Sediment Manual for Stakeholders

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DanubeSediment

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Impressum

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Cover image: Innovative groyne type at low flow: reduces riverbed degradation to ensure the needed fairway depth for navigation and improves at the same time ecological situation at the river bank through disconnection from the bank (© Philipp Gmeiner / IWA-BOKU).

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Project Introduction

The Danube near Hainburg, Austria. (© Philipp Gmeiner/IWA-BOKU)

Sediments are a natural part of aquatic systems. During the past centuries, humans have strongly altered the Danube River. Riverbed straightening, hydropower dams and dykes have led to significant changes in the sediment load. This sediment imbalance contributes to flood risks, reduces navigation possibilities and hydropower production. It also leads to the loss of biodiversity within the Danube Basin.

To tackle these challenges, 14 project partners and 14 strategic partners came together in the DanubeSediment project. The partnership included numerous sectoral agencies, higher education institutions, hydropower companies, international organisations and nongovernmental organisations from nine Danubian countries.

Closing knowledge gaps: In a first step, the project team collected sediment transport data in the Danube River and its main tributaries. This data provided the foundation for a Danube-wide sediment balance that analysed the sinks, sources and redistribution of sediment within the Danube – from the Black Forest to the Black Sea. In order to understand the impacts and risks of sediment deficit and erosion, the project partners analysed the key drivers and pressures causing sediment discontinuity.

Strengthening governance: One main project output is the Danube Sediment Management Guidance (DSMG). It contains recommendations for reducing the impact of a disturbed sediment balance, e.g. on the ecological status and on flood risk along the river. By feeding into the Danube River Management Plan (DRBM Plan) and the Danube Flood Risk Management Plan (DFRM Plan), issued by the International Commission for the Protection of the Danube River (ICPDR), the project directly contributes to transnational water management and flood risk prevention.

International Training Workshops supported the transfer of knowledge to key target groups throughout the Danube River Basin, for example hydropower, navigation, flood risk management and river basin management, which includes ecology. The project addressed these target groups individually in its second main project output: the Sediment Manual for Stakeholders. The document provides background information and concrete examples for implementing good practice measures in each field.

DanubeSediment was co-funded by the European Union ERDF and IPA funds in the frame of the Danube Transnational Programme. Further information on the project, news on events and project results are available here:
www.interreg-danube.eu/DanubeSediment

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Executive summary

Socio-economic development has gradually altered the Danube River and its tributaries and consequently changed the sediment regime. The DanubeSediment project identified the following **key drivers** of these changes as flood protection, hydropower, navigation, water supply, land use (agriculture and urbanisation) and dredging. Further boundary conditions may arise, e.g. from ecology and climate change.

Due to these many drivers, the Danube River and its tributaries are subject to different **legislative instruments** of the European Union (EU), which influence sediment management in the Danube River Basin (DRB). The most important directives are described below in Part A.

The key drivers cause **key pressures** that strongly impact the sediment regime of the Danube, for example transversal structures, river training and maintenance works. Transversal structures for hydropower use and water supply, like dams and weirs, interrupt sediment continuity to a large extent. Bank protection measures and cut-off side channels as well as flood protection dykes hinder the lateral exchange of sediments.

Especially in the **Upper (DE, AT and SK/HU section) and Middle (SK/HU, HU, HR/RS, RS and RS/RO section) Danube, which corresponds to the river section from the source to rkm 943**, large-scale engineering **transformed** the formerly complex **river morphology** to a uniform channel over large stretches. The total river **length** was reduced by 134 river kilometres (rkm), whereby the Upper Danube was shortened by 11 % and the Middle Danube by 4 %. The **average width** of the riverbed was **reduced** by 39 % in the Upper and by 12 % in the Middle Danube. The results of the DanubeSediment project show, that in the Lower Danube, lateral restrictions of the river due to river training are **less severe**. Here, the length was marginally reduced by around 1 % and the average width by 4 %.

Consequently, the **sediment regime** in the Danube River Basin has **severely changed**: free-flowing sections are prone to erosion due to higher transport capacities and a lack of sediment continuity (from upstream to downstream), while the reduced energy slope in the impoundments leads to sedimentation. In total, about 733 rkm (29 %) of the Danube River are dominated by erosion and 857 rkm (34 %) by sedimentation, excluding data for the Lower Danube. In the Lower Danube, 670 rkm (27 %) show an erosional trend, but a lack of data hinders a detailed analysis, for example local relative sedimentation exists in stretches showing general riverbed erosion. Thus, about 56 % of the river length, including reaches without sufficient data for a detailed analysis, are facing erosional tendencies. Along 241 rkm (10 %) of the Danube River, a dynamic balance prevails, or no significant changes occur (details see Chapter B.2.4).

The **interruption of river continuity prevents bedload transport**, which leads to a lack of those sediments downstream of the barriers that shape the riverbed. Additionally, in some river stretches, our data analysis shows that the dredging amounts exceeded the sediment supply from upstream. The results of the DanubeSediment project clearly show the effects of sediment alterations from the Upper Danube through to the Danube Delta. The **total suspended sediment input** to the Danube Delta and the Black Sea **decreased** by more than 60 %, from former amounts of about 60 Mt/yr and 40 Mt/yr to approximately 20 Mt/yr and 15 Mt/yr nowadays (details see Chapter B.2.1).

The data collected and analysed in the project show that data availability is too low to produce a sediment balance for the whole Danube River. Therefore, the project recommends establishing a **harmonized transnational sediment quantity monitoring network** and setting-up new monitoring stations. According to the project results, the most important sediment monitoring elements are: suspended sediments, bedload, bathymetry data (riverbed and riverbanks), bed material, dredging and feeding and floodplain deposition. The **sediment data** collected should be stored in a centralised, **Danube Basin-wide system or database**, such as the Transnational

Monitoring Network (TNMN) of the International Commission for the Protection of the Danube River (ICPDR).

Despite some data gaps, the numbers above show that the **sediment balance is disturbed** and they underline the **need for action**. Therefore, sediment management in the Danube River Basin should **aim** to achieve a **balanced sediment regime with a dynamic equilibrium** between sedimentation and erosion, providing type-specific natural riverbed forms and bed material.

The DanubeSediment project concluded that sediments are a **Significant Water Management Issue** (SWMI). According to the resolution of the ICPDR Heads of Delegations, the sediment balance alteration has been identified as a new sub-item under the existing SWMI "Hydromorphological alterations" for the preparation of 3rd Danube River Basin Management Plan.

When deciding on measures to improve sediment management, sediment-related problems should preferably be treated at the source. In some cases, measures implemented at the catchment level might be of great importance. Any measure that impacts the sediment regime, e.g. in relation to hydropower, flood risk, land use (land reclamation), river restoration and navigation should consider sediment from the beginning of a project in a harmonized and integrated way. To further the acceptance of any sediment-related management measure, **all relevant stakeholders should be included** in the planning phase. With their expertise, the feasibility of a measure can be analysed and adopted to site-specific conditions.

The in-hand **Sediment Manual for Stakeholders** (SMS) offers assistance for sediment-related actions in the Danube River Basin and for future programmes of sediment-related measures. The SMS provides a **collection of good practice examples**, highlighting the benefits and impacts of measures that improve the sediment balance and continuity. Part C describes the good practice measures for each key stakeholder group, being hydropower, navigation, flood risk management as well as river basin management including land use and ecology. In Part D, the sediment management measures are structured according to different spatial scales in harmonized factsheets.

Part A Introduction and background

Elaboration process of the Sediment Manual for Stakeholders

The Sediment Manual for Stakeholders (SMS) was prepared based on the results of the DanubeSediment project. These results were obtained through a broad participative process, with involvement of all key stakeholders such as representatives from administrations, flood risk management, hydropower, waterway authorities, environmental organisations (e.g. national parks), NGOs and the scientific community. The stakeholders were involved through various national and international expert meetings and workshops as well as through personal consultations with the project partners.

General objective and scope

The Sediment Manual for Stakeholders provides suggestions for future planning of sediment management measures and describes sediment-related good practice examples. The document provides comprehensive and robust information about sediment in the Danube, which can support decision-makers and practitioners in planning future sediment management measures. The manual aims to complement the Danube Sediment Management Guidance (DSMG) published in the DanubeSediment project by giving detailed and stakeholder-oriented background information complimenting this with a large collection of concrete examples of good practice measures in sediment management.

A.1 LEGAL BACKGROUND INFORMATION

The most important legislative instruments of the European Union (EU) in the context of sediment management are the Water Framework Directive (2000/60/EC), the Floods Directive (2007/60/EC) as well as the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC). Other Directives related to the topic are the Renewable Energy Directive (2009/28/EC), the Strategic Environmental Assessment Directive (2001/42/EC) and the Marine Strategy Framework Directive (2008/56/EC). These directives, including their relationship to sediments, are briefly presented below. Furthermore, a short summary on the Trans-European Transport Network (TEN-T) Guidelines and the "Good navigational status" is provided.

A.1.1 Water Framework Directive

In the European Water Framework Directive (WFD) of 2000 (Directive 2000/60/EC), the European Commission stated the need for action to avoid long-term deterioration of fresh water quality and quantity and to improve the protection of the waters (European Commission, 2000). The objective of the WFD for all inland surface waters, transitional and coastal waters is to achieve a "good chemical and ecological status" or a "good ecological potential" for water bodies with significant physical alterations such as e.g. hydropower ("Heavily Modified Waterbodies"). Since "Clean water", which is not polluted by organic substances, nutrients and dangerous substances, is essential, threshold values were set on the European level for a set of selected hazardous substances, called priority substances, which define the "good chemical status" (ICPDR, 2015a). However, it is not enough to only have "clean water" when the natural ecosystems are significantly damaged or dysfunctional and this is why, in a holistic approach, also the "good ecological status" is required (ICPDR, 2015). This means "*that riverbed and banks have to be well structured and enough water has to be ensured so that migration routes and natural habitats are provided for aquatic animals and plants*" (ICPDR, 2015a). To fulfil these requirements for the Danube River Basin, the ICPDR published its first "Danube River Basin Management Plan" (DRBM Plan) in 2009, which is complementary to the national river basin management plans. Besides the assessment of the river system, the DRBM Plan also included measures to achieve the "good status" by 2015. Considering that not all waters would reach the target in six years, the WFD also requires an updated River Basin Management Plans (RBM Plans) every six years (European Commission, 2008).

Although sediments are a natural and essential part of river basins and aquatic environments, the WFD does not specifically deal with sediments or sediment processes in river systems (Brils, 2008). Sediment quantity is, for most of the classes, only of indirect importance via the Biological Quality Elements (BQE). This means that if the indicator species, e.g. fish, do not achieve a good status, the causes, including sediment issues, have to be addressed (Hauer et al., 2018). Sediment quantity is only mentioned directly in the WFD in connection with the high status of a waterbody. In this case, the "undisturbed

sediment transport" is one quality criterion pertaining to the hydromorphological conditions that are analysed to assess the status.

A.1.2 Floods Directive

Many large rivers in Europe, including the Danube River are heavily impacted by multiple pressures. When looking at the Danube, we find significantly altered conditions along the channel and in former inundation areas. Through the intensified use of the river floodplains, the vulnerability of those areas is increased when inundated or if flood protection measures fail (e.g. De Kok and Grossmann, 2010; Habersack et al., 2004). To cope with this specific natural hazard, the European Parliament released the directive on the assessment and management of flood risks (Floods Directive, Directive 2007/60/EC), which was put into force in 2007 (European Commission, 2007). This Directive requires Member States to assess all water courses and coast lines for the thread of flooding, to identify areas of potential significant flood risk (APSFR), to provide flood hazard maps and flood risk maps, which additionally can indicate areas, where floods with a high content of transported sediments and debris floods can occur. The Member States need to take adequate and coordinated measures to reduce this flood risk.

The first Flood Risk Management Plan for the Danube River Basin District (ICPDR, 2015b) was prepared in 2015. It sets out appropriate objectives for the management of flood risk on the level of the international river basin district, covering the whole Danube catchment. The plan highlights issues relevant for the basin-wide perspective and as such, it is complementary to the national flood risk management plans. These plans provide all necessary information on measures, flood maps and other national activities in the section of flood protection, prevention and mitigation in a more detailed way. The DFRM Plan (ICPDR, 2015b) foresees the development of concepts, plans, projects and strategies on catchment scale to improve the water and sediment balance. These are important tools to implement sediment management measures for maintaining the river transport capacity. The Floods Directive is closely coordinated with the Water Framework Directive. In particular, the coordination of flood risk management plans and river basin management plans, together with the coordinated involvement of public participation procedures in the preparation of these plans is of great importance. In the ECOSTAT report "good ecological potential" (GEP)/flood group (Bussettini et al., 2018) aspects of fluvial altered sediment dynamics are addressed with descriptions of how the GEP could be achieved in terms of an integrative flood risk management. As measure to mitigate the impacts from flood defences like bank re-enforcement/protection and channel straightening, the enforcing sediment dynamics via self-forming development of rivers is mentioned.

A.1.3 Nature Protection Directives: Habitats Directive and Birds Directive

The protection of migratory bird species often requires cross-border cooperation. Because of the decline of these species, the European Commission adopted the Directive 79/409/EEC (Birds Directive) in April 1979. Amended in 2009, it became the Directive 2009/147/EC. The directive places great emphasis on the protection of habitats for endangered and migratory species as habitat loss and degradation are the most serious threats to the conservation of wild birds. It established a network of Special Protection Areas (SPAs) including the most suitable territories for these species. Since 1994, all SPAs are included in the Natura 2000 ecological network of protected areas, safeguarded against potentially damaging developments, which is set up under the Habitats Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, adopted in 1992 (European Commission, 2019a). It aims to promote the maintenance of biodiversity, taking account of economic, social, cultural and regional requirements (European Commission, 2019b).

Wetlands are temporary habitats for migrating birds as well as permanent biotopes for type-specific aquatic communities and water dependent terrestrial communities and therefore a very important habitat. They are dependent on sediments and natural sediment processes. Therefore, in the sense of the flora and fauna, sediments contribute to the protection of autochthonous species, mainly fish, and to the provision of food for non-aquatic species like birds. Poor quality or contaminated sediments may negatively influence the conservation status of aquatic species or habitats (Casper, 2008).

A.1.4 Renewable Energy Directive

The original Renewable Energy Directive (2009/28/EC) established an overall policy for the production and promotion of energy from renewable sources in the EU. The policy aimed for every member state to produce 20 % of the gross energy consumption from renewable energy by 2020. In December 2018, the revised renewable energy directive (2018/2001/EU) entered into force and established a new renewable energy target for the EU to produce at least 27 % renewable energy by 2030. A consequence of those targets will be the increase

and the extension of hydropower production, besides an increase of wind and photovoltaic production, etc. Although hydropower is a renewable form of energy, an intensive use of the kinetic and potential energy of river systems has negative impacts on the riverine ecology and are (very often) in contradiction to the objectives of the WFD (Hauer et al., 2018). Therefore, the ICPDR developed Guiding Principles for integrating environmental aspects in the use of hydropower for the Danube Basin in 2013 (ICPDR, 2013a). They aim to ensure a balanced and integrated development and to deal with the potential conflict of interest from the beginning. These Guiding Principles note the disturbed or severely altered character of the sediment balance in most large rivers and name hydropower as one of the most significant causes. Thus, measures have to be implemented to improve the situation, which should be addressed in the Danube River Basin District Management Plan. On the EU-level, the WFD CIS Working Group Ecological Status (ECOSTAT) has recommended measures for sediment management in hydropower-regulated rivers. These are the mechanical break-up of bed armouring, removal of sediments, re-introducing sediments, restoration of lateral erosion processes and introducing mobilising flows (flushing flows) (Halleraker et al., 2016).

A.1.5 Environmental Impact Assessment Directive

The Environmental Impact Assessment (EIA) Directive (85/337/EEC) is effective since 1985 and has to be considered for numerous public and private projects, defined in Annexes I and II. Annex I contains all projects, which are linked with major environmental impacts and therefore, demand a mandatory EIA, e.g. long-distance railway lines, motorways and express roads, projects for the disposal of hazardous waste, etc. For projects mentioned in Annex II, national authorities have to check the need for an EIA, based on the assessment of effects (compliance with thresholds and criteria listed in Annex III) or case-by-case screening. Annex II includes projects such as the construction of flood spillways, urban development projects and further activities, which are not mentioned in Annex I (railways, roads, waste disposal facilities, etc.). In the case of an EIA procedure, the project applicant has to provide information regarding potential environmental risks of the proposed project. Stakeholders and the public are then asked to introduce their knowledge, experiences and eventual concerns. After that, authorities have to decide about the realisation of the project, taking into account the incorporated objections. Afterwards, the public is informed of the decision and can enforce it in court (85/337/EEC, Joziasse et al., 2007).

Regarding dredging activities, the EIA Act (UVPG, 1990, 2005) clarifies as follows: *"The project-related impacts have to be assessed by the difference between the environmental status before and after project execution at the dredging site and at the site of dredged-material disposal."* Sediments and in particular suspended particles, as they are potentially affected by contaminants must not be negatively influenced at these locations. At the disposal site, surface water also has to be protected (Manz et al., 2007).

A.1.6 Marine Strategy Framework Directive

The main objective of the Marine Strategy Framework Directive (MSFD) (2008/56/EC) is to achieve Good Environmental Status (GES) of EU's marine waterbodies by 2020 (European Commission, 2008). It is the first European Directive to protect marine biodiversity with the primary regulatory goal that *"biodiversity is maintained by 2020"*. In the first years after implementation on 17 June 2008, the MSFD aimed to set consistent and comparable assessment standards by developing common methodologies and indicators. These were reviewed in 2017, resulting in a new definition of GES. To achieve the goals of the MSFD, the European Commission has determined eleven qualitative descriptors of GES and listed them in Annex I, e.g. contaminants in water and sediments, biodiversity, hydrographical conditions, etc. The Directive differentiates between four geographical marine regions: the Baltic Sea, the Northeast Atlantic Ocean, the Mediterranean Sea and the Black Sea. Each member state must develop a marine strategy, presenting their concepts and approaches for improving the marine environment. This strategy has to be kept up-to-date and needs to be re-evaluated every six years. Furthermore, the MSFD also considers land-based and riverine issues and tries to establish similar techniques as in the Water Frame Directive (WFD) (European Commission, 2008). The pollution of sediments and biota is one of the main indicators, which needs to be considered in terms of the environmental assessment. The contaminant transport out of the catchment area into the marine systems are of particular importance when dealing with sediments, especially in tidal areas (Förstner and Köster, 2018).

A.1.7 TEN-T Guidelines – GNS (Good Navigation Status)

The Trans-European Transport Network (TEN-T) exists since 1993 and aims at the enhancement of European-wide infrastructural facilities, such as inland

waterways. The promotion of inland navigation as a sustainable type of transportation is another one of its main objectives. Therefore, the TEN-T guidelines demand that by 2030, European navigable waterways must gain Good Navigation Status (GNS). In particular, Article 15(3)b specifies that *"rivers, canals and lakes are maintained so as to preserve Good Navigation Status (GNS) while respecting the applicable environmental law"*. GNS is defined as *"the state-of-the inland navigation transport network, which enables efficient, reliable and safe navigation for users by ensuring minimum waterway parameter values and levels of service"* (Muilerman et al., 2018). The GNS process consists of "hard" and "soft" components. "Hard" components describe quantitative requirements regarding physical dimensions of the fairway channel, locks and bridges. Moreover, the capacity and temporal availability of these dimensions is determined e.g. closures, available draught during the year. "Soft" components contain mainly qualitative information on infrastructure management, e.g. waterway maintenance, fairway marking, and traffic management, such as river information services, traffic regulations, incident management, as well as other issues like facilities along waterways, clean fuels, mooring places, etc.

Due to the potentially negative impacts of inland navigation on river ecosystems, the ICPDR has teamed up with Danube Commission (DC) and the International Sava River Basin Commission (ISRBC) to discuss a common strategy for sustainable and environmental-friendly navigation on a cross-sectoral basis. In 2007, these discussions resulted in a "Joint Statement on Guiding Principles on the Development of Inland Navigation and Environmental Protection in the Danube River Basin" (ICPDR, 2008), which takes into account the interests of navigation, river ecology and water management in the Danube Basin. On the one hand, this Joint Statement aims to serve as a guiding document for stakeholders dealing with inland waterway transport and other hand for water managers working on riverine and navigation projects.

A.2 BOUNDARY CONDITIONS

Within the DanubeSediment project, the key drivers acting on the sediment regime in the Danube River and its major tributaries have been identified as flood protection, hydropower, navigation, water supply, agriculture and dredging (Figure 1). Additional boundary conditions that may impact the sediment regime can arise, for example from ecology and climate change. In the following, these boundary conditions are briefly described.

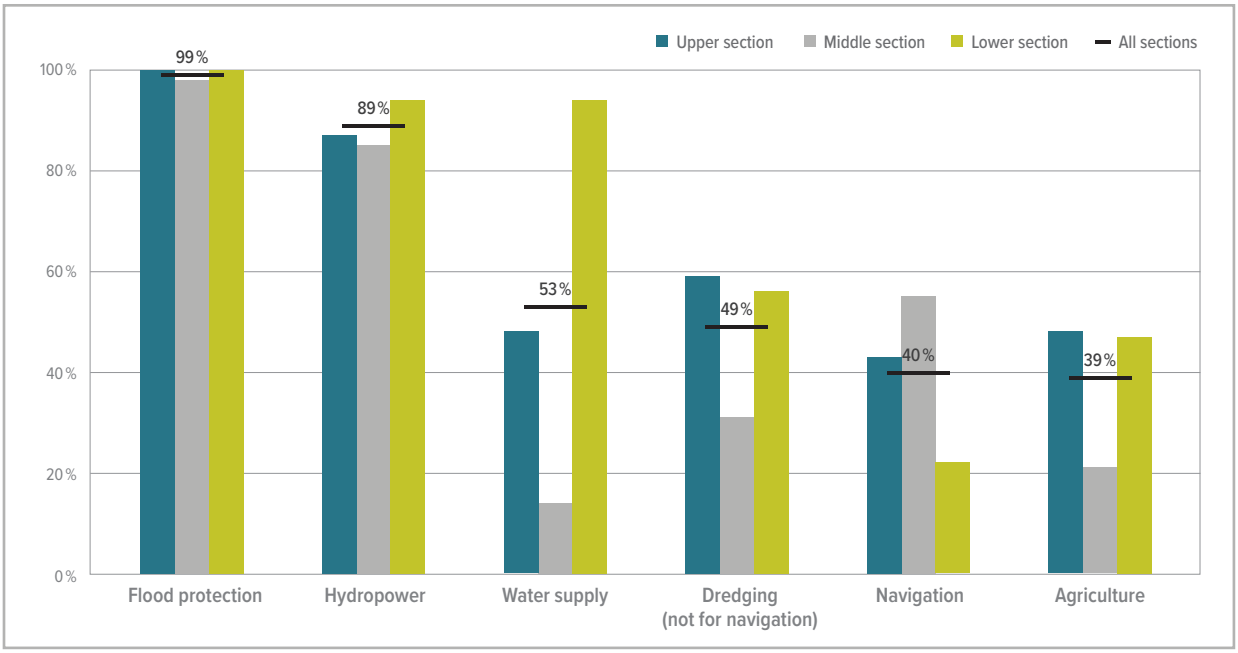


Figure 1: Percentage of river stretches to absolute length affected by key drivers on the Upper, Middle and Lower Danube River section and on all sections (from the DanubeSediment report "Interactions of Key Drivers and Pressures on the Morphodynamics of the Danube")

A.2.1 Hydropower generation

Chains of hydropower plants (Figure 2) in the Danube itself and along many tributaries interrupt natural transport of sediments. Almost 2000 hydropower plants (HPPs), excluding small ones with less than 1 MW, impound the rivers in the DRB (Schwarz, 2019). More than 50 of these are located in the Danube itself. In addition, 700 hydropower plants are under construction or planned (Schwarz, 2019). Nearly all Danube countries depend on hydropower. Due to the river's natural gradient, the Upper Danube is well-suited for the construction of hydropower plants (Bachmann, 2010). Nevertheless, the Middle and Lower Danube sections also offer a high hydro energetic potential due to the large volume of water that can be used for energy production. However, future developments in terms of climate change may affect hydropower generation, since increasing droughts will influence the hydrology of the Danube River. The chains of impoundments for hydropower plants in Germany and Austria and the HPP Gabčíkovo in Slovakia impound a major share of the Upper Danube River. The impounded stretch makes up approximately 575 rkm or around 20 % of the total length of the Danube and 54 % of the Upper Danube. In Austria, around 61 % of the electricity generated yearly originates from hydropower (e-control, 2019), around 34 % of which is produced along the Danube (Wagner et al., 2015). Hydropower counts for about 16 % of the energy mix in Slovakia, of which 11 % is derived from the HPP Gabčíkovo (ICPDR, 2010a). The largest hydropower dam and reservoir system along the Danube are the Iron Gate dams I and II, which are located in the 117-km-long Djerdap Gorge (Lower Danube). According to ICPDR these hydropower plants are jointly operated by Serbia and Romania and produce about 37 % of the total energy used in Serbia and 27 % of the energy in Romania (ICPDR, 2010a).

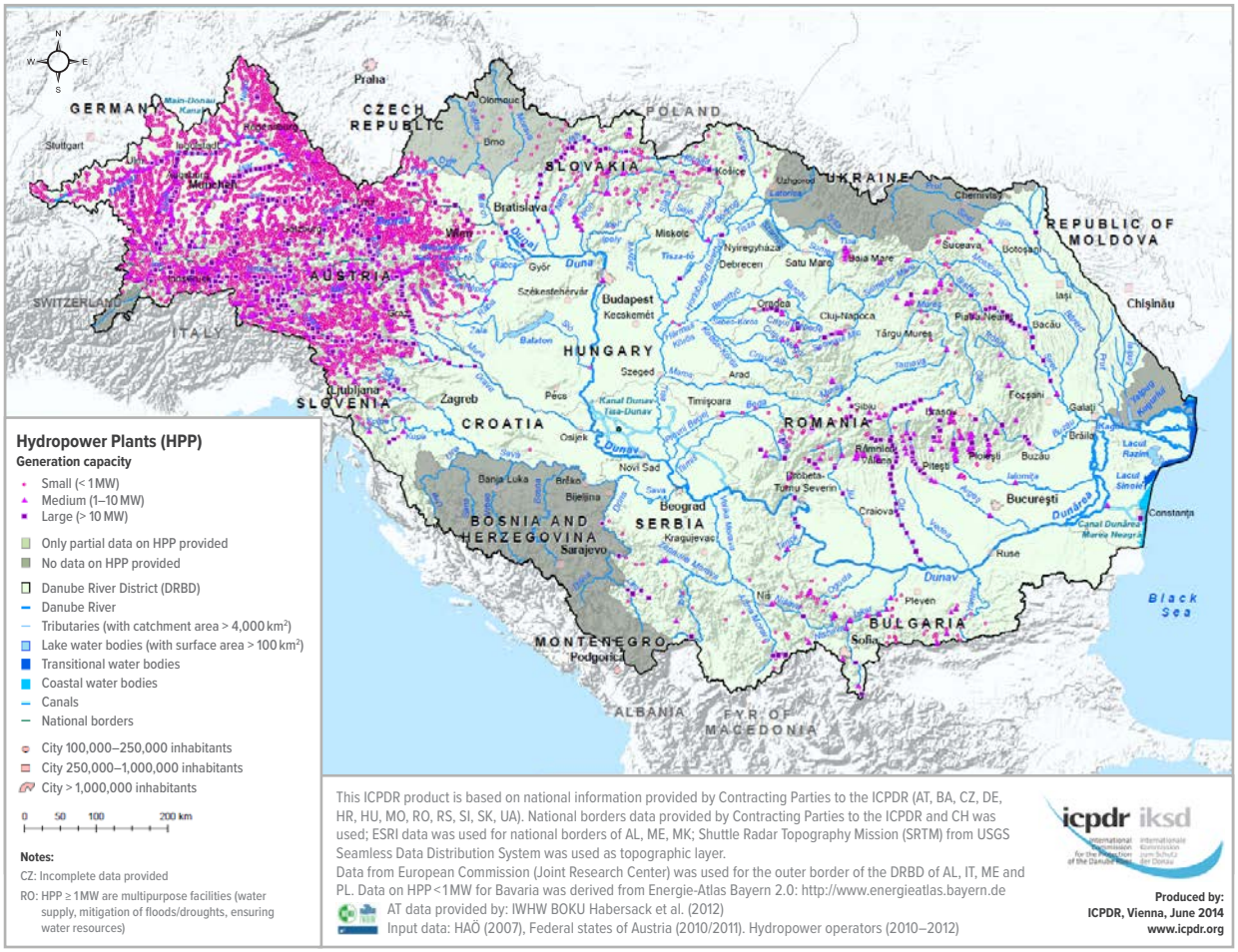


Figure 2: Distribution of hydropower plants in the Danube River Basin (ICPDR, 2013a)

Figure 3: Cargo vessel on the Danube River (© IWA/BOKU)

The EU-Energy-strategy (European Commission, 2014) aims to increase energy efficiency and promotes the use of renewable energy sources. Hence by 2030, at least 27 % of all energy consumption in European Union member countries must come from renewable sources, e. g. hydro, wave, solar, wind, and biomass. For hydropower, the strategy to achieve this is to upgrade existing power plants by improving their efficiency and environmental performance, besides increasing the development of new facilities.

Based on the findings of the „Assessment Report on Hydropower Generation in the Danube Basin" (ICPDR, 2013b), the amount of electricity production from hydropower will increase in most of the Danubian countries until 2020 in order to achieve the renewable energy targets. According to the projection trends in key economic indicators and drivers up to 2021, which were delivered by Danube countries in the frame of DRBM Plan update 2015, ICPDR expects to register significant growth till 2020 (ICPDR, 2015a). This expected growth "*can have significant impacts on water bodies […] through hydromorphological impacts*" (ICPDR, 2015a). Hydromorphological impacts resulting from the construction of hydropower facilities are the changes in the rivers' hydrological characteristics and the disruption of the longitudinal continuity of the rivers. Due to the reduced flow velocities in the impoundments and reservoirs of the hydropower plants, sedimentation occurs, resulting in a surplus of sediments upstream and a sediment deficit downstream of the transversal structure.

A.2.2 Navigation

Navigation is of high importance for the Danube River, dating back at least to Roman times. Since 1856, navigation has been regulated by an international commission and since 1948 by the Danube Commission. The Convention Regarding the Regime of Navigation on the Danube ("Belgrade Convention") of 18th August 1948 ensures free navigation on the Danube for all commercial vessels sailing under the flags of all nations (viadonau, 2019). Starting from Sulina, located at the end of the middle Danubian arm that enters the Black Sea in Romania, the Convention covers the river stretch until Kelheim (rkm 2415), the end of the Danube as a German federal waterway. This means that about 85 % of the Danube River is available for international waterway freight transport (viadonau, 2019). Since the completion of the Rhine-Main-Danube-Canal in the beginning of the 1990s, an international waterway was created between the Black Sea and the North Sea. This waterway has a total length of 3,504 kilometres and provides a direct waterway connection between 15 European countries. This highlights that navigation is of multilateral importance. However, the size and curve radii of the fairway and the height of bridges limit waterway transport on the Upper Danube and Rhine-Main Danube-Canal.

Currently, inland navigation does not play a major role in every Danube country, as there is no commercial inland navigation in the countries on the edges of the Danube River Basin and on the tributaries of the Upper Danube River Basin (ICPDR, 2015a). The total freight transport on the entire Danube is approx. 79.5 million tons yearly, related to the Danube – Black Sea Canal. These figures include transit traffic and bulk cargo, but there is no separate estimation for these categories. The countries with the highest tonnage transported on the Danube are Romania, followed by Austria and Serbia (all three countries move more than 10 million tons of cargo annually) (ICPDR, 2015a).

Figure 4: Mobile flood protection Danube River, Austria (© Robert Zinterhof)

In many Danubian countries, especially in the Upper Danube, the river and its course were significantly altered for navigation. The channel was narrowed and channelized and bank protection measures hinder the lateral sediment exchange. Additional river training works, such as groynes and guiding walls, seek to guarantee fairway depth at low water conditions, but further decrease the channel width. Furthermore, dredging performed for river maintenance in ford sections influences the sediment regime, especially when these sediments are not fed back into the river system.

Climate change could affect the flow regime of the Danube River and may have an impact on the future development of inland waterway transport. Thus, the issues of climate change have to be considered in navigation management, planning and development (ICPDR, 2007). However, navigation can also contribute to reaching environmental goals, e.g. for reducing greenhouse gas emission by making more intensive use of the free navigation and transportation capacities of the Danube Basin waterways. This can contribute to coping with traffic volumes in a manner that is emission-friendly and positive for society, also taking advantage of non-structural measures, such as fleet innovation and infrastructure investments (ICPDR, 2007).

A.2.3 Flood protection

The Danube River has been modified to help prevent flooding, for navigation, for hydropower (Habersack et al., 2016) and to obtain new land for urban development (Hein et al, 2016). Nowadays, more than 80 % of the length of the Danube is regulated (ICPDR, 2019a). With respect to flood protection, the Danube River was trained so that the riparian area is protected against floods with recurrence intervals of up to 1 in 100 years (Danube FloodRisk, 2013). For example, ever since the 16th century, humans have built dyke systems to prevent flooding along the Danube. Especially in the Upper and Middle Danube, these river training works changed river courses and channels considerably, with meanders and branches straightened, narrowed, redirected and cut off. Consequently, river narrowing and channelization increased the sediment transport capacity and bank protection hinders the lateral sediment exchange.

By reducing and degrading the floodplain system, their capacity for water retention is reduced and thus the frequency and duration of floods is changed (Habersack et al, 2016). Huge inundation areas have been impacted by river regulation or flood protection measures. For instance in Hungary, where an area of no less than

3.7 million hectares has been dyked (ICPDR, 2019a). Only about a fifth of the 19th century Danube floodplains still remain (ICPDR, 2009). In the Danube Delta, embankments were built in an area of over 100,000 hectares that was mostly exposed to temporary flooding. In recent years, the natural conditions have been restored through ecological restoration schemes for about 15 % of this area (ICPDR, 2019a).

Furthermore, dredging performed for flood protection influences the sediment regime, especially when these sediments are extracted and not fed back into the river system.

During the last decades, the Danube River Basin suffered major catastrophic floods in the years 2002, 2006, 2010, 2013 and 2014 (ICPDR, 2015b), which highlights that flood protection is still a crucial concern on the Danube Basin level. In future, floods may become more serious and more frequent due to climatic changes (ICPDR, 2019b). The impacts of major floods in the DRB may increase considerably in the future, since the intensified use of the floodplains means that these areas are more vulnerable if inundated or if flood protections measures fail (e. g. Habersack et al., 2004). Another issue is that sedimentation in the floodplain and in settlements can significantly increase damages.

A.2.4 Ecology and Biodiversity

The Danube River Basin consists of a variety of diverse and dynamic ecological habitats that are home to some 2,000 vascular plants and more than 5,000 animal species, including mammals, birds, fish species, reptiles and amphibians (ICPDR, 2013c). The Danube River and its tributaries are important migration paths for fish species such as sturgeons. Furthermore, the Danube's remaining large floodplain forests and the Danube Delta are the last refuges in continental Europe for the white-tailed eagle and white pelicans (ICPDR, 2013c).

Hydromorphological alterations, such as changes to the river profile and width, water depth and flow velocity as well as disconnection of floodplains, threaten riverine ecosystems and their biodiversity. Multiple human activities, including the construction of hydropower plants, expansion of agriculture, and large-scale river regulation measures related to navigation and flood protection significantly alter the sediment regime and disturb the aquatic environment. For example, this occurs through an ongoing loss or degradation of habitats, such as the disconnection of animals from their spawning grounds. In this context, the provision of type-specific natural bed forms and bed material are of major importance, which can only be provided by a balanced sediment regime. Furthermore, vessel-induced waves caused by inland navigation can negatively affect the aquatic life (e. g. spawning, bank-breeding birds), which therefore should be avoided. Wetlands and floodplains and their connection to adjacent river water bodies play an important role in the functioning of aquatic ecosystems, since they provide important habitats for fish and other fauna, providing a positive effect on the status of the waterbody (Schofield et al., 2018). The interruption of migration routes of species may lead to fragmentation or loss of habitats, to altered compositions of populations, a decline of species biodiversity and abundance as well as to a decrease in the capacity for self-recovery. Certain species are more sensitive to changes of their habitat condition than others and can decrease or, in some cases, disappear (Fedorenkova et al., 2013). For example, the sturgeon was once present in a large population in the Danube River Basin (Sandu et al., 2013).

Figure 5: Wetland at the Danube River (left: © WRI; right: © NARW)

Since sturgeons are sensitive to environmental pressures, they are valuable indicators for healthy rivers. Their dramatic decline in the last decades has become an issue of basin-wide importance (Sandu et al., 2013). The modified habitat can also provide an opportunity for invasive species to expand their range of distribution and to increase the fragility of native species (Godinho and Ferreira, 2000; Marchetti and Moyle, 2001; Brown and Ford, 2002; Fedorenkova et al., 2013).

A.2.5 Others

A.2.5.1 Water supply

In the Danube basin, the water is mainly used for domestic drinking water supply, industry and irrigation. Many waterworks along the Danube and its tributaries use bank-filtered water (Natchkov, 1997). In Germany and Austria, only a small portion of the water supply comes from bank-filtered Danube water, e.g. ca. 5 % of Vienna's water is provided by groundwater including bank-filtered water from the Danube (Vienna Water, 2019). The water supply of Bratislava however relies on alluvial aquifer water that is recharged by bank-filtered water from the Danube (Mucha et al., 2002). In Hungary, 95 % of the drinking water supply is provided from groundwater (MTA, 2017), whereby riverbank-filtered water sources play an important role, totalling 40 % of the drinking water supply. Almost all citizens of Budapest are supplied by bank-filtered water. The bank-filtered well system is located along the Danube River, especially in the upper and middle sections, where gravel and sand characterize the riverbed.

In the lower part of the Danube River Basin, especially the lowlands of Romania and Bulgaria, the majority of drinking water is provided from surface waters, which are regularly treated by chemicals (Storck et al., 2015). In the downstream countries, the main user of water from the Danube is agriculture (Natchkov, 1997). For example in Bulgaria, 70 % of the total water abstraction is used for irrigation, 20 % for industry and 10 % go to public water suppliers (Natchkov, 1997).

Conventional river engineering works may negatively influence the quantity of the water supply, as well as its quality. Large dykes, as well as cross-cutting meanders and river branches can influence groundwater levels by suppressing the exchange of water between the rivers and the groundwater reserves, which affects the renewal of riverbank filtrate. Riverbed incision may negatively influence groundwater connections and can cause a lowering of the groundwater level. Dredging of the riverbed might result in a decrease of the thickness of the water supply layer. Furthermore, sedimentation between groynes can result in clogging effects and consequently in lowering of the water supply capacity (MTA, 2017).

A.2.5.2 Land use

In the Danube Basin, the natural vegetation cover would be woodland, with exceptions of areas, where forest cover is not possible due to extreme climate, soil or relief conditions. However, anthropogenic interventions over a long time, partly since the Roman age, have essentially changed the vegetation cover. The vegetation and surface cover found today is mainly a result of deforestation and afforestation (Schiller et al., 2010). The Upper Danube Basin is a region with comparatively rich woodland, which is mostly a result of anthropogenic forestation, with forests covering more than one third of the area (Schiller et al., 2010). Scarcely wooded areas are for example the Hungarian and the Moldavian Lowlands with a tree cover of less than 10 %. The main reason for the deforestation was to obtain farm and grazing land (Schiller et al., 2010) in the lowlands and later for the production of charcoal in the uplands.

Land use, like agriculture and afforestation, is a driver of sediment input into rivers, especially concerning synergistic interactions with sediment load (Walling and Fang, 2003). Alongside land use change and accompanying intensification of human uses, climate change acts as a 'big player' among the drivers of habitat change in rivers (Palmer et al., 2009). Land use types with crop cultivation like cropland, fallow, tree crops and vineyards, have higher mean soil loss rates than land use types under (semi-) natural vegetation like grassland, rangeland, shrubland, forest and post-fire. Nevertheless, there are still large variations within each of these land use types (Maetens et al., 2012). Annual runoff rates follow the same pattern as annual soil loss rates and thus influence the fine sediment input into the rivers, but differences between land uses are less clear (Maetens et al., 2012). Furthermore, water supply and flood may be affected by the ongoing trend of soil sealing in the catchment.

Besides providing habitat, hydrological connectivity and area for flood retention, riparian land is also of great importance for the sediment regime. It reduces sediment fluxes in the freshwater systems by trapping sediments generated on the hillslopes before they reach the stream network (Vigiak et al., 2016). However, anthropogenic influences have also rather diminished the formerly large floodplain woods (Schiller et al., 2010).

A.2.5.3 Climate change

The Earth's climate system has changed over the past century. An increasing body of observations gives a collective picture of a warming world and other climate system changes (IPCC, 2014). Climate change is having

and will have an important effect on agricultural lands, forestry and waters, in addition to the direct and indirect impacts from agriculture (among other sectors). These direct impacts include the modification of land-use, habitat loss, degradation and the indirect impacts include the accumulation of sediment in rivers. The results of the climate change scenarios for the Danube River Basin published in the "Climate change adaption strategy" (ICPDR, 2019b) are shortly summarized in this chapter.

An increase of **the annual and seasonal air temperature,** with a gradient from northwest to southeast, was reported as a main future trend in the "ICPDR strategy on adaption to climate change (ICPDR, 2013d) and confirmed in the "Climate change adaption strategy". This trend is predicted for all three sub-basins (Upper, Middle and Lower Danube), but particularly the south-eastern Danube region is expected to have the largest temperature increase compared to the last decades. In winter, the number of frost days is expected to decrease.

In the DRB, an increase of **precipitation** is expected for Northern Europe and a decrease for Southern Europe. The mean annual values for precipitation will likely remain the same, while the general trend of wet regions becoming wetter and dry regions becoming drier is apparent. With a relatively high certainty, there will be significant changes in the seasonality towards more precipitation in the winter months and drier months in summers. The development of snow cover is less clear for the DRB. Higher temperatures in winter might change the precipitation from snow towards more rain. Together with an earlier onset of the snow melt, this would imply a decrease in snow cover and a shorting of the snow season. However, other findings for mountainous areas state no trend or even a slight increase of snow fall due to a possible increase in winter precipitation. The glaciers will completely disappear in all mountainous areas of the catchment of the Middle Danube River and will be significantly decimated in the catchment of the Upper Danube River. Consequently, the glacial discharge regime of rivers will change considerably.

For the whole DRB, a future increase in **extreme weather events** is expected, including an increase in the intensity and frequency of dry spells, hot days and heat waves as well as local and regional heavy rainfall. The spatial and temporal localisation of extreme events, especially heavy rainfall, are very difficult to model and therefore the results are linked with related uncertainties.

The increase in air and water temperature, combined with changes in precipitation, water availability, and increasing extreme events, such as floods, low flows and droughts, may lead to changes in water quantity and quality, to changes in ecosystems, life cycles, and biodiversity in the DRB in the long-term. Changes in precipitation patterns, leading to an increase in torrential rain and flash flood events can intensify soil erosion and increase the sediment input to rivers. More extreme events and permafrost thawing might further increase the sediment input in the river system (ICPDR, 2019b). Being of primal importance for the close future, this subject needs to be dealt with in future projects and adaptation strategies.

A.2.5.4 Dredging

Nowadays, dredging is mainly done in the context of flood protection and navigation. In the past, and in some cases still today, commercial dredging is performed to gain raw material for the construction industry (buildings, roads, infrastructure, etc.). Between 1971 and 2016, the total dredging volume in the Danube amounted to approximately 400 Mio. m^3 (see Chapter B.2.5 Dredging and feeding). A considerable portion of this amount was used for commercial purposes. The perspective on dredging has begun to change along some sections of the Danube. For example, between 1996 and 2005, 30 % of the material dredged from the Austrian Danube River was removed. Since 2006, the entire amount of excavated material is fed back in the main channel. In some reaches of the Danube River, the responsible authorities no longer permit commercial dredging, whereas in other stretches it still takes place. This sediment extraction mainly affects bedload material, which is already significantly influenced by continuity interruptions in the river. Consequently, this further intensifies riverbed erosion and the resulting impacts. The deficit of bedload causes significant morphological and ecological degradation, since e.g. certain grain sizes necessary for spawning habitats are lacking. Therefore, commercial dredging and sediment extraction from the Danube River and its tributaries is a highly problematic issue and should generally not be permitted. In case dredging works are necessary for reasons of flood protection or navigation, the excavated material should be dumped back in appropriate river sections, if possible upstream, in order to keep the sediments in the river system.

