# 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.*

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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).*

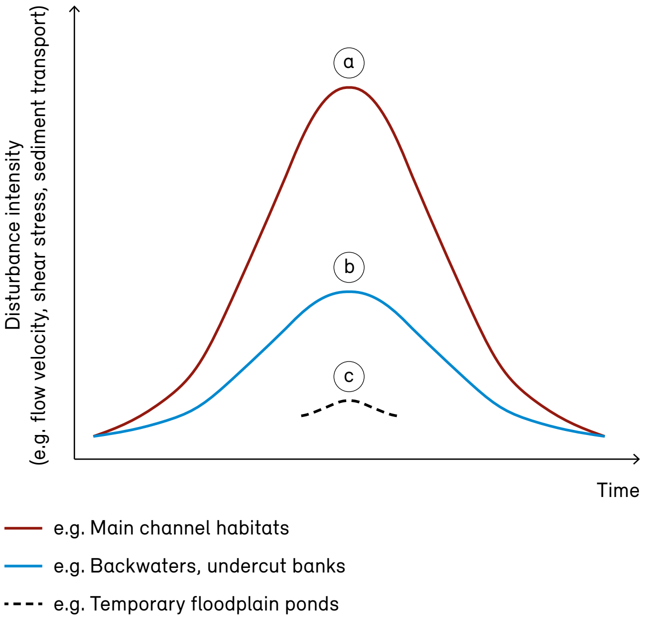


Figure adapted from Weber *et al.* (2013)

