour 2016) or roof-shaped lateral diversion structures. The side weir discharge coefficient strongly influences the calculated lateral overflow. Here, the De Marchi approach with C_M defined by Hager (1987) is used:

$$C_M = 0.728\sqrt{\frac{2+Fr_o^2}{2+3Fr_o^2}} \quad (2)$$

For many situations, the upstream discharge Q_o, the downstream discharge Q_u, and the flow conditions in the downstream channel (downstream velocity v_u, water depth h_u, hydraulic head H_u and channel width B) can be defined. Assuming no energy loss along the lateral diversion structure, the upstream flow conditions (upstream velocity v_o, water depth h_o and hydraulic head H_o) can be calculated using the Bernoulli equation. Di Bacco and Scorzini (2019) proposed the following equation to calculate the necessary length of the lateral diversion structure L to reduce Q_o to Q_u:

$$L = \frac{3B}{2C_M} \cdot (\Phi_u - \Phi_o) \quad (3)$$

where $\Phi_i = \frac{2H_i-3w}{H_i-w} \cdot \sqrt{\frac{H_i-h_i}{h_i-w}} - 3 \cdot arcsin\left(\frac{H_i-h_i}{h_i-w}\right)$ and $i = o,u$

4.2.2 Impact of morphodynamics

Lateral overflow during a flood event reduces the bedload transport capacity in the main channel. Thus, local deposition near the lateral diversion structure and sediment aggradation in the main channel downstream of the lateral diversion structure may occur (Fig. 22). The local deposition starts at the beginning of the lateral diversion structure (weir) and reaches its maximum height at the downstream end of the weir. The lateral overflow might increase by a factor of up to three due to the sediment aggradation (Rosier 2007).

Rosier (2007) presented an empirical and iterative way to estimate the local deposition due to a lateral diversion structure based on physical experiments (see also Rosier *et al.* 2008). The iterative estimation is cumbersome and requires the setup of a numerical model and hydrodynamic simulation for each iteration step. However, a detailed estimation of the sediment aggradation and lateral overflow using numerical model simulations, including bedload transport, is recommended for designing lateral diversion structures and is presented here.

4.3 Numerical Modelling of lateral diversion structures

4.3.1 Modelling approaches

To assess the impact of sediment aggradation dynamics on lateral overflow, different numerical modelling approaches were evaluated using the software BASEMENT version 2.8.2, a freeware for simulating river hydro- and morphodynamics (*www.basement.ethz.ch*) developed at the at the VAW of ETH Zurich. Several hydrodynamic (fixed bed, no bedload transport) and morphodynamic simulations were run considering the different modelling approaches, and results were compared with observed experimental data from Rosier (2007). Specifically, trapezoidal and rectangular channels with lateral diversion structures were simulated. Four different numerical modelling approaches were tested, three of which were selected (Fig. 24):

(a) **1D:** The lateral overflow due to a lateral diversion structure is implemented in a 1D BASEMENT model considering the reduction of water with specific sink terms

(Eq. 1) at each cross section along the lateral diversion structure. Specific C_M values must be defined for the specific sink terms. The loss of streamwise momentum due to lateral overflow is considered in BASEMENT.

(b) **1D–2D coupled**: The laterally coupled model in BASEMENT includes a 1D channel and a 2D floodplain. Lateral overflow is computed using Eq. 1, and a specific C_M value must be defined. The reduction of streamwise momentum due to lateral overflow is considered in BASEMENT.

(c) **2D**: The geometry of the lateral diversion structure and the topography of the surrounding overflow section is modelled. C_M does not have to be specified for this simulation.

Examples of these approaches are provided on the BASEMENT website (*www.basement.ethz.ch* > Download > Test cases).

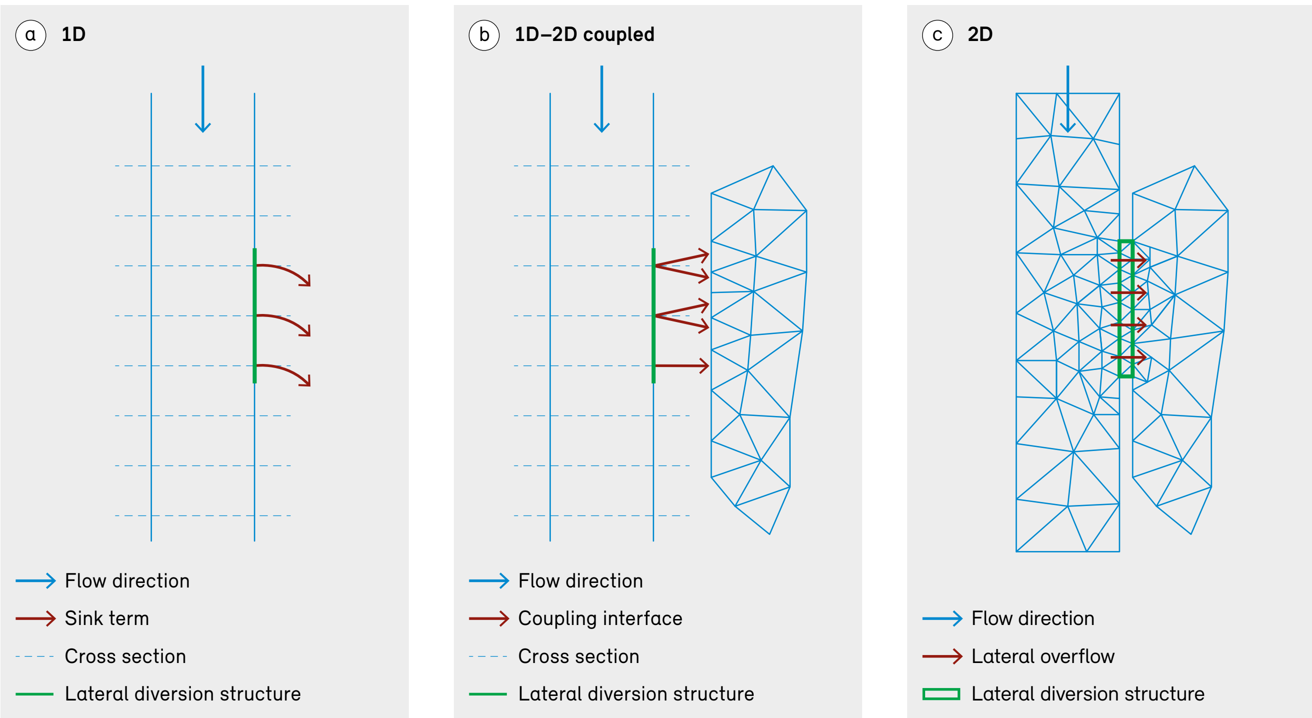
4.3.2 Comparison of different modelling approaches

1D or 1D–2D coupled models are most suitable for straight river reaches. Usually, these models require less topography data and have a short computing time. Neither of these model types shows the flow deviation in the main channel and the floodplain. The 1D–2D coupled model approach may be favourable when the flow field in the floodplain is of importance. Regarding the lateral overflow, the side weir discharge coefficient is the most sensitive parameter and a corresponding sensitivity analysis is recommended. Good results for rectangular channels with a sharp-crested weir and for trapezoidal channels with a roof-shaped weir can be achieved using the side weir discharge coefficient from Hager (1987) (Eq. 2). In Table 3, the 1D and 1D–2D coupled simulations are compared with the 2D simulation, where no C_M value is needed, and with the physical experiment conducted by Rosier (2007).

For the 2D model, the topography must be provided and the roughness at the weir crest has to be specified. However, the lateral overflow is less sensitive to roughness

Figure 24

(a) 1D, (b) 1D–2D coupled, and (c) 2D approaches used in the software BASEMENT to model lateral overflow at a lateral diversion structure.



Source: VAW, ETH Zurich

than the 1D or 1D–2D coupled model is to the side weir discharge coefficient. The 2D model gives the flow deviation in the main channel and floodplain.

4.3.3 Impact of morphodynamics

For the design of lateral diversion structures in rivers with distinct bedload transport, morphodynamic simulations are recommended. The sediment aggradation downstream of the lateral diversion structure and the resulting higher lateral overflow can be simulated with all three modelling approaches. However, the spatial extent of the local deposition near the lateral diversion structure cannot be captured with a 1D model. The lateral overflow, sediment aggradation, and geometry and location of the local deposition calculated in the morphodynamic 2D model (Fig. 25) are in good agreement with the physical experiments conducted by Rosier (2007).

Table 3 compares the lateral overflow for the hydro- and morphodynamic simulations, as well as the physical experiment conducted by Rosier (2007). The lateral overflow is significantly greater in the morphodynamic simulations where bedload deposition is considered. In the purely hydrodynamic model, the lateral overflow might be underestimated and the retention area or flood corridor might be designed with insufficient capacity.

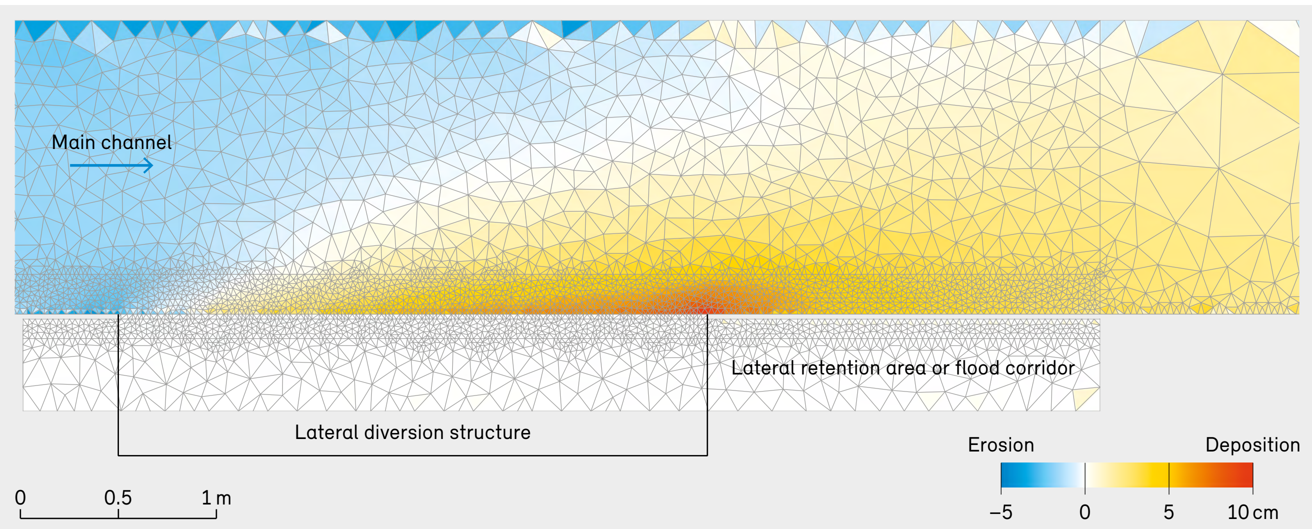
Table 3

Comparison of the lateral overflow (Q_D in [l s^{-1}]) between the hydrodynamic and morphodynamic simulations and the physical experiment B02 by Rosier (2007). The rectangular flume has the following dimensions: width = 1.5 m, bottom slope = 0.2%, length of lateral diversion structure L = 3 m, weir height w = 10 cm, constant discharge Q_o = 181 l s^{-1}.

	Hydrodynamic	Morphodynamic	Morphodynamic (with riprap)
Physical experiment by Rosier (2007)	–	52	–
1D model (C_M=0.6 for all 11 sink terms)	33	48	43
1D–2D coupled model (C_M=0.6)	33	47	43
2D model	32	42	40

Figure 25

Local deposition along the lateral diversion structure and sediment aggradation in the main downstream channel (2D model from the B02 experiment from Rosier (2007), lateral diversion structure L = 3 m).



Source: VAW, ETH Zurich.

The water surface elevation and the bed elevation for the hydrodynamic simulation and for the morphodynamic simulations with and without riprap are shown in Figure 26 for the 1D modelling approach. The same results are obtained with the 1D–2D and 2D modelling approaches. A significant amount of sediment can be deposited downstream of the lateral diversion structure and consequently reduce the cross-sectional area (Fig. 26b). There is less water in the channel downstream of the lateral diversion structure, so no rise in water level occurs (Fig. 26). Due to the drawdown curve upstream of the lateral diversion structure (Fig. 26a), stabilization of the bed with riprap is recommended (Tab. 3 and Fig. 26c). The sediment aggradation and local deposition become larger as the length of the lateral diversion structure increases.

Lateral overflow responds rapidly to discharge changes, unlike local deposition and aggradation. The analysis with a short flood hydrograph shows less aggradation, less local deposition and less lateral overflow compared with a simulation with a long flood hydrograph. During the falling limb of the flood hydrograph, the local deposition and the sediment aggradation are completely eroded again and the bed level prior to flooding is restored.

4.3.4 Effect of spatial discretization

The main channel in 1D or 1D–2D coupled models is discretized using cross sections. The water depth, velocity and lateral overflow can be simulated with three to four cross sections along the lateral diversion structure for hydrodynamic simulations. Multiple cross sections (up to 10) along the lateral diversion structure lead to smoother morphodynamic simulation results.

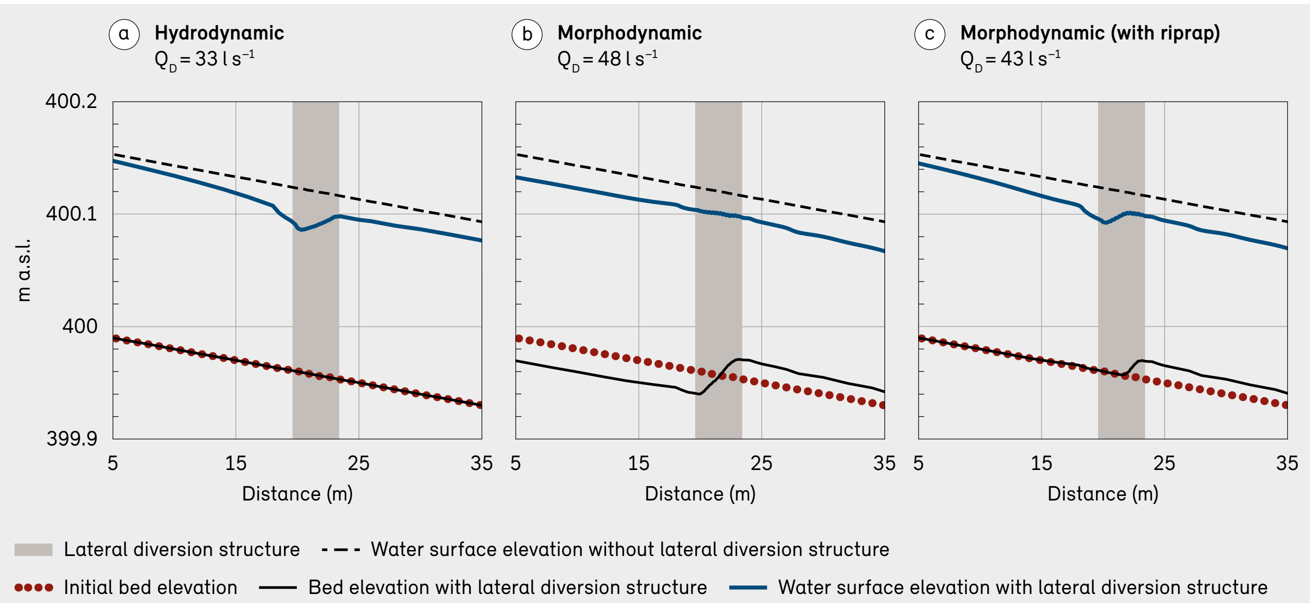
In 2D models, the system is spatially discretized into mesh cells (Figs 24c, 25). Small mesh cells at the lateral diversion structure are necessary to capture the local deposition in morphodynamic simulations. As a rule of thumb, the mesh cells close to the lateral diversion structure should be smaller than *B/20* to capture the local deposition. In hydrodynamic simulations and up- and downstream of the lateral diversion structure, larger mesh cells may be reasonable.

4.4 Recommendations for practical applications

Empirical approaches (e.g. Eq. 1) can be used to roughly estimate lateral overflow, but they are limited to steady flow analysis and do not consider bed level changes in the

Figure 26

Bed elevation and water surface elevation for the 1D modelling approach, for (a) hydrodynamic, (b) morphodynamic, and (c) morphodynamic (with riprap) simulations. The settings of the simulations are described in Table 3.



Source: VAW, ETH Zurich

Table 4

Advantages (green) and disadvantages (orange to red) of the three modelling approaches for the simulation of lateral flow diversion.

	1D	**1D–2D coupled**	**2D**
Lateral overflow model	Sink, using Eq. 1	Model coupling, using Eq. 1	Topography of the overflow section
Parameter for lateral overflow	For each cross section with lateral overflow: *Weir crest height* *Weir crest length* C_M	*Weir crest height* C_M	*Roughness* for weir crest
Hydrodynamic results			
Lateral overflow prediction	Good	Good	Good
Flow in channel	No flow diversion[1]	No flow diversion[1]	Flow diversion
Flow in floodplain	No floodplain	Approximate flow field (90° at inflow boundary)	2D flow field
Morphodynamic results			
Lateral overflow prediction due to deposition	Good	Good	Good
Deposition	Sediment aggradation down-stream good, but no transversal distinction of local deposition	Sediment aggradation down-stream good, but no transversal distinction of local deposition	Good
Relative computing time	Short	Medium	Long

1 The flow in the main channel is not angled at the lateral diversion structure.

main channel. In general, the presented numerical models facilitate transient hydrodynamic simulations of flood events, accounting for discharge reduction due to lateral overflow over the diversion structure. All of the presented model types (1D, 1D–2D coupled and 2D) show the sediment aggradation downstream of the lateral diversion structure, which may increase lateral overflow and thus the required capacity of the retention area or the flood corridor. The side weir discharge coefficient C_M in the 1D and 1D–2D coupled modelling approaches is subject to uncertainty, and good results can be achieved using the simplified approach proposed by Hager (1987). In a 2D model, the coefficient C_M becomes obsolete and the flow in the floodplain or retention area can be simulated in addition to the channel flow. Only 2D models capture local deposition, making them the most suitable option for simulating bed level changes near the diversion structure.

The advantages (green) and disadvantages (red) of the three modelling approaches for simulating lateral diversion structures are listed in Table 4. We recommend designing lateral diversion structures using morphodynamic models. The choice of modelling approach to simulate the lateral overflow, i.e. 1D, 1D–2D coupled or 2D, depends on the model requirements, data availability and objectives.

Box 7: In practice – Ecological flooding of retention areas

Eva Gerke, VAW, ETH Zurich

The goal of ecological flooding is to establish stable, self-sustaining and flood-tolerant populations, i.e. to accustom the flora and fauna to regular flooding (Meurer and Pfarr 2018). In contrast, infrequent flooding with a return period of 30 years or more is not sufficient for the dynamic development of biodiversity in floodplains in retention areas.

A prerequisite for effective ecological flooding is the diversion of water into the retention area at low discharge. This requires a controllable inlet structure, which can be arranged separately from the diversion structure used for flood protection. Free flow of water through the retention area is needed, and stagnant water zones with oxygen depletion should be avoided. Additionally, high flow dynamics are beneficial for erosion and sedimentation processes typical of floodplains. Attention must also be paid to land use. In particular, original floodplains or separated floodplains are suitable. If the retention area is already used for agriculture, ecological flooding makes little sense. However, in the case of mixed use, part of the area can be considered for ecological flooding.

An example of the implementation of ecological flooding is the Altenheim flood retention area along the upper Rhine river in Baden-Württemberg (Germany). The frequency, duration and amount of discharge diverted during an ecological flooding event depend on the current runoff situation in the Rhine river. The status of the restoration of biotic communities in the floodplains is monitored using random samples. Overall, a trend towards both higher biodiversity and a visible dominance of more flood-tolerant species in the frequently flooded areas has been observed (Pfarr 2014).

5 Aquatic refugia during floods

Refugia are habitats where organisms retreat during a disturbance (e.g. flood, drought). Due to their reduced intensity of physico-chemical conditions, refugia allow organisms to withstand a disturbance. Despite their important ecological role, refugia are poorly studied and often neglected in practical management (e.g. river restoration). Through descriptions of field and laboratory experiments, this chapter illustrates the structure and function of flood refugia and emphasizes the role of the sediment regime in refuge provision.

Cristina Rachelly, Kate Mathers, Volker Weitbrecht, David Vetsch and Christine Weber

Natural river systems are biodiversity hotspots, providing habitat for a huge range of plants, animals, fungi and microorganisms. A habitat is defined as a place where organisms find acceptable conditions to live. During their life cycle and depending on the time of year, many species require different habitats for feeding, reproducing and resting. Natural river systems provide a diverse mosaic of habitats subject to continuous changes in space and time. The habitat mosaic in a specific river is strongly dependent on its morphology, which is in turn formed by fluvial processes, interactions with plants and animals, and catchment geology (Castro and Thorne 2019).

