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RIVER RESTORATION TOOLBOX

MEASURES TO IMPROVE
SEDIMENT BALANCE OF RIVERS
IN THE 5-COUNTRY BIOSPHERE RESERVE
MURA-DRAVA-DANUBE

Interreg
EUROPEAN UNION
Danube Transnational Programme
lifelineMDD

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Preface

The River Restoration Toolbox offers simple and concise information on the methods that can be used and combined for achieving sediment input through revitalisation.

This topic is in focus, because bedload deficit, the resulting riverbed incision, and the associated loss of morphological dynamics jointly represent one of the largest river engineering and ecological problems in the TBR MDD (Transboundary Biosphere Reserve Mura-Drava-Danube) area.

The toolbox shows a selection of basic "planning modules", which are applicable on their own or in combination with each other, as well as other types of measures to increase bedload input using natural erosion processes. For the basic modules, key planning steps and planning tools are presented.

The River Restoration Toolbox represents a framework of possible measures. Detailed, interdisciplinary planning steps, combined with hydraulic and sediment modelling are required for all cases of river restoration in order to determine the reasonable planning variants, the suitable combinations of measures and finally for the successful implementation of the measures.

The aim of the toolbox is not to provide specific spatially allocated suggestions or plans for revitalisation actions. It cannot replace planning processes that have to take into consideration the local, mostly very complex framework conditions on-site.

We recommend the toolbox to be used mainly by river experts, but also by biologists, landscape planners, stakeholders and everyone interested in the topic or involved in integrated river management in some way. Through the toolbox we intend to motivate readers to implement measures which result in increased bedload input or to prioritise these over other river engineering solutions.

It pays off: the proposed measuring types for local bedload mobilisation are multifunctional and bring added value for a wide variety of topics.

We hope the River Restoration Toolkit will find widespread use in order to help making our unique riverine landscapes even safer against floods, more ecologically diverse and attractive for recreation.

Summary

The rivers Mura, Drava and Danube (MDD) represent the lifeline of one of the most valuable river corridors in the Danube Basin, protected as the world's first 5-country UNESCO biosphere reserve. However, connectivity within the corridor is reduced due to human-made changes to rivers and their natural processes. The overall goal of the project lifelineMDD is to protect and restore ecological connectivity and biodiversity in the Mura–Drava–Danube river corridor through cross-sectoral cooperation.

The development of a strategic integrated approach to river restoration in the transboundary river corridor is based on scientific studies on the bioindicators fish and river birds, sediment transport, river training structures, hydrology and climate change. A cross-sectoral learning process between nature protection and water management authorities, based on pilot restoration actions, raises institutional competences and cooperation between key stakeholders. Involvement of NGOs, local and national policy makers and the local population ensures awareness raising and sustainable results.

Abiotic and biotic investigations in the lifelineMDD project and previous studies showed that the lack of bedload in river systems, caused by various man-made modifications like hydropower plants with dams in the catchments, run-of-river power plants, river training, bedload extraction etc. is a central problem along Mura, Drava and Danube. The River Restoration Toolbox focuses on measures to reduce these impacts.

It focuses specifically on ways to improve lateral connectivity with the riparian zone and mobilise bedloads along the rivers, as well as improve the morphological conditions to better use and keep the sediment in the system. It contains a set of planning approaches to counteract the ongoing riverbed incision and the foreland disconnection from the rivers (oxbow lakes, floodplain forests, wetlands and lands appropriate for retaining waters).

The following key planning modules, which were selected and discussed with project partners, are described in the River Restoration Toolbox:

- Erodible ("soft") banks
- Mechanical widening
- Initial channels
- Lowering of the foreland
- Additional input of sediment
- Structures to enhance erosion

The planning modules and their possible applications and combinations are considered from a river engineering, hydraulic and river morphology perspective, with an additional emphasis on incorporating lessons learned and experiences from the implementation of previous projects in the Central European region. The potential impacts and challenges of implementing measures in the TBR are addressed. Best practice examples along the rivers Mura, Drava and Danube, as well as from other rivers in the greater Central European region show how local restoration measures can

- break the tight corset of regulated and straightened river stretches
- mobilise bedload from riverbanks and foreland areas
- allow and promote self-dynamic processes to bring rivers closer to their natural state and
- reduce the pressure and thus erosional processes on the riverbed.

The River Restoration Toolbox is part of an integrated transboundary strategic framework for future river restoration, based on research, pilot projects and shared learning. It provides a crucial contribution to improve ecological corridors and cooperation among key stakeholders along Mura, Drava and Danube.


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Fig. 1: Highly dynamic Mura-Drava confluence at Legrad (Croatia)

Introduction

Lifelines Mura-Drava-Danube

On September 15, 2021, the Biosphere Reserve Mura-Drava-Danube was officially designated by the UNESCO. It is the world's first 5-country biosphere reserve and covers 13 protected areas and river stretches from southern Austria through Slovenia, Hungary and Croatia to Serbia (Fig. 6).

With its valuable floodplain forests, gravel and sand banks, islands and oxbow lakes, the new Mura-Drava-Danube Transboundary Biosphere Reserve (TBR MDD) encompasses an extraordinary biodiversity. The region has the highest density of breeding white-tailed eagles in continental Europe and is home to otters, beavers and highly endangered sturgeons. Every year, it is also an important stopover for more than 250,000 migratory birds.

However, the river and floodplain landscapes are not just important for the preservation of biodiversity. In addition, they have also provided the livelihood of local people. Moreover, natural rivers ensure favourable groundwater conditions and increase the self-purifying power of water - essential prerequisites for clean drinking water, intact riparian forests and sustainable agriculture. Floodplains provide people with natural flood protection, as well as a place for adventure and recreation.

Morphological diversity

All typical fluvio-morphological river types, from straight to braided, down to meandering channel characteristics are present in a broad range within the TBR MDD (Fig. 2-6). Along the Austrian-Slovenian border, the Mura had originally been an anabranching gravel-bed river. Further downstream, in its historical state, it changes into a sinuous and meandering type with a gravel bed.

The upper course of the Austrian Drava is historically an alpine river which is partly straight, sinuous or anabranching. Upstream of the confluence with the Mura it turns into a braided gravel bed river system, partly with multiple channels. After its confluence with Mura, the Drava River in its historic state builds a transition type of meandering and anabranching systems. The sediment consists of gravel and coarse sand. This leads to a very rich morphological diversity.

The Danube, upstream the confluence with the Drava can be described as a meandering channel with some side channels and sandy sediment. Further downstream it evolves into a large lowland river with sand beds and meanders, and partially anabranching with steep erodible riverbanks.

When developing restoration measures, these specific morphological characteristics have to be taken into account.


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Fig. 2: Braided Mura river section along the Slovenian and Croatian border


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Fig. 3: Near-natural Drava section in Croatia, with a side channel and large gravel bars


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Fig. 4: Meandering Lower Drava


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Fig. 5: Danube at Kopački rit

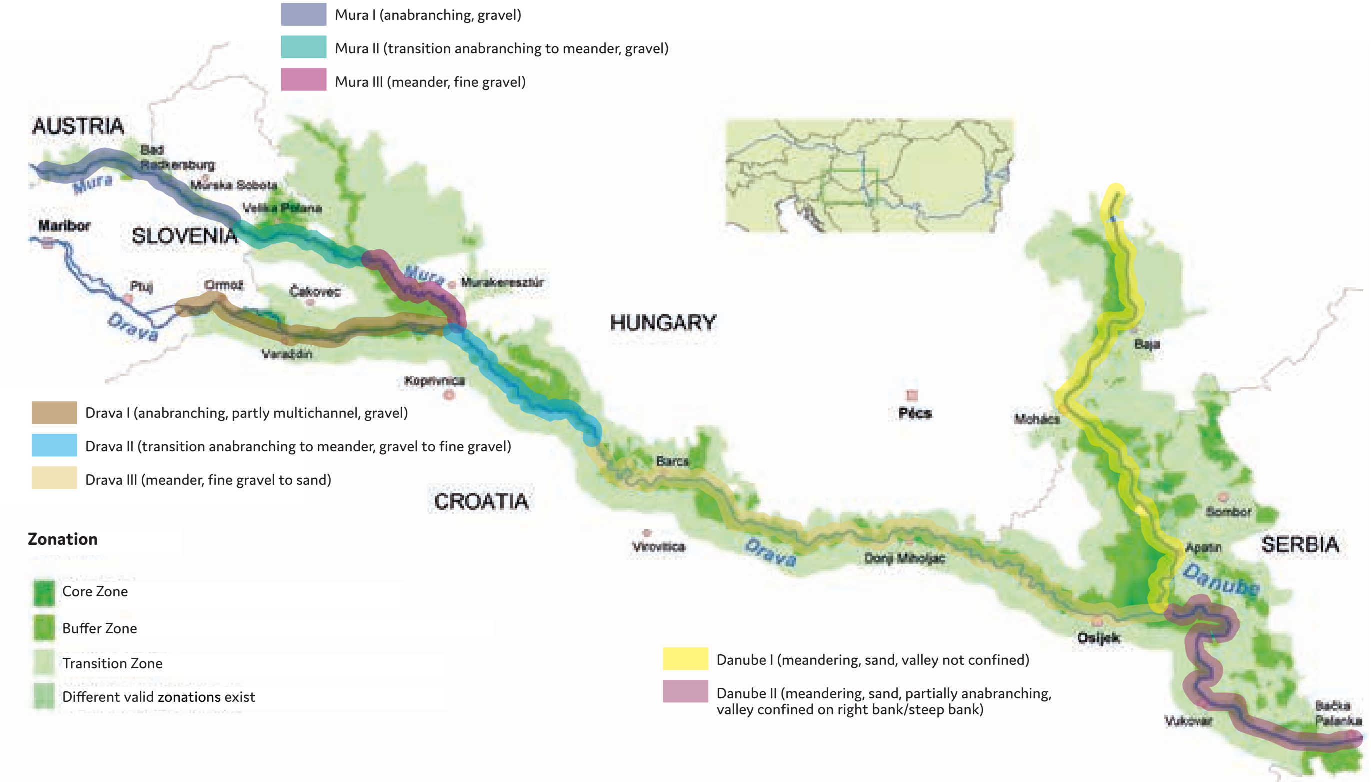

Fig. 6: Morphological reference conditions of Mura, Drava and Danube within the 5-Country Biosphere Reserve (Schwarz, 2014; modified)

Section-type	Morphological reference conditions
Mura I	Moderate anabranching river with small side channels, medium-large lowland river with gravel
Mura II	Transition type from a braided, towards a sinuous and meandering river type, moderate anabranching with small side channels, medium-large lowland river with gravel
Mura III	Meandering single-channel river system, few small side channels, medium-large lowland river with gravel
Drava I	Predominantly braided river system, anabranching with a lot of small side channels, with less slope, increasing sinuosity and less side channels, large lowland river with gravel
Drava II	Transition type from Drava I (see above) towards a sinuous and meandering river type, only partial anabranching, large lowland river with gravel and coarse sand
Drava III	Meandering single-channel river system, several small side channels and typical floodplain waters, large lowland river with sand
Danube I	Mainly one strongly meandering main channel with some smaller anastomosing side channels, sandy, large lowland river.
Danube II	Partially anabranching large, sandy lowland river, building truncated meanders alongside the steep loess terrace on its southern bank.

Problems encountered

In the 19th and 20th century, when the demand for agricultural land, infrastructure and settlements increased and flood protection gained importance, the Mura, Drava and Danube underwent systematic channelisation. The river course was partially straightened and the flow was constrained into a narrow channel between protected riverbanks (Habersack & Piegay, 2007).

River channelisation

The construction of river channelisation structures like groynes, riprap and dykes led to the loss of floodplains or natural terraces and shortened the river length by cutting off meanders, as well as straightening the river course (Fig. 7).

The state of riverbanks within the TBR MDD shows that only 9% (189 km) of the banks of Mura, Drava and Danube are natural, 38% (765 km) are still close to near-natural. More than 53% or 1081 km of riverbanks were changed by some form of training structures (Fig. 14).

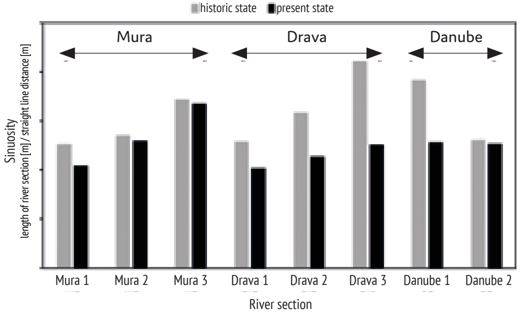

Fig. 7: Historic and present state of river sinuosity (Klösch et al., 2022, based on Ulrich Schwarz, 2022)

Sediment out of balance

The sediment budget of rivers is determined by multiple factors (Fig. 9). For natural dynamic river ecosystems, a balanced sediment regime and a dynamic riverbed are key elements. Normally, gravel and sand are constantly transported along the river. In channelised rivers, transport capacity is increased beyond the supply from upstream. Instream reservoirs for hydropower plants often significantly decrease the amount of sediment available for downstream river sections, or at least change the natural seasonal cycles and processes.

The incision is further accelerated by influences that decrease sediment supply from upstream. The missing sediment is the result of a disturbed sediment connectivity, caused by e.g. check dams or dredging. Lateral bedload mobilisation is often retained by bank protection. The total suspended sediment input to the Danube delta and the Black Sea decreased by more than 60% over the past century (Fig. 10).

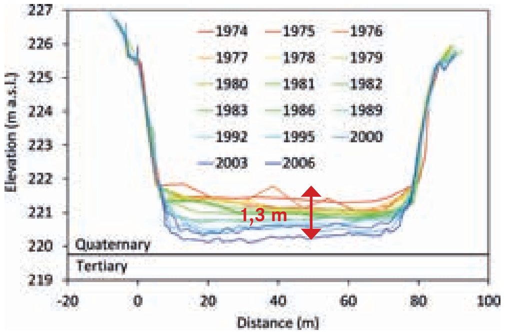

Fig. 8: Cross section of Austrian-Slovenian Mura 1975-2006. The incision reaches up to 1.3 m. The depth of the gravel layer over the underlying fine grained sediment is less than 0,5 m in places, which indicates the risk of a riverbed breakthrough (Klösch et al. 2021).

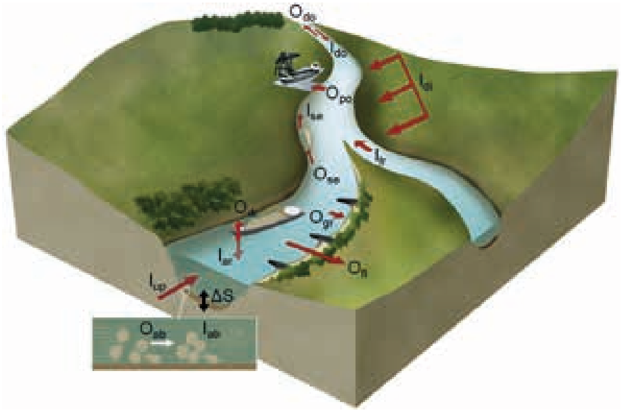

Fig. 9: System factors for the sediment balance of a river (Hillebrand&Frings, 2017)

Sediment input

I_{up}	sediment input from upstream reach
I_{tr}	sediment input from tributaries
I_{se}	sediment input from secondary channels
I_{di}	sediment input from diffuse sources (for example bank erosion)
I_{ar}	artificial sediment input
I_{ab}	input through abrasion of coarser grain size fractions
I_{or}	sediment input from downstream area

Sediment output

O_{do}	sediment output to downstream reach
O_{se}	sediment output into secondary channels
O_{dr}	sediment output due to dredging
O_{gr}	sediment output to groyne fields
O_{fl}	sediment output on floodplains
O_{po}	sediment output in ports
O_{ab}	sediment output put through abrasion
ΔS	bed level difference

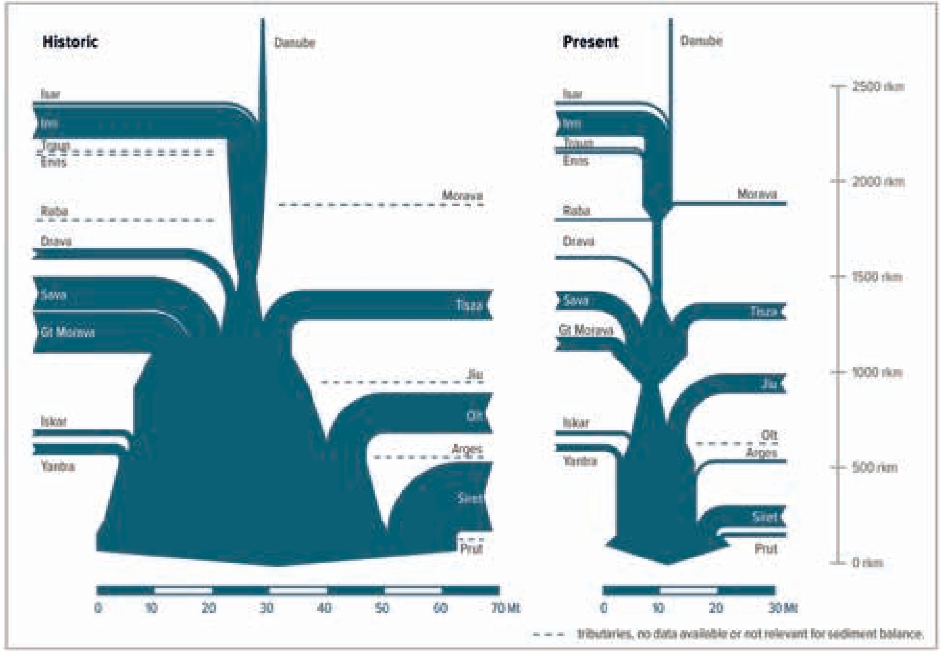

Fig. 10: Historic and present balance of suspended sediment in Danube river system (Habersack et al., 2019a)


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Fig. 11: Riverbed incision can have serious and costly consequences, such as undermined bank protection or unstable bridge foundations.


