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

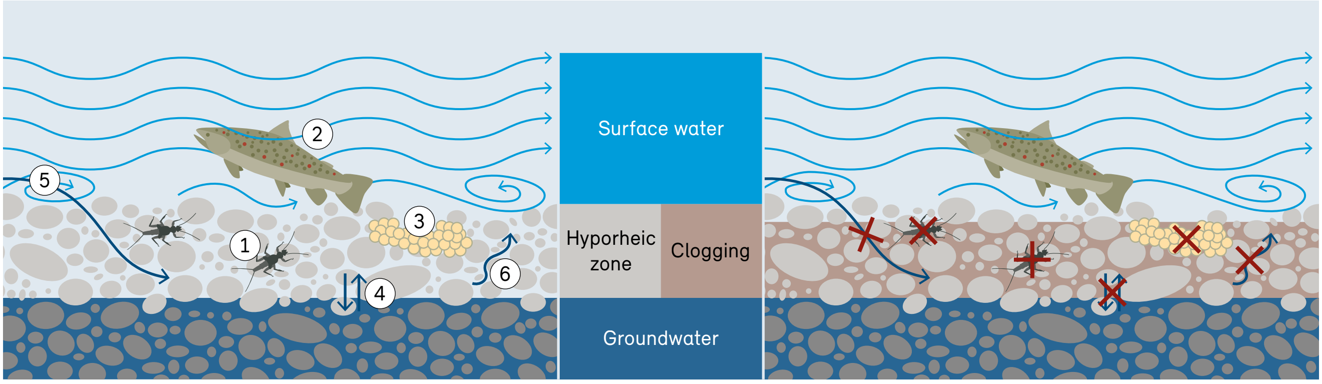
In natural, bedload-carrying rivers, the porous streambed accommodates a rich ecological community. The layer of streambed substrate connecting surface water and groundwater is called the hyporheic zone (Brunke and Gonser 1997). It is usually dominated by gravel, stones and boulders. As shown in Figure 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

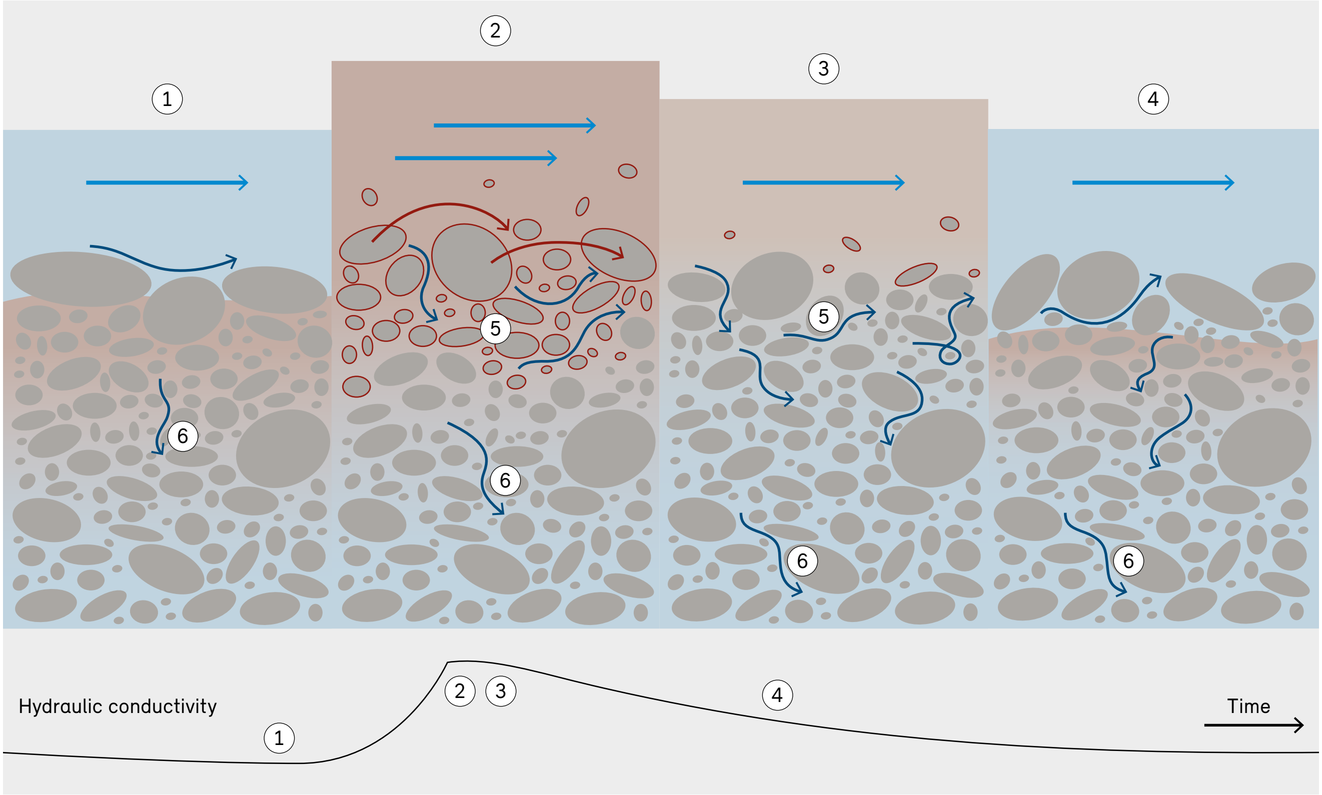
on macroinvertebrates and fish (Fig. 40; Sternecker *et al.* 2013). Macroinvertebrates depend directly on pore spaces as habitat and a rough grain surface to prevent drift. Fish require loose substrate to build their redds. The disturbance of fluxes deprives macroinvertebrates, fish eggs and fish larvae 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.