5.1 What do we mean by refugia?

Refugia are a special type of habitat. They provide space for organisms to survive during harsh conditions (disturbances), such as floods and droughts. During disturbances, biotic and abiotic processes in residential habitats can reach exceptional intensities that cannot be withstood by specific species, which might be displaced, injured or killed. To avoid these risks, organisms have developed diverse strategies. Mobile organisms can change their location and find a refuge in order to survive the disturbance. After the disturbance, organisms can return to their residential habitats or colonize newly created habitats, thus maintaining the species pool (Van Looy *et al.* 2019). Refugia have two main functions: (i) they allow organisms to withstand a disturbance (resistance) and (ii) they allow organisms to recover from a disturbance (resilience).

Figure 27 shows schematically the dynamics within three habitats during a flood. Habitat *a* represents the main channel, where disturbance intensity (flow velocity, flow depth, shear stress or sediment transport) is high and closely follows the flood hydrograph. Several species from habitat *a*, which under baseflow conditions is a residential habitat, need to find zones with significantly reduced disturbance intensity (habitat *b*) during a flood event, such as backwaters and undercut banks (Fig. 28f, j). More vulnerable species find refuge in habitat *c*, which experiences even lower disturbance intensities. In our example, habitat *c* represents a floodplain pond (Fig. 28c) that only forms during floods.

Figure 27

Intensity of a pulse disturbance such as a flood. Lines (a), (b) and (c) show disturbance intensities in different habitats of a river reach. Pulse disturbances arise suddenly, reach their maximum intensity within a short time, and generally last for hours or days. The intensity of any disturbance varies among habitats. Habitats with a lower disturbance intensity (b and c) provide refugia for species whose residential habitat has a higher disturbance intensity (a). Refugia are disturbance-specific, with some refugia forming only during a disturbance (c).

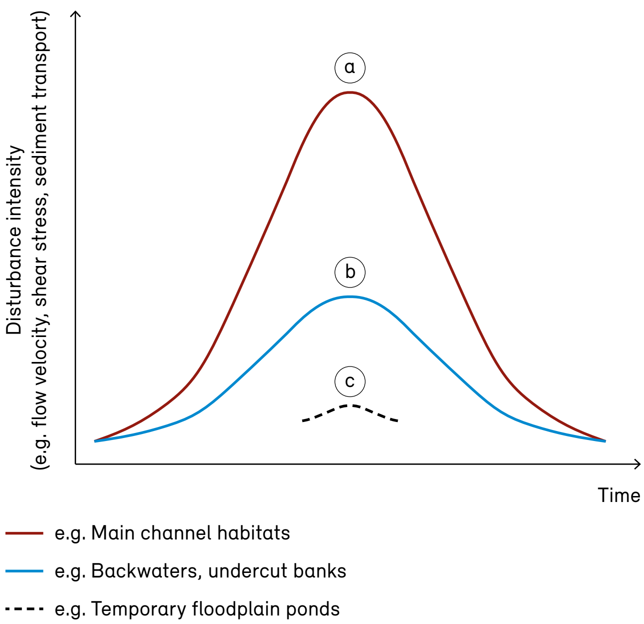


Figure adapted from Weber *et al.* (2013)

Figure 28

Morphological structures that can function as refugia in river systems. Source: VAW, ETH Zurich

Photo credits: (a) Federal Office of Topography 2014, (b) Federal Office of Topography 2013, (c) K. Mathers, (d) Federal Office of Topography 2014, (e) V. Weitbrecht, (f) M. Roggo, (g) I. Schalko, (h) M. Roggo, (i) M. Roggo, (j) M. Mende, (k) K. Mathers

5.2 Refuge functioning

Different factors define how a refuge functions, which species use it, and when and for how long it is used:

Characteristics of the organisms: Otter, trout, spider – riverine animals differ profoundly in their mobility and therefore their sensitivity to floods. Further, an individual's mobility can change over its lifetime. For mayflies such as *Baetis* sp., for example, an immobile phase during which eggs are cemented to the underside of rocks is followed by a more mobile larval phase, a second immobile phase as a submerged pupa, and then a final mobile phase as a flying adult. An individual's chance of surviving a disturbance in a refuge is further influenced by its state of health. Diseases, parasites or a weakened body condition, e.g. resulting from scarce food resources, can severely affect survival.

Characteristics of the flood: Floods come in different forms, from typical freshets after summer thunderstorms to rare mid-winter floods following sudden warming and snowmelt. For any organism, the timing of a flood matters, for instance because its activity level follows seasonal patterns (e.g. overwintering) or because different life stages occur at different times of the year (e.g. trout spawning in autumn). The higher the predictability of a flood, i.e. the more typical it is for a given season, the greater the potential for organisms to be adapted to the environment. Equally important is the intensity of the flood, with substrate mobilization representing a major element of disturbance. Different properties of a disturbance, such as vibration, sound and hydraulic change, can be sensed by organisms, thereby functioning as an early warning system that triggers effective refuge seeking.

Characteristics of the river reach: Different river morphologies result in distinct refuge types (Fig. 28), such as pools behind boulders and instream wood in steep headwater creeks, and temporary ponds on well-connected floodplains in lowland reaches. Generally, habitat diversity is positively linked with refuge availability, at both large scales (e.g. tributary mouths) and small scales (e.g. heterogeneous substrate). For an organism with a given mobility to reach a refuge in due time, the proximity of residential habitats and refugia is crucial. For instance, upstream refugia might be inaccessible for organisms with poor swimming capabilities. In addition, a refuge must be persistent, providing safe conditions during the entirety of the disturbance, i.e. until a safe return to the residential habitat is possible.

Human modifications of fluvial landscapes have substantially affected refuge functioning, as well as disturbance characteristics. River channelization has reduced and simplified complex habitats that would naturally be present in riverscapes. Obstructed sediment conveyance and associated channel incision have resulted in a decoupling of floodplains from main channel habitats. Further, land-use change and hydropower production have profoundly altered the hydrological disturbance regime. Examples include the acceleration of surface runoff due to expanding impervious surfaces and the reduction of flood frequency by dam operation. Additionally, human modifications can negatively impact the health of riverine organisms, thus diminishing their resistance towards disturbance.

5.3 Refuge availability and assessment – three studies

Direct assessment of refuge provision and use during floods is difficult, owing to accessibility and safety issues and to unpredictability in the timing and intensity of floods. Below we describe a variety of methodological approaches used to study refugia despite these difficulties: direct monitoring of refugia use after an artificial and thus predictable flood when access was possible (Section 5.3.1), macroinvertebrate surveys to infer refuge availability during floods (Section 5.3.2), and a combined laboratory and numerical study considering various flood intensities (Section 5.3.3).

5.3.1 Refuge use during an artificial flood in the Spöl river

We studied the use of refugia by riverine macroinvertebrates, such as insects and snails, during an artificial flood in the Spöl river located in the Swiss National Park (Mathers *et al.* 2021a; Mathers *et al.* 2022). Our study took place in the most downstream residual (minimum) flow section, before its confluence with the Inn river. We monitored four reaches over a 1.5 km section. We (i) sampled instream habitats (e.g. Fig. 28a, f), shoreline areas

(Fig. 28e) and floodplains (Fig. 28c) that may serve as flow refugia; and (ii) investigated utilization of the hyporheic zone, a dynamic habitat located between the surface and groundwater sediments (Fig. 28l).

Benthic flow refugia

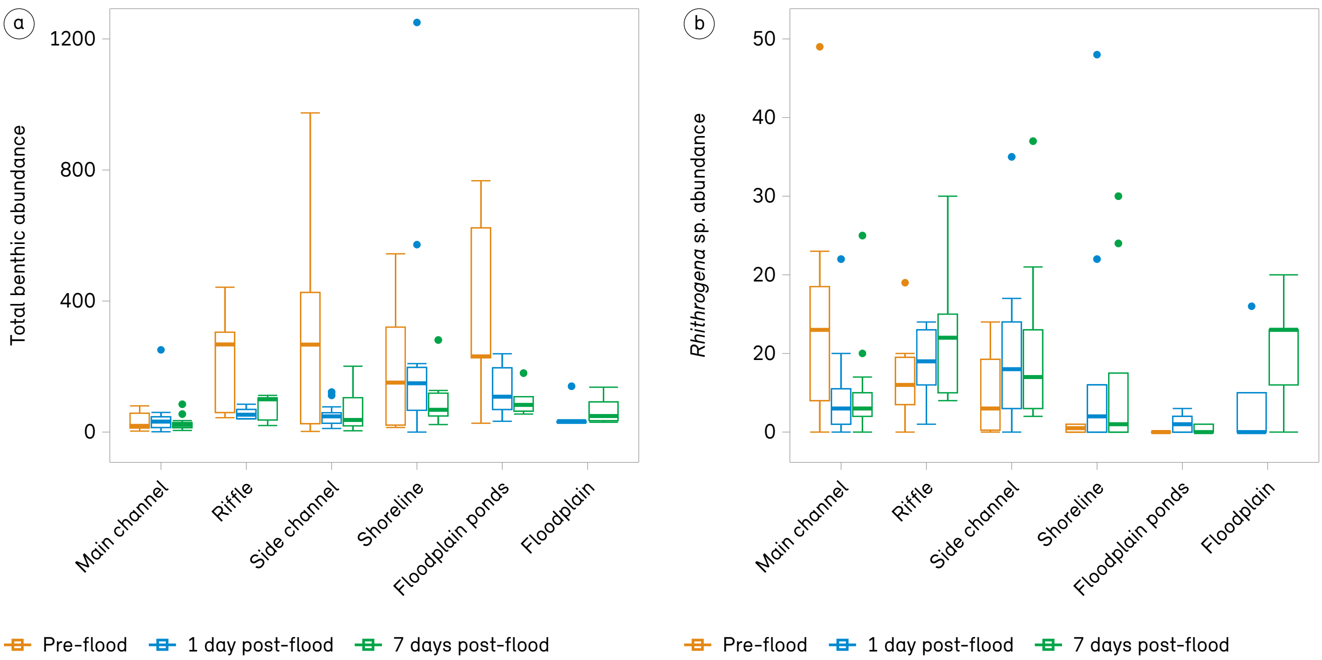
Prior to the artificial flood, benthic macroinvertebrates in each reach represented distinct communities, likely reflecting the habitat heterogeneity present. Following the flood, communities became more similar to each other, with little variation between reaches. However, the number of different insect taxa (richness) remained generally stable following the flood, suggesting the presence of flow refugia that enabled the persistence of more sensitive taxa that contributed to overall richness (Fig. 29a). Riparian shoreline areas and an inundated floodplain maintained high abundances of organisms following the flood (Fig. 29a), highlighting their function as a refuge. In contrast, low substrate stability in riffles and side channels, owing to sediment transport, diminished refuge availability, as indicated by lower benthic abundances (Fig. 29a). Refuge use was particularly evident for the mobile mayfly *Rhithrogena* sp. but was spatially patchy, with some samples containing considerable numbers of individuals following the flood (see outliers in Fig. 29b).

Hyporheic refugia

The interstitial pore space (Figs 28k, 30) between gravels has been acknowledged to provide refuge for many organisms. Contrary to our expectations based on the findings of Dole-Olivier *et al.* (1997), in our study few species used the hyporheic zone (Fig. 28l) as a refuge, and abundances typically declined or remained stable directly following the flood, most likely associated with low substrate stability in the Spöl river. The stonefly *Leuctra* sp. was an exception, displaying limited refuge-seeking behaviour in the hyporheic zone. However, the artificial flood did flush fine sediment (particles <2 mm) from surface and subsurface substrates (0.25 and 0.50 m deep), resulting in a reconnection of interstitial pathways that were previously blocked. As a result, increased abundance and taxa richness at substrate depths of 0.25 m and 0.50 m were recorded 7 days post-flood (Fig. 30). Increased utilization of previously inaccessible hyporheic substrates and improved dissolved

Figure 29

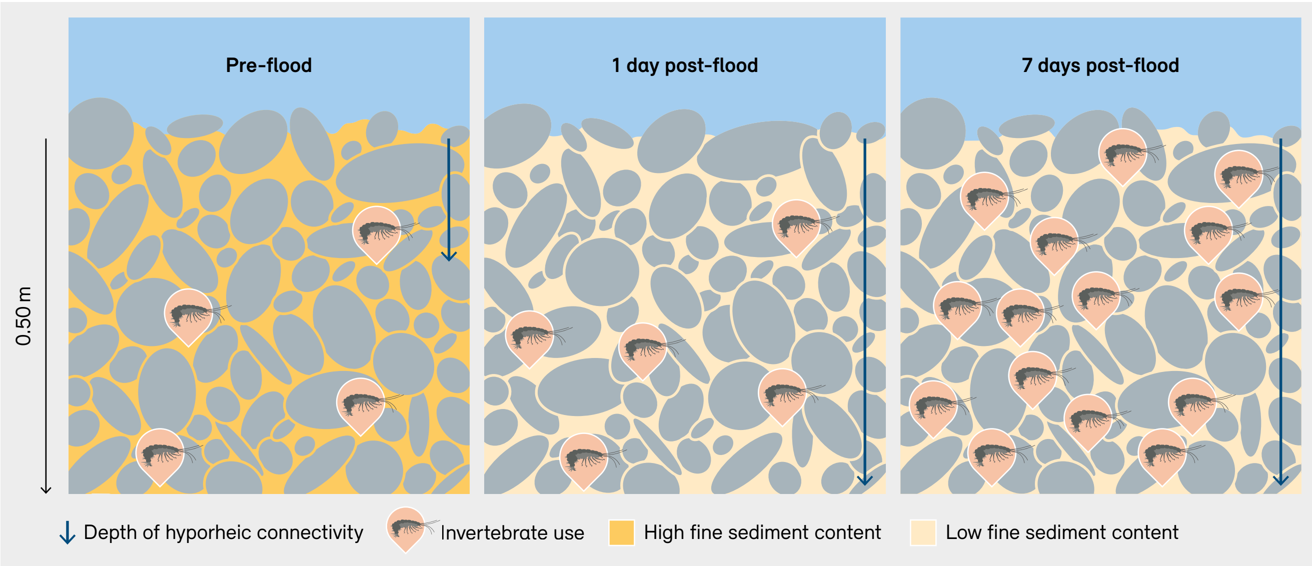
Boxplot of (a) total benthic macroinvertebrate abundance and (b) Rhithrogena sp. benthic abundance associated with an artificial flood in the Spöl river. Abundance represents the number of individuals per 30-second kick sample (following Murray-Bligh 1999).



Source: Mathers *et al.* (2022)

Figure 30

Conceptualization of interstitial pore space between gravels and connectivity with the hyporheic zone to a depth of 0.50 m below the riverbed, before and following the studied artificial flood in the river Spöl.



Source: Mathers *et al.* (2021a)

oxygen conditions mean that substrates will most likely be available as potential refugia from predators and low flow or drought conditions in the future. However, regular flushing flows (1–2 per year) would be required to maintain these benefits (Robinson 2018).

5.3.2 The influence of sediment traps on refuge provision

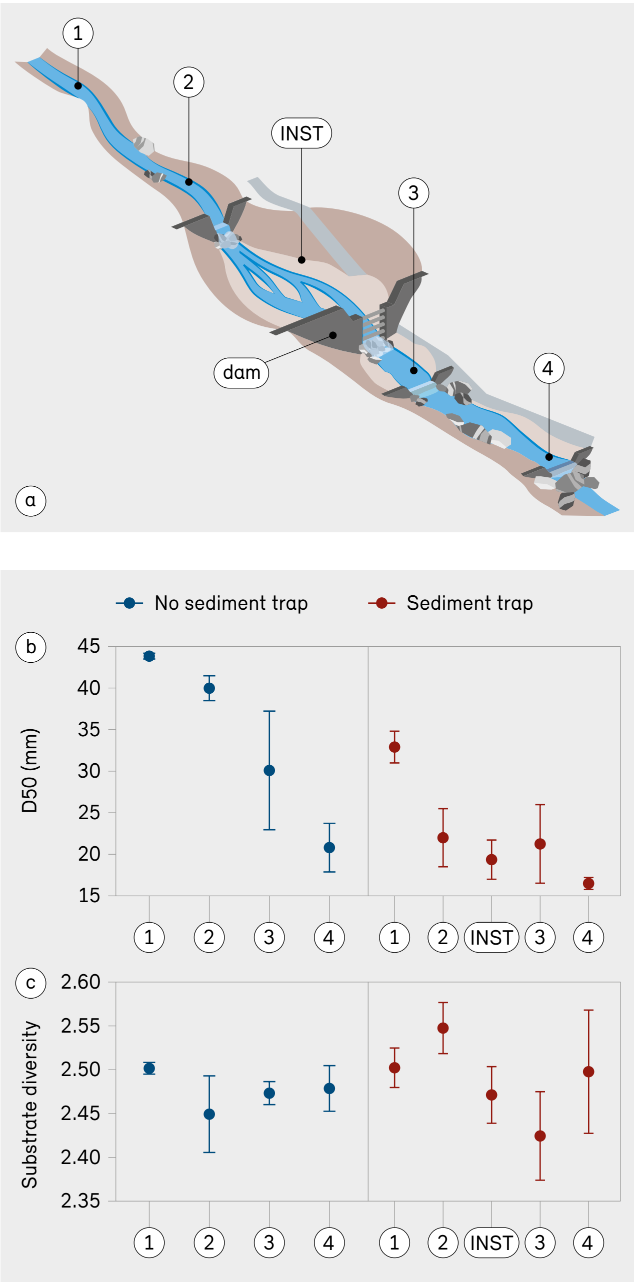
We studied the effects of sediment traps on instream refuge provision and associated macroinvertebrate communities in four streams with a sediment trap and compared them with three streams without a sediment trap in central Switzerland (Mathers *et al.* 2021b). All streams were chosen to have comparable characteristics (e.g. channel size, geology). Streams with a sediment trap were surveyed at two locations upstream and two locations downstream of the trap (Fig. 31a). For streams without a trap, the surveys were performed at the slope knickpoint between a steep canyon and a lower-gradient alluvial fan where traps are usually located. The most upstream and downstream locations were ca. 50 m from the trap (ca. eight wetted widths).

We found a reduction in median grain size (Fig. 31b) and substrate diversity (Fig. 31c), and therefore in refuge provision within the sediment traps themselves and immediately downstream, most likely associated with a decrease in sediment transport of larger particles. In three of the four streams with a sediment trap, substrate diversity recovered to values comparable to those observed in streams without a trap, approximately eight wetted widths downstream of the trap. In the fourth stream, high levels of artificial bank protection limited recovery, and substrate diversity remained reduced downstream of the trap.

The disconnection in sediment transport also led to disruptions in the longitudinal composition of the macroinvertebrate community, as well as its ability to resist disturbance. For instance, we observed an increase in the proportion of macroinvertebrate taxa possessing no resistance strategies immediately downstream of the sediment trap, again indicating a reduction in refuge provision. In contrast, communities within the sediment trap were more likely to possess a resistance strategy (e.g. dormancy, cases resistant to drying out), which may reflect the braided nature of the sediment trap basin, which leads to frequent fluctuations in discharge levels at the habitat scale.

Figure 31

(a) Schematic illustrating the components of a sediment trap and the locations sampled. 1–4 indicate sampling locations; INST indicates the sediment retention basin; and dam indicates the open check dam that prevents sediment transport from taking place downstream. (b) mean D50 (median grain size) values and (c) mean substrate diversity values (± 1 SE) recorded at each sampling location in streams with and without a sediment trap.



Source: Mathers *et al.* (2021b)

Overall, our study demonstrates that sediment traps can significantly disrupt the sediment regime, with important consequences for instream ecology and environmental conditions. Nonetheless, these effects can be longitudinally limited and their severity likely depends on local management strategies.