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Fig. 12: Large quantities of bedload (about 200.000 t per year) are still irretrievably lost from the river system through dredging.

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Fig. 13: Many hydropower plants with dams hold back sediments in the TBR MDD catchment area.

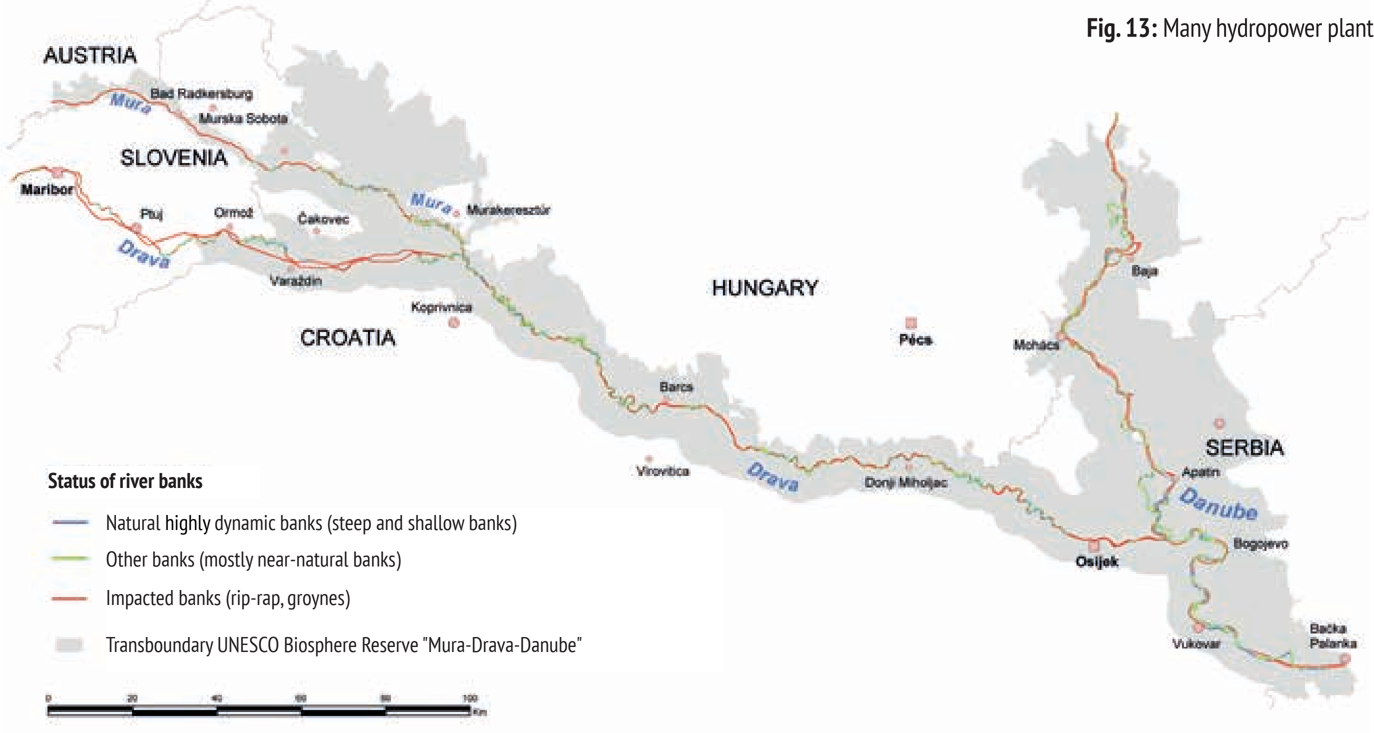

Fig. 14: State of riverbanks along Mura, Drava and Danube within TBR MDD (Schwarz, 2022; modified)

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Fig. 15: River course of Austrian-Slovenian joint Mura, shortened by channelisation. Franciscan military survey of the Habsburg Empire 1821-1836 (above), orthophoto 2006 (below)

Need for action

The development of Mura, Drava and Danube in recent decades shows a disbalance between erosion, transport, sedimentation and remobilisation. There are many hydropower plants with dams that hold back sediments in the TBR MDD catchment area (Fig. 13). However, a sediment balance is needed to sustain river functions which provide high quality habitats and ecosystem services (Fig. 16).

Urgent measures need to be taken to restore sediment balance, stop riverbed erosion and improve river dynamics within the TBR MDD. As there is a hierarchy of sediment supply (from basin to reach to local scale), the deficits regarding bedload continuity in the catchment cannot be improved with measures at selected river sections only. **This requires long-term and catchment-wide bedload management concepts**. Basic strategies are discussed in this toolbox (see chapter "Further sediment mobilisation strategies"), but also in several lifelineMDD studies.

However, according to relevant parameters for bedload transport (Fig. 17), it is possible to take countermeasures by breaking the tight corset of dykes and river straightening and to re-establish lateral connectivity with the surrounding land and enhance bedload mobilisation from banks and foreland areas.

When planning measures in a river section, a feasible "target state" has to be defined for a long river stretch, based on the historical "reference" status of the river, taking into account prevailing framework parameters (e.g. existing infrastructure, built-up areas).

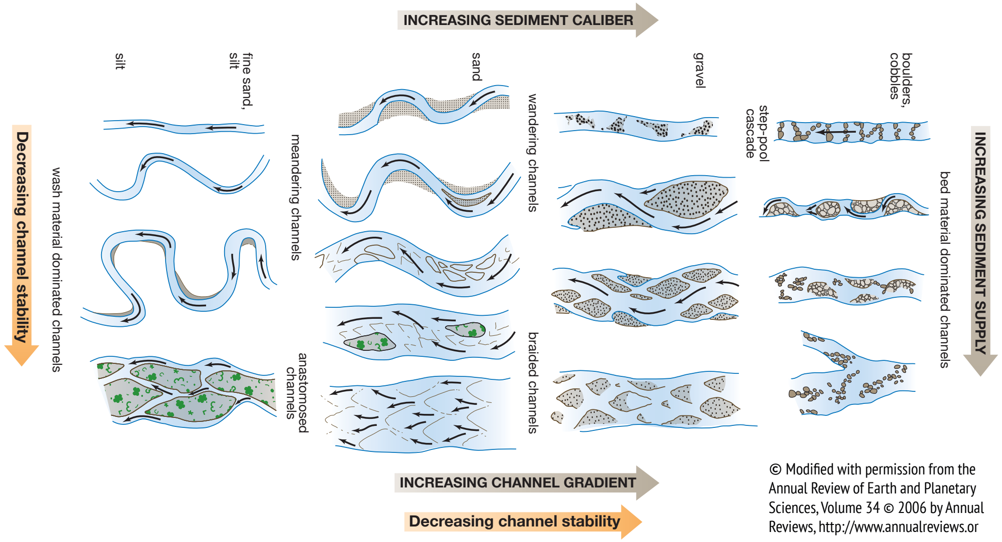

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Fig. 16: Sediment supply, together with gradient and sediment calibre, determines morphology and channel width of natural rivers. To remain stable, rivers need a minimum amount of bedload. Otherwise they get narrow, forelands are cut off and riverbeds deepen.

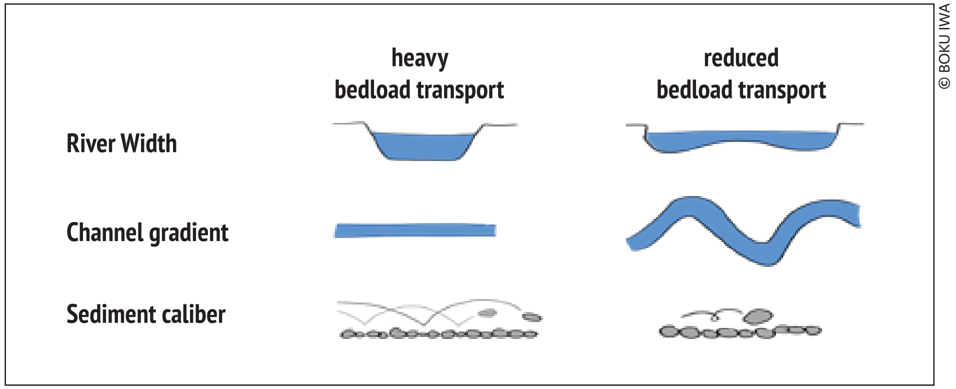

Fig. 17: Relevant parameters for bedload transport. Transport capacity is reduced when river width, sinuosity and grain sizes increase (Klösch et al., 2021).

River restoration potential

Large sections of Mura, Drava and Danube rivers still exhibit relevant potential for removing bank protection, reconnecting side-channels and re-mobilisation of bedload (Schwarz, 2014):

- 60% of about 1.081 km impacted banks could be restored to highly dynamic banks and near-natural banks.
- 120 major side-channels (secondary channels, former river channels) with a length of 519 km could be reconnected with the rivers.
- 36% of floodplains outside the dykes could be reconnected.

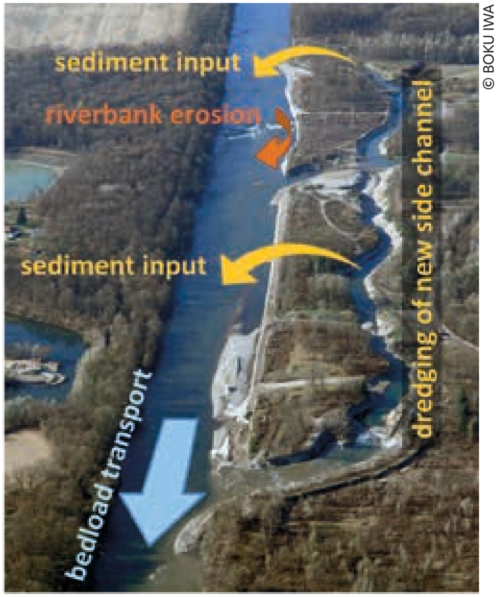

Fig. 18: Restoration measure at border Mura near Gosdorf which aims on mobilising bedload and improving the morphological situation (Klösch & Habersack, 2008).

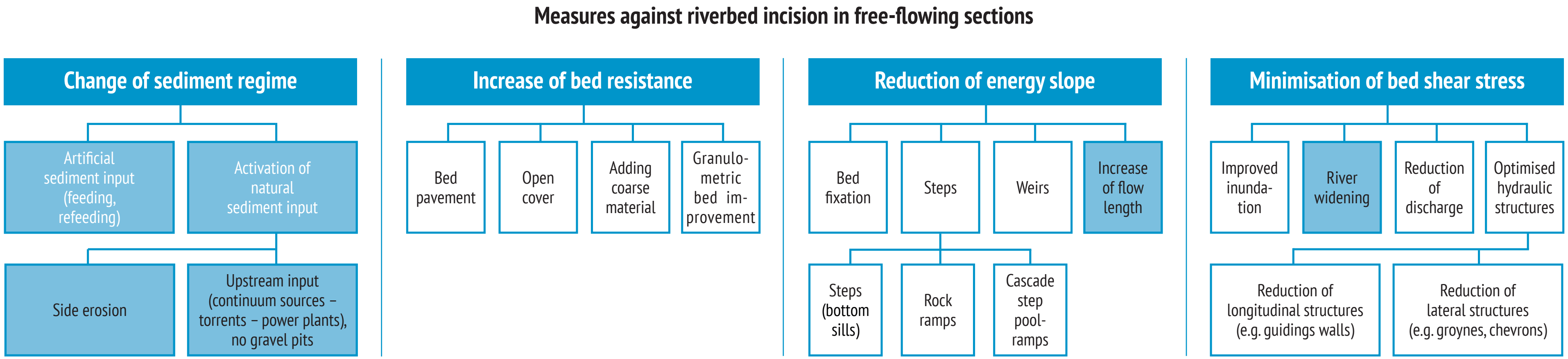

Fig. 19: Riverbed stability can be achieved in a number of ways. The River Restoration Toolbox focuses on local measures that activate natural bedload on site and, at the same time increase flow length or widen the riverbed (marked blue; based on Habersack et al., 2019b).

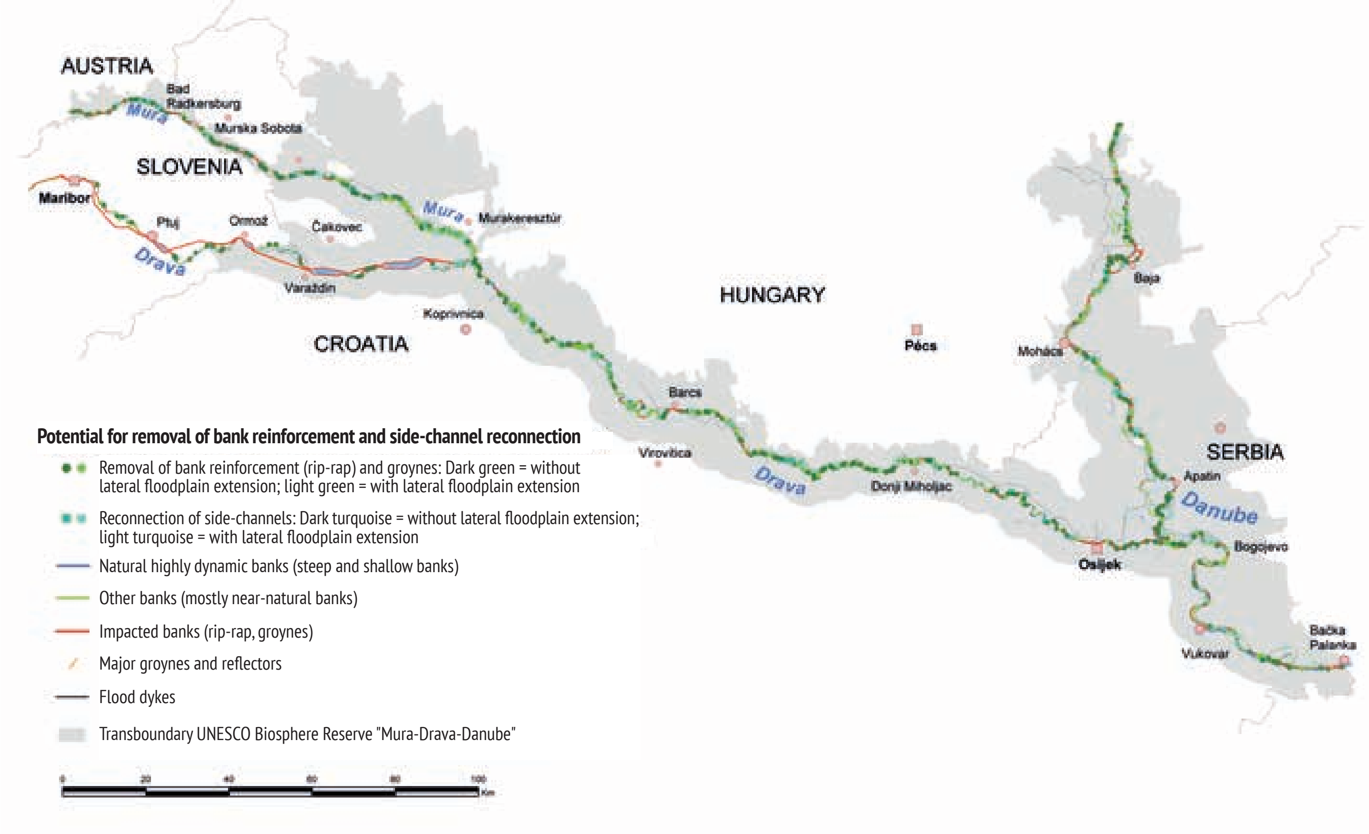

Fig. 20: Restoration potential of riverbanks and former river channels along Mura, Drava and Danube within TBR MDD (Schwarz, 2022; modified)


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Fig. 21: Potential for natural bank erosion at Libanovec (Croatian Drava)

Key planning steps

"Think globally, act locally"

River systems fulfil a wide variety of economic, ecological and social functions. They serve to facilitate flood retention, the safeguarding of groundwater, nature conservation, local recreation, and also the provision of settlement and production areas. Modern river basin management faces the challenge of harmonising often conflicting spatial demands and interests in the river basin to get greater flood safety, more nature and more recreation.

In addition, legal requirements, such as those of the EU Floods Directive, the Water Framework Directive or the Habitats Directive, but also the change in social values call for a reorientation in flood protection towards more sustainable approaches. This means: modern river management must take into account not only economic, but also ecological and social aspects.

This requires cooperation and communication in river management. Beyond administrative boundaries in future, rivers are to be managed on basin level, including participation of stakeholders and the general public (Fig. 22).

That way, it's also easier to achieve sustainable solutions that are widely accepted and feasible in the river basin, by making use of synergies, particularly in the areas of flood protection, aquatic ecology and local recreation.

When preparing the concept of measures within a River Basin Management Concept, this toolbox may assist in selecting and defining suitable actions.

O Overall coordination needed

Measures to mobilise bedload, as described in this toolbox, should therefore always **be coordinated with overarching regional planning considerations such as the River Basin Management Plan, Flood-risk Management Plan or (if relevant) Natura 2000 Management plan.** Ideally, these plans are brought into line with one another, as is already successfully practiced in Austria with the planning instrument "River Development and Risk Management Concept" - "Water development and risk management concept" GE-RM (see Box and https://life-iris.at).