A.3 PROBLEMS AND NEEDS

A.3.1 Problem description

As a result of these numerous human interventions, the sediment regime of the Danube has changed drastically over the last two centuries. With the beginning of the 19th century, systematic training works for flood protection and navigation were executed in large parts of the Danube River (Figure 6).

As a consequence, the morphology of the river was severely altered (Figure 7). Especially in the Upper and the Middle Danube, which includes the SK-HU border reach and southern HU sections, the width of the Danube River and its floodplains was drastically reduced by bank protection measures, cutting off side-channels and disconnecting floodplains. In the Upper Danube, the total width was decreased on average by 39 % (the active width by 22 %) and in the Middle Danube by 12 % (the active width by 1 %). The construction of artificial structures such as guiding walls and groynes additionally decreased the width at low water level.

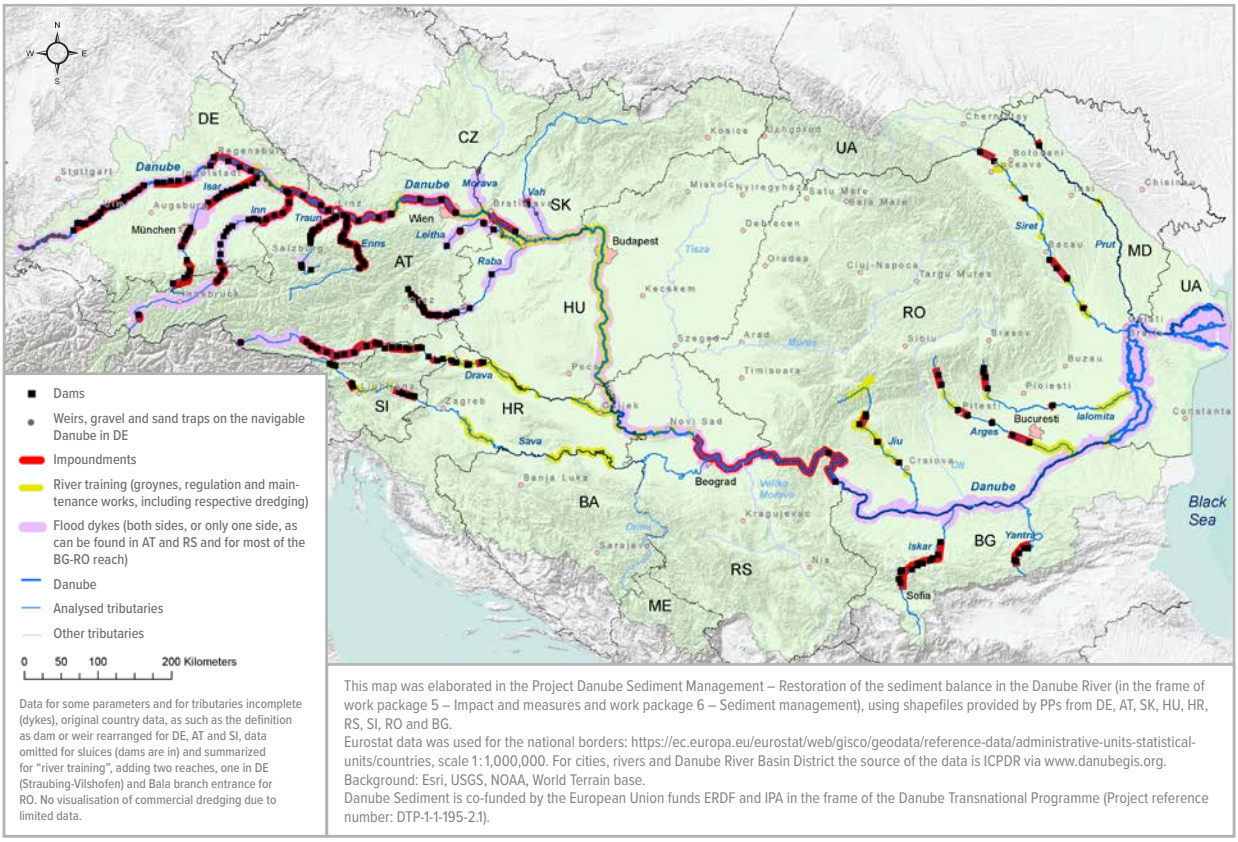


Figure 6: Pressures related to the sediment regime of the Danube River and selected tributaries (based on results from the DanubeSediment report "Interactions of Key Drivers and Pressures on the Morphodynamics of the Danube")

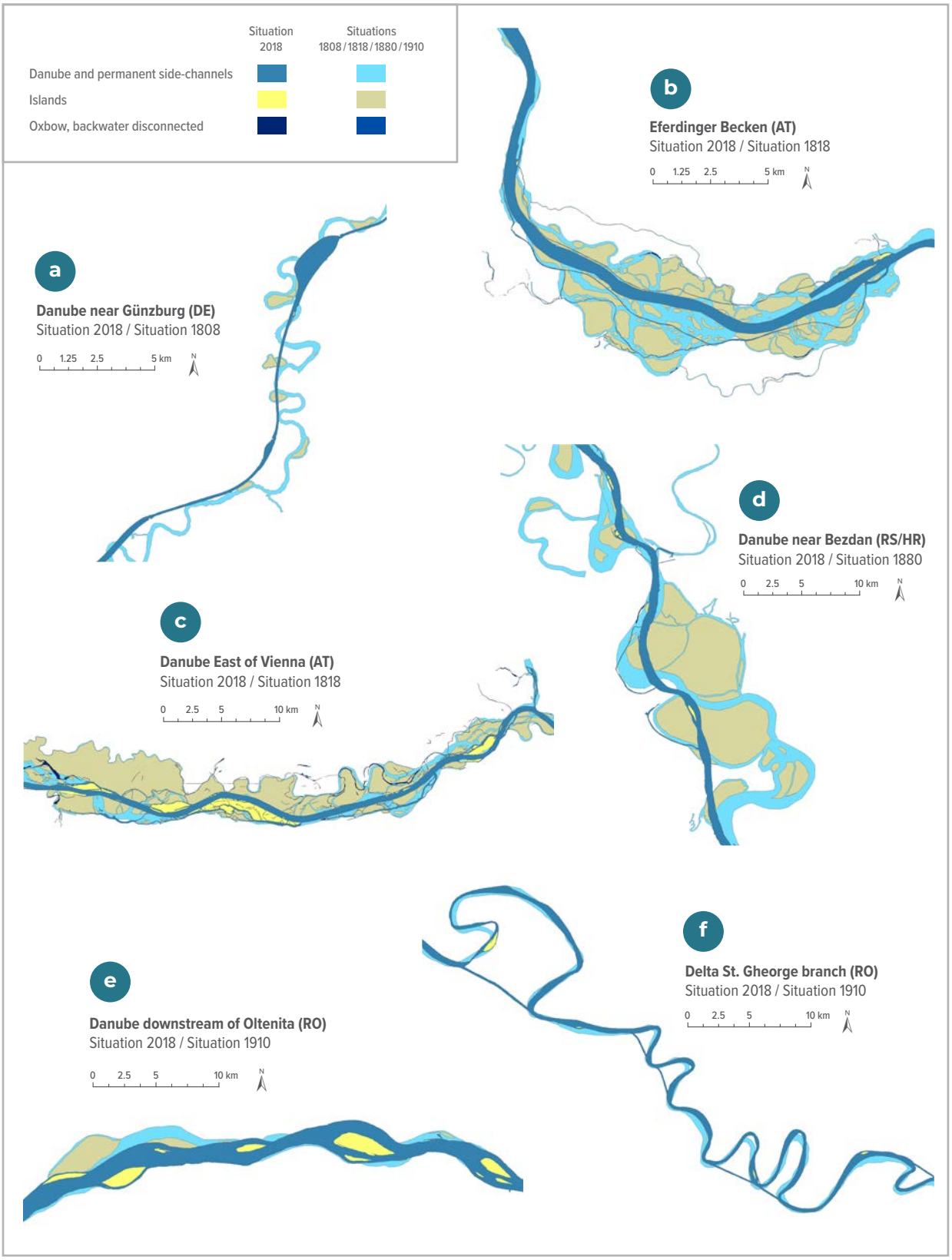


Figure 7: Comparison of the historic and current planform of the Danube River in selected reaches (a) near Günzburg (DE), (b) Eferdinger Becken (AT), (c) East of Vienna (AT), (d) near Bezdan (RS/HR), (e) downstream of Oltenita (RO), (f) Delta St. Gheorge branch (RO) (based on results from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

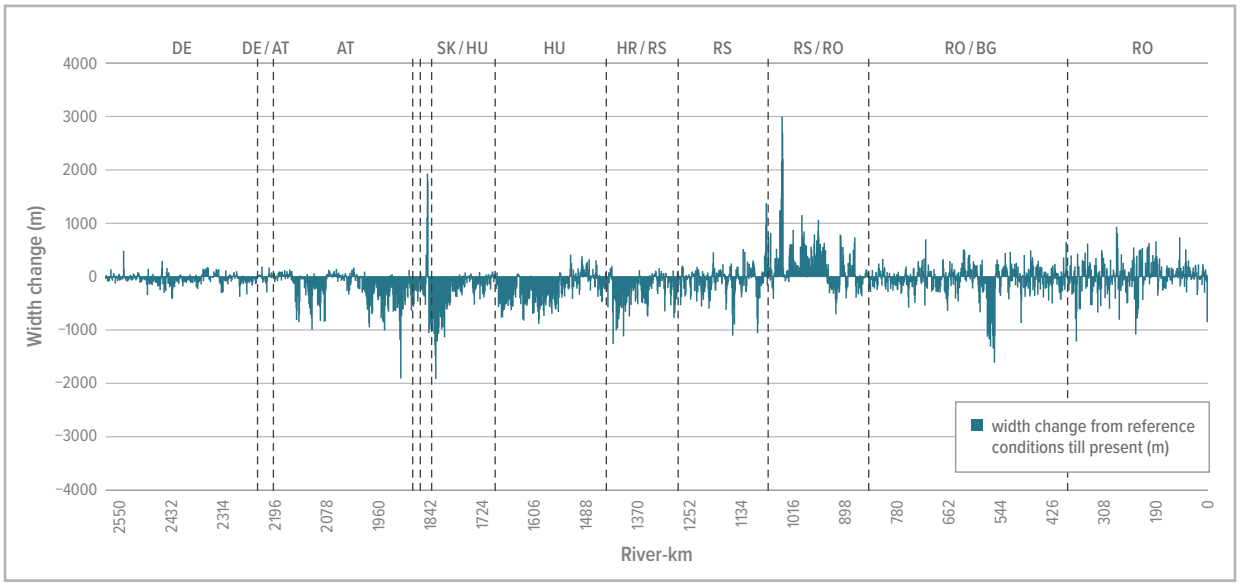


Figure 8: Widening (+) and narrowing (−) of the Danube river system (incl. branches, side arms etc) from reference state until present (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

Figure 8 shows the the widening (+) and narrowing (−) of the Danube river channel in upstream to downstream direction. Severe narrowing and unification of the river channel in the Upper and Middle section was caused by river training such as bank protection measures, longitudinal and lateral structures for navigational purposes, cutting-off side channels, and their related consequences, such as reduced lateral connectivity and movement, incision of the riverbed, which causes a further cutting-off of the floodplain areas. Although damming of the river created wider sections (wetted areas) within some of the impoundments, the flow velocities and water surface slopes are lower, which causes sedimentation and disables the active development of the river channel in some stretches.

In addition to the changes in the river width, the river length of the Danube was decreased, mainly by cutting off meanders. The length of the river was decreased by about 100 rkm (−11%) in the Upper Danube, about 30 rkm (−4%) in the Middle Danube and about 4 km (−1%) in the Lower Danube. This led to an increased sediment transport capacity in the free-flowing sections. Furthermore, the lateral exchange of sediments is hindered by bank protection measures, cut-off side channels (due to river regulation or incision of the riverbed) and flood dykes. Presently, some non-impounded sections of the Danube River lack lateral self-forming processes, which corresponds with a reduction of morphodynamics. Historically, the main river type "multi-thread anabranching" covered 1685 rkm, of which 390 rkm were classified as high energy and 1295 rkm as low energy type (Figure 9). At present, there are only 745 rkm of "multi-thread anabranching" (low energy) river type left in the Lower Danube, whilst "multi-thread anabranching" (high energy) is not presented anymore. In the Upper and Middle Danube, larger sections of the former complex river morphology with meandering and sinuous river types with several multi-thread anabranching reaches have changed to a single thread sinuous river type (Figure 10). The former river systems with complex channel networks are now divided into the two clearly distinguishable units: river and floodplain, whereas the floodplains were drastically reduced. Only one fifth of the floodplains remain compared to the 19th century (ICPDR, 2009).

As a consequence of these changes, various forms of riverbed degradation occur and naturally-formed sediment bars, islands, side channels and oxbow lakes have been drastically reduced in the remaining free-flowing sections. The results of this project show that the lateral restrictions due to river training are less severe in the case of the Lower Danube River. Therefore, the length was only decreased by around 1% and the change of the mean total width was 4%, with a width increase of the active river by 1% (Figure 8). Details for the Upper, Middle and Lower Danube can be found in the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance".

At the end of the 19th century and the beginning of the 20th century, the first transversal structures (weirs, dams) were constructed for e.g. hydropower use and water supply. For the whole Danube River Basin, a total

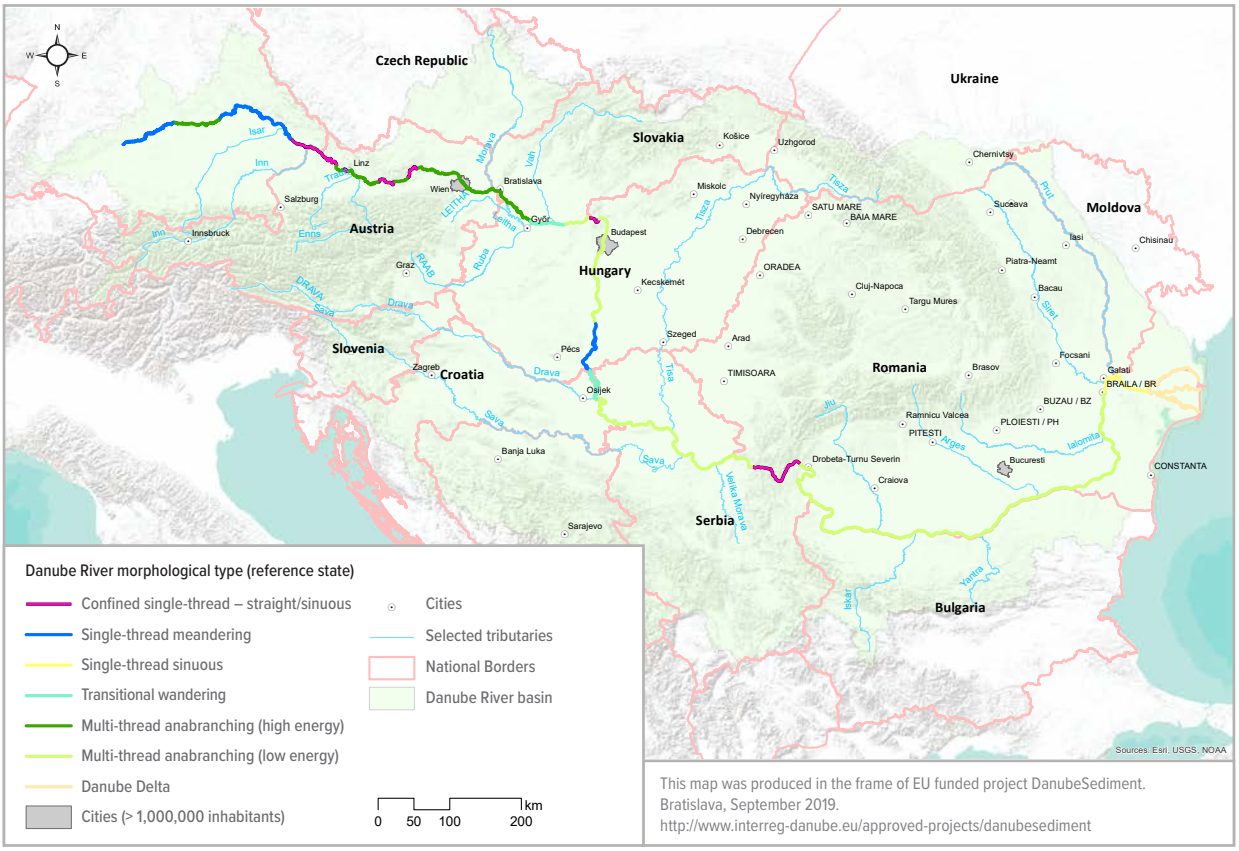


Figure 9: Danube River morphological type (reference state) (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

number of 1030 barriers were reported in the DRBM Plan – Update 2015 (ICPDR, 2015a). However, this number does not include all barriers in the entire basin. Approximately 30 % of the length of the main channel of the Danube River is impounded through 92 dams and weirs of various sizes. Many of these transversal structures were constructed for hydropower production and are located in the catchment of the Upper Danube River (Figure 6).

Due to the reduced flow velocities, sedimentation occurs in the impoundments and reservoirs of the hydropower plants, resulting in a surplus of sediments. In case of major flood events, fine sediments can be remobilised. Such an event can lead to sedimentation in the floodplains and thus contribute to major damage in the developed and cultivated foreland. Furthermore, this can negatively affect river ecosystems, by e. g. congesting the respiratory system of fauna, clogging of spawning places, burying of plants or increased oxygen demand. Downstream of hydropower plants, e. g. downstream of HPP Freudenau (East of Vienna), as well as downstream of HPP Gabčíkovo and of HPP Iron Gate II, a lack of sediments can be observed. The combination of an increased transport capacity that is caused by planform and riverbed regulation, including a reduction of width and length, with a corresponding increase of bed slope, as well as the reduction of lateral river-floodplain connections and sediment input, are responsible for a riverbed incision of several cm per year. On the Lower Danube, erosion processes dominate in the long-term. Local sedimentation processes can occur, especially after large floods, but in the long-term, the riverbed level has been lowered. Bank erosion is an important process, since the sediment input may partially reduce the overall sediment deficit. The erosion processes are especially evident in the long-term between Iron Gate to Zimnicea (rkm 553).

The results of the DanubeSediment project clearly show the effects of alterations from the Upper Danube through to the Danube Delta and the Black Sea. Today, the Danube transports only about one third of suspended sediments into the Danube Delta and into the Black Sea (details see B.2.1). Between Ceatal Izmail and the Black Sea, the suspended sediment load decreases, although there are also uncertainties about the data from the last monitoring stations due to marine and tidal influence.

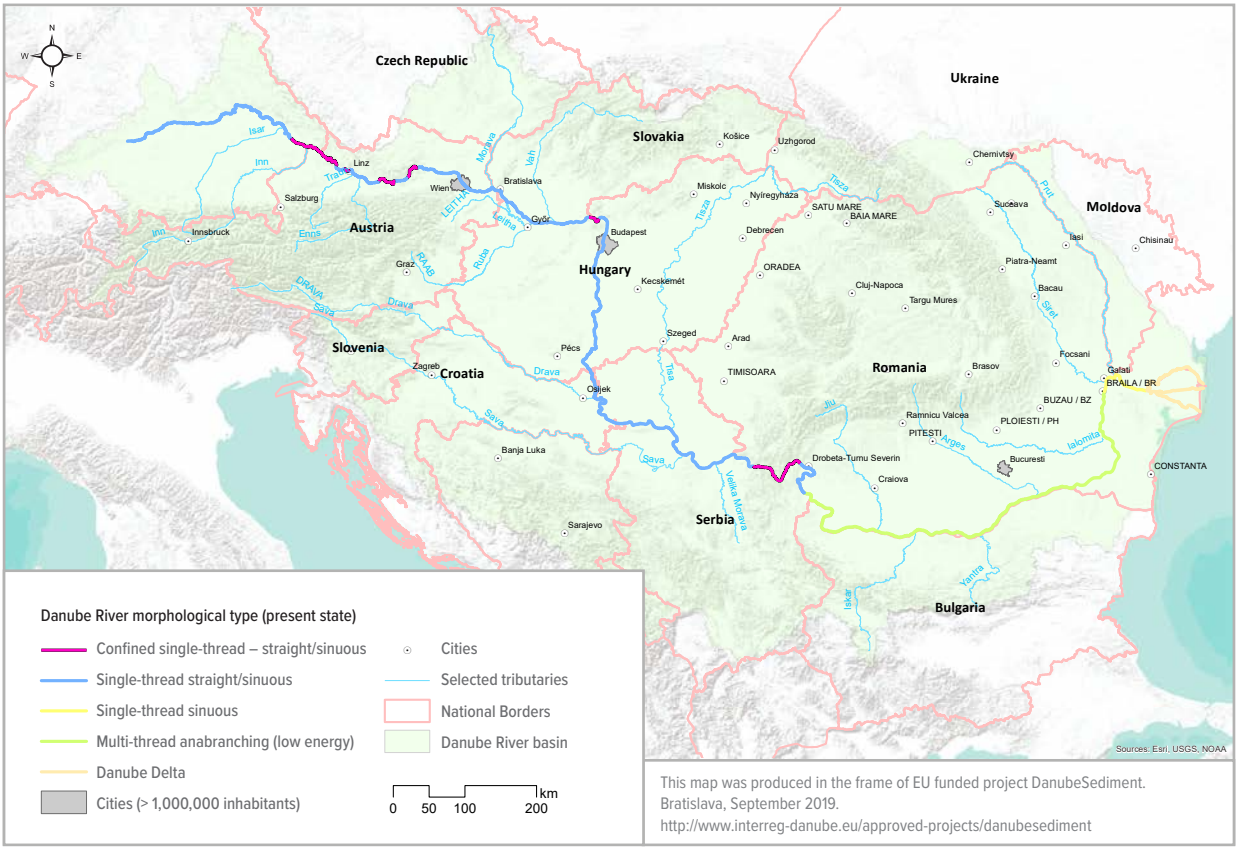


Figure 10: Danube River morphological type (present state) (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

The above-mentioned impacts of alterations in the sediment regime may be intensified by increased agricultural use and deforestation in the catchment, which in turn increases the sediment yield and consequently results in a loss of fertile soil. Changes in fine sediment transport, deposition and remobilisation dynamics can also affect the transport of pollutants and nutrients from point and diffuse sources, since they are often attached to fine sediments. This means that knowledge about the quantitative sediment fluxes is an important part in the evaluation of the sources and transport paths of contaminated particulate matter (Habersack et al., 2016).

A.3.2 Definition of needs and aims

The points mentioned above highlight the need for an international, sustainable basin-wide sediment management in the DRB that

- Is based on the understanding of the system and the underlying processes, supported by comprehensive sediment, hydrological and morphological data.
- Aims to restore the sediment regime as much as possible and to find a dynamic equilibrium in the Danube River and its tributaries, by reducing the pressures of the water users such as hydropower, navigation, flood risk, agriculture, recreation and takes into account
  - user needs as well as
  - safety aspects such as flood protection and
  - ecological aspects such as the necessities of aquatic communities and water dependent terrestrial ecosystems.
- Considers not only the current situation but also possible future changes such as different types of land use or climate change.

The aim of sediment management in the Danube River Basin is to achieve a balanced sediment regime where a dynamic equilibrium between sedimentation and erosion exists and type-specific natural bed forms and bed material are provided. Dynamic equilibrium means that maximum morphodynamics are allowed, with no overall trend of erosion and sedimentation. A balanced sediment regime as well as improved morphodynamics are beneficial to type-specific aquatic communities and water dependent terrestrial ecosystems.

Part B Situation concerning sediments in the Danube River

B.1 SEDIMENT MONITORING

The monitoring programme for sediments currently applied in Danubian countries comprises not only the sediment transport but also particle sizes of the transported sediment and bed material as well as morphological monitoring. Artificial sediment extraction and feeding are to some extent also covered. However, at present, monitoring and analysis methods and monitoring frequencies differ between the countries. This chapter provides a short summary about the monitoring equipment and applied methods. For a more detailed description of the monitoring methods, see the DanubeSediment reports "Sediment Monitoring in the Danube River" for suspended sediment and bedload transport monitoring and "Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube" for the monitoring of bed material, dredging and feeding as well as bathymetry measurements.

B.1.1 Sediment transport monitoring

The monitoring of sediment transport comprises suspended sediments a well as bedload. Currently, 55 suspended sediment monitoring stations and ten stations that monitor bedload continuously operate along the Danube. Additionally, bedload data from field measurement campaigns are available at a few sites in Germany (6) and Slovakia (3). At 17 important tributaries suspended sediment monitoring is performed regularly, whereas bedload monitoring is only undertaken at the Morava

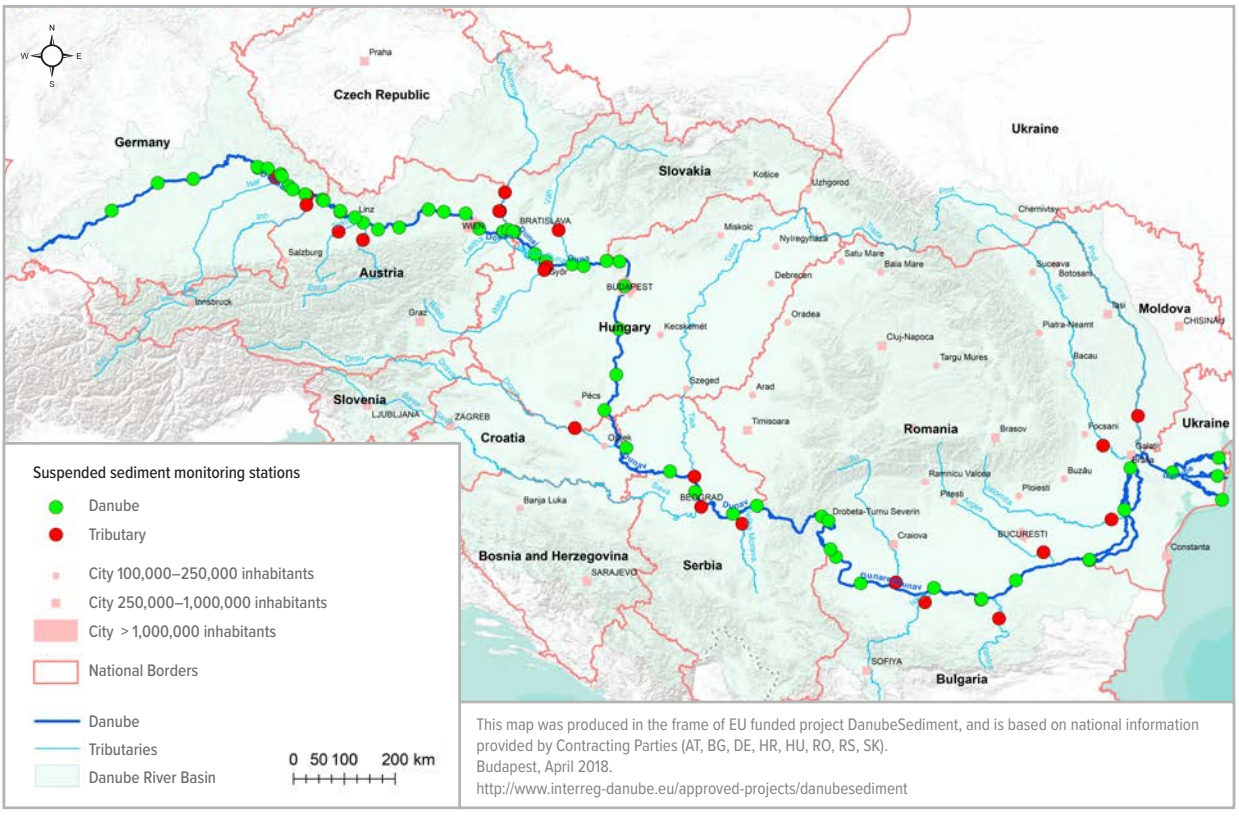


Figure 11: Suspended sediment monitoring stations along the Danube and at the most important tributaries (closest to the confluence) (from the DanubeSediment report "Sediment Monitoring in the Danube River")

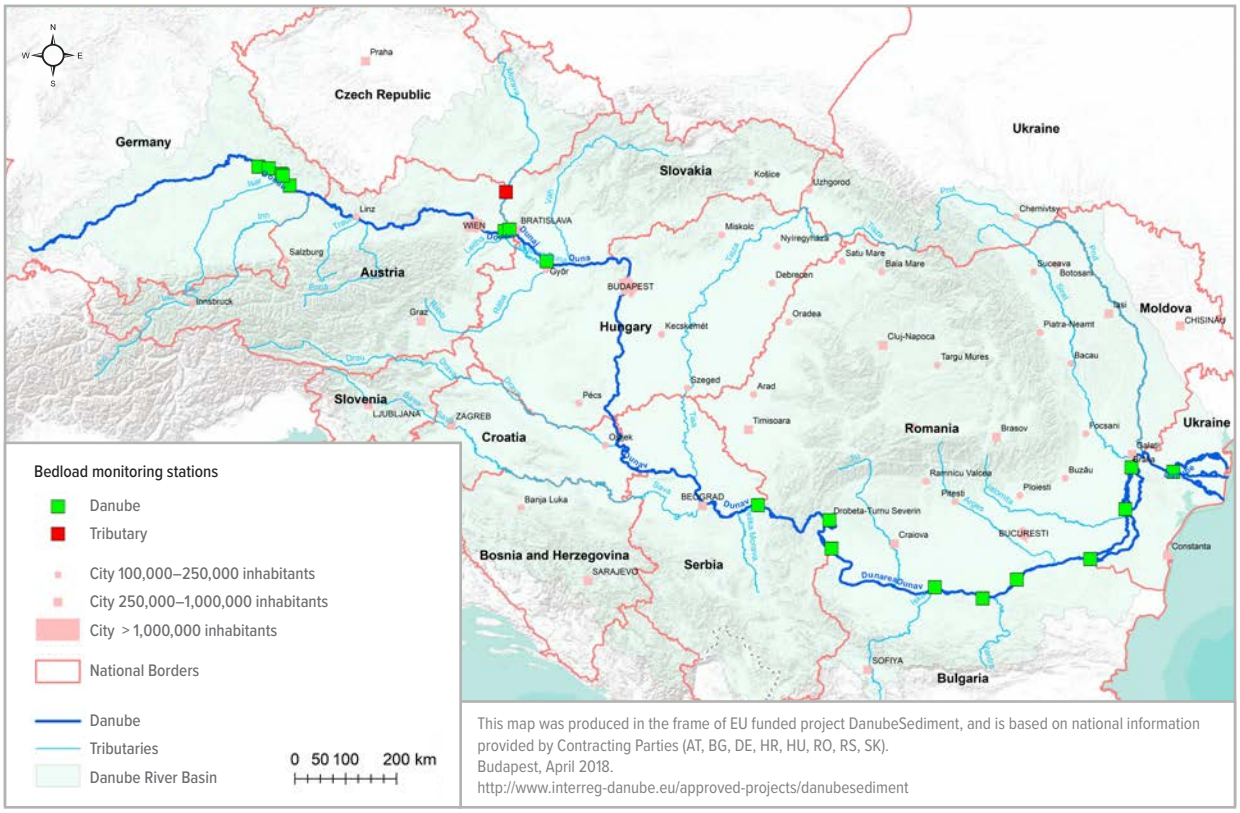


Figure 12: Bedload monitoring stations along the Danube and at the most important tributaries (closest to the confluence) (from the DanubeSediment report "Sediment Monitoring in the Danube River")

River during campaigns. The locations of these monitoring stations are shown in the maps in Figure 11 and Figure 12. The applied monitoring methods for suspended sediment and bedload are described in the following.

B.1.1.1 Suspended sediment monitoring

Suspended sediment monitoring is already performed in all Danubian countries and also in a large number of the most important tributaries. The methods applied at the different stations are briefly described in the following. Some examples of the monitoring devices applied in Danubian countries are depicted in Figure 13.

Continuous measurements based on calibrated optical backscatter sensors

In Germany and some stations in Austria, calibrated Optical Backscatter Sensors (OBS) (e.g. Figure 13a) are applied to measure the turbidity continuously in a 15 min sampling frequency. These measurements are performed in one point of the cross-section. This is complemented by isokinetic physical sampling and acoustic suspended sediment concentration mapping over the whole cross-section (complementary multipoint measurements, e.g. Figure 13b). The multipoint measureb ments are performed 1–5 times a year and are used to calibrate the near-bank suspended sediment concentration with the cross-sectional mean concentration. The daily suspended sediment load is calculated using the calibration curves to get the mean suspended sediment concentration and by multiplying this with the discharge.

Physical, non-isokinetic sampling

In Croatia, Serbia and Romania, physical, non-isokinetic sampling (e.g. Figure 13c and f) on daily basis in one point of the cross-section, with complementary multipoint measurements 4–6 times a year are applied. The multipoint measurements are used to calibrate the near-bank suspended sediment concentration with the cross-sectional mean concentration. The daily suspended sediment load is calculated based on the product of the mean cross-sectional concentration and the actual flow discharge.

Isokinetic, depth-integrating physical sampling

In some stations of Slovakia, isokinetic, depth-integrating physical samples (Figure 13e) are taken on a daily basis in one point of the cross-section. The sampling is performed in a carefully chosen vertical, which provides suspended sediment concentration representative for

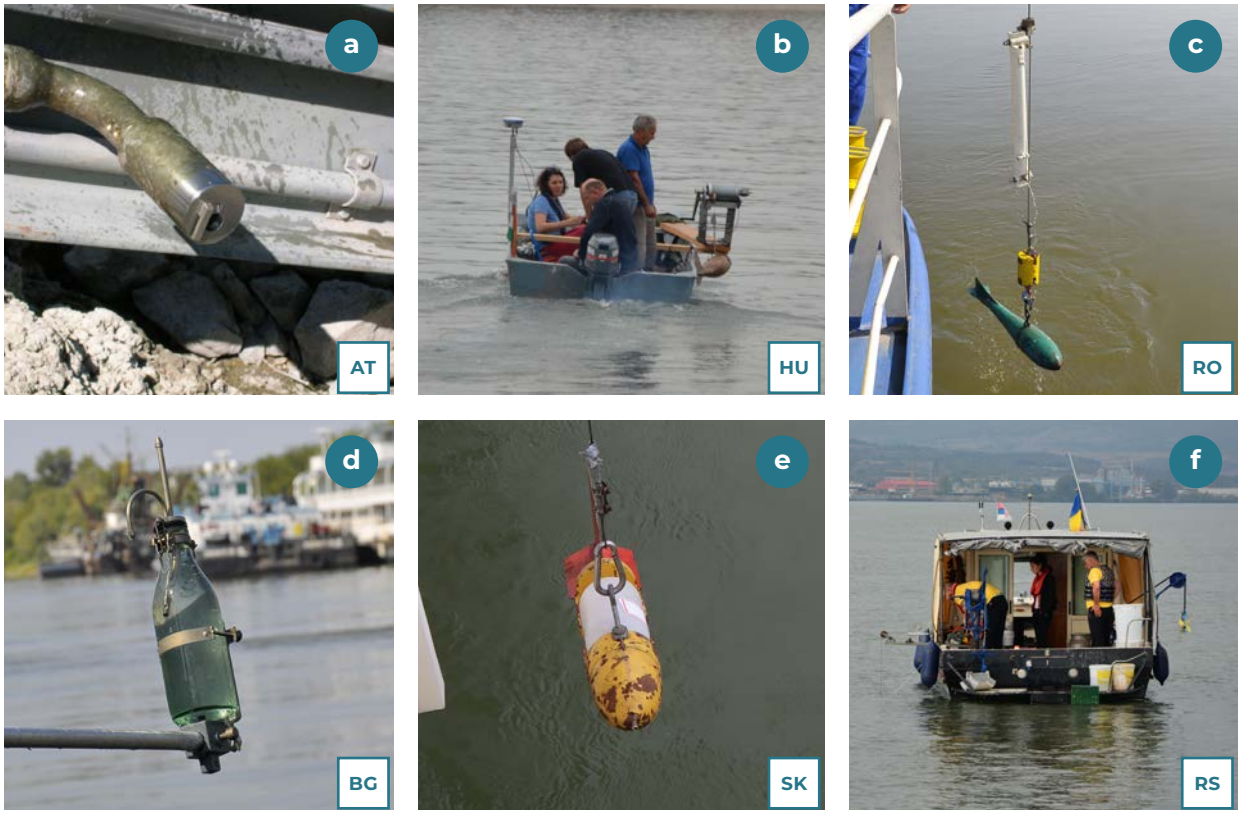


Figure 13: Different monitoring devices applied in the partner countries (a) turbidity sensor, (b) ADCP-measurements combined with samples taken with an isokinetic, point-integrating US-P61-A1 sampler from a boat, (c) instantaneous suspended sediment sampler, (d) time-integrating sampler, (e) depth-integrating WRI-sampler and (f) pump-sampling from a boat (pictures: (a) © viadonau; (b–f) © IWA-BOKU)

the whole cross-section. The daily suspended sediment load is calculated based on the product of the measured concentration and the actual flow discharge.

(Automatized) non iso-kinetic sampling
In Austria besides continuous monitoring via turbidity sensors, automatized pump sampling or bottle sampling with a flow discharge dependent sampling frequency (from 6 times a day to 3 times a week) is performed in one point of the cross-section. When estimating the suspended sediment load, it is assumed that the measured sediment concentration is representative for the whole cross-section.

Physical, non-isokinetic sampling
In Bulgaria and at some stations in Slovakia, physical, non-isokinetic samples (Figure 13d) are taken on a daily basis in one point of the cross-section. When estimating the daily suspended sediment load, it is assumed that the measured sediment concentration is representative for the whole cross-section. The daily sediment load is calculated based on the product of the concentration and the actual flow discharge.

Physical, non-isokinetic multipoint sampling
In Hungary, physical, non-isokinetic multipoint sampling is performed 4–6 times a year. A regression curve is set up for the mean cross-sectional concentration and the flow discharge, and consequently the monthly suspended sediment load is calculated based on this regression and the characteristic flow discharge.

As to the suspended sediment concentration (SSC) determination methods, there are basically three methods applied by the responsible institutes:

Filtering method (DE, AT, SK, BG): the suspended sediment concentration is determined by vacuum filtration (Figure 14a) using cellulose acetate or cellulose nitrate filters with pore diameters of 0.45 µm. Before filtering, the sample volume is determined. The whole sample volume is filtrated. After filtering, the filter and contents are removed and dried for nearly 2 hours at 105 °C. The filter, including the content, is weighed with an analytical balance of an accuracy of ±0.1 mg. The suspended sediment concentration is calculated by dividing the filter content by the volume of the sample.

Figure 14: Methods to determine SSC: (a) filtering method, (b) evaporation method and (c) turbidity method (from the DanubeSediment report "Sediment Monitoring in the Danube River")

Evaporation method (HU, HR and RS): This method uses a sample of 10 l. After a settling process (at least a few days long), 1–1.5 l of concentrated sediment is decanted and transported into the sediment laboratory. After 24 hours of sediment settling, a sample of 100 ml of sediment is taken. The settling process is repeated for another 24 hours, and then all of the sediment dried on 105 °C for 4 hours and weighed (Figure 14b). The sediment concentration is calculated on the basis of known volume of sample and the weight of sediment. For the particle size distribution (PSD) analysis a sedimentation instrument and a sieving instrument is used.

Turbidity method (RO): a portable turbidity meter (Figure 14c) provides the concentration values of the water samples directly in mg/l. To perform the calibration of the equipment, a blank sample of distilled water is used. Then the specific glass of the equipment is filled with the collected water sample and the SSC will be given. The water sample is shaken well before being placed in the equipment for reading. After the first reading, the glass is shaken, rotated 180 degrees and the reading is repeated. At least two readings are performed, and the final value is obtained as the arithmetic mean of the readings.

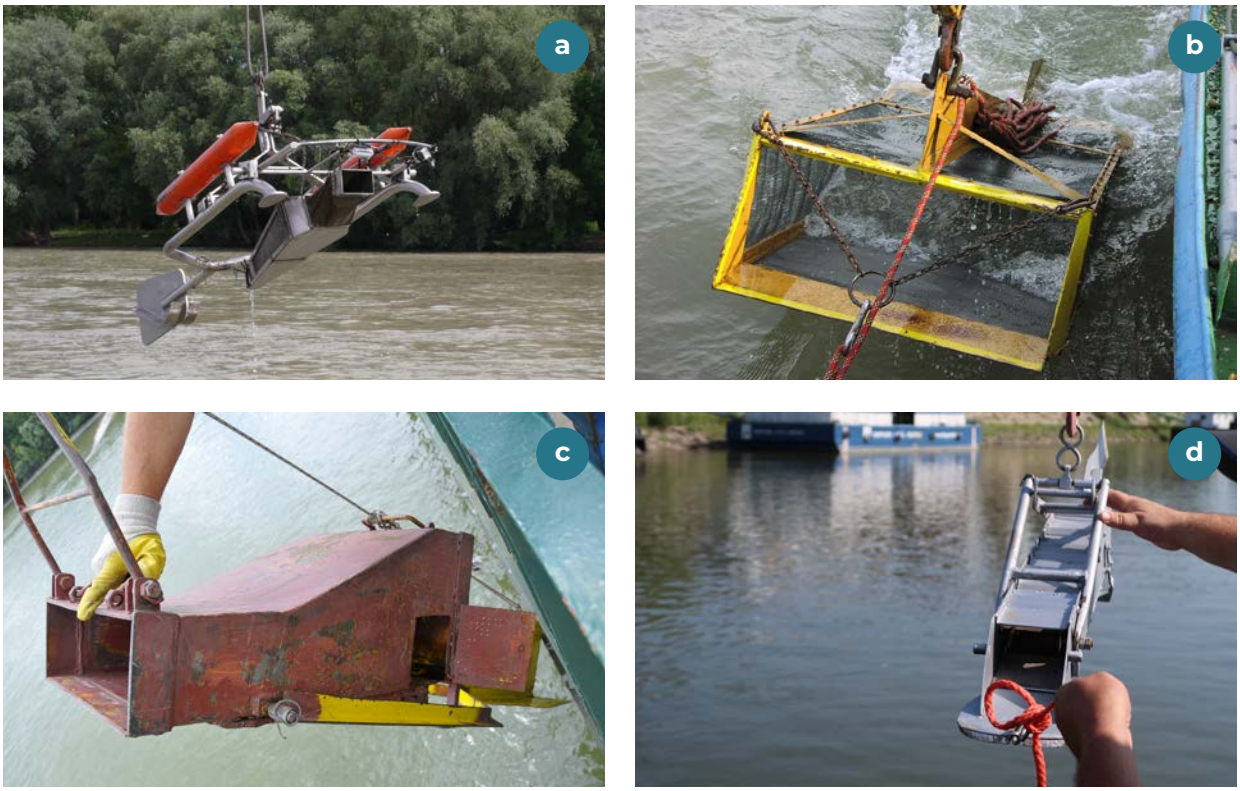


Figure 15: Different bedload sampler applied in the partner countries: (a) BfG-sampler (DE, AT), (b) WRI-sampler (SK), (c) Karolyi-sampler (HU) and (d) IMH bedload equipment (RO) (from the DanubeSediment report "Sediment Monitoring in the Danube River")

B.1.1.2 Bedload monitoring

Bedload monitoring is currently only undertaken in some countries and often not on a regular basis, but only in the frame of monitoring campaigns. In the following the applied techniques are described per country.

- **Germany** applies the BfG sampler (Figure 15a), a well-tested pressure-difference sampler. The measured flow range does not cover high flows.
- **Austria** also uses the well-tested pressure-difference sampler BfG (Figure 15a). The measured flow range covers low flow to extreme floods.
- **Slovakia** measures bedload with a Swiss-type sampler (basket sampler, Figure 15b). The measured flow range does not cover high flows. Data shows significant discrepancy with HU data, so further tests and improvement are needed.
- **Hungary** applies a Károlyi-type sampler (Figure 15c), which is a well-tested pressure-difference sampler. The measured flow range does not cover high flows. The data shows significant discrepancy to the SK data, so further tests and improvement are needed.
- **Romania** uses the IMH (Institute of Meteorology and Hydrology) bedload equipment (Figure 15d). The provided data covers a wide flow range. Due to the complex nature of bedload transport in sand bed rivers, this technique might not be suitable here. Further tests and improvement are needed.