5.3.3 Sediment supply versus dynamic river widening

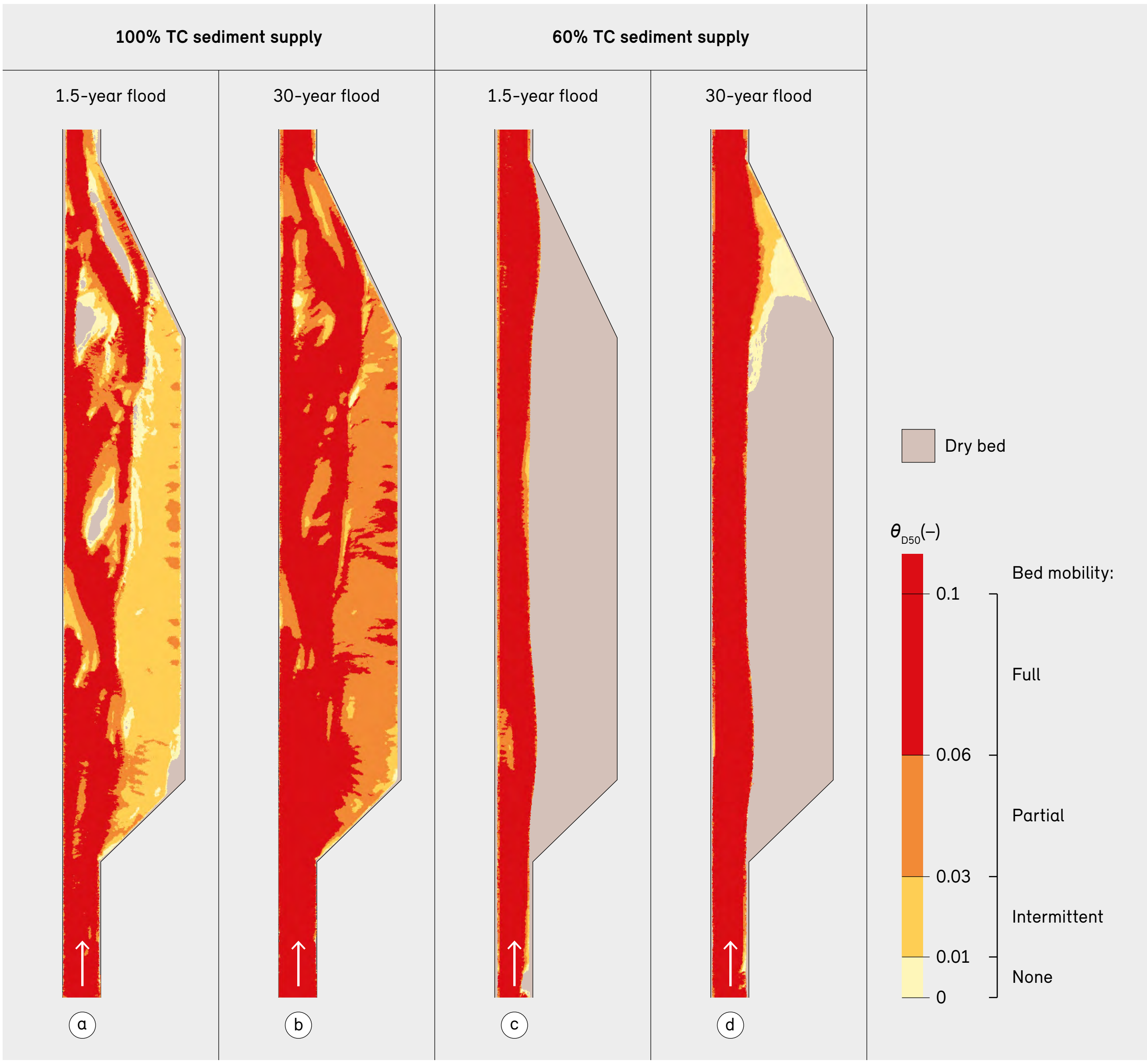
Dynamic river widening is a reach-scale restoration measure implemented to re-establish morphodynamic activity and lateral channel–floodplain connectivity in channelized rivers. We investigated how the morphology of dynamically widened rivers may differ as a function of sediment supply and how this may influence the availability of aquatic flood refugia (Rachelly *et al.* 2021).

A laboratory model of an initially channelized gravel-bed river with a slope of 1% and an adjacent erodible floodplain on its right side was set up to study channel widening. Sediment supply was set at 100%, 80%, 60% or 20% of the channelized river's transport capacity (TC), and steady discharge corresponding to a 1.5-year flood ($HQ_{1.5}$) was applied. The laboratory experiments were combined with a 2D hydronumeric BASEMENT model (version 3.0; Vanzo *et al.* 2021), using discharges ranging from mean annual flow to a 100-year flood, to assess the flow field of each resulting morphology with a high spatial resolution. The availability of potential refugia during floods was studied via: (i) the persistence of zones with low bed shear stress, as a measure of disturbance intensity (Fig. 28d); (ii) shoreline length, as a measure of marginal refuge provision (Fig. 28e); and (iii) inundation dynamics, as a measure of floodplain accessibility (Fig. 28c).

Reducing sediment supply below 80% TC led to erosion of the initial bed level (i.e. counter-clockwise rotation of longitudinal bed profile around downstream channel end). During the subsequent widening phase, distinctly different widening morphologies developed for a sediment supply of 100% and 80% TC versus 60% and 20% TC. A 100% or 80% TC supply led to dynamic, heterogeneous widening with spatially variable bed shear stress (Fig. 32a, b) and greater shoreline length compared with a channelized reach. Lateral channel–floodplain connectivity

Figure 32

Spatial bed shear stress distribution in dynamic river widenings developed with a sediment supply of (a, b) 100% of the channelized river's transport capacity (TC) and (c, d) 60% TC. Both morphologies were developed with a steady discharge corresponding to a 1.5-year flood, but bed shear stress distributions are shown for both (a, c) a 1.5-year flood and (b, d) a 30-year flood. Darker colours indicate greater bed shear stresses, displayed as dimensionless bed shear stresses for the median grain diameter related to certain intensities of bed mobility. Note that results for a sediment supply of 80% TC and 20% TC are not shown here but are very similar to the 100% TC and 60% TC cases, respectively (Rachelly et al. 2021).



Source: VAW, ETH Zurich

during floods was intact, potentially enabling the floodplain to function as a refuge, while the main channel was subject to high hydraulic stress and bedload transport. In contrast, lower sediment supply (60% or 20% TC) resulted in stable, homogeneous channels with uniform flood intensities, shorter shorelines, and a persistent lateral disconnection (Fig. 32c, d). Overall, roughly balancing sediment supply with the channelized river's transport capacity was identified as a major driver of progressive channel widening and active morphodynamic processes.

5.4 Preserving and restoring refugia

Like flood protection measures for humans, refugia are essential for the resistance and resilience of riverine organisms. The preservation of available refugia and the establishment of new refugia require explicit consideration in the planning, construction and maintenance of river engineering projects.

During planning, commonly performed morphological and biological surveys describing the current state can be expanded to include refuge-specific considerations, such as habitat availability during floods (Section 5.3.3) and resistance or mobility traits of organisms (Sections 5.3.1 and 5.3.2). The results can serve as a basis for before–after comparisons, but may also indicate opportunities or constraints for planning in terms of maintaining and enhancing refuge availability. Knowing the location and type of available refugia can prevent potential negative impacts of planned work, for instance during construction.

Several aspects that control refuge availability and persistence can be considered in project design. Sufficient sediment availability can promote channel rearrangement or lateral erosion during floods, and thus refuge provision (Section 5.3.3). Instream structures, both natural (e.g. large wood) and artificial (e.g. engineered log jams), can support refuge establishment. Preserving the connectivity between residential habitats and refugia has proven to be important (Section 5.3.1). Refuge management requires understanding that: (i) flood characteristics can change (e.g. frequency, intensity), for instance under climate change, and (ii) other types of disturbance (e.g. drought) can require different types of refugia (Section 5.2).

After construction, the monitoring of previously existing refugia and of newly formed refugia, either intended or unexpected, supports adaptive management. The case studies presented here exemplify the monitoring methods applicable during base-flow conditions (Section 5.3.2) or predictable flood events (Section 5.3.1).

This chapter illustrates that hydro-morphological variability and complexity are prerequisites for habitat provision and refuge functioning. These conditions are strongly related to the flow and sediment regime, i.e. sediment availability, transport and rearrangement (Wohl *et al.* 2015). While sediment transport acts as a disturbance to aquatic organisms, it is also a key driver of long-term morphodynamic variability and complexity and community viability (Lepori and Hjerdt 2006). Many aquatic organisms have evolved resistance and resilience strategies that enable persistence during disturbances, including the use of refugia, and a natural sediment regime contributes critically to refuge availability.

Box 8: In practice – Bird Track Springs Fish Habitat Improvement Project

Phil Roni and Meghan Camp, Cramer Fish Sciences

The Bird Track Springs Fish Habitat Improvement Project (*https://www.grmw.org/data/project/478/*) is located in the Grand Ronde River (Oregon, US). The project area has experienced human impacts (e.g. beaver trapping, logging, channelization, livestock grazing), resulting in the loss of 70% of the pools, a lack of habitat complexity (e.g. large wood), embedded substrate, elevated stream temperatures, increased sediment supply, and decreased water quality.

The project goal was to improve the habitat for imperilled native fish species (e.g. Chinook salmon). The specific design objectives were to re-establish a forced island-braided channel with a full floodplain connection; increase floodplain inundation, groundwater connection and thermal diversity; create off-channel refugia; and improve riparian habitat.

Portions of the channel were relocated to encourage it to re-engage with the floodplain and create fish refugia, such as swales and ponds. Side channels and alcove features were enhanced at historical channel meander scars and depressions throughout the floodplain to enhance floodplain access and refugia availability during floods. Channels were also constructed to facilitate connectivity to spring-fed side channels and provide suitable refugia for juvenile fish and adult fish migrating upstream. Large wood structures, such as trees and rootwads, were added to direct flow towards the floodplain, increase channel complexity, create scour pools, store sediment, and provide additional refugia for fish during high-flow events.

The project resulted in 55 hectares of reconnected floodplain, 2896 m of new channel, an increase in main- and side-channel pools, and more than 550 log structures. Project success is being assessed through the evaluation of changes in channel morphology, floodplain habitats and refugia, through fish surveys, and through stream flow and temperature monitoring.

6 Simulation of fine sediment deposition on floodplains

Rivers extend beyond the channels that are typically associated with this word. Of particular interest are floodplains, where important hydro- and morphodynamic processes occur as a result of recurrent flooding. Ecologically, they also support the establishment of many species in need of conservation. In this chapter, relevant fine sediment deposition processes are introduced and the numerical tools used to forecast fluvial responses are presented. This is a topic that is especially relevant for river restoration projects.

Daniel Conde, Carmelo Juez, Davide Vanzo, Christoph Scheidegger, Giovanni De Cesare and David Vetsch

6.1 Introduction

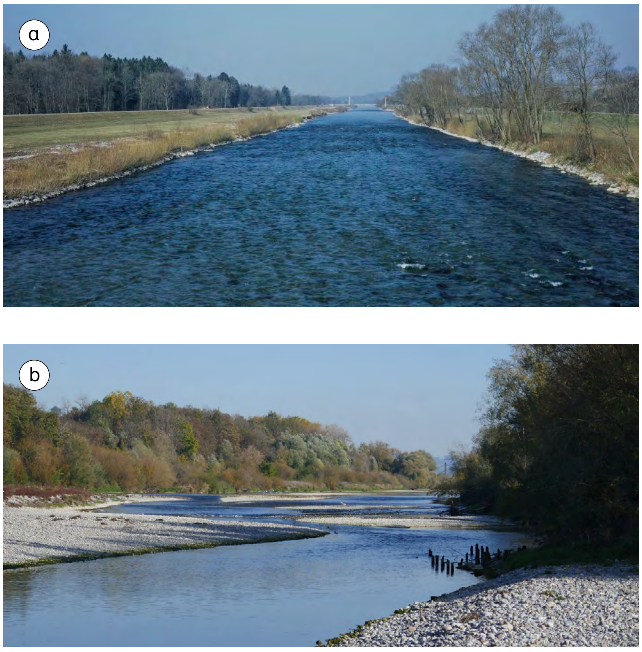
As rivers and streams flow along valleys, they convey water together with considerable amounts of inorganic sediment and organic material. Coarser grains, such as cobbles and gravel, are transported as bedload, along and in close contact with the riverbed (Van Rijn 2005). Finer grains, typically those not exceeding 2 mm in diameter, are transported as suspended load (Van Rijn 1984), and are mainly kept aloft by the flow. The fine grains that comprise the suspended load are most often a combination of silt, clay and fine sand, and their concentration varies along the flow depth: high near the riverbed and decreasing towards the surface. The primary focus of this chapter is the identification and modelling of processes that control suspended loads and the quantification of their impacts on riverine hydrodynamics and morphodynamics. We concentrate on floodplain regions in particular (Fig. 33), due to their double role in flood protection and ecological functions (Baptista *et al.* 2018).

Regarding protection against floods, floodplains provide the space necessary to accommodate increased river conveyance, while safely preserving human settlements and activities during high-flow conditions. Moreover, they provide retention storage and they enable transitional flow regulation, containment of driftwood, and deposition of sediment. In terms of ecological functions, floodplains play an important role as connectors between riverine ecosystems and the adjacent terrestrial ecosystems. A variety of riparian species settle in these regions and are sensitive to the delicate balance between the deposition of new sediment and the erosion of old material. The healthy preservation of these riparian corridors is critical for ecological continuity.

The geomorphological evolution of the river corridor is tied tightly to the added value of floodplains. Whether erosion or deposition becomes the dominant process is mainly controlled by the exchange of water and fine sediment between the main channel and the floodplain. The presence of vegetation on the floodplain has a significant impact on these hydrodynamic exchanges, as it imposes a reduction in fluid velocity compared with the main channel. This flow pattern develops with all vegetation types, creating strong tangential

Figure 33

Examples of Thur river: (a) reach with artificial compound channel and (b) reach with widening after restoration.



Photos: (a) ETH-Bibliothek Zurich, Bildarchiv / Photographer: R. Huber. (b) VAW, ETH Zurich forces between the flow on the riverbed and that on the floodplain, forming an internal shear layer (Fig. 34). This layer typically exhibits multiple vortical motions that induce lateral exchanges and mixing. Quantifying these lateral fluxes is crucial to correctly assess the effective discharge capacity of the river, especially under higher flow conditions, as well as the expected ecological and morphological changes.

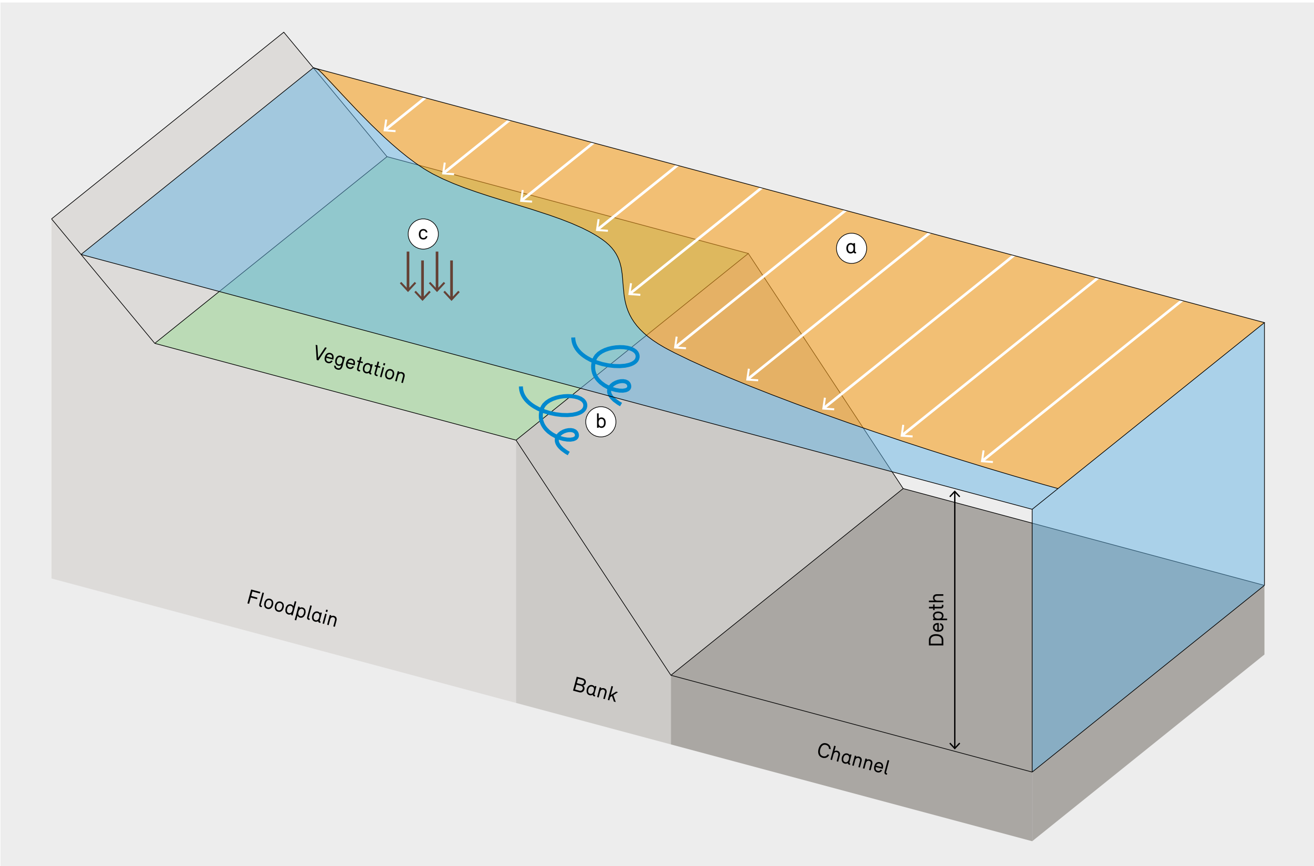
The Federal Waters Protection Act (WPA, 1991) and the Waters Protection Ordinance (WPO, 1998) have called for the restoration (Fig. 33) of thousands of kilometres of rivers in an approach combining hydromorphology and ecology. The policy goal is to restore habitats for characteristic animals, plants and fungi while retaining or improving flood protection and sediment continuity. Consequently, there is a need for robust models to accurately forecast morphodynamic behaviour.

6.2 Numerical Modelling

In the simplest terms, a numerical hydro- and morphodynamic model provides a virtual representation of water flow and consequent river bed changes. Such models form a widespread and well-accepted hydraulic engineering toolset, with multiple applications in practice. The herein used software BASEMENT (Vanzo *et al.* 2021) is a numerical modelling freeware developed at VAW at ETH Zurich. Hence, the most relevant waterways are rivers, streams and estuaries. The hydrodynamics module comprises the core of this software, capable of simulating hydro- and morphodynamic processes through a variety of modelling approaches accounting for water flow, frictional forces, turbulence and sediment motion.

Figure 34

Typical configuration of flow over a floodplain: (a) velocity distribution, (b) horizontal vortices in the shear layer, and (c) lateral sediment deposition.



Source: VAW, ETH Zurich

Turbulent quantities play a significant role in determining the total resistive forces, as well as the buoyancy of the carried matter. Energy-conserving models are used to quantify the turbulent kinetic energy of the flow. Other simpler and less demanding types of turbulence computation methods are also implemented. Regarding the modelling of suspended load, an advection-diffusion module is combined with well-established empirical formulas known in the literature (Van Rijn 1984), where higher shear stress on the riverbed results in greater sediment mobility.

All features of BASEMENT are implemented within an intuitive workflow that provides modellers with an effective way to forecast hydro- and morphodynamic behaviour at multiple river engineering scales (Vanzo *et al.* 2021). In this chapter, the capabilities of BASEMENT are leveraged for fine-scale process modelling, supported by experimental observations (Juez *et al.* 2019), and then upscaled to the river-reach scale through a case study of an engineering application.

6.3 Processes

A series of experiments were designed and performed to assess the influence of channel geometry and floodplain vegetation cover on the hydro- and morphodynamic behaviour of compound channel flows (Juez *et al.* 2019). The outcome of these experiments is expected to support model development and usage, for example when designing future fluvial interventions, thereby contributing to the mitigation of problems related to fine sediment.