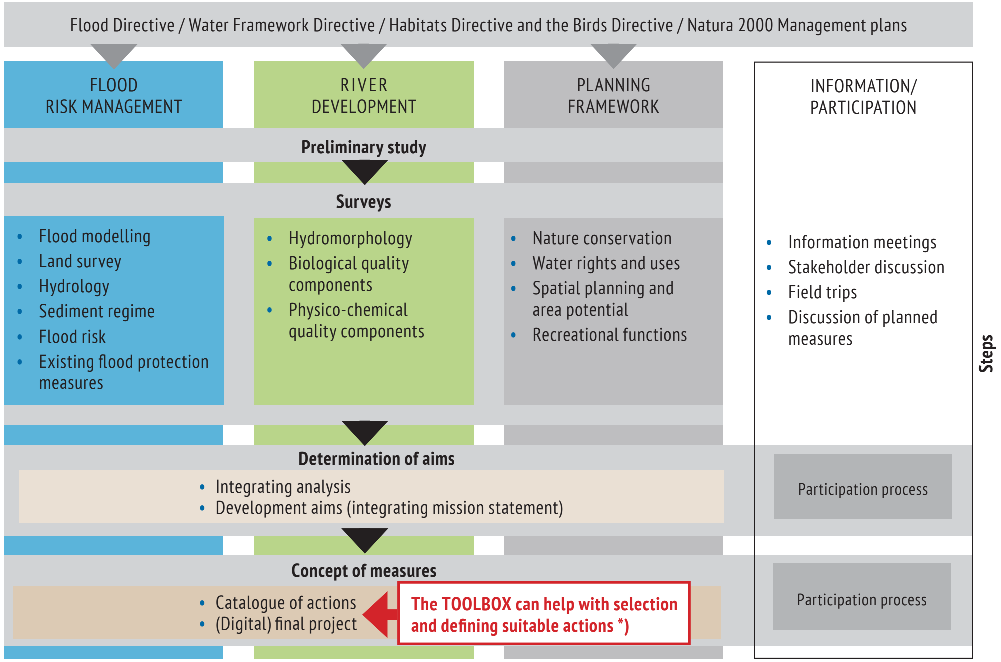


Fig. 22: Components of River Basin and Risk Management Concepts in Austria and their potential link with the toolbox (source: BMLRT 2018) *) Note: The toolbox does not replace detailed planning and hydraulic or sediment modelling.

How to coordinate measures in longer water bodies

A look at Austria´s "GE-RM"

The River Basin and Risk Management Concept ("GE-RM") in Austria is created primarily for water bodies and catchment areas with a need for action regarding flood risk management and river basin management. Apart from the flood hazard, the ecological status, land use, spatial planning, third party rights etc. are considered. On the basis of studies and status quo assessment, interdisciplinary objectives and measures are defined. This is the basis for subsequent general projects and detailed planning.

A "GE-RM" comprises the following steps:

- **Preliminary study**: In the interest of efficient planning, existing data is reviewed and tasks for the subsequent revision are specified.
- **Inventory:** collection of relevant missing data necessary in order to determine deficits, objectives and measures.
- **Setting objectives**: Based on the inventory and cross-linking to the goals of river basin management, as well as the objectives of flood risk management, potential deficits can be identified. Through this integrated approach guiding principles are defined, serving as a common target state to be reached.
- Based on a consistent catalogue of measures, the **concept of measures** finally describes the intended measures in the planning area, ranked by priority.

Key planning steps & planning principles

1 Map and analyse the current situation, identify deficits

- Long-term development of bedload situation (incision/sedimentation, bed load retention, excavation)
- Morphology (potentials, bottlenecks)
- Hydrology, hydraulics
- Geometry of river and surrounding area
- Habitats/animals, biological quality elements

2 Clarify framework conditions

- Availability of land (e.g. purchase, lease, bartering)
- Land use of higher value, infrastructure, bridges, water supply, settlements
- Spatial planning
- Hydrological and bedload framework conditions
- Financial framework

3 Define objectives of measures

concerning

- Riverbed stabilisation
- Provision of bedload
- Flood protection - structures, increase of retention capacity
- Choriotopes and fish habitats (e.g. spawning grounds)
- (Semi-)terrestrial habitats (gravel bars etc.)

4 Define target state

- Reflect on the water body's "reference state" and define the "target state" by taking into account the prevailing framework parameters
- Consider longitudinal slope, hydrology, grain size
- Estimate expected river morphology by using empiric hydraulic engineering formulas as the method of DaSilva or HyMoCARES tools (https://hymo.azurewebsites.net/
- Match goals and measures with the target morphology

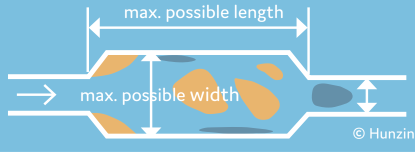
5 Find the best variant

Follow basic hydraulic engineering approaches

- Define a "river development corridor," wherein the planning modules can be placed as initial measures, creating a dynamic river landscape in the long term
- Achieve target morphology by using planning modules or combinations as described in the toolbox
- Suggest variants of combinations of measures
- Analyse the pros and cons of the variants
- Select, coordinate and optimise the best variant in an interdisciplinary manner

Planning principles:

- Provide as much width and length as possible to achieve full potential for aquatic, terrestrial and semiterrestrial habitats, with a range from gravel bars to alluvial forests
- Secure bedload material
- Allow the river to erode its banks and foreland



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6 Create a detailed plan

- Define measures in detail to achieve the target morphology in future: apply measures that initiate erosion, reduce stabilisation measures to the necessary extent
- Use hydraulic modelling to optimise the set of initial measures (location, extension)
- Analyse impacts on nature protection, biodiversity, use of water and land, ...
- Secure bedload material: leave the material in the system. Ensure, restore or improve bedload feed in the upper reaches

7 Obtain permits and get the land

- Prepare documents for obtaining the permits linked to legal framework (water law, nature conservation law, forestry law)
- Agree on and sign contracts to make the necessary land available (e.g. lease land over decades, purchase land)

8 Consider logistics and tender

- Prepare execution plans considering implementation logistics, construction roads, material transport, time schedule, etc.
- Use tendering to get the best price

9 Implement pilot actions and monitor them

- Control success for hydromorphology, river ecology, nature conservation, etc.
- Identify weak points and improve them

Planning tools

Hydrological models

One of the most important planning inputs in hydraulic engineering is the discharge, in particular size and annuality of high and low water discharge, as well as the mean discharge. These are usually determined by statistical analyses of data from gauging stations. Alternatively, hydrological models can be considered. These are fed with data from a digital terrain model, its surface properties and various amounts of precipitation. From this, the model determines the runoff waves of the flowing waters.

Grain size analysis

Knowledge of the grain sizes and the type of subsoil is required to assess the effect of the measures. Grain size analyses, which are carried out by sieving out sediment samples with standardised sieves, are common here. The analysis of the formed surface layer, e.g. on gravel bars, provides information about its stability and, conversely, about the transport forces that are necessary to break up the surface layer and enable the transport of bedload.

In the bank zone and the foreland, experimental dredging makes sense. Knowledge of the material and the predominant stratification of gravel and fine sediments provide information about the potential for the dynamic development of banks and foreland under different discharge conditions (low water, bed-forming water level, different flood scenarios).


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Fig. 23: Grain size is a decisive factor for bedload transport

Terrain surveys

Before river sections can be examined hydraulically, a detailed survey of the channel, the riverbanks and the foreland is required. The river channel is usually recorded cross section by cross section by means of an echo sounder. The profile spacing is chosen so that relevant fixtures and structures in the flow channel are recorded in detail. On land, the site is usually recorded using a laser scan. Bridges, flood dykes, culverts, upper edges of embankments, gravel banks - so-called relevant breaklines - are measured terrestrially. A three-dimensional terrain model is built from the recordings as the basis for hydraulic modelling.

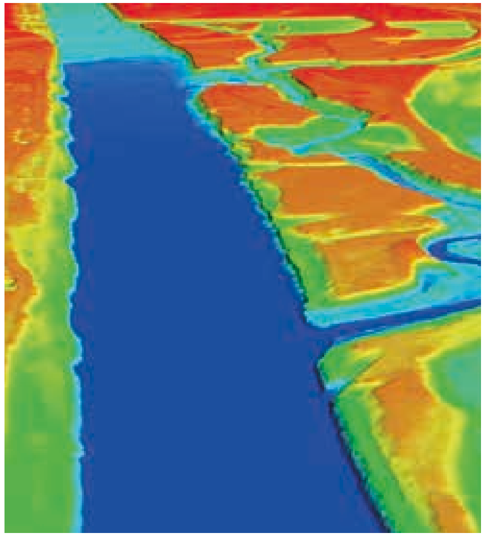
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Fig. 24: New 3D terrain model of Mura River at Austrian-Slovenian border


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Fig. 25: Boat equipped with modern sonar and laser technology for measuring the bed of Mura

Numerical models

In the past, discharge and bedload transport were calculated manually by cross sections, today computer simulation models (so-called "numerical models") calculate discharge events and scenarios for bedload transport (Fig. 26). Which type of numerical model is used depends on the question and the size of the study area. The more detailed the model resolution and the larger the model area, the longer the simulation takes.

1-D models (e.g. Hec-RAS) based on transverse cross sections are suitable for large-scale and long-term river observations. They provide mean results per cross-section, such as water level elevation or flow velocity. They are best suitable for simple geometries with low lateral flow components (regulated stretches). The models reach their limits when complex geometries such as river widenings or braided sections are present.

Based on digital terrain models, **2-D models** (e.g. Hydro_AS-2D) are created. The geometry is mapped using triangular and square elements. For each element, the model provides e.g. water level elevation, water depth and flow velocities. 2-D models are used for calculating the precise water level and flow velocity data in complex river geometries (such as river widenings, braided river systems etc.).

2D-Models give depth-averaged results for the relevant hydraulic parameters per each cell of the geometry. They reach their limits, when relevant vertical flow components have to be considered (e.g. weirs, power intakes of hydropower plants etc.).

Wherever small-scale, turbulent vertical flows are to be investigated, **3-D models** (e.g. Flow-3D) are the appropriate tool. For example, local scour processes on bridge piers can be simulated.

In addition to water discharge, the **sediment transport** can also be simulated with numerical models e.g. basement or DHI-MIKE. This enables statements on morphological processes impacting on the riverbed. The sediment transport calculations are based on empirical formulas, the results depend on the chosen method.

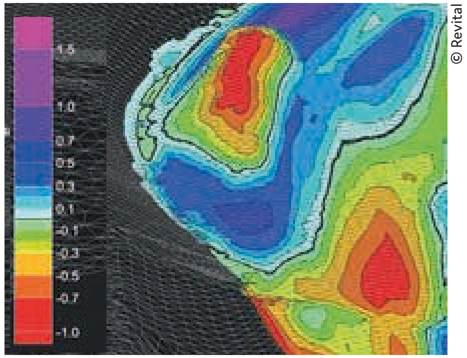


Fig. 26: Detailed simulation of the development of water depths with a 3-D model

Physical models

Physical models are used when particularly complex flow conditions in combination with sediment transport issues have to be investigated which can hardly be calculated with numerical models.

One disadvantage is the flexibility: planning changes mean a significantly higher effort than with numerical models. In practice, hybrid models are therefore often used. The boundary conditions for the physical model test are specified using numerical models. The physical model is used for verification of numerical models and for fine-tuning and dimensioning of details.

Fig. 27: Physical model for Mura River widening at Gosdorf (Styria, A)

Geographic information systems

Geographic information systems (GIS) are suitable for displaying and overlaying data relevant to planning (from your own on-site survey or from existing sources).

The more relevant data available, the more precisely the planning framework with its development potentials and obstacles (taboo zones) can be defined.

Examples for planning-relevant data could be:

- Habitat mapping
- Natura 2000 area boundaries
- FFH protected habitat types and species
- Fish or benthos sampling
- Faunistic mapping
- Ecological water status
- Hydromorphological status
- Land uses (e.g. Corine)
- Zonation plans
- Spatial planning
- Water rights etc.

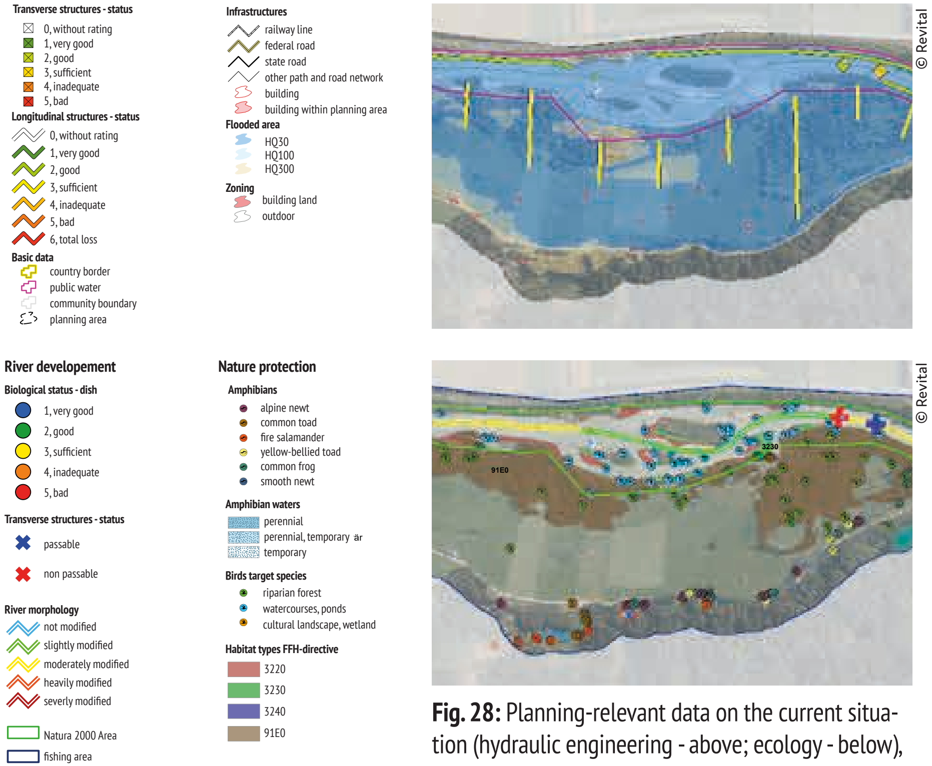


Fig. 28: Planning-relevant data on the current situation (hydraulic engineering - above; ecology - below), visualised with GIS, help to define the planning framework (example).

Toolbox & planning modules

River restoration toolbox

This toolbox offers a practical **overview** of how to

- develop river restoration measures, that focus on re-establishing natural morphodynamic processes in river systems
- remove or set back constraints to provide a corridor, allowing lateral dynamics such as widening and migration
- supply sufficient sediment to maintain a more natural morphology at dynamically stable bed levels.

As a contribution to achieve this goal on a local level the following **6 key planning modules** have been identified:

- **Erodible ("soft") banks** (M01)
- **Mechanical widening** (M02)
- **Initial channels** (M03)
- **Lowering of the foreland** (M04)
- **Additional input of sediment** (M05)
- **Structures to enhance erosion** (M06)

On the following pages these modules are characterised in more detail. First, the measures and their possible applications are described from a river engineering point of view, whereby emphasis is placed on contributing experience from previous projects. The possible effects and challenges of the measures are also briefly discussed. **Best practice examples** from the Mura, Drava and Danube and from the neighbouring Central European region show how local restoration measure can

- break the tight corset of regulated and straightened river stretches
- mobilise bedload from riverbanks and foreland areas
- allow and promote self-dynamic processes to bring rivers closer to their natural state and
- reduce pressure and erosional processes on the riverbed.

How to select and combine planning modules

The planning modules can be implemented individually, but their full effect is achieved when they are applied combined over longer river sections and sediment supply from upstream is provided. If a "river development corridor" is defined, the planning modules can be placed specifically as initial measures, which, in the long term, will enhance a dynamic river landscape.

The goal must be to keep the riverbed elevation in a dynamic equilibrium. If, at the same time, it is possible to also improve the ecology and local recreational capacity along the rivers, we can achieve win-win situations through the implemented projects.

The table on p.17 shows the **suitability of the planning modules** for different initial situations, framework conditions and applications, based on the following **criteria**:

- situation of riverbed incision
- prevailing sediment
- framework conditions (e.g. availability of land, nature conservation aspects)
- morphological target state
- time to achieve the target state

Numerous possible combinations can be derived from this. On pages 18-19 examples of possible combinations of measures for theoretical river sections with narrow or wide spatial corridors are shown.

At the beginning of measure development an analysis of variants should be carried out in which different solution approaches are considered with regard to the morphological target condition, flood safety, the availability of land, the existing framework conditions in terms of nature conservation etc. (see p.12-13).