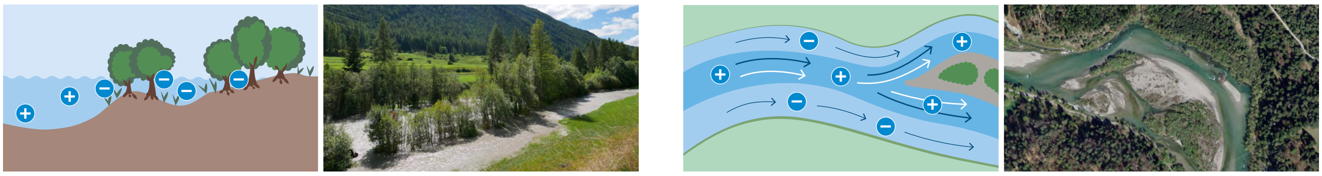
**Figure 28**

*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*

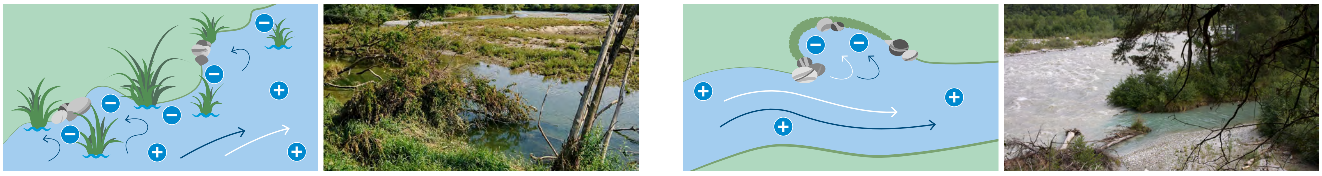
ⓐ **Reach/side channel**

ⓑ **Tributary**



ⓒ **Floodplain (including ponds)**

ⓓ **Hydraulic variability**



ⓔ **Complex shoreline**

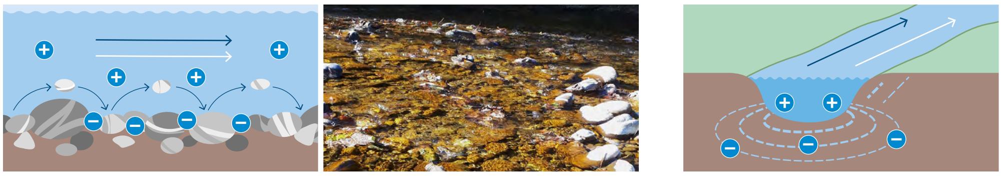
ⓕ **Backwater**

ⓖ **Large wood accumulations**

ⓗ **Vegetation**

ⓘ **Boulders**

ⓙ **Undercut banks/roots**



ⓚ **Interstitial pore space**

ⓛ **Hyporheic zone**

⟶ Flow

⟶ Bedload transport

⊕ High intensity

⊖ Low intensity

## 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*

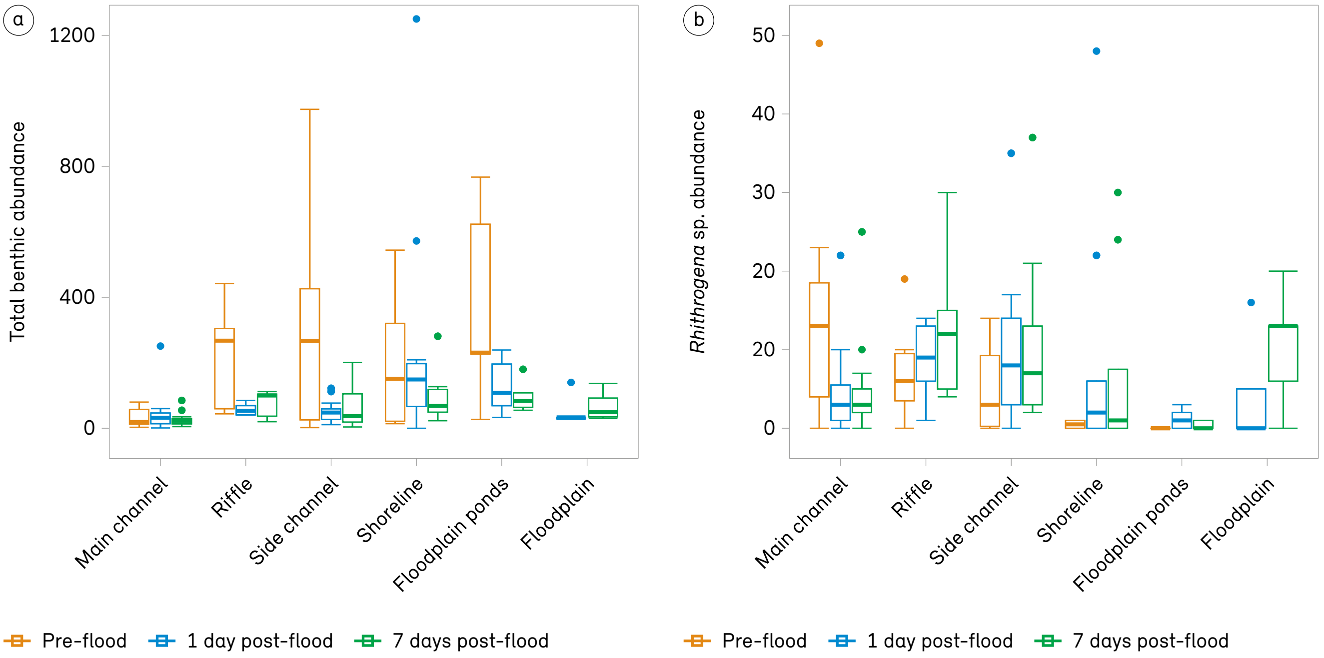
Prior to the artificial flood, benthic macroinvertebrates in each reach represented distinct communities, likely reflecting the habitat heterogeneity present. Following the flood, communities became more similar to each other, with little variation between reaches. However, the number of different insect 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**