Compound channel flows were physically characterized through multiple tests on a reduced-scale model based at the Platform PL-LCH at EPFL. The same tests were also simulated in the virtual environment of BASEMENT, to selectively study and confirm which parameters are most relevant. These were found to be as follows:

(i) depth-ratio, the relationship between the flow depth of the main channel and that of the floodplain
(ii) velocity-ratio, the relationship between the average flow velocity of the main channel and that of the floodplain
(iii) width-ratio, the relationship between the width of the floodplain and that of the main channel
(iv) type and roughness of the land cover on the floodplain

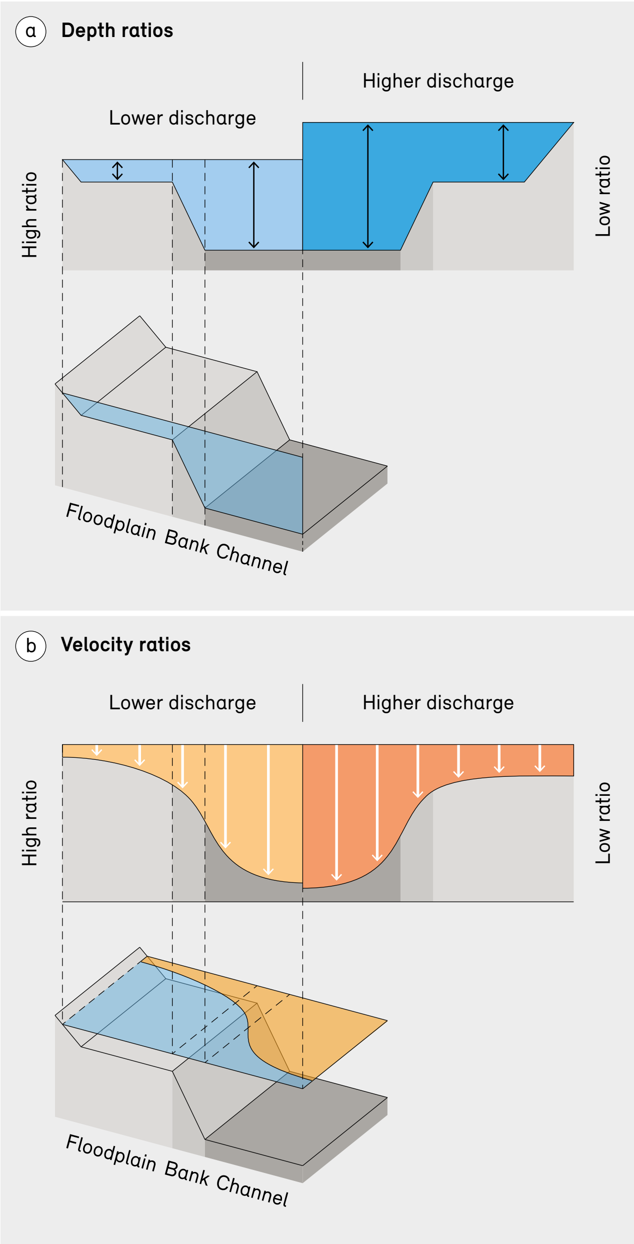
The reduced-scale model and its virtual counterpart comprised a rectilinear flume with a laterally adjustable floodplain, floodplain covers with varying resistance, and instrumentation to measure flow depth, surface velocity and suspended sediment concentrations. To ensure consistent readings, all measurements were recorded under steady and uniform flow conditions, with local depths and velocities kept constant in time and space.

The range of experiments covered realistically scaled discharges, drawn from known river hydrology. Results from these experiments indicated that higher discharges lead to lower depth-ratios and velocity-ratios (Fig. 35). The velocity-ratio was also found to be sensitive to the width-ratio, with lower values occurring in narrower channels (higher width-ratio). The relative difference in velocity between the main channel and the vegetated floodplain (Fig. 36a) was observed to promote the appearance of horizontal vortices, which are critical for lateral mass exchanges. Furthermore, wider main channels (lower width-ratio) were associated with a greater variation in velocity (shown as arrows in Fig. 36a), along with wider shear layers and vortices (Fig. 36b).

The experiments demonstrated that, compared with a bare cover, the presence of vegetation on the floodplains imposes even stronger frictional forces, contributing to a greater velocity-ratio. A secondary effect was observed in the shear layer, with a shrinking of its width introducing a slight increase in maximum stress intensity for narrower densely vegetated channels. Regarding the deposition of suspended sediment, the experiments indicated that the discharge and corresponding depth-ratios (Fig. 35) also have a significant influence. At lower discharges (shallower flows with a higher depth-ratio) on vegetated floodplains, the sedimentation in the main channel was observed to be mostly controlled by the width-ratio, with narrower geometries concentrating more sediment in the channel (Fig. 36c). For deeper flows (lower depth-ratio) at higher discharges, sediment was found to propagate further into the floodplain and predominantly settle there (Fig. 36d), with almost no sedimentation occurring within the main channel. With a bare floodplain, greater lateral diffusion of sediment was observed, especially in narrower channels (high width-ratio).

Figure 35

Effect of lower (left) and higher (right) discharges on (a) depth-ratios and (b) velocity-ratios.



Source: VAW, ETH Zurich

Finally, the experiments demonstrated that the lateral flux of water and suspended sediment is primarily controlled by the depth- and width-ratios and is secondarily influenced by the floodplain roughness. A narrower main channel was observed to exhibit higher lateral entrainment. This may be attributed to the turbulent dynamics in the shear layer and ultimately leads to an increased sediment dispersion along the floodplain, especially for deeper flows. The clearest controlling factor in both the hydro- and the morphodynamic behaviour of a compound channel flow with a vegetated floodplain was found to be the velocity-ratio, while the most marginal factor was the presence of taller tree-like vegetation. This pertains mostly to compound channels with a simple geometry, such as the reduced-scale one used in the experiments. For more complex geometries, the behaviour must be studied separately, either numerically or experimentally.

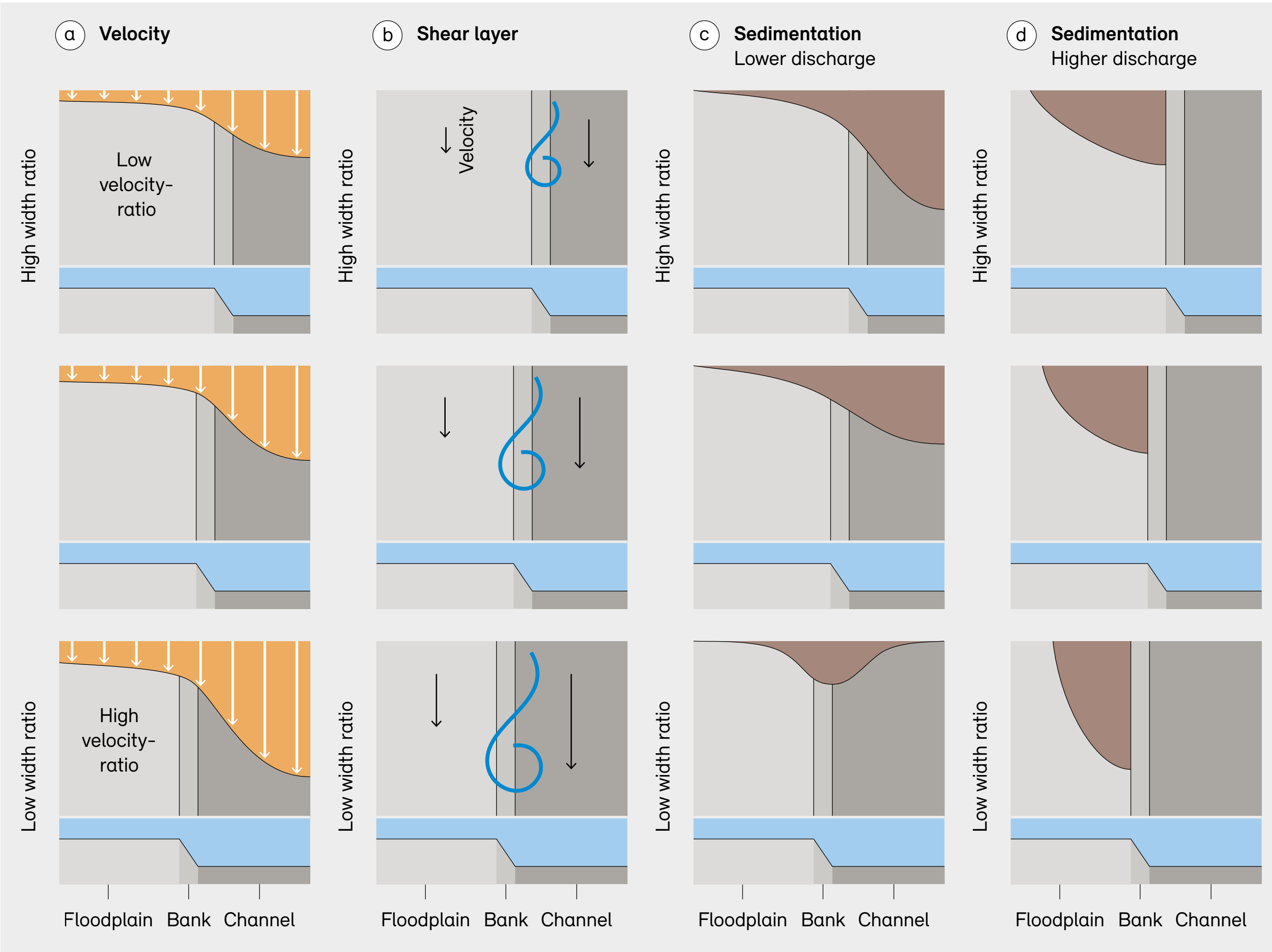
6.4 Ecological aspects

In ecology, 'floodplains' are riparian ecosystems that depend on disturbance regimes involving floods, transport of sediment, and fluctuating groundwater. Different sediment grain sizes play an important role in shaping habitats, mainly because the water storage capacity of sediment increases with decreasing grain size. Spaces with high proportions of fine sediment act as key germination beds for plants, bryophytes and lichens, and they drive the succession of riparian vegetation. Strong dependencies between channel morphology, structural elements (such as gravel bars), woody debris and boulders form a diverse and laterally connected environment that facilitates the development of diverse and resilient ecosystems.

Given the limited space available, floodplain restoration focuses on highly dynamic ecosystems, including gravel bars and early successional stages of floodplain forests (*Salicion elaeagni, Alnion incanae*). Late successional floodplain forests, including ponds and strongly desiccated open areas (*Psoretea decipientis*, coloured soil crust communities) with infrequent disturbances from floods, are currently underrepresented habitats in restored floodplains. The frequent fog and high air humidity in these otherwise dry environments foster communities with species such as the enigmatic starry breck lichen *Buellia asterella*, a frequent colonizer of rarely inundated compacted sand. This species is now extinct in Switzerland and endangered worldwide.

Figure 36

Various effects (top view) of a narrower (high width-ratio) or wider (low width-ratio) channel: (a) velocity distributions, (b) shear layer, and sedimentation distribution under (c) lower discharge or (d) higher discharge.



Source: VAW, ETH Zurich

According to the results from the above experiments, the presence of taller trees does not strongly influence hydro- or morphodynamics. The effect of bushes was not tested in the laboratory, although their presence in large numbers could increase the effects of grass-like vegetation and possibly lead to greater deposition. The availability of large structural elements is also relevant for creating high diversity and establishing characteristic floodplain biodiversity. Coarse woody debris plays an important role in the vicinity of an anabranching river, where some infrequently inundated sites can also be built. Creating gravel bars and placing boulders at rarely inundated levels could substantially increase habitat diversity in restored floodplains.

6.5 Case study

We use a reach of the Alpine Rhine river near Widnau (CH) and Höchst (AT) (Fig. 37) as a case study to demonstrate the morphodynamic simulation of fine sediment on floodplains. The source of the Alpine Rhine lies in the canton of Grisons in the Swiss Alps and in the international reach the river flows along the border to Liechtenstein and Austria, towards Lake Constance. Due to the densely populated areas and major infrastructure along the Alpine Rhine downstream of the Ill confluence, the protection of this region from flooding is essential: the material damage potential from major flooding events is estimated at over

CHF 10 billion. Ongoing projects have the aim of increasing the conveyance capacity of the Alpine Rhine by river restoration by means of channel widening.

An example application of BASEMENT as a design-support tool is shown here. The study area spans from km 80.1 to km 82.6 of the Alpine Rhine (Fig. 37), where the urban settlements span to the edge of the outer flood protection levees. The modelling framework encompasses most of the available modules in BASEMENT, namely hydrodynamics – with friction and turbulence modelling and morphodynamics – with both bedload and suspended-load modelling.

Friction is modelled with a quadratic friction law, where shear stress between the riverbed and the flow is inferred from a roughness coefficient that depends on the grain roughness and bed forms. The presence of vegetation, and its hydrodynamic drag, is also accounted for with this coefficient, irrespective of its type. Turbulence generated from the shear layers, between the main channel and the floodplain, and at the riverbed, is considered in terms of flow resistance and sediment dispersion with a standard ‘k-ε’ model. Regarding sediment dynamics, vertical exchange rates are modelled after the formulas proposed by Meyer-Peter-Muller for bedload and by Van Rijn for suspended load (Vetsch *et al.* 2021). Example setup files for such types of applications are provided on the BASEMENT website (*www.basement.ethz.ch*).

Figure 37

River reach considered in case study: Alpine Rhine river at Widnau (a) under low flow and (b) under flood conditions (view in flow direction).

Source: IRR

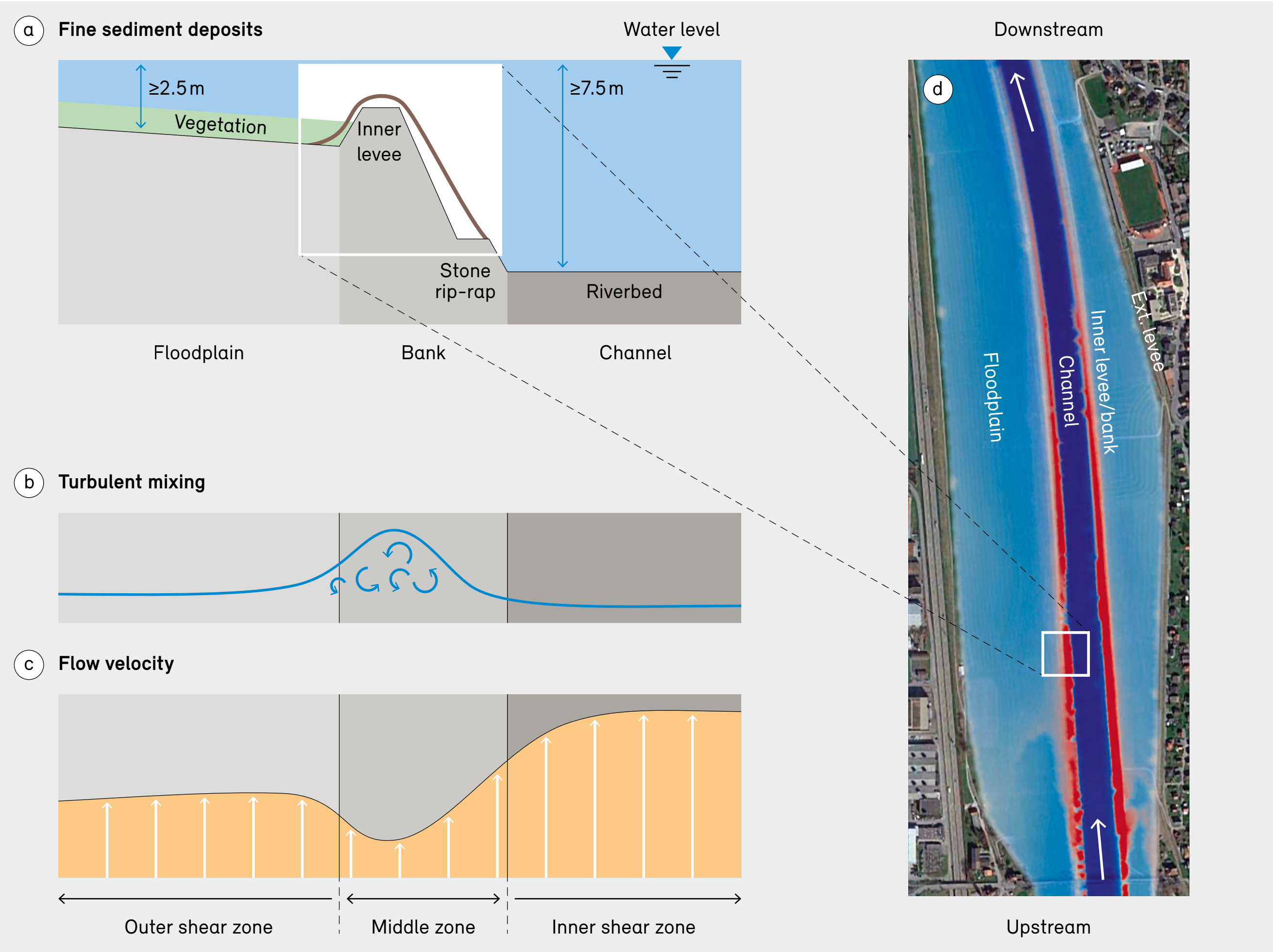
The studied domain is depicted in Figure 38d. Two boundary conditions are present in the model, one upstream and one downstream, both imposing uniform flow conditions: all forces acting on the flow are balanced and it neither accelerates nor decelerates. The roughness coefficients are calibrated with observed hydrometric data from hydrological stations. The obtained values are compatible with the well-established values for grassy floodplains (taller vegetation, such as trees, has been shown to have less impact and bushes were not taken into account), gravel-bed river channels, and protective stone embankments.

As in the laboratory experiments, the influence of turbulent processes is clear, with two distinct shear zones developing on each side of the inner levees (Fig. 38b, c), exhibiting a smooth velocity transition between low and high roughness areas. Without a careful parametrization of this process, the shear layers are not captured and the cross-sectional velocity distribution may not be physically correct. The simulated sediment deposition patterns tend to appear along the channel-side bank of the inner levees (Fig. 38a), with additional sedimentation occurring on the floodplains in the case of overtopping at higher discharges (>2000 $m^3 s^{-1}$), although in a smaller amount. Although the geometry of this system is not comparable to the one used in the lab experiments, the same behaviour was observed during recent floods in 2005 and 2009. This pattern is also realistic in terms of the velocity patterns, as lower-velocity areas lead to higher deposition rates (Fig. 38a, c). Two discharge scenarios are considered, 1000 $m^3 s^{-1}$ and 2000 $m^3 s^{-1}$, corresponding to main channel flow conditions and compound channel flow conditions, respectively. The annual average suspended sediment concentration for the Alpine Rhine is applied at the upstream boundary condition.

The deposited sediment quantity increases with increasing discharge, suggesting that sediment availability is a

Figure 38

Schematic of the results for the present situation in the Alpine Rhine river at 2000 m³ s⁻¹: (a) section view of the deposited sediment (brown line), (b) turbulent mixing, (c) velocity distribution, and (d) top view of the studied reach, with sediment deposits in red.



Source: VAW, ETH Zurich / aerial photo ©swisstopo

critical factor and that the likelihood of subsequent floods washing away previous floodplain deposits is reduced. The probable outcome is a continuous deposition process over the floodplain areas next to the levees when they are inundated at discharges >2000 $m^3 s^{-1}$, and on the banks as well, even at discharges <1000 $m^3 s^{-1}$. This leads to a reduction in channel conveyance. For the reference scenarios, the total deposition covers between 0.8% to 1.6% of the usable flow area in the floodplain (a volume of some 8000 to 16 000 m^3), after short flood events (48 h).