B.1.2 Bed material

Although, data about bed material is available in all countries along the Danube River, sampling of the Danube riverbed is usually performed only occasionally within field investigation related to research projects or tasks, for example in the scope of navigation, hydropower or infrastructure projects. Thus, these data often do not cover the whole national stretch. Bed sampling is either performed along cross-sections, or on some locations only point samples are taken. The sampling equipment differs between the partner countries (examples shown in Figure 16). Depending on the applied sampler, either volumetric samples (Figure 16a, b and c), containing material from the surface and subsurface layer, or samples allowing a distinction between

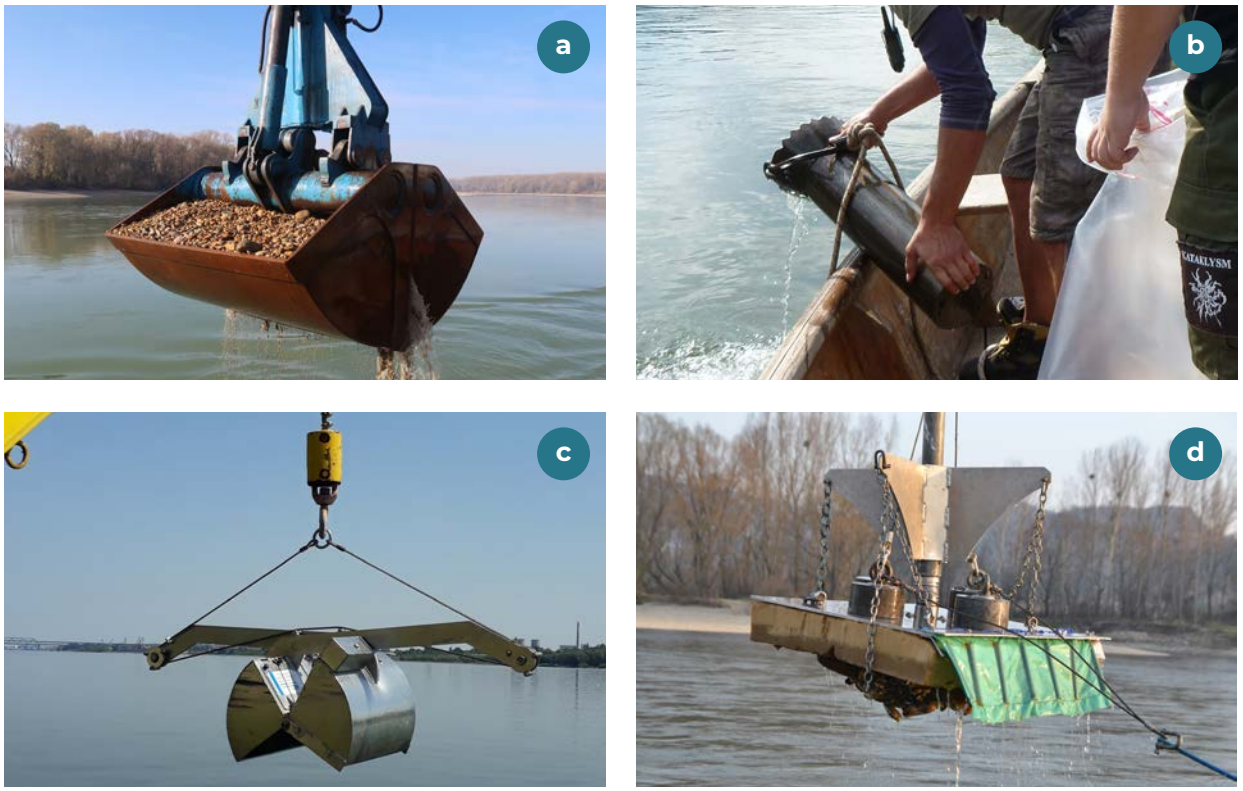


Figure 16: Different bed material sampler applied in the partner countries: (a), (b) and (c) grabbing volumetric bed material samples, (d) freeze panel to sample the surface layer (from the DanubeSediment report "Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube")

Figure 17: (a) Bathymetry measurement performed by SWME using an multi-beam vessel (© SWME), (b) example of a singlebeam measurement with a profile spacing of 50 m and (c) example of a multi beam plot (pictures b and c: data source viadonau) (from the DanubeSediment report "Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube")

surface (Figure 16d) and subsurface layer can be applied. Additional methods such as Wollman pebble count with heel-to-toe walk or photographs are sometimes applied at e.g. gravel bars. In general, grain sizes are determined by sieving using square-hole sieves and mesh sieves with a minimum mesh size of 0.063 mm.

B.1.3 Morphological monitoring

Methods to detect bathymetry have undergone a significant change since the beginning of the monitoring from e.g. 16-point monitoring methods using echolot, to cross-sectional measurements in higher resolution applying single-beam technology or Acoustic Doppler Current Profiler (ADCP) and scanning of the riverbed (multi-beam) (Figure 17). Regular measurements of the riverbed topography and morphology at the Danube River are performed in Germany, Austria, Slovakia, Hungary and Serbia. In recent years, most of these countries use or used single-beam technology to measure bed morphology at the Danube River. When bathymetry was or is measured in cross-sections, these measurements have a distance between 250 and 50 m. The cross-sections are geodetically defined and often marked at the riverbank. Nowadays, the single-beam method is increasingly replaced by multi-beam technology, which scans the riverbed and provides 3D information of it. Single-beam as well as multi-beam technology only detects the bathymetry under the water surface, thus additional measurements to measure the banks or gravel bars have to be performed to detect the whole cross-section. These measurements often take place less frequently than single-beam or multi-beam measurements.

In the Romanian-Serbian section, in the area of the Iron Gate I and II reservoirs and down to the mouth of the Timok River, bathymetry measurements are performed more regularly covering the whole cross-section and even have to be performed according to the laws.

In Romania, regular riverbed measurements are only performed in the hydrometric gauging stations (3 to 5 series of the riverbed measurements per year) using ADCPs to determine the variability of the Danube riverbed in these particular cross-sections. The distance between the cross-sections vary, depending on the distance between hydrometric gauge stations (e.g. 20 km to 40 km). In addition to the locations of hydrometric gauging stations, other locations are also selected for riverbed surveying in view of the distance from the confluences of tributaries and/or islands. Once a location is in selection, a cross-section is surveyed at the same location (though less frequently). Several measurements were performed also in other different sections along the Danube River in connection with some project contracts by different institutions after 2006.

B.1.4 Dredging and feeding

For the Danube River, information about fairway maintenance and critical reaches for navigation are submitted to the Danube Commission and published in a report on a yearly basis. Data about dredging performed in the course of this work (Figure 18) should be reported by each country and included in the report of the Danube Commission. Data of dredging performed for other purposes, e.g. for flood protection or commercial sediment extraction, are stored at national institutions, but is not typically collected and published basin-wide to date. Furthermore, the documented amounts are often only the projected or licenced amounts and can therefore vary from the actual dredged amount. Thus, the project recommends putting an emphasis on the collection of the actual amount of all the dredging and

feeding data in a high quality. To monitor the dredging activities the amounts and the type of material (fine sediment or gravel) should be noted in time and space (m^3, rkm and year). Unfortunately, this information is not available in all countries and often not publicly available.

Gravel feeding at the Danube River (Figure 18) only takes in Austria downstream of the HPP Freudenau (Vienna) (rkm 1921 to 1910) and the purpose is the compensation of the impact of the hydropower plant on the gravel supply from the upstream reach. Feeding of the VHP is noted in time and space (m^3, rkm and year).

Figure 18: Dredging and feeding (© IWA/BOKU)

B.1.5 Other sediment-related monitoring

Further important element for a sediment balance are for example, the input from and output to floodplains, groyne fields and banks as well as an estimation of abrasion and selective transport (for gravel bed rivers).

Flood events along the Danube River showed that several meters of sedimentation (after one flooding) can occur on the floodplains in case of inundation (Figure 19). However, concrete information about the height and extent of these sediment deposits is only partially available. Thus, monitoring and analysis of fine sediment accumulation on the Danube floodplains, especially those occurring in relation with larger flood events, should be started. The interval of the monitoring should be based on the hydrological conditions, i. e. after major flood events. These measurements can

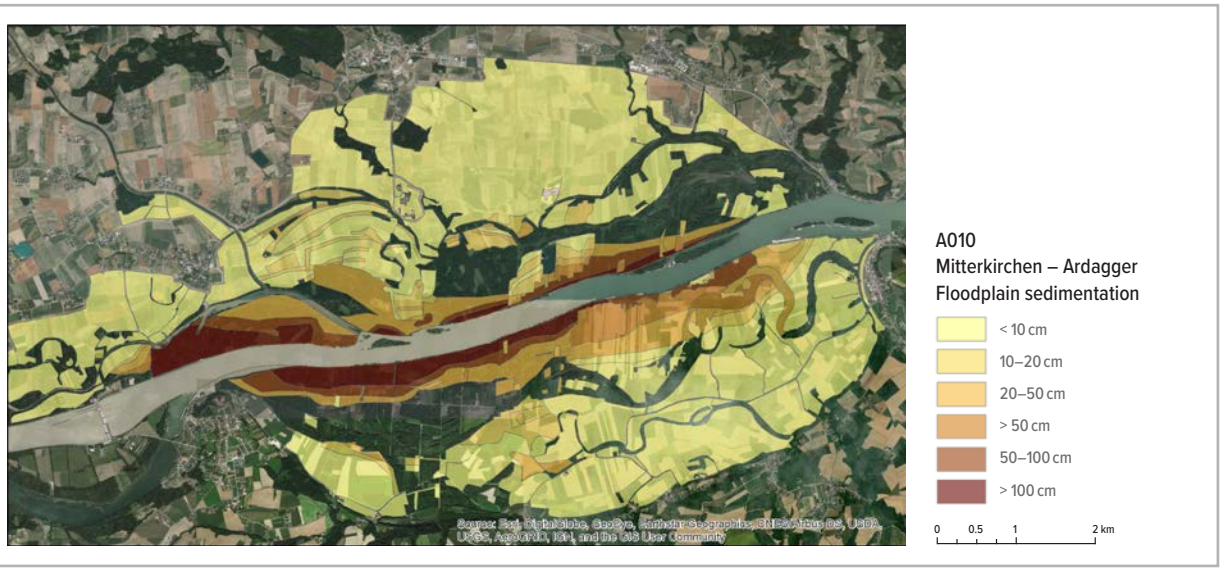


Figure 19: Extent and deposition height of floodplain sedimentation (Habersack et al., 2015, data base: LW-Kammer OÖ)

be complemented by aerial mapping, taking photos of soil erosion, erosion of stream banks, landslides and mechanical movements.

Furthermore, long-term measurements of the (low) water level provide a good estimation of the development of the riverbed and thus should be performed in addition to the above mentioned sediment-related monitoring.

B.1.6 Harmonized monitoring along the Danube River and its tributaries

The comparative analyses of sediment transport monitoring performed especially in the border reaches (see DanubeSediment report "Analysis of Sediment Data Collected along the Danube"), highlighted that when different monitoring methods are applied by the countries the differences and uncertainties in the monitoring results increase. Thus, it is recommended to harmonize the monitoring methods taking the temporal and spatial variability of sediment transport into account. The recommended sediment transport monitoring strategy is summarized in the "Handbook on Good Practices in Sediment Monitoring" derived in the project DanubeSediment. Especially in the border sections, a comparison and harmonisation of the measurement results should be performed on a regular basis. Analysing the spatial coverage of the sediment transport monitoring network, it could be concluded that additional monitoring locations are needed to have a better understanding on unique local features of the sediment transport, such as the sedimentation at impoundments and reservoirs at hydropower plant, role of significant tributaries, and also to support future sediment data assessment activities for more reliable sediment budget calculations.

Besides sediment transport monitoring, recommendations were also formulated for the improvement/harmonisation of bathymetry measurements, sampling of bed material, determination of the floodplain sedimentation and collection of dredging and feeding information. So far, not all of these measurements are performed regularly in all countries of the DRB and thus not in all river reaches there is enough data available to establish a sediment balance and to evaluate the prevailing sediment processes. A detailed formulation of these recommendations can be found in the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance". Suggestions for the harmonized sediment monitoring are furthermore summarized in the "Danube Sediment Management Guidance". Furthermore, comparing the results of different monitoring methods and setting up a sediment balance helps to verify the results of individual parameters.

B.1.7 Sediment transport modelling

Numerical sediment transport models can be implemented as prognostic or planning tools. For example, 1D sediment transport models are suited for longer river reaches and time scales (decades and more) and individual 2D and 3D sediment transport models for shorter or critical river reaches and shorter time scales (years to events). Therefore, models should be considered as important supplements to the monitoring data. They can also be used to close data gaps in the measurements or for spatial and/or temporal inter- and extrapolation of sediment data. In addition, for some specific sediment-related measures the performance of physical models with large scales are recommended. To support international cooperation on sediment transport modelling, the DanubeSediment project collected an array of physical and numerical models applied throughout the DRB (see Danube Sediment deliverable "River Model Network"), which provides some examples what these models can be used for.

B.2 SEDIMENT DATA

This chapter provides only a short summary about the monitoring results and analysis concerning sediment transport, bed material, bed elevation as well as dredging and feeding. Furthermore, a short recommendation on a common data management is given. For a more detailed description of the monitoring results and analyses see the DanubeSediment reports "Analysis of Sediment Data Collected along the Danube" for suspended sediment and bedload transport and "Long-term Morphological Development of the Danube in Relation to the Sediment Balance" for the monitoring results of bed material, dredging and feeding as well as bathymetry measurements.

B.2.1 Suspended sediment transport

The suspended sediment transport was evaluated for two different periods. The actual situation was determined based on the time period 1986–2016. The period before the construction of hydropower plants was analysed based on different time periods when the nearby hydropower plants were put in operation. Monitoring data were provided by project partners and additionally, the sediment data introduced in the study of UNESCO (1993) were also used at stations, where data were not provided. For further information on data availability and quality see the DanubeSediment report "Analysis of Sediment Data Collected along the Danube".

For the time period 1986–2016, the suspended sediment load remains below 1 Mt/yr along the larger part of the German section. The inflow of the Isar River has no major influence, but the Inn River transports a significant amount of sediment, which results in a local increase up to almost 5 Mt/yr. Along the Austrian reach, local smaller scale variation within 1 Mt/yr can be observed, which can be explained by the influence of the fine sediment deposition and remobilisation in HPPs, especially from the HPP Aschach during the floods in 2002 and 2013, the tributaries Traun and Enns and some scatter in the suspended sediment load values. The reservoirs at the Slovakian HPPs, on the other hand, seem to have significant trapping effect, where a local drop of the sediment load from 3.5 Mt/yr upstream to 1.3 Mt/yr downstream of the HPPs is shown. There is a slight increase along the Hungarian section at the Rába River, however, due to the rather small tributaries along this section, the sediment load is quite constant. From the Hungarian-Croatian border a continuous increase of the load from 1.6 Mt/yr to 13.7 Mt/yr is observed until the upstream end of the Iron Gate I reservoir. This is due to the entrance of the large tributaries Drava (0.3 Mt/yr), Tisza (2.6 Mt/yr), Sava (2.9 Mt/yr) and Great Morava (Velika Morava) (2.1 Mt/yr). There is a significant drop in the sediment load at the Iron Gate I hydropower plant, where the reduction to a mean annual load of 2.5 Mt downstream of the reservoir indicates sediment trapping of ~60–80 %. Downstream of Iron Gate I and II, there is a significant increase of the load from 2.5 Mt/yr to 13.5 Mt/yr at the Iantra River inflow (rkm 536.7). This growth can partly be explained with the contribution of the tributaries (e.g. Jiu River: 3 Mt/yr). Additionally, the availability of sediments is limited due to the blocking effect of the hydropower plants and rather small compared to the sediment transport capacity of the river. Subsequent, a quite stable section with only slight increase in the sediment load follows between Zimnicea (rkm 553.23) and Chiciu Calarasi (rkm 379.58), with mean annual values of 13 Mt/yr to 14.6 Mt/yr. There is a reduction of the sediment load between Chiciu Calarasi and Vadu Oii (rkm 238.0) from 14.6 Mt/yr to 10.7 Mt/yr. From Vadu Oii until the inlet section of the Danube Delta region (Isaccea, rkm 100.2) again continuous increase of the load can be observed rising from 10.7 to 21.4 Mt/yr. The Siret River and the Prut River contribute with 4 Mt/yr. The Danube Delta region indicates lowering transport towards the Black Sea. However, it is important to note that sediment load data is available only from the three main branches (Chilia, Sfantul Gheorghe, Sulina) but not from the other branches of the system and therefore, the total load is underestimated.

Comparing these data with the time periods before the construction of the HPPs a decrease in the mean annual suspended sediment load can be observed at all stations where both data sets were available. The reduction ranges between ca. 15 % (in RS at the monitoring site Novi Sad) and ca. 70 % (at the monitoring site Budapest downstream of HPP Čunovo and Gabčíkovo and the monitoring sites in the sections downstream of the HPPs Iron Gate I and II). In conclusion, the total suspended sediment input to the Danube Delta and the Black Sea decreased by more than 60 %, from ca. 60 and 40 Mt/yr historically to ca. 20 and 15 Mt/yr nowadays, (measured at the monitoring station Ceatal Izmail for the input into the Danube Delta for 1931–1972 and 1986–2016; input to the Black Sea measured and summed up for the stations Periprava, Sfantul Gheorghe Harbour and Sulina for 1986–2016 and determined from the stations Periprava (measured), Sfantul Gheorghe Harbour and Sulina (back calculated) for 1961–1972). From Ceatal Izmail to the Black Sea, the suspended sediment load is decreasing (Figure 20), although there are

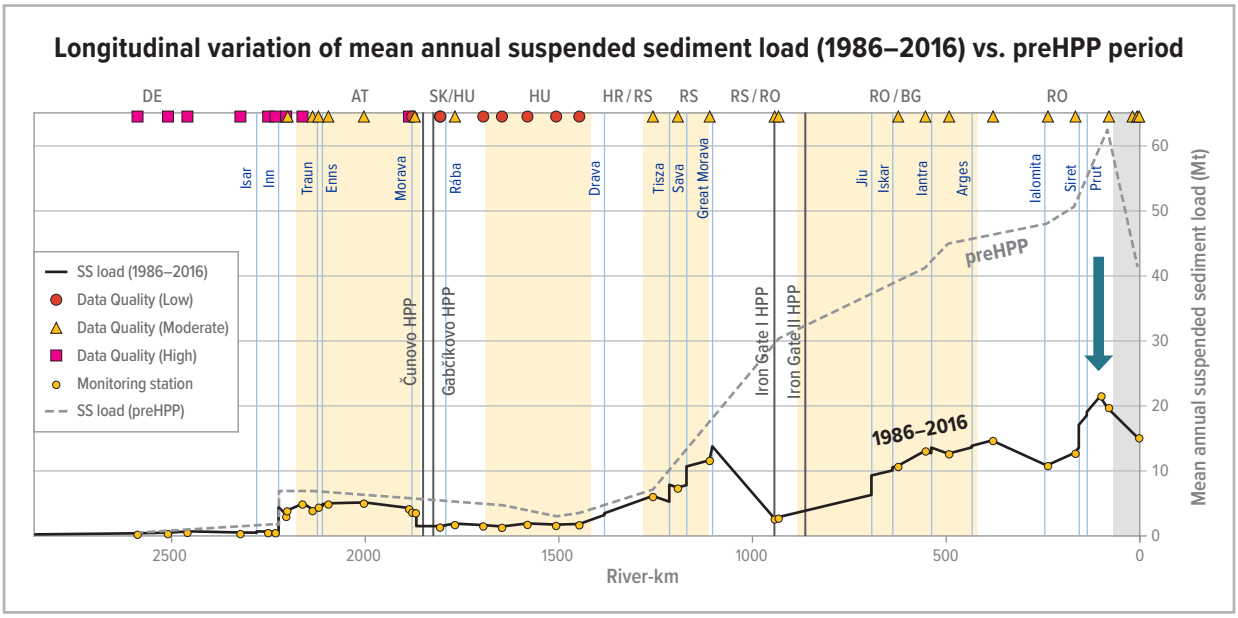


Figure 20: Suspended sediments along the Danube River: past and present. The arrow indicates a reduction of the suspended sediment input into the Danube Delta and the Black Sea of about 60 %. The data quality indicator only refers to the present situation: high data quality: good practices of suspended sediment monitoring, moderate data quality: less accurate datasets and improvement is suggested, low data quality: significant improvement is needed (Figure and details on data quality can be found in the DanubeSediment report "Analysis of Sediment Data Collected along the Danube")

also uncertainties at the last monitoring stations due to tidal influence from the Black Sea. It is important to note that not only the hydropower plants built at the Danube River are responsible for the decreasing of suspended sediment load. Significant anthropogenic influences took place along the river basins of the Romanian tributaries as well, among which several hydropower plants were built in the tributaries, too.

B.2.2 Bedload transport

The bedload transport was also evaluated for different time periods (Figure 21), but the data set is significantly smaller than the data set for suspended sediments. In general bedload continuity is interrupted by dams and the existing bedload transport is compensated by river bed erosion. Along the Austrian Danube, the mean annual bedload transport in Vienna respectively East of Vienna was around 0.94–1.01 Mt/yr for the period after the regulation, but before the construction of the relevant hydropower plants. This value decreased significantly to around 0.44 Mt/yr (or by 55 %) East of Vienna after the construction of the last hydropower plant in the Austrian Danube. The source of the bedload is the degrading riverbed and gravel feeding downstream of the HPP Freudenau. The number of 0.44 Mt/yr compares well with the mean annual bedload transport of 0.40 Mt/yr measured at Devín (Slovakia). Downstream of the Slovakian HPPs a significant increase was found compared to the period before the hydropower plants were commissioned. For instance, the mean annual bedload transport at rkm 1825.6 was around 0.19 Mt/yr in the period 1940–1960, increasing to about 0.55 Mt/yr (at Klížska Nemá, rkm 1795.58). This temporal variation suggests a locally increasing transport capacity of the river downstream of the HPP Gabčíkovo. Indeed, sigo nificant bed erosion was observed along the upper Slovakian-Hungarian Danube section in the years after the commissioning of the Gabčíkovo HPP (see e. g. Török and Baranya, 2017). Based on the mean annual bedload transport, values estimated for the Romanian stations show low values at the Iron Gate reservoir, ranging between 0.02–0.1 Mt/yr. An increase up to about 0.5 Mt/yr can be observed directly downstream of the Iron Gate hydropower plants, which can be explained by erosion downstream of the dam.

B.2.3 Grain sizes

Composition of the riverbed is a key information required for bedload transport modelling, estimation of the riverbed roughness (needed flow regime modelling) or assessment of morphological changes of the riverbed. The Upper and a part of the Middle Danube are characterised as a gravel bed river, with the transition from gravel to sand happening over 240 km

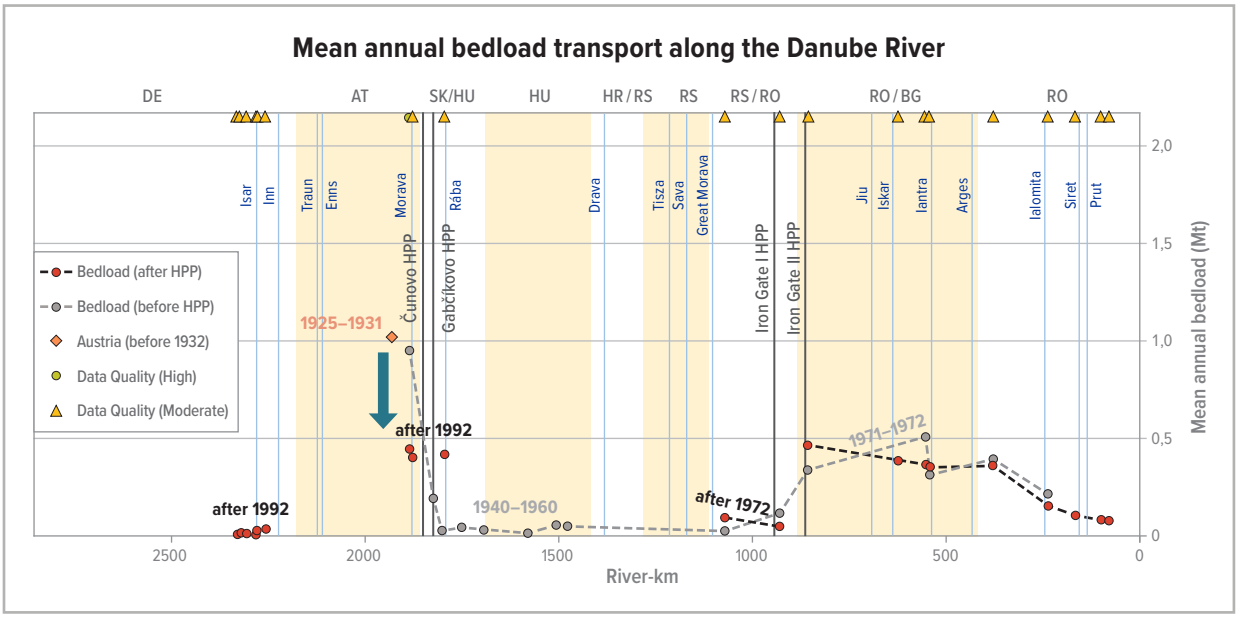


Figure 21: Longitudinal variation of mean annual bedload transport along the Danube River: past and present. The arrow indicates a reduction of the bedload transport in the Austrian Danube East of Vienna of about 50 %. The data quality indicator only refers to the present situation: high data quality: good practices of bedload monitoring, moderate data quality: less accurate datasets and improvement is suggested. (Figure and details on data quality can be found in the DanubeSediment report "Analysis of Sediment Data Collected along the Danube")

(rkm 1660–1420) in the Hungarian part of the Danube River (Figure 22). Further downstream, the riverbed mainly consists of sand, with short sections of gravel that is supplied by the tributaries, e.g. Great Morava (Velika Morava). The grain sizes downstream of the Iron Gate dams mainly consist of fine and coarse sand interrupted by short parts with gravel, which is supplied from the tributaries. Over the last 300 km, the sizes gradually become finer, with fine sand and silt making up the bigger part of the riverbed.

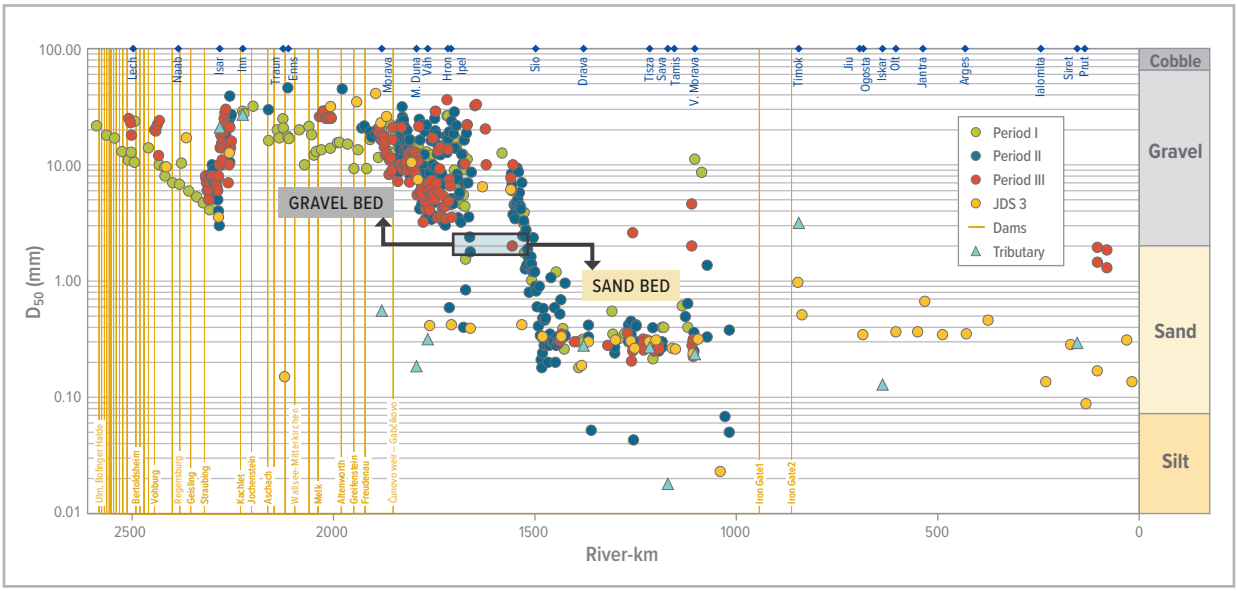


Figure 22: Variation of the median size of the bed sediments D_{50} (surface layer) over three periods (I: 1920–1970; II: 1971–1990; III: 1991–2016) along the Danube River between rkm 2600 – rkm 1000 (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

Figure 23: Samples of bed sediments taken from the Upper, Middle and Lower Danube in period III (1991–2016) (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

The Upper Danube is characterized by gravel fractions in the free-flowing sections and by fine sediments (sand and silt) in the impoundments. In Germany an increase of the grain sizes is evident downstream of the confluence with the tributaries Lech, Isar and Inn. In free-flowing reaches downstream of HPPs, a riverbed coarsening can be observed. Even in most of the impounded sections directly downstream of the Hydropower plants the riverbed still consists of gravel and sand, changing to mainly (fine) sand and silt when approaching the next hydropower plant. In general sorting of the grain sizes along the river is clearly dominated by the influence of the hydropower plants (Figure 23).

Fine sediments are also dominating in the reservoir of the HPP Gabčíkovo, whereas downstream of the HPP the Danube riverbed largely consist of coarse and fine gravel. The impact of dredging in the upper reach of the gravel bed section results in a riverbed fining in period II and III. Downstream, the sediment sizes are gradually decreasing until rkm 1660 were the Danube River changes from a gravel to a sand bed river over the next 240 kilometres. In the rest of the Middle Danube until the confluence with the Great Morava (Velika Morava) the riverbed mainly consists of fine and coarse sand. At the confluence of the Great Morava (Velika Morava) again gravel can be found on the riverbed. Due to the influence of the Iron Gate I the grain sizes are fining further downstream consisting of sand, silt and clay.

The bed sediments of the Lower Danube mainly consist of coarse sand and fine sand (rkm 862.8–rkm 100). Coarser grain sizes (gravel and coarse sand) occur in the section downstream of the Iron Gate II. Gravel bed tributaries (Timok, Jantra, Iskar) induced a natural coarsening of the Lower Danube sand bed in areas of tributaries mouth (local effect). This effect is currently considerably reduced by damming of the tributaries. Over the last 300 km the sizes are gradually fining, and fine sand and silt make up the bigger part of the riverbed. This natural downstream fining of the Danube bed sediments indicates more natural conditions compared to the Upper and Middle Danube.

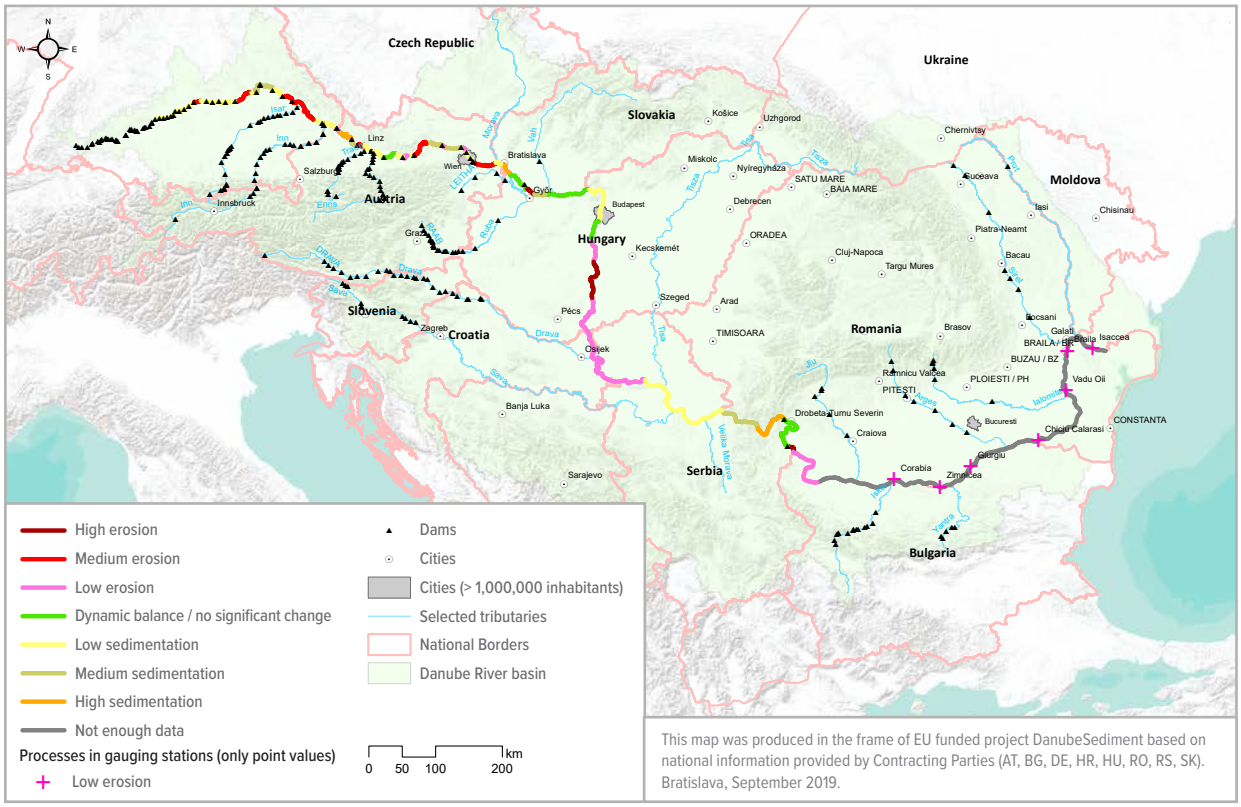


Figure 24: Reaches at the Upper, Middle and Lower Danube showing sedimentation and erosion (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance")

B.2.4 Morphological changes

Based on bathymetry measurements, the changes in bed levels were investigated for the latest period (1991–2017). Details can be found in the DanubeSediment reports "Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube" and "Assessment of the Sediment Balance of the Danube". Volume changes were calculated and reaches of sedimentation or erosion identified along the Danube River for the Upper and Middle Danube as well as for a short section at the Lower Danube, meaning from rkm 2582 to rkm 750 (Figure 24).

In total about 733 rkm (29 %) of the Danube River is dominated by erosion (56 % when including the Lower Danube, see below) and 857 rkm (34 %) of the Danube River by sedimentation. Along 241 rkm (10 %) of the Danube River, a dynamic balance prevails, or no significant changes occur. In summary, the river either has too much or not enough sediment, which underlines the need for action. Reaches with high erosion are located in the Hungarian section and downstream of the Iron Gate II dam. High sedimentation occurs in the impoundments of the HPPs Aschach, Gabčíkovo and Iron Gate I. For the greater part of the Lower Danube (670 rkm, from rkm 750 to 80), there is not enough data available for the period indicated above to be able to evaluate the changes in the riverbed in detail. The evaluation of cross-sectional measurements with time series of more than 25 years, starting in the 1980ies and 1990ies, show low riverbed degradation (trend) at eleven out of twelve Romanian gauging stations. Thus, including these reaches ca. 56 % of the river length are facing erosional tendencies.

The spatial resolution of cross-sectional measurements at Lower Danube is not sufficient to make a reliable statement for the whole stretch. Analysis, relying on more than 300 cross-section profiles covering two time steps (2008 and 2017), shows local deposition relative to the overall riverbed lowering on many sectors of the Lower Danube. However, this is a consequence of the flood in 2006, which leads to a low riverbed level as a starting point and cannot be used for further analysis and conclusions. More detailed measurements are required in the future. Furthermore, two time steps do not allow a determination of erosion or deposition trends.

B.2.5 Dredging and feeding

In the past, dredging in the Danube River was performed for a variety of purposes, e.g. commerce, navigation, flood protection, river training, road constructions, land reclamation and during the construction of the hydropower plants. At present, dredging is undertaken mainly for navigation and flood protection purposes and in some cases to remove sediments from the impoundments of hydropower plants and for river restoration projects. Further sediment is dredged at the mouth of tributaries in impounded reaches, as well as in harbours and harbour entrances. In the Upper and Middle Danube, commercial dredging (of gravel) is not performed anymore and is forbidden. In these Danube sections, dredged material is returned to the main channel, thereby made available for sediment transport. Alternatively, it is used for the construction of instream structures like gravel bars or islands. In Austria, the material is reinserted upstream of the dredging site. Since 2015, the upstream transport has increased notably. In other parts of the Danube River, the situation is also changing towards more sustainable dredging. The DanubeSediment project collected dredging data in the Danube River for three different time periods: 1920–1970, 1971–1990 and 1991–2016. Within the first period, only the data in Germany and Austria cover longer periods of over 10 years, whereas the data from other countries is available only for several years. For Croatia, the dredging data only consist of three years, which were documented in the third period. The dredged amounts were highest in the period 1971–1990, of which the largest amount was removed in the Middle Danube (Figure 25 left). During this period, the dredged amounts were higher than in the Upper and Lower Danube together. The most active countries in terms of dredging were Slovakia, Serbia and Romania (Figure 25 right). In some river stretches, e.g. in some parts of Slovakia, Hungary and Serbia, dredging amounts even exceeded the bedload amounts supplied from upstream. Since the project team assumes that the dredging data provided by the partner countries does not cover all dredging activities within the three time periods, the absolute figures are subject to some uncertainty. To answer open questions on the long-term impact of dredging, more investigations and better monitoring of dredging amounts is required.

In the Danube River, gravel feeding is only undertaken in Austria downstream of the HPP Freudenau (Vienna). The purpose of feeding is to compensate the negative impact of the hydropower plant on the gravel supply from the upstream reach. The amount of gravel feeding in the maintenance reach between rkm 1921 to 1910 was approximately 186,000 m³/yr between 1996 and 2017. This amount has recently been increased to 235,000 m³/yr (BMNT, 2018a).

B.2.6 Data management

Sediment-related data are a prerequisite for appropriate planning and the evaluation of any sediment management measure. Long-term data that are measured regularly must be available to assess trends and long-term effects of sediment management measures and climate change. Additionally, sediment data are also an important input for numerical and physical sediment transport models and are a necessity for their calibration and validation.

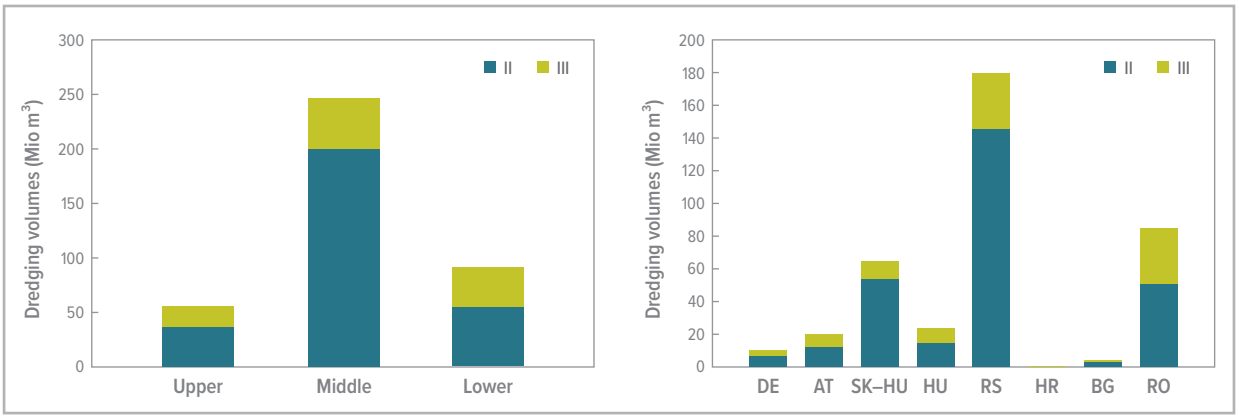


Figure 25: Dredging volumes at the Upper, Middle and Lower Danube for two different time periods: 1971–1990 (blue) and 1991–2016 (green). These graphs are based on results from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance".

To date, sediment data is collected, stored and managed in different ways in the Danubian countries. In many countries the sediment data, bathymetry measurements and bed material data are collected and stored by regional institutions and are not available for public use. In many cases, no data exchange exists on the transnational level among Danubian countries. Therefore, at the moment, no centralized information system about sediment data exists for the Danube River.

It is the intention of the DanubeSediment consortium that data collected and calculated during the project shall be stored and made available via the Danube GIS of ICPDR. The project also suggests to store future sediment data after processing and validation in a centralised system, e.g. in the Danube GIS or to publish them in the yearbook of Transnational Monitoring Network (TNMN).

The most relevant data in relation to sediment quantity and that should be stored are:

- **Suspended sediment data:** suspended sediment loads and concentrations as annual values and for flood events as well as particle size distributions
- **Bedload data:** bedload yield and characteristic grain sizes as annual values and for flood events
- **Bathymetry data:** volume changes, mean bed level changes
- **Bed material:** characteristic grain sizes
- **Dredging data:** dredged volumes, date, indication of material (gravel, sand, silt), rkm, extracted/refed/...
- **Feeding data:** volumes, date, indication of material (gravel, sand, silt), rkm
- **Floodplain deposition:** area, sedimentation height, type of sediment (sand, silt, clay)

B.3 SEDIMENT BUDGET

Based on the collected suspended sediment data, published in the DanubeSediment report "Analysis of Sediment Data Collected along the Danube", a suspended sediment balance for the Danube River and the major tributaries was prepared. This balance shows the present situation and compares it with the historic situation before the construction of the hydropower plants on the Danube River (Figure 26). Amongst the tributaries for which historic data is available, the Siret in the Lower Danube had the greatest contribution to the suspended sediment transport of the Danube River. Its mean annual load is about 12 Mt (1965–1985, UNESCO, 1993). Other important tributaries in terms of mean annual loads of suspended sediments were the Inn (about 5 Mt) for the Upper Danube, the Tisza (about 5 Mt, 1956–1985), Sava (about 5.5 Mt, 1956–1985) and Great Morava (Velika Morava, about 6.9 Mt, 1956–1985) for the Middle Danube and the Olt (about 6.8 Mt, 1956–1985) for the Lower Danube (UNESCO, 1993). Additionally, another major tributary for the sediment balance was the Drava. However, the data displayed in Figure 26 is already influa enced by the first HPPs, which were built earlier. For the newest time period from 1986–2016, the most important tributaries in terms of suspended sediment transport (mean annual loads) were the Inn (about 4.1 Mt) for the Upper Danube, the Sava (about 2.9 Mt) and the Tisza (about 2.6 Mt) for the Middle Danube and the Romanian tributaries Jiu (about 3 Mt) and Siret (about 3.5 Mt) for the Lower Danube.

The comparison of the two time periods highlights that the decrease of suspended sediment input from the tributaries, especially in the Middle and Lower Danube, leads to a reduction of suspended sediment transport in the Danube River. The project results show that the reduction ranges between 20 % and 70 % for tributaries with sufficient data available for both periods. Furthermore, the chain of HPPs on the Upper Danube and especially the large reservoirs of Gabčíkovo and Iron Gate I have an impact on the suspended sediment balance, since large amounts of material are trapped in these reservoirs.