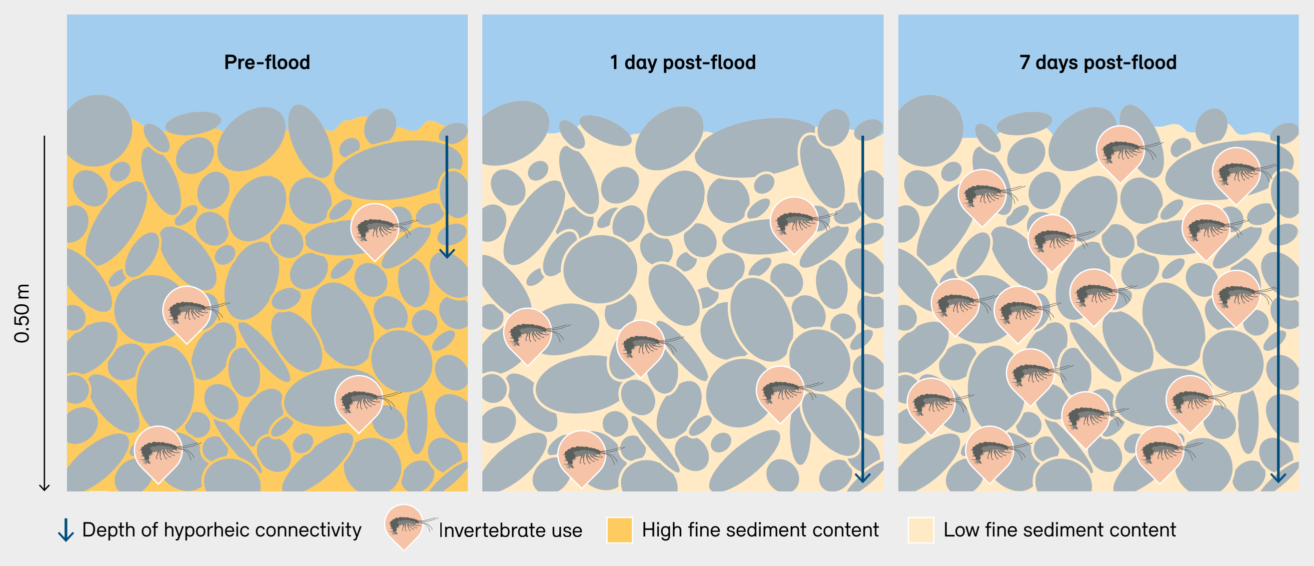
*Boxplot of (a) total benthic macroinvertebrate abundance and (b) Rhithrogena sp. benthic abundance associated with an artificial flood in the Spöl river. Abundance represents the number of individuals per 30-second kick sample (following Murray-Bligh 1999).*



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

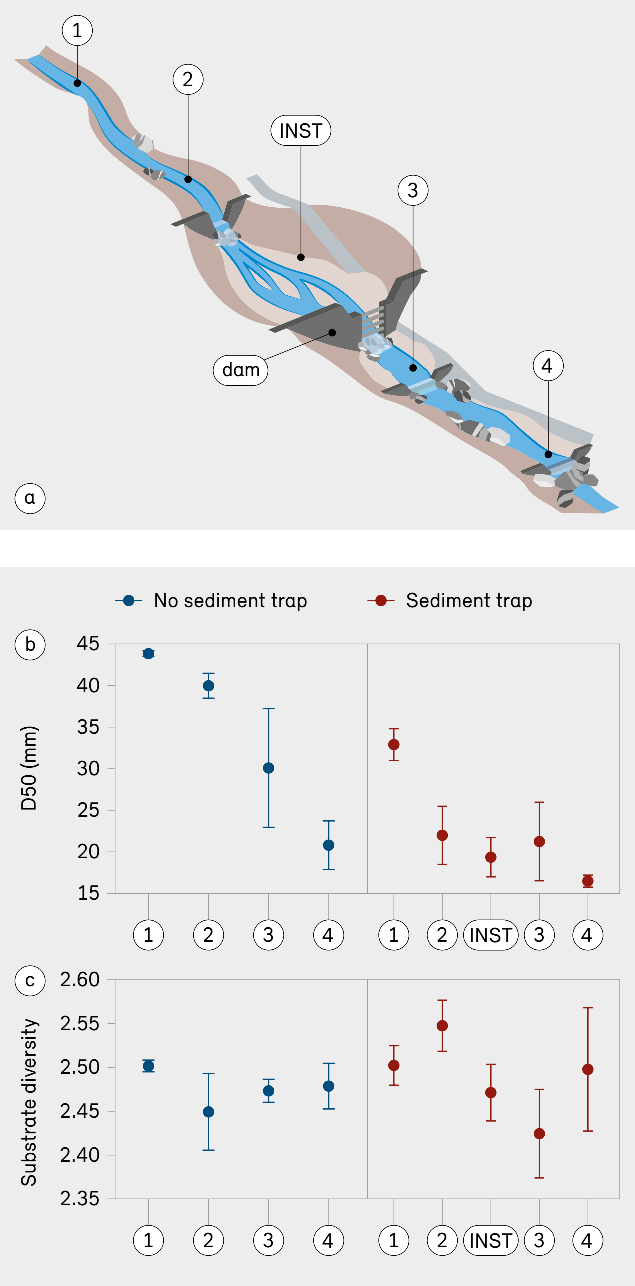
We studied the effects of sediment traps on instream refuge provision and associated macroinvertebrate communities in four streams with a sediment trap and compared them with three streams without a sediment trap in central Switzerland (Mathers *et al.* 2021b). All streams were chosen to have comparable 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