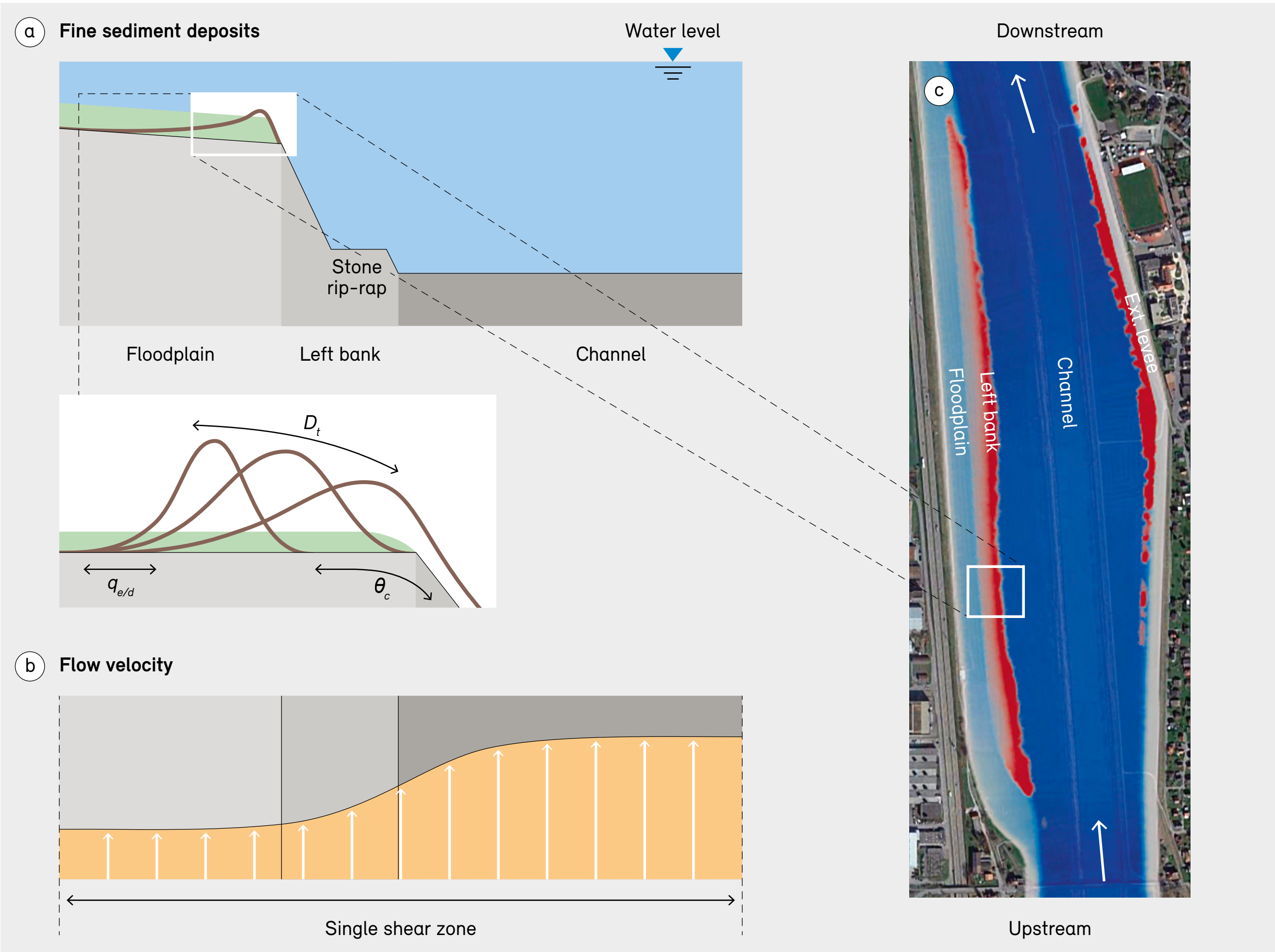
This application shows how BASEMENT can be used to assess present and future maintenance needs regarding floodplain conditions. A simple setup, as described here, is also applicable when planning future river projects. As an example, we take a restored configuration of the same reach (Fig. 39c), while maintaining the models and assumptions from the first application. Such a configuration features a large widening of the main channel, with full suppression of the right floodplain and a shortening of the left floodplain by approximately half.

At high discharges (2000 m^3 s^{-1}), the results show a single shear layer (Fig. 39b) and predominant accumulation of fine sediment on the single left floodplain (Fig. 39a, c), amounting to 0.4% to 0.9% of its usable flow area (2000 to 4500 m^3), depending on the configuration of the fine sediment morphodynamics module. For lower discharges (<1000 m^3 s^{-1}), deposition happens mostly on the banks and in the main channel.

The most relevant parameters (Fig. 39a) in this example are turbulent diffusion (D_t), critical shear stress (θ_c) and vertical exchange rate ($q_{e/d}$). Turbulent diffusion is the main proxy for the mass exchange between the main channel and the floodplain, promoting lateral sediment entrainment and dispersion onto the floodplain. Critical shear stress controls the onset of sediment mobility, transferring sediment deposition from the main channel towards the lateral areas. The remaining parameters determine the erosion and deposition rates and therefore control how the flow over the floodplain becomes depleted of suspended sediment.

Figure 39

Schematic of the results for the configuration of the restoration project at 2000 m^3 s^{-1}: (a) section view of the deposited sediment (brown line) and influence of model parameters, (b) velocity distribution, and (c) top view of the studied reach, with sediment deposits in red. The displayed parameters are: turbulent diffusion (D_t), critical shear stress (θ_c), and vertical exchange rate ($q_{e/d}$).



Source: VAW, ETH Zurich / aerial photo ©swisstopo

Box 9: In practice – Fine sediment removal from floodplains

Daniel Dietsche and Mathias Speckle, International Rhine Regulation (IRR)

The reach of the Alpine Rhine river described in this chapter is the responsibility of the International Rhine Regulation (IRR), which has reported that rapid removal of sediment after flooding, i.e. excavating it and returning it to the main channel, has proved to be highly effective. Branches and root material are transported to the estuary and used for ecological landscaping. The deposited sediment may also be removed later, but regular surveillance and forecasting are necessary to ensure that the design flow capacity is maintained. The presence of vegetation has been observed to result in more sediment being deposited, even at low water levels. This practical example shows the need for accurate tools to forecast the amount of deposited sediment and test potential solutions for its disposal. From government administrations to private engineering companies, the advances in the new numerical capabilities of BASEMENT will support the safe and ecologically conscious development of Swiss rivers.

7 Impact of substrate clogging on vertical connectivity

Connectivity between the hyporheic zone and the flow is essential for the development of benthos and the reproductive success of spawning fish. The infiltration of fine sediment leads to clogging of the riverbed, reducing porosity and vertical water exchange. Natural clogging cycle is altered by infrastructure and land use. This chapter includes a short review of the process and influencing factors, which are illustrated with some experimental results. These principles are then applied to a selection of common cases.

Romain Dubuis, Robin Schroff and Giovanni De Cesare

7.1 Clogging

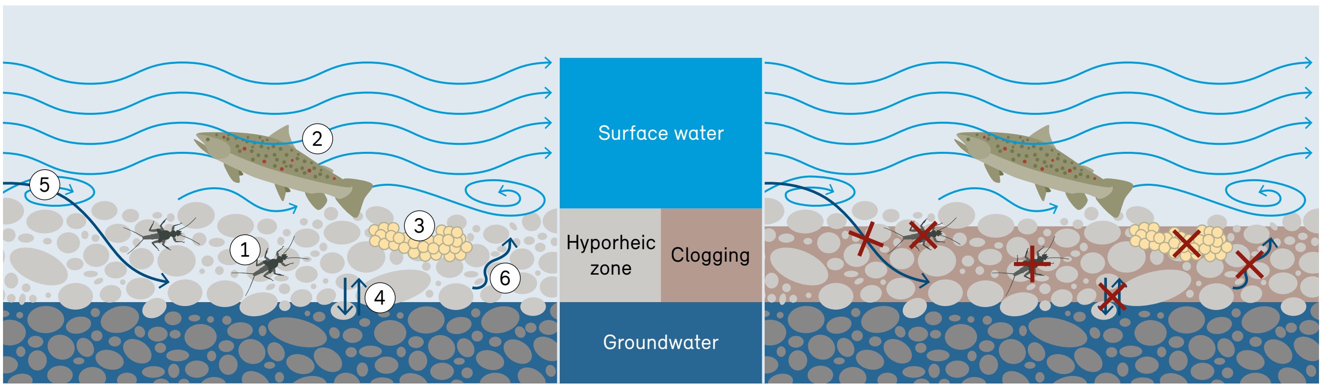
In natural, bedload-carrying rivers, the porous streambed accommodates a rich ecological community. The layer of streambed substrate connecting surface water and groundwater is called the hyporheic zone (Brunke and Gonser 1997). It is usually dominated by gravel, stones and boulders. As shown in Figure 40, the interstices between the substrate's grains are the primary habitat of many organisms. Functional vertical connectivity allows active exchange between free-flowing surface water, pore water of the hyporheic zone, and groundwater. This vertical connectivity can support the river's self-purification capacity and help regulate the groundwater balance of the alluvial zones. Undisturbed fluxes of water, particles, nutrients, oxygen, and other dissolved compounds provide the habitat conditions required by the native ecological community. The suitability of the hyporheic zone as habitat is impaired when the interstitial pore space becomes clogged by fine sediment (Bo *et al.* 2007).

7.1.1 Impacts of clogging

Clogging describes the gradual infilling of the streambed's interstitial spaces with fine sediment (Wharton *et al.* 2017). Clogging is inherently a natural phenomenon, but is often intensified by human activity. Most of the time the detrimental ecological effects of excessive clogging prevail. Clogging degrades streambed habitat by altering its composition and disturbing fluxes (Pulg *et al.* 2013). The changes in composition have direct adverse effects

Figure 40

The hyporheic zone serves as primary habitat for interstitial organisms, including (1) macroinvertebrates. (2) Gravel-spawning fish bury their (3) eggs in the substrate, where conditions are suitable (Kondolf 2000). Exchanges occur between the groundwater and river (4) and between the hyporheic zone and surface flow (5, 6). Changes that occur with a clogged hyporheic zone are shown on the right.



Source: EPFL

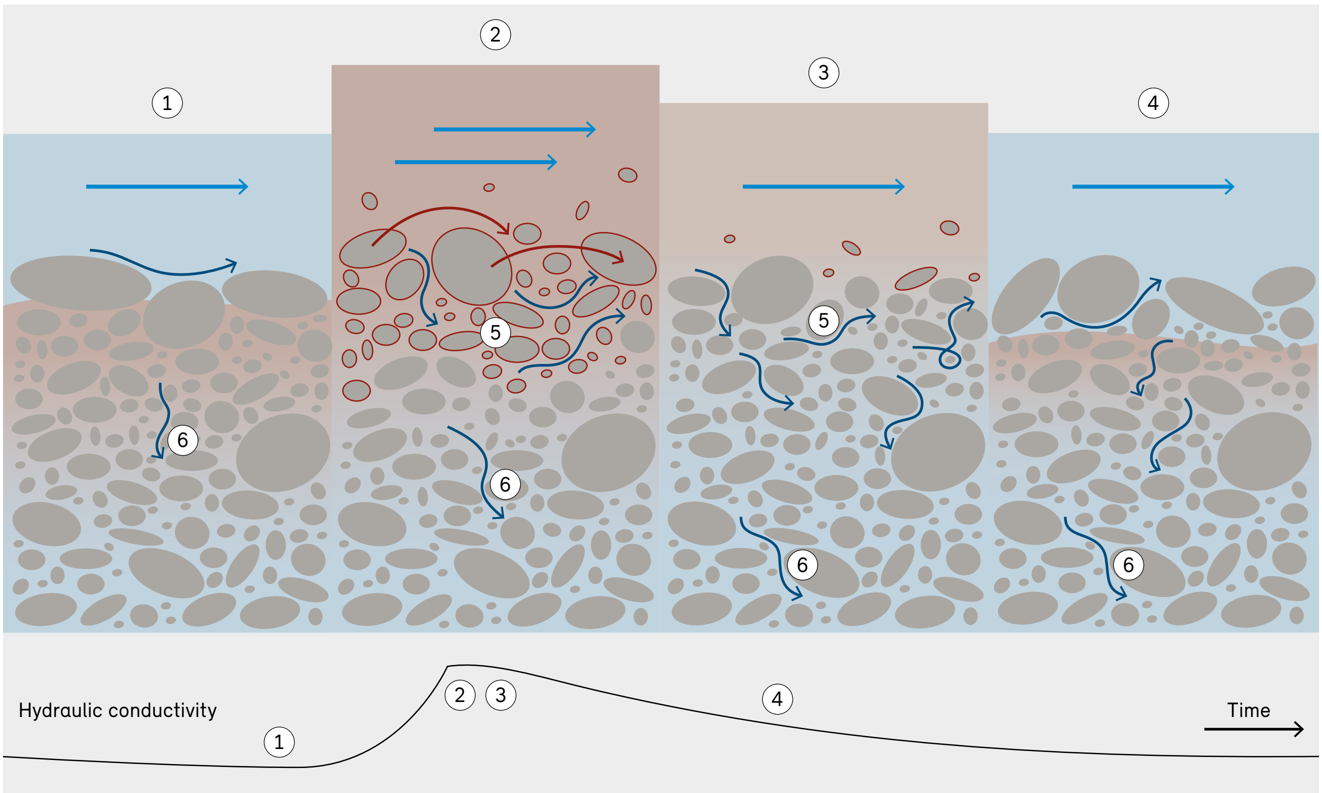
on macroinvertebrates and fish (Fig. 40; Sternecker *et al.* 2013). Macroinvertebrates depend directly on pore spaces as habitat and a rough grain surface to prevent drift. Fish require loose substrate to build their redds. The disturbance of fluxes deprives macroinvertebrates, fish eggs and fish larvae of nutrients and oxygen, and disturbs the removal of metabolic waste during the incubation period (egg development). Further, the interrupted exchange with the usually warmer or colder groundwater disturbs the ecologically important temperature regulation in the substrate.

7.1.2 The clogging process

The three principal formation processes of streambed clogging which are generally differentiated are physical clogging, bio-clogging and chemical clogging. Physical clogging describes the intrusion of suspended fine sediment into the riverbed substrate and the formation of a layer with low hydraulic conductivity, low porosity and often a high degree of consolidation. It results in poor vertical connectivity. The presence of fine material, warmer water and sunlight as well as the absence of disturbing events promote the development of various organisms, such as algae, diatoms and bacteria, which fill the pores and consolidate the substrate (bio-clogging). Reduced vertical connectivity and substrate consolidation can also arise through chemical reactions of solutes, such as calcium, which precipitate and create bonds. The present chapter focuses on physical clogging, but the reinforcing effects of bio-clogging and chemical clogging should not be neglected in the overall analysis of a streambed's degree of clogging.

Figure 41

Clogging process and cycle. (1) Clogged substrate with low hydraulic conductivity; (2) flood event with declogging, where the flow penetrates below the gravel and releases fine particles; (3) falling limb, where the substrate has a low fine sediment content and vertical connectivity is maximized; (4) creation of a new clogged layer; 5) advective pumping; and (6) downwelling.



Source: EPFL

The process of clogging and declogging is cyclic and natural. It depends on the frequency of floods capable of mobilizing the riverbed and breaking the clogged layer, partially or completely. As soon as the gravel forming the riverbed returns to a stable state, a new clogging phase starts (Park *et al.* 2019). This whole cycle is presented in Figure 41. Two different types of physical clogging are usually differentiated. Surface clogging (Fig. 43a) refers to the natural deposition on top of the substrate in the case of low flow velocity and natural sedimentation (Schälchli, Abegg + Hunzinger, 2001). Inner clogging, (Figs 41, 43b), corresponds to the build-up of a layer of fine sediment inside the hyporheic zone. This process involves a source of fine sediment, a substrate matrix as support, and infiltration as the driver.

The concentration of fine sediment in the river flow depends on the hydrogeological conditions. During floods and the following receding period, or in catchments with a glacier, the concentration of fine sediment is much higher (Fig. 41.2, 41.3), due to soil erosion and the release of fine sediment trapped in the riverbed. The substrate acts as a filter, trapping at least part of the fine sediment entering the hyporheic zone. A high degree of permeability is a prerequisite for functional vertical connectivity. As more particles become deposited, interstices become smaller and only finer particles can find a way into the substrate matrix (Fig. 41.1, 41.4). A reduced amount of water, potentially loaded with suspended sediment, can flow through this 'filter', and the clogged layer eventually reaches a stable level (Fig. 41.1). This filtering process is driven by multiple mechanisms. Surface flow can penetrate through the hyporheic zone by advective pumping (Fig. 41.5), a process triggered by small differential pressures at the local scale (Fries and Taghon 2010). The exchange between surface flow and groundwater plays an important role in the process of clogging, since it forces or impedes the penetration of surface flow loaded with fine particles (Boano *et al.* 2014; Fox *et al.* 2018). Up- and downwelling (Fig. 41.6) are generated by the pressure gradient between the groundwater and surface flow, or result of the river morphology, for instance in presence of riffles or steps.

7.1.3 Influencing factors and laboratory experiments

The deposition of fine sediment and the formation of a clogged layer depend on various influencing factors, such as: (i) the grain size ratio between suspended sediment and riverbed substrate, (ii) the flow conditions, (iii) the exchanges between groundwater and surface flow, and (iv) the fine sediment concentration. These factors, and the interactions between them, are common in both natural and disturbed rivers.

Figure 42

Experimental setup used to study the clogging of riverbed substrate at the Platform PL-LCH at EPFL. The flume is composed of a 30-cm-thick gravel layer, and both the direction and intensity of the flow through the gravel, as well as the surface flow conditions, can be controlled in the experiments.

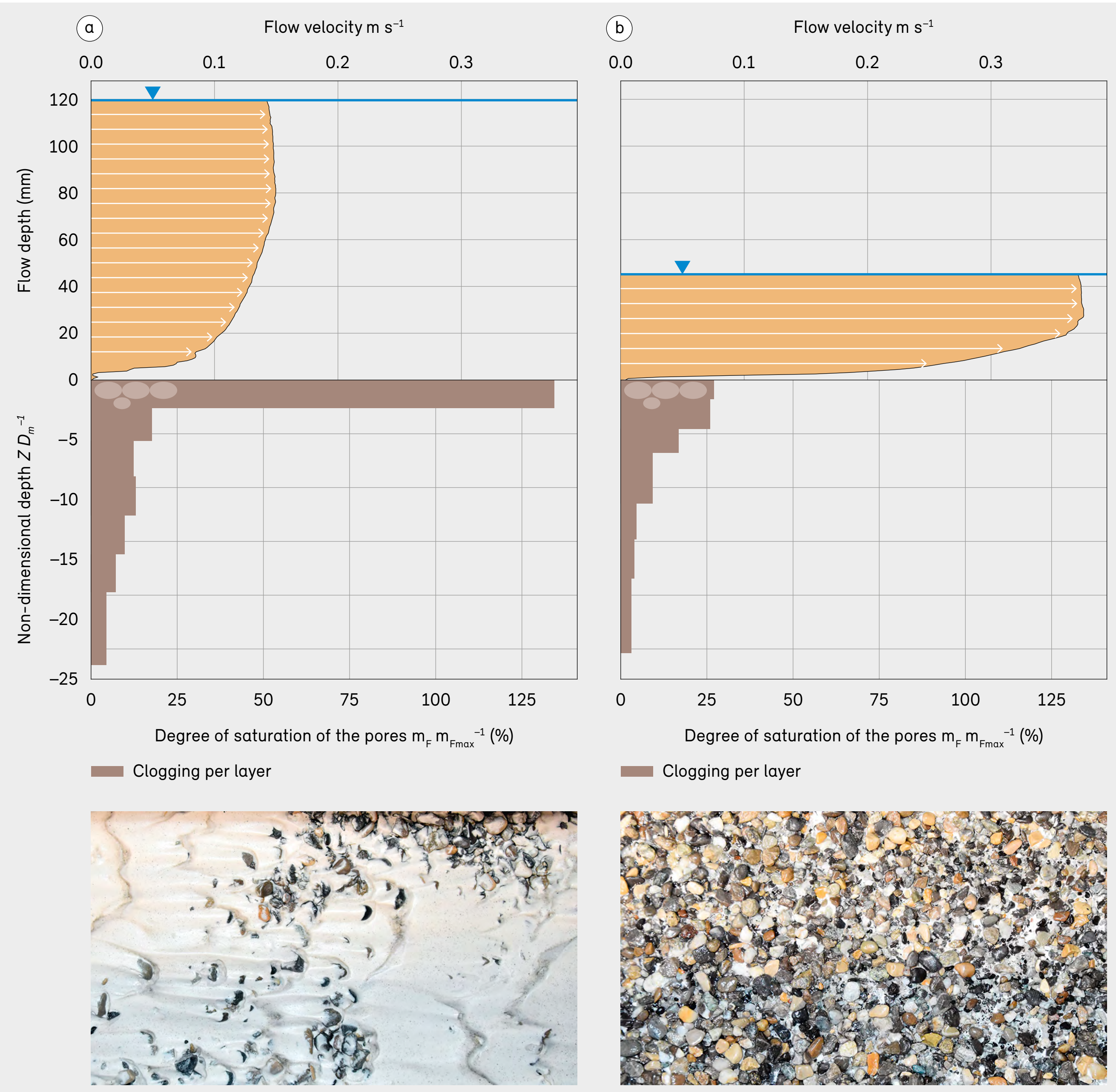
Photo: R. Dubuis

Laboratory experiments were carried out using a flume at the Platform PL-LCH at EPFL (Fig. 42) to reproduce the clogging process under different sets of parameters. The aim of the research was to analyse how the gradient of infiltration and the flow conditions influence the hydraulic conductivity and the vertical distribution of deposited material. Some of the results from these experiments are presented in Figures 43–45.

(i) The grain size ratio between the suspended sediment and the riverbed substrate, as well as the degree of uniformity (i.e. the standard deviation of the grain size distribution), are the main parameters defining how deep fine sediment can penetrate into the substrate matrix. Coarser and more uniform substrate leads to more free percolation across the matrix, until an impermeable or finer layer is reached. Substrate containing both coarse and fine grains results in a thinner clogged layer, due to the filtering effect

Figure 43

Comparison between two experiments at PL-LCH with the same discharge but different slopes and flow depths, resulting in (a) surface clogging and (b) inner clogging. The upper graphs display the flow velocity profiles and the lower ones show the corresponding fine sediment content in the substrate at the end of the experiments, expressed as $m_F\ m_{Fmax}^{-1}$, the mass of fine sediment divided by the maximum mass at saturation; Z = vertical depth, D_m = geometric mean diameter of substrate. Lower flow velocities and corresponding lower shear stress (a), as often observed in pools or on gravel bars, result in surface clogging, visible in the corresponding photo where most of the substrate is covered by fine substrate. At higher flow velocities and corresponding higher shear stress (b), fine sediment is deposited only below the armour layer.