All these HPPs contribute in varying degrees to the total sediment deficit in the Danube River. A portion of the sediments entering the reservoirs has already been reduced by impoundments and reservoirs located upstream or in the tributaries. 60 % of the sediment input is deposited in the HPP Gabčíkovo reservoir and 60–80 % of the sediment input in the HPP Iron Gate I reservoir (now less than at the beginning of the period). This data is calculated by comparing the monitoring stations upstream and downstream of the reservoirs as described in the DanubeSediment report "Analysis of Sediment Data Collected along the Danube". The sedimentation rate of HPP Iron Gate I (filling of the reservoir), based also on bathymetric surveys (sedimentation volume compared to the original reservoir volume) is 10 to 17 %. In conclusion, the total suspended

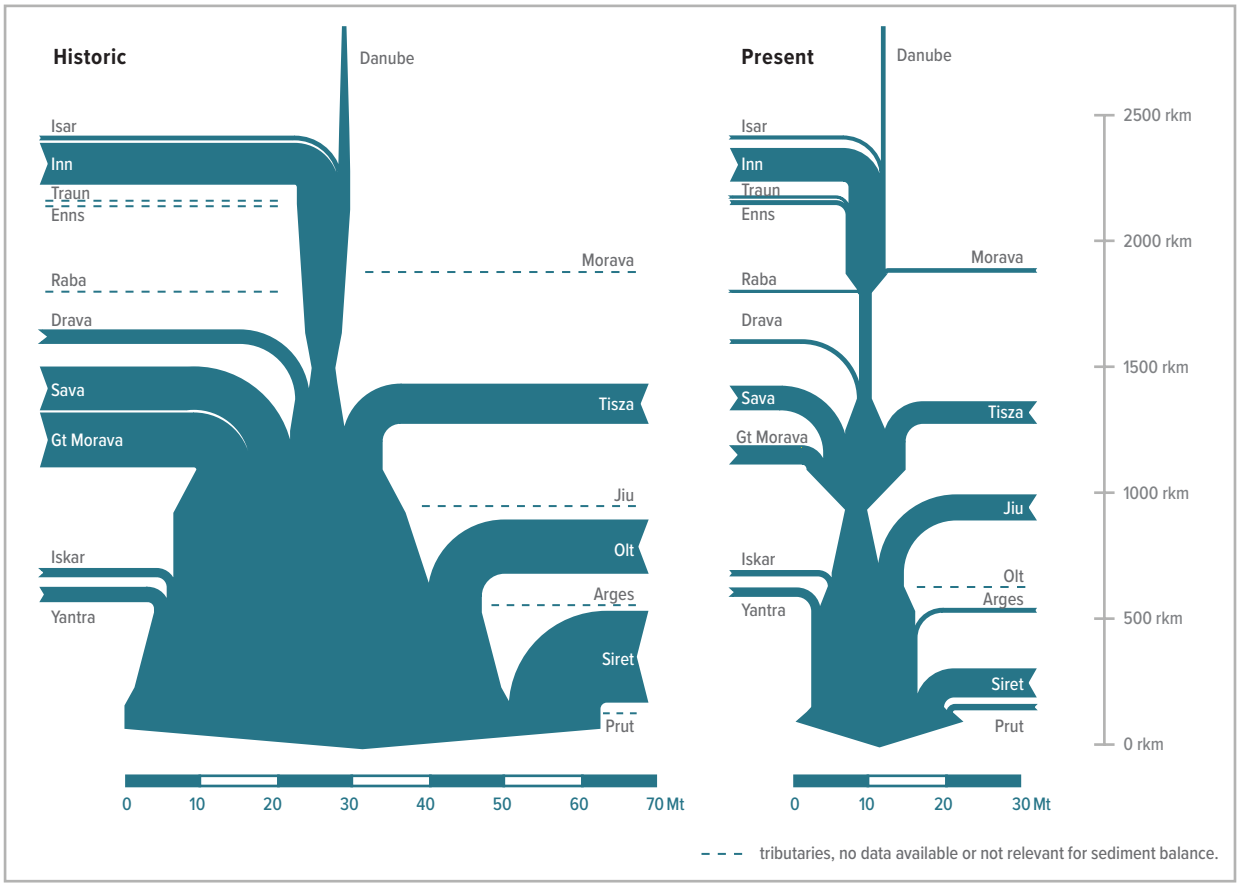


Figure 26: Suspended sediment balance along the Danube River and its major tributaries before (left) and after (right) HPP construction on the Danube River (dashed lines: tributaries, where no data is available or which are no longer relevant for the suspended sediment balance). The horizontal scale (Mt) applies for both the Danube River and its tributaries.

sediment input to the Danube Delta and the Black Sea decreased by more than 60 %, from ca. 60 and 40 Mt/yr historically to ca. 20 and 15 Mt/yr nowadays (details see Chapter B.2.1). From Ceatal Izmail to the Black Sea, the suspended sediment load is decreasing (Figure 20), although there are also uncertainties at the last monitoring stations due to tidal influence from the Black Sea.

The data collection within the project DanubeSediment highlights, that at the moment the data base is too incomplete to be able to set up a sediment balance for the whole Danube River. Unfortunately, not all the data described above were available for the whole river. Furthermore, when looking at the sediment balance equation, there are important elements missing to complete the picture. For example, the input from and output to floodplains, groyne fields and banks as well as an estimation of abrasion and selective transport are needed. Thus, the DanubeSediment project recommends an improved sediment monitoring that is described in the project output “Danube Sediment Management Guidance”.

B.4 RISK ANALYSIS OF THE CURRENT STATUS

In the DanubeSediment project, a methodology for risk assessment was proposed and applied to four pilot sections (see DanubeSediment report “Risk Assessment Related to the Sediment Regime of the Danube”). The methodology follows a stepwise process to decide if a specific section is at risk of failing the good ecological status by going through the hydromorphological quality assessment. The decision for continuing with the biological assessment is made based on the result of the hydromorphological quality assessment. The potential

impact and risks associated both with hydromorphological and ecological alteration were provided.

It is clear that there is a causal chain from sediment transport to river morphology and ecology and that sediment budget is a prerequisite for river morphodynamics and habitat dynamics. Furthermore, there is no doubt that habitat quality directly influences the ecological status. Thus, the link between sediments and aquatic species is given by providing habitats, spawning places etc. Of course, there are other factors (e.g. water quality, water temperature, ship waves) influencing the biological status. Besides the risk of not achieving the good ecological status, an imbalanced sediment regime also puts other sectors such as navigation, flood protection and water supply at risk.

The application of the above-mentioned method in pilot sections is a first step to assessing the risk related to a change in the sediment regime. For this, a set of parameters to evaluate sediment continuity and balance was selected. These parameters were erosion rate, suspended sediment concentration/load and sediment continuity. For a more comprehensive assessment in the future, further parameters such as channel width change, changes of riverbed or water surface slope, capacity-supply-ratio and/or transport capacity of bedload, thickness of the gravel layer in combination with erosion rate (riverbed break-through), changes of bed material grain sizes and bed armouring might be considered.

In addition, the thresholds used to score the sediment-related parameters in the method applied should only be considered as a first attempt. They require further refinement/calibration. The DanubeSediment project suggests to take the value for "sediment continuity" as a threshold that does not allow any other parameter dependent on sediments, e.g. morphology to receive a better score. This approach aims to reflect that the sediment regime determines the overall hydromorphological and ecological status of the water body.

In the future, such sediment relevant parameters should be integrated into the update of CEN standard EN 15843:2010 (Water quality – Guidance standard on determining the degree of modification of river hydromorphology), which is currently in the revision procedure. They should also be set in correlation to the existing results and data pools of hydromorphological assessments and surveys done within the past decades.

B.5 EXISTING SEDIMENT-RELATED MEASURES

A collection of sediment management measures, based on predefined factsheets was performed in the frame of the project DanubeSediment. The information was provided by the project partners and does not comprise a complete list of all measures implemented in the DRB. Furthermore, some factsheets present potential measures that are not yet applied in the DRB. However, the collected examples clearly indicate that measures are in place, with efforts to improve the sediment regime. As can be seen from this survey, already several actions are taken at the Danube River itself, at many tributaries and in the catchment. The received feedback highlights, that especially in the catchment of the Upper Danube River, already various measures were implemented, which – although it might not always have been the main aim of the measure – improve the sediment regime. These measures were summarized in the "Catalogue of measures" prepared in the frame of the DanubeSediment project.

In the catchment, the implemented measures are mostly in connection with agriculture and aim to reduce the input of fertile soil into the river system. The taken actions consider technical measures that reduce soil erosion such as afforestation or retain the sediment like riparian puffer stripes and runoff retention basins. Non-technical measures in form of organisational and administrative support such as the provision of water consultants (for farmers and land-users) were also reported. Furthermore, sediment transfer is improved by retrofitting check-dams to self-flushing barriers.

The collected measures against erosion in the free-flowing sections of the Danube River consists of river restoration measures such as removal of bank protection (Figure 27), river widening and the reconnection or revitalisation of side-channels. The removal of levees for an earlier inundation of floodplains was also already implemented. Hydraulic structures such as groynes and guiding walls were optimized in some reaches to be only active at low water levels and to improve flow as well as habitat conditions (Figure 28). Gravel feeding and adding coarser material are applied or tested measures to increase the sediment supply and increase bed resistance. Intelligent dredging and feeding management (eventually in combination with a bedload trap)

Figure 27: Removal of bank protection at the Slovakian Danube (© WRI)

is applied to keep the sediments longer in the river system. Besides the before mentioned measures which were also applied at the Danube River, additional measures as to increase the length of the river and consequently decrease the river slope and transport capacity were implemented at tributaries. Open revetment and the modification from weir to ramp are applied.

The measures against sedimentation are mainly focused on the remobilisation of deposited sediments in impoundments. For coarser sediments, this is done by dredging. These coarser sediments are mainly kept in the river system and used to build structures, which also improve habitat diversity. Another possibility is feeding sediments back downstream of the dam to compensate the effects of the barrier. An applied measure to remobilise fine material is flushing also in combination with flood events. Additional constructive measures (e.g. groynes) were implemented in impoundments at tributaries to optimize flushing management. Furthermore, adaptations at the existing weirs such as reducing the fixed weir height, reducing the width of the HPP or the installation of innovative hydropower plants (e.g. movable hydropower plant) aim to improve sediment continuity. Non-technical measures include for example the optimisation of operating rules to improve sluicing and flushing.

Acting players for these sediment management measures were water management authorities, hydropower companies and governmental agencies. Many of the compiled measures do not only address one discipline but were realized in cooperation with many stakeholders and serve more than one discipline. However, feedback on measures considering cross-border issues and cross-border cooperation was rather scarce.

Figure 28: Hydraulic structures before (left) and after (right) optimisation (© viadonau)

Part C Good practice examples and potential measures for sediment management

Based on the project results, the DanubeSediment consortium concluded that sediments are a Significant Water Management Issue (SWMI). According to the resolution of the ICPDR Heads of Delegations, the sediment balance alteration has been identified as a new sub-item under the existing Significant Water Management Issue "Hydromorphological alterations" in the 3rd Danube River Basin Management Plan (for details see the DanubeSediment publication "Danube Sediment Management Guidance"). In order to mitigate the impacts of an altered sediment balance, the project consortium provided a collection of good practice examples of sediment measures. In order to allow a straight forward and beneficiary oriented use the following chapter structures these measures according to key stakeholder groups, aiming to provide them with information on the benefits and impacts of measures to improve the sediment balance and continuity in their area of work.

Selection of suitable measures

Water and sediment are the fundamental elements of a fluvial system and therefore need to be managed together. Neglecting sediments in the planning process can result in undesired outcomes of the planned "solution". Therefore, in an integrated planning process, the sediment regime and related problems must be considered. Those problems can either be ones that are already existing or potential ones that can arise when ignoring sediments.

Before selecting any measure, it is important to understand the river system. This means, the historical development, surveys of the present situation, including monitoring of the sediment transport and the morphology, should be taken into account. Only then can a deficit analyses be performed and the need for action be assessed.

If the need for an action is defined, the source of the problem must be identified. Wherever possible, the source of the problem, rather than the symptoms, should be treated. In some cases, even measures implemented in the catchment scale might be the right choice. Only then should an integrated planning process be started. Essential features for an integrated planning are (ICPDR, 2010b):

- Identify integrated project objectives
- Integrate relevant stakeholders from the initial phase of a project
- Carry out an integrated planning process
- Conduct comprehensive environmental monitoring

Since most measures can be applied in different ways, there is no 'one size fits all' solution. Each measure must be adapted to the site-specific conditions but has to regard upstream and downstream effects as well as the river basin boundary conditions. Therefore, the process of choosing a suitable measure should follow a set of criteria. After thorough discussions with stakeholders, the DanubeSediment project recommends the following points: The early involvement of all relevant stakeholders can improve the decision-making process, since they have a broad knowledge and expertise regarding the feasibility and limitation of measures in practice. An informed and open cross-sectoral dialogue will also improve acceptance of the chosen measure. This provides the chance to integrate all relevant perspectives of river management and to raise synergies and avoid conflicts between different aims. Such a process should also take future challenges e.g. climate change, into account. When appropriate, consider transboundary aspects and the whole Danube basin perspective.

To find measures that fit the particular situation, one needs to consider that different temporal and spatial scales are involved in terms of sediment-related processes and indicators. Keeping this in mind also helps to set the scale of the measures in proportion to the problem. Further, the effects of the measure need to be assessed, e.g. how does a measure impact the hydrodynamics, water level, sediment-dynamics, morphodynamics and ecology. Also, consider the impact of a measure on different stakeholders needs.

Measures that relate to several stakeholder groups, e.g. hydropower, flood risk and navigation, should consider sediment transport in a harmonized and integrated way. For example, in order to increase the water depth for navigation, the river width can be decreased, thus enhancing riverbed erosion, which in turn affects the ecosystem and flood risk. The same is true for flood risk measures that lead to a disconnection between river and floodplain or when dykes are built close to the river,

leading to an increase in erosional tendencies during higher discharges. Hydropower schemes that disrupt the sediment continuity can lead to sedimentation upstream and erosion downstream, thus affecting navigation, flood risk and ecology. River restoration can in turn have consequences for navigational infrastructure or on flood risk if too much sedimentation or lateral erosion occurs. These examples show why an inter-sectoral planning process is needed to take advantages of synergies and avoid potential conflicts between the stakeholders.

Once the adequate measure is chosen, the feasibility should be analysed in cooperation with the relevant stakeholders. This could be done in the frame of a feasibility study and pilot measures that could include the following:

- Legal issues, e.g. regulations that require a constant water level; landownership
- Technical issues, e.g. need for research/modelling or has it been tested?
- Economic issues, e.g. competing interests such as navigation or flood protection?
- Ecological issues, e.g. effects of the measures on the ecosystem?
- Financial/Funding issues, which can be analysed through a cost-benefit analysis
- Public acceptance

Adequate monitoring before, during and after construction works are carried out to document and evaluate the success of the measure, to eventually adapt the measure and to learn from the implementation for future measures.

Types of measures

In order to support sediment management stakeholders in selecting suitable measures, we have categorised the measures according to several factors: the location and the spatial scale. The location describes the relationship of a measure on sediment, either reducing erosion in the free-flowing section or reducing sedimentation in the impounded section. The spatial scale relates to the area where the measure is implemented, being "catchment", "reach/sectional" or "point/local" scale.

The scheme in Figure 29 shows measures against erosion in free-flowing sections. These can act by changing the sediment regime, increasing bed resistance, reducing energy slope or by minimizing bed shear stress. The equation in Figure 29 shows the excess shear stress (η) available for sediment transport in relation to the parameters that are adjustable through river engineering, like the grain size (d), the hydraulic radius (R_h) respectively the water depth (h), the energy slope (S) and the bed shear stress (θ) (Habersack et al., 2013). Increasing a parameter in the numerator increases the sediment transport capacity, while increasing a

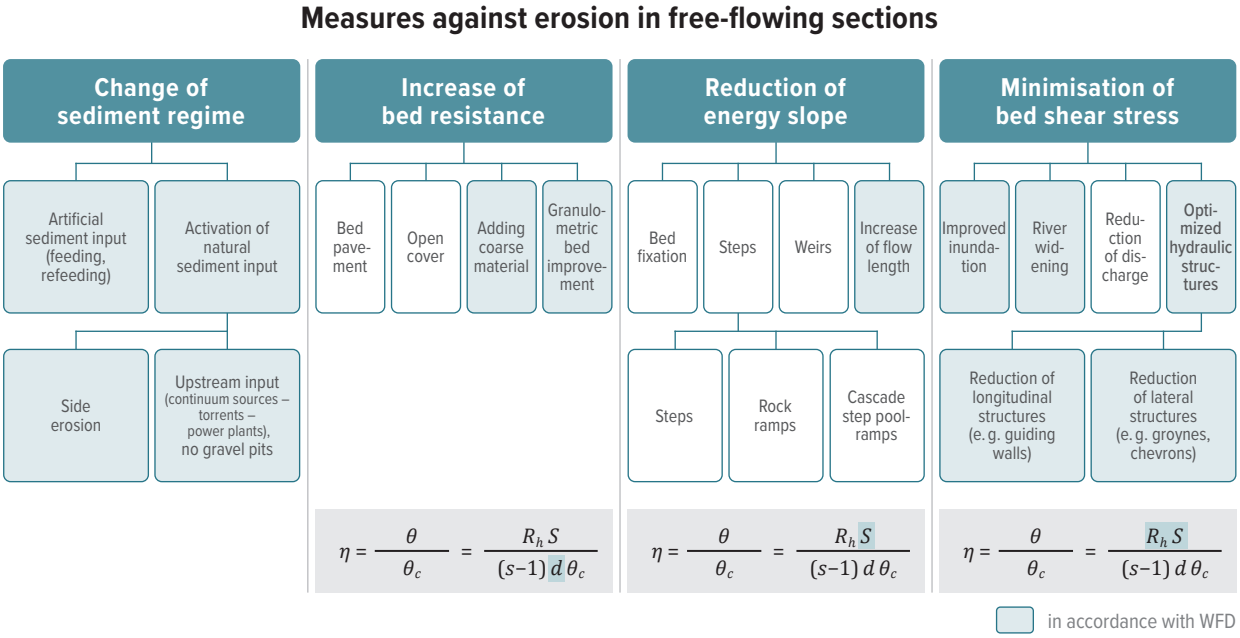


Figure 29: Sediment management measures to stop bed erosion (modified after Habersack et al., 2013); measures in accordance with the WFD are highlighted with a thick line. θ (Shields parameter), θ_c (critical Shields parameter), R_h (hydraulic radius), S (energy slope), s–1 (dimensionless submerged specific gravity of sediment), d (grain diameter).

parameter in the denominator decreases the same. Based on these parameters, it is possible to distinguish four different groups of measures with the sediment regime acting as an overall influencing factor. The sediment input can be changed by artificially increasing the sediment input, which can be done by augmenting (feeding sediment) directly downstream of a dam or by feeding the sediment at several locations in a river reach. Dumping (re-feeding) of dredged sediments from e.g. fairway maintenance is also part of this type of measure. Natural sediment input can be increased by enabling side erosion and by increasing the input from upstream; meaning the continuity from sources, torrents to hydropower plants is improved. To increase bed resistance the grain diameter of the bed material has to be increased. Here, measures that are in accordance with the WFD are the adding of coarser material or the granulometric bed improvement. Sediment transport can also be decreased by reducing the energy slope, which can e.g. be done by increasing the flow length of a river. To minimize the bed shear stress several options are available. Here, improved inundation, riverbed widening and optimisation of hydraulic structures (longitudinal and lateral structures) can be mentioned. Which measure obtains the best results depends on the site and the underlying problem and has to be selected for each site separately. Also, the application of a combination of measures should be considered.

Measures against sedimentation in impoundments and reservoirs can act by changing the sediment regime, routing sediments, increasing the energy slope or increasing the bed shear stress (Figure 30). The sedit ment regime can be changed by sediment extraction or relocation by mechanical excavation and hydraulic scour. Furthermore, the natural sediment input to the impoundments and reservoirs can be controlled by reducing the production of sediment. Another option is to route sediments either by bypassing the barrier that causes the impoundment or reservoir, e.g. the weir or dam, or by routing them through the barrier. The former can be realised with sediment bypass tunnels or off-stream reservoirs, whereas examples for the latter are turbidity currents, sediment turbines or the modification of operating rules. The energy slope can be increased by changing the water surface or bed slope. This can be done by a drawdown of the water surface (flushing), a reduction of the fixed weir height or by removing the dam or weir. The increase of the bed shear stress can be achieved by increasing the discharge, optimizing the geometry of the impoundment or reservoir or by optimizing hydraulic structures.

Whether the measure addresses sedimentation or erosion, the best results are obtained when considering the site and the underlying sediment-related problem, which needs to be selected individually for each site.

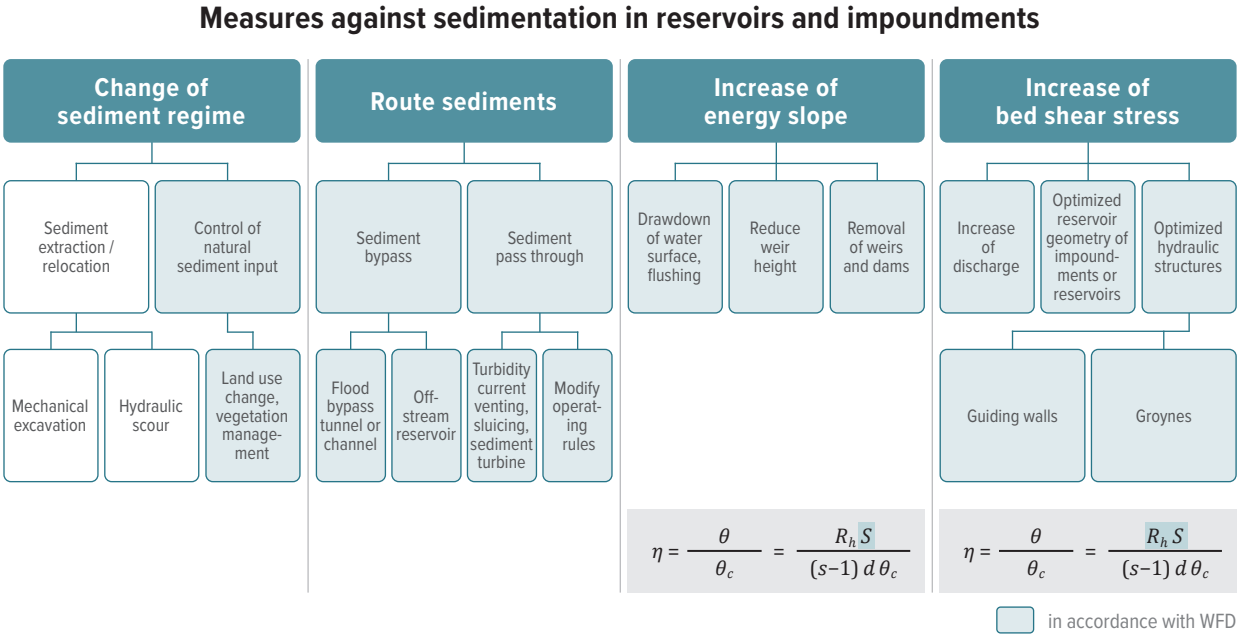


Figure 30: Sediment management measures addressing sedimentation; measures in accordance with the WFD are highlighted with a thick line. θ (Shields parameter), θ_c (critical Shields parameter), R_h (hydraulic radius), S (energy slope), s-1 (dimensionless submerged specific gravity of sediment), d (grain diameter).

Also the application of a combination of measures could be considered. Besides considering the erosion or sedimentation tendencies, also the bed material (sand or gravel) and the location where the measure can be implemented, e.g. free-flowing section or impoundment, main channel or riverbank, has to be respected and limits the available options. In general, the boundary conditions and the connectivity in a catchment that influences the sediment regime should be considered when managing sediments and implementing measures.

Figure 31 depicts an overview of sediment management measures divided according to spatial scales. These measures are shortly summarized and described for key stakeholders, i.e. hydropower, navigation, flood risk management, river basin management including land use and ecology. Some of the measures are presented in a harmonized way as factsheets in Part D.

Measures at catchment scale
Measures in the catchment are of great importance, since they permit addressing the problems at the source, i.e. where the sediment production takes place. The catchment is where the input of water and sediments into the fluvial systems begins. The various measures aim at both reducing excessive fine sediment inputs, e.g. from agricultural areas, and improving the sediment continuity especially for coarser sediments, which supply downstream river reaches with bedload. In addition, legal and administrative measures as well as sediment management concepts are related to the catchment, respectively the basin scale, since they have a larger scope and deal with a variety of ecosystems and aspects, e.g. forestry, agriculture, land use, land use planning and regulation, rivers, flood protection, floodplains, lakes, waterways and navigation, energy production.

Measures at reach/sectional scale
Measures at the reach scale, respectively in impoundments and reservoirs, typically have a strong impact on the spatial and temporal scales that are important for river and sediment managers. Awareness of the greater context of the river basin scale is nevertheless important, as it influences the management and the measures implemented at the reach scale.

The measures at the reach scale are divided into measures in the reservoirs and measures in free-flowing sections. Measures in the impoundments and reservoirs mainly deal with the issue preventing sedimentation, routing/removing/remobilizing sediments and considering adaptive strategies. The measures in the free-flowing sections in turn mainly deal with increasing the sediment supply and reducing erosional tendencies in the main channel.

Measures at point/local scale
For weirs and dams, these measures are ones that are implemented directly or in the vicinity (up- or downstream) of the structure. In terms of free-flowing sections, the extent of the measure is local in the sense that they are implemented on a small spatial scale (up to a few river widths), with dimensions that differ depending on the size of the river. Both sets of measures nonetheless can have much larger spatial dimensions and a cumulative effect can occur, when several local measures are implemented in parallel.

Measures at the dam mainly deal with the topic of how to pass sediments. In other words, they consider installations that are useful to increase the efficiency of sediment management measures. Also, they include innovative types of hydropower plants that try to incorporate sediment transfer already into the design. In the free-flowing section, the measures aim at increasing supply by feeding, reducing erosion, respectively sedimentation, controlling the location of sediment deposition, or in protecting the river against erosion at the local scale.

Catchment scale

Measures in the catchment

- Sediment management concept
- Raise awareness and capacity building
- Minimize urbanisation and construction of buildings on sloped terrain (RBM1)
- Minimize anthropogenically caused excessive debris flow, mass movements and landslides (RBM2/F1)
- Improve or adjust land use and management (RBM3)
- Reduce surface runoff through infiltration and retention (RBM4/F2)
- Reduce undesired (fine) sediment input (RBM5)
- Controlled sediment transfer at barriers (improve sediment continuity) (F3/H1)
- Adapt to impacts of climate change

Reach / sectional scale

Measures in reservoirs or impoundments

- Minimize width (by hydraulic structures) (H2)
- Sediment bypass (tunnel, channel) (H3)
- Off-stream reservoirs (H4)
- Sluicing (H5)
- Venting of turbid density currents (H6)
- Environmentally-friendly flushing (H7)
- Flood-conditioned flushing (H8)
- Optimize flushing or sluicing strategies for dams in series (H9)
- Prevent sedimentation by artificial turbulence (jet screens)
- Wet or dry dredging and reinsertion (H10)
- Bedload drift (H11)

Measures in free-flowing sections

- Enlarge morphological space of rivers (RBM6/F4)
- River widening (artificial or self-forming) (RBM7/F5)
- Riverbank restoration (RBM8)
- Increase river length to reduce the slope (RBM9/N1)
- Reconnection of side-channels or enhance floodplain erosion (RBM10/F6)
- Opening or removal of flood dykes (RBM11/F7)
- Relocation or set-back of flood dykes (RBM12/F8)
- Removal of natural near-river levees (bank erosion or mechanical) (RBM13/F9)
- Restore wetlands (RBM14/F10)
- Coarse particle feeding (granulometric bed improvement) (RBM15/N2)
- Break-up of bed armouring (artificial flood or mechanical) (RBM16)
- Intelligent dredging and feeding management (N3)
- Fairway shifting or narrowing (N4)

Bathymetric survey
Minimize or stop commercial dredging

Local / point scale

Measures at the dam

- Minimize dam width (H12)
- Minimize fixed weir sill height (H13)
- Construct local sediment bypass (H14)
- Modify weir fields to increase sediment continuity
- Install large bottom outlets or gates for venting, sluicing or flushing (H15)
- Route sediments through turbines (H16)
- Pressure scouring
- Open ship locks for local remobilisation
- Apply local artificial turbulence
- Local dredging at intake structures
- Optimize operating rules
- Innovative hydropower plants
- Remove dam or weir

Measures in free-flowing sections

- Sediment feeding (RBM17/N5)
- Optimisation of river engineering structures to reduce sedimentation (N6)
- Optimisation of river engineering structures to reduce erosion (N7)
- Install bedload traps (as part of intelligent dredging and feeding management) (N8)
- Remobilisation of consolidated gravel bars (RBM18/N9)
- Local bank protection (F11)
- Modify or remove barriers (weirs or ramps) (RBM19/F12)

Figure 31: Overview of sediment management measures

C.1 HYDROPOWER

C.1.1 Description of Measures

Figure 32 depicts sediment management measures related to hydropower, divided according to different spatial scales and highlighted in bold. All measures in the following chapters that are described by a factsheet (see Part D Factsheets) have been marked with an alphanumeric identifier in the title of the measure.

C.1.1.1 Catchment scale

Controlled sediment transfer at barriers (improve sediment continuity) (H 1)
Sediment management strategies and implemented measures should be coordinated among the different dam operators in order to harmonize and improve the effect of sediment-related measures throughout a catchment. In addition, catchment-related measures like the reduction of sediment production by adjusting land use practices, e.g. in forestry and agriculture, to reduce the input of undesired fine sediment into rivers, should be coordinated with the relevant stakeholders from forestry, agriculture, spatial planning etc. to improve the sediment management in impoundments and reservoirs.

Low dams or check dams located e.g. just upstream of reservoirs can function as traps for (mostly coarse) sediment and large woody debris. Despite the extent of and large investment in (check) dams, the experiences reported in the literature illustrate that the benefits from (check) dam storage are temporary at best, and the sediment-filled (check) dams can become potentially unstable and costly to maintain (Kondolf et al., 2014). These should therefore be designed for easy access by heavy equipment, in order to easily excavate the trapped material and transport it downstream to increase the amount of sediment entering the river channel. A better option that helps to improve sediment continuity in head waters, respectively the upstream area of a catchment, is the retrofitting or construction of barriers in such a way that bedload material can pass the barrier while boulders and large woody debris is retained. These self-flushing barriers or open check dams can also reduce the need for periodic dredging works.

Additional measures
Further measures, which predominantly affect the stakeholder group river basin management, land use and ecology might additionally have an effect on hydropower-related activities to a certain degree. These measures deal with activities in connection with land use and agriculture. Examples are “Improve/adjust land use management (RBM3)”, “Reduce surface runoff by infiltration and retention (RBM 4)” or “Reduce undesired (fine) sediment input (RBM 5)” and are described in Chapter C.4.1.1 in detail.

C.1.1.2 Regional Scale – in reservoirs/ impoundments

Minimize width (by hydraulic structures) (H 2)
This measure aims at increasing flow velocity and shear stress by implementing hydraulic structures such as groynes or guiding walls in impoundments or reservoirs. Ideally, those structures are not made of rip-rap stones but are built of coarse gravel, if gravel structures are able to withstand also flood discharges. The resulting river-narrowing effects aim to channelize the water flow and increase the sediment transport capacity during sluicing and flushing. In this case, the original width of the river serves as a baseline for the narrowing effect that should be achieved. These current-controlling structures help to sustain the movement of the sediments towards the dam, which should lead to an optimized flushing or sluicing efficiency. They enhance the sediment transport through the impoundment/ reservoir and reduce the sediment deposition. The effects on the aquatic environment in the downstream reach need to be considered due to potentially excessive concentrations and durations of suspended sediments, if the flushing is not performed during higher discharges with

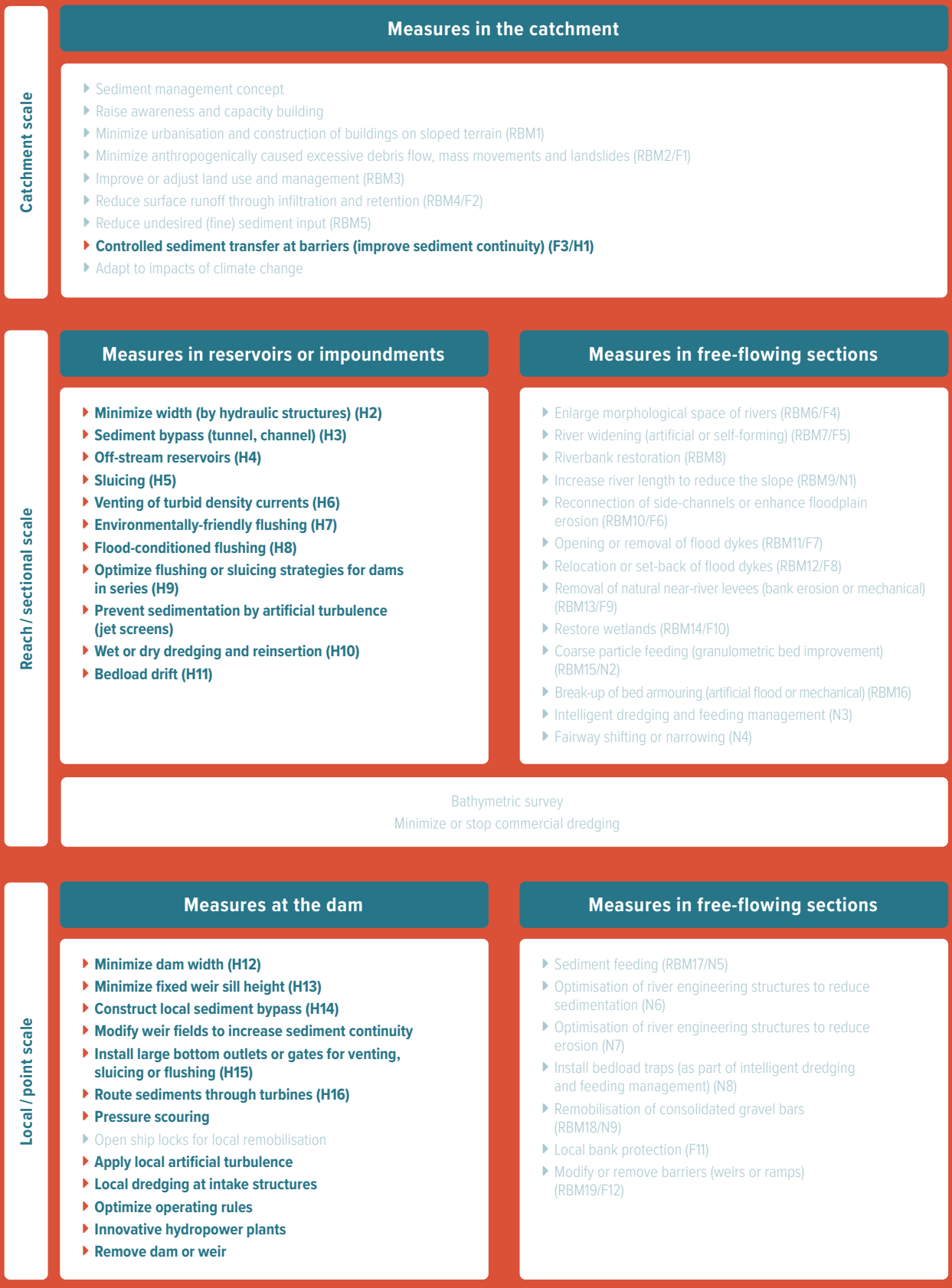


Figure 32: Overview of sediment management measures; measures related to hydropower are highlighted

high sediment loads. Installing guiding walls in impoundments or reservoirs already affected by sedimentation is usually more difficult and expensive (Bechteler, 2006). Depending on how those structures are designed, they can further provide shelter for aquatic life, since they separate shallow zones from the areas of maximum velocity during floods. Those structures can also be applied in the head of the impoundment/reservoir where coarse sediments are deposited, to enhance their remobilisation and to reduce the flood risk. In this case, the potential risk of increased riverbed erosion at the head of the impoundment or reservoir due to the narrowing, in combination with a lack of upstream bedload supply, needs to be considered. The risk of (further) degradation of those parts of an impoundment should be reduced. The reason is that in some impoundments this part already resembles a free-flowing section during higher discharges, which leads to local erosion and thus negatively affects the sediment balance.

Sediment bypass (tunnel, channel) (H 3)
A sediment bypass routes high sediment loads, mostly resulting from floods, around a reservoir so that they never enter the reservoir (Morris and Fan, 1998). Usually, the high sediment loads are diverted at a weir or guiding wall and are then discharged back to the river downstream of the dam. Large boulders and woody debris should be trapped upstream, ideally already at the diversion weir to prevent them from entering the tunnel (Sumi, 2015). This measure can significantly reduce sedimentation and furthermore, damages at the dam and/or hydropower plant are prevented. A bypass is either built as a tunnel, a canal or a pressurized pipeline, with tunnels being the most common form. In contrast to sediment routing through the reservoir or impoundment, where mainly fine sediments are passed through the barrier or dam, bypass tunnels are very effective regarding both bedload and suspended sediments (Kantoush et al. 2011, Auel et al., 2011).

The intake is either located upstream of the reservoir (high-level bypass) or in longer reservoirs, the intake is closer to the dam (low-level bypass). In the latter case, a drawdown is necessary to bypass bed material (Annandale et al., 2016). Depending on the location of the intake structure, the inflow takes place either under free surface conditions (intake at the reservoir head) or under pressurized conditions (intake downstream of the reservoir head) (Auel and Boes, 2012). Using a high-level outlet, no drawdown of the reservoir is required and bypassing sediments does not interfere with the regular reservoir operations. The intake structure is equipped with a gate that is opened during higher discharge events when transfer of coarse material is ensured. The ideal site for a bypass is the point, where the river makes a sharp turn to minimize the length of the bypass. This takes advantage of the higher gradient (Annandale, 1987). If this unique site characteristic does not exist, the measure is most practical for relatively short reservoirs.

Bypass tunnels come with a high price for both construction and maintenance due to potential damages because of abrasion effects due to bedload. This might be one of the reasons why the amount of operated tunnels is still limited. The majority is located in Japan and Switzerland. However, interest in the technology is increasing and it can also be useful to retrofit existing dams that were not constructed with outlets for sediment management (Sumi et al, 2004). Despite the cost, bypasses have many advantages, since the sediments do not enter the reservoirs but are routed around it (Kondolf et al., 2014). Bypassing sediments has a lesser downstream impact on the environment compared to other management strategies. Usually, the bypass operates multiple times a year, transporting lower amounts of sediments downstream compared to emptying and flushing a reservoir (Annandale et al., 2016). Therefore, sediment concentration downstream of the dam is not significantly higher than the inflow into the reservoir, which benefits the ecology and the environment. Furthermore, during flood events, the sediment load discharged downstream is approximately the same as the one from the upstream reaches of the river (Auel and Boes, 2011).

Off-stream reservoirs (H 4)
The construction of an off-stream reservoir outside of the natural river channel dramatically reduces sedimentation. An intake structure only

diverts clear water into the reservoir, while the sediment-laden runoff is bypassed during the flooding event. This also means that it can be possible to maintain sediment and flood dynamics, which benefits the hydromorphology in the downstream reach. Off-channel storage could be more widely used than is the case, as experiences show that the entire bedload transport can be passed beyond the intake (Kondolf et al., 2014). Only a small amount of suspended sediments is captured by the water diversion into the off-stream reservoir, significantly prolonging the storage capacity. However, fine solids emerging from erosion activities in the watershed tributary and its catchment will be completely trapped in the reservoir. Therefore, a minimized catchment, together with optimized land use practices reducing erosion processes, will benefit a long-term hydropower operation (Annandale et al., 2016) and the sediment regime of the river. Ecological impacts that can occur due to this measure, such as the alteration of the composition and the abundance of aquatic plant and animal species, or the risk of stranding and wash-out (drift) of aquatic animals due to hydropeaking, need to be considered and mitigated. One important point is the amount of water abstraction, especially during low flow periods, and the impacts on the residual flow reach downstream. This means that the necessary environmental flow needs to be assessed and set to the respective discharge. Furthermore, hydropeaking should be addressed when applying this measure to mitigate impacts from rapidly changing water levels. This can be done for example by modifying the hydropower plant operation by reducing the rate at which the water level increases and decreases, or by installing a retention basin to attenuate hydropeaking. Also, morphological mitigation on the local scale by self-formed near-natural morphology that provides sheltering habitats can help to mitigate the impacts of hydropeaking (Hauer et al., 2017).

Sluicing (H 5)

Sluicing is a sediment routing strategy with the main objective to pass sediment through the impoundment or reservoir and to minimize sedimentation. It should not be confused with flushing, which remobilises sediments that are already deposited. For sluicing to be successful, the availability of excess water and relatively large bottom outlets or gates are necessary, with a rather small reservoir capacity-mean annual runoff ratio of less than 0.2 year and < 0.03 year in semi-arid regions (ICOLD, 2009). The operational procedure involves a partial or full water level drawdown during periods of high discharge and sediment load. This drawdown increases flow velocity (Annandale et al., 2016), enabling the sediment-laden water to pass through the impoundment or reservoir. Free outflow conditions are preferable, but as long as the sediment transport capacity through the impoundment or reservoir is large enough during flood stage, only a partial drawdown is necessary (ICOLD, 2009).

However, the lowering of water levels must be coordinated with the approaching flood and with potential downstream impoundments/reservoirs, in order to prevent depositions in the tailwater. Finer sediments are transported more effectively through the impoundment or reservoir than coarser ones. An advantage is that sediments are transported downstream during floods when the sediment load is naturally already high (Kondolf et al., 2014). The measure works on all sizes of impoundments or reservoirs, but efficiency varies depending on the configuration of the impoundment or reservoir, i. e. that long and narrow ones are more efficient, and the hydrology. Furthermore, relatively large capacity outlets or gates are required to discharge large flows and effectively sluice sediments. When routing through bottom outlets, which are operated under pressure conditions, the flow velocities are very high and this means the outlets need to be reinforced as not to risk damage due to abrasion or blockage (Auel and Boes, 2011).

Another option is to route sediment-laden water through the turbines. However, the fine sediment concentration must not exceed defined limit values, in order to prevent abrasion effects and adverse effects on ecology in the downstream reach. In addition, the size of the sediments and the petrography of the catchment might enhance abrasion effects and limit the applicability (Morris and Fan, 1998). Fine solids must remain suspended in order to reach the intake, which might be achieved by applying local artificial turbulence (Jenzer-Althaus et al.,

2015). For example, local artificial turbulence can be applied by jet screens. These installations prevent finer solids from depositing and thus, enhance sluicing efficiency.

Venting of turbid density currents (H 6)

This measure is part of the sediment routing strategies, which involves fine sediment transfer through the reservoir and a low-level outlet at the dam. This hinders the incoming turbidity current from settling in the reservoir. Turbid density currents are part of the much wider category of density currents, and they are mainly caused by the presence of suspended sediments (turbidity) or they occur when sediment-laden water enters a reservoir and plunges beneath the clear water (Morris and Fan, 1998). Temperature differences between the inflowing water and the water in the reservoir influence the plunge point of the currents (Chamoun et al., 2016) and therefore control the development of the current, meaning whether it can pass the reservoir and reach the dam. Among sediment management methods in reservoirs, this method can be very efficient and economical. It also helps to preserve a certain sediment continuity in rivers obstructed by dams (Chamoun et al., 2016). One of the biggest advantages of venting turbid density currents is that sedimentation is reduced without drawing down the reservoir level (Sahnaz and Aras, 2012). The low-level outlets are opened as soon as the current reaches the dam, which means an adequate and in-time outlet operation is necessary (Wan et al., 2012). Furthermore, the outlet discharge and the height of the outlet are crucial parameters, besides the timing (Morris and Fan, 1998). The important prerequisites are that turbid density currents must already exist, that a substantial amount is transported to the dam and that a bottom or low-level outlet with a certain capacity is present (Chamoun et al., 2016). This means that obstacles, respectively roughness elements, which can disturb the approaching turbid density current near the reservoir thalweg, need to be removed. Turbid density currents may also be used to pass fine sediments, but not coarse ones, through turbines (Morris and Fan, 1998). With the installation of a turbidity siphons, e. g. selective withdrawal intake or over the spillway using a curtain, it might be possible to avoid problems of clogging low-level outlets, respectively release currents in deep reservoirs, by venting them through higher outlets or over the spillway (Annandale et al., 2016). The efficiency of turbid density current venting will decrease when the reservoir fills with sediments and it varies depending on the reservoir configuration. This also means the measure is one of the first applied during the lifetime of a reservoir (Annandale et al., 2016). According to Kondolf et al. (2014) this sediment management measure can be used even at large reservoirs where other techniques are not feasible. Another advantage is that suspended sediments are routed downstream during floods when the sediment load is naturally high.