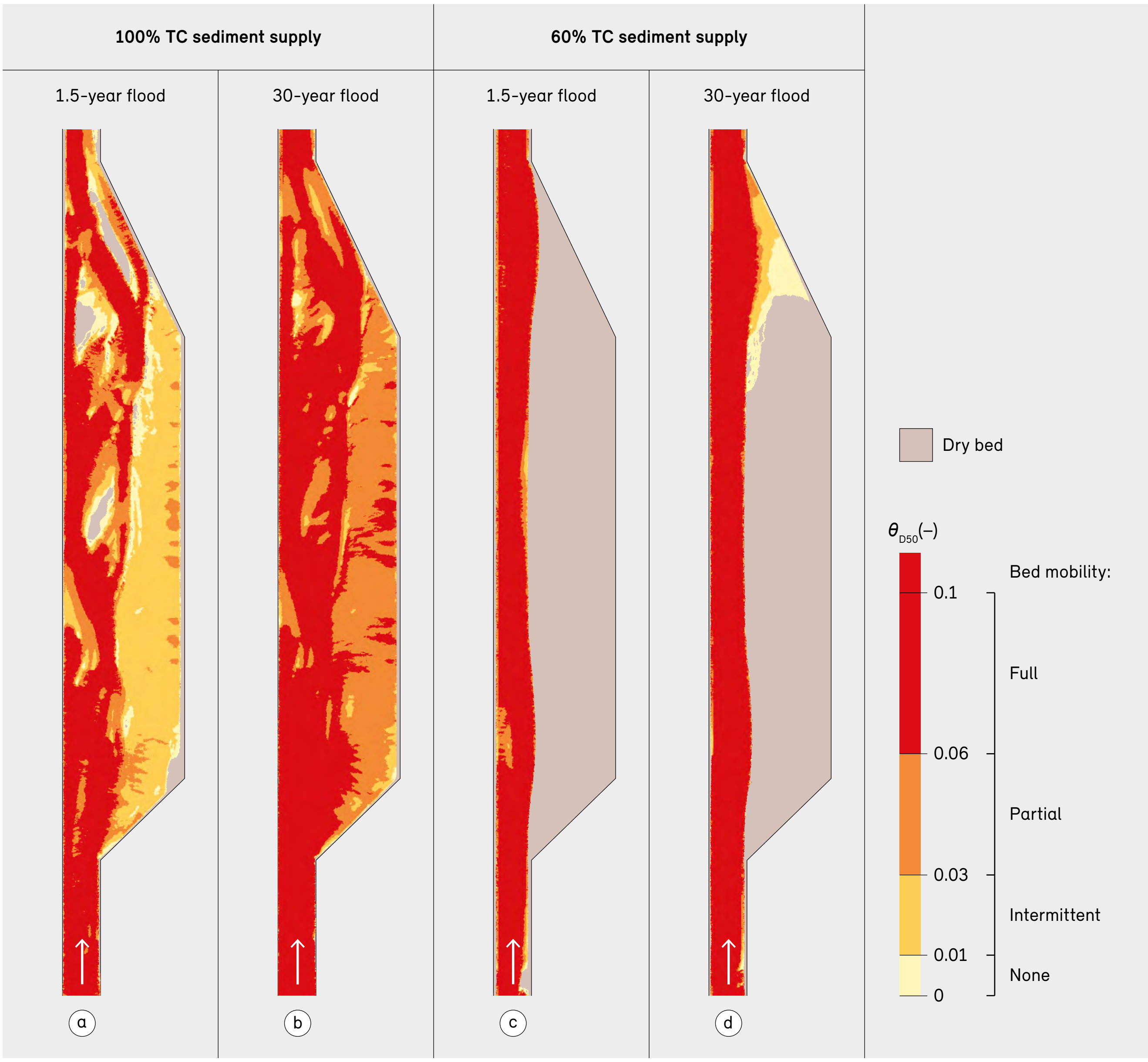
Dynamic river widening is a reach-scale restoration measure implemented to re-establish morphodynamic activity and lateral channel–floodplain connectivity in channelized rivers. We investigated how the morphology of dynamically widened rivers may differ as a function of sediment supply and how this may 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.