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.

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6.1 Introduction

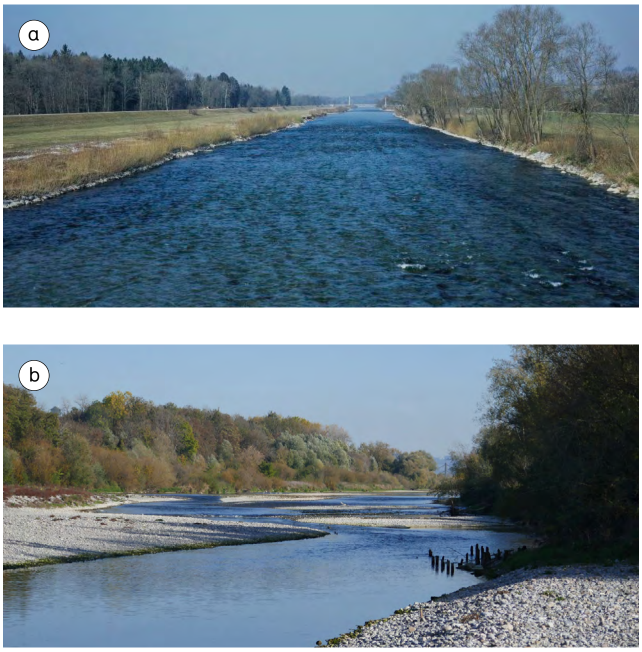
As rivers and streams flow along valleys, they convey water together with considerable amounts of inorganic sediment and organic material. Coarser grains, such as cobbles and gravel, are transported as bedload, along and in close contact with the riverbed (Van Rijn 2005). Finer grains, typically those 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.

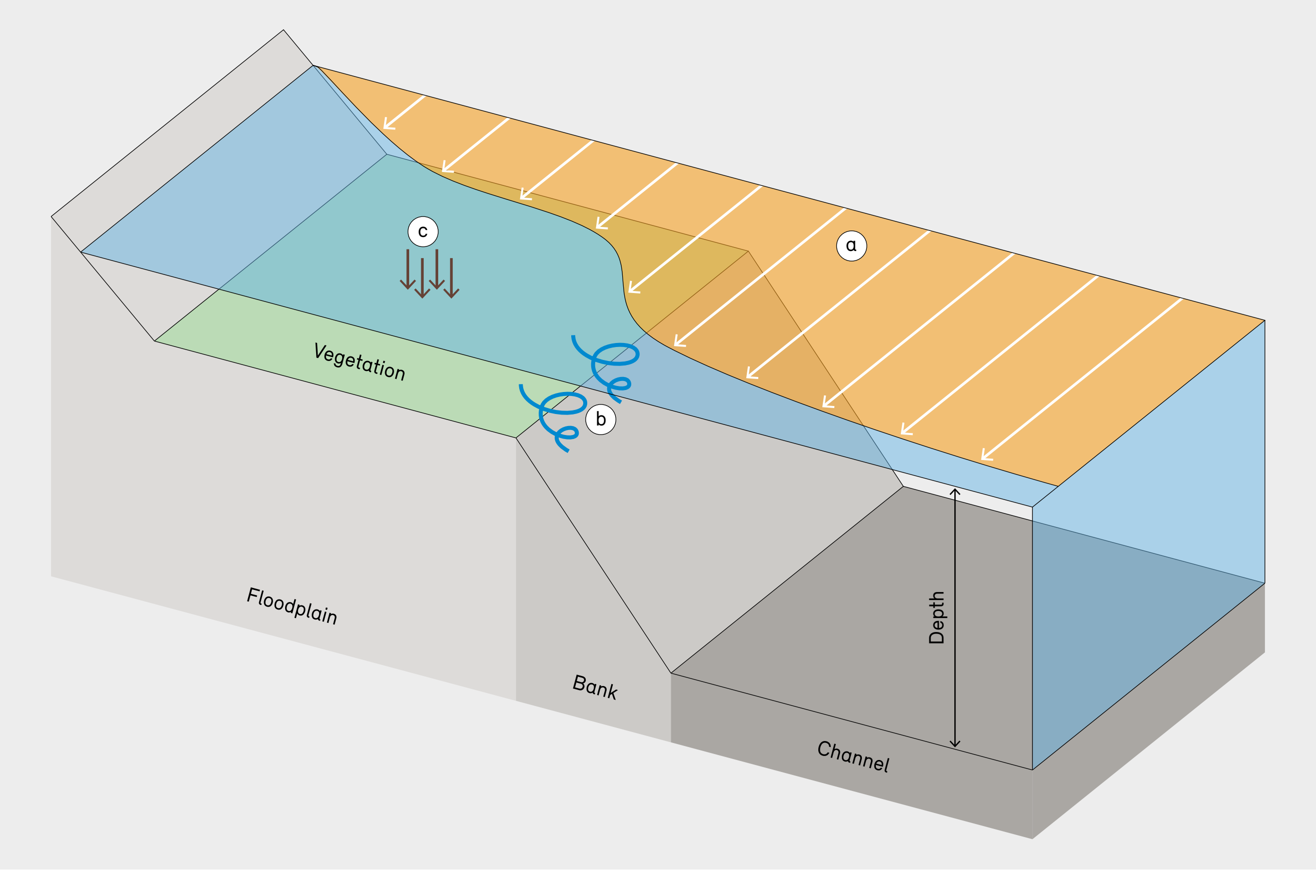