Source: EPFL

of the sand. Fine sediment concentration in the substrate usually follows an exponentially decreasing profile, with the maximum concentration occurring near the top of the clogged layer, corresponding to pore saturation (Figs 43, 44; Cui *et al.* 2008; Gibson *et al.* 2009). However, the finest part of suspended sediment can reach deeper layers of the riverbed.

Larger pores allow more advection inside the riverbed, bringing particles into zones with low shear stress where they can easily settle. Experiments have shown that coarser gravel increases the deposition of clay in comparison to sand substrate (Mooneyham and Strom 2018). In this way, coarser gravel on top of finer substrate, i.e. an 'armour layer', can increase deposition and the formation of a clogged layer beneath the top layer.

(ii) The flow conditions impact the advection within the hyporheic zone, as well as the deposition rate. Deposition of fine sediment through advection seems to lead to less consolidation than through infiltration (Cunningham *et al.* 1987), due to less forcing and a smaller pressure differential in the absence of seepage. In the long term, flow conditions have an influence on the grain size distribution of the substrate. At low velocity and thus low shear stress, fine sediment can be deposited by gravity and surface clogging is possible (Fig. 43). Under high shear stress, the top of the clogged layer is positioned below the surface of the riverbed, at a depth where no resuspension is possible. This limits the increase of the degree of clogging, i.e. hydraulic conductivity reaches a minimum level (Schälchli 1993).

(iii) Exchanges between the groundwater and surface flow have a considerable effect on clogging, through infiltration and exfiltration. In the case of exfiltration (or upwelling), the mean flow is towards the surface, impeding the penetration of surface flow and the deposition of fine particles. Clogging is limited to local areas, depending on the non-uniformity of the hyporheic flow. In the case of infiltration (or downwelling), part of the surface flow loaded with suspended particles is directed towards the groundwater, and the riverbed substrate acts as a filter. The water flux depends on the percolation gradient (loss of water head over a certain distance) and the hydraulic conductivity. A high gradient of percolation usually increases the depth of the clogged layer (Schälchli 1993; see also Fig. 44). Up- and downwelling can have different mechanisms, from dune-shaped beds to regional exchanges between the groundwater and surface flow (Tonina and Buffington 2009).

(iv) Findings from various studies have suggested that higher fine sediment concentrations increase the deposition rate and accelerate the clogging process (Schälchli 1993; Mooneyham and Strom 2018). The quantity of deposited material and the related decrease in hydraulic conductivity depend on the concentration of fine sediment (Fig. 45). A more consolidated and thicker clogged layer seems to appear when particles accumulate slowly, as more particles are able to fill the pores (Fetzer *et al.* 2017)

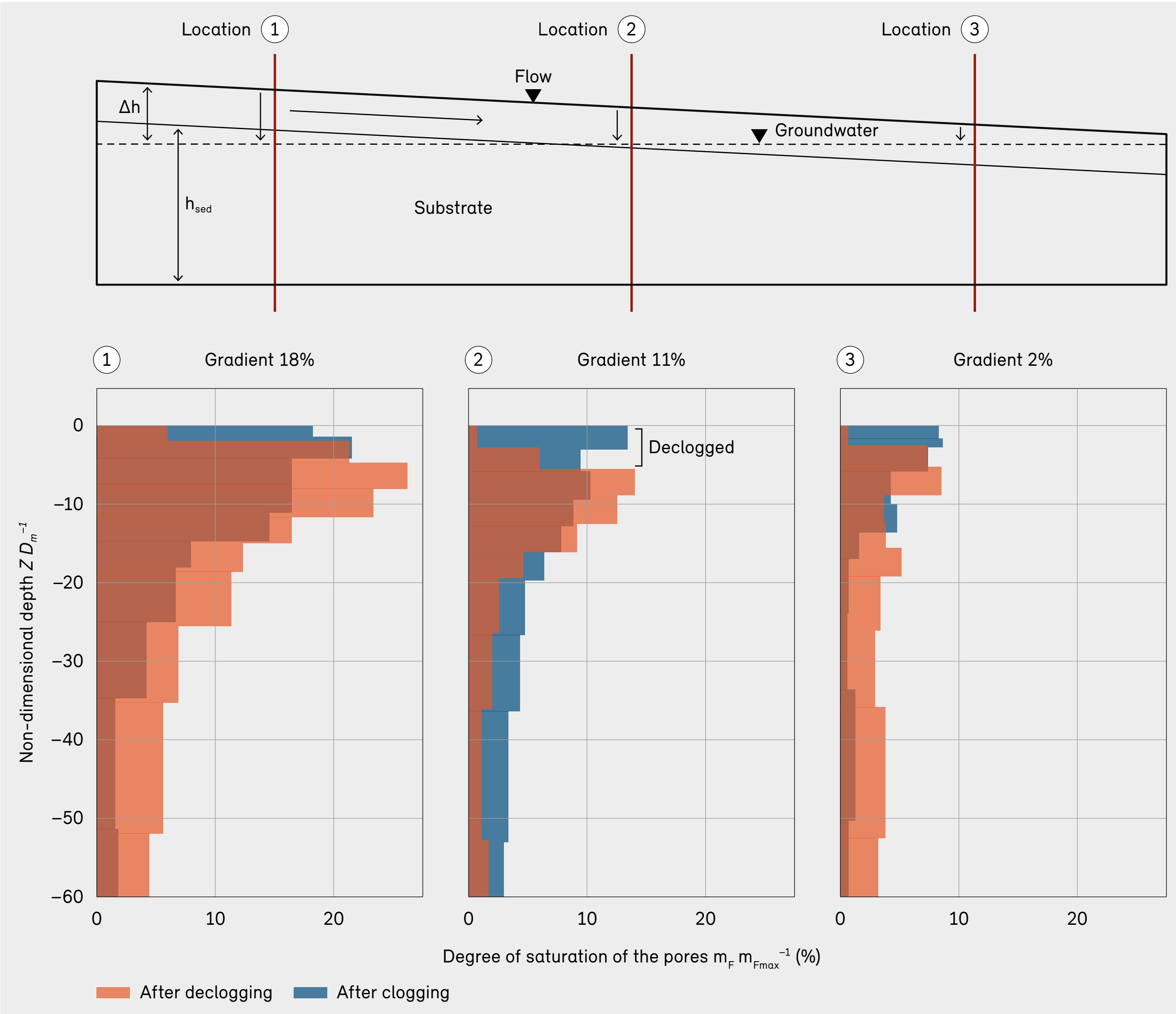
7.1.4 Spatial distribution and riverbed dynamics

Natural riverbeds can be seen as a mosaic of locally varying hydro-morphological conditions at the scale of the river width, leading to the development of clogging in various forms and to varying degrees within the same river. The degree of clogging in a river section must be analysed in both space and time, including seasonal changes in flow and fine sediment concentration. It is usually defined in terms of hydraulic conductivity, porosity and degree of consolidation of the hyporheic zone. Surface clogging takes place in areas of low flow velocity, i.e. in shallow water on gravel bars and near riverbanks, and possibly also in pools.

The sediment transported by the river affects the type and degree of clogging that occur. Some rivers are characterized by mass sediment transport happening only during bed-mobilizing flood events, which enable declogging. In other situations, for instance in the channelized Rhone river in the Alps, the transit of finer material over coarser gravel is observed even under low shear stress. Bedload transport does not result in the destruction of the armour layer or the release of trapped fine sediment, since the transport capacity is not able to mobilize more than the fine bedload material.

Figure 44

Effect of declogging on the degree of saturation of the pores at three locations along the flume at PL-LCH, corresponding to different infiltration intensities induced by the steep slope and the horizontal groundwater level. At location 1, the large local gradient of percolation ($\Delta h/h_{sed}$) results in more clogging, as suggested by the high degree of saturation of the pores. At location 3, the small gradient of percolation results in less fine sediment being trapped in the pores, whereas location 2 shows an intermediate situation. Declogging takes place only in the upper part of the substrate, where a decrease in pore saturation is observed over 1 to 4 D_m (geometric mean diameter of substrate) at the three locations.



Source: EPFL

7.2 Declogging

7.2.1 Declogging efficiency

The efficiency of the declogging process depends on the thickness of the mobilized layer during the flood event. In the experiments at PL-LCH, up to around 3 D_m (geometric mean diameter of substrate) were mobilized (Fig. 44). Hydraulic conductivity increases accordingly, with a marked gain when the riverbed begins to be mobilized (Fig. 45). The top layers of substrate are usually the most clogged but also the first to be declogged. Visible declogging does not mean all infiltrated fine sediment has been released to the flow.

According to Schälchli (1993), the non-dimensional shear stress needed to start declogging is around $\theta_K = 0.06$ and full declogging of the riverbed can be observed at $\theta_D > 0.07$, corresponding to a very well developed bedload transport. The minimum duration of a flood required to rinse a river reach depends on the length of the reach and the flow velocity near the riverbed (drift velocity). The latter influences whether the suspended sediment is transported along the entire river reach, as most of the suspended mass usually stays below 20% of the flow depth. This velocity can be estimated from typical log-law profiles.

7.2.2 Consequences of consolidation

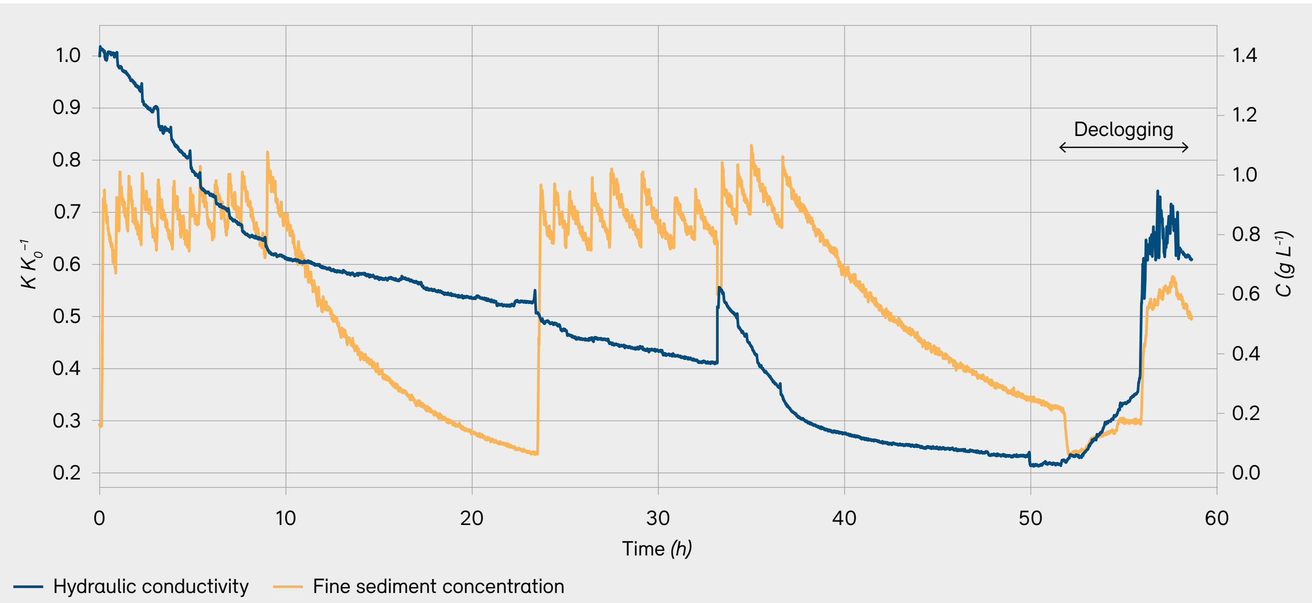
The clogging of substrate entails its consolidation. The first consequence is that the effort needed for fish to free the substrate of fine sediment before spawning is substantially increased. Similarly, it is more difficult for benthos to penetrate the hyporheic zone. The second consequence is that declogging is less likely to occur. This negative feedback loop reduces the possibility of maintaining naturally clogged riverbeds that follow flood cycles. However, research has shown that bioturbation can increase bed mobility, through the winnowing of fine sediment, and can enhance spawning habitat (Buxton 2018). Providing suitable areas for species that contribute to bioturbation, such as salmonids and some types of macroinvertebrates, could therefore help to reduce clogging in the future.

7.3 Human-induced changes and consequences

Even though clogging is a natural process, changes to land use and infrastructures strongly modify the flow and sediment regime in rivers. These elements mainly affect fine sediment concentrations and riverbed mobilization.

Figure 45

Measured global hydraulic conductivity ($K K_0^{-1}$, relative to initial value) during a clogging–declogging cycle. $K K_0^{-1}$ decreases faster under high concentrations of fine sediment. The peak around 33 hours is due to sample collection. Declogging accelerates when the bed starts to be mobilized.



Source: EPFL

Multiple factors affect the concentration of fine sediment in rivers. The timing and duration of periodically high fine sediment concentrations directly determine its effect on clogging. The concentration of fine sediment in rivers like the Rhone, which is characterized by the presence of many hydropower plants and glacier melt water, stays at medium to high levels all year round. In this case, infiltration over long periods leads to pronounced inner clogging. However, more research is necessary to understand the cyclic effect of variable flow conditions and high fine sediment concentrations combined with flooding.

In more natural river basins, medium or high fine sediment concentrations in the flow are usually correlated with flood events, and most of the clogging process takes place during the hours or days following these events. In rivers with riffles and pools, dynamic conditions and local up- and downwelling create a patchy distribution of fine sediment. The dynamic shape of the river over time contributes to the declogging of previously clogged bars and the renewal of suitable spawning habitat.

Changes associated with human activities can be summarized as follows:

- Changes to land use and, the presence of open soil and erosion due to agriculture and construction: more clogging due to higher fine sediment concentrations can result in a more consolidated clogged layer which is more difficult to break during natural floods.
- Climate change: higher temperatures, an increase in extreme precipitation events, and accelerated glacier melting result in increased water flow with high concentrations of fine sediment.
- River channelization: uniform flow conditions are combined with low variation in gravel size. The infiltration rate can vary along a section and result in different degrees of clogging. In the presence of an armour layer, the riverbed is rarely mobilized and renewed. Bedload transport, or occasional breaking of the armour layer, can limit the formation of a clogged layer near the substrate surface, but a deeper clogged layer can form.
- Regulated (residual) flow in rivers downstream of dams, sediment discontinuity, reduction of flood frequency, and mobilization of sediment: obstruction of sediment transport leads to coarser substrate, due to bedload deficit and riverbed erosion (Facchini 2017; see also Chapter 9; Mörtl *et al.* 2023). It leads to the formation of a coarse armour layer that is rarely remobilized. As a consequence, declogging is hampered. The absence of floods transforms the riverbed into a sink for fine sediment. Bio- and chemical clogging can increase these effects. The coarse armour layer promotes the capturing of fine sediment, which deposits underneath the armour layer, as observed along the Sarine River (FR). Regulated flow decreases the potential for morphogenic flood responses and thus diminishes declogging possibilities.
- Sudden release of a large amount of fine sediment (reservoir flushing): large amounts of fine sediment are deposited on the surface and top layers of the riverbed. Surface clogging is likely to occur in pools and in temporarily wetted or low shear stress areas. A rinsing with clean water can help recover an unclogged riverbed surface, but a sufficient shear stress is needed to release the fine sediment trapped in the hyporheic zone.
- Hydropeaking: even though variable flow occurs, the shear stress developed by flood pulses is usually not enough to achieve declogging. An armour layer that is resistant to recurrent discharge can build up. It is sometimes suggested that hydropeaking leads to more clogging (Schälchli, Abegg + Hunzinger 2002). However, even though more research is needed, a recent study (Hauer *et al.* 2019) indicated that no direct correlation seems to exist between fine sediment infiltration and the magnitude of discharge variability in rivers affected by hydropeaking. However, in such rivers a difference often exists between the permanently wetted area, without surface clogging, and the temporarily wetted area, where fine sediment accumulates and forms a seal. This may be due to the erosion and deposition on banks caused by the high frequency of flow pulses.

7.4 Conclusions

The grain size distribution of substrate and the interaction between the surface flow and the groundwater have significant effects on clogging and declogging, with upwelling preventing large-scale clogging. The natural and cyclic process is modified by human infrastructures and activities, due mainly to higher fine sediment concentrations and changes to the flood regime and sediment transport.

Instead of the patchy, locally varying degree of clogging found in more natural systems, channelized rivers with regulated flow experience more clogging of large areas and almost no seasonal declogging. To maintain good vertical connectivity in order to improve fish spawning success and habitat conditions for benthos, at least partial declogging events should take place on a yearly basis. Successful declogging of the hyporheic zone is highly dependent on floods capable of mobilizing the substrate and breaking the armour layer. More natural rivers with more natural floods (resulting in declogging) and more natural sediment transport are needed. Further, the adverse effects of bio- and chemical clogging should not be neglected, especially in systems with warmer water.

Box 10: In practice – Evaluate clogging

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An important aim of Swiss water protection policy is to restore watercourses by defining space provided for water, implementing restoration measures, and reducing the ecological damage caused by the use of hydropower. In this context, two implementation guides describe practical methods for analysing internal and external clogging (Tonolla *et al.* 2017).

These analysis methods have been applied in several Alpine and pre-Alpine rivers, e.g. the Saane/Sarine, the Rhone, the Dranse de Ferret, the Dranse de Bagnes and the Matter Vispa. The method of Schälchli, Abegg + Hunzinger (2002), which involves assessing the degree of clogging (from none to very high) using comparative images, is practical and widely used, but it is limited to the temporarily wetted part of the river. The assessment is ideally made during severe low water conditions and good weather. The method developed by Guthruf (2014) (pull-out force of a rod) and the boot method (force required to enter the substrate) (Schälchli, Abegg + Hunzinger 2002; Pulg *et al.* 2013) are alternatives for assessing clogging in wetted areas. However, their applicability is inadequate in highly structured alpine streams with steep slopes (>1%). Due to the relatively coarse substrate and potential presence of armouring, there is a high risk of always assigning the highest clogging class, regardless of the actual degree of internal clogging.

To obtain robust results, three or four samples per site should be collected, different methods should be compared and river reaches which are not influenced by human activities should be analyzed. In the interpretation, it is important to consider the background conditions as (1) natural clogging, often present in the case of glacial water; (2) the last flood that reshaped the bed or removed the armouring layer; and (3) particular events such as debris flows, landslides and reservoir flushing.

Safe working conditions in the riverbed and especially downstream of hydroelectric installations must also be considered. Thorough work planning is a key factor in ensuring efficient site assessments.

8 Grain size distribution and brown trout life history

Using brown trout, a dominant fish in most Swiss rivers, as a study system, the present chapter focuses on age and sex dependencies in habitat preference and local specificity of life-history traits, including female size at maturity and juvenile traits. The importance of taking these aspects into account when developing strategies to mitigate the impacts of substrate modification on ecologically and economically important species in Swiss rivers is emphasized.

Kunio Takatsu, Marcel Michel, Darryl McLennan, Lucas Aerne and Jakob Brodersen

8.1 Introduction

Of all the environmental components determining habitat quality for organisms, substrate is particularly important for most animals that live within river ecosystems, such as fish, amphibians and aquatic insects. Substrates of a suitable size create shelter, provide quality spawning and nursery habitat, and help support a more dynamic food web and the provision of abundant food resources (Brown 2003; Jonsson and Jonsson 2011). Consequently, any modification to river substrates can impact the animals that are dependent upon them. This consideration is especially important today, as disruption to river substrates is occurring increasingly, in large part due to anthropogenic activities such as the construction of hydropower structures (Baxter 1977; Chen *et al.* 2015). However, in order to effectively establish how the disruption of river substrates can be suitably mitigated, it is imperative that we also investigate how river substrates can affect individual organismal traits (e.g. rates of growth, development and reproduction) and overall river population demographics. In this chapter, using brown trout (*Salmo trutta*) in Swiss rivers as a study system, we present the relationships between substrate structure and demographic and organismal traits.