Environmentally-friendly flushing (H 7)

Environmentally-friendly flushing means to discharge only solid concentrations that the environment can endure (Fruchard and Camenen, 2012), compared to the more traditional flushing, which has the aim to discharge as much sediments as possible and does not consider ecological impacts. In comparison to sluicing, flushing is a removal strategy for sediments that have already been deposited. These are remobilized and discharged downstream of the dam. Environmentally-friendly flushing is defined as the opening of weir gates even at relatively low flood discharges, in order to more frequently create lower suspended sediment concentrations rather than rarely creating very high concentrations. This should limit the potential impacts of flushing on downstream aquatic life. This type of flushing is performed under restrictions concerning duration and concentration of suspended sediment concentrations that are not allowed to exceed a certain level. This means a real time monitoring has to be implemented to control the concentration thresholds. In addition, seasonal restrictions such as spawning times, can limit the period where flushing is possible. The low-level gates need to be large enough to pass the necessary flushing discharge. If a dam is equipped with outlets at several levels or a dilution supply tunnel for clear water, concentrations can be controlled to a certain degree. For example, water with high sediment concentrations and cleaner water from higher in the water column can be mixed during drawdown flushing to stay within the required concentrations

(Peteuil et al., 2013; Meile et al., 2014). Post-flushing with clear water can additionally mitigate the impacts of this sediment management measure on ecology (Reckendorfer et al., 2019). This measure further aims to approach the natural suspended sediment regime (frequency) and to reduce depositions in the impoundment or reservoir. This flushing strategy benefits sediment continuity and additionally has lower impacts on ecology in the downstream reaches. When inland navigation is present, the flushing needs to be coordinated with navigation authorities as not to affect ship traffic.

Flood-conditioned flushing (H 8)
This measure involves water level drawdown when a flood is approaching with the aim of remobilizing the deposited sediments. The success of the measure mainly depends on the geometry of the impoundment or reservoir, the magnitude of siltation and the degree of the water level drawdown. Also, the degree of consolidation of cohesive sediments or increased sediment erosion thresholds due to biofilm growth can have an impact (Fang et al., 2017, Hauer et al., 2018). During flood conditioned flushing, it is not possible to control the suspended sediment concentrations, but they are naturally high due to the flood stage. Due to the remobilisation of the sediments from the impoundments or reservoirs, higher sedimentation rates in the downstream floodplains can occur.

Optimized flushing or sluicing strategies for dams in series (H 9)
This measure involves the coordinated water level drawdown between two or more hydropower plants, in order to improve sediment continuity in the best possible way and to prevent depositions in the downstream impoundments or reservoirs. Flushing strongly affects ecological conditions and therefore suspended sediment concentrations must be restricted. This means a real time monitoring has to be implemented to control the concentration thresholds.

Prevent sedimentation by artificial turbulence
Sedimentation may be controlled by applying artificial turbulence. In order to keep fine sediments suspended and to pass them through the outlets or intakes, jet screens can be a suitable option (Schleiss et al., 2016). By preventing finer solids from depositing, the efficiency of measures such as "routing through turbines" can be increased. This enhances the sediment transfer and the reservoir capacity is maintained, leading to a prolonged lifetime. One must take note that the efficiency and applicability of this measure is still in the state-of-research.

Wet or dry dredging and reinsertion (H 10)
This measure involves wet dredging in the reservoir mainly to sustain the capacity and operability of a hydropower plant, but also for reasons of flood protection and to ensure necessary fairway conditions such as fairway depth and width and free clearance height at bridges. In order to improve the sediment continuity and to be really sustainable, e.g. that sediment disposal is excluded, the excavated material should be resupplied to the river. The measure itself does not require changing reservoir operations and uses a relatively small amount of water. Nevertheless, dredging and reinsertion is a relatively cost and energy intensive activity that comes with a high maintenance effort. Also, environmental impacts need to be considered during dredging and when the sediments are refed. Especially in reservoirs, the continuous release of dredged sediments does not coincidence with natural discharge events. This needs to be taken into account in terms of potential environmental impacts. The feasibility will depend on how effectively this issue can be addressed. Furthermore, when only dredging fine sediments close to the dam, coarse delta deposits that are needed to restore downstream river reaches will not be transferred. Especially in smaller dams in mountainous areas, frequent downstream release of coarser dredged sediments can be a good alternative, if the sediments can be temporarily stored in-channel and are then mobilized by natural or artificial floods (Annandale et al., 2016).

One option is wet dredging, where the sediments are transported via hydrosuction systems, which are installed on a floating platform. They suck water and fine sediments through a tube and then transport them to the dam or directly transfer the material into the tailwater. This measure benefits sediment continuity, since fine solids are automatically and continuously

transferred downstream, requiring no adaption of the dam and having no effect on the hydropower plant operation. On the other hand, the suction dredger has to run permanently and is limited to specific grain sizes depending on the dredging equipment (i.e. the maximum grain size fraction that can be transferred with state-of-the-art equipment is sand/fine gravel). However, continuously dredging and releasing sediment does not coincide with natural discharges. This can have negative impacts on downstream river reaches. The impact can however be mitigated, for instance by settling basins, where remobilisation takes place at higher discharges.

Dry dredging requires that the reservoir level is lowered or that the reservoir is emptied. Basically, it is more easy to remove coarse deposits than poorly consolidated fine sediments. However, on a larger scale, dry dredging is usually more expensive (Annandale et al., 2016).

Bedload drift (H 11)
Bedload drift is an innovative management technique with the goal of improving bedload continuity, flood protection and habitat diversity. If excessive fine sediment concentrations in the initial stage of the drawdown and downstream siltation of the riverbed are a concern, the water level in the impoundment or reservoir should be lowered slowly over a longer period of time, for example during floods. This activates mainly the movement of bedload throughout the impoundment or reservoir. The slow drawdown operation aims to remobilise mainly coarse sediments, while fine solids remain settled. Bedload material that is not transferred through the entire impoundment or reservoir to the downstream reach must be mechanically dredged and reinserted in the tailwater (i.e. downstream of the dam). The effect of the measure can further be increased by additional hydraulic structures in the impoundment or reservoir to increase the sediment transport capacity. Depending on the width of the river directly downstream, it might be necessary to build additional hydraulic structures to prevent sedimentation directly downstream of the weir, respectively the hydropower plant. The positive effect of this measure is further enhanced when the downstream river reach is already in a good morphological condition, with for instance higher widths to support the development of morphological features like bars and islands and to promote instream sediment storage. This means that the supplied sediments are not only transferred through the downstream river reach but have a higher residence time compared to a regulated river, thus benefitting the ecosystem of the river section.

C.1.1.3 Local scale – at the dam

Minimize dam width (H 12)
Minimizing the dam width and the impoundment or reservoir widths is a constructive measure to enhance sediment transfer and remobilisation due to increased shear stresses (Sindelar et al., 2017). This measure primarily aims at preventing sedimentation or enhancing transfer as well as remobilisation in impoundments or reservoirs during sluicing or flushing and thus, improving sediment continuity. Moreover, the enhanced bedload transfer benefits flood protection, reduces maintenance and operational costs as well as aquatic habitats in the downstream stretch. Reducing the dam width at existing hydropower plants requires high implementation efforts, but this measure should be considered as an option at planned HPPs.

Minimize fixed weir sill height (H 13)
Larger fixed weir sill heights lead to larger sedimentation volumes in the impoundment or reservoir, reduce the efficiency of sluicing or flushing operations and a lack of sediments downstream (Sindelar et al., 2017). Lowering of the weir sill height in order to approach the natural slope, respectively a higher equilibrium slope in the impoundment or reservoir helps to improve the sediment continuity. At larger dams, an option can be to lower and/or merge the spillway gates to enlarge the capacity to conduct sluicing by partial drawdown during floods (Sumi et al., 2015). As in the previous measure, the primary goal is to prevent or reduce sedimentation in the impoundment or reservoir by enhancing transfer and remobilisation processes during sluicing or flushing operations. This further reduces maintenance and operational costs of the hydropower plant. Depending on the layout of the river directly downstream, it might

be necessary to build structural measures to prevent sedimentation directly downstream of the weir, respectively the hydropower plant. Flood protection and the aquatic environment benefit from this measure since deposition in the impoundment or reservoir are reduced, and gravel (e.g. needed for spawning habitats) is supplied in the downstream reach. It is beneficial to incorporate sediment management and such designs in the planning phase, since retrofitting weirs is more expensive or might not be feasible at all.

Construct local sediment bypass (H 14)

This measure and its effects are already described above ("Sediment bypass (tunnel, channel)") with the only difference of the spatial scaling (here: local scale). In this case, the bypass is located near the dam or weir, which means it is only effective if the bedload is transported to the entrance of the bypass. The vortex tube, for instance, is a system that transfers sediments from the headrace channel into the residual channel by applying a vortex stream. This technique provides continuous sediment transfer but requires a specific construction design. Two parallel channels are necessary, with the vortex tube located on the upper channel and the weir on the lower channel. The weir is positioned further upstream than the vortex tube so that the sediment transported into the lower channel ends up downstream of the weir. Another example is the slotted pipe sediment sluicer, which is a horizontal pipe with small openings. Sediments are sucked in through the slots and transferred downstream of the hydropower plant.

Modify weir fields to increase sediment continuity

The aim of this measure is to maximize the sediment transport capacity when the weir fields are opened during sluicing or flushing. Therefore, the number and dimensions of the weir fields in terms of width and fixed weir sill height, as well as the overall dam width and the cross-sectional width, should be optimized in terms of sediment throughput. Ideally, the powerhouse with the generators is positioned at the riverbank(s) to avoid unnecessary widening at the dam and to enhance the sediment transport capacity, especially in the close range to the hydropower plant. Potential intake losses that can occur due to the position of the powerhouse near the riverbank need to be addressed in the design phase. In general, this measure aims at an integrated design incorporating the aforementioned measures "Minimize dam width" and "Minimize fixed weir sill height". Also, an innovative design of hydropower plants can help in the implementation of this measure. It is very beneficial to incorporate sediment management and state-of-the-art designs into the planning phase, since retrofitting is more expensive or might not be feasible at all.

Install large bottom outlets or gates for venting, sluicing or flushing (H 15)

This measure helps to increase sediment continuity by preventing sediments from depositing in the impoundment or reservoir and by passing them through large low-level/bottom outlets or gates. Outlets or gates with a high discharge capacity are necessary to successfully route or remove sediments in impoundments or reservoirs. It is beneficial to incorporate sediment management and these types of installations into the planning phase, since retrofitting a dam with large outlets or gates is more expensive or might not be feasible at all.

Route sediments through turbines (H 16)

An option is to route the sediment-laden water directly through the turbines when sluicing, or venting turbid density currents. However, in order to prevent abrasion effects and adverse effects on ecology in the downstream reach, the fine sediment concentration must not exceed defined limit values. Furthermore, the size of the sediments and the petrography of the catchment might enhance abrasion effects and limit the applicability (Morris and Fan, 1998). Therefore, coarse delta sediments are not allowed to enter the turbines (Morris, 2015). To reduce the damage by abrasive processes the turbines need a hard coating. To provide a sound basis for decision-making in operation and maintenance, monitoring of concentrations and particle sizes is recommended (Felix, 2017). Overall, additional innovations are needed to develop turbines that are sediment-fit.

Pressure scouring
Pressure scouring is used to remove sediments in the close range directly upstream of a dam. This keeps intakes as well as bottom outlets free and operational. This measure does not require the reservoir levels to be lowered, but the outlets are opened and the scouring takes place under pressurized flow, with a scour cone forming in a very short time period and with only a relatively small amount of sediments being scoured (Lai and Shen, 1996). According to Lai and Shen (1996), this measure mainly serves to reduce sediment concentrations around the entrance of the intake and thus reduces abrasion of hydraulic structures by sediments. Pressure scouring is not an effective technique to maintain or restore reservoir capacity (Kondolf et al., 2014). It can lead to uncontrolled sediment concentrations downstream and therefore should only be applied when the sediment concentration is naturally high, i.e. during floods.

Apply local artificial turbulence
This measure aims at keeping sediments in suspension and avoids settling of sediments near the dam. This occurs by generating a local artificial flow field and the related turbulence (Jenzer-Althaus et al., 2015), for instance by routing the sediments through the power intake to the turbines. This rotational flow can be generated by mechanical mixing, water jet or air-bubbler systems.

Local dredging at intake structures
Dredging at intake structures is performed to remove sediments on the local scale and to keep intakes as well as bottom outlets free and operational. In contrast, this measure is not effective in maintaining or restoring the reservoir capacity. It can be seen as an accompanying measure to ensure that sluicing, venting or flushing of sediments is possible by keeping the outlets free from sediments.

Optimize operating rule
To achieve an effective sediment transport along a river system, dams should be managed together in order to avoid poor results and conflicts between upstream and downstream dams. This means, dam operators should pay attention to properly coordinate and share the relevant data with each other, with the goal of achieving a high efficiency in passing sediments through a series of impoundments or reservoirs (Kondolf et al., 2014). Another more formal step is to replace old operating rules with sediment-guided operation rules, which should be based on real-time hydrological and sediment data (Annadale et al., 2016). For example, by optimizing the magnitude and duration of the maximum available shear stress for sediment transport, sediments can be efficiently sluiced or flushed through the impoundment or reservoir.

Innovative hydropower plants
Innovative HPPs include a series of innovative techniques with the overall goal of improving continuity for both aquatic biota and sediments. One example is the movable hydropower plant, which constitutes a compact system that can be lifted, in order to pass bedload material and fish. Similar to a movable upper part of the weir, the level of the headwater is kept constant due to a surplus of water supply. At the same time counteracts sedimentation of the weir by enabling bedload transport downstream of the powerhouse. A second example is the shaft HPP, which can be installed at existing weirs. Depending on the installed turbine and the head difference, gravels of less than 20mm in diameter may be allowed to pass the turbine without damage or erosion of the blades. If this is not possible, a flushing channel for gravel can be built around the intake box. Additionally, trash rack cleaning must be provided in order to remove floating material from the trash rack. These techniques have in common, that (especially) bedload needs to be transported towards the close range of the hydropower plant for it to run effectively. This means that depending on the layout of the impoundment or reservoir and the weir height, additional measures might be necessary to achieve the desired effect of transferring bedload.

Remove dam or weir
Dam or weir removal can be an option if energy production no longer pays off, the maintenance effort for removing depositions in the reservoir becomes too inefficient, the structure has no beneficial use anymore, repairs are too costly or the structural elements are deteriorating.

Further reasons for removal can be that public safety is threatened due to a risk of flood events or that new environmental requirements may require the removal. The aim of this measure is to recover the continuity of water and sediment flows and to enable the organism connectivity in both directions. These are crucial steps to recover the principal attributes of naturally functioning rivers. As a result of this measure, the initial river-morphodynamics can be restored. Managing sediments deposited behind a dam is one of the bigger technical challenges of dam removal, and this challenge is greatest for large dams with large volumes of accumulated sediments (Kondolf et al., 2018). When removing a barrier, the types of impacts resulting from a large amount of sediments moving downstream in a short period of time need to be considered and the measure must be designed appropriately. Therefore, at an early stage in planning, the amount of sediment present, the type (i.e. fine vs. coarse) and the amount of sediment likely to be transported downstream must be determined. Also, the downstream impacts and benefits that could result from sediment release need to be assessed. Downstream aggradation of sediment can, for instance, increase the flood risk. This means that it may be necessary to manage the accumulated sediments in order to reduce the potential of flooding. Sediment that is highly contaminated can negatively affect human health and the ecosystem. Therefore, it may need to be removed and relocated to an approved off-site location. It is important to note that not all dams accumulate the same amount of sediment, not all sediment in the impoundment or reservoir will be transported by such a measure, and even then, not all the sediment will move at once. Some projects allow for a natural release of sediment that will gradually move downstream and will ultimately be replenished from upstream through restored river function after dam removal. Sediment, particularly sand and gravel, can be beneficial for rebuilding downstream gravel beds and creating habitat, as well as rebuilding estuary habitats downstream.

C.1.2 Recommendations for hydropower

According to the Guiding Principles "Sustainable Hydropower Development in the Danube Basin" (ICPDR, 2013a), hydropower development needs to address the principles of sustainability, taking into account environmental, social and economic factors in an equally balanced way. In the frame of environmental factors, sediment regime should also be considered. When national/regional hydropower strategies are developed, these strategies should consider the impacts on the environment including impacts on the sediment regime.

Thus, when assessing the possibility of constructing hydropower plants in river stretches, as is foreseen in the Guiding Principles (ICPDR, 2013a), sediments should be considered in the evaluation process. For the construction of new hydropower plants, a strategic planning approach (linked to the Renewable Energy Action Plan and the River Basin Management Plan) is recommended. According to ICPDR (2013a), "*The national/regional assessment is an instrument for administrations in the process of directing new hydropower plants to those areas where minimum impacts on the environment are expected. This can be achieved by an integration of hydropower production and ecosystem demands as well as by supporting decision making through clear and transparent criteria, including aspects of energy management as well as environment and landscape aspects. Danube-basin wide or transboundary aspects need to be taken into account where appropriate.*" Furthermore, ICPDR (2013a) states that *"In order to support hydropower in the most sustainable way, incentive schemes for new hydropower projects should take into account the results of the strategic planning approach and adequate mitigation measures."* In the case of sediment management, this should mean that not measures enabling only fish migration but also sediment continuity should be considered.

It is also in the self-interest of the hydropower development to incorporate sediments, respectively their management, during the early planning phase of new HPPs. This can reduce the maintenance costs and increases the lifetime of a dam. Therefore, it is recommended that sediments are explicitly addressed in the planning phase, including the quantity of upstream sediment yield. Since rivers differ in their sediment load, sizes of sediments and petrography, it is important to incorporate those factors in the design and management. Such plans should also indicate how sediments in reservoirs or impoundments are going to be managed in order to contribute to a sustainable development of the river.

Incorporating sediment strategies in the initial design and construction of a hydropower plant is normally less expensive than improving sediment continuity by retrofitting or reconstructing existing hydropower plants (Kondolf et al., 2014). Therefore, considering sediments in the initial planning phases is always beneficial, since it enables the incorporation of necessary installations for sediment management from the beginning.

At existing hydropower plants where the sediment transport is already interrupted by lateral structures (dams, weirs), there is a need to improve or restore the continuity of fine as well as coarse sediments. Sedimentation processes in impoundments or reservoirs can usually not be completely eliminated but an emphasis should be put on reducing them. When realising any measure, a robust planning process is needed to confirm that the most practical, efficient, environmentally-friendly and cost-effective option is selected. In some cases, the combination of different effective measures can be the best solution.

Also, when existing hydropower plants have to be renovated or reconstructed, the combination of technical upgrading with ecological and sediment-related restoration of existing hydropower installations should be considered. This means that not only should the possibility for fish migration but also sediment continuity needs be considered. These measures can be either performed directly at the dam or weir, e.g. height of the fixed weir sill, gates to allow flushing, width of the dam, sediment turbine, or

in the impoundment or reservoir, e.g. sediment bypass, geometry of impoundments or reservoirs. The most suitable option or combination of measures has to be selected on a case-by-case basis according to the specific site. For a series of dams, a coordinated flushing or sluicing management is recommended, which improves sediment continuity in the best possible way and prevents depositions in the downstream impoundments or reservoirs.

When implementing measures against sedimentation, no material should be extracted from the river system. As long as there is a sediment deficit, all the sediments – regardless if fine or coarse sediments – from the Danube and its tributaries should be reinserted, if excavated. Reinsertion should take place in river sections with a significant lack of sediments, or these sediments (mostly bedload) can also be used to build structures such as islands or bars in the river, in case they fit the natural planform patterns and sediment transport capacity. The sediment quality and other ecological boundaries have to be considered, as well as possible impacts on flood risk and navigation. If sediments are deposited and then measures applied that remobilize (fine) sediments, these can cause a temporal shift of the sediment transport; meaning a large amount of sediment is transported within a short time period. This can negatively affect ecology, e.g. by increased sedimentation of fine material on floodplains and gravel bars. Thus, any release of fine material should be controlled and ecologically compatible. In cases of large floods however, the control of fine sediments is almost not possible. In the long-term, the emphasis needs to be placed on a more continuous and natural sediment regime by preventing either sediment settling or more frequent remobilisation, meaning that smaller amounts of sediments are transported.

In addition to our above-mentioned recommendation, we encourage the Danube countries' authorities, HPP operators and bilateral commissions to initiate an in-depth investigation of sediment issues, to set new sediment management rules and to include these into the operational procedures for HPPs along the Danube and its tributaries.

The DanubeSediment project does not recommend removing all existing barriers, but if the operation is no longer profitable or technically feasible, the decommissioning and the controlled removal of the dam or barrier should be considered as a viable option.

C.2 NAVIGATION

C.2.1 Description of Measures

Figure 33 depicts sediment management measures related to navigation, divided according to different spatial scales and highlighted in bold. All measures in the following chapters that are described by a factsheet (see Part D Factsheets) have been marked with an alphanumeric identifier in the title of the measure.

C.2.1.1 Catchment scale

Measures implemented on the catchment scale can also be relevant for inland navigation, since navigation takes place on the most downstream, i.e. the lowest, part of the catchment. However, measures, which predominantly affect the stakeholder group river basin management, land use and ecology might additionally have an effect on navigation-related activities to a certain degree. These measures deal with activities in connection with land use and agriculture. Examples are "Improve/adjust land use management (RBM 3)", "Reduce surface runoff by infiltration and retention (RBM 4)" or "Reduce undesired (fine) sediment input (RBM 5)" and are described in Chapter C.4.1.1 in detail.

C.2.1.2 Regional Scale – free-flowing sections

Increase river length to reduce the slope (N 1)

Increasing the river length and decreasing the river slope can very effectively improve sediment management on the regional scale in free-flowing sections. Such measures include the reconnection of separated oxbows and cut-off meanders in combination with the relocation of the main channel. These restoration measures reduce the shear stress, flow velocity as well as riverbed degradation and stabilize the riverbed. This also decreases the transport velocity of the bedload, which means the sediments remain in the river for a longer period of time. In addition, habitat diversity benefits from this measure. For example, in terms of flow velocities, water depths and grain sizes, hydromorphological diversity increases and the newly created or reconnected meanders also provide habitats for a wide range of aquatic and terrestrial species (Jähnig et al., 2009). This measure aims to create a dynamic equilibrium. However, without bedload supply from upstream, morphodynamic processes might vanish and riverbed deepening will remain. In the sense of flood protection, such restoration measures positively contribute by retaining more runoff, thus reducing flood risk. Concerning inland navigation, an increased river sinuosity can influence ship traffic, since the bend radius is reduced. Therefore, these kind of measures should be coordinated, according to navigational requirements in order to prevent negative effects.

Coarse particle feeding (granulometric bed improvement) (N 2)

This measure involves the supply of the riverbed with coarse gravel that is within the natural grain size spectrum. Its goal is to reduce the frequency and amount of transported gravel. The measure is sensitive to the size and grain size distribution of the added gravel, which should mix with the natural subsurface material, in order to increase the mean grain diameter of the riverbed material. This measure increases the critical shear stress, reduces the sediment transport capacity and reduces riverbed incision, thereby dynamically stabilizing the bed levels in the long-term. However, one must emphasise that the ultimate goal is not to stop bedload transport, only to reduce sediment transport and to allow morphodynamic processes in the riverbed, i.e. erosion, transport and deposition. Moreover, this measure aims at reducing the maintenance effort, i.e. less ford-dredging is needed, and at achieving a dynamic equilibrium, which is also beneficial for ecology. So far, there is little practical experience, but first pilot studies have taken place in the Danube, e.g. in Germany and in Austria east of Vienna (Liedermann et al., 2016). These studies have shown that in order to achieve sustainable

Figure 33: Overview of sediment management measures; measures related to navigation are highlighted

effects, the optimal grain size must be defined separately for each case.

Intelligent dredging and feeding management (N 3)
The main objectives of this measure are both the removal of local sedimentation and the reduction of riverbed erosion. The dredging itself acts against local sedimentation in the fairway and ensures safe navigational conditions in critical spots. The refeeding of the dredged sediments mitigates riverbed incision by transferring the sediments upstream or downstream to areas where sediments are missing, respectively the water depth is large enough. The overall goal is to keep the sediments in the fluvial system instead of removing them and intensifying erosional trends. A bedload trap can be part of this measure, in order to intercept bedload before it reaches shallow sections and to gather sediment for further bedload management (WSD-SW, 2007; viadonau, 2018). By adding (external) coarser sediments, the measure can be adapted to reduce sediment transport and to counterbalance abrasion when the sediments are transferred upstream after dredging. This approach helps to improve the navigational status, while it simultaneously helps to dynamically stabilize the riverbed and counteract the bed degradation, which is often caused by a lack of sediments due to retention at barriers and increased transport capacity due to river training. It further counteracts the subsequent lowering of the water levels as a result of riverbed incision, and thus improves ecology.

Fairway shifting or narrowing (N 4)
Fairway realignment is applicable in morphologically dynamic river stretches with sufficient width, where the morphological development does not affect the entire river width and leaves enough space for the measure (Platina-2, 2016). To be able to perform fairway realignment, regular bathymetry measurements in the critical sectors are necessary in order to monitor and analyse the occurring morphological processes and to understand the riverbed dynamics (Platina-2, 2016). By applying this measure, river training and maintenance works such as dredging might be reduced. Therefore, this measure has a lower impact on the river, is usually cheaper, easier and faster to implement. Furthermore, it allows more natural morphodynamics and river patterns and thus benefits ecology. Another operational measure to reduce the impact of waterway management on the sediment regime can be the narrowing of the fairway width, respectively dredging only a narrow part of the fairway instead of the full width.

Bathymetric surveys
Bathymetric surveys aim at gaining information on the morphological evolution of the riverbed. These surveys form the basis for any sediment-related measure in the planning, operational and implementation stage. In the scope of this measure, volumetric and bed level changes can be determined, which are basic information for hydropower operation and management well as for flood protection measures. Bathymetric measurements further serve as an important data basis for ensuring safe and long-term navigational conditions such as fairway depth and width, to update the Electronic Navigational Charts (ENC) and to enable a proactive sediment management (Platina-2, 2016). In order to obtain appropriate information on the volumetric and bed level evolution, surveys should be performed on a regular basis, especially after flood events.

Minimize or stop commercial dredging
This measure aims at keeping sediments in the system through legal limitations or prohibitions of commercial dredging. This is especially important in river stretches that are in the stage of degradation. This prevents adverse effects on the sediment regime, which further benefits the aquatic environment by ensuring valuable river habitats. In case dredging activities are required for reasons of e.g. flood protection or fairway maintenance, the excavated material should be reinserted downstream of the dam or in areas that are in need of sediments, which can also be located upstream.

C.2.1.3 Local scale – free-flowing sections

Open ship locks for local remobilisation
Opening ship locks at hydropower plants during floods can lead to increased flow velocities and shear stresses, thus consequently remobilizing

deposited sediments. It has the advantage that the sediment load is already high, and the additional remobilisation will have no additional adverse impact on the environment. An adverse effect that needs to be considered is the potential clogging of the locks that might cause difficulties when trying to close them after the flood. In general, this measure is only effective on the local scale near the ship lock and therefore has a limited impact on sediment continuity.

Sediment feeding (N 5)

Sediment feeding, for example by adding material in the main channel via ship or by placing the sediments on the riverbanks downstream of a dam or weir, helps to compensate the bedload deficit that is caused by the construction of dams and weirs. Depending on the size of the river, transport and distribution of the added sediments might require appropriate discharges, e.g. upstream impoundments or reservoirs might need to release water to induce a morphogenetic flow. The amount and size of the sediments fed into the river should be based on analyses and calculation of a sediment budget for the river (Bunte, 2004) with the aim of not affecting flood protection, navigation or habitat conditions. The overall goal is to increase the coarse sediment storage in the river, to improve the sediment transport and continuity, to balance sediment transport and supply and therefore to reduce riverbed degradation in the downstream reach, which ultimately improves the morphology. Sediment feeding is most beneficial when the material is not only transported through the river reach, but when the river is able to store at least a portion of the sediments in evolving morphological structures like bars and islands. This means that river restoration further downstream enhances the positive effect of sediment feeding by promoting instream sediment storage. Besides having positive effects on the riverbed, e.g. raising or stabilizing it, this measure can improve ecology, since higher water levels caused by higher riverbed can e.g. benefit the side-channel systems, as well as ground water levels and ground water recharge. Reducing, respectively stopping riverbed incision also serves flood protection, since the risk of eroding flood protection structures by destabilisation of the riverbank is reduced.

Optimisation of river engineering structures to reduce sedimentation (N 6)

This measure involves the adaption of existing river training structures such as e.g. groynes and guiding walls, regarding length, height, distance and shape. Goal is to increase shear stress in the main channel and consequently to reduce sedimentation in the main channel, i.e. the fairway. This reduces the amount of dredging required for fairway maintenance or unfavourable flood water levels (Glas et al, 2018). This measure primarily aims at ensuring safe and sustainable navigational conditions, i.e. fairway depth and width, and flood protection. Similar effects can be obtained through instream structures such as gravel bars and islands, if these fit the river pattern. Sediments from maintenance dredging can for instance be used to build those structures. Furthermore, they can be important spawning habitat for fish, but also important habitat for rheophilic invertebrate species (Jungwirth et al., 2005). These structures might need some maintenance to keep them efficient, which means they are not sustainable on their own. In general, they need to be based on thorough planning and be implemented with caution, since overdesigned hydraulic structures might cause excessive river narrowing effects, which leads to long-term riverbed deepening. Also, sediments remobilized from the location of the measure might deposit further downstream, creating unfavourable conditions and thereby only shift the problem to a new location.

Optimisation of river engineering structures to reduce erosion (N 7)

This measure involves the adaption of existing river training structures such as groynes and guiding walls, regarding length, height, distance, orientation and shape. Goal is to reduce shear stresses in the main channel and consequently, decrease riverbed incision. This helps to stabilize or raise the water levels of the surface water and ground water. The measure reduces sediment transport capacity, which might lead to unfavourable depositions in the fairway, if not executed properly. Thus, an adaptive implementation might be necessary. In addition, by lowering the groyne root to increase the near-bank discharge, respectively the flow velocities,

in combination with the removal of bank protection, this measure can improve the ecological conditions at the riverbanks by increasing the morphodynamics and reducing sedimentation in the groyne field (Liedermann et al., 2016).

Install bedload traps (as part of intelligent dredging and feeding management) (N 8)

The measure aims at trapping bedload at single locations to in order to control the downstream transport of sediments. These traps need to be dredged periodically to ensure their efficiency (Platina-2, 2016). They can be described as an intermediary between river engineering and maintenance dredging (Platina-2, 2016). Sediment traps are viable option in combination with (re-)feeding management in order to gain sediments for sediment management and to keep them in the river system. The traps can either be placed in the main stream or they can be located in a bypass or side-channel, when it is feasible to install diverting structures. Placing them outside of the main channel has the main purpose to reduce transport during high floods, in order to control sediment transport during extreme events. When installing bedload traps, size and extent should be based on sediment transport data, respectively a sediment budget that assesses the required dimensions. Since the trapping of sediments influences the downstream sediment supply, this effect must be considered in planning the measure so as not to worsen potential downstream riverbed degradation. The depth of the trap also needs to consider the thickness of the gravel layer so that it will not cut into fine tertiary sediments or rock. Installing a bedload trap can help to reduce the need for maintenance dredging for inland navigation, if they are installed upstream of shallow sections (WSD-SW, 2007; viadonau, 2018). Bedload traps can also be used to improve flood protection if they are active during flooding, since they reduce the downstream transport of sediments, and thus prevent uncontrolled sedimentation near settlements.

Remobilisation of consolidated gravel bars (N 9)

This measure is implemented by breaking-up clogged and consolidated (fine) sediments that are situated on top of the riverbed. The bed armour can either be broken-up by artificial floods, i. e. an increased water outflow from an upstream impoundment or reservoir, or mechanically with dredging equipment. When both methods are combined, the mechanical break-up of the riverbed and consolidated bars serves as an initial measure followed by the artificial flood. When mechanically breaking up consolidated bars, the sediments can also be relocated towards the main channel to make them more readily available for transport. The main objectives are to stabilize the riverbed level and to improve sediment continuity, respectively to improve the availability of sediment, as well as improving grain size variability. For the riverbed, this measure reduces external clogging through consolidated fine sediments, reduces internal clogging due to the break-up of the armour layer and improves the vertical connectivity to the ground water. Furthermore, this activity positively affects the hyporheic zone, i. e. the interstitial water-filled space beneath riverbeds, and therefore also improves aquatic habitats and ensures adequate oxygen levels. The remobilisation of consolidated gravel structures requires flood discharge. In case of flood absence, gravel bars will start to increase again.

C.2.2 Recommendations for navigation

Navigation is an important factor at the Danube River and thus the Good Navigation Status (GNS) should be achieved where possible. Keeping in mind the high sediment dynamics of the Danube River, maintenance of navigation conditions is inevitable. Nevertheless, this should not contradict the natural sediment regime and navigation measures should aim to establish a dynamic equilibrium of the riverbed. All future works should be in line with the "Joint Statement on Inland Navigation and Environmental Sustainability in the Danube River Basin" (ICPDR, 2007) that has the main goal of preserving the sediment balance and improving the environmental status of the river. In addition to the documents published by the DanubeSediment project, further documents and manuals provide guidance on how to apply integrated planning principles, how to appropriately implement waterway infrastructure projects and they also give good practice examples. Such documents should be taken into account when planning navigation measures, e.g. the "Manual on Good Practices in Sustainable Waterway Planning" (ICPDR, 2010b), "Guidance Document on Inland waterway transport and Natura 2000" (European Commission, 2012), "Guide for applying Working with Nature to Navigation Infrastructure Projects" (PIANC, 2018), "Good Practice Manual on Inland Waterway Maintenance" (PLATINA-2, 2016), "Guidance Document on Environmental Issues regarding Maintenance of Federal Waterways" (bmvdi, 2015) and the practical manual "Environmentally sound waterway management in the Danube River Basin" (Danube STREAM, 2019).

When realising any measure, a robust integrated planning process must be implemented to ensure that the most practical, efficient, environmentally-friendly and cost-effective option is selected. In some cases, a combination of different measures can be the best option. The best solution should be selected on a case-by-case approach considering the larger spatial scale, different boundary conditions and requirements. The impacts of structural/hydraulic engineering interventions in the river system should be minimized through mitigation and restoration. Other non-technical measures such as the reduction of the fairway width, relocation of the fairway or landing stages should also be considered. Newly constructed or reconstructed measures should be built in such a way that the effect on the sediment regime is minimized and that they are ecologically friendly, e.g. alternative groyne types, (gravel) bars and islands, instead of technical measures. Any new or existing river training works should be constructed to guarantee minimal fairway depth and should only be active during low water conditions in order to minimize bed shear stress at higher discharges, especially in reaches with riverbed erosion. In reaches where no strong changes are expected, such as the inside bend, bank protection (rip-rap) should be removed and bank erosion, and consequently river widening, should be allowed. In such cases, safety aspects, especially the effect on infrastructure, must be considered.

Banks or islands that do not endanger navigation conditions and safety should be left to themselves. Active monitoring and surveying of the stability of the islands and banks should be ensured in the interest of safe navigation. Re-creation of typical riverine habitats such as floodplain islands or the creation of side channels increases the range of natural habitats available for local wildlife.

If dredging is performed, e.g. in fords, the sediments should be reinserted into the river at sections with a significant lack of sediments. If the dredged material consists mostly of bedload, it can also be used to build structures such as islands or bars in the river, in case they fit the natural planform patterns. In sections with sediment deficit where erosion occurs, dredged sediments must be refed. The sediment quality and other ecological boundaries need to be considered, for example the duration and maximum concentrations associated with feeding and spawning times.

In the past, the Upper Danube was over-regulated over long stretches for flood protection but also for navigation and is now being restored to more natural conditions. This was a long learning process that took place in the Upper Danube over many decades. Therefore, the same mistakes should not be made in the (nearly) natural river reaches, which still exist, for example in sections of the Lower Danube.

C.3 FLOOD PROTECTION

C.3.1 Description of Measures

Figure 34 depicts sediment management measures related to flood protection, divided according to different spatial scales and highlighted in bold. Additionally, measures, such as "Minimize urbanisation and construction of buildings on sloped terrain (RBM1)", "Improve or adjust land use and management (RBM3)" and "Adapt to impacts of climate change" are relevant for flood risk management, too. All measures in the following chapters that are described by a factsheet (see Part D Factsheets) have been marked with an alphanumeric identifier in the title of the measure.

C.3.1.1 Catchment scale

Minimize anthropogenically caused excessive debris flow, mass movements and landslides (F 1)

Spatial planning can help to regulate excessive debris flow, mass movements and landslides. For instance by regulating which areas should be kept free from development, where development is acceptable and to which degree. Avoiding structural disturbances of (steep) slopes and leaving those areas undisturbed can minimize the potential of mass movements, respectively the erosion potential. Common human-induced factors that affect the potential for landslides are increased urbanisation and development, deforestation and removal of deep-rooted vegetation, changes or disturbances in drainage patterns of ground and surface waters, destabilisation of slopes (Dai et al., 2002; Turner, 2018) or badly cited dams. Anthropogenically caused debris flows can also result from the production of debris such as dump sites of mines and quarries, depositions of soil and construction material during the construction phase of e.g. roads. The loss of vegetation cover, for instance, has a destabilising effect on the soil if the extensive root systems that bind the soil are largely gone and excess water, which was formerly used by the vegetation, now remains in the soil. This excess water leads to slope saturation in the soil profile and is considered to be the primary cause of landslides and their occurrence. The water is directly related to rainfall, with geology, soil type, and topography as contributing factors (Highland and Bobrowsky, 2008). Managing a landslide means to manage the water in and around the affected area. Directing water away from the site by building technical structures or to enhance drainage, as well as increasing the water use by increased vegetation are one of the main methods to address the problem (Highland and Bobrowsky, 2008).

There is a variety of nature-based solutions designed to prevent natural hazards and reduce erosion risks in steep areas. Some of them are e.g. mass stabilisation to prevent landslides through specific plantations and protective forests, which prevent rockfall and reduce the amount and speed of surface runoff with different kinds of plants (Alpine Convention, 2019). This protective function is often assigned to existing forests and habitats, therefore restoration of protective vegetation/forests is another important point to ensure their functionality (Alpine Convention, 2019).

Reduce surface runoff through infiltration and retention (F 2)

As a natural retention measure, this activity aims at reducing surface runoff and restoring a more natural flow regime by enhancing the infiltration efficiency. This is the preferred solution because it tackles the problem of excessive surface runoff and erosion at the source. This measure aims to reduce soil sealing, meaning to minimize additional land consumption for settlement purposes and infrastructure facilities through administrative restrictions. The preservation of green areas and natural land cover reduces surface runoff, leading to increased retention of water and sediments. It therefore leads to less sediment being transported into the receiving waters. Additionally, this measure improves flood protection, respectively reduces flood peaks, by enhancing the infiltration efficiency and increasing groundwater recharge. However, the effect

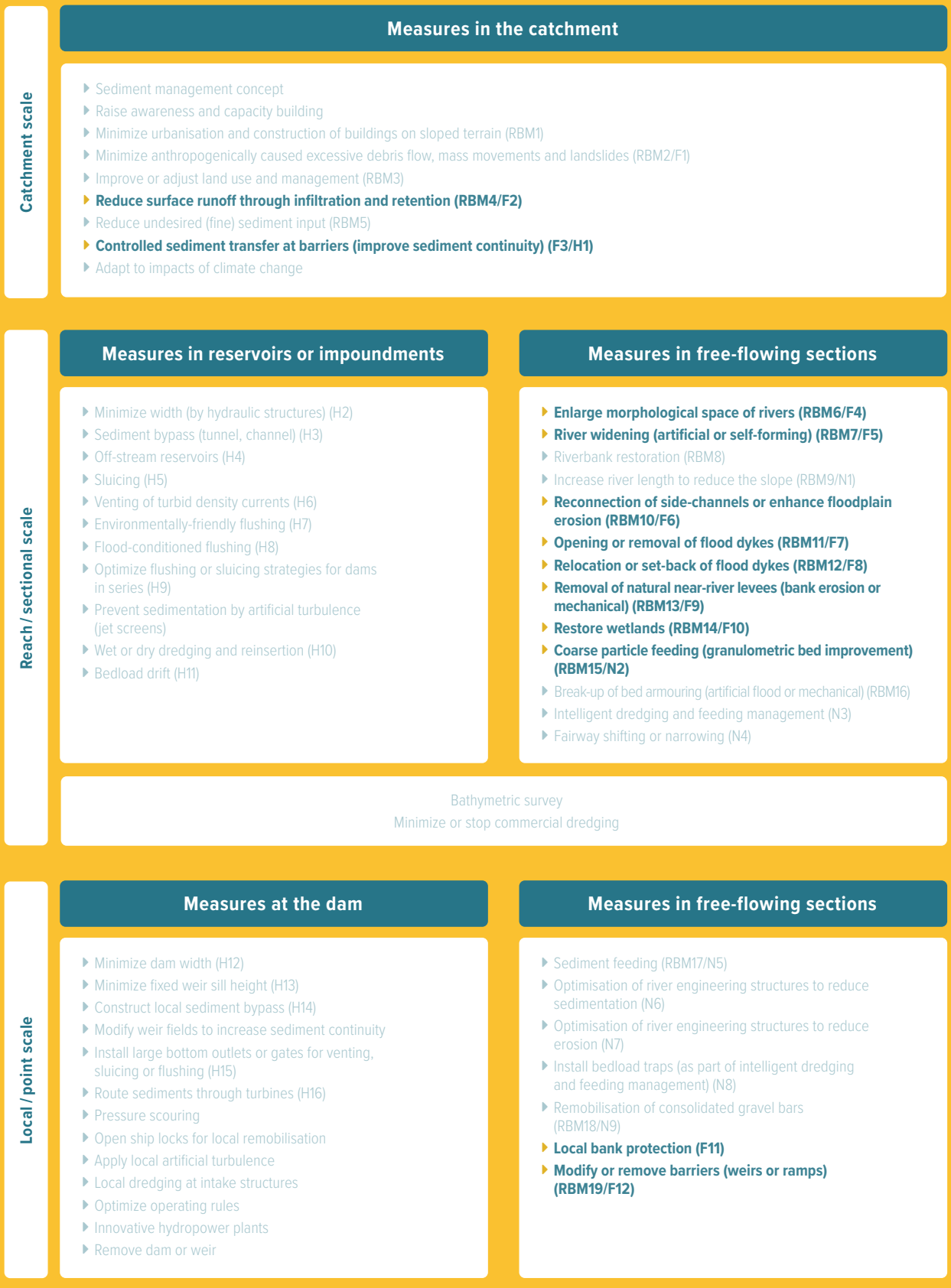


Figure 34: Overview of sediment management measures; measures related to flood risk management are highlighted

during extreme rainfalls events can be limited, if the soil is oversaturated and loses its retention capacity. An alternative on the small scale is, to reduce peak flows during rainfall events through retention, detention or infiltration basins. They are designed to have a retention effect or serve as a settling or filtering pond. The latter can also retain fine sediments, which need to be removed, depending on the amount of settled sediments. Detention or infiltration basins are usually vegetated and free from water in dry weather conditions, whereas retention ponds or pools contain water during dry weather and provide additional storage capacity to attenuate surface runoff (NWRM, 2015). Infiltration basins in comparison to detention basins allow water to infiltrate into the underlying soil. By reducing the storm-water runoff they also help to reduce excessive erosion respectively fine sediment input into rivers. However, these measures address the problem as an end-of-pipe solution, not at the source.

Controlled sediment transfer at barriers (improve sediment continuity) (F 3)
Sediment management strategies and implemented measures should be coordinated among the different dam operators in order to harmonize and improve the effect of sediment-related measures throughout a catchment. In addition, catchment-related measures like the reduction of sediment production by adjusting land use practices, e.g. in forestry and agriculture, to reduce the input of undesired fine sediment into rivers, should be coordinated with the relevant stakeholders from forestry, agriculture, spatial planning etc. to improve the sediment management in impoundments and reservoirs.