The Federal Waters Protection Act (WPA, 1991) and the Waters Protection Ordinance (WPO, 1998) have called for the restoration (Fig. 33) of thousands of kilometres of rivers in an approach combining hydromorphology and ecology. The policy goal is to restore habitats for characteristic animals, plants 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

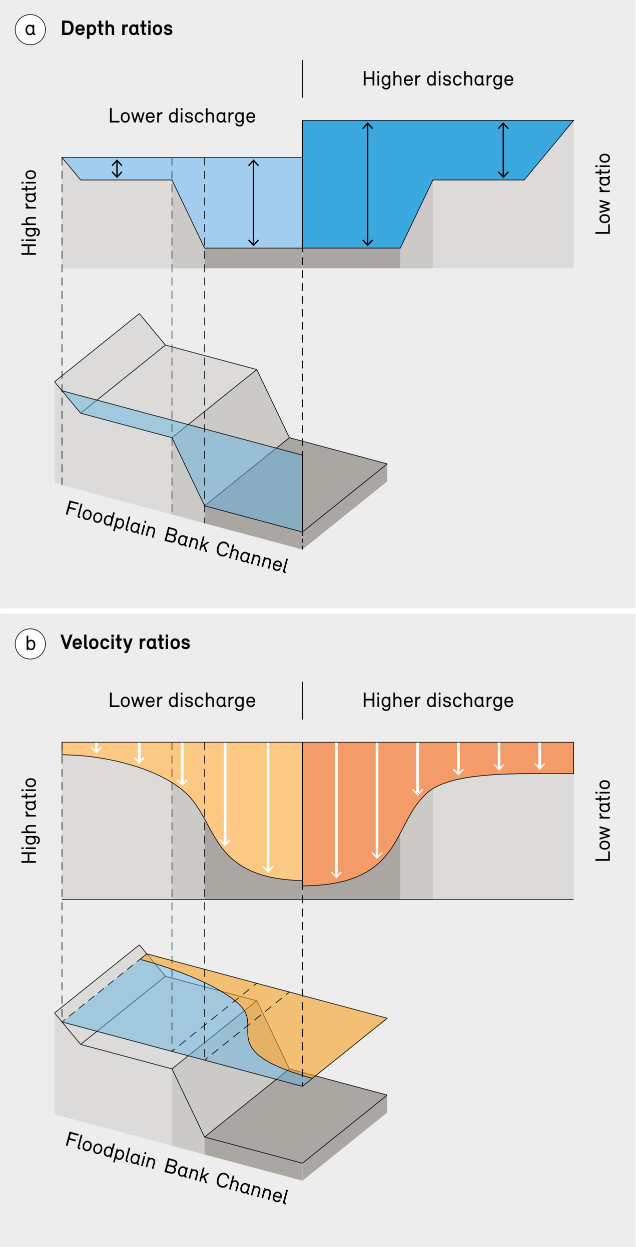
The reduced-scale model and its virtual counterpart comprised a rectilinear flume with a laterally adjustable floodplain, floodplain covers with varying resistance, and instrumentation to measure flow depth, surface velocity and suspended sediment concentrations. To ensure consistent readings, all measurements 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.