Brown trout in Swiss rivers serve as an excellent study system to examine the link between substrate structure and life-history traits for multiple reasons. First, their wide distribution across Switzerland means it is possible to study populations originating from habitats with a range of substrate structures. Thus, by investigating how life-history traits vary among populations, we can better understand how substrate structure can affect brown trout ecology. Notably, brown trout is not only widely distributed across Switzerland but also the dominant fish species in most Swiss rivers. For instance, based on the data from the Progetto Fiumi reference collection of Swiss river fish, which was carried out by Eawag in 2013–2018, more than half of the fish that were caught were brown trout in 69% of the rivers sampled across Switzerland (212 out of 308 sampled sites; Brodersen *et al.* 2023). Moreover, brown trout are acknowledged as an ecologically and economically important species (Box 11). Consequently, any changes to brown trout populations can have strong propagating effects on riverine community members. Knowledge on how substrate structure can affect brown trout ecology is therefore essential for predicting how substrate modification, such as compensation for sand and gravel deficit, affects riverine communities in Swiss rivers. In the present chapter, we report results from surveys conducted to examine how substrate can affect trout life-history traits. Specifically, we examine: (i) how habitat (substrate) preference differs depending on trout age and sex and (ii) how female size at maturity differs depending on substrate structure.

8.2 Age- and sex-dependent differences in substrate preference

Substrate structure can affect brown trout spatial distribution, partly because this species is highly dependent on prey items residing on substrate surfaces and in interstitial spaces, and also because it is a substrate-spawning species (Armstrong *et al.* 2003; Jonsson and Jonsson 2011). Notably, as is the case for most animal species (Werner and Gilliam 1984), brown trout individuals exhibit diet shifts during their life span (Jonsson and Jonsson 2011). Moreover, females dig their nests into the substrate when spawning, whereas males are not involved in this activity (Jonsson and Jonsson 2011). It is thus expected that the substrate preference of brown trout differs depending on age and sex. Indeed, age- and sex-dependent differences in substrate preference in salmonid species, including brown trout, are well documented (Armstrong *et al.* 2003; Aas *et al.* 2011; Jonsson and Jonsson 2011). Here, using a brown trout population in the Latrejebach river in the canton of Bern (46°37'18''N, 7°46'04''E; Fig. 46), we examined whether age- and sex-dependent substrate preferences similar to those documented in previous studies are also observed in the Swiss river population (Aerne 2020). We assessed the spatial distribution of brown trout in this small river in early October, just a few weeks before spawning started. Specifically, the sampling site had a total length of 210 m along the river, which we split into 14 subsections 11.5–19 m in length. We then measured brown trout density in each subsection. At the same time, we measured abiotic environmental variables in each subsection: mean water depth, width and velocity, and mean grain size. Moreover, we measured prey invertebrate density in each subsection. Then, we explored the links between trout spatial distribution, age, sex, and abiotic and biotic environmental variables.

There were large variations in both brown trout density and focal environmental variables among subsections. Importantly, trout density changed with mean grain size but the relationship differed depending on stage and sex, as expected, although most relationships were only marginally significant because of the small number of replicates (Fig. 47). Specifically, the total density of brown trout declined as mean grain size increased (Fig. 47a). However, our findings suggested that this overall relationship may differ depending on the stage structure and sex ratio of the population. First, total adult density decreased with increasing mean grain size (Fig. 47b), and this negative relationship was stronger in adult females than adult males (Fig. 47c, d). Further analyses demonstrated that the strong negative relationship between adult female density and mean grain size was partly driven by the females' preference for the river subsection with a higher proportion of substrate theoretically suitable for spawning (<10% female body length; Kondolf and Wolman 1993). In contrast, juvenile density increased with increasing mean grain size (Fig. 47e). Additional analyses indicated that this positive relationship was partially due to the juveniles' preference for the river subsection with a higher abundance of their food items. These results are generally consistent with findings from previous studies on age and sex dependencies in the habitat preference of brown trout and other salmonid species (Armstrong *et al.* 2003), demonstrating the importance of maintaining spatial habitat (substrate) heterogeneity within a river to conserve fish populations as a whole.

Figure 46

Photograph of the Latrejebach river study site (BE).

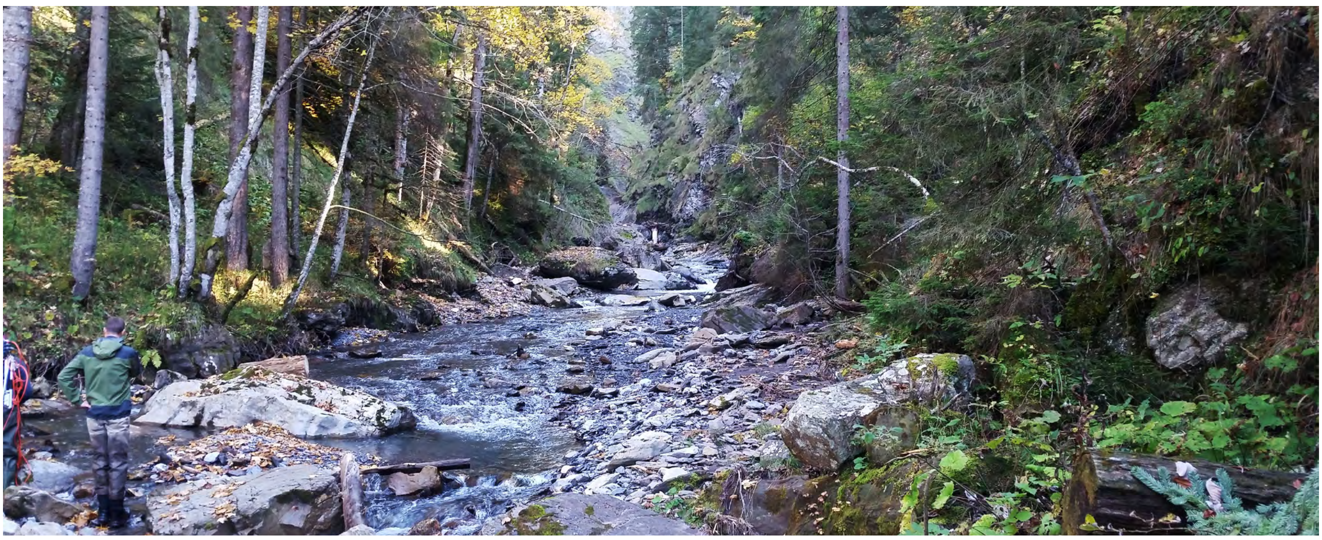
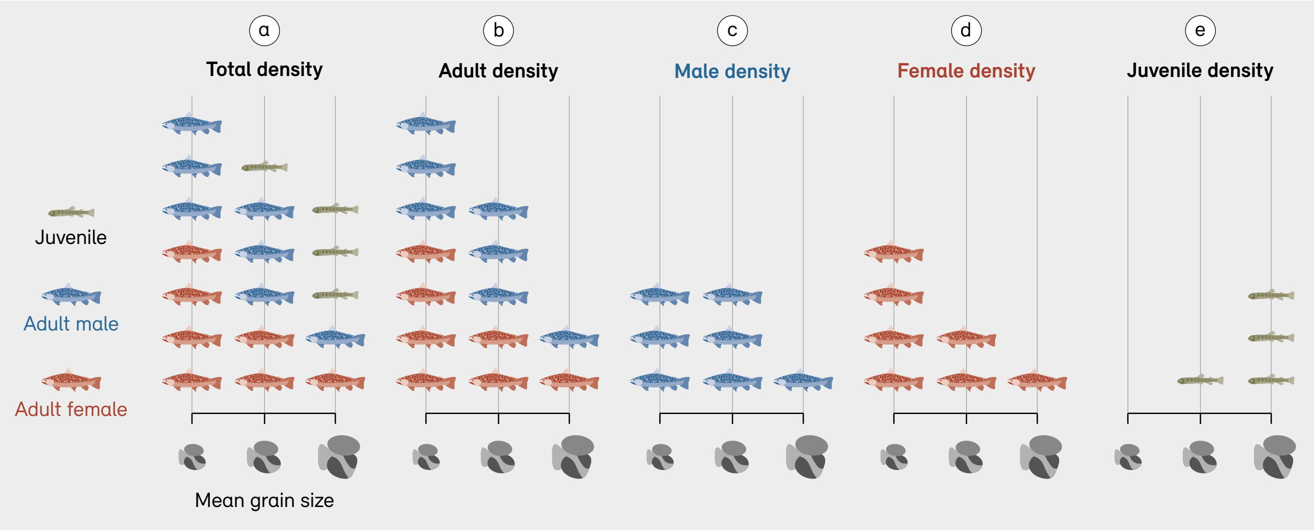


Photo: K. Takatsu

Figure 47

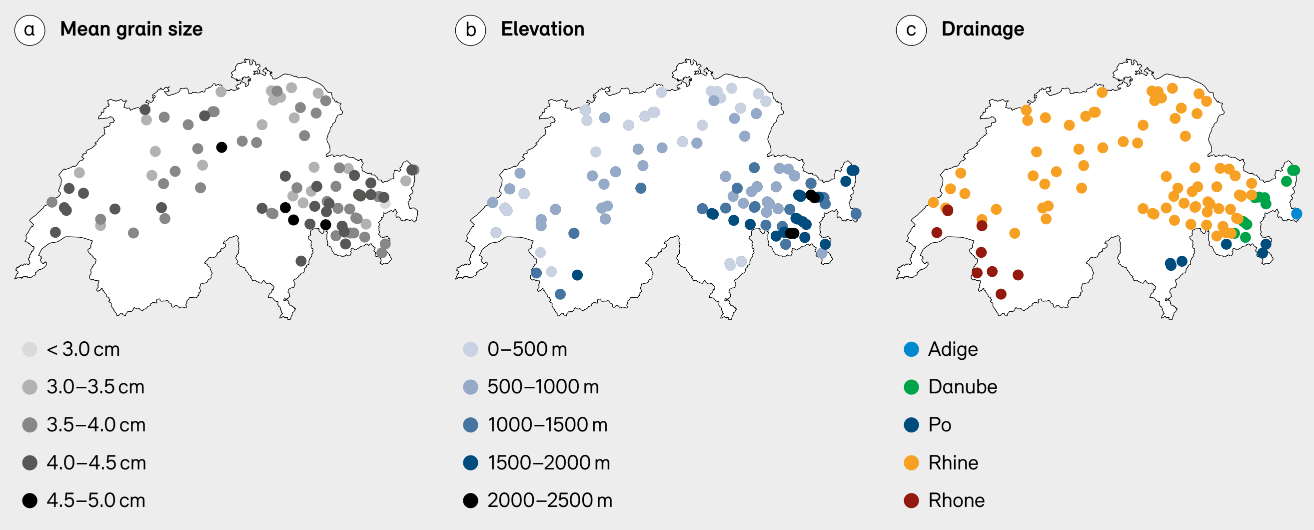
Relationships between mean grain size and (a) total, (b) adult, (c) adult male, (d) adult female, and (e) juvenile brown trout density in the Latrejebach river.



Data source: Aerne (2020)

Figure 48

*Maps of 120 study sites on Swiss rivers. Variation in (a) geometric mean grain size, (b) elevation and (c) drainages. The geometric mean grain size (dg) was calculated using the following equation: dg = (D84) * (D16) $^{0.5}$ (Kondolf and Wolman 1993), where D16 and D84 are 16th and 84th percentile substrate diameters, respectively.*



Data source: Progetto Fiumi and Eawag

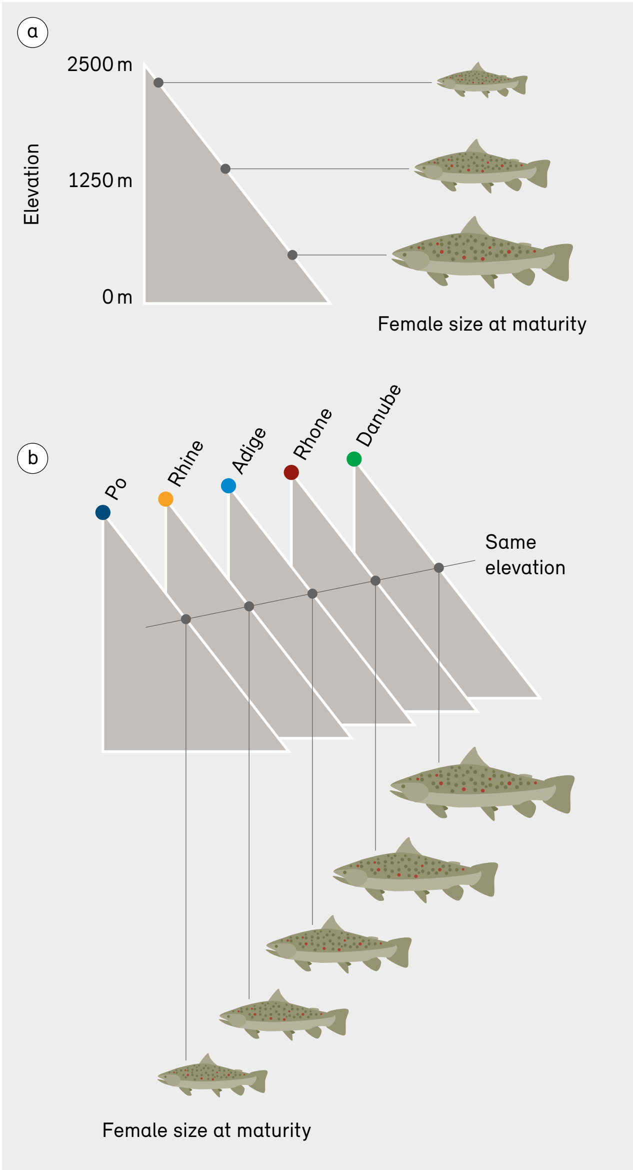
8.3 Link between female size at maturity and substrate structure

As shown in the study on brown trout in the Latrejebach river described above (Fig. 47), adult female brown trout exhibit a preference for habitat with substrate suitable for spawning, which is partly determined by female body size (Kondolf and Wolman 1993). The females' habitat preference is expected to have been acquired and maintained, probably because occupying a habitat with substrate suitable for spawning can strongly affect their reproductive success. Notably, as well as within-river variability, there is large variation in substrate structure among Swiss mountain rivers (Fig. 48a). For example, in 120 rivers containing brown trout (Progetto Fiumi reference collection of Swiss river fish), the largest mean grain size was about 1.7 times larger than the smallest mean grain size (Fig. 48a). It has therefore been proposed that females mature at a larger size in rivers with a larger mean grain size (Riebe *et al*. 2014). Examining the relationship between female size at maturity and local substrate structure can provide valuable knowledge relevant for fine-tuning strategies for mitigating possible harmful effects of substrate modification on brown trout, such as adding fine/coarse pebbles. In this study, we assessed the body size and maturity status of 562 female brown trout collected from the 120 rivers across Switzerland during the Progetto Fiumi survey (Fig. 48). Specifically, we investigated the link between mean grain size and female size at maturity.

In general, larger females tended to be assigned as mature regardless of their origin. However, there were differences in maturity status even among same-sized females. Suppose that a larger female size at maturity is favoured in a river with a larger substrate. At a given female size, we would then expect that female trout originating from a river with a larger mean grain size would not be assigned as mature, while female trout originating from a river with a smaller mean grain size would be assigned as mature. Contrary to this expectation, we did not detect a significant relationship between mean grain size and female maturity status. Instead, we found that female maturity status differed with the elevation of the collection sites and across the Swiss drainages (i.e. Adige, Danube, Po, Rhine and Rhone; Fig. 49). First, at a given size, high-elevation female trout were assigned as mature more often than females at lower elevations, meaning that high-elevation female trout exhibit a smaller size at maturity than those at lower elevations (Fig. 49a). Second, at a given size and elevation, the probability of a female trout being assigned as mature differed across the drainages: Po > Rhine > Adige > Rhone > Danube. This indicates that female size at maturity was largest in the Danube and smallest in the Po drainage (Fig. 49b).

Figure 49

(a) Relationship between elevation and female brown trout size at maturity. (b) Drainage-dependent differences in female size at maturity.



Data source: Progetto Fiumi and Eawag

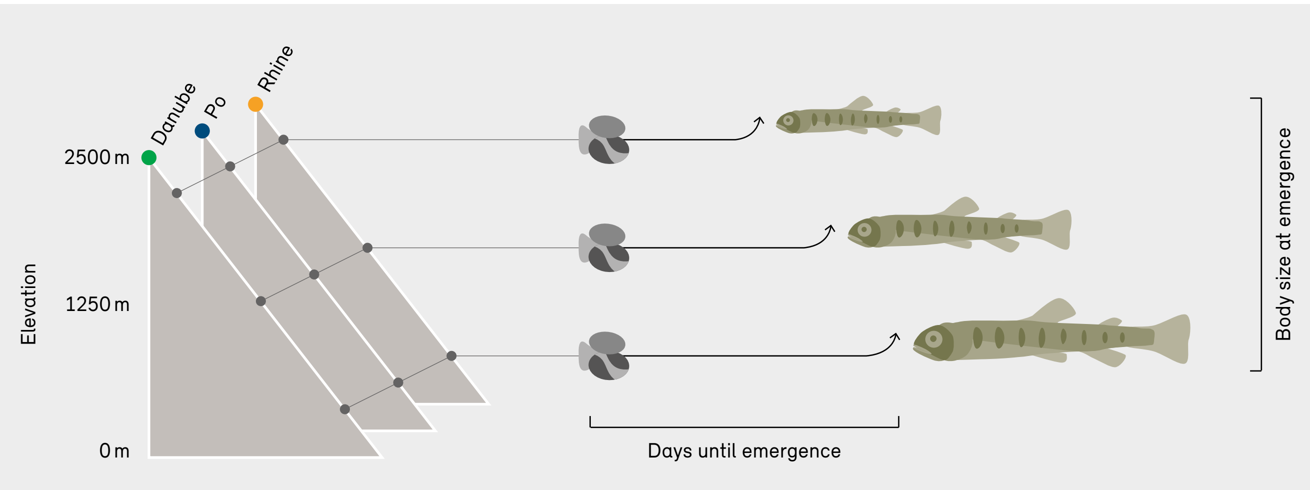
Interestingly, not only female size at maturity but also very early life-history traits, time until emergence, and body size at emergence from the gravel nest differed with the elevation of the collection sites. In an additional study, we reared brown trout embryos from 14 populations from different elevations from three Swiss drainages (Danube, Po, Rhine) in the canton of Grisons. Although we kept the embryos in the same rearing environment (i.e. a common-garden experiment), the time until emergence was shorter and body size was smaller for high-elevation trout than for low-elevation trout (Fig. 50). These differences along the elevation gradient were partly the result of the smaller egg size of high-elevation trout (Fig. 51).

These findings on adult and juvenile trout suggest that environmental factors that vary along an elevation gradient, such as water temperature, conspecific density, predator and prey density, and species composition, could be a critical factor in shaping the whole life history of brown trout. It would be interesting to investigate the adaptive significance of smaller female size at maturity and earlier emergence with smaller body size in high-elevation rivers, and also to determine key environmental factors shaping trait variation along the elevation gradient. Studies exploring mechanisms explaining the drainage specificities in the life-history traits of brown trout would be another interesting next step. It is worth mentioning that intensive stocking activities using several million captive-reared trout could have altered the relationships between elevation, drainage, substrate structure and trout life-history traits in our study (but see Keller *et al.* 2011, 2012). Thus, it would also be useful to examine how stocking history affects female size at maturity and juvenile traits.

Considering the importance of the body size of females in determining their substrate preference (Kondolf and Wolman 1993), the observed variation in female size at maturity is expected to be linked to female substrate preference. For instance, since female size at maturity was found to be smaller for high-elevation trout than for low-elevation trout (Fig. 49a), high-elevation females would be expected to exhibit a stronger preference for smaller substrate. Similarly, since the size at maturity of females from the Po drainage was smallest among the Swiss drainages (Fig. 49b), female trout originating from Po would be expected to exhibit a stronger preference for smaller substrate. Therefore, it could be important to take elevation and drainage specificity into account when fine-tuning substrate modification strategies to benefit brown trout. For instance, the size of fine pebbles used for substrate compensation to improve spawning habitat should be smaller at higher-elevation sites and in the Po drainage than at lower elevation sites and in other drainages.

Figure 50

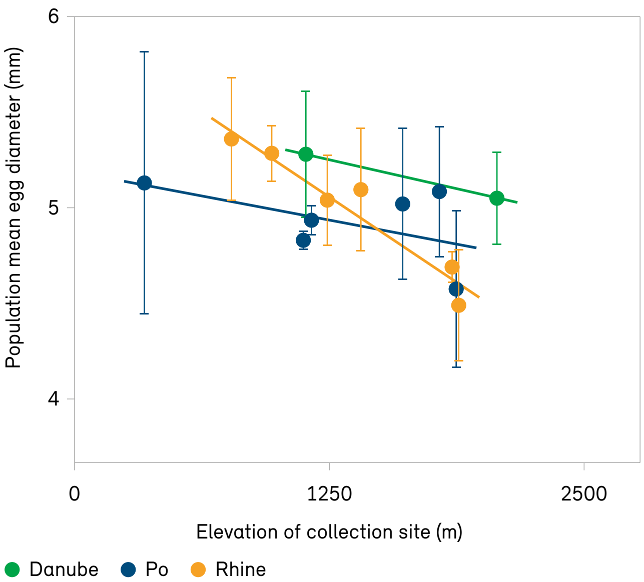
Relationships between elevation of the collection site, drainage, days until emergence, and body size at emergence from the gravel nest. Regardless of the drainage, high-elevation brown trout generally emerged from the gravel nest earlier and with a smaller body size.