Low dams or check dams located e.g. just upstream of reservoirs can function as traps for (mostly coarse) sediment and large woody debris. Despite the extent of and large investment in (check) dams, the experiences reported in the literature illustrate that the benefits from (check) dam storage are temporary at best, and the sediment-filled (check) dams can become potentially unstable and costly to maintain (Kondolf et al., 2014). These should therefore be designed for easy access by heavy equipment, in order to easily excavate the trapped material and transport it downstream to increase the amount of sediment entering the river channel. A better option that helps to improve sediment continuity in head waters, respectively the upstream area of a catchment, is the retrofitting or construction of barriers in such a way that bedload material can pass the barrier while boulders and large woody debris is retained. These self-flushing barriers or open check dams can also reduce the need for periodic dredging works.

Additional measures
Further measures, which predominantly affect the stakeholder group river basin management, land use and ecology might additionally have an effect on flood protection-related activities to a certain degree. These measures deal with activities in connection with land use and agriculture. Examples are “Improve/adjust land use management (RBM 3)”, “Reduce undesired (fine) sediment input (RBM 5)”, „Minimize urbanisation and construction of buildings on sloped terrain (RMB 1)“ and „Adapt to impacts of climate change“, which are described in Chapter C.4.1.1 in detail.

C.3.1.2 Regional Scale

Enlarge morphological space of rivers (F 4)
The minimum morphological spatial demand of rivers (MMSD) is an essential space requirement within the EU flood management framework. It is defined as the river width that should be kept free from buildings, infrastructure and other anthropogenic uses in order to have space available for morphological changes in case of major flood events and thus to reduce damage (Habersack et al., 2010). It comprises areas in the riparian zone and the floodplain of rivers that are endangered by morphological changes (e.g. avulsions, river widening) in the event of flooding. According to Krapesch et al. (2011), for floods exceeding a 100 year return-interval, the MMSD is threefold to sevenfold the width of the existing riverbed (measured from the riverbanks), but also values as high as 14 times the riverbed width have been observed. If possible, the potential river morphological space demand, defined by the potential river floodplain system, should be aimed for. Keeping the MMSD free from settlements and infrastructure provides more space for channel forming processes, decreases riverbed incision

as well as damage potential in case of floods. Moreover, if this measure is combined with river restoration (especially the removal of bank protection), then the enabled lateral erosion widens the river and thus reduces hydrodynamic forces on the riverbed. A comparable approach is the erodible corridor concept, where a corridor in the alluvial floodplain is defined within which erosion is not controlled by engineering measures (Piegay et al., 2005). It seeks to create a balance between environment and economy by letting the river migrate freely within the corridor and by protecting infrastructure outside the corridor. Another measure that is orientated towards the actual spatial demand of running waters in the context of catchment hydrology is, for instance, hazard zone planning. In this case, areas for potential future measures or areas with flood retention potential and those required for flood conveyance are marked (BMNT, 2018b). Aim is to restore or preserve space for rivers for potential future measures in the context of flood risk management.

River widening (artificial or self-forming) (F 5)
Regulated rivers tend to become vertically unstable, resulting in increased erosion in one location and increased deposition in downstream parts (SEPA, 2010), if the sediment input and width are too small and no bank erosion is possible. Widening in turn, allows the river to develop a more natural and balanced state with less erosion and deposition. Widenings are especially successful when the widened reach is long, with an intact bedload supply from upstream (Hunziker, 2012). Passive river widening involves the removal of river training or bank fixation structures such as bank protection and groynes and the removal or setting back of dykes. This initiates self-dynamic, morphological processes. The lateral development can be further enhanced by additional bioengineering, such as adding large woody debris to the riverbank. Artificial or active widening means that the river width is increased by removing the river training and actively increasing the river width, e.g. by dredging (Habersack and Piegay, 2007). Side erosion processes lead to an increased short-term sediment input and the widening itself reduces the shear stress and flow velocity and thus erosional processes in the riverbed. It also decreases the transport velocity of the bedload, which means sediments remain in the river longer. Widening can lead to a short-term downstream sediment deficit, therefore an implementation from downstream to upstream can be beneficial. Habitat diversity additionally benefits from this measure since the hydromorphological diversity in terms of flow velocities, water depths and grain sizes increases (Jähnig et al., 2009). Flood protection is enhanced by increased runoff retention. Excessive widening might cause adverse effects on nearby infrastructure, navigational conditions (fairway depth) or flood protection measures, respectively flood water levels. Therefore, additional measures such as burying groynes in the floodplain, might have to be taken into consideration.

Reconnection of side-channels or enhance floodplain erosion (F 6)
This measure involves the reconnection of existing side-channels and oxbows or the creation of new side-channels, preferably also at low-flow conditions. This improves the lateral connectivity between the main channel and the floodplain. This sediment exchange between river and floodplain can further be enhanced by removing barriers and bank protection in the side-channels, eventually supported by dredging. As a consequence, the discharge in the main channel is reduced, which results in a lower bed shear stress and decreased riverbed incision. To avoid sedimentation of fine sediments in the side-channel, it is necessary to ensure discharge and water level fluctuations. In this case, the high shear stresses are able to prevent excessive fine sediment accumulation in the side-channel during times of higher discharges. Flood protection benefits from the increased discharge retention and the lower water levels during flood stage. Moreover, sediment transport and dynamics are improved because of morphodynamic processes in the side-channels. Ecology benefits from this measure, since the characteristic island and river landscape is re-established and habitat diversity is improved, aquatic biota find permanent refugial areas (Buijse et al., 2002) and are also protected from vessel-induced waves in navigable rivers. Furthermore, this measure improves ground water recharge. In navigable rivers, the amount of diverted water, especially during low

flow conditions, need to be considered so as not to negatively affect fairway depths.

Opening or removal of flood dykes (F 7)
Local opening of flood dykes or removing them completely can be an option to reduce the hydraulic impacts on the main channel and to increase the river-floodplain sediment exchange. This measure contributes to stabilizing riverbed levels by reducing shear stresses and the sediment transport capacity at discharges above bankfull stage. The increased water retention in the floodplain reduces peak discharges and water levels, which also benefits flood protection. Subsequently, this measure also creates and maintains different floodplain features and increases the habitat diversity of a floodplain (Roni et al., 2005). However, attention must be paid to critical infrastructure and settlements nearby, in order to not deteriorate their flood protection. Therefore, this measure is only feasible in areas with sufficient space available and in the absence of critical infrastructure.

Relocation or set-back of flood dykes (F 8)
The setting back of dykes is defined in relation to the existing dyke (Dahl et al., 2017). Moving an existing dyke away from a river provides more space to accommodate flood waters, reduces flood heights and the pressure on the dyke itself. The increase in space also reduces flow velocities, respectively shear stress, and therefore reduces the sediment transport capacity in the main channel, thus counteracting riverbed degradation. Further positive aspects are an increased sediment exchange with the floodplains at high flow and a reduction of flood damage or risk due to increased flood retention and lowered flood water levels. A reduced dyke height and the possibility to place the dyke on more stable ground farther from the main channel may reduce the cost of constructing the set-back (USACE, 2012). Set-backs can also result in reduced costs for operation and maintenance, as well as a reduced risk of failure (USACE, 2012; Smith et al., 2017). Another benefit is that this measure creates and maintains different floodplain features and increases the habitat diversity of a floodplain (Roni et al., 2005). The setting back of flood dykes provides the potential to restore some elements of riparian ecosystems (Rohde et al. 2005). This measure might require changes in land use and is only feasible in areas with sufficient space available and where critical infrastructure is absent. In addition, it can limit the expansion of settlements.

Removal of near-river natural levees (bank erosion or mechanical) (F 9)
Riverbank levees occur as a result of fine sediment depositions on riverbanks during overbank flow. Due to river regulation, these levees cannot be eroded naturally by side erosion. The removal can either be done mechanically or by removing the bank protection to reinstall lateral erosion. The removal of these depositions aims at reducing the water level at bankfull discharge and at improving the lateral connectivity between main channel and floodplain. The sediment regime benefits from this measure, since shear stresses are reduced in the main channel. This counteracts bed level degradation, since inundation of the floodplain occurs at an earlier stage. In rivers with a narrow floodplain, those levees can reduce the cross-section and have an effect on flood conveyance, which in turn can affect flood protection. Therefore, their removal also has positive effects in terms of flood defence. However, the effects have to be evaluated for each case separately.

Restore wetlands (F 10)
Reactivating former wetlands can increase water retention in the long-term and dampen flood events (Camaro-D, 2019). This measure aims to restore or improve the disrupted lateral dimension of a river system (riverine-riparian-floodplain), which was affected by human-induced alterations (Ward, 1998), and to re-establish the „river pulse" (Schiemer et al., 1999, Tockner et al., 2000). Former floodplains and wetlands were characterised by e.g. high morphological dynamics and oxbows. These characteristics changed over time, calling for necessary restoration measures to improve the ecological situation of this riverine area. Wetland restoration involves techniques such as opening or removal of dikes in order to restore the hydrology of an area. Also, deconstructing ditches and drainage systems directly affects flood events by increasing the retention capacity of the floodplain (Camaro-D, 2019). (Restored) wetlands retain water

from floods, which increases the travel time of the water to the receiving waterbody, thereby reducing flood peaks. This, in turn, reduces the sediment transport capacity in the main channel and reduces the input of fine sediments into rivers. Wetlands are good sediment and contaminant filters and therefore have positive effects on water quality. Their restoration also aims to re-establish ecological processes and functions in damaged or destroyed wetlands, including the creation of new habitats. Once the hydrology has been restored, wetland vegetation can recover and the wildlife can utilize the restored aquatic habitat. Creating artificial or constructed wetlands in urban areas can also contribute to flood attenuation, water quality improvement and habitat and landscape enhancement.

C.3.1.3 Local scale

Local bank protection (F 11)
Lateral movement of a river with erosion and deposition of bed and bank material are natural processes. Nevertheless, if critical infrastructure or settlements are nearby, it is necessary to protect them. Measures to improve the situation should first try to address the causes. Good examples are the reduction of non-natural peak flows, e.g. modifying hydropeaking or reducing anthropogenically-induced flow peaks, or the reduction of riverbed incision, e.g. by increasing sediment supply from upstream. Also, livestock fencing to reduce damage due to stream-bank trampling, which removes protective vegetation (Belsky et al., 1999), can be an option to prevent or reduce bank erosion. If the above-mentioned measures cannot be applied, or they would take too long to be effective, riverbanks can be stabilized locally, preferably by using bioengineering techniques such as vegetated crib walls, brush mattress or brushwood fascines, in order to protect threatened critical infrastructure or settlements.

Modify or remove barriers (weirs or ramps) (F 12)
Transverse structures such as weirs and ramps constitute barriers for both sediment transport and fish migration. As a consequence of the barriers, mainly the coarser sediments are deposited upstream and fish are hindered from reaching their habitats both upstream and downstream, e.g. for spawning. Measures such as the removal of existing weirs and ramps therefore restore the river continuity for bedload material as well as for aquatic organisms. However, one of the aims of such structures can be to achieve stable riverbed levels. Thus, in some cases it is not feasible to completely remove a weir, but it has to be replaced by other measures, e.g. by ramps or open-cover for grade control. The modification of existing weir structures to ramps primarily aims at improving fish migration. However, if the height of the ramp is lower than the previous situation, then also sediment (bedload) continuity is improved. This enables the purpose of the structure to still be fulfilled, namely, to prevent bed erosion by controlling the upstream riverbed slope. To serve the transport of sediment, such a measure must consider the lowering of the sill in order to increase the riverbed slope upstream of the structure and thus, enhance bedload transport towards the sill. Another option is the open-cover, where large intermittent stones are placed on the riverbed to provide additional riverbed resistance, channel roughness and energy dissipation, which hinders or starkly reduces riverbed incision (Downs and Gregory, 2004). More natural and sediment transport-friendly alternatives to open-cover are sediment feeding or, if feasible, widening the river, which reduces the erosive energy and can counterbalance riverbed incision.

C.3.2 Recommendations for flood risk management

For sediment management to become more effective, all levels of governance need to understand the importance of sediment and integrate sediment-related issues into river management throughout the entire river basin. For example, sediment management should be integrated into the National River Basin Management Plans (according to EU Water Framework Directive) and the National Flood Risk Management Plans (according to the EU Flood Directive).

The restoration of the sediment balance and the dynamic equilibrium of the riverbed should be amongst the main priorities for flood risk management. Changes in the riverbed, whether long-term or short-term, can have negative impacts on flood protection during flood events. Erosion of the riverbed can cause instability of flood protection structures or can lead to a failure of the protection structures during flood events. Sedimentation can raise the riverbed level and consequently the water surface level, and thus causing earlier inundation. Furthermore, sediment trapping in impoundments or reservoirs can raise flood water levels and remobilise of this fine sediments during large floods, thereby increasing the damage in case of flooding. Thus, the DanubeSediment project recommends the development of a sediment management concept and the implementation of measures to improve the sediment regime and to reduce river reaches with sedimentation or erosion for flood management.

To improve the understanding of sediment processes during flood events, the implementation of sediment monitoring activities during flood situations as well as event documentations for post flood analyses is recommended in flood risk management tasks. This also helps to improve the process understanding in impoundments and reservoirs, free-flowing sections and their interaction. The data collected can also serve as input and calibration and/or validation parameters for numerical simulations. Numerical simulations used for flood forecasting, to plan or evaluate measures to mitigate floods, should include sediment transport and morphological processes. The consideration of sediments in the planning phase of flood protection measures is of high importance, since high amounts of sediments can be transported during flood events and significant changes of the riverbed (erosion and sedimentation) can occur.

As stated by ICPDR (2004), "*a strategy to mitigate floods in an ecological manner should be based on improving river basin land-use, preventing rapid runoff both in rural and urban areas [...].*" These catchment-related measures to counterbalance accelerated surface runoff also improve the sediment regime by reducing, e.g. soil erosion in agricultural areas, and thus should be intensified.

Furthermore, the project supports the intention of ICPDR (2004) of "*improving a transnational effort to restore rivers' natural floodplains. This will reactivate the ability of natural wetlands and floodplains to alleviate negative flood impacts. Besides flood mitigation, this will lead to ecological benefits in the form of maintaining biodiversity, frequent recharging underground aquifers and availability of cleaner water for drinking, areas for recreation, opportunities for tourism and so on.*" The preservation and recovery of flood inundation areas, especially in free-flowing sections prone to erosion, reduces flow velocities and bed shear stress during flood conditions, and prevents or reduces riverbed erosion.

In the past, the Upper Danube was over-regulated over long stretches for flood protection but also for navigation and is now being restored to more natural conditions. This was a long learning process, that took place in the Upper Danube over many decades. Therefore, the same mistakes should not be made in the (nearly) natural river reaches, which still exist, for example in sections of the Lower Danube.

Attention should be given to enabling the lateral sediment exchange by improving or removing existing flood dykes, where possible, and avoiding additional interruptions. Lateral erosion shall be allowed at locations where it has no significant negative effects, e.g. on flood protection for settlements. Removal or set-back of flood dykes reduces the discharge

concentration and the water levels in the main channel and subsequently reduces the sediment transport capacity, thus counteracting riverbed degradation.

We recommend fostering river restoration measures, including side channel and meander reconnection to counteract the reduction of river width and length that was historically often undertaken to improve flood protection. It is also recommended to consider the morphological spatial demand of a river and the effect of extreme events in relation to sediment transport and morphological changes such as avulsion, widening or erosion, to reduce the damage potential. Securing this enlarged fluvial corridor and making room for the river is an important goal that should be considered in catchment-oriented spatial planning.

It is recommended to allow bank erosion to prevent or reduce natural levee formation, where possible. If natural removal by bank erosion is not an option, artificial removal might be considered as an option to allow an earlier inundation into the floodplains. This can be important since the degradation of lateral connectivity between main channel and floodplain increases water levels in the main channel at bankfull discharge, thereby causing higher shear stress occurs and increasing the risk of bed level degradation.

Furthermore, it is necessary to consider bed level changes that might occur during flood events. Morphological changes can result in significant bed level changes, which consequently changes the water level during floods. Flood protection measures should take the movable bed and the resulting water level differences into account in the planning stage of technical flood protection.

Furthermore, in reaches with erosional tendencies, a stabilisation or even an increase of the riverbed is recommended. Mitigation measures have to consider how to compensate the increasing bed and consequently increasing water level.

In reaches where sedimentation occurs, e.g. due to sediment trapping in impoundments or reservoirs, sediment routing by e.g. sluicing, or more frequent removal, e.g. environmentally-friendly or flood-conditioned flushing, should be encouraged. This decreases flood water levels and the remobilisation of fine sediments during large floods and consequently decreases the damage in the developed and cultivated foreland.

If dredging is performed for flood protection, we recommend reinserting the dredged material into the river system in areas with sediment deficits. Alternatively, use the coarse sediment to build natural structures such as gravel islands where these fit the natural river pattern.

C.4 RIVER BASIN MANAGEMENT, LAND USE AND ECOLOGY

C.4.1 Description of measures

Figure 35 depicts sediment management measures related to river basin management, land use and ecology, divided according to different spatial scales and highlighted in bold. All measures in the following chapters that are described by a factsheet (see Part D Factsheets) have been marked with an alphanumeric identifier in the title of the measure.

C.4.1.1 Catchment scale

Sediment management concept

Sediment management becomes necessary wherever anthropogenic activities influence sediment quantity and/or quality and affect the environmental status or human activities. Like water, sediment is a cross-cutting issue, with links to – and possible consequences for – many different economic sectors, regulatory interests and management requirements (Owens et al., 2008). Therefore, sediment as an essential, integral and dynamic part of the river basins can affect various environmental, social and legal objectives (Cullmann and Heininger, 2015). Research projects such as SED_AT (Habersack et al., 2014) showed that changes in the sediment balance, sediment transport and river morphology cause problems in most of the water-relevant sectors and that there is a need for action towards improved sediment management. Thus, as stated in the Austrian National River Basin Management Plan (BMLFUW, 2017), there is a need for the development of catchment-related sediment management concepts as central element for cross-sectoral work. With river basins being the most appropriate scale for sediment management, this should be an essential element in river basin management plans (Owens, 2005).

Effective sediment management requires a holistic approach taking into account:

- system understanding both in terms of quality and quantity
- the integrated management of soil, water and sediment
- upstream-downstream relationships
- supra-regional and transboundary collaboration
- respecting natural processes and functioning
- balancing environmental and socio-economical values
- an adaptive management approach
- a participatory approach, i.e. stakeholder involvement

It is very important for such sediment management strategies to try to work with nature, and not against it (Owens et al., 2008; SedNet, 2014; Heininger et al., 2015).

Sediment management must be based on knowledge of the sediment system, with its sources, sinks and transport paths, what the impacts are and the consequences of changes for different stakeholders (Owens, 2005; Walling and Collins 2008; Cullmann and Heininger, 2015). The sediment budget in this respect is an important concept for assisting management as it helps to get an overall understanding of (basin-wide) sediment-related processes and serves as a basis for sectoral planning. It provides an organisational framework to relate the different components and interacting variables, i.e. of sediment production, erosion, transport, deposition and remobilisation, and helps to identify the key components (Reid and Dunne, 1996; Habersack et al., 2004; Frings and TenBrinke, 2017).

When budgeting the sediment flux in the river basin, we are able to determine the effects of human influences such as transversal structures, river training or dredging on the downstream sediment regime, usually resulting in a sediment imbalance (Klösch and Habersack, 2017). Within the framework of such a concept, the sediment transfer (continuity) or reintroduction of material over barriers into the receiving water, should be made possible. These measures need to meet ecological and river engineering boundary conditions (Habersack et al., 2014). At the same time,

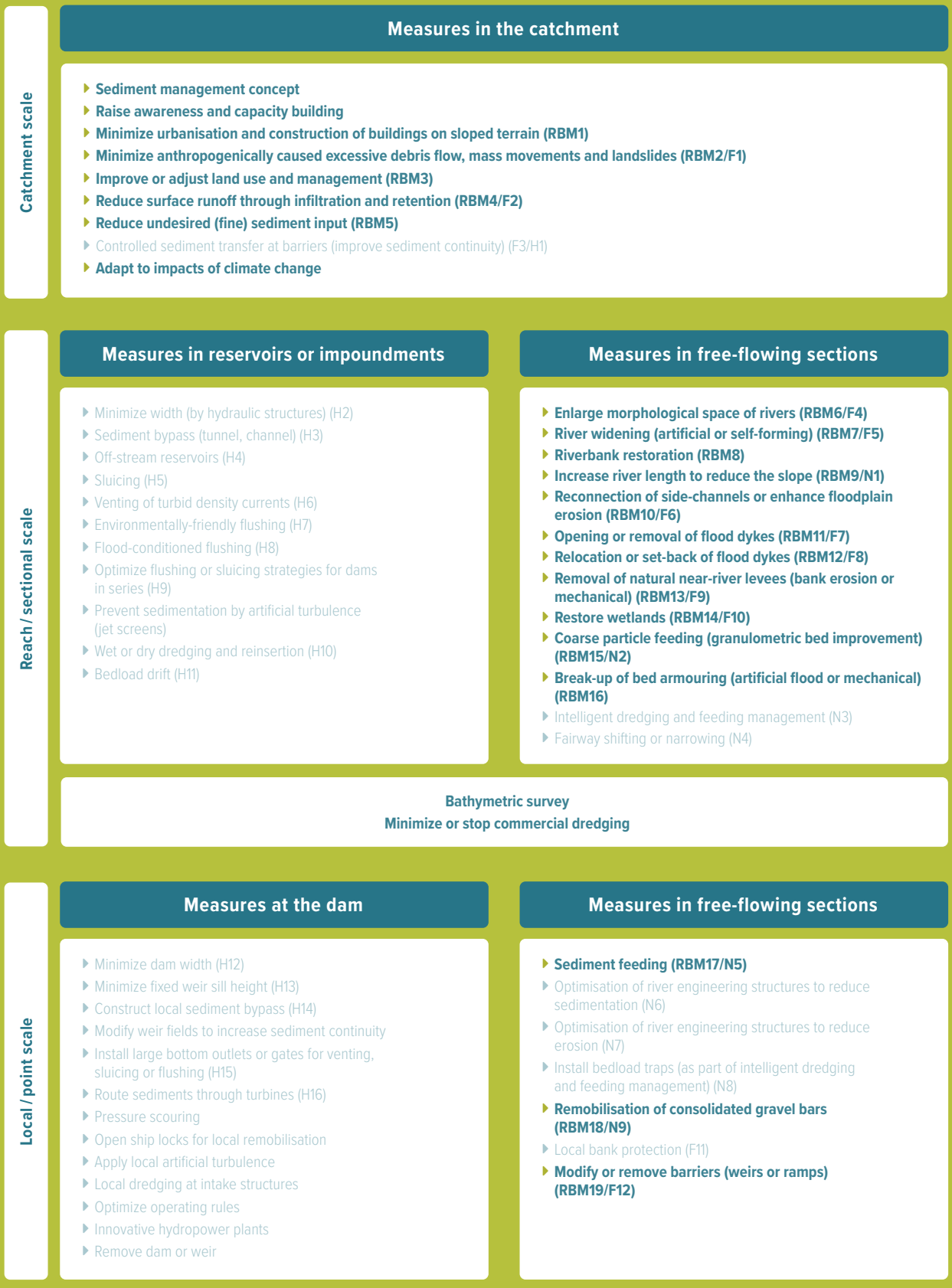


Figure 35: Overview of sediment management measures; measures related to river basin management, land use and ecology are highlighted

the problem of surplus in the retention areas and the deficit in the free-flowing sections can be reduced.

A hierarchical approach (catchment area → river network → reach), where the smaller scales depend on the larger scales, can help to avoid underrepresenting important boundary conditions or missing large-scale effects, if they are only evaluated isolated on the small scale. Hydromorphological assessment tools such as HYMET (Klösch and Habersack et al., 2017) allow the identification of suitable scales for the implementation of sediment-related measures.

To be able to give recommendations for actions, one needs to evaluate the risk and to set priorities in the design of a sediment management concept. Since causes and effects of sediment-related issues can be widespread, direct relationships are sometimes hard to determine or information is missing. This means that sediment management and the concept needs to deal with uncertainty and also needs to be prepared to adapt existing strategies when additional information is available.

From a jurisdictional perspective, sediment management is subject to different legal requirements. The WFD can provide the necessary platform and instruments, such as the RBM Plans. Including sediment management in RBM Plans is a promising future approach. Nevertheless it is important to recognize that sediment management could also be part of other approaches, such as navigation or flood risk management planning (SedNet, 2009).

Raise awareness and capacity building
An important aspect is to raise awareness that sediments are a vital component of river basins, and that they are part of a connected system that ranges from the mountains to the sea (SedNet, 2017). To overcome obstacles such as the lack of public awareness or the complexity of the sediment topic, active and inclusive stakeholder involvement, including experts who take the time to explain the issue and make their knowledge available, are important in the process (Owens et al., 2008; Slob et al., 2008). Besides raising awareness, participator planning via communication and active involvement also helps to gain public support for the measures and thereby ensures a transparent planning and decision-making process (ICPDR, 2010b). Promoting different best management practices is also a way to change, or at least mitigate land use practices that cause soil erosion or surface runoff. This administrative measure involves government-funded advisory activities for land users and farmers. Workshops and in-person consultation offer information about and use measures to reduce soil erosion and excessive surface runoff as well as possibilities for subsidies. The main objective is for practitioners to gain more insights and awareness regarding different management practices. As a long-term support, this measure has major impacts on the catchment scale in terms of changing awareness and the recipients of this information have a multiplier effect.

Minimize urbanisation and construction of buildings on sloped terrain (RMB 1)
Building regulation in sloped terrain is an administrative measure in the context of spatial planning that aims to minimize urbanisation, respectively construction of buildings and roads, in these areas. Avoiding structural disturbances of (steep) slopes and leaving those areas undisturbed basically minimizes the potential of mass movements, respectively the erosion potential. During and after construction activities, the development on steep slopes increases soil erosion and storm water runoff. Avoiding or managing development on steep slopes also preserves the existing vegetation, which minimizes the erosion potential. This eliminates the problem of re-establishing vegetation in these areas.

Minimize anthropogenically caused excessive debris flow, mass movements and landslides (RBM 2)
Spatial planning can help to regulate excessive debris flow, mass movements and landslides. For instance by regulating which areas should be kept free from development, where development is acceptable and to which degree. Avoiding structural disturbances of (steep) slopes and leaving those areas undisturbed can minimize the potential of mass movements, respectively the erosion potential. Common human-induced factors that affect the potential for landslides are

increased urbanisation and development, deforestation and removal of deep-rooted vegetation, changes or disturbances in drainage patterns of ground and surface waters, destabilisation of slopes (Dai et al., 2002; Turner, 2018) or badly cited dams. The loss of vegetation cover, for instance, has a destabilising effect on the soil if the extensive root systems that bind the soil are largely gone and excess water, which was formerly used by the vegetation, now remains in the soil. This excess water leads to slope saturation in the soil profile and is considered to be the primary cause of landslides and their occurrence. The water is directly related to rainfall, with geology, soil type, and topography as contributing factors (Highland and Bobrowsky, 2008). Managing a landslide means to manage the water in and around the affected area. Directing water away from the site by building technical structures or to enhance drainage, as well as increasing the water use by increased vegetation are one of the main methods to address the problem (Highland and Bobrowsky, 2008).

There is a variety of nature-based solutions designed to prevent natural hazards and reduce erosion risks in steep areas. Some of them are e.g. mass stabilisation to prevent landslides through specific plantations and protective forests, which prevent rockfall and reduce the amount and speed of surface runoff with different kinds of plants (Alpine Convention, 2019). This protective function is often assigned to existing forests and habitats, therefore restoration of protective vegetation/forests is another important point to ensure their functionality (Alpine Convention, 2019).

Improve or adjust land use and management (RBM 3)

Improving, respectively adjusting, land use management practices, e.g. in agriculture, addresses the reduction of undesired (fine) sediment input into waterbodies. These are non-structural measures that aim at controlling erosion at the source. Erosion control is the preferred solution with the clear advantage that it reduces the amount of generated and transported sediment, thereby reducing the need for extensive sediment control measures. Size, costs and maintenance of sediment control measures may be reduced when they are implemented together with erosion control measures.

The reduction of sediment input that occurs from agriculture or the floodplain through water erosion, can be either addressed at the source or the sink (see “Reduce undesired (fine) sediment input (RBM 5)”). Measures to reduce water erosion at the source for example are no-tillage or counter farming, cover crops, vegetation buffers, extensive sustainable agriculture, grassed waterways or permanent vegetation cover (NWRM, 2015). Optimized cultivation techniques on agricultural land reduce soil erosion and therefore the fine sediment input into rivers. Contour farming, for instance, means to plough and plant across inclined areas following its contour lines and thereby creating a surface runoff break by ploughing in perpendicular direction to the slope. These measures should be favoured because they also reduce the risk of gully formation and consequently, fine sediment input to water bodies.

Covering important infiltration areas with permanent vegetation cover (preferably grass), provides filtration and retention effects for surface water. The grassed area is ideally managed in an extensive manner. Such management and measures will decrease surface runoff and erosion potential and provide a much better control over those processes than arable land (Camaro-D, 2019).

Pasture management is a way to avoid intensive contact of animals with water bodies, serious damages of turf, bare and exposed soil and damages to trees and bushes (Camaro-D, 2019). The effect is that accelerated surface runoff is reduced as well as soil erosion, and it also has a positive effect on water quality.

Continuous cover forestry is a broad range of forest management practices, which have some beneficial effects in terms of hydrology and the erosion potential (NWRM, 2015). Maintenance of a forest cover is especially important in headwater areas, which are basically the zones of sediment production. An uninterrupted tree canopy has higher interception and ensures that soils are never exposed, which limits sediment

production (NWRM, 2015) and excessive sediment input into rivers. The main idea behind continuous cover forestry is a reduction in the number or size of clear-cuts, including the reduction of large-scale management measures for forest die-back, e.g. due to wind-throw, bark beetle or forest fires (Camaro-D, 2019). Avoiding or prohibiting clear cuts, especially on steep slopes, forest fire prevention, also in the light of a changing climate, afforestation and reforestation are potential measures to reduce erosion. In order to restore areas strongly affected by deforestation and storm damage, planting of trees helps to increase soil resistance.

Road planning and road rehabilitation reduces sediment supply, restores hydrology and improves water quality. Roads and other impervious surfaces increase peak and magnitude of peak flows, channel incision and simplification of habitats by altering the hydrologic regime and sediment supply to streams (Roni et al., 2005). They further alter sediment supply through increased landslide frequency and surface erosion (Best et al., 1995). An efficient design at road networks helps to reduce the number of roads needed. Constructing roads along ridge lines instead of across slopes, limits the destabilisation that is caused by cutting into sloped terrain and removing supporting material. Proper drainage ensures that erosion and flood risk is reduced, by letting the road runoff flow of in regular intervals and by increasing the local water infiltration. This also ensures that runoff from roads does not contribute to problems caused by excess water like landslides.

Reduce surface runoff by infiltration and retention (RBM 4)

As a natural retention measure this activity aims at reducing surface runoff and restoring a more natural flow regime by enhancing the infiltration efficiency. This is the preferred solution because it tackles the problem of excessive surface runoff and erosion at the source. This measure aims to reduce soil sealing, meaning to minimize additional land consumption for settlement purposes and infrastructure facilities through administrative restrictions. The preservation of green areas and natural land cover reduces surface runoff, leading to increased retention of water and sediments. It therefore leads to less sediment being transported into the receiving waters. Additionally, this measure improves flood protection, respectively reduces flood peaks, by enhancing the infiltration efficiency and increasing groundwater recharge. However, the effect during extreme rainfalls events can be limited, if the soil is oversaturated and loses its retention capacity. An alternative on the small scale is, to reduce peak flows during rainfall events through retention, detention or infiltration basins. They are designed to have a retention effect or serve as a settling or filtering pond. The latter can also retain fine sediments, which need to be removed, depending on the amount of settled sediments. Detention or infiltration basins are usually vegetated and free from water in dry weather conditions, whereas retention ponds or pools contain water during dry weather and provide additional storage capacity to attenuate surface runoff (NWRM, 2015). Infiltration basins in comparison to detention basins allow water to infiltrate into the underlying soil. By reducing the storm-water runoff they also help to reduce excessive erosion respectively fine sediment input into rivers. However, these measures address the problem as an end-of-pipe solution, not at the source.

Reduce undesired (fine) sediment input (RBM 5)

Measures to reduce undesired (fine) sediment input address the problem at the end-of-the-pipe, meaning when the sediment enters the waterbody. They are considered as structural measures aiming at sediment control. While non-structural measures are usually implemented to control or prevent erosion at the source, structural measures have the aim to manage runoff and filter or facilitate the settling of sediments. Erosion control (see previously described measures such as “Improve/adjust land use and management (RBM 3)”) is the preferred solution with the clear advantage that it reduces the amount of generated and transported sediment, thereby reducing the need for extensive sediment control measures. Size, costs and maintenance of sediment control measures may be reduced when they are implemented together with erosion control measures. A reduction in fine sediment erosion from agriculture also reduces nutrient input into the river.

Buffer stripes are one of those sediment control techniques to reduce the input of fine sediments into rivers. In general, they are areas of vegetation cover (grass, shrubs or trees) situated at margins of fields, arable land, transport infrastructure and water courses as well as karstic features like dolines and sinkholes (Camaro-D, 2019). They promote natural retention of water, since they are permanently vegetated, and therefore enhance water infiltration and slow down the surface flow. Furthermore, they can significantly reduce the amount of suspended solids and nutrients originating from agricultural runoff (NWRM, 2015). The effectiveness concerning fine sediment retention decreases with decreasing sediment particle size. Buffer stripes are most effective when the flow enters uniformly, when it is slow and shallow and if the vegetation is not submerged (Barling and Moore, 1994). On long steep slopes, buffers can be supported through hedges that can reduce soil erosion, as they intercept and slow surface runoff water before it builds a damaging flow (NWRM, 2015). Buffers situated along water courses (streams, lakes and wetlands) are termed riparian buffers and have multiple functions, e.g. to stabilize banks, to reduce fine sediment input, to provide habitat, as wildlife corridors, to protect cropland from flood damage by reducing lateral erosion, and to reduce nutrient loads (Pollock, 2005; Roni et al., 2005). Their overarching function is to protect the rivers, streams and lakes from the direct impact of adjacent land use, especially from agriculture. Therefore, preservation and rehabilitation, e.g. with fencing, removal of grazing, planting of trees and vegetation, helps to mitigate or reverse impacts of land use change by improving channel stability, aquatic habitats and terrestrial biodiversity as well as reducing excessive fine sediment input and lateral erosion processes (Barling and Moore, 1994; Dosskey, 2001; Feld et al., 2018).

Prevention of controlled gully erosion reduces soil loss and results in less fine sediment input to rivers, thereby reducing sedimentation. A gully is an erosional channel that occurs where erodible soil is exposed to concentrated surface runoff. Inclined terrain benefits the formation of such channels. They can initially emerge out of a small rill, when water flow is concentrated by, e.g. a trail, road, ditch or drain, or when runoff is increased due to upstream changes in land use practices. In general, it is easier and more economical to prevent gully erosion, respectively to implement measures, before a newly formed gully grows into a large one. Measures to repair large gullies are more costly and they are more difficult to get under control. Since runoff is moderated by vegetation that protects the soil, gullies can usually be prevented by an adequate land management that ensures a vegetation cover and even infiltration rates. Vegetation also protects the soil from direct rainfall and holds the soil together with its root system. Controlling a gully involves measures in the catchment, e.g. diverting and storing water, increasing infiltration rates, and stabilizing the gully itself (Geyik, 1986). When gully erosion occurs, control measures can be applied that aim at stabilizing the eroding channel by initiating self-maintaining vegetation. These measures also include diverting the concentrated surface runoff away from the advancing gully headwall and stabilizing the gully head, reducing gully slope by construction of e.g. wire netting, logs across the gully, gabions, planting of the gully bed to retard runoff, trap sediments and increase soil resistance, or the implementation of non-erodible channel lining (see also Morris and Fan, 1998).

Adapt to impacts of climate change

The Earth's climate system has changed over the past century and observations give a collective picture of a warming world (IPCC, 2014). Climate change is having and will have an important effect on agricultural lands, forestry and waters, next to the direct impact from agriculture (among other sectors) through modifying land-use, habitat loss, degradation and indirect impacts including the accumulation of sediment in rivers (ICPDR, 2019b). An increase in air and water temperature, combined with changes in precipitation, water availability, water quality and increasing extreme events, such as floods, low flows and droughts, may lead to changes to ecosystems, life cycles, and biodiversity in the DRB in the long-term. Changes in precipitation patterns and an increase in torrential rain and flash flood events can lead to more intense soil erosion, landslides and debris flows. Sediment input in the river system is

likely to increase due to more extreme events, permafrost thawing and glacier retreat (ICPDR, 2019b). Being of primal importance for the close future, this subject needs to be dealt with in future projects and adaptation strategies. This means that studies are necessary to evaluate the potential effects, to project them into the future and to integrate them into sediment management concepts. Concerning vegetation those envisioned strategies are mainly focused on the resilience and stability of the existing ecosystem (Alpine Convention, 2019) respectively potential changes away from monocultures to an autochthonous set of tree species. Wildfire prevention and the management of occurring wildfires for instance are other issues that need to be addressed (Camaro-D, 2019). The loss of vegetation cover due to fire and post fire logging can increase sediment production dramatically, often increases peak stream discharge due to an increased post-burn runoff via overland flow or water quality and subsequently drinking water supply (Kunze and Stednick, 2006; Shakesby and Doerr, 2006; Moody et al., 2008). The responses are ranging from no impact to large floods, debris flow and damages due to sedimentation (Moody et al., 2013).

C.4.1.2 Regional Scale

Enlarge morphological space of rivers (RBM 6)
The minimum morphological spatial demand of rivers (MMSD) is an essential space requirement within the EU flood management framework. It is defined as the river width that should be kept free from buildings, infrastructure and other anthropogenic uses in order to have space available for morphological changes in case of major flood events and thus to reduce damage (Habersack et al., 2010). It comprises areas in the riparian zone and the floodplain of rivers that are endangered by morphological changes (e.g. avulsions, river widening) in the event of flooding. According to Krapesch et al. (2011), for floods exceeding a 100 year return-interval, the MMSD it is threefold to sevenfold the width of the existing riverbed (measured from the riverbanks), but also values as high as 14 times the riverbed width have been observed. If possible, the potential river morphological space demand, defined by the potential river floodplain system, should be aimed for. Keeping the MMSD free from settlements and infrastructure provides more space for channel forming processes, decreases riverbed incision as well as damage potential in case of floods. Moreover, if this measure is combined with river restoration (especially the removal of bank protection), then the enabled lateral erosion widens the river and thus reduces hydrodynamic forces on the riverbed. A comparable approach is the erodible corridor concept, where a corridor in the alluvial floodplain is defined within which erosion is not controlled by engineering measures (Piegay et al., 2005). It seeks to create a balance between environment and economy by letting the river migrate freely within the corridor and by protecting infrastructure outside the corridor. Another measure that is orientated towards the actual spatial demand of running waters in the context of catchment hydrology is, for instance, hazard zone planning. In this case, areas for potential future measures or areas with flood retention potential and those required for flood conveyance are marked (BMNT, 2018b). Aim is to restore or preserve space for rivers for potential future measures in the context of flood risk management.

River widening (artificial or self-forming) (RBM 7)
Regulated rivers tend to become vertically unstable, resulting in increased erosion in one location and increased deposition in downstream parts (SEPA, 2010), if the sediment input and width are too small and no bank erosion is possible. Widening in turn, allows the river to develop a more naturally and balanced state with less erosion and deposition. Widenings are especially successful when the widened reach is long, with an intact bedload supply from upstream (Hunziker, 2012). Passive river widening involves the removal of river training or bank fixation structures such as bank protection and groynes and the removal or setting back of dykes. This initiates self-dynamic, morphological processes. The lateral development can be further enhanced by additional bioengineering, such as adding large woody debris to the river bank. Artificial or active widening means that the river width is increased by removing the river training and actively increasing the river width, e.g. by dredging (Habersack and Piegay, 2007). Side erosion

processes lead to an increased short-term sediment input and the widening itself reduces the shear stress and flow velocity and thus erosional processes in the riverbed. It also decreases the transport velocity of the bedload which means sediments remain in the river longer. Widening can lead to a short-term downstream sediment deficit, therefore an implementation from downstream to upstream can be beneficial. Habitat diversity additionally benefits from this measure since the hydromorphological diversity in terms of flow velocities, water depths and grain sizes increases (Jähnig et al., 2009). Flood protection is enhanced by increased runoff retention. Excessive widening might cause adverse effects on nearby infrastructure, navigational conditions (fairway depth) or flood protection measures, respectively flood water levels. Therefore, additional measures such as burying groynes in the floodplain, might have to be taken into consideration.

Riverbank restoration (RBM 8)

Riverbank restoration by a local removal of the bank protection (e.g. riprap) helps to restore the riverbanks towards more natural conditions. It is also a precondition respectively a part of other measures like river widening or re-meandering, in order to re-establish or initiate lateral channel dynamics and migration. As this measure initiates/improves morphodynamic processes and lateral erosion, it results in an increased short-term sediment input from the banks, reduces respectively prevents the build-up of natural levees and further improves the lateral connectivity of floodplains. The degree of reduction of flow velocities and bed shear stress in the main channel is depending on the extent of the removal of bank protection and the allowed widening of the river due to lateral erosion. However, in some cases, the toe of the bank has to be protected to prevent complete bank erosion and channel widening to ensure navigability, flood protection or protection of critical infrastructure and settlements.

Increase river length to reduce the slope (RBM 9)

Increasing the river length and decreasing the river slope can very effectively improve sediment management on the regional scale in free-flowing sections. Such measures include the reconnection of separated oxbows and cut-off meanders in combination with the relocation of the main channel. These restoration measures reduce the shear stress, flow velocity as well as riverbed degradation and stabilize the riverbed. This also decreases the transport velocity of the bedload, which means the sediments remain in the river for a longer period of time. In addition, habitat diversity benefits from this measure. For example, in terms of flow velocities, water depths and grain sizes, hydromorphological diversity increases and the newly created or reconnected meanders also provide habitats for a wide range of aquatic and terrestrial species (Jähnig et al., 2009). This measure aims to create a dynamic equilibrium. However, without bedload supply from upstream, morphodynamic processes might vanish and riverbed deepening will remain. In the sense of flood protection, such restoration measures positively contribute by retaining more runoff, thus reducing flood risk. Concerning inland navigation, an increased river sinuosity can influence ship traffic, since the bend radius is reduced. Therefore, these kind of measures should be coordinated, according to navigational requirements in order to prevent negative effects.

Reconnection of side-channels or enhance floodplain erosion (RBM 10)

This measure involves the reconnection of existing side-channels and oxbows or the creation of new side-channels, preferably also at low-flow conditions. This improves the lateral connectivity between the main channel and the floodplain. This sediment exchange between river and floodplain can further be enhanced by removing barriers and bank protection in the side-channels, eventually supported by dredging. As a consequence, the discharge in the main channel is reduced, which results in a lower bed shear stress and decreased riverbed incision. To avoid sedimentation of fine sediments in the side-channel, it is necessary to ensure discharge and water level fluctuations. In this case, the high shear stresses are able to prevent excessive fine sediment accumulation in the side-channel during times of higher discharges. Flood protection benefits from the increased discharge retention and the lower water levels during flood stage.

Moreover, sediment transport and dynamics are improved because of morphodynamic processes in the side-channels. Ecology benefits from this measure, since the characteristic island and river landscape is re-established and habitat diversity is improved, aquatic biota find permanent refugial areas (Buijse et al., 2002) and are also protected from vessel-induced waves in navigable rivers. Furthermore, this measure improves ground water recharge. In navigable rivers, the amount of diverted water, especially during low flow conditions, need to be considered so as not to negatively affect fairway depths.

Opening or removal of flood dykes (RBM 11)
Local opening of flood dykes or removing them completely can be an option to reduce the hydraulic impacts on the main channel and to increase the river-floodplain sediment exchange. This measure contributes to stabilizing riverbed levels by reducing shear stresses and the sediment transport capacity at discharges above bankfull stage. The increased water retention in the floodplain reduces peak discharges and water levels, which also benefits flood protection. Subsequently, this measure also creates and maintains different floodplain features and increases the habitat diversity of a floodplain (Roni et al., 2005). However, attention must be paid to critical infrastructure and settlements nearby, in order to not deteriorate their flood protection. Therefore, this measure is only feasible in areas with sufficient space available and in the absence of critical infrastructure.