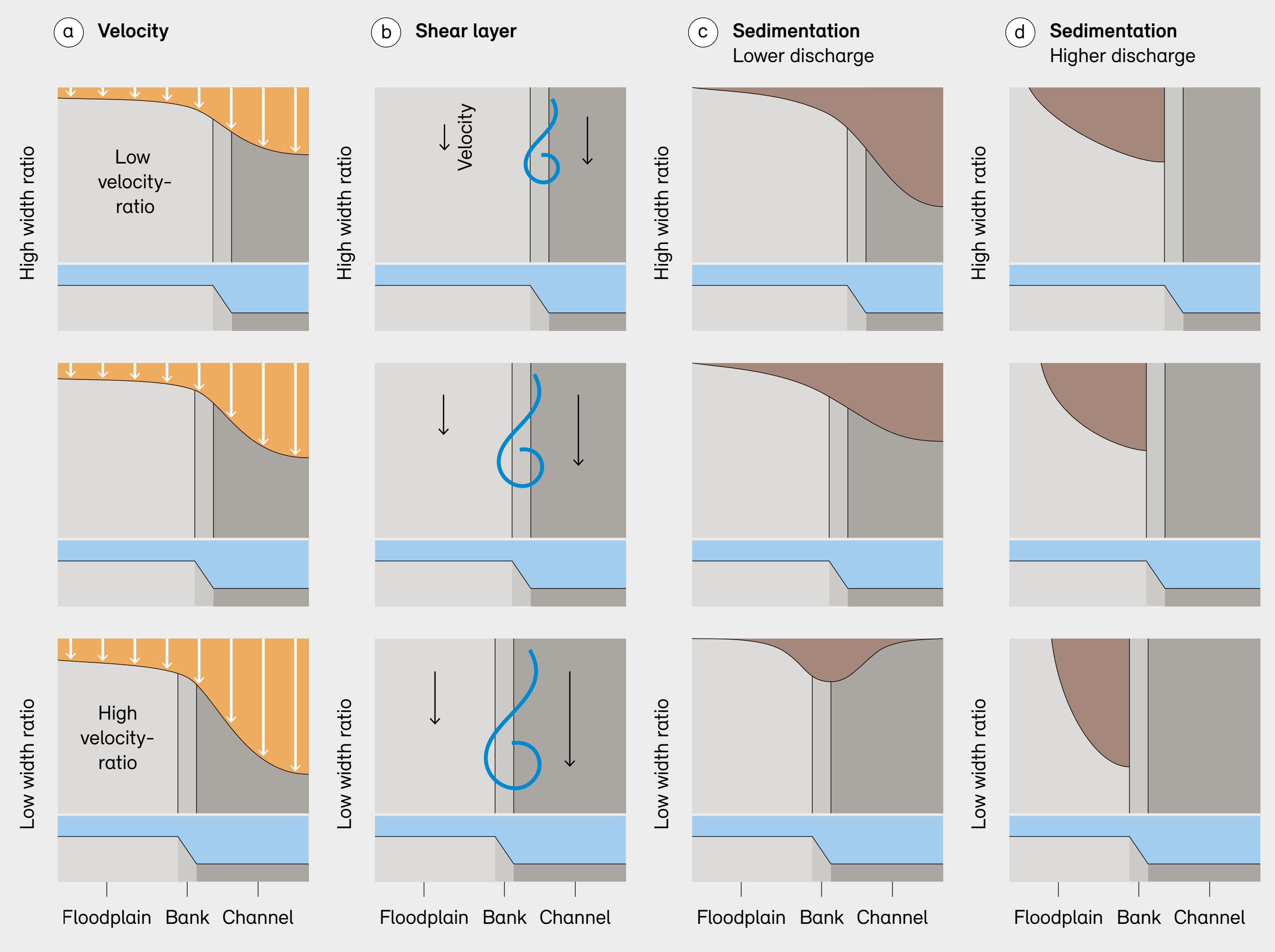
6.4 Ecological aspects

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

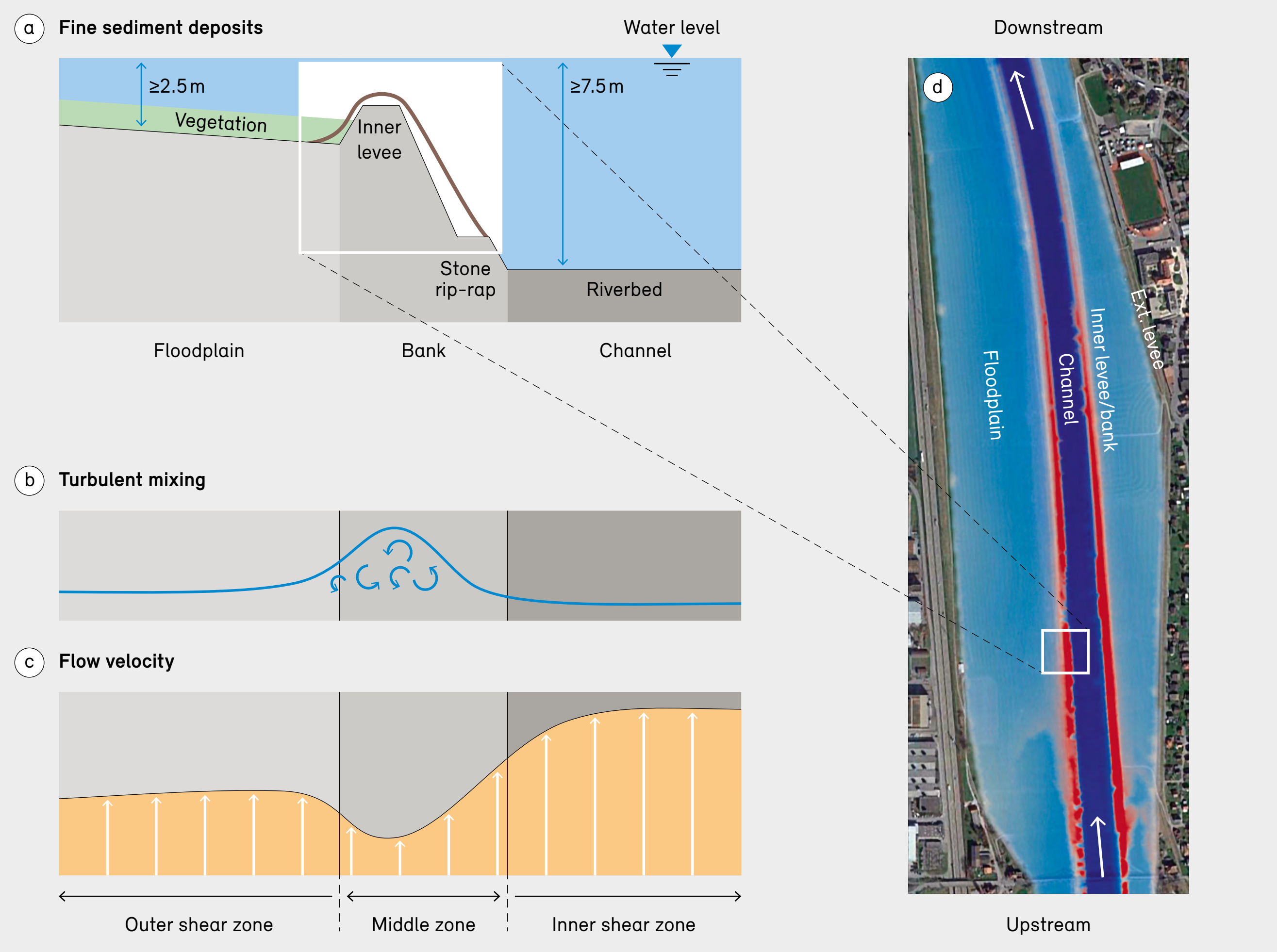
The studied domain is depicted in Figure 38d. Two boundary conditions are present in the model, one upstream and one downstream, both imposing uniform flow conditions: all forces acting on the flow are balanced and it neither accelerates nor decelerates. The roughness coefficients are calibrated with 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 m³ s⁻¹, and on the banks as well, even at discharges <1000 m³ 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 m³), after short flood events (48 h).