Planning module M01
Erodible ("soft") banks (p.20-23)

Planning module M02
Mechanical widening (p.24-27)

Planning module M03
Initial channels
(p.28-31)

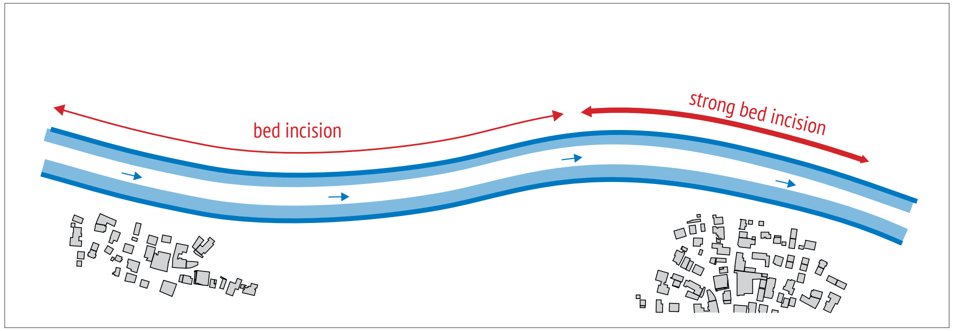
Planning module M04
Lowering of the foreland (p.32-35)

Planning module M05
Additional input of sediment (p.36-39)

Planning module M06
Structures to enhance erosion
(p.40-43)

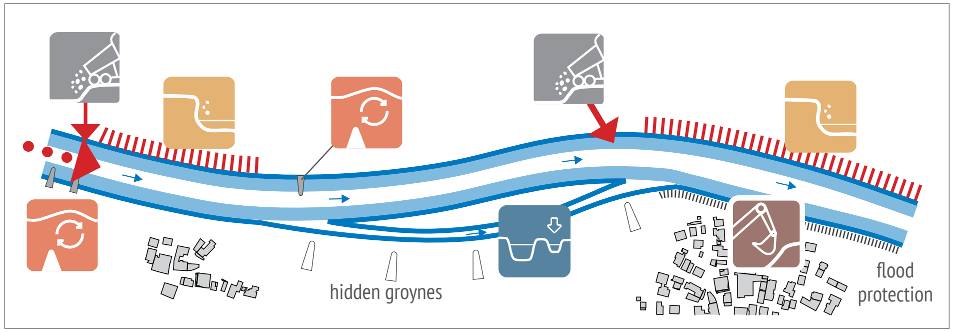
Criteria	Planning modules					
	Erodible ("soft") banks	**Mechanical widening**	**Initial channel**	**Lowering of the foreland**	**Additional input of sediment**	**Structures to enhance erosion**
Situation of riverbed incision						
local moderate riverbed incision		x			x	x
local strong riverbed incision		x			x	x
section with moderate riverbed incision	x		x	x	x	x
section with strong riverbed incision	x	x		x	x	x
Prevailing sediment in the foreland						
Gravel / coarse sediment	x	x	x	x	x	x
Sand	x	x	x	x	x	x
Framework conditions (availability of land, nature conservation aspects)						
Narrow river corridor without high-value habitats/protected areas	x	x		x	x	x
Narrow river corridor with high-value habitats/protected areas	x	x		x	x	
Wide river corridor without high-value habitats/protected areas	x	x	x	x	x	x
Wide river corridor with high-value habitats/protected areas	x		x	x	x	x
Time to achieve the morphological target state						
short term (1-2 years)		x		x	x	x
medium term (2-5 years)	x		x	x	x	x
long-term (> 5 - 15 years)	x		x			
Morphological target state						
Main river with one or more side channels and widenings	x	x	x	x	x	x
Braiding river with gravel / sand banks	x	x	x	x	x	x
Meander / re-connection of oxbow lakes		x	x			x

EXAMPLE: Planning modules combined in a narrow river corridor



Current state

This theoretical initial situation shows a narrow river corridor with a pronounced incision tendency near a flood-prone settlement. The availability of land for the implementation of measures is limited, valuable alluvial forests are located along the banks.



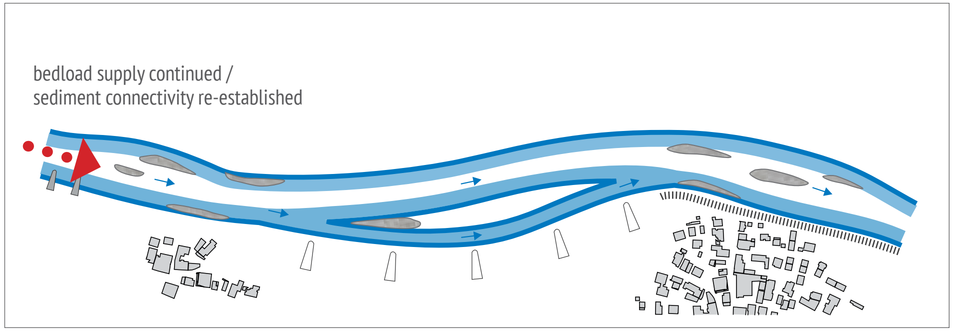
Initial state

Banks are mechanically widened, the bank protection is repositioned for short-term mitigation of riverbed incision. Erodible banks are planned on the opposite bank in order to give the river the possibility to widen further in the medium term.

A flood protection dyke is built along the mechanically widened stretch. The sediment removed for widening is re-introduced into the river upstream so that it remains available for providing sediment input and stabilising the riverbed.

Upstream, in the area of existing high-quality habitats, erodible banks are implemented. An initial channel is built and protected with hidden groynes. The stones of the removed bank protection will be reused for their construction.

Active tree clearing affects only a narrow strip along the bank. Stones from the removed bank protection are used to build groynes that direct the flow to the erodible banks of the initial channel and thus promote side erosion.

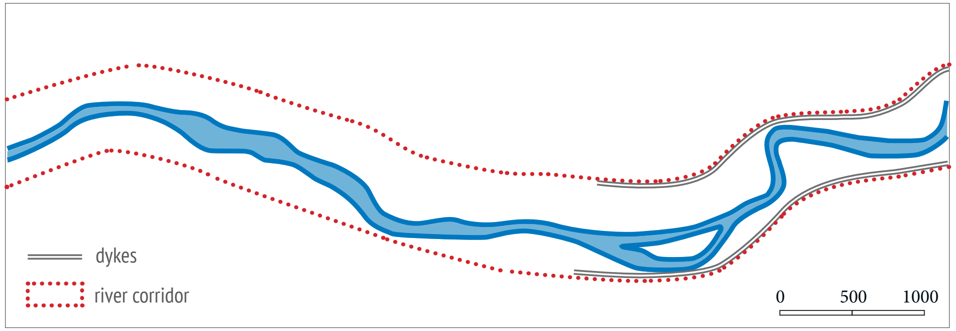


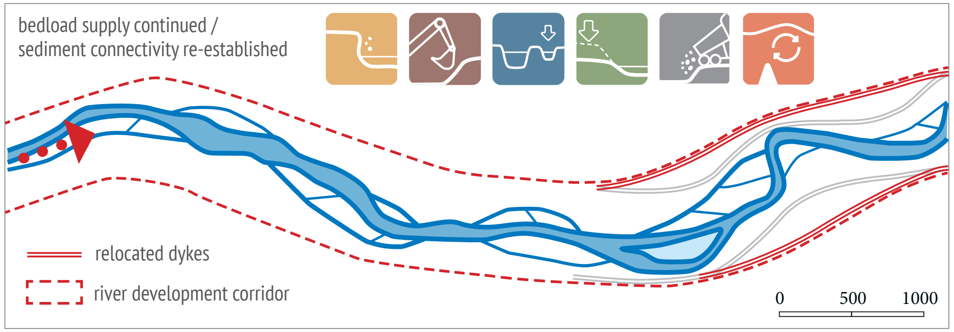
Target state

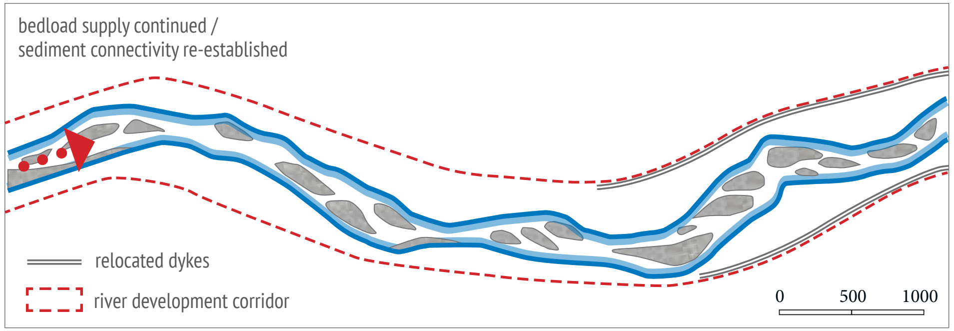
The result is a river landscape with a dynamically stable bed, in which erosion and deposition are balanced. As an added value, this also brings advantages for the fauna and flora and additional opportunities for local recreation.

However, for long term effect, bedload supply needs to be continued or sediment connectivity re-established.

EXAMPLE: Planning modules combined in a wide river corridor







Current state

In the theoretical initial state, the river runs sinuously in a wide corridor, partially bordered by dykes. Historically, the river was wider and more branched. Lack of bedload from upstream led to increasing riverbed incision, the riparian forests are becoming more and more decoupled from the river and dynamic processes which create pioneer habitats are steadily decreasing.

Initial state

A river development corridor is defined. Within the corridor all 6 modules described in the toolbox are combined, creating a dynamic river system in the long term. In the foreland, initial channels are first dredged parallel to the main river. Groynes and structures at the inlet areas increase the inflow into the new channels. Their banks are not fixed, in order to allow self-dynamic erosion and widening processes. Connecting channels between the main channel and the newly built initial channels create a network, that increases the potential for dynamic development in the foreland.

In sections with distinctive riverbed incision, immediate measures are taken. The riverbed is mechanically widened, and foreland areas are lowered. This reduces the erosion pressure on the riverbed and provides sediment. Finally, bank protection is removed and reinstalled along the river corridor boundary as hidden groynes. The dredged bedload is not removed, but is added to the river. As an ecologically desirable side effect, an anabranching river course with side channels and gravel areas develops after a while. The inundation area gets larger. By sectional relocation of the dykes, bottlenecks can be defused.

Target state

Years pass before the river reaches the hydraulically predicted width through its own dynamics. As the channel width increases, the erosion pressure on the riverbed decreases, bedload is deposited, and the riverbed is stabilised and begins to rise. The main river divides into several side branches, sinuosity increases, the longitudinal gradient decreases. As a result, the bedload remains longer in the widened riverbed. That way, a variety of structures are created within the river corridor: gravel islands, gravel banks and pioneer vegetation characterise the area.

However, for long term effects, bedload supply needs to be continued or sediment connectivity re-established. The wider and more curved channel needs less sediment for an equilibrium than in the channelised current state.

Fig. 29: **Freely** erodible banks after removing revetments (Salzach, Austria)

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Planning module M01

Erodible ("soft") banks

Description

For the implementation of erodible banks, sometimes also called "dynamic banks" or "soft banks", the bank protection is removed. As time passes, erosion processes form the bank and successively bedload and sediment mobilisation, as well as erosion occur (Fig. 30).

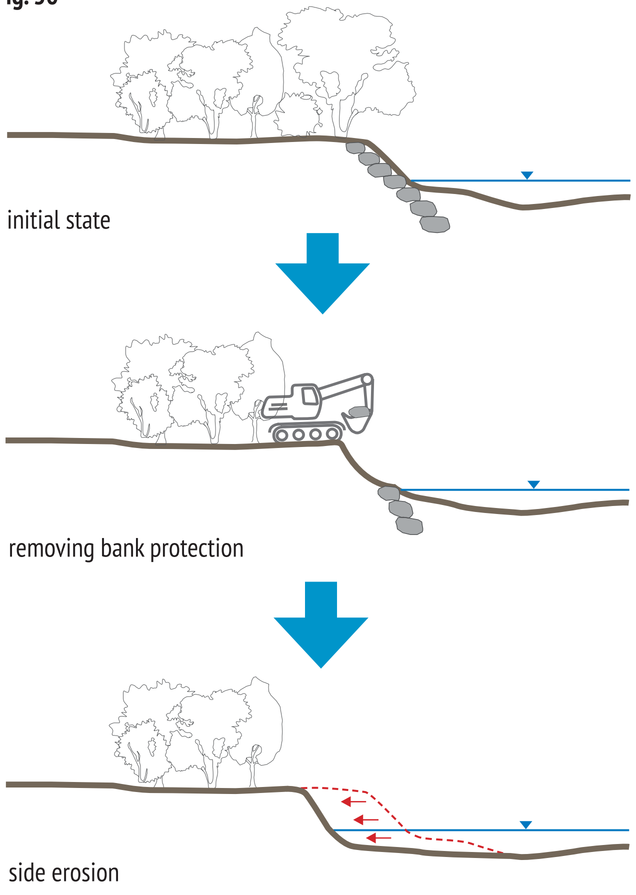
Depending on the composition of the bank material (grain size distribution) and the occurrence of relevant runoff events (smaller and larger floods), the banks are gradually eroded and the bank moves into the foreland. The river gains more space through self-dynamic widening and rearrangement processes and constantly reshapes the riverbank zone.

Bank erosion widens the channel, decreases bedload transport on the bed and therefore has a stabilising effect.

Efficient bedload supply from upstream accelerates the dynamic development of the riverbanks.

In most cases, only selective clearing of riparian forests is required, extensive clearing is not necessary. Due to the self-dynamic erosion processes, bushes and trees can fall down, form small erosion-promoting structures again or are washed away.

Fig. 30



When to implement?

- When **long-term dynamic processes** are intended and banks should gradually develop or widen over a longer period of time. Soft banks are not suitable as quick-acting emergency measures!
- When **side erosion** / **recurring bedload input** caused by the river itself is required in the event of a flood.
- When slow but sustainable widening of the riverbed in **ecologically** valuable foreland (alluvial forests) is accepted.
- When **legal approval** from nature conservation and forestry should be obtained **as easy or quickly as possible**. As the process of erosion is happening in a natural way, soft banks require little or no clearing, therefore usually no/less replacement afforestation and no/fewer compensatory measures are necessary. This makes approval and project implementation easier.
- **Useful combinations** with other types:

Basic rules & knowledge

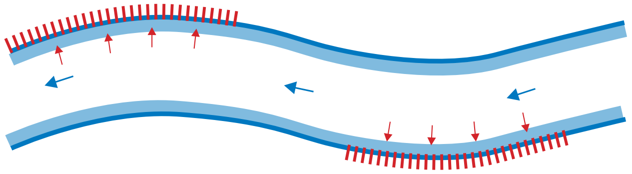
Dimensioning & planning

The following factors have a particular influence on the dynamic development of soft banks:

Flow direction

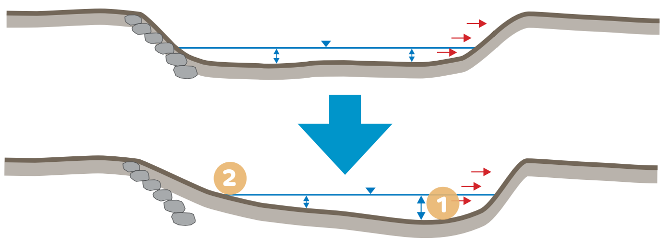
Soft banks should possibly be situated on the outer side of a river bend (Fig. 31). That way, there is a natural flow towards the banks and side erosion will be increased.

Fig. 31



The removal of the bank protection is particularly useful in the **outer bends** of the river

Fig. 32

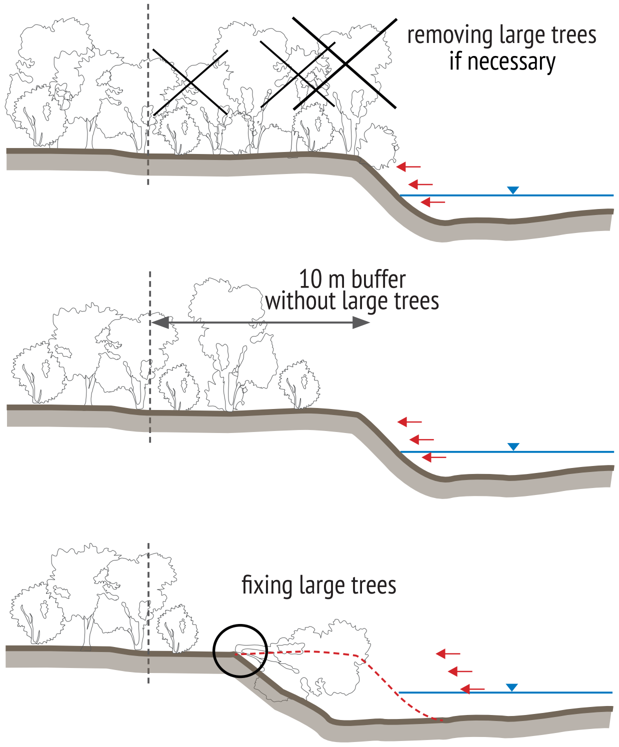


Where the bank protection is removed, the river will create a **steep bank** with a **pool** ①, the opposite bank becomes **flat** ②.

Avoiding driftwood and unintentional log jams

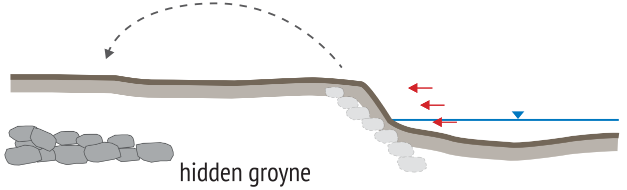
Trees, bushes, herbaceous vegetation, reeds, etc. stabilise the bank through their cover and roots. In order to get the side erosion going, but also to avoid too much driftwood and the danger of locking bridges, larger trees and shrubs may have to be removed along the planned soft banks over a certain width (depending on the erosion potential). Ecologically valuable old trees can be left in place, but may be fixed to prevent them from being washed away (see Fig. 33).

Fig. 33

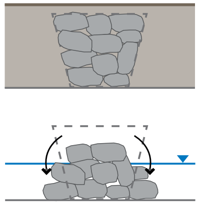


The prevailing ecological situation should be included in the decision-making process.

Fig. 34

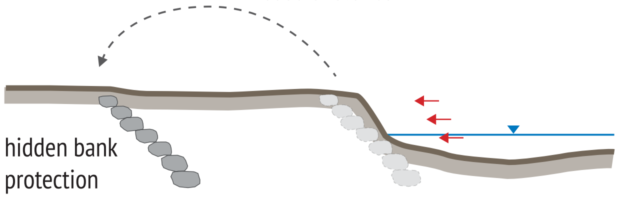


After removing the existing bank protection the maximum side erosion is limited by **hidden groynes** in the foreland. They are sensibly made from stones obtained from the bank protection.



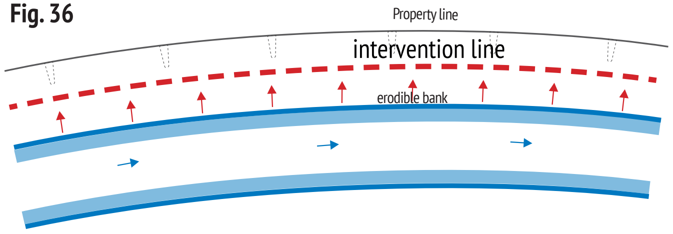
How to build hidden groynes?
It is advisable to build the hidden groynes so that initially only a vertical slot is filled with stones. If the surroundings are removed by the river, the stones form stable groynes. This procedure saves space and costs.

Fig. 35



Hidden longitudinal protection limits side erosion area.

Fig. 36



When the river reaches the **intervention line**, further measures are taken.