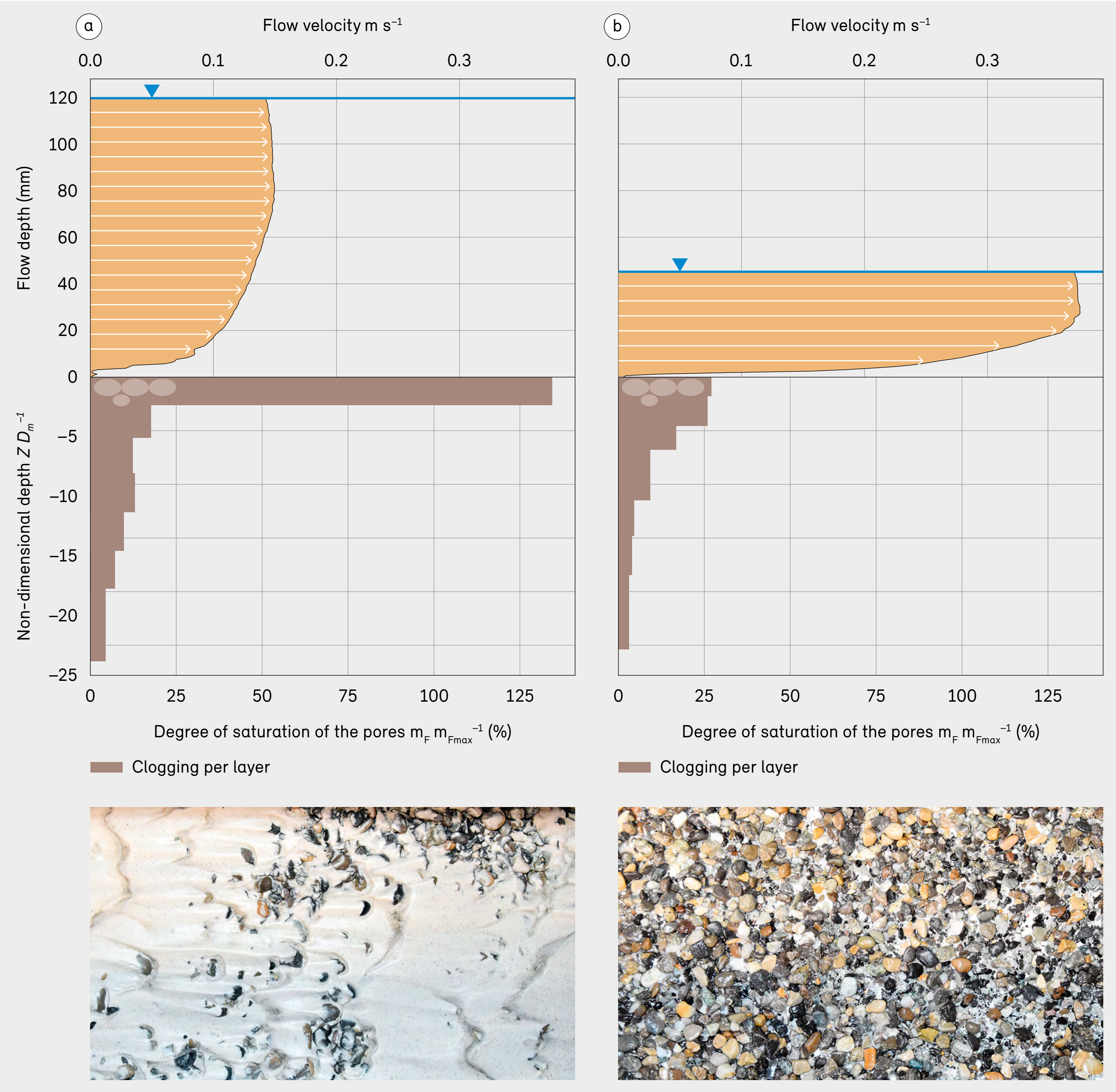
Photo: R. Dubuis

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)