Relocation or set-back of flood dykes (RBM 12)
The setting back of dykes is defined in relation to the existing dyke (Dahl et al., 2017). Moving an existing dyke away from a river provides more space to accommodate flood waters, reduces flood heights and the pressure on the dyke itself. The increase in space also reduces flow velocities, respectively shear stress, and therefore reduces the sediment transport capacity in the main channel, thus counteracting riverbed degradation. Further positive aspects are an increased sediment exchange with the floodplains at high flow and a reduction of flood damage or risk due to increased flood retention and lowered flood water levels. A reduced dyke height and the possibility to place the dyke on more stable ground farther from the main channel may reduce the cost of constructing the set-back (USACE, 2012). Set-backs can also result in reduced costs for operation and maintenance, as well as a reduced risk of failure (USACE, 2012; Smith et al., 2017). Another benefit is that this measure creates and maintains different floodplain features and increases the habitat diversity of a floodplain (Roni et al., 2005). The setting back of flood dykes provides the potential to restore some elements of riparian ecosystems (Rohde et al. 2005). This measure might require changes in land use and is only feasible in areas with sufficient space available and where critical infrastructure is absent. In addition, it can limit the expansion of settlements.

Removal of near-river natural levees (bank erosion or mechanical) (RBM 13)
Riverbank levees occur as a result of fine sediment depositions on riverbanks during overbank flow. Due to river regulation, these levees cannot be eroded naturally by side erosion. The removal can either be done mechanically or by removing the bank protection to reinstall lateral erosion. The removal of these depositions aims at reducing the water level at bankfull discharge and at improving the lateral connectivity between main channel and floodplain. The sediment regime benefits from this measure, since shear stresses are reduced in the main channel. This counteracts bed level degradation, since inundation of the floodplain occurs at an earlier stage. In rivers with a narrow floodplain, those levees can reduce the cross-section and have an effect on flood conveyance, which in turn can affect flood protection. Therefore, their removal also has positive effects in terms of flood defence.

Restore wetlands (RBM 14)
Reactivating former wetlands can increase water retention in the long-term and dampen flood events (Camaro-D, 2019). This measure aims to restore or improve the disrupted lateral dimension of a river system (riverine-riparian-floodplain), which was affected by human-induced alterations (Ward, 1998), and to re-establish the „river pulse" (Schiemer et al., 1999, Tockner et al., 2000). Wetland restoration involves techniques such as opening or removal of dikes in order to restore the hydrology of an area. Also,

deconstructing ditches and drainage systems directly affects flood events by increasing the retention capacity of the floodplain (Camaro-D, 2019). (Restored) wetlands retain water from floods, which increases the travel time of the water to the receiving waterbody, thereby reducing flood peaks. This, in turn, reduces the sediment transport capacity in the main channel and reduces the input of fine sediments into rivers. Wetlands are good sediment and contaminant filters and therefore have positive effects on water quality. Their restoration also aims to re-establish ecological processes and functions in damaged or destroyed wetlands, including the creation of new habitats. Once the hydrology has been restored, wetland vegetation can recover and the wildlife can utilize the restored aquatic habitat. Creating artificial or constructed wetlands in urban areas can also contribute to flood attenuation, water quality improvement and habitat and landscape enhancement.

Coarse particle feeding (granulometric bed improvement) (RBM 15)

This measure involves the supply of the riverbed with coarse gravel that is within the natural grain size spectrum. Its goal is to reduce the frequency and amount of transported gravel. The measure is sensitive to the size and grain size distribution of the added gravel, which should mix with the natural subsurface material, in order to increase the mean grain diameter of the riverbed material. This measure increases the critical shear stress, reduces the sediment transport capacity and reduces riverbed incision, thereby dynamically stabilizing the bed levels in the long-term. However, one must emphasise that the ultimate goal is not to stop bedload transport, only to reduce sediment transport and to allow morphodynamic processes in the riverbed, i. e. erosion, transport and deposition. Moreover, this measure aims at reducing the maintenance effort, i. e. less ford-dredging is needed, and at achieving a dynamic equilibrium, which is also beneficial for ecology. So far, there is little practical experience, but first pilot studies have taken place in the Danube, e. g. in Germany and in Austria east of Vienna (Liedermann et al., 2016). These studies have shown that in order to achieve sustainable effects, the optimal grain size must be defined separately for each case.

Break-up of bed armouring (artificial floods or mechanical) (RBM 16)

This measure is implemented by breaking-up clogged and consolidated fine sediments on the top of the riverbed. The bed armour can either be broken-up by artificial floods (increased water outflow from an upstream reservoir) or mechanically with dredging equipment. When both methods are combined the mechanical break-up of the riverbed and consolidated bars serves as an initial measure followed by the artificial flood. Additionally, bedload augmentation with external sediments (deposited in the riverbed or near the banks) can be undertaken when there is no or not enough bedload available to be mobilized. On the riverbed this leads to a reduction of external clogging by consolidated fine sediments, internal clogging due to the break-up of the armour layer and improves the vertical connectivity to the ground water. Further this activity positively affects the hyporheic zone (interstitial water filled space beneath riverbeds) and therefore also maintains aquatic habitats and ensures adequate oxygen levels.

Bathymetric surveys

Bathymetric surveys aim at gaining information on the morphological evolution of the riverbed. These surveys form the basis for basically any sediment-related measure in the planning, the operational and the implementation stage. In the scope of this measure, volumetric and bed level changes can be determined, which are basic information for hydropower operation and management as well as flood protection measures. Bathymetric measurements further serve as an important data basis for ensuring safe and long-term navigational conditions (fairway depth and width), to update the Electronic Navigational Charts (ENC) and to enable a proactive sediment management (Platina-2, 2016). In order to obtain appropriate information on the volumetric and bed level evolution, surveys should be performed on a regular basis and also after flood events.

Minimize or stop commercial dredging

This measure aims at keeping sediments in the system by legal limitations or prohibitions of commercial dredging. This is especially important in degrading river stretches. As a result, adverse effects on the sediment regime are

prevented, which further benefits the aquatic environment by ensuring valuable river habitats. In case of required dredging activities for reasons of e.g. flood protection or fairway maintenance, the excavated material should be reinserted downstream of the dam or in areas that are in need of sediments that can also be located upstream.

C.4.1.3 Local scale

Sediment feeding (RBM 17)
Sediment feeding, for example by adding material in the main channel via ship or by placing the sediments on the riverbanks downstream of a dam or weir, helps to compensate the bedload deficit that is caused by the construction of dams and weirs. Depending on the size of the river, transport and distribution of the added sediments might require appropriate discharges, e.g. upstream impoundments or reservoirs might need to release water to induce a morphogenetic flow. The amount and size of the sediments fed into the river should be based on analyses and calculation of a sediment budget for the river (Bunte, 2004) with the aim of not affecting flood protection, navigation or habitat conditions. The overall goal is to increase the coarse sediment storage in the river, to improve the sediment transport and continuity, to balance sediment transport and supply and therefore to reduce riverbed degradation in the downstream reach, which ultimately improves the morphology. Sediment feeding is most beneficial when the material is not only transported through the river reach, but when the river is able to store at least a portion of the sediments in evolving morphological structures like bars and islands. This means that river restoration further downstream enhances the positive effect of sediment feeding by promoting instream sediment storage. Besides having positive effects on the riverbed, e.g. raising or stabilizing it, this measure can improve ecology, since higher water levels caused by higher riverbed can e.g. benefit the side-channel systems, as well as ground water levels and ground water recharge. Reducing, respectively stopping riverbed incision also serves flood protection, since the risk of eroding flood protection structures by destabilisation of the riverbank is reduced.

Remobilisation of consolidated gravel bars (RBM 18)
This measure is implemented by breaking-up clogged and consolidated (fine) sediments that are situated on top of the riverbed. The bed armour can either be broken-up by artificial floods, i.e. an increased water outflow from an upstream impoundment or reservoir, or mechanically with dredging equipment. When both methods are combined, the mechanical break-up of the riverbed and consolidated bars serves as an initial measure followed by the artificial flood. When mechanically breaking up consolidated bars, the sediments can also be relocated towards the main channel to make them more readily available for transport. The main objectives are to stabilize the riverbed level and to improve sediment continuity, respectively to improve the availability of sediment, as well as improving grain size variability. For the riverbed, this measure reduces external clogging through consolidated fine sediments, reduces internal clogging due to the break-up of the armour layer and improves the vertical connectivity to the ground water. Furthermore, this activity positively affects the hyporheic zone, i.e. the interstitial water-filled space beneath riverbeds, and therefore also improves aquatic habitats and ensures adequate oxygen levels. The remobilisation of consolidated gravel structures requires flood discharge. In case of flood absence, gravel bars will start to increase again.

Modify or remove barriers (weirs or ramps) (RBM 19)
Transverse structures such as weirs and ramps constitute barriers for both sediment transport and fish migration. As a consequence of the barriers, mainly the coarser sediments are deposited upstream and fish are hindered from reaching their habitats both upstream and downstream, e.g. for spawning. Measures such as the removal of existing weirs and ramps therefore restore the river continuity for bedload material as well as for aquatic organisms. However, one of the aims of such structures can be to achieve stable riverbed levels. Thus, in some cases it is not feasible to completely remove a weir, but it has to be replaced by other measures, e.g. by ramps or open-cover for grade control. The modification of existing weir structures to ramps primarily aims at improving

fish migration. However, if the height of the ramp is lower than the previous situation, then also sediment (bedload) continuity is improved. This enables the purpose of the structure to still be fulfilled, namely, to prevent bed erosion by controlling the upstream riverbed slope. Another option is the open-cover, where large intermittent stones are placed on the riverbed to provide additional riverbed resistance, channel roughness and energy dissipation, which hinders or starkly reduces riverbed incision (Downs and Gregory, 2004). To serve the transport of sediment, such a measure must consider both the flattening of the sill itself and the increase of slope upstream of the sill (that enables bedload transport towards the sill). More natural and sediment transport-friendly alternatives to open-cover are sediment feeding or, if feasible, widening the river, which reduces the erosive energy and can counterbalance riverbed incision.

C.4.2 Recommendations for river basin management, land use and ecology

The aspect of sediment quantity in the Danube River Basin was already mentioned in the 1st DRBM Plan 2009 and was considered a potential Significant Water Management Issue in 2013 by ICPDR. Supported by the project recommendations and analyses, the ICPDR Heads of Delegations identified the alteration of the sediment balance as a new sub-item under the existing Significant Water Management Issue "Hydromorphological alterations".

In the Danube River Basin, the protection and preservation of the nearly undisturbed sediment regime, which still exists within the remaining natural free-flowing river sections and tributaries, should be of utmost priority. This reflects the no-deterioration-principle of the WFD. Strategies should be developed to preserve the sediment continuity and morphology in these few remaining, functioning river stretches or rivers.

For sediment management to become more effective, all levels of governance need to understand the importance of sediment and integrate sediment-related issues into river management throughout the entire river basin. For example, sediment management should be integrated into the National River Basin Management Plans (according to EU Water Framework Directive) and the National Flood Risk Management (according to the EU Flood Directive).

The DanubeSediment project recommends the development of an integrated Danube River Basin sediment management concept, which could be elaborated in a follow-up project. This concept should balance environmental and socio-economical values, consider different legal requirements and operate on a transboundary basis at different spatial and temporal scales, including upstream – downstream relationships. It should consist of a detailed analysis, based on existing knowledge, and proposals for measures. This concept must consider the high natural variability of sediment dynamics and should not compromise the ability of the system to respond. An adaptive management will help to deal with a highly dynamic system that contains uncertainty concerning the spatio-temporal variability of sediment transport.

Another important aspect for a follow-up project should be to analyse the risk of failing the good ecological status or potential of the WFD due to sediment-related problems along the Danube River and the tributaries. Furthermore, we recommend performing a risk analysis at the national levels in connection with the on-going assessments related to the national river basin management plans. Such a methodology must incorporate the alteration of the sediment regime into the assessment of the hydromorphological state. This methodology should then be tested and applied on several rivers in the DRB and based on these results, the method should be evaluated and eventually further improved.

Many ecological measures that are being implemented to improve ecology in the DRB, such as side-arm and floodplain reconnection, removal of bank protection and river widening, often also have positive effects on the sediment regime. Many aquatic and semi-terrestrial species depend on habitats provided by a diverse morphology, natural grain sizes etc. A poor status of the sediment regime and of the morphodynamics might have an adverse effect on these species. This means that measures that only consider improvements for the species, e.g. improved migration at barriers, but not for the sediments, may not or may only partially have the desired success. We therefore recommended strengthening the cooperation between biotic and abiotic components of the river. The linkages between efforts to develop a sediment framework and e.g. the Habitats Directive, should be strengthened within future development of a European sediment framework.

Since sediment-related problems should rather be treated at the source of the problem, measures implemented in the catchment area are essential and important steps in many cases. If an increase of fine sediment fractions is the problem, land use management and optimized cultivation to reduce the sediment output from,

e.g. agriculture, need to be considered as relevant measures. Such measures are more effective when they are supported by administrative measures. In addition, when we look at the output from agricultural areas, the loads of nutrients entering the river system can be reduced with adequate measures. In cases of bed material deficit in the river, the amount of bedload entering the river should be increased, e.g. by modifying torrent barriers to allow bedload to pass into the river system, which needs to always take flood risk management into account.

When ecological measures are implemented, these should fit to the general pattern and the morphological type of the river. Here, we recommend to carefully select the reference state and general orientation. The historical state can give some valuable indications, but in an altered river system, where the rivers are narrowed and channelized and the sediment input from upstream is interrupted, also the current situation needs to be taken into account. Ecologically worthwhile measures can have negative impacts on the sediment regime when implemented at the wrong location. For example, when islands are built to improve habitat diversity, this is generally seen as positive. However, if implemented at the wrong locations, such as narrow reaches with bed erosion tendencies, these islands can have negative impacts and further increase bed erosion.

In the Danube River Basin, there are still several sediment data-related issues that need to be addressed. These issues will require a harmonized sediment monitoring that applies the same methodology on a transboundary level. The sediment monitoring should consist of sediment transport, bed material, bed level changes, dredging and feeding as well as floodplain sedimentation. In addition to collecting these parameters, the regular hydromorphological assessments described in the update of CEN standard EN 15843:2010 (Water quality – Guidance standard on determining the degree of modification of river hydromorphology), which is currently in the revision procedure, should be closely interlinked with the sediment monitoring. This would support the recognition of ongoing processes and planning targets for larger, often transboundary river reaches. The harmonized monitoring system should be coordinated on a high level of transboundary governance, e.g. by ICPDR. Long-term sediment data should be stored in well-managed databases in the respective countries and be provided to a central database at e.g. ICPDR, which and should be made available for stakeholders.

Part D Factsheets

STRUCTURE OF THE FACTSHEETS

The following factsheets describe in a generalized way potential and implemented sediment management measures that improve the sediment regime. These factsheets can support various stakeholders dealing with sediment-related issues. It must be noted that the same measure can always be seen from different points of view, depending on the stakeholder and the site-specific impact of the measure. This is the main challenge of designing and implementing a measure, since it is important that a measure not only meet the needs of one stakeholder but can be harmonized with the needs of others.

The measures in the factsheets have the aim to improve/solve/mitigate the anthropogenically induced sediment imbalance of the Danube. Simply put, this means that there is too much sediment in one place and too little in another. Over two pages, the factsheets provide basic information on sediment management activities and are grouped according to the stakeholder for whom the measure is relevant. They contain information on the scale of application, the objective of the measure, the effects on hydromorphology and ecology as well as interrelations with other stakeholders and measures. In general these interrelations, synergies or conflicts that may arise due to the implementation of a measure, are typically site-specific and usually depend on local conditions and factors. Combining sediment-related measures adds an additional layer of complexity, especially when at the same time multiple purposes and goals are pursued or need to be achieved. In these cases, the interrelations indicated in the factsheets can have an effect and need to be considered by the stakeholders involved.

The factsheets present a selection of types of restoration and engineering measures, including the integrated aims from the perspective of hydromorphology (water and sediments), ecology and technical aspects. Content and structure of the factsheets is as follows:

Header of the factsheet:

- Alphanumeric identifier for the measure referenced to the overview table; the letter indicates the stakeholder (F – Flood protection, H – Hydropower, N – Navigation, RBM – River Basin Management including Land Use and Ecology) for whom the measure is of relevance
- Stakeholder who benefits from the implemented measure or with whom the measure is related, e.g. inland navigation, hydropower, flood protection, ecology, river basin management including land use and ecology
- **Measure:** Name, short description of the measure.

Factsheet table:

- **Location:** Indicates where the measure is implemented (e.g. river channel/main stream, riverbanks/near bank zone, floodplain, dam , weir, impoundment, reservoir)
- **Application:** Describes if the measure is applied in the catchment, an impoundment or reservoir, a free-flowing section and in a gravel or sand bedded river
- **Main aim:** Short description of the intended purpose of the measure
- **Goal(s) of the measure:** Description of the function/objective of the measure in relation to sediments and the addressed stakeholder
- **Parameter:** The main hydromorphological variables that the measure mainly has an effect on (e.g. sediments: bedload and suspended sediment transport; hydraulics: flow velocity, water depth; fluvial energy: bed shear stress, stream power; substrate; channel dimensions; connectivity/continuity resp. fragmentation)

- **Effects:** Specification of the changes that are caused by a measure, concerning different variables that are associated with a hydromorphological process (e.g. hydrodynamics, sediment dynamics) and the subsequent ecological response. The effects are rated as low, medium and high based on expert judgment according to the intensity of the associated changes.
- **Recurrence of the measure:** Indicates if a measure needs to be repeated after implementation or if some sort of maintenance is necessary. Feeding, for instance, is a recurring measure, which is necessary to maintain the effect. Reconfiguration of hydraulic structures, for instance, is non-recurring in the sense that it is effective after implementation or as long as the structure is not damaged and boundary conditions (e.g. bed levels) do not change. This does not imply that adaptations should not be undertaken, since any structure built in a dynamic system might need to be changed, depending on the boundary conditions.
- **Level:** Refers to the level of development of a measure. State-of-the-art (functional/practical efficiency was tested and proven), tested (at least one successful implementation in a pilot project), state-of-science (no field test yet – conceptual stage, tested in a laboratory or a numerical model)
- **Scaling:**
  - Spatial: Indicative of the location of the implemented measure (local/point, reach/sectional, catchment); it also indicates if there is an impact in lateral, upstream and/or downstream direction.
  - Temporal: Indicative for the length of time in which the measure is effective (short-term, mid-term or long-term).
- **Interrelation:** Interrelations with other relevant stakeholders that might be affected and/or that might implement sediment-related measures. This indicates potential conflicts or synergies with other stakeholders.
- **Assessment:** Describes ways to assess the effect and success of a measure – mostly in terms of monitoring (abiotic and biotic parameters).
- **Notes/Risks:** Additional points that need to be considered in relation to the measure.
- **Interrelation with other measures:** Lists possible combinations with other measures to achieve the same aim and increase synergies.

Controlled sediment transfer at barriers (improve sediment continuity) (© IWA/BOKU)

D.1 CATCHMENT SCALE

Figure 36 shows sediment management measures in the catchment. The ones highlighted in bold are described in the following factsheets.

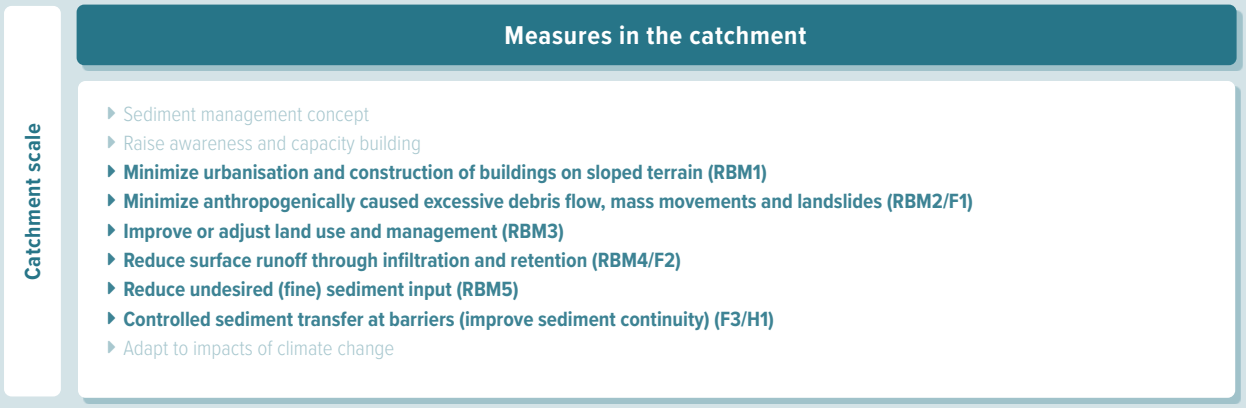
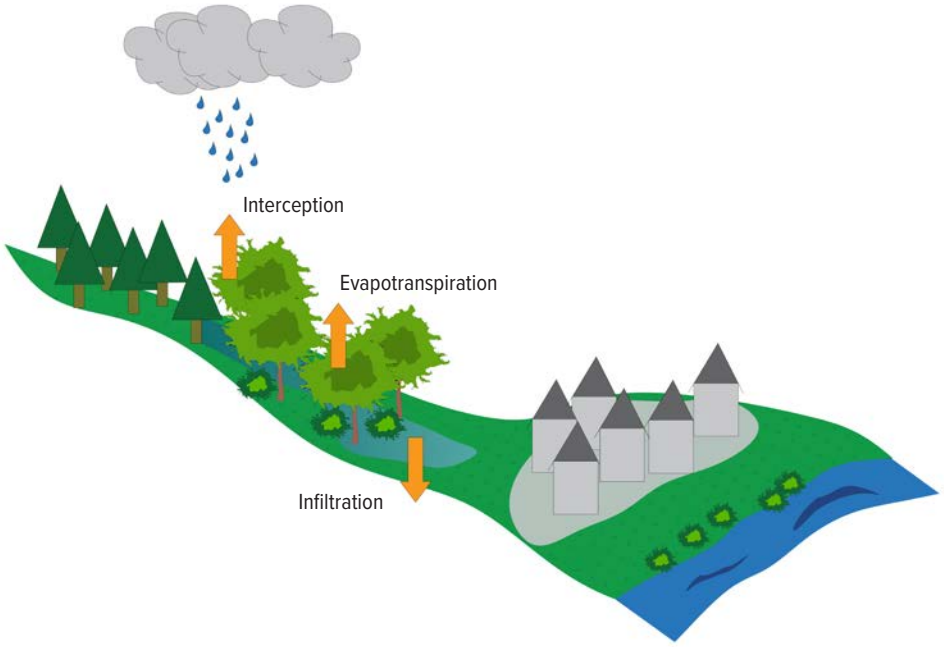


Figure 36: Overview of sediment management measures in the catchment; measures that are described in a factsheet are highlighted in bold

RIVER BASIN MANAGEMENT								RBM 1
Measure			**Minimize urbanisation and construction of buildings on sloped terrain**					
Location			Sloped terrain					
Application			Catchment					
Main aim			Reduce soil erosion and mass movement (reduce surface runoff and thus soil erosion and fine sediment inflow to rivers)					
Parameter			Surface runoff, infiltration, groundwater level, evaporation					
Goals of measure	**Sediment**		Reduce storm water runoff and soil erosion					
	River basin management		Increase green areas for the development of plant growth					
			Ensure mass stabilisation to prevent landslides, rockfall etc. through specific structural or planting measures					
			Increase of groundwater level					
Effects	**L** Low **M** Medium **H** High		**Parameter**		**Effects (main channel)**			
	Hydro-dynamics		Water level	**H**	decreased at high flow			
			Flow velocity	**L**	decreased at high flow			
			Shear stress	**L**	decreased at high flow			
	Sediment-dynamics		Transport capacity	**L**	decreased at high flow			
			Continuity		no effects			
	Morpho-dynamics		River morphology		no effects			
	Ecology		Habitat diversity / refugial habitats	**L**	no effects in the river			
Type of measure					Non-recurring	X	Recurring	
Categories			State of the art	X	Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**		Local scale		Reach scale	X	Catchment scale	
					Upstream effects	X	Downstream effects	
	Temporal		Short-term		Mid-term	X	Long-term	
Interrelation with		X	Flood protection	X	Hydropower			
			River basin management incl. Ecology		Navigation			
Assessment	–							
Notes / Risks	Increasing demand of space due to growing population must be considered.							
Interrelation with other measures	Sediment management concept, improve or adjust land use and management							

RIVER BASIN MANAGEMENT	RBM 1
Measure	**Minimize urbanisation and construction of buildings on sloped terrain**

POSITIVE



NEGATIVE

Examples	–
Reference	–

RIVER BASIN MANAGEMENT / FLOOD PROTECTION	RBM 2	F 1
Measure	**Minimize anthropogenically caused excessive debris flows, mass movements and landslides**	

Location		Torrents, head water streams, sloped terrain
Application		Catchment Gravel / debris carrying tributaries in the mountainous region
Main aim		Reduce sedimentation (prevent debris flows from entering the rivers)
Parameter		Input of coarser material, rock fall, landslide, water level, reservoir capacity
Goals of measure	**Sediment**	Reduce excessive inflow of coarser sediments into rivers
	Flood protection	Enhance flood protection and water retention, e.g. by increased vegetation
	River basin management	Ensure mass stabilisation to prevent landslides, rock fall etc. through specific structural or planting measures

Effects	L Low M Medium H High	**Parameter**	**Effects (main channel)**	
	Hydro-dynamics	Water level	L decreased at high flow	
		Flow velocity		
		Shear stress		
	Sediment-dynamics	Transport capacity	M decreased input of coarser sedi-ments	
		Continuity	M decreased	
	Morpho-dynamics	River morphology	M	
	Ecology	Habitat diversity / refugial habitats	L eventually decreased	

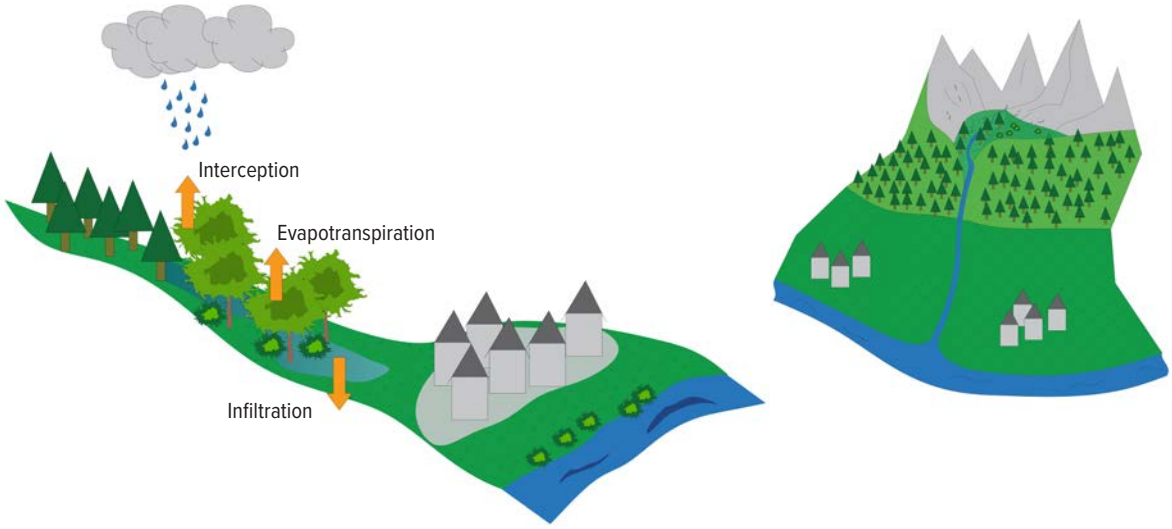
Type of measure			X	Non-recurring		Recurring
Categories		X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**			Reach scale	X	Catchment scale
				Upstream effects	X	Downstream effects
	Temporal			Mid-term	X	Long-term
Interrelation with		X Flood protection	X	Hydropower		
		X River basin management incl. Ecology		Navigation		

Assessment	Aerial and satellite images
Notes / Risks	Periodical removal of deposited debris near the barrier.
Interrelation with other measures	Reduce undesired (fine) sediment input, controlled sediment transfer at barriers (improve sediment continuity), adapt to impacts of climate change

RIVER BASIN MANAGEMENT / FLOOD PROTECTION	RBM 2	F 1
Measure	**Minimize anthropogenically caused excessive debris flows, mass movements and landslides**	

POSITIVE

Minimize excessive water inflow in the catchment by enhancing vegetative growth.



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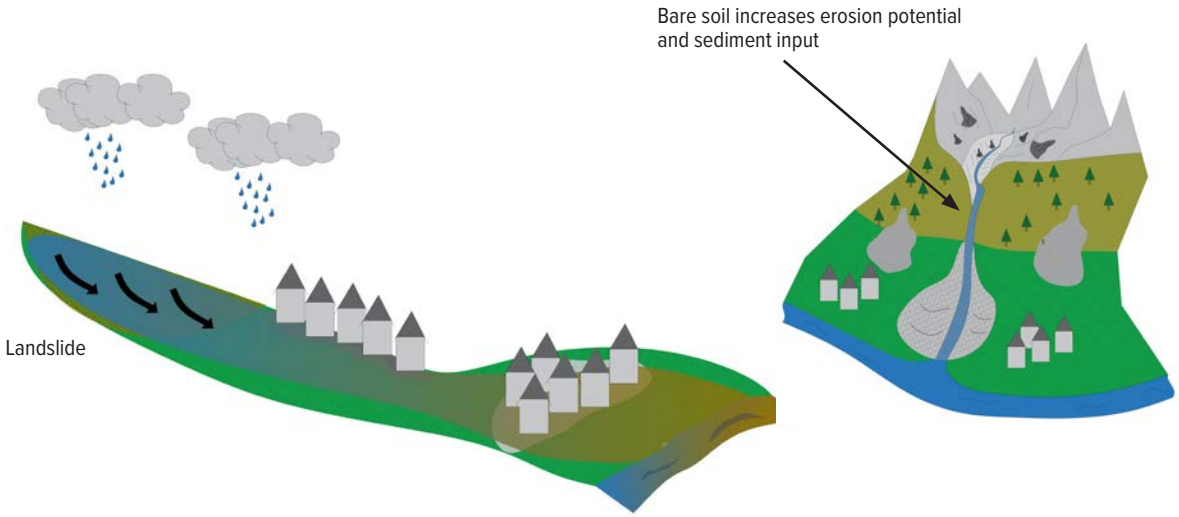


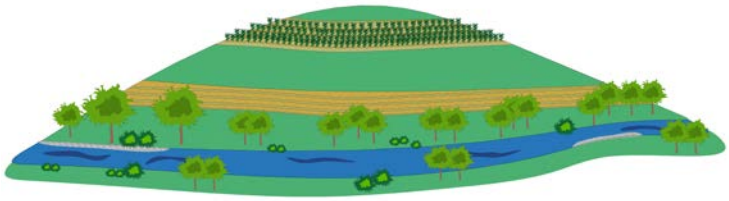
Examples	–
Reference	–

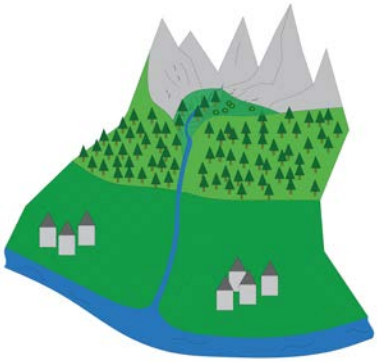
RIVER BASIN MANAGEMENT								RBM 3
Measure			**Improve or adjust land use and management**					
Location			Riverine area					
Application			Catchment					
Main aim			Reduce sedimentation (less soil erosion on agricultural land)					
Parameter			Substrate, sediment input into rivers					
Goals of measure	**Sediment**		Control soil erosion at the source through non-structural measures					
			Retention of sediments, water and nutrients					
			Ensure mass stabilisation to prevent landslides, rockfall etc. through specific structural or planting measures					
	River basin management		Maintain sustainable function of agricultural land					
Effects	**L** Low **M** Medium **H** High		**Parameter**		**Effects (main channel)**		**Note**	
	Hydro-dynamics		Water level	**L**	decreased			
			Flow velocity	**L**	minor effects			
			Shear stress	**L**	minor effects			
	Sediment-dynamics		Transport capacity	**L**	decreased input of fine sediments into water bodies		depending on e.g. size, vegetation, etc. of measure	
			Continuity	**L**	minor effects			
	Morpho-dynamics		River morphology	**L**	minor effects		depending on e.g. size, vegetation, etc. of measure	
	Ecology		Habitat diversity / refugial habitats	**L**	improved habitats (less fine sediment clogging)			
Type of measure					Non-recurring	X	Recurring	
Categories		X	State of the art		Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**		Local scale		Reach scale	X	Catchment scale	
					Upstream effects	X	Downstream effects	
	Temporal		Short-term		Mid-term	X	Long-term	
Interrelation with		X	Flood protection	X	Hydropower			
			River basin management incl. Ecology		Navigation			
Assessment	–							
Notes / Risks	This administrative measure effectively supports land users and /or farmers in reducing soil erosion and thereby reduces the input of fine sediment and nutrients into water bodies. In the sense of the WFD, this measure is an important contribution to improving or achieving the good ecological and chemical status.							
Interrelation with other measures	Sediment management concept, reduce surface runoff through infiltration and retention, minimize urbanisation and construction of buildings on sloped terrain							

RIVER BASIN MANAGEMENT — RBM 3

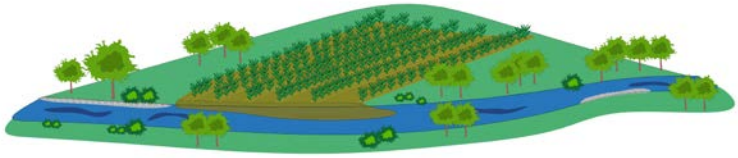
Measure | **Improve or adjust land use and management**

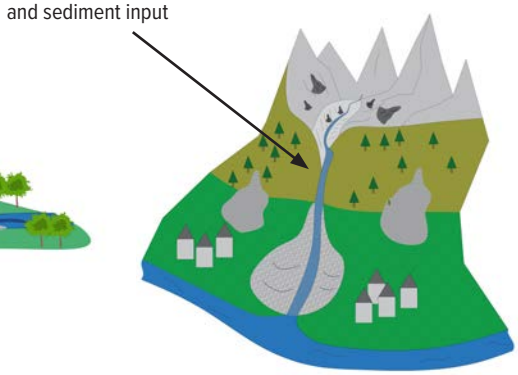
POSITIVE





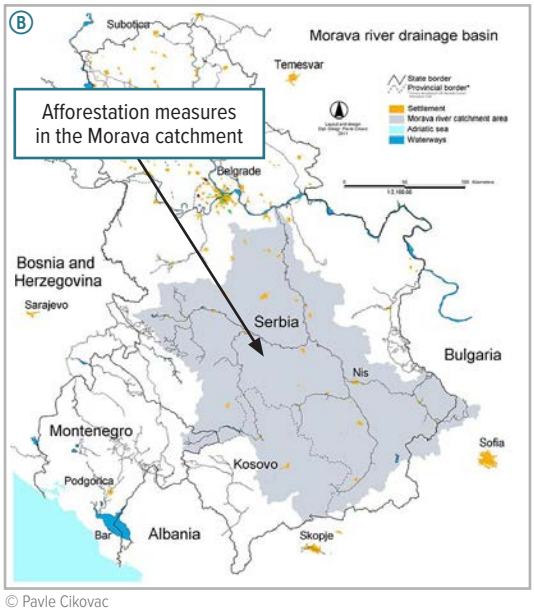
NEGATIVE





Examples

© USDA/Tim McCabe



© Pavle Cikovac

Reference

(A) Contour ploughing in Iowa, USA (https://livinghistoryfarm.org)
(B) Afforestation measures are implemented in the Morava catchment
(See DanubeSediment report „Sediment Management Measures for the Danube", factsheet code in annex 2: E_FF_H_T_P02)

RIVER BASIN MANAGEMENT / FLOOD PROTECTION	RBM 4	F 2

Measure	**Reduce surface runoff through infiltration and retention**

Location		Urban and infrastructure areas, riverine area
Application		Catchment
Main aim		Reduce sedimentation (reduce surface runoff and thus fine sediment input to water bodies)
Parameter		Surface runoff, infiltration rate, groundwater level, evaporation
Goals of measure	**Sediment**	Reduce surface runoff and consequently increase water and fine sediment retention
	Flood protection	Improve flood protection through increased infiltration
	River basin management	Ensure mass stabilisation to prevent landslides, rockfall etc. through specific structural or planting measures
		Increase of groundwater level

Effects	L Low / M Medium / H High	**Parameter**		**Effects (main channel)**	
	Hydro-dynamics	Water level	H	decreased at high flow	
		Flow velocity	L	decreased at high flow	
		Shear stress	L	decreased at high flow	
	Sediment-dynamics	Transport capacity	L	decreased at high flow	
		Continuity		no effects	
	Morpho-dynamics	River morphology		no effects	
	Ecology	Habitat diversity / refugial habitats	L	no effects in the river, but increased vegetated areas in the catchment	

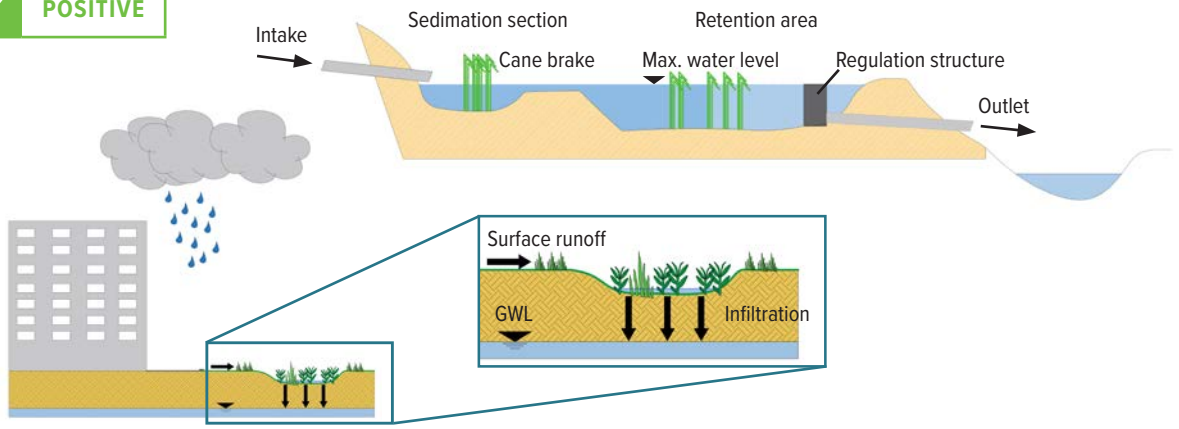
Type of measure				Non-recurring	X	Recurring
Categories	X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling		Local scale		Reach scale	X	Catchment scale
	Spatial			Upstream effects	X	Downstream effects
	Temporal	Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection	X	Hydropower		
	X	River basin management incl. Ecology		Navigation		

Assessment	–
Notes / Risks	–
Interrelation with other measures	Improve or adjust land use and management, reduce undesired (fine) sediment input

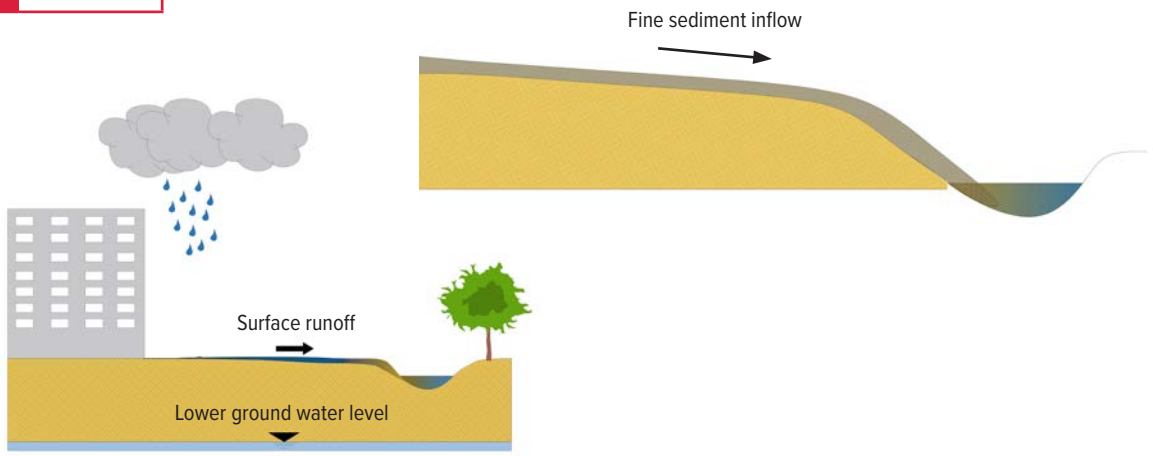
RIVER BASIN MANAGEMENT / FLOOD PROTECTION — RBM 4 — F 2

Measure — **Reduce surface runoff through infiltration and retention**

POSITIVE



NEGATIVE



Examples

Trough-trench system

© AxelHH

Reference — Runoff retention reservoirs, project „boden:ständig“ (https://bit.ly/retenres) see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_C_A_T_GP71

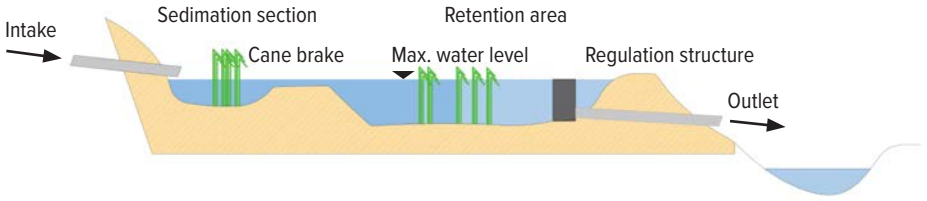
RIVER BASIN MANAGEMENT								RBM 5
Measure			**Reduce undesired (fine) sediment input**					
Location			Agricultural areas and grassland next to riverbanks					
Application			Catchment					
Main aim			Reduce sedimentation (prevent sediments from entering the water bodies)					
Parameter			Water level, flow velocity, input of fine sediments and nutrients					
Goals of measure	**Sediment**		Reduce soil erosion on agricultural land and consequently decrease fine sediment input to rivers					
	River basin management		Increase soil resistance during heavy rain events by planting of vegetation					
			Ensure mass stabilisation to prevent landslides, rockfall etc. through specific structural or planting measures					
Effects	**L** Low **M** Medium **H** High		**Parameter**		**Effects (main channel)**			
	Hydro-dynamics		Water level		**L** decreased due to runoff retention			
			Flow velocity		**L** minor effects			
			Shear stress		**L** minor effects			
	Sediment-dynamics		Transport capacity		**M** decreased input of fine sediments into water bodies			
			Continuity		**L** minor effects			
	Morpho-dynamics		River morphology		no effects			
	Ecology		Habitat diversity / refugial habitats		**L** improved habitat conditions			
Type of measure				X	Non-recurring		Recurring	
Categories		X	State of the art		Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**		Local scale		Reach scale	X	Catchment scale	
					Upstream effects	X	Downstream effects	
	Temporal		Short-term		Mid-term	X	Long-term	
Interrelation with		X	Flood protection	X	Hydropower			
			River basin management incl. Ecology		Navigation			
Assessment			Monitoring of surface runoff and sediment erosion					
Notes / Risks			Buffer strips show best effects when created as u-formed hollow and combined with related measures. Roughness of surface and filtering function can be optimized depending on vegetation. This measure is no replacement for erosion protection measures on agricultural areas, but a good addition. For steep slopes, runoff retention reservoirs are recommended for controlled drainage of water (see corresponding measure). If such measures are planned, farmers and water authorities must be involved as early as possible. The riparian buffer strips can also include shrubs and trees suitable for the location next to water bodies.					
Interrelation with other measures			Reduce surface runoff through infiltration and retention, improve or adjust land use and management, minimize urbanisation and construction of buildings on sloped terrain					