Safety concept

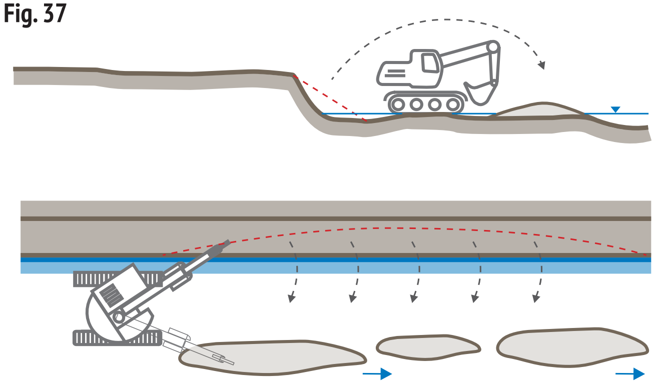
If the riverbank consists of coarse-grained material (stones, coarse gravel), a much higher force is required for the removal of material than with sandy subsoil. The banks remain more stable and only erode when there are large runoffs. If there is fine-grain, sandy sediment, the banks are removed quicker. Unforeseen erosion processes can occur. Countermeasures are sometimes required, which can be taken into account in the planning phase, e.g. by installing hidden groynes (Fig. 34) or hidden longitudinal bank protection (Fig. 35).

Hidden bank protection does not have to be built immediately. A line of intervention with sufficient distance to the limit of the available land (Fig. 36) can be determined. When this line is reached through bank erosion, further steps to limit side erosion have to be taken.

Implementation tip - Initial dredging

Side erosion can be accelerated by using an excavator to remove not only the stones, but also the underfilled material (Fig. 37). Steeper banks erode more easily. Excavated materials are put directly into the riverbed.

Fig. 37



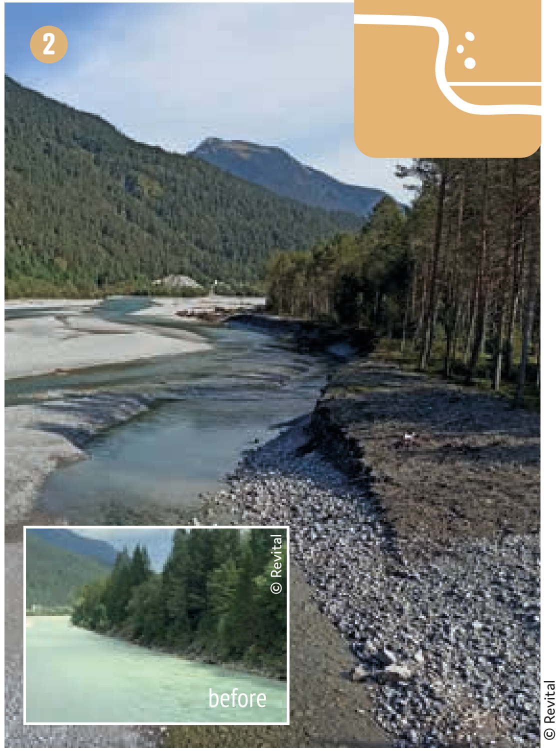
Effects

- **Reduced maintenance costs** as bank protection no longer needs to be renewed.
- **Higher habitat diversity:** Variable bank slopes (flat banks, steep banks) and embankment demolitions create diverse habitats for endangered animal and plant species, e.g. sand martin
- **Reduced claim of ecologically valuable areas**, as only a narrow strip of land is required. The river itself will gradually take up additional land. This means that there is less potential for conflict with nature conservation.

Challenges

- **Limited prediction:** The development of soft banks depends on many different factors and can only be predicted with high uncertainty.
- **Ensure sufficient bedload supply:** Bank erosion may eventually not occur when bedload supply from upstream is missing; see Mura at Gosdorf (AT, SI) - if there is no deposition in the channel, there is only limited bank erosion.
- **Participation:** For good acceptance by residents/those looking for relaxation, hiking trails should be relocated, and the accessibility to the river should be improved.

Best practice



① Soft banks on the Salzach River (Austria). Although a small measure, it shows large morphological effects: small ponds filled with groundwater (juvenile fish habitats), flat banks with gravel banks (spawning habitats) and backwater (valuable for juvenile fish, especially under hydropeaking stress).

② Massive side erosion after removing bank protection – Tyrolean Lech

③ Freely erodible bank on the Upper Drava (Austria)

④ Natural dynamic banks at Libanovec – River Drava (Croatia)

Planning module M02

Mechanical widening


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Fig. 38: Excavating gravel to widen side-channel entrance (Danube, Wachau, Austria)

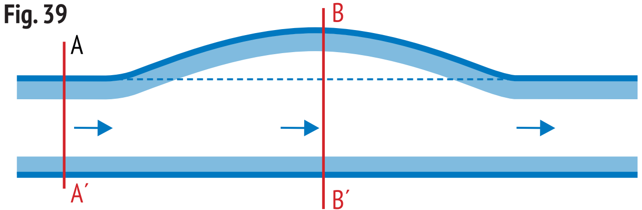
Description

Mechanical widening requires mechanical equipment such as excavators or wheel loaders. After bank protection is removed on the defined stretches, the river widening is executed by excavating and then removing the materials. Before work can start, the widening area must be logged and cleared from bank protection (if existing), tree trunks, branches and rootstocks.

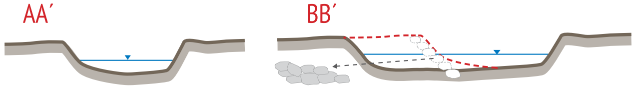
The sediment material is also removed or, in the best case, actively added into the river as bedload input - in the area of measures (Fig. 41; see also planning module M05).

It also has to be determined whether further self-dynamic development is desired (see M01). If necessary (based on the hydraulic modelling), measures may finally be implemented, such as new bank protection or hidden groynes, which only get functional, when river widening reaches a defined intervention line.

Fig. 39

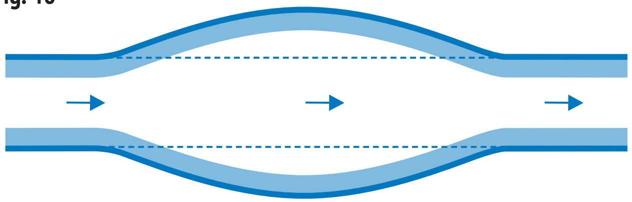


unilateral river widening



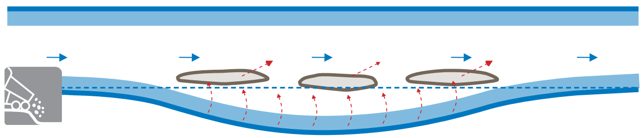
unilateral river widening - schematic section

Fig. 40



bilateral river widening

Fig. 41

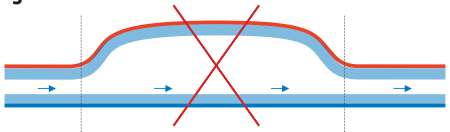


direct input of bedload (in the area of action or upstream)

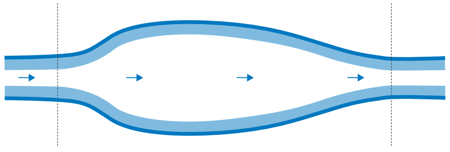
Where to implement?

- In areas with particularly **strong riverbed erosion**, where countermeasures (additional bedload) must be implemented quickly and have an **immediate effect.**
- Where sediment needs **to be excavated** for bedload supply.
- If **little self-dynamic lateral erosion** is to be expected.
- Near settlements and infrastructures, where **rather narrow and limited land is available.**
- **Useful combinations**:

Fig. 42



unfavourable form of riverbed widening (abrupt change in width)



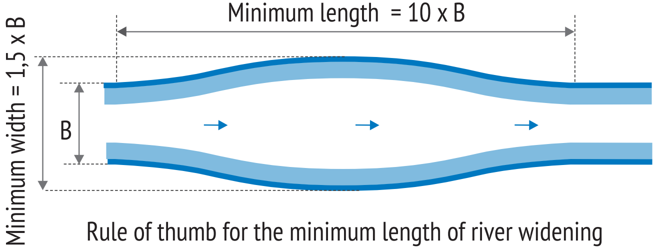
favourable form (gradual change in width)

Basic rules & knowledge

Dimensioning & planning

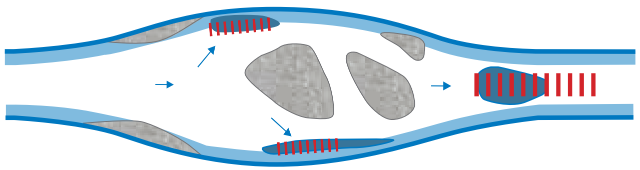
In general, the riverbed widening leads to a reduction of discharge depths and consequently to a reduction of the bed shear stress. Bed erosion is reduced and bedload is deposited. With large widths, gravel/sediment banks, riffles and pools are formed (Fig. 44).

Fig. 43



Rule of thumb for the minimum length of river widening

Fig. 44



the wider the riverbed the deeper the pool

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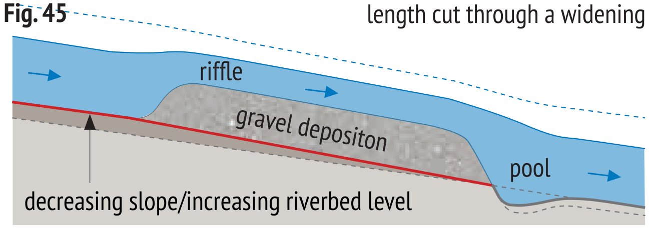
Fig. 45



length cut through a widening

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Shape

The preferred form of widening is "lenticular, elongated" (Fig. 42). Both, the channel widening and the channel narrowing at the lower end of the widening should not be abrupt, but formed hydraulically optimised, so that the erosion phenomena are reduced at a minimum.

Length and width

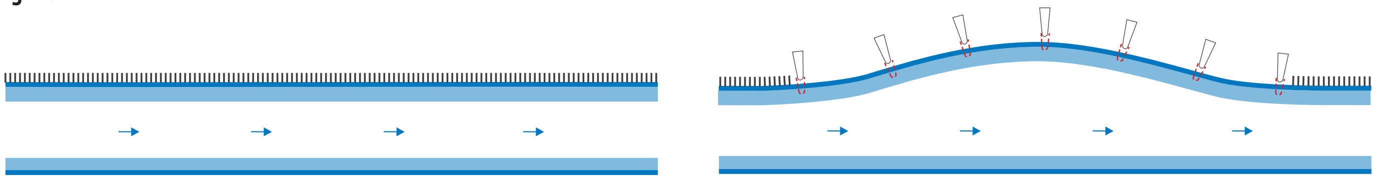
In order to maintain the effect of bed stabilisation in the long term and to preserve morphological dynamics in the widening area, the bedload input must not be too low and the widening not too short. The length should be at least 10 times the original width, the minimum width 1.5 times the original width (Fig. 43).

Increasing morphological dynamics and increased sinuosity tend to cause deepening (pools) and sedimentation processes in the reach of the widening measures (Fig. 44).

The widened river system strives for a new state of equilibrium (Fig. 45). Over time, more and more bedload accumulates in the widened area. The gradient increases until it is sufficiently large, so that bedload is transported through the widening. Downstream of the widening, the trapped bedload can cause a bedload deficit temporarily.

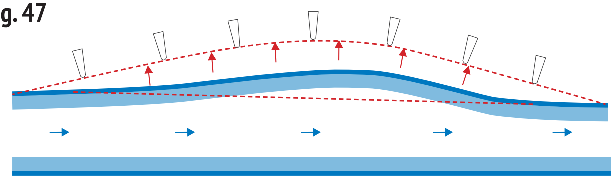
Bedload dredged during the construction of the widening should be added again (above) to support the achievement of the new equilibrium state described.

Fig. 46



Transverse (ri.) instead of longitudinal (le.) bank protection; advantage: flexibility

Fig. 47



Combination with self-dynamic river widening

Fig. 48: Combining mechanical widening and the initial channel to replace existing ramps (photo montage; Licca liber, Augsburg, Germany)

Safety concept

In the widening area, reverse currents develop, bedload and sediment are accumulated, and gravel bars and a branched channel form if the river is wide enough. On the other hand, especially the banks and the bed (immediately downstream of the constriction to the original river width) are exposed to increased erosion pressure (Fig. 44). Mechanical widening therefore requires a hydraulically verified, adjusted protection concept.

Especially the areas with increased erosion must be protected adequately. In principle, transverse protection in the form of groynes is preferable to linear protection, because it offers more flexibility in controlling the widening width (Fig. 46).

If further self-dynamic widening of the banks is possible, hidden protection can be installed in the hinterland along a defined intervention line. In this case, one has to ensure that the remaining bank protection is adequately connected to the hidden groyne structures (Fig. 47).

Combinations with other types

Mechanical widening can e.g. be connected with soft banks, which have more potential for self-dynamic development (Fig. 48). If mechanical widening is combined with lowering of the foreland, part of the excavation work can be reduced.

Effects

- Mechanical widening offers **limited self-dynamic development potential**, which, however, can be hydraulically modelled in detail.
- Mechanical widening works quickly, but **bedload input** from the river is necessary in order to maintain the effect long term.
- Unfavourable **side effects** can be a high construction effort (amounts of excavated material), water turbidity or intervention in sensitive areas.
- Nonetheless, diverse, **ecologically valuable** (semi-)aquatic and terrestrial habitats are being created.
- Ecological **stepping stone biotopes** can also develop along the restored stretch and have positive effects.

Challenges

- **Conflicts can arise**: If valuable animals and plants are affected due to clearing and implementation, a balance of interests must be sought. It must be clarified at an early stage whether compensatory measures are required.
- Right **dimensioning** of a widening is different in every river and river stretch, depending on the river's initial condition and parameters. Local deepenings as well as siltations and rising water levels must be avoided.

Best practice

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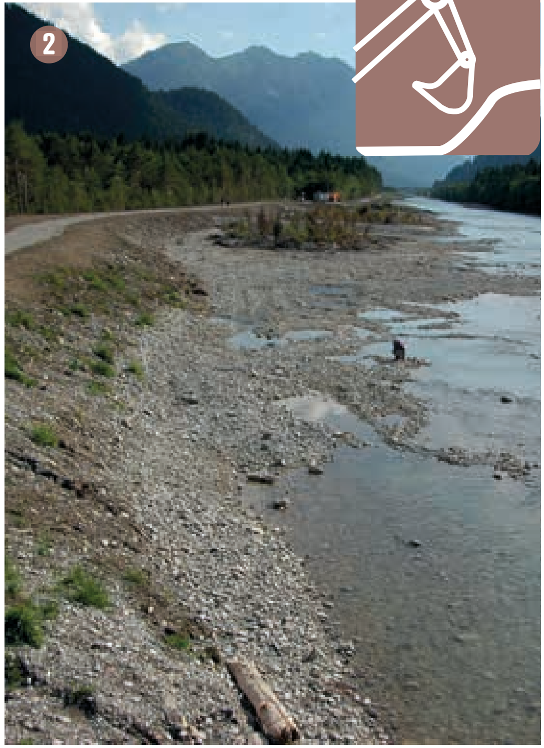

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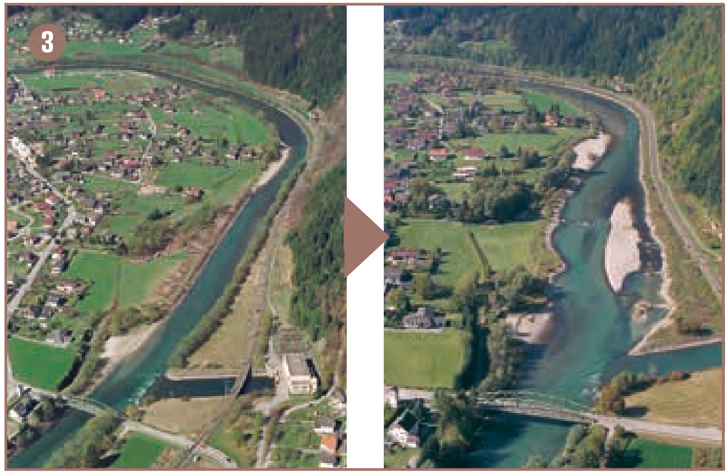

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① Mechanical widening combined with removing bank protection – Tyrolean Lech (Austria), during implementation

② ... at the end of construction work.

③ Riverbed widening to improve flood protection – Upper Drava, Sachsenburg (Austria)

④ Mechanical widening of Salzach riverbed near Freilassing (upstream of Salzburg, Austria). Gravel material was put directly into the river.

Fig. 49: Initial channel – Upper Drava near St. Peter (Austria)

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Planning module M03

Initial channel

Description

Initial channels are aimed to divert a certain proportion of the main stream runoff and to initiate self-dynamic erosion processes (Fig. 50). Depending on the hydrological conditions or the prevailing sediment conditions in the foreland (fine or coarse material), side channels develop as they successively erode.

Initial channels are usually built with a quite narrow profile. The channel geometry is designed simply, e.g. as trapezoidal profile. The initial channel is usually dredged to the level of the main riverbed. The material is removed and, if possible, used as sediment input (see M06).