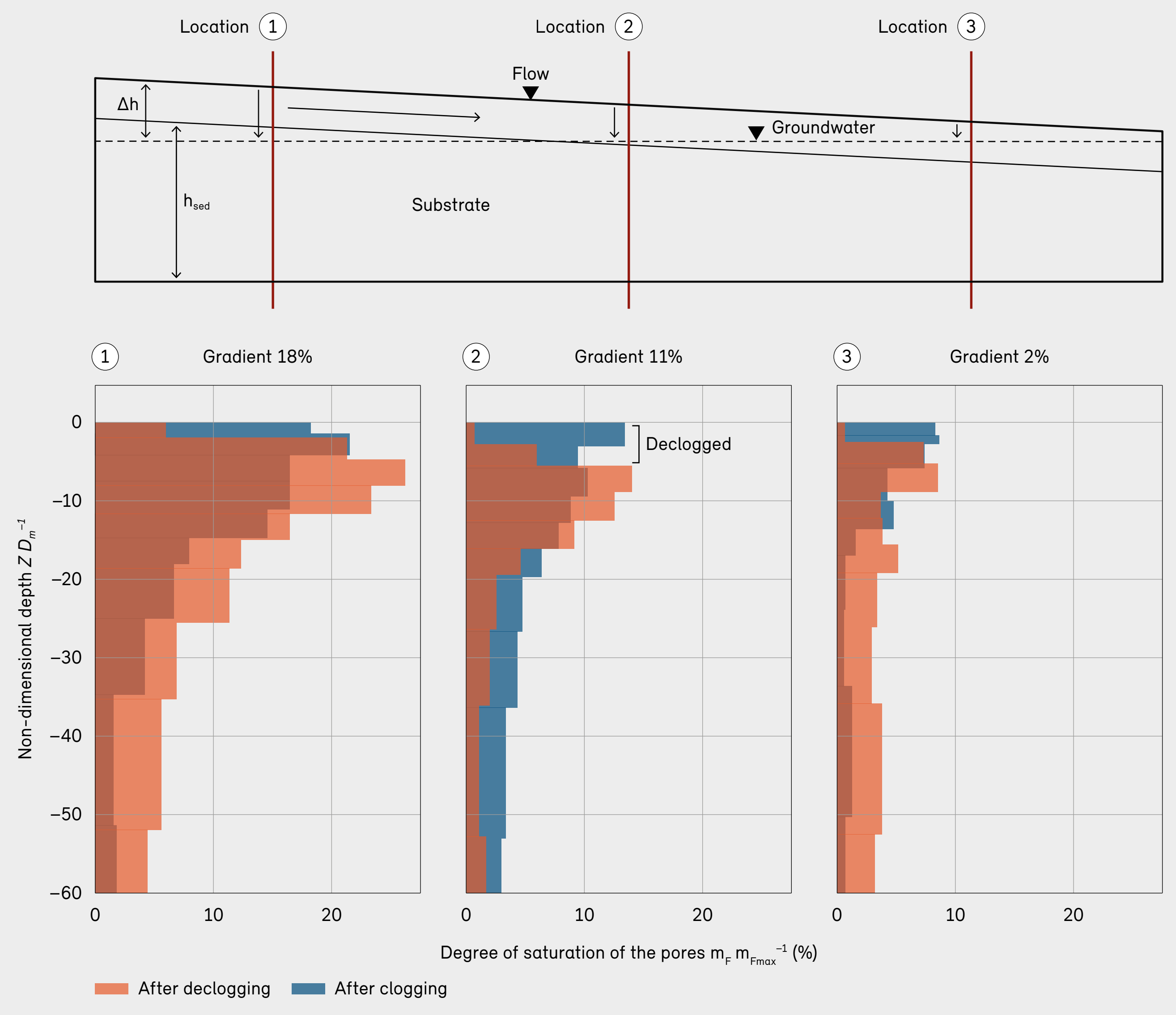
7.1.4 Spatial distribution and riverbed dynamics