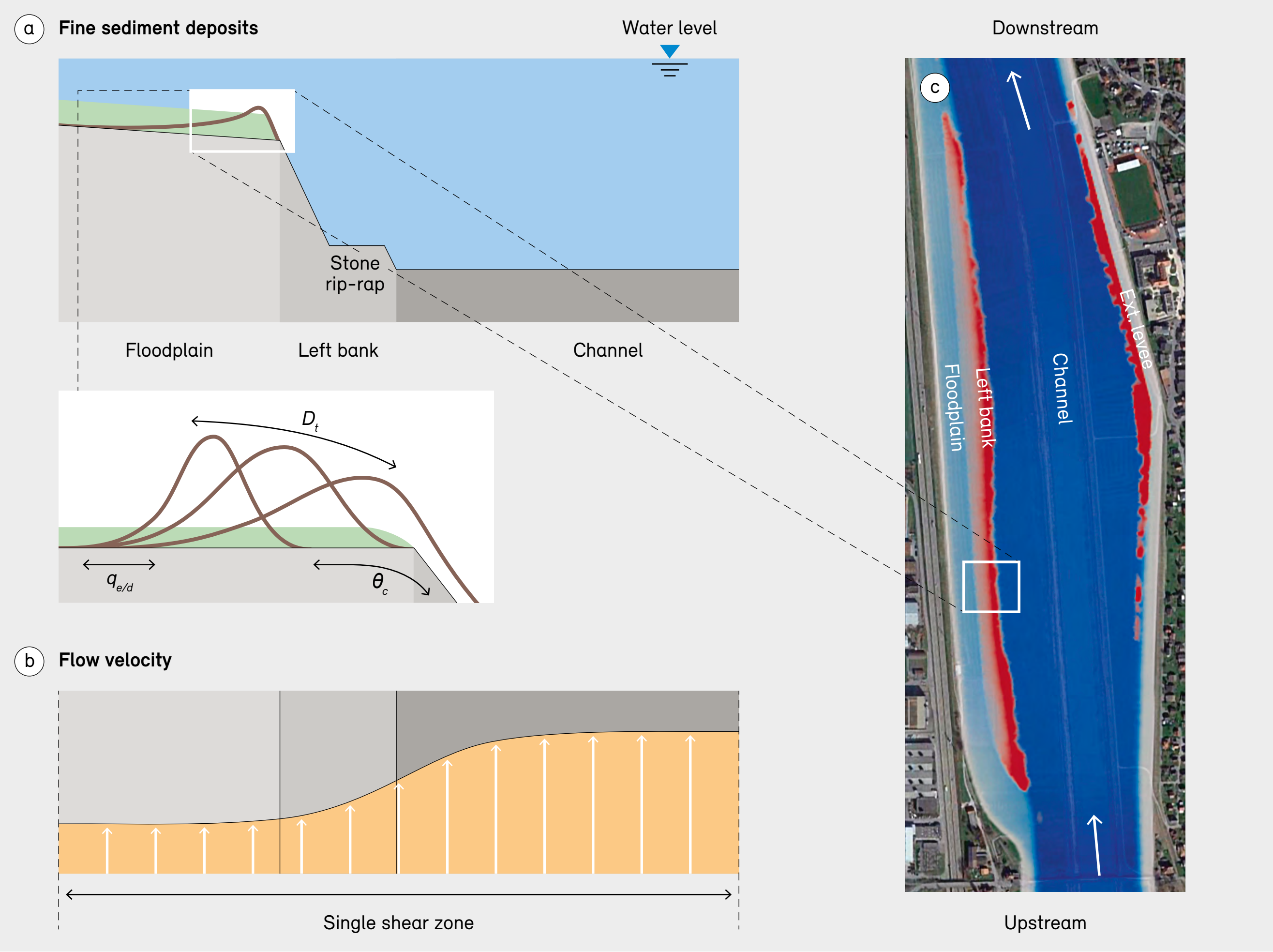
This application shows how BASEMENT can be used to assess present and future maintenance needs regarding floodplain conditions. A simple setup, as described here, is also applicable when planning future river projects. As an example, we take a restored configuration of the same reach (Fig. 39c), while 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.