Fig. 51

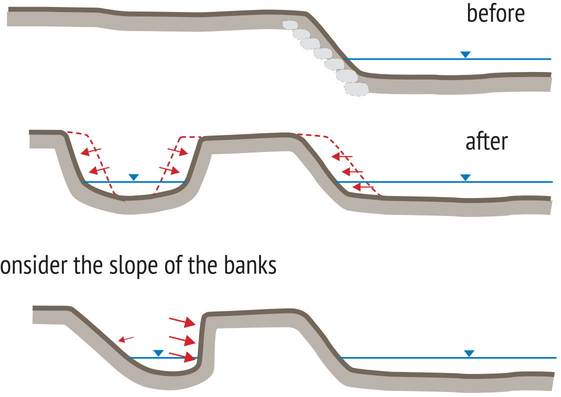
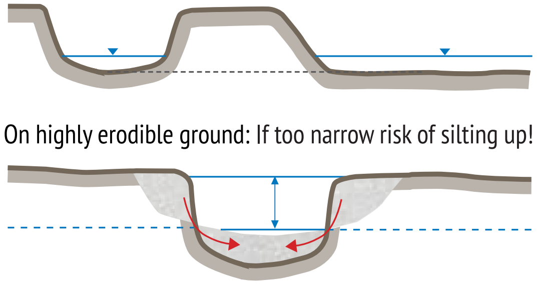


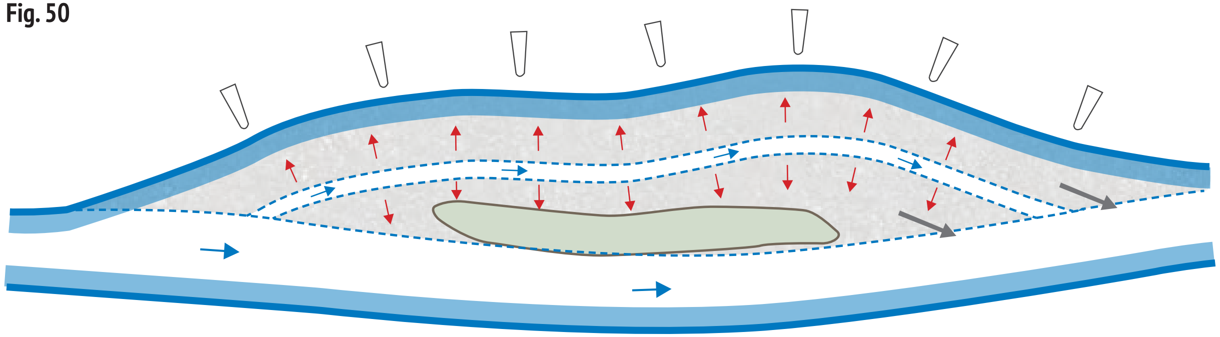
Fig. 52

Ideal depth of the initial channel



On highly erodible ground: If too narrow risk of silting up!

Fig. 50



Initial channel – schematic representation: The simply designed small channel is supposed to develop, creating a self dynamic braided river system with dynamic flow areas and dynamic morphological elements.

When to implement?

- When measures in the foreland are also possible for reasons of land availability (**large-scale measures**).
- When it is **hydraulically useful** to remove erosion pressure from the riverbed by diverting a part of the discharge into an initial channel.
- When **input of dredged material** into the main river is wanted.
- When **successive erosion** of the foreland is **aimed for** and is to be expected due to hydraulic conditions.
- When **existing channel systems** can be reconnected.
- When ecologically valuable habitats/floodplain forest areas are to be preserved, initial channels should be created **outside the critical areas**.
- **Useful combinations**:

Basic rules & knowledge

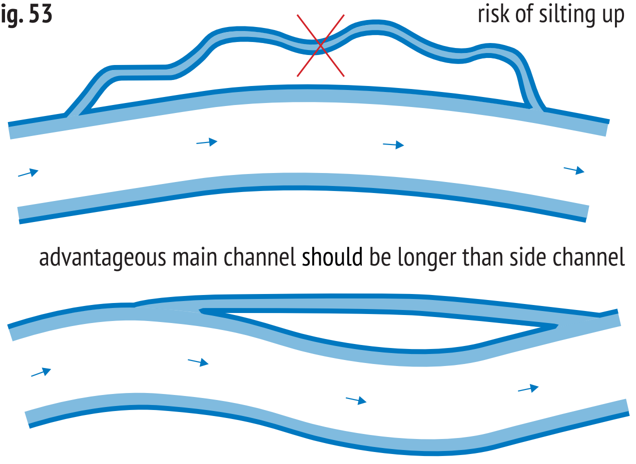
Dimensioning & planning

Slope gradients
Initial channels should have a simple trapezoidal profile with steep banks, especially since steep banks erode more easily than shallow ones. Steeper banks and curvature promote erosion - this can be used to actively support erosion directions (Fig. 51).

Depth
The bed level of the initial channel should be at about the same level as the bed level of the main river course (Fig. 52).

Length
The flow length in the initial channel should generally not be significantly longer, if possible even shorter than in the main stream (see second diagram, Fig. 53). If the initial channel is too long (Fig. 53), there is a risk of sedimentation due to the resulting lower longitudinal gradient and the low flow velocity in the initial channel.

Fig. 53



Correct position and dotation
One crucial element regarding an efficiently designed initial channel is the appropriate positioning of the inlet. Ideally, it should be located at the end of the outer bend of the river (Fig. 54).

If possible, the longitudinal gradient of the initial channel should not be lower than that of the main channel, so that a sufficiently high flow velocity is achieved and material drawn in from the main river or eroded in the initial channel can be transported. As a rough indication, about 1/3 of the runoff should be a target value for the flow through the initial channel directly after construction (Fig. 55).

Ideally, together with a respective bedload input from upstream, the initial channel develops dynamically into a braided river section with diverse morphological structures. A dynamic equilibrium between sedimentation and erosion is thereby achieved.

Fig. 54

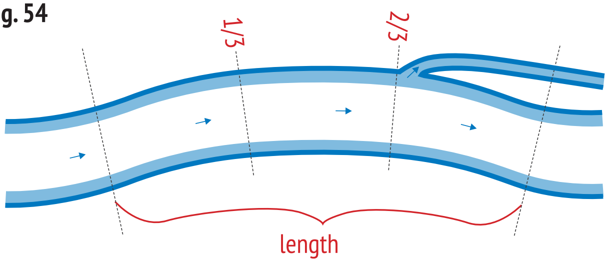
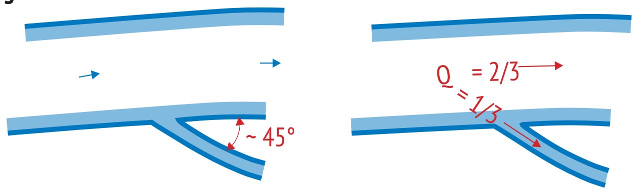


Fig. 55



Safety concept

As initial channels are supposed to develop dynamically, the banks are not protected. Nevertheless, in most cases it will be necessary to define an intervention line, combined with hidden groynes or longitudinal bank protection (see Figs. 34-36).

During the self-dynamic erosion processes, adjustments can become necessary, such as the addition of bank protection at crucial points which are at a particular risk of erosion or the installation of structures that enhance erosion in areas where dynamic processes should be enhanced.

Combinations with other types

Branched channel system

Several initial channels can also be provided along a river section with pronounced incision tendency (Fig. 56).

By repeatedly diverting and flowing towards erodible banks, an embedding channel becomes a branched river system with dynamic relocation sediment. It may take several years or even decades, until the predicted target state is reached. The required riverbed width has to be estimated in the planning process, using available morphological calculation approaches (see chapters "Key planning steps" (p. 12) and "Planning tools" (p.14)).

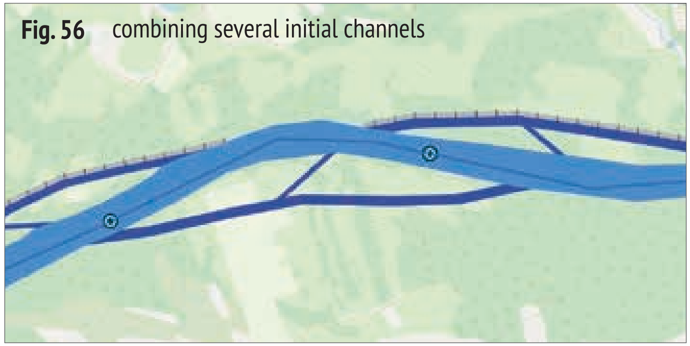


Fig. 56 combining several initial channels

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Relocation of river course

In straightened, narrowed rivers, it can make sense to relocate the river course in order to increase sinuosity, achieve a greater flow length, decrease the gradient and thus reduce pressure on the riverbed. For this purpose, initial channels can be dredged or, especially in lowland rivers, oxbows can be reconnected. With this goal, it is important to direct the major part of the runoff into the new river course. Again, the suitable position of the side channel entrance is important for the desired function. E.g. groynes, supporting the deflection of the flow on the opposite river bank, may be necessary (see Fig. 89).

Intensive erosion processes can be expected. Therefore, sufficient land and (hidden) protection in the hinterland, along an intervention line could become necessary. The development from the initial measures to the estimated target state (see second picture, Fig. 57) can take decades.

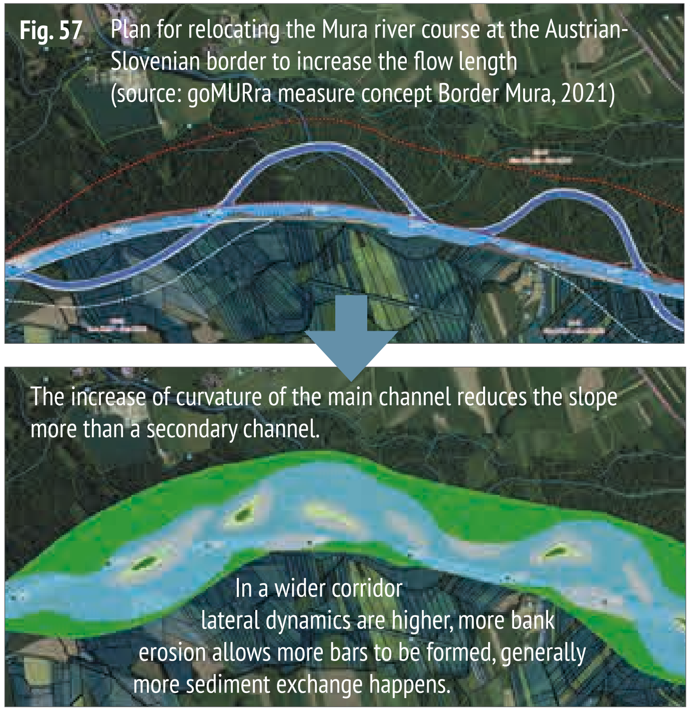

Fig. 57 Plan for relocating the Mura river course at the Austrian-Slovenian border to increase the flow length (source: goMURra measure concept Border Mura, 2021)

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The increase of curvature of the main channel reduces the slope more than a secondary channel.

In a wider corridor lateral dynamics are higher, more bank erosion allows more bars to be formed, generally more sediment exchange happens.

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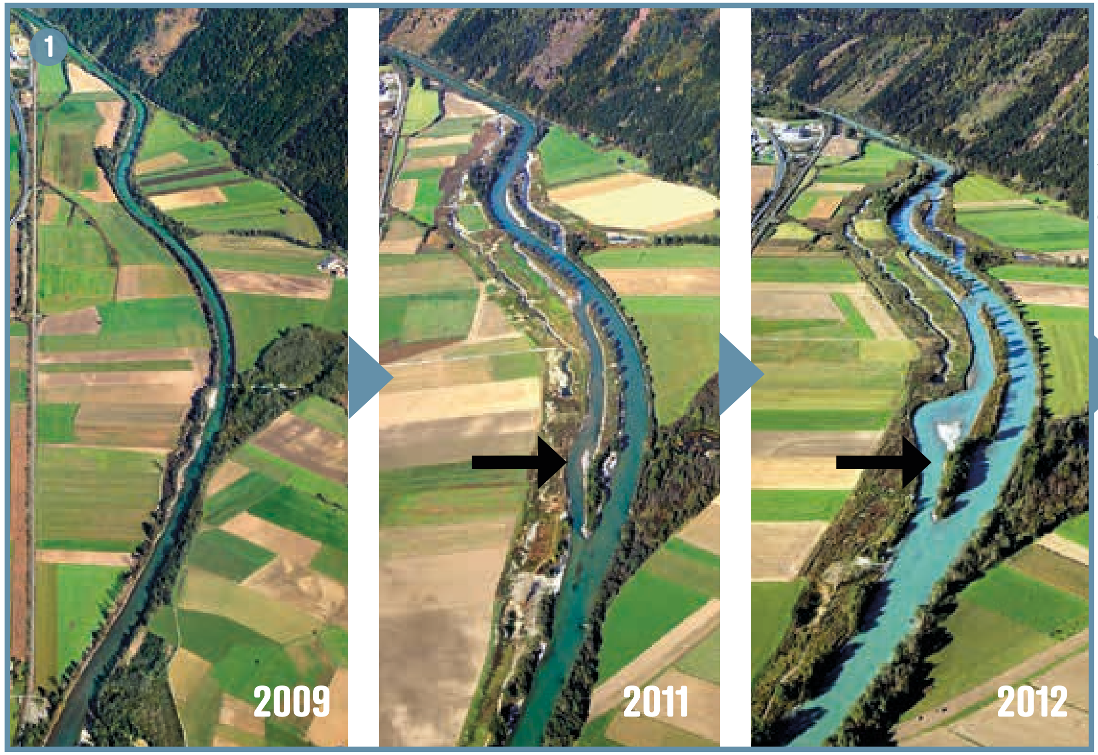
Effects

- Initial channels **break the ground** for large self-dynamic river systems. They **significantly increase** the sediment input from the foreland into the river.
- By means of a hydraulically favorable connection, **large-scale erosion zones** can be created, which bring long-term bedload input.
- A **mosaic of valuable habitats** is created, which is constantly evolving on its own.

Challenges

- Too rapid self-dynamic development can **endanger infrastructure** in the foreland.
- **Availability of land** is crucial. Thus, it is important to have a reliable estimation of the area affected and the area needed in the planning phase.
- If initial channels do not develop as desired, **additional measures** which avoid or promote erosion have to be considered.
- **Conflicts** with nature conservation goals can occur, if nature protection does not regard the value of successively disappearing habitats and alternately emerging new (semi-) aquatic habitats.
- **Reconciliation of interests** must be sought: gravel companies or residents/recreationists may exert pressure.

Best practice



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① Development of an initial channel at Upper Drava near Obergottesfeld (Austria) – between 2009 and 2011

② Upper Drava riverbed at Obergottesfeld in 2021

③ Opening the initial channel in 2012

④ Massive side erosion in the channel during a flood in 2012

Fig.58: Lowering the foreland at Tyrolean Lech (Austria)

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Planning module M04

Lowering the foreland

Description

This planning module involves lowering riverbanks and foreland areas for establishing better connected floodplains and areas suitable for self-dynamic erosion. Before excavation starts, the area is defined and cleared, ecologically valuable habitats should be preserved.

To allow a dynamic development, the bank protection is removed. Parts can be left to stabilise river islands, woody vegetation and rootstocks are cleared and can be re-used as habitat structures (Fig. 59). The dredged material is subsequently removed using machines such as excavators, wheel loaders, transport boats, etc. Parts of the dredged material can be deposited directly into the river as bedload addition (Fig. 60; see also planning module M05).

Dredging trenches in the planning phase can be helpful to specify the type and quality of the subsurface material.

The lowering of the foreland is designed in accordance with the objective, i.e. more frequent flooding of the foreland is envisaged or to initiate more self-dynamic erosion processes. Existing bank protection, which is partly left in place, can act twofold - as structures to enhance erosion and to stabilise certain parts.

Fig. 59

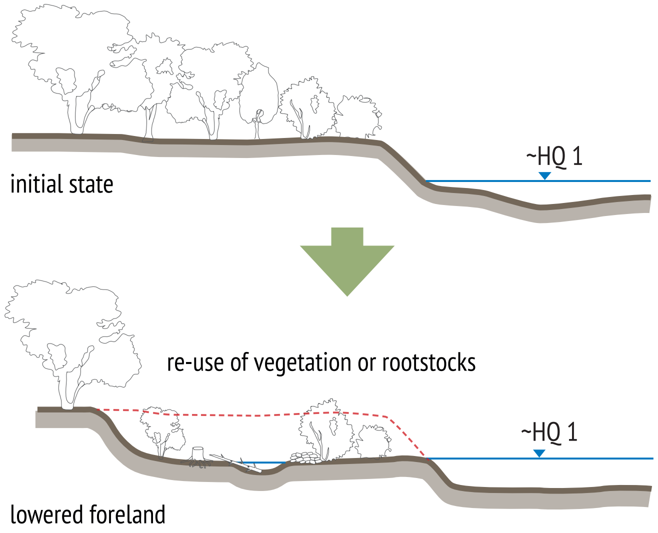
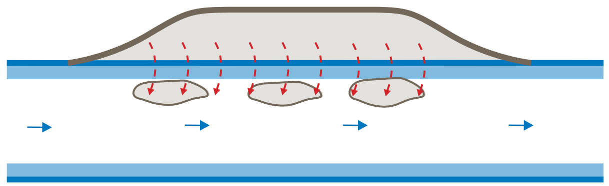


Fig. 60 dredged material deposited in the riverbed within the area of measures or upstream



When to implement?

- When bed incision is already advanced and the **floodplain is already widely disconnected from the river** (no more flooding takes place).
- When it is **impossible to raise** the riverbed elevation in order to reconnect floodplains.
- When, due to incision processes, a **large amount of bedload** is required within and downstream of the measure.
- When a dynamic **bedload input is intended** in the event of a flood.
- When a **secondary alluvial forest** in the lowered foreland of the river should be initiated.
- **Downstream of hydropower plants** to compensate the bedload deficit.
- When no immediate measures are required, and instead **long-term dynamic processes** are intended and banks should gradually develop or widen over a longer period of time.

			P1	P2	P3
Depth	h	[m]	7,50	5,00	3,30
Grain size	d_{50} bzw. d_m	[m]	0,10	0,10	0,10
Water level width	B_W	[m]	100	200	400
	h/D	[-]	7,50E+01	5,00E+01	3,30E+01
	B/h	[-]	1,33E+01	4,00E+01	1,21E+02

Basic rules & knowledge

Dimensioning & planning

Lowering of the foreland creates a larger discharge profile, at higher water levels, and thus reduces the pressure on the riverbed. Therefore, the function of the foreland lowering, and especially the level of the lowered foreland, is a crucial design factor and has to be simulated and optimised using hydraulic models. As a first estimation, the foreland level can be lowered to the waterlevel, corresponding to an annual flood (HQ1) (Fig. 60).

If the lowering of the foreland is combined with (self-dynamic) widening, different river morphological structures arise depending on the width of the riverbed. The development can be estimated using the diagram by DaSilva (1991).

The "(B/h;h/D)-plan" of Ahmari & Da Silva (2011) relates the ratio between channel width (B) and water depth (h) to the ratio between water depth (h) and grain size (D), which allows delineating different morphological river types (Fig. 61). This diagram can be used to estimate the channel width, which has to be provided to restore a certain river morphology type (also usable for M01 and M02).

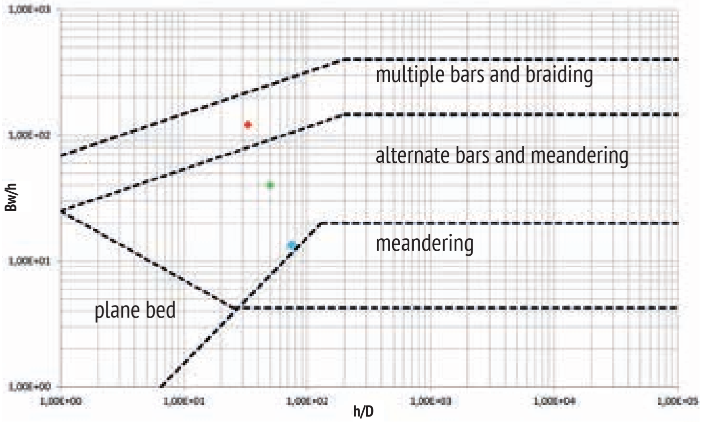


Fig. 61: Diagram to estimate the river morphology based on channel width, channel depth and grain size according to Ahmari & DaSilva (2011).

Safety concept

The bank protection is usually removed and reinstalled as a hidden protection in the hinterland (longitudinal structures; Fig. 62). Dynamic processes are possible at the level of the lowered foreland, and are spatially limited by the protection measures.

Alternatively, the removed bank protection can also be reinstalled in the form of hidden groynes (Fig. 63). However, the distance and length of the groynes should be checked using hydraulic simulations. Between the groynes, self-dynamic expansion and erosion processes are possible to a limited extent.

Fig. 62

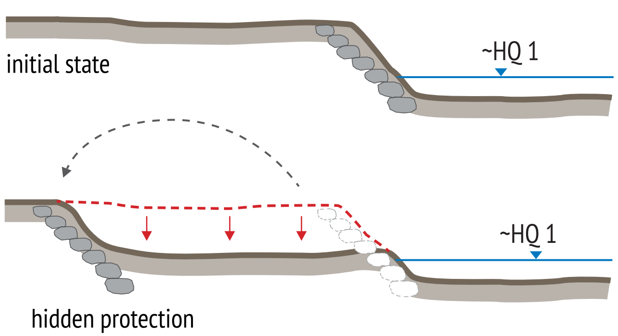


Fig. 63 lowered foreland

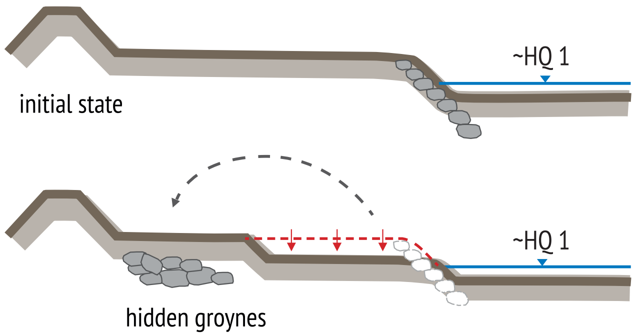
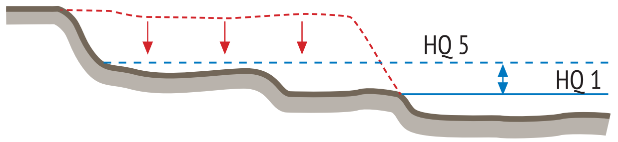
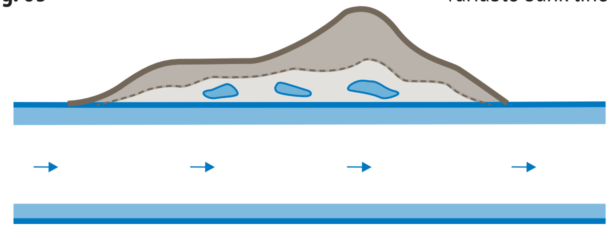


Fig. 64



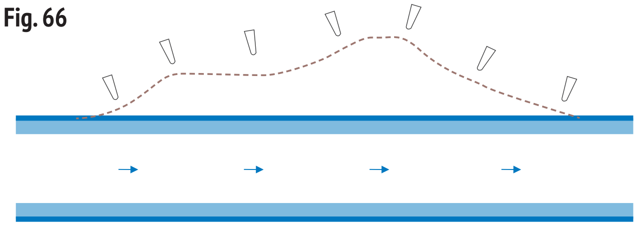
variable terraces

Fig. 65



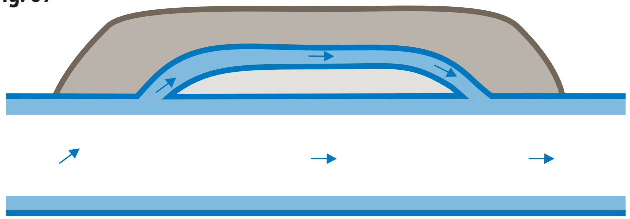
variable bank lines

Fig. 66



combined with hidden groynes along the intervention line

Fig. 67



combined with initial side-channel

Combinations with other types

The foreland lowering can be realised in stages, e.g. the berm near the river can be lowered to HQ1 water level and can rise to HQ5 water level (Fig. 64). Thereby, various development stages of floodplain zones can be initiated, from pioneer habitats to soft- and hardwood alluvial forests. The surface of the berm is shaped unevenly, pools and waterlogging will develop (Fig. 65), which also creates habitats for (semi-)terrestrial species.

Lowering of the foreland can also be combined with freely erodible banks and self-dynamic river widening. In this case, the bank protection and the vegetation cover are removed and the maximum extent of the dynamic expansion can be limited by hidden groynes along the intervention line (Fig. 66).

If foreland lowering is combined with an initial channel (Fig. 65), stronger erosion processes occur, as the surface of the terrain has already been torn up and erosion can mobilise the sediment more easily. Bedload is constantly being introduced into the river. Over time, a highly dynamic river landscape with side-channels, gravel bars and various habitats emerges. The resulting river morphological type can be estimated with the diagram by Ahmeri & DaSilva (2011) (see Fig. 61).

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Fig. 68: Combining the lowering of the foreland with an initial channel (photo montage; Licca liber, Augsburg, Germany)

Effects

- By lowering the foreland, the river will overflow the foreland area at lower water stages, the runoff profile for flood discharges becomes larger, the **erosion pressure on the riverbed is reduced**.
- In the lowered foreland, a secondary alluvial forest zone is initiated with various ecologically valuable habitats (riverine willow scrub, wet areas, temporary and permanent still water biotopes, shallow bank areas).

Challenges

- Lowering the foreland is usually associated with a **high demand for land**, as well as with large-scale clearing of the areas affected. This can lead to conflicts with forestry and nature conservation. It must be clarified whether compensatory measures are necessary.
- Large amounts of material have to be excavated. This means **high demand on material logistics**. Areas are required for the intermediate storage of sediments and for the subsequent successive addition of bedload to the river.
- **Pressure** can arise from gravel extraction companies which would rather sell the gravel than to reintroduce it to the river.

Best practice

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① Terrain lowering along Tyrolean Lech near Forchach (Austria) - Preparatory clearing

② ... mechanical sediment removal

③ ... situation one year later (ongoing self-dynamic widening)

④ ⑤ Heavy machinery pushes the sediments from the lower foreland into the Salzach (Austria)

Fig. 69: Extraction of sediment (Danube side-branch; Hungary)

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Planning module 05

Sediment input

Description

As described in the introduction chapter, bedload and suspended load input from upstream is crucial for active dynamic development of a river section. Planning module M05 describes the active bedload input along stretches, where sediment continuity is disturbed and the lack of sediment from upstream is a main issue. Bedload addition can be realised in different ways.

- Optimisation of bedload/sediment transport through reservoirs by adapting reservoir geometry and weir functionality (Fig. 70).
- Backfilling bedload material at riverbanks as a deposit that is gradually eroded, especially with higher discharge or floods (Fig. 71, Fig. 72).
- In large river widenings cable excavators or boats can be used. The removed sediment can be transported by boats upstream to the point of reintroduction (Fig. 69, Fig. 73). This point can be chosen flexibly. If the bedload is introduced directly into the stream, increased turbidity can occur.

The added sediment is transported by the flowing water and is available downstream as material for the development of dynamic morphological structures.

Fig. 70

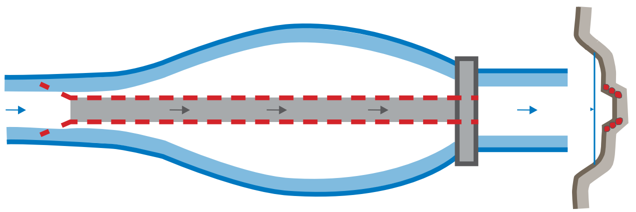


Fig. 71

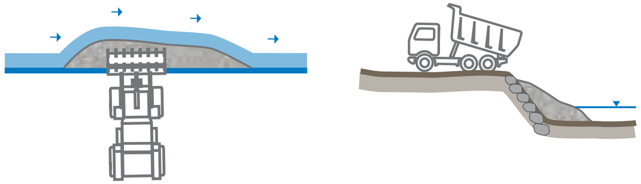


Fig. 72

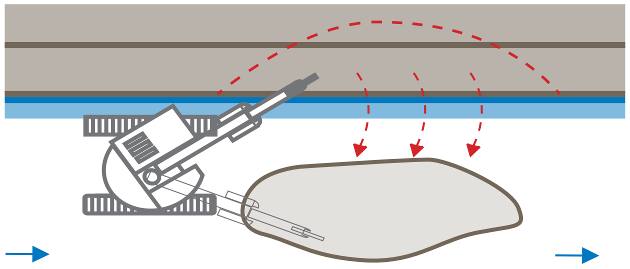
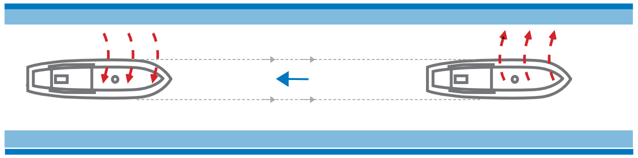


Fig. 73



Where to implement?

- Generally along river sections with a **lack of bedload**/riverbed incision.
- Where **sufficient and adequate input material** is available.
- **Upstream** of widened river stretches to actively support a dynamic development downstream.
- At locations, where the river **transport capacity** allows transport or where the erosion of deposits and the subsequent transport further downstream is possible.
- Where **bedload from other measures** (e.g. from forelands, reservoirs, dredging at tributaries/check dams) is available.
- **Useful combinations**: In general, bedload input should always be a combination of measures. In widened riverbeds, bedload has a stronger positive effect on riverbed stability.

Basic rules & knowledge

Dimensioning & planning

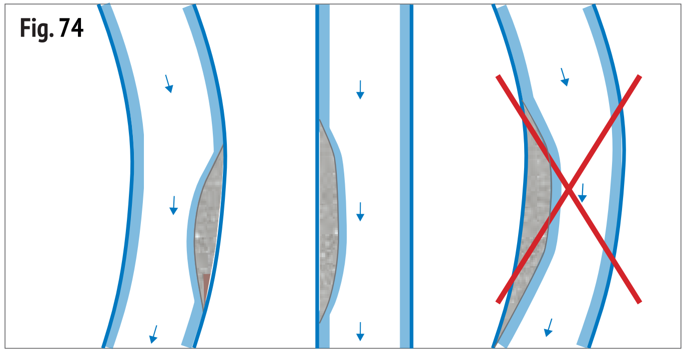
In the past, when rivers were regulated, the combination of river width and longitudinal gradient was usually dimensioned to maximise transport capacity, so that the bedload was transported through the river channel without accumulation.

Today there is a lack of bedload in many rivers, so the riverbed incises and countermeasures are necessary to stop this process. The most common countermeasures are riverbed widening and adding bedload. The planning modules M01-M04 (or combinations) described above are suitable measures to widen the runoff profile, to reduce transport capacity and also to provide bedload. This bedload can be introduced directly within the field of action or added upstream at suitable points.

Experience shows that several parallel or alternating bedload fills in the discharge profile lead to a more sustainable bedload input. In general, islands in the middle of the river (Fig. 75) are eroded more quickly than bedload fills along the banks.

The sediment input is more easily eroded on cutbanks (outer banks) or in sections with a stretched course. Additions of bedload in the slip bank (inner bank) are not ideal, because bedload cannot be mobilised that easily due to flow conditions (transverse flow to the inner bank; Fig. 74).

Fig. 74



Grain size distribution is crucial for the addition of bedload. Finer grain fractions are eroded faster and more easily than coarse material. The material used for sediment input has to match the conditions in the river section downstream, as well as the specific purpose. The potential bedload transport in characteristic flow profiles can be determined using different bedload transport formulas e.g. Meyer-Peter & Müller (1949) or Smart & Jäggi (1983). An overview on different approaches is given by Hunziker (1995).

Safety concept

When determining the amount of input material, it is recommended to align to the mean annual bedload transport capacity or use a load that enables the formation of near-natural morphological structures. Excessive bedload introduction and the possible resulting excessive bedload deposits at hydraulic unfavourable sections can lead to problems in flood protection.

Detailed monitoring can compensate uncertainties with sediment transport calculations. Unwanted bedload accumulation can be recognised at an early stage, and measures (e.g. structures that promote erosion, see M06) can be counteracted.

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Fig. 75: Bedload deposit island (Danube, Austria).

Fig. 76

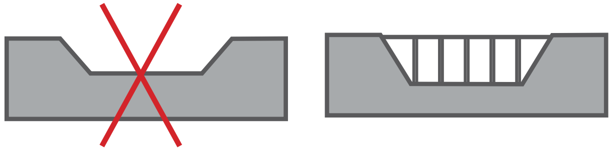


Fig. 77: New opened bedload retention dam on Feistritzbach (Upper Drava, Austria). The old dam was removed, the retention area emptied.

Bedload continuity - Removing barriers

In principle, the input of sediment can be combined with all measures that provide bedload. It is important that the bedload is not deposited outside the river corridor, but is added back into the river at a suitable point. No bedload should be removed from the rivers at all.

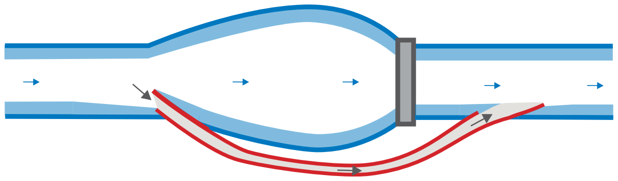
Rivers often face a pronounced bedload deficit, as a large amount of bedload is retained in the catchment areas and in large reservoirs of hydropower plants.

At tributaries and torrents carrying sediment, the catchment area can be increased by re-opening retention dams for debris flow (Fig. 76, Fig. 77).

To counteract the sediment trap effect of reservoirs, there is the possibility to adapt the weirs in a way that at least a certain amount of sediment can be transported downstream. Reservoir flushing is often carried out during larger flood events, where especially fine sediment is flushed out of the reservoirs (which can cause problems downstream).

Regarding coarse material, especially in steeper tributaries within the catchment area, there is the option of creating a diversion channel at the head of the reservoir. The bedload reaches the downstream river section via this bypass with sufficient transport capacity (Fig. 78).

Fig. 78



bedload bypass channel

Effects

- Sediment is moved through **natural transport processes** to places with bedload deficit.
- Bedload input **reduces erosion pressure** on the riverbed and supports lateral erosion.
- Added bedload forms **morphological structures,** which are characteristic for the river type (like gravel banks, sandbanks, gravel islands, ...)

Challenges

- Transport of bedload from exctracting areas to the point of input can cause high efforts regarding **material logistics** or can **disturb** settlements and ecologically sensitive zones.
- Added bedload can cause **local water level rise and increased flood risk**, but also lead to **accumulations** downstream in widening areas or reservoirs. Ideally, widening and bedload input should be coordinated in a way that in the medium to long term a bedload balance between sedimentation and erosion is achieved (detailed monitoring helps to understand processes and react in time).
- Gravel is a mineral resource, which is in great demand by gravel companies, and therefore conflicts are likely. Nevertheless, it should be returned to the river. **In principle, bedload should not be removed from the river system at all!**

Best practice

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① 44,000 m^3 of coarse sediment dredged from the St. Sauver reservoir

② Initial channel combined with gravel input into Mura near Gosdorf (Austria)

③ Removing sediment from a Danube side-branch (Liberty island, Hungary) ...

④ ... reintroducing the sediment into the Danube (Hungary)


© WWA Kempten

Fig. 79: Massive groyne intended to direct the river to the opposite bank and promote dynamic processes there (Tyrolean Lech; Austria)

Planning module 06

Structures to enhance erosion

Description

Erosion-promoting structures cause a local increase in transport capacity by directing the flow specifically to the areas that should be eroded. This accelerates erosive processes and improves bedload supply for downstream sections (Fig. 80).

Structures that promote erosion are often constructed of armourstones (Fig. 79). The structures are exposed to strong currents and should resist higher discharge events. Therefore, adequate dimensioning (foundation, stone size) is important. In some cases, armourstones from removed bank protection can be reused for this purpose.

Also properly arranged deadwood log jams, rhizomes, rootstocks, can form structures that promote erosion (Fig. 81).

Likewise, deliberate deposits of coarse bedload that withstands the transport capacity in the river can direct the stream toward the opposite bank and initiate erosion processes there (Fig. 82).