Data source: Eawag

Figure 51

Relationships between drainage, elevation of the collection site, and population mean egg diameter of 14 brown trout populations in the canton of Grisons. Error bars denote standard deviation.



Data source: Eawag

8.4 Implications for strategies to support trout populations and improve their habitats

In the present chapter, we report the results from surveys showing: (i) age- and sex-dependent differences in substrate preference (Fig. 47) and (ii) no clear link between female size at maturity and substrate structure, but instead variation in female size at maturity among drainages and across an elevation gradient (Fig. 49). The former results emphasize the importance of maintaining spatial substrate heterogeneity within a river to conserve the important fish species. Considering the female preference for substrate suitable for spawning and the female body size dependency of the substrate preference (Kondolf and Wolman 1993; Riebe *et al.* 2014), the latter results suggest that females' preference for substrate differs depending on the drainage and elevation. Therefore, the drainage and elevation should be considered when fine-tuning strategies for restoring brown trout spawning habitat. For example, while an increase in spatial substrate heterogeneity might improve habitat quality for brown trout overall, sections with relatively small pebbles should be established in the Po drainage, considering the smaller female size at maturity of trout originating there (Fig. 49). However, in our study we did not directly examine how the differences in female size at maturity among drainages and across populations at different elevations are linked to female substrate preference. Therefore, investigating the variation in substrate preference among drainages and across elevations would be an important next step. Moreover, studies on the link between substrate and the ecology of other fish species, particularly species residing in slow-flow rivers (e.g. chub, barbel, stone loach and gudgeon), are needed for a comprehensive understanding of how substrate modification affects the fish community in Swiss rivers.

Moreover, our study provides insight into trout fishery management (Box 11). Female size at maturity differed among drainages and across populations from different elevations (Fig. 49). Similarly, the timing and size at emergence from the nest differed among populations from different elevations (Fig. 50). Suppose that the variation in life-history traits among drainages and across elevations has been shaped and maintained by natural selection associated with environmental variables that vary across the drainages and along the elevation gradient. Implementing uniform fishery management strategies across rivers, including harvest size regulations and stocking strategies, could result in different consequences for the local trout populations, depending on the drainage and elevation.

While fishery management strategies considering the local specificities of trout life-history traits, so-called 'small-scale fisheries management' strategies, have been acknowledged, implementing them is often challenging, as described in Box 11. Further studies on Swiss brown trout ecology are needed to form feasible fishery management strategies. For instance, examining egg size variation across Swiss rivers (e.g. Fig. 51) could provide helpful information for improving stocking strategies. This is because egg size is a key factor determining trout early life-history traits, and eventually growth and survival in later life stages (Einum and Fleming 1999). Suppose that the egg size variation among drainages and elevations observed for Swiss brown trout (Fig. 51) has been shaped and maintained by natural selection acting on the early life stages. Fisheries managers could stock juveniles originating from eggs whose size is similar to that observed in the natural population of a focal stocking site and from the same management unit (individuals within the same unit are assumed to be genetically more similar than those in different units). The phenotypic characters of the stocked juveniles would be then suitable for that site and their genetic characters would be similar to those observed in the wild. Thus, even no changes to the current, relatively coarse management unit (Box 11), fisheries managers could effectively supplement the trout with consideration of local genetic specificity. The accumulation of such knowledge regarding the basic ecology of Swiss brown trout might help set management strategies for this ecologically and economically important fish species while still considering feasibility and genetic integrity.

Box 11: In practice – The challenge of small-scale fishery management

Marcel Michel, Office for Hunting and Fishing, GR

About one-third of all brown trout catches in Switzerland's rivers are made in the canton of Grisons. Accordingly, angling is of great importance in Grisons. For the past 160 years, the Canton has been the sole holder of fishing rights and has been responsible for fisheries management. For an entire century, river-specific characteristics were only given marginal consideration in fisheries management. There was little differentiation in catch regulations, and management guidelines were geared towards expansion. The function of brown trout as a usable product rather than local, river-specific considerations formed the cornerstones of fisheries management.

Based on the findings from the present study, the previous fisheries management strategy, implemented by the cantonal administrations, would have to be classified as a failure. However, if one takes into account the degeneration of the river habitat, the growing number of anglers, and the lack of knowledge about genetic integrity during the same period, the decisions made at that time are certainly understandable. And where does Canton Grisons stand today in terms of setting goals for fisheries management? The poor condition of the rivers and the high demand for use on the part of fisheries have remained as the boundary conditions. Scientific findings and first-hand experience have led to a new approach to fisheries management over the last 20 years. The limitations and negative effects of 'haphazard' management of brown trout, as well as the problem of poorly differentiated catch size limits, have been recognized. The principle of 'small-scale fisheries management' has been accepted, but it poses considerable challenges to the responsible parties. For example, evaluating the size of brown trout as they enter sexual maturity was possible for only 50 stream segments, within the inventory of 1600 km of rivers and about 2500 m of elevation. Limitations in terms of time, logistics and funding restricted the level of detail at which river-specific catch size limits could be defined. Based on these surveys, 6 minimum catch sizes or catch windows were defined for about 450 river sections, depending on the elevation, river size and fishing pressure. The findings from the study presented here concerning local adaptation of the size of female brown trout at sexual maturity should thus carry more weight in management strategies.

It is particularly difficult to consistently consider local-scale aspects in brown trout management. Until a few years ago, the management units (MUs) were kept large and were based on eight main catchment areas. In the medium term, Canton Grisons aims to define 19 regions as MUs. To fulfil the regional stocking plan, brown trout spawning material from a particular MU should only be used within that MU. The same applies to the offspring of any parent stock. The separation into 19 MUs poses major logistical challenges for the 7 fish hatcheries in the canton of Grisons. For example, in a given hatchery, the fish used for stocking and also the mother strains of up to six MUs must be kept strictly separate. The Canton is aware that there is a wide range of rivers within the 19 MUs in terms of elevation, but further refinement of the MUs into elevation bins is not currently feasible. However, if elevation, rather than geographic unit, is the main driver of local adaptation, then it is worth considering dividing the MUs into cross-regional elevation bins rather than regions (sub-catchments).

Finally, and most importantly, the threshold for stocking requirements must be further refined. Specifically, fish stocking should only be applied where it can be proven that natural spawning cannot make a sufficient contribution to a usable trout stock. The Canton has a legal mandate that includes ensuring sustainable use. Correctly executed fish stocking and river-specific catch regulations continue to be an important component of modern fisheries management.

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.

Christian Mörtl, Robin Schroff and Giovanni De Cesare

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.

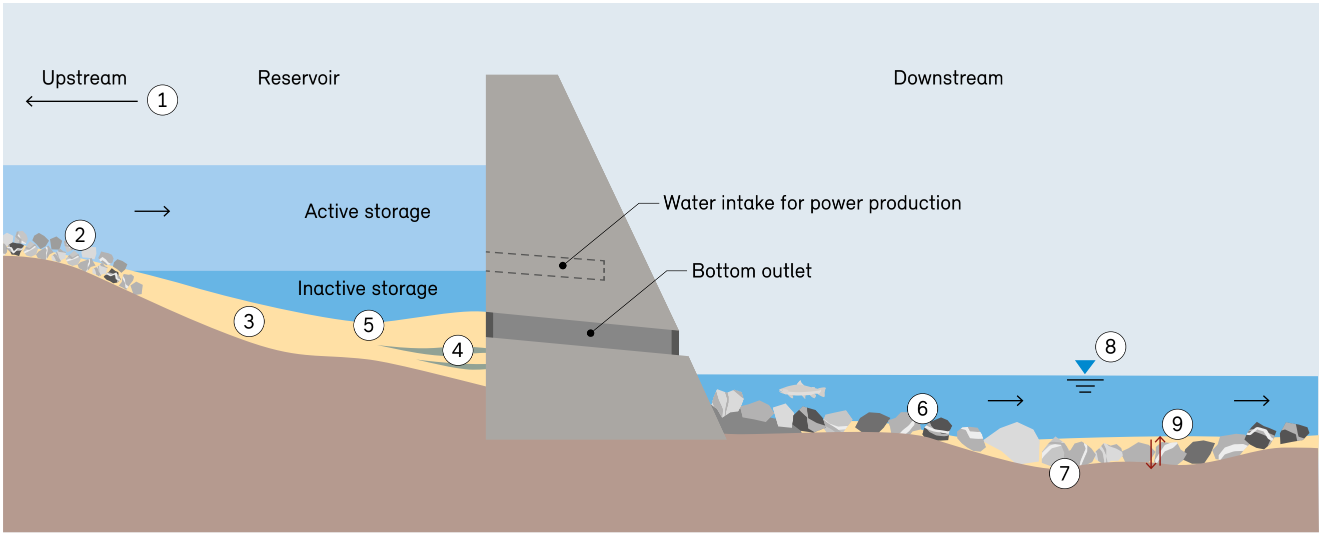


Figure adapted from Mörtl *et al.* (2020)

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

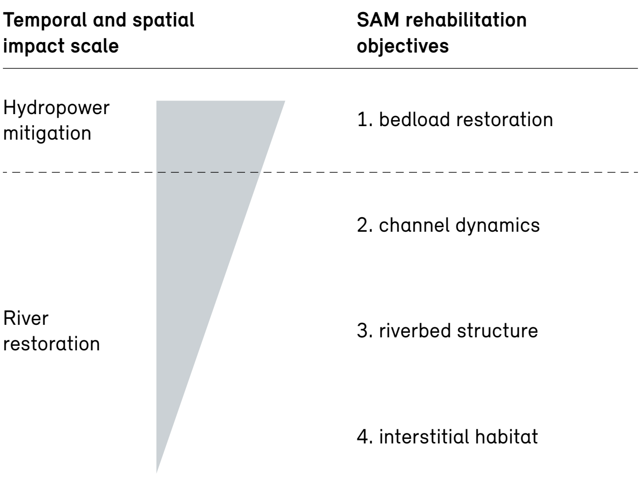
All of the main objectives of sediment augmentation are related to improving the eco-morphodynamics at different spatial and temporal scales (Fig. 53; Mörtl and De Cesare 2021). For example, the aim of bedload restoration is to re-establish natural bedload transport, resulting in better morphological 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

Figure 53

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



Source: EPFL

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.

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,

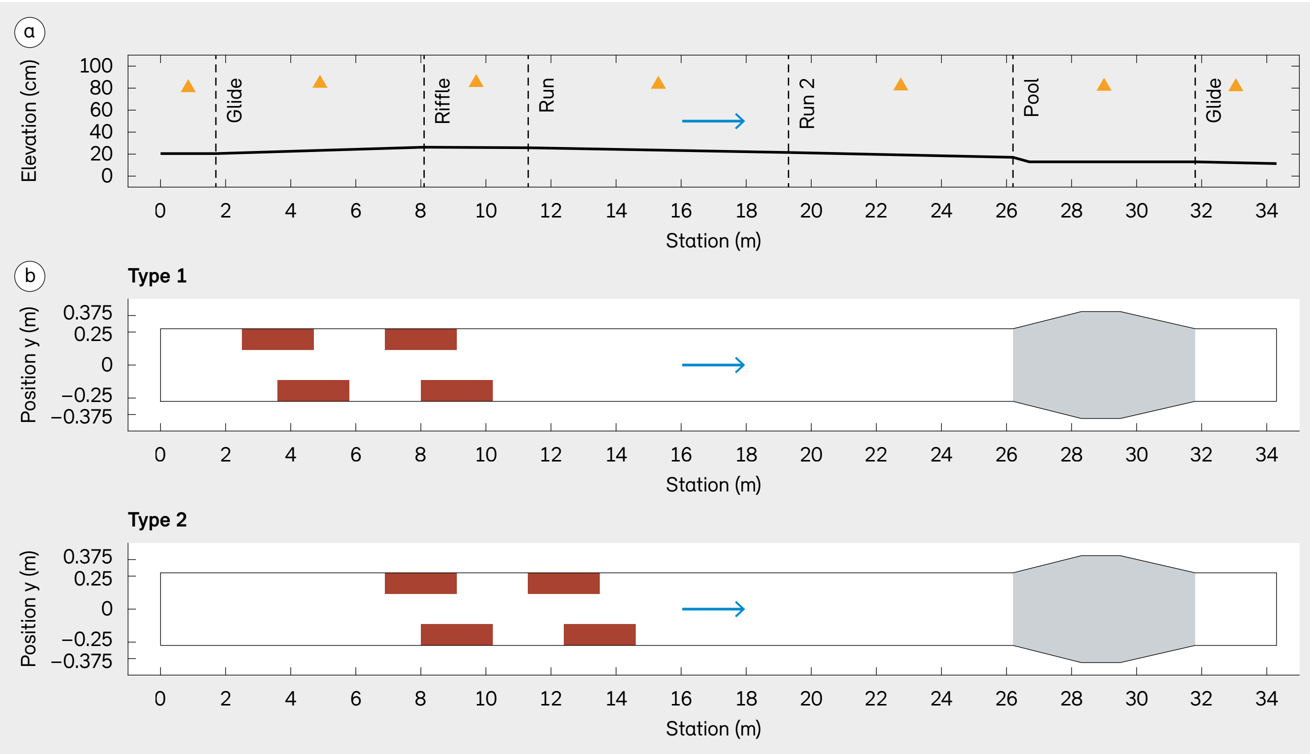
Figure 54

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‰).

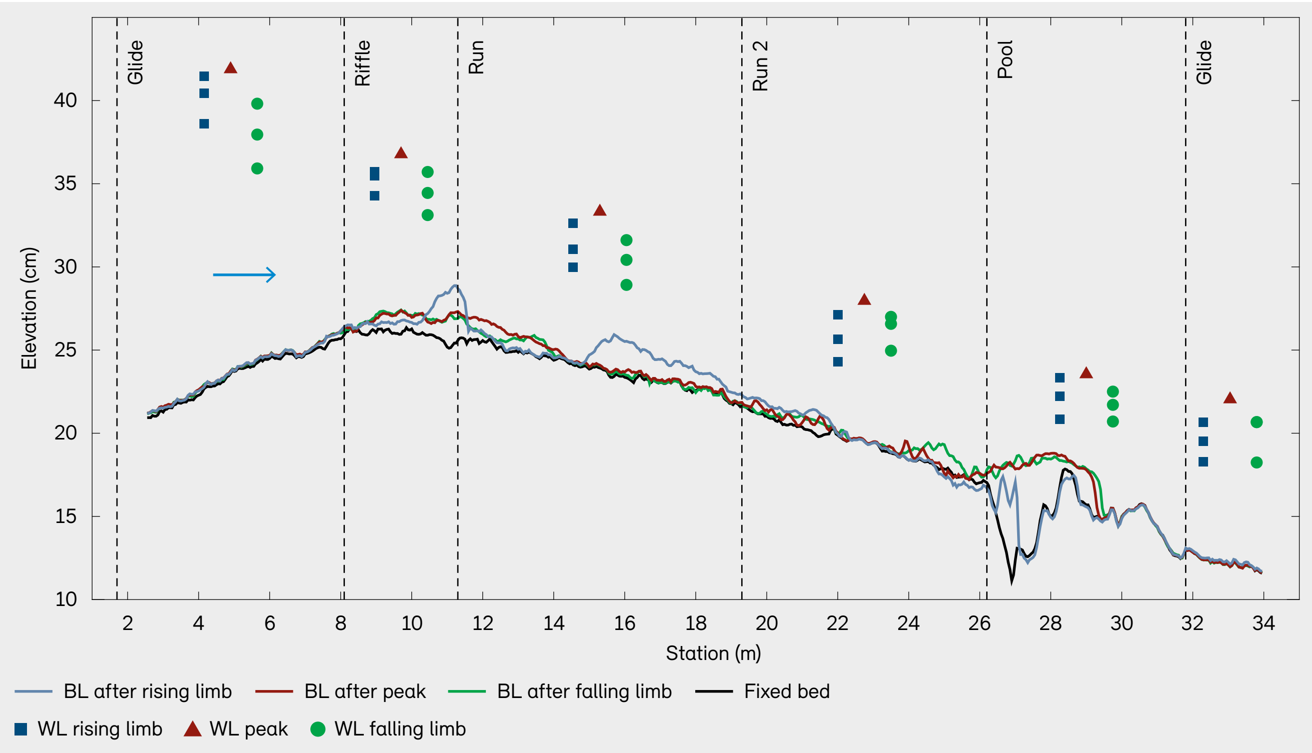
In a typical sequence in a gravel bed river, pools are formed downstream of runs. They act as sediment retention basins, which store and send out waves of sediment sporadically and are thought to be a major contributor to sediment pulse releases (Dhont and Ancey 2018). In the laboratory experiment, most 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.

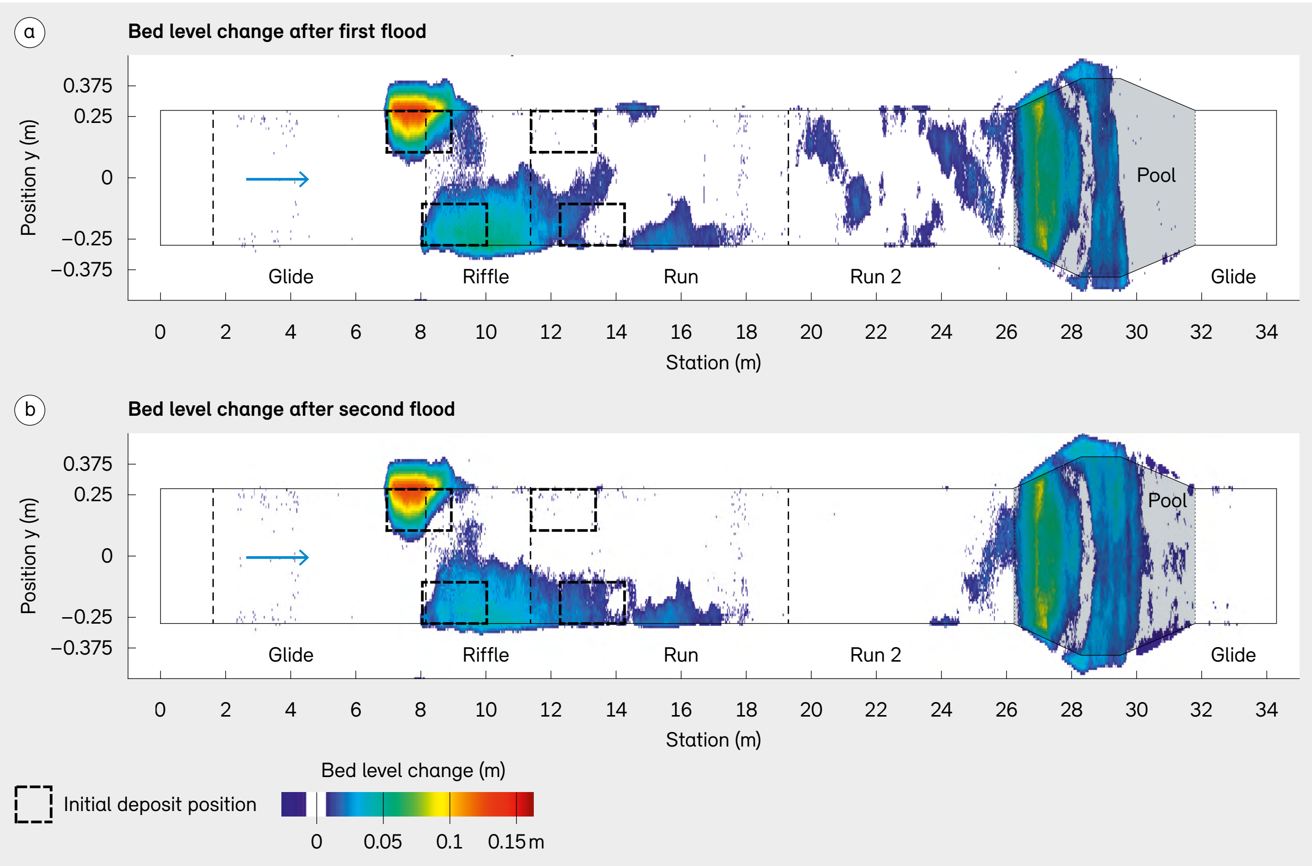
9.4 Outcome evaluation

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
Sandro Ritler, Holinger AG

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.

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