RIVER BASIN MANAGEMENT — RBM 5

Measure | **Reduce undesired (fine) sediment input**

POSITIVE

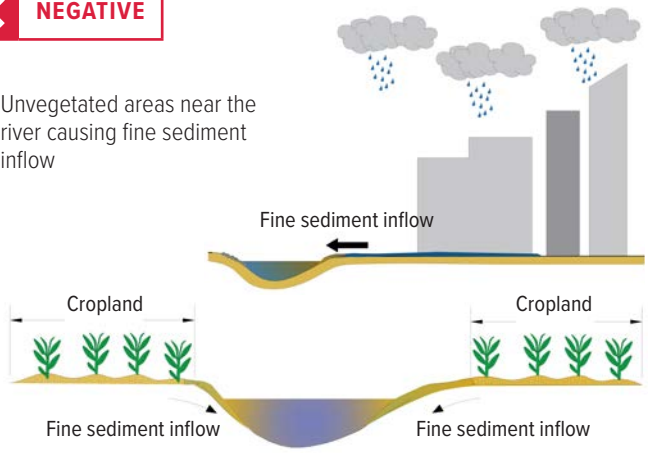
Retention basin
(for sediment settling)



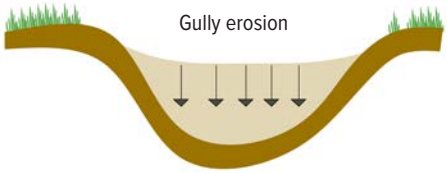
Buffer strips

NEGATIVE

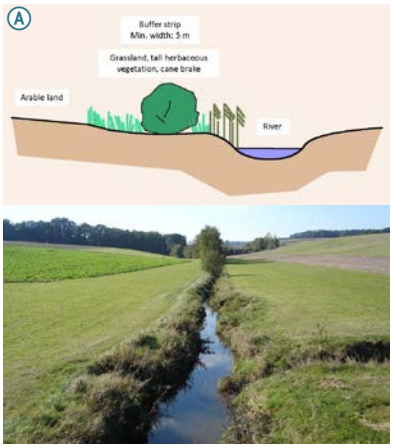
Unvegetated areas near the river causing fine sediment inflow



Unvegetated areas can lead to gully erosion



Examples



© ARGE Lenz/Knogler/Karlstetter

© Lakew & Belayneh

Reference

Ⓐ Riparian buffer strips in Bavaria, GER (https://bit.ly/buffer_strip) see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_C_A_T_GP72. Source: ARGE Lenz/Karlstetter/Knogler (2006): Sanierung des landschaftlichen Stoffhaushalts durch Ländliche Entwicklung, Ingenieurökologische Entwicklungskonzepte zum Ressourcenmanagement: Integration in die Landschaftsplanung in der Ländlichen Entwicklung aufgezeigt am Einzugsgebiet des Schwimmbachs, Niederbayern; Teil A: Planungs- und Umsetzungshilfen)

Ⓑ Gabion check dam filled with soil and its effect after one year in South Gondar, ET (Lakew, D. & Belayneh, A., 2012. Nile Basin Initiative. A Field Guide on Gully Prevention and Control)

FLOOD PROTECTION / HYDROPOWER — F 3 — H 1

Measure		**Controlled sediment transfer at barriers (improve sediment continuity)**
Location		Head water streams, torrents
Application		Gravel and boulder bed rivers
		Head water streams, torrents
Main aim		Improve sediment continuity, reduce riverbed erosion in the downstream reach and reduce bedload deposition upstream of, or at the barrier.
Parameter		Substrate (quantity and size), bedload transport continuity, transport rates, large woody debris
Goals of measure	**Sediment**	Reactivating bedload transport and enhancing sediment continuity
		Reducing the need for bedload removal upstream of the barrier
	Flood protection	Ensure mass stabilisation to prevent landslides, rock fall etc. through specific structural or planting measures

Effects — L Low / M Medium / H High

Parameter		Effects (upstream of the barrier)		Effects (downstream of the barrier)	
Hydro-dynamics	Water level	L	decreased at high flows	L	eventually increased
	Flow velocity	M	increased during high flows	L	eventually increased during high flows
	Shear stress	M	increased during high flows	L	eventually increased during high flows
Sediment-dynamics	Transport capacity	M	increased	M	more available for transport
	Continuity	H	increased (esp. bedload material)	H	improved bedload supply
Morpho-dynamics	River morphology	M	increased morphodynamics	M	increased morphodynamics (esp. bedload transport)
Ecology	Habitat diversity / refugial habitats	L	minor effects	M	improved due to supply of bedload

Type of measure			Non-recurring		Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling — **Spatial**			Reach scale		Catchment scale
			X Upstream effects		X Downstream effects
Temporal			Mid-term		X Long-term
Interrelation with	X Flood protection		X Hydropower		
	X River basin management incl. Ecology		Navigation		

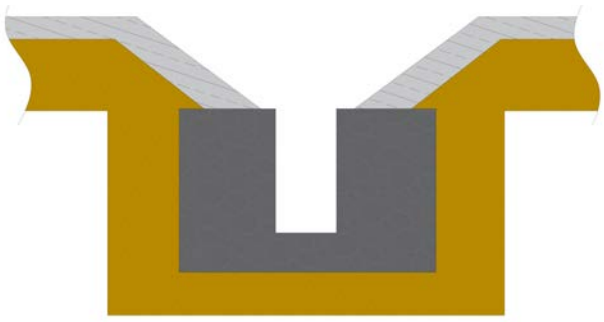
Assessment	Survey of the downstream riverbed; survey of the sediment deposits upstream of the barriers.
Notes / Risks	Traditional check dams only provide temporal storage and can become potentially unstable and costly to maintain. Retrofitting the barriers is a good option but more expensive than incorporating this measure early into the planning or design phase. Proper design necessary since large boulders and woody debris should be trapped during events to reduce the natural hazard. However, the transfer of bedload material needs to be enabled. Easy access for heavy equipment, since there is still a need for maintenance after larger events. Trapped sediments should be removed and reinserted downstream. To reduce downstream impacts, especially concerning flood protection, integrated planning is necessary, especially together with water and flood risk management.
Interrelation with other measures	Sediment management concept, all other measures in the catchment, sediment bypass (tunnel, channel), bedload drift, wet or dry dredging and reinsertion, minimize fixed weir sill height, local sediment bypass, enlarge morphological space of rivers, river widening, increase river length to reduce slope, modify resp. remove barriers

FLOOD PROTECTION / HYDROPOWER

F 3 | H 1

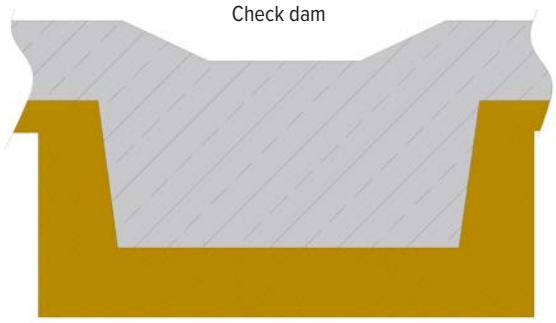
Measure | **Controlled sediment transfer at barriers (improve sediment continuity)**

POSITIVE



Bedload material can pass the barrier, while boulders and large woody debris are trapped.

NEGATIVE



Bedload transport is completely stopped at the barrier.

Examples

© WWA Weilheim

© Steinwendtner

© Gmeiner/IWA-BOKU

Reference

Ⓐ Self-flushing barrier at the river Isar near Wackersberg, GER (see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_FP_T_P10)
Ⓑ Slit-Check dam, AT (Institute of Mountain Risk Engineering, BOKU Vienna (2003): WLS report 50 / Band 2)
Ⓒ Slit-Check dam, JPN

River bank restoration (© IWA/BOKU)

D.2 REACH / SECTIONAL SCALE

Figure 37 shows sediment management measures on the reach/sectional scale for reservoirs or impoundments and free-flowing sections. The ones highlighted in bold are described in the following factsheets.

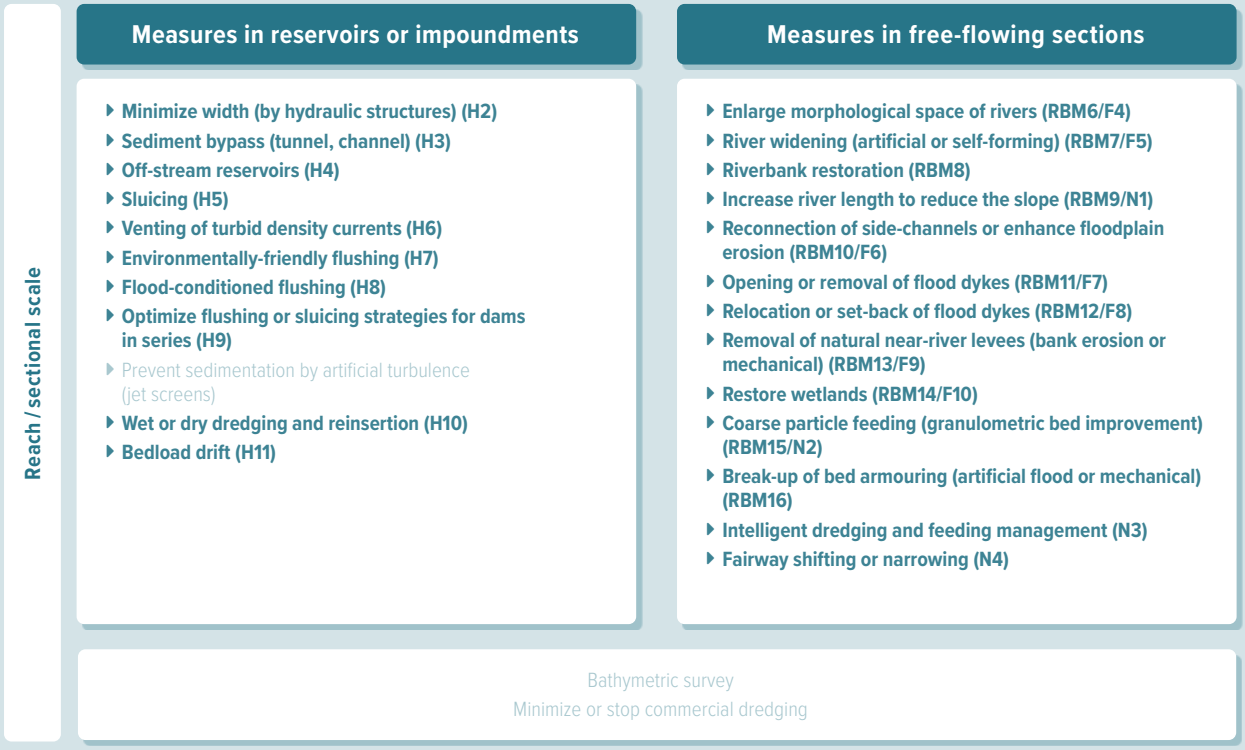


Figure 38: Overview of sediment management measures on the reach/sectional scale for reservoirs or impoundments and free-flowing sections; measures that are described in a factsheet are highlighted in bold

D.2.1 Measures in reservoirs/impoundments

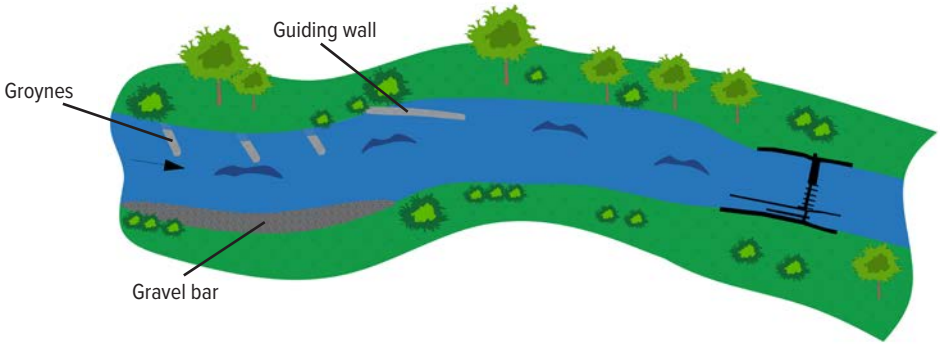
HYDROPOWER							**H 2**
Measure			**Minimize width of the impoundment or reservoir (by hydraulic structures)**				
Location			Impoundments and reservoirs in the near bank zone				
Application			Existing and newly built reservoirs and impoundments Gravel and sand bed river				
Main aim			Reduce sedimentation, improve sediment transport capacity, improve sluicing and flushing efficiency				
Parameter			Sediment transport, water level, flow velocity, shear stress, habitat diversity				
Goals of measure	**Sediment**		Prevent / reduce sedimentation due to narrowing effects in the impoundment and improve sediment transport capacity				
	Ecology		Improve ecological conditions at riverbanks when structures made of gravel or sand Create refugial habitats for aquatic fauna to find shelter from flood events and vessel-induced waves				
	Flood protection		Enhance flood protection through reduced sedimentation				
	Hydropower		Ensure long term hydroelectric power production by preserving the reservoir capacity, reduce maintenance works				
Effects	**L Low** **M Medium** **H High**	**Parameter**		**Effects (impoundment / reservoir)**		**Effects (riverbanks)**	
	Hydro-dynamics	Water level		**L**	increased	**M**	higher diversity (bars and islands)
		Flow velocity		**M**	increased	**M**	higher diversity (bars and islands)
		Shear stress		**M**	increased	**L**	decreased
	Sediment-dynamics	Transport capacity		**M**	increased	**L**	eventually decreased
		Continuity		**M**	increased	**L**	eventually decreased
	Morpho-dynamics	River morphology		**L**	increased morphodynamics in the main channel	**L**	increased morphodynamics
	Ecology	Habitat diversity / refugial habitats				**H**	increased
Type of measure				X	Non-recurring		Recurring
Categories		X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**		Local scale	X	Reach scale		Catchment scale
					Upstream effects	X	Downstream effects
	Temporal		Short-term	X	Mid-term	X	Long-term
Interrelation with		X	Flood protection		Hydropower		
		X	River basin management incl. Ecology	X	Navigation		
Assessment		Bathymetric surveys and surveys of the structures Bedload and suspended sediment load (especially when measure part of flushing operation) Water levels Structures made of gravel or sand: Grain sizes, fish, macrozoobenthos Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules					
Notes / Risks		Width reduction of the impoundment/reservoir (original width of the river can serve as a baseline for the required narrowing effects) In a cascade of dams, analyse the potential influence on downstream dams and the need for their incorporation into an overarching sediment management. Risk of bedload deposition directly downstream of the dam, if not mitigated by additional measures. Flushing should be performed in an environmentally friendly way (i.e. sediment concentrations that the environment can endure). Can reduce deposition of coarse sediments and flood risk in the head of the reservoir / impoundment. Risk of enhanced erosion in the head of impoundments if too much narrowing occurs and if an upstream bedload supply is missing. Especially in the head of impoundments with nearly free flowing conditions, there is a possibility for habitat enhancement. Risk of fine sediment deposition in areas not influenced by the main stream current after flood events.					
Interrelation with other measures		All measures related to hydropower, bathymetric surveys					

HYDROPOWER — H 2

Measure	**Minimize width of the impoundment or reservoir (by hydraulic structures)**

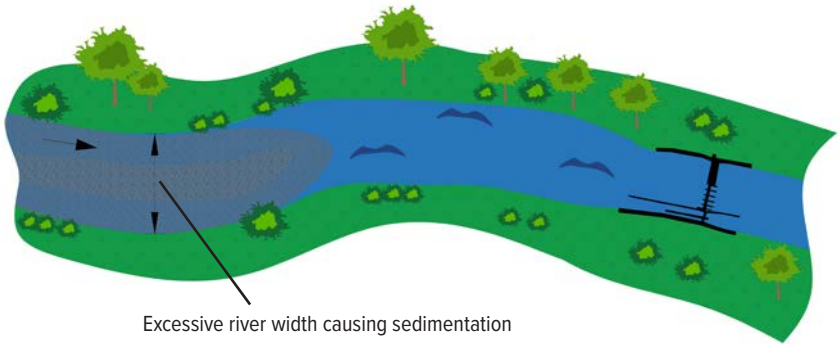
POSITIVE

A dynamic equilibrium is reached (short-term erosion and sedimentation processes, but stable riverbed in the long run).



NEGATIVE

Excessive river width leading to long-term sedimentation processes.



Examples

© Google maps

Reference	Implementation of a guiding wall at HPP Ering-Frauenstein (Inn, AT/ D) Further examples: See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_R_H_T_GP53

3

HYDROPOWER — H 3

Measure	**Sediment bypass (tunnel, channel)**
Location	Reservoirs and impoundments – upstream part or close to the dam
Application	Existing and newly built reservoir or impoundment
	Gravel and sand bed river
Main aim	Route sediments around the reservoir to reduce sedimentation and maintain transport
Parameter	Sediment transport continuity, substrate, transport rates, water depth, water level, reservoir capacity
Goals of measure – **Sediment**	Prevent reservoir sedimentation
	Improve / restore sediment continuity
Flood protection	Enhance flood protection through reduced sedimentation
Hydropower	Maintain reservoir capacity and reduce damages at the dam and the hydropower plant

Effects (L Low / M Medium / H High)

Parameter	Effects (upstream of the HPP)	Effects (downstream of the HPP)
Hydro-dynamics		
Water level	L decreased	L eventually increased
Flow velocity	no effects	no effects
Shear stress	no effects	no effects
Sediment-dynamics		
Transport capacity	H increased	
Continuity	H increased	H increased supply
Morpho-dynamics		
River morphology	L minor effects	M improved morphodynamics
Ecology		
Habitat diversity / refugial habitats	L minor effects	M improved when bedload supplied

Type of measure		X Non-recurring	Recurring
Categories	X State of the art	X Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale	X Reach scale	Catchment scale
		X Upstream effects	X Downstream effects
Temporal	Short-term	Mid-term	X Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	Navigation	

Assessment

Monitoring of potential damages in the bypass tunnel due to abrasion
Bathymetric surveys of the riverbed downstream and in the reservoir
Assessment of effects on ecology and plant operation.
Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

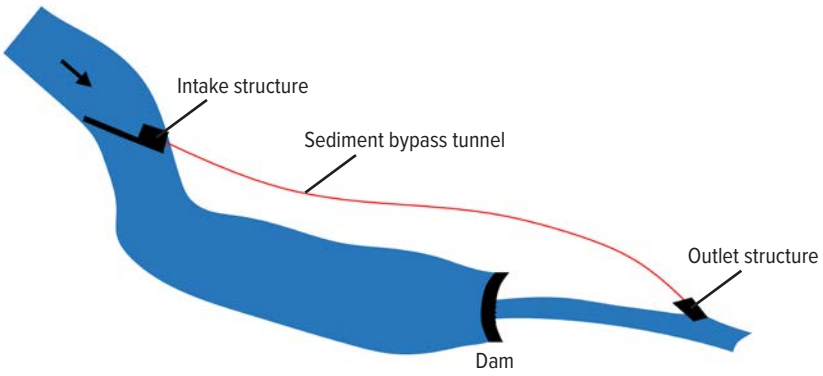
Despite the pros, the number of realized SBTs in the world is limited primarily due to high investment and maintenance costs.
Big advantage since sediments do not enter the reservoir but are routed around, allowing also coarse sediments to pass.
Depends on topography; ideal site: Sharp turn of the river to have short bypass. A certain bed slope is also necessary.
Weir or guiding wall might be necessary to divert sediments into the bypass.
Can be useful to retrofit at dams without appropriate outlets for sediment management (e.g. sluicing, environmentally friendly flushing).
High maintenance costs are caused by distinctive invert abrasion effects as a result of significant sediment transport rates at high velocities, putting the sustainable operation of these tunnels at risk.
Environmentally friendly: Downstream impact is lower than other sediment management strategies since sediment concentration below HPP is not significantly higher than at the inflow.

Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures; all measures in the downstream free-flowing sections that enhance the retention time of sediments (e.g. river widening, riverbank restoration, increase river length to reduce slope, relocation or set-back of flood dykes)

HYDROPOWER — H 3

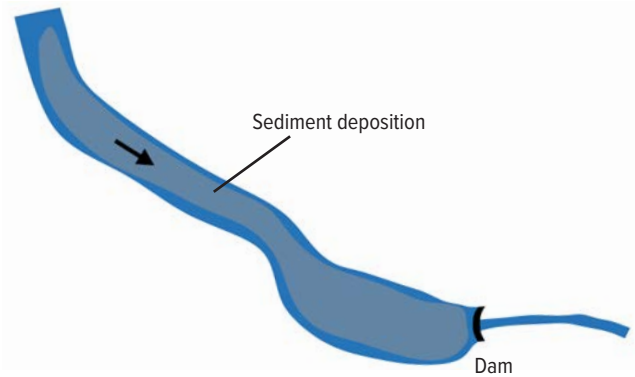
Measure | **Sediment bypass (tunnel, channel)**

POSITIVE

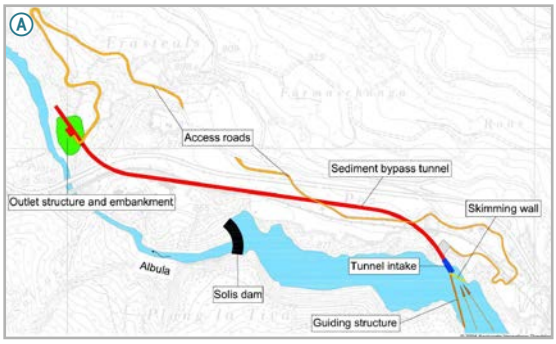


NEGATIVE

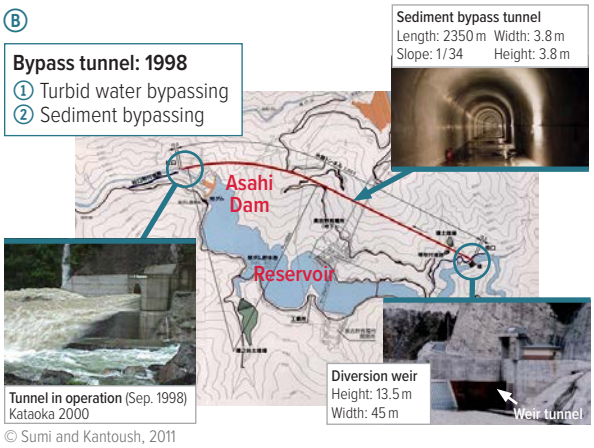
In case of no sediment bypass tunnel, sediments might deposit in the reservoir.



Examples



© Auel and Boes, 2011



© Sumi and Kantoush, 2011

Reference

Ⓐ Sediment bypass tunnel at Solis Dam, Switzerland (https://bit.ly/SolisSBT) (Auel, C. and Boes, R. 2011. Sediment bypass tunnel design - review and outlook. Dams and Reservoirs under Changing Challenges. Editors: Schleiss and Boes. Taylor & Francis Group, London, ISBN 978-0-415-68267-1)
See DanubeSediment report „Sediment Management Measures for the Danube", factsheet code in annex 2: S_R_H_O_GP59
Ⓑ Asahi Dam, Japan (Sumi, T. and Kantoush, S.A. 2011. Comprehensive Sediment Management Strategies in Japan: Sediment bypass tunnels.)

HYDROPOWER — H 4

Measure	**Off-stream reservoir**

Location		Bypass (off the main channel)
Application		Newly built reservoir
		Gravel and sand bed river
Main aim		Route sediments to reduce sedimentation in the reservoir and maintain transport
Parameter		Reservoir capacity, water depth, sediment inflow, sediment size
Goals of measure	**Sediment**	Prevent reservoir sedimentation by reduced inflow of sediment-laden water
		Increase sediment continuity in the main channel
	Hydropower	Ensure and prolong operability of hydropower plants, bypass sediments beyond the intake

Effects

L Low / M Medium / H High

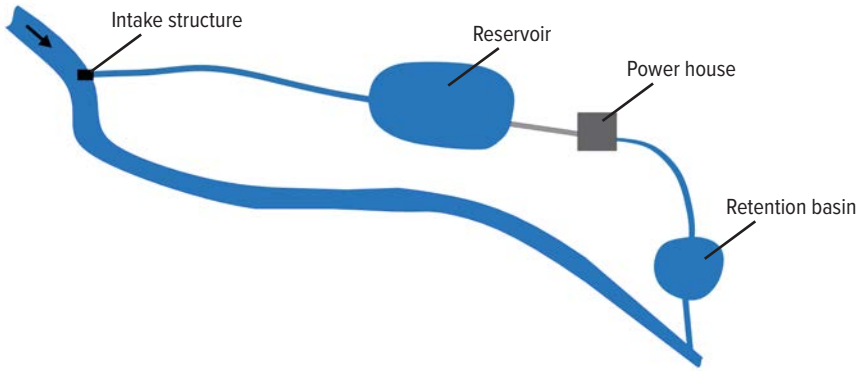
Parameter	Effects (reservoir)	Effects (main channel)
Hydro-dynamics		
Water level	H reduced increase of water level and depth	M reduced during lower flows – consistent during higher discharges
Flow velocity	no effects	M reduced during lower flows – consistent during higher discharges
Shear stress	no effects	M reduced during lower flows – consistent during higher discharges
Sediment-dynamics		
Transport capacity	H decreased sediment input	H preserved at higher discharges
Continuity	no effects	H preserved at higher discharges
Morpho-dynamics		
River morphology	no effects	M reduced during lower flows – consistent during higher discharges
Ecology		
Habitat diversity / refugial habitats	no effects	M reduced during lower flows – consistent during higher discharges

Type of measure		X Non-recurring	Recurring
Categories	X State of the art	Tested (implemented at least once)	State of science (no field test yet)
Scaling			
Spatial	Local scale	X Reach scale	Catchment scale
		X Upstream effects	X Downstream effects
Temporal	Short-term	Mid-term	X Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	Navigation	

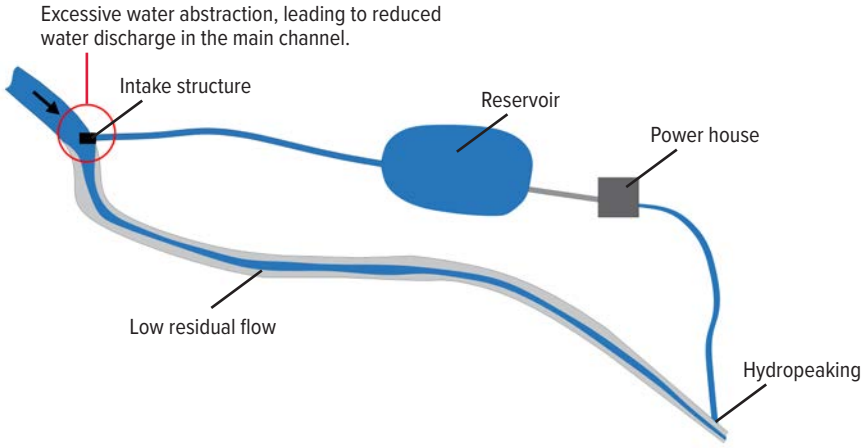
Assessment	Bathymetric surveys of the riverbed and in the reservoir, discharge measurements, suspended load and bedload
Notes / Risks	Proper location (e.g. on the outer bend) and construction of the intake to avoid sediment transport into the intake. Very fine sediments (wash load) will still be trapped; supplementary measures in the reservoir and in the catchment. Amount of water abstraction especially during low flow periods and downstream impacts need to be considered – assessment of necessary environmental flow needs to be done. Vegetation encroachment in the residual flow reach can lead to reduced morphodynamics and can reduce the discharge capacity during flood stage. Risk of stranding or wash-out (drift) of aquatic species, therefore hydro-peaking (rapidly changing water levels) needs to be mitigated; for example by hydropower operation or retention basins.
Interrelation with other measures	All measures in the catchment; all measures in the downstream free-flowing sections that enhance the retention time of sediments (e.g. river widening, riverbank restoration, increase river length to reduce slope, relocation or set-back of flood dykes); minimize fixed weir sill height, construct local sediment bypass

HYDROPOWER	H 4
Measure	**Off-stream reservoir**

POSITIVE



NEGATIVE



Examples	–
Reference	–

HYDROPOWER — H 5

Measure	**Sluicing**
Location	Reservoirs and impoundments
Application	Existing and newly built reservoirs or impoundments
	Gravel and sand bed river
Main aim	Route sediments through the reservoir to reduce sedimentation and maintain transport
Parameter	Sediment continuity (mainly fine sediments), sediment transport capacity, flow velocity, shear stress, outlet / gate capacity
Goals of measure – **Sediment**	Prevent sedimentation through water level drawdown during floods, which passes sediment-laden water through the reservoir / impoundment
Goals of measure – **Flood protection**	Long-term increase of flood protection by reducing sedimentation in the reservoir
Goals of measure – **Hydropower**	Ensure sustainable long term operability of the hydropower plant, reduce maintenance works

Effects (L Low / M Medium / H High)

Parameter	**Effects (upstream of the dam)**	**Effects (downstream of the dam)**
Hydro-dynamics – Water level	M decreased	M increased
Hydro-dynamics – Flow velocity	H increased	M increased
Hydro-dynamics – Shear stress	H increased	M increased
Sediment-dynamics – Transport capacity	M increased	M increased
Sediment-dynamics – Continuity	H increased (mainly fine sediments)	H increased (mainly fine sediment input)
Morpho-dynamics – River morphology	L increased morphodynamics	L increased morphodynamics especially when gravel is sluiced
Ecology – Habitat diversity / refugial habitats	L de-colmation effects, less silting	M transport during flood where load is naturally high

Type of measure			Non-recurring	X	Recurring
Categories	X	State of the art	Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X Reach scale		Catchment scale
			X Upstream effects	X	Downstream effects
Scaling – **Temporal**	X	Short-term	X Mid-term		Long-term
Interrelation with	X	Flood protection	Hydropower		
	X	River basin management incl. Ecology	Navigation		

Assessment

- Bathymetric surveys
- Monitoring of suspended sediment concentrations and bedload
- Monitoring of water levels to coordinate hydropower operation with approaching flood
- Impact on environment due to (changed) sediment management operation
- Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

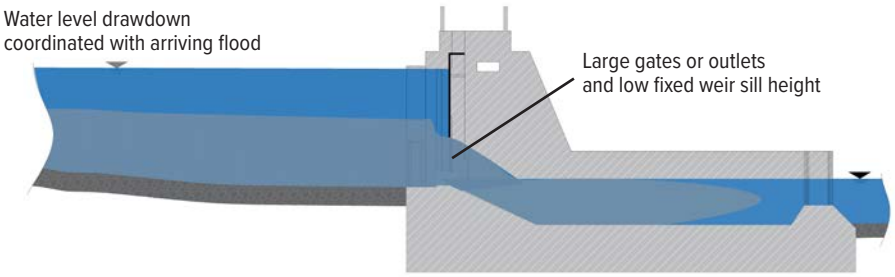
- Applied during periods of high discharges and sediment loads, with partial or full water level drawdown. Sediment transport capacity through the reservoir / impoundment needs to be high.
- Works on all sizes of reservoirs / impoundments; highest efficiency in long and narrow ones.
- Availability of excess water and large capacity gates needed to discharge large flows and to successfully sluice sediments. Retrofitting of such gates is expensive, therefore consider sediment management strategy already during planning phase of the HPP.
- Fine sediments transported more effectively than coarser ones.
- Flushing can lead to sedimentation in the downstream reservoirs and should therefore be coordinated with all hydropower plants in the cascade. The potential for excessive downstream sedimentation needs to be considered so that it does not hinder flood protection. In reservoirs with the purpose to attenuate flood waves, dam operations need to consider impacts on downstream water levels.
- Coordination with inland navigation to avoid potential conflict.
- Comparably low impact on the environment, since sediment loads are naturally high during sluicing.

Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, flood-conditioned flushing, optimized flushing or sluicing strategies for dams in series, minimize fixed weir sill height, install large bottom outlets or gates; bathymetric survey

HYDROPOWER — H 5

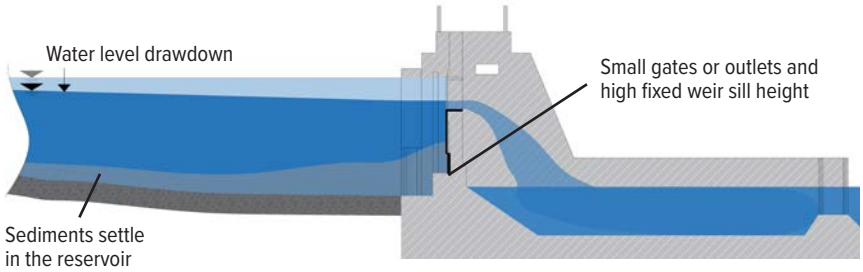
Measure | **Sluicing**

POSITIVE

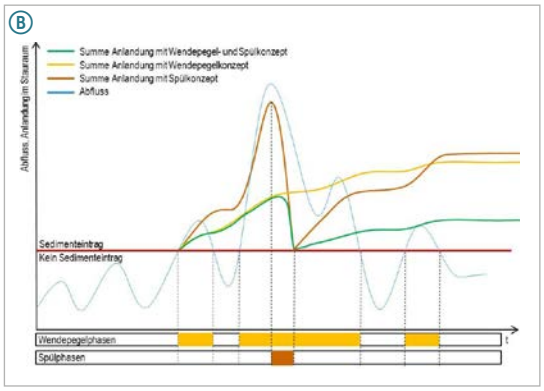


NEGATIVE

Wrong or no sluicing procedure leads sedimentation in the reservoir.



Examples



Reference

Ⓐ Sluicing at hydropower plant Melje, Drau River, SI (http://www.dem.si)

Ⓑ „Wendepegelkonzept“ at HPP Leoben, Mur River, AT (enhanced procedures regarding water level lowering in the reservoir in order to improve sediment management) (Badura, H. et al. 2016. Wendepegelkonzept zur dynamische Sedimentbewirtschaftung von Flussstauhaltungen am Beispiel Kraftwerk Leoben,Wasserbau – mehr als Bauen im Wasser. Beiträge zum 18. Gemeinschafts-Symposium der Wasserbau-Institute TU München, TU Graz und ETH Zürich vom 29. Juni bis 1. Juli 2016 in Wallgau, Oberbayern. ISBN 978-3-940476-10-3, Nr. 134, 400 Seiten.)

6

HYDROPOWER — H 6

Measure	**Venting of turbid density currents**
Location	Reservoirs and impoundments
Application	Existing and newly built reservoirs
	Gravel and sand bed river
Main aim	Route sediments through the reservoir to reduce sedimentation and maintain transport
Parameter	Sediment continuity (fine sediments), flow velocity, turbulence
Goals of measure – **Sediment**	Prevent / reduce sedimentation by routing turbid density currents through and out of the reservoir
Goals of measure – **Flood protection**	Long-term increase of flood protection by reducing sedimentation in the reservoir
Goals of measure – **Hydropower**	Ensure sustainable long term operability of the hydropower plant, reduce maintenance works

Effects (L Low / M Medium / H High)

Parameter	**Effects (upstream of the dam)**	**Effects (downstream of the dam)**
Hydro-dynamics – Water level	no drawdown necessary	M increase depends on entering discharge
Hydro-dynamics – Flow velocity	M maintained, by opening of outlets	M increase depends on entering discharge
Hydro-dynamics – Shear stress	M maintained, by opening of outlets	M increase depends on entering discharge
Sediment-dynamics – Transport capacity	H maintained, by opening of outlets	M depending on the downstream reach
Sediment-dynamics – Continuity	H maintained, by opening of outlets	H increased (fine sediment)
Morpho-dynamics – River morphology		
Ecology – Habitat diversity / refugial habitats	L Concentation naturally high during floods	L Sediment concentration inflow approx. equals outflow concentration

Type of measure		Non-recurring	X Recurring
Categories	State of the art	X Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale	X Reach scale	Catchment scale
		X Upstream effects	X Downstream effects
Scaling – **Temporal**	X Short-term	Mid-term	Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	Navigation	

Assessment

Bathymetric surveys
Monitoring of suspended sediment concentration upstream and close to the dam, to manage reservoir operations
Monitoring of water temperature
Impact on environment due to (changed) sediment management operation
Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

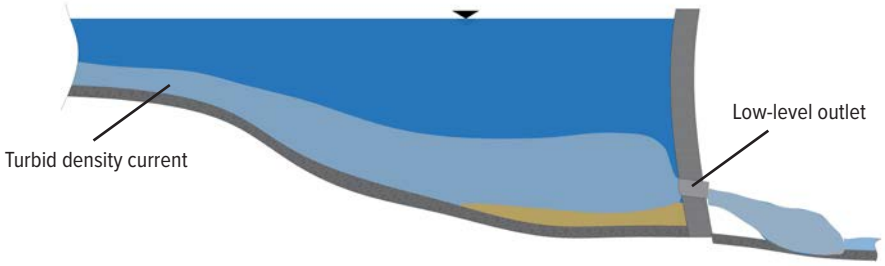
Turbid density currents must already exist and they must reach the dam.
The measure can also be applied at large reservoirs.
Outlets with a certain capacity are needed for successful venting. Retrofitting is expensive, if feasible at all, therefore include them already in the dam design.
Important is an adequate and in time operation of the outlets, which is coordinated with the inflowing turbid density current. Ideally based on real-time monitoring of concentrations close to the dam outlet.
Obstacles / roughness that disturb the approaching turbid density current should be removed.
Efficiency of the measure will decrease when reservoir fills.
Suspended sediments are routed downstream during floods when the concentration is naturally high, reducing the environmental impact.

Interrelation with other measures	All measures in the catchment; Sediment bypass (tunnel, channel), sluicing, flood-conditioned / environmentally-friendly flushing, prevent sedimentation by artificial turbulence, wet or dry dredging and reinsertion, install large bottom outlets or gates, route sediments through turbines, apply local artificial turbulence

HYDROPOWER H 6

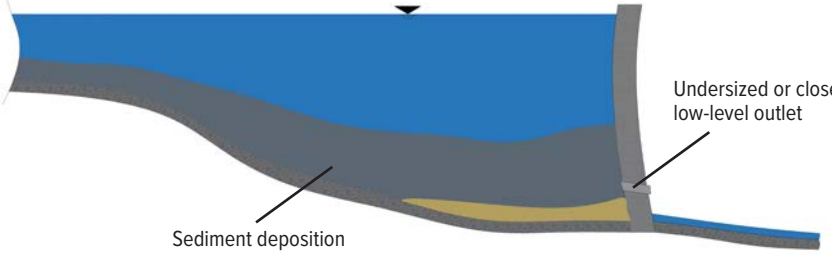
Measure	Venting of turbid density currents

POSITIVE



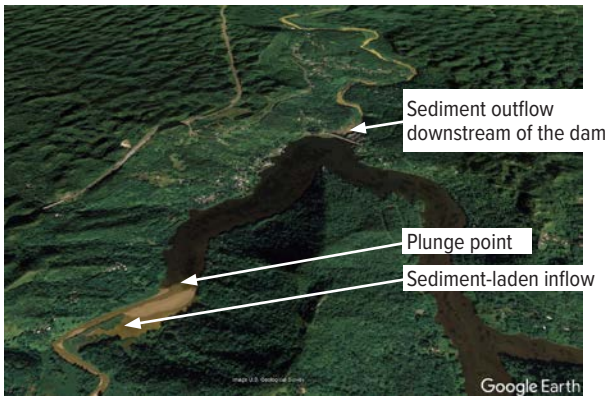
NEGATIVE

The turbid density current might deposit near the dam if a) the low-level outlet is undersized, b) the low-level outlet is closed or not opened in time or c) in case of insufficient slope because of increasing depositions over time.



Examples

© Google Earth



© Google Earth

Reference	Dos Bocas dam, Puerto Rico

7

HYDROPOWER — H 7

Measure	**Environmentally-friendly flushing**

Location		Reservoirs and impoundments
Application		Existing and newly built reservoirs or impoundments
		Gravel and sand bed river
Main aim		Remove / remobilize sediments in a reservoir or impoundment to reduce sedimentation
Parameter		Sediment continuity, sediment transport capacity, water level, flow velocity, shear stress, suspended sediment concentration
Goals of measure	**Sediment**	Reduce sedimentation by lowering the water level to remobilize sediments
	Ecology	Limit impact on downstream environment (limit suspended sediment concentration during flushing), supply gravel
	Flood protection	Increase / maintain flood protection by reducing sedimentation
	Hydropower	Ensure sustainable long-term operability of the hydropower plant, maintain reservoir capacity

Effects — L Low / M Medium / H High

Parameter	**Effects (upstream of the dam)**	**Effects (downstream of the dam)**
Hydro-dynamics		
Water level	M decreased	M increased
Flow velocity	M increased	M increased
Shear stress	M increased	M increased
Sediment-dynamics		
Transport capacity	M increased	M increased
Continuity	M increased	H increased
Morpho-dynamics		
River morphology		L increased morphodynamics
Ecology		
Habitat diversity / refugial habitats		L low effect (depends on concentration and duration)

Type of measure			Non-recurring	X	Recurring
Categories	X	State of the art	Tested (implemented at least once)		State of science (no field test yet)
Scaling — **Spatial**		Local scale	X	Reach scale		Catchment scale
			X	Upstream effects	X	Downstream effects
Temporal	X	Short-term		Mid-term		Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology	X	Navigation		

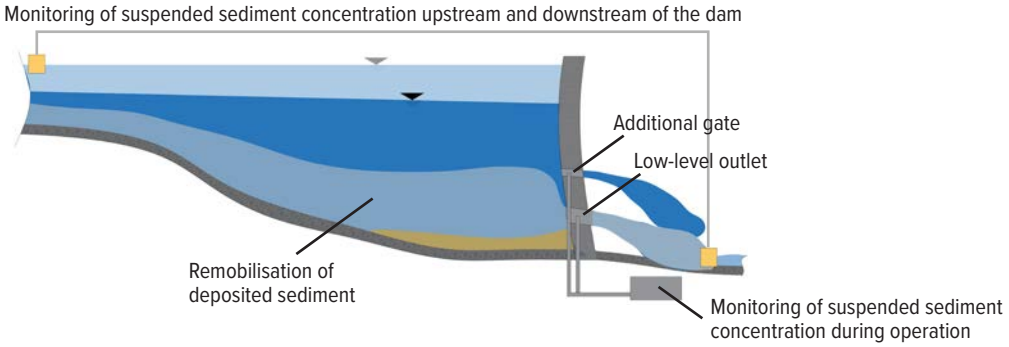
Assessment	Bathymetric surveys of the riverbed Monitoring of suspended sediment concentration (real time), oxygen and temperature during flushing Assessment of the downstream habitats: grain sizes, deposition of the flushed fine material; abundance of aquatic species Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules
Notes / Risks	Flushing can strongly affect ecological conditions (e.g. long duration and high concentration of suspended sediments can have negative impacts on fish and macrozoobenthos like oxygen depletion, stress or mechanical damage / water quality is degraded). Environmentally-friendly flushing is: „to send downstream only the concentration and duration of sediment that the environment can withstand“ and not to flush higher amounts. Flushing is performed under restrictions concerning duration, concentration of suspended sediments and season of the year (e.g. spawning time). Outlets / gates need to be large enough to pass the necessary discharge. At larger dams, outlets installed at different heights can be used to control suspended sediment concentrations to a certain degree. Flushing can lead to sedimentation in the downstream reservoirs and therefore should be coordinated with all hydropower plants in the cascade. The potential for excessive downstream sedimentation needs to be considered so that it does not hinder flood protection. In reservoirs with the purpose to attenuate flood waves, dam operations need to consider impacts on downstream water levels. Coordination with inland navigation to avoid potential conflict.
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, minimize fixed weir sill height, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules

HYDROPOWER H 7

Measure | **Environmentally-friendly flushing**

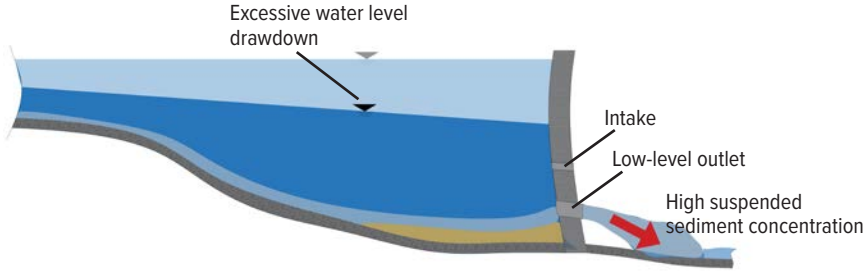
POSITIVE

Water level drawdown more frequently at lower discharges to reduce ecological impacts. An additional gate for clear water discharge can reduce the suspended sediment concentration in the downstream section.