Fig. 80 material: stones

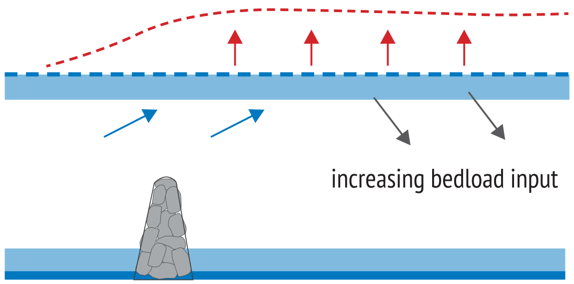


Fig. 81 material: wood ("log jam")

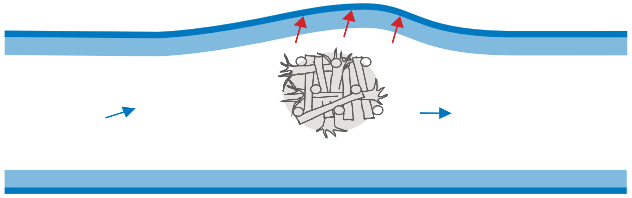
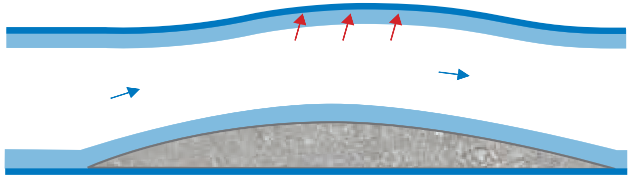


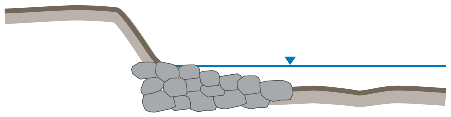
Fig. 82 material: bedload deposit



Where to implement?

- Where there is space for self-dynamic widening, but there is **lack of dynamic processes** due to a lack of bedload or hydraulically unfavorable conditions.
- Where freely erodible banks do not lead to the **expected effects**.
- Where local dynamic processes are to be initiated or strengthened in order to **mobilise and remove unwanted sediment deposits** or solidified bed debris (e.g. in widenings).
- Ideally, structures are used in **upstream ends** of longer river reaches as the disturbance will propagate.

Fig. 83 install groyne at the water level where bedload transport begins



Basic rules & knowledge

Dimensioning & planning

Depending on the length and arrangement of structures, the erosion effect may be increased in the foreland areas or on the opposite bank. Important planning aspects are the appropriate arrangement and elevation of the structures.

- **Rectangular groynes** only moderately change the flow direction and just slightly influence the bank. They mainly create pools in the riverbed (Fig. 84a).
- **Inclining groynes** are orientated upstream and direct the flow towards the middle of the river when overflown (Fig. 84b)
- **Declining groynes** are directed downstream and, as soon as they are overflown, direct the flow more towards the downstream bank (Fig. 84c).

The elevation of inclining and declining groynes should be dimensioned properly , so that they are overflown when bedload transport begins (Fig. 83). This has to be calculated and determined individually. The bedload transport starts, when the current bottom shear stress exceeds a critical value, the so-called limit shear stress (see Meyer-Peter & Müller, 1949).

Flow directing structures in the middle of the river: Structures can also be placed in the middle of the channel, such as

- Log jams (built from wooden pilots, deadwood trees and rootstocks) (Fig. 81)
- Sickle groynes/sickle-shaped flow guides (e.g. reused bank protection material) to promote erosion on the bank behind (Fig. 85)
- Groynes at the inflow to initial channels (Fig. 88)
- Protected tip of the island - islands act as flow deflectors towards the erosion area (Fig. 89, Fig. 90).

Depending on their position in the river and the elevation of the structure (overflown/not overflown), they have different hydraulic effects. Their function has to be checked and optimised in hydraulic models.

Fig. 85 sickle groynes/sickle-shaped flow guide

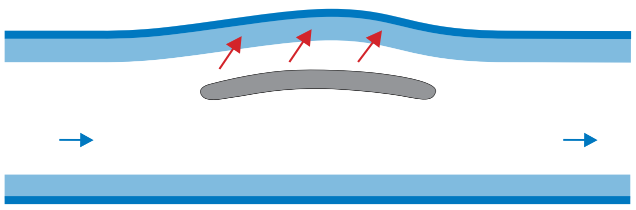
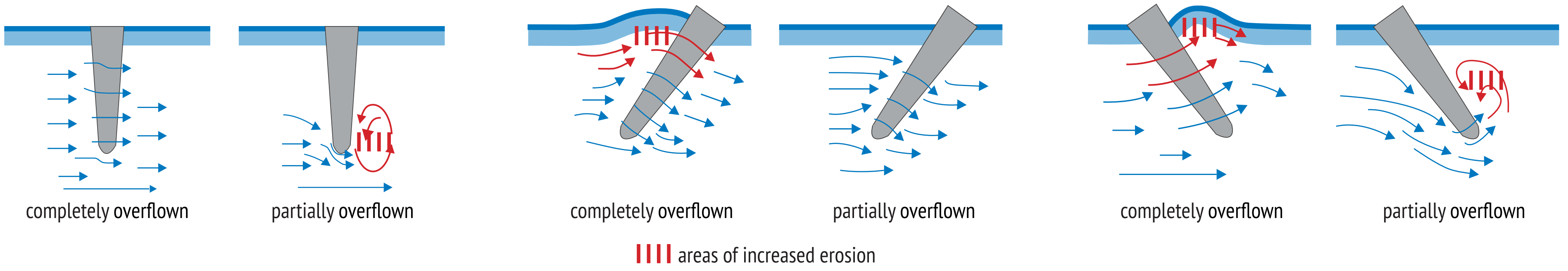


Fig. 84



a) rectangular groyne

b) inclining groyne

c) declining groyne

Fig. 86 groyne field to cause erosion on the opposite riverbank

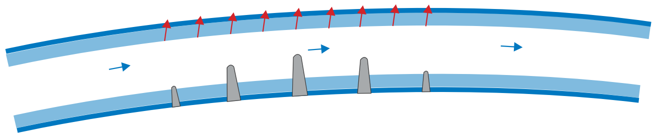


Fig. 87 groynes combined with freely erodible banks

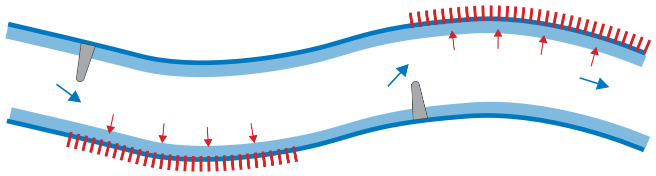


Fig. 88 groynes combined with initial channel

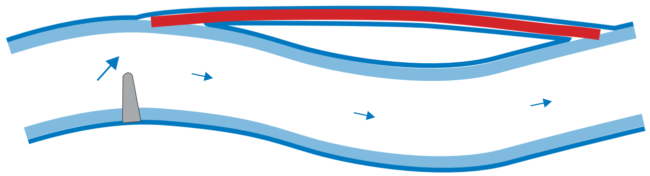
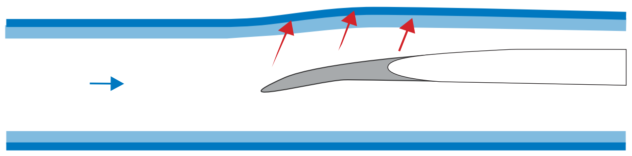


Fig. 89 stone protected island peak deflects flow towards erosion area



Combinations with other types

Groynes combined with bedload input (planning module M05) generally support a faster bedload removal.

Groyne fields protect the bank and direct the flow line to the opposite bank, where erosion can be enhanced. As a rough guide, the distance between the groynes can be estimated 1.5 times their length (Fig. 86).

Long, massively dimensioned groynes, placed at the upstream end of soft banks can direct the stream towards unprotected banks. Dynamic erosion processes are initiated (Fig. 88). Appropriately dimensioned and located massive groynes can also be applied to initiate the relocation of the main river course.

When combined with an initial channel, a groyne on the opposite bank of the inlet can support an enhanced inflow situation (Fig. 89). There is also the option of protecting the junction of the initial channel with a curved groyne. This supports a stronger inflow from the main river into the initial channel (Fig. 89, Fig. 90).

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Fig. 90: Curved groyne dividing the water flow between river and intial channel (Upper Drava, Austria).

Useful combinations:

Effects

- Instream-structures are **local measures** that can have a **big impact**.
- On the one hand, they can **accelerate** erosion and, on the other hand, fix morphological elements. The effects need to be weighed.
- They can be used **flexibly** and can easily be adapted afterwards in order to optimise the effect.
- Local structures, such as groynes or log jams promote **habitat diversity** in both, aquatic and (semi-) terrestrial areas.
- However, they can also cause **local vertical erosion,** which can be problematic at certain river sections (e.g. risk of riverbed breakthrough.

Challenges

- The areas where structures have to be located are often **difficult to access** and include a great amount of effort in order to access the construction site.
- The detailed effectiveness of the measures is **not always predictable**. Optimisation works may be necessary.

Best practice

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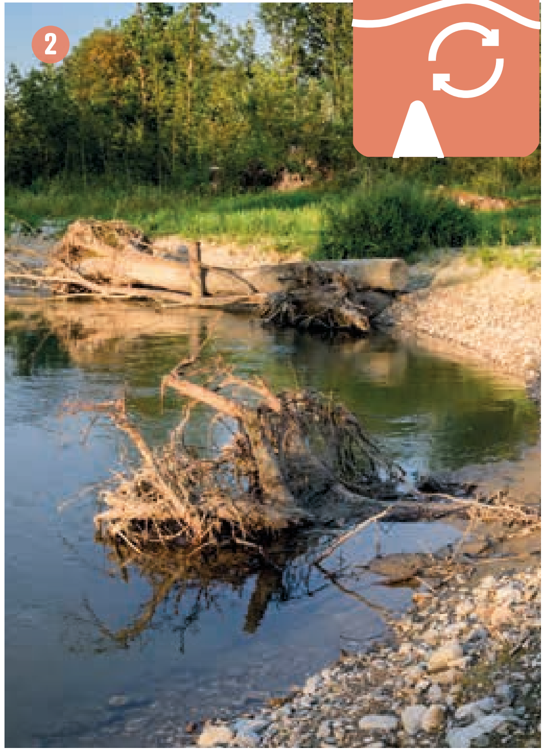

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① Inclinant groynes direct the flow line to the opposite bank in order to increase the bedload re-mobilisation there (Tyrolean Lech, Germany)

② Wooden stakes, roughwood and rootstocks promoting side-erosion (Reitbach, Austria)

③ ④ ⑤ Remnants of an old groyne were left in the riverbed (left on Fig. 3). They cause increased side erosion locally. Loss of yield on agricultural land in the surrounding area is compensated (Drava at Libanovec, Croatia).

Fig. 91: Erodible Drava bank at Libanovec, Croatia. River proximity is shifted to extensive land use in order to reduce risk potential and allow bank erosion

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Additional sediment mobilisation strategies[1]

- **Extensive land use** in the river proximity (e.g. by buying land, leasing or bartering) to reduce risk potential and allow bank erosion (e.g. Drava riverbank at Libanovec – DRAVA LIFE)

- **Prohibition of sediment extraction** (sand, fine and coarse gravel)

- **Sediment management** aligned between energy sector and water management, including potential sediment introduction

- Achieve **sediment continuity** in the river itself, in the tributaries and from the tributaries to the main river

- **River corridor concept:** By designating a river development corridor for restoration actions according to the (potential) river reference type, a self-dynamic river system should be promoted in the long-term (see Fig. 57).

- Natural river development should be gained by implementing **initial measures** within the river corridor (see modules of this toolbox) or even by relocating the dyke.

- **Activate potential sediment input** in the floodplain according to this toolbox. The segmentally widening of the riverbed, slope decrease by e.g. increasing curvature, building initial channels, activating side erosion, etc. are measures targeted at reactivating dynamic morphological river processes and decreasing the transport capacity of the river. The joint effect is an improved sediment budget/ balance.

- **Reach a fundamental consensus between nature protection and water management** institutions regarding the guiding principle of river restorations: “dynamic nature protection” shall overrule “nature conservation” (e.g. priority habitats such as Gallery forests 91E0 may be temporarily sacrificed, if a greater river dynamic can be achieved or if lack of action means gradual degradation of such habitat types). Establish this principle e.g. in the River Restoration Strategy, or align nationally, based on the EU Habitats Directive requirements).

[1] based on: Klösch M., Schobesberger J., Sandberger J., Franta F., Nagl L., Sindelar C., Habersack H. (2022): Hydromorphological laboratory model. Report WPT2/A.T2.1/D.T2.1.1, compiled in the frame of the Project DTP3-308-2.3- lifelineMDD, co-funded by European Union funds (ERDF, IPA).

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Glossary

Bank protection
Structural and/or bioengineering measures against damage or destruction of a bank.

Bank revetment
Structure to fortify a sloped embankment, e.g. rockfill, stone packing, plaster, concrete, asphalt, spreading film.

Bedload
Rounded rock material or debris transported by a glacier or watercourse. In hydraulic engineering and limnology, solids transported by currents that slide, roll or bounce along the riverbed are referred to as bedload.

Bedload management
Sediment management. All measures that serve to regulate bedload transport in a catchment area or a section of a watercourse.

Bed shear stress
Exerted force of flow direction related to the unit area of the riverbed. (Integral of shear and pressure effects on the individual soil asperity / grains).

Characteristic grain diameter/calibre
Grain size, which characterises a grain mixture with a specific particle size distribution curve.

Course development
In near-natural hydraulic engineering, space is given back to the river, so that it can once more develop independently and natural river landscapes are created. This return of space usually takes place through the removal of riverbed and bank reinforcements.

Connectivity
Exchange processes and interactions between different aquatic habitats and between aquatic and terrestrial habitats., including the transport of water, bedload, energy, nutrients, detritus, and the active and passive transport of organisms.
Lateral connectivity describes the connection of the stream to its floodplain habitats and terrestrial habitats. Longitudinal connectivity is between its upstream and downstream habitats. Vertical connectivity describes the connection between river and groundwater.

Critical shear stress
Shear stress, in which sediment movement or the destruction of the riverbed begins.

Critical flow velocity
Flow velocity at which e.g. sediment transport begins.

Floods Directive
The Floods Directive (Directive 2007/60/EC) is the legislation in the European Commission on the assessment and management of flood risks. The Floods irective basically prescribes a three-step procedure: Preliminary Flood Risk Assessment, Risk Assessment, Flood Risk Management Plans

General project or study
Studies to obtain an overview of the necessary protection required by water management objectives. Drafts that outline both the water management objectives and the way in which a measure is to be implemented. They form the basis for detailed planning.

GE-RM “River Development and Risk Management Concept”
GE-RM stands for “River Development and Risk Management Concept” (“Gewässerentwicklungs- und Risikomanagementkonzept”). It is a planning instrument for coordinating measures in river basins or along long river sections.

GE-RM planning processes are primarily implemented for water bodies or river basins with a need for action with regard to flood risk management and river ecology. In addition to the hazard situation, the ecological status of the water body and other framework conditions such as existing uses and rights, land use plans, etc. are also taken into account. Based on data analysis, interdisciplinary goals and measures are defined. These provide the basis for subsequent actions and measures in the river basin.

Groyne
River training measure, crosswise sills.
Groyne field: Area between two groynes.
Groyne head: Water-side end of a groyne.
Groyne root: Bank-side end of a groyne, landside integrated into the bank.

Habitat
Site where animal or plant species regularly occur.

Hydraulics
Study and computation of the characteristics, e.g. depth (water surface elevation), velocity, and slope of water flowing in a stream or river.

Hydrology
Study of the properties, distribution, and circulation of water on the surface of the land in the soil and in the atmosphere.

Intervention line
Planning line, which represents the maximum extent of bank erosion allowed.
If this line is reached, countermeasures must be considered.

Monitoring
Observation and evaluation of river section where measures have been implemented on the basis of certain indicators (abiotic, biotic).

Redistribution stretches
River sections in which alternating deposition and erosion processes take place. During major floods, bedload is deposited, and during subsequent smaller events, it is transferred to the lower reaches in doses. The bed in these sections is subject to a dynamic equilibrium.

Restoration / Renaturation
Revitalisation of watercourses. It is a task spanning several generations with numerous synergies between water protection, flood protection, biodiversity and upgrading, which usually also benefits local recreation.

Riverbed incision
Deepening of the riverbed, caused by lack of bedload input from upstream, narrowing of the riverbed and disconnection of forelands. The energy dissipation of the water occurs through riverbed erosion.

River widening
Increasing the cross-sectional area of flow and reducing the velocity of flow, while maintaining flow. The river has more space for natural development.

Sediment budget
Quantitative comparison of sediment supply and removal within a catchment area or a river stretch.

Sediment transport capacity
Ability of a flow to transport a given mass of sediment in dependence of particle size and shape.

Sedimentation
Deposition of material in a watercourse and the resulting uplift of the watercourse bed.

Shear stress
Tangential stress between water and riverbed surface.

Sliding bank
Slightly overflown inner bank in the curve of a watercourse.

Water Framework Directive
Directive 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy. The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater.


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Links - Toolboxes

https://www.alpine-space.eu/hymocares

https://hymo.azurewebsites.net/ HyMo-CARES-Tools

Links - further information

http://www.amazon-of-europe.com/en/

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Cover photo
Erodible ("soft") banks of the Drava near
Libanovec (Croatia)

Edition 1

May 2022

Riverbed incision due to bedload deficit, and the associated loss of morphological dynamics represent a large river engineering and ecological problem in the TBR MDD area. The River Restoration Toolbox offers simple and concise information on methods that can be used and combined for achieving sediment input through revitalisation.

The River Restoration Toolkit was designed to be used by river experts, but also by biologists, landscape planners, stakeholders and everyone interested in the topic or involved, in some way, in integrated river management. It will help to make our unique riverine landscapes even safer against floods, more ecologically diverse and attractive for recreation.

Thanks to all partners who contributed with their inputs and comments during the preparation of the Toolbox.

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