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

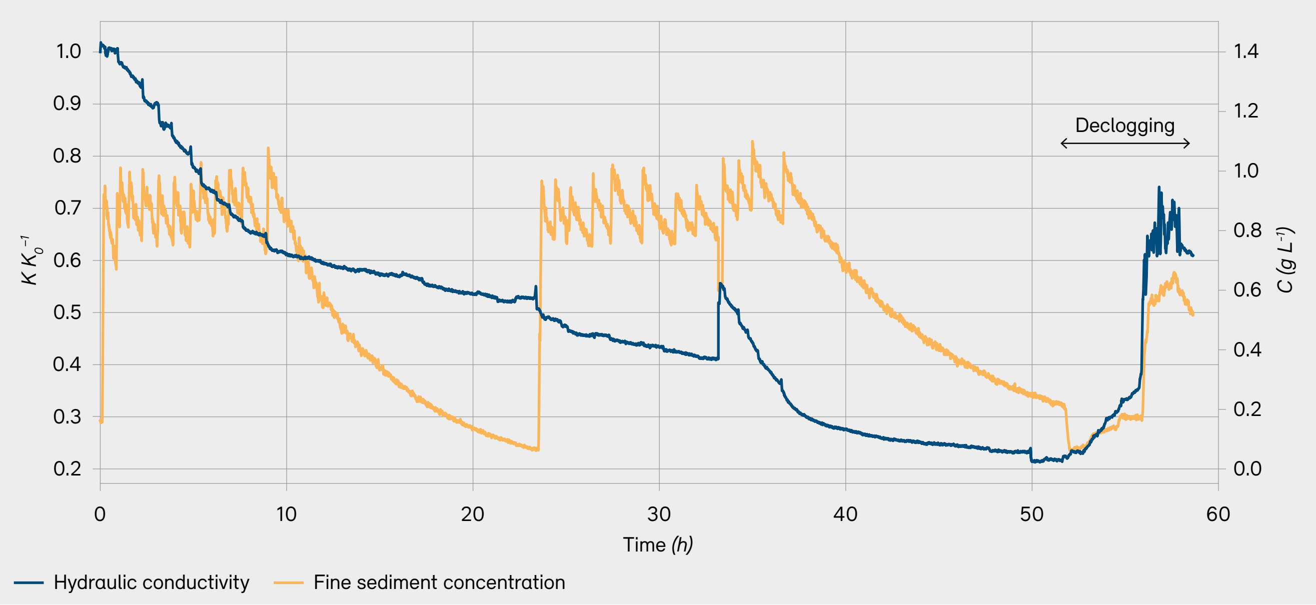
The clogging of substrate entails its consolidation. The first consequence is that the effort needed for fish to free the substrate of fine sediment before spawning is substantially increased. Similarly, it is more difficult for benthos to penetrate the hyporheic zone. The second consequence is that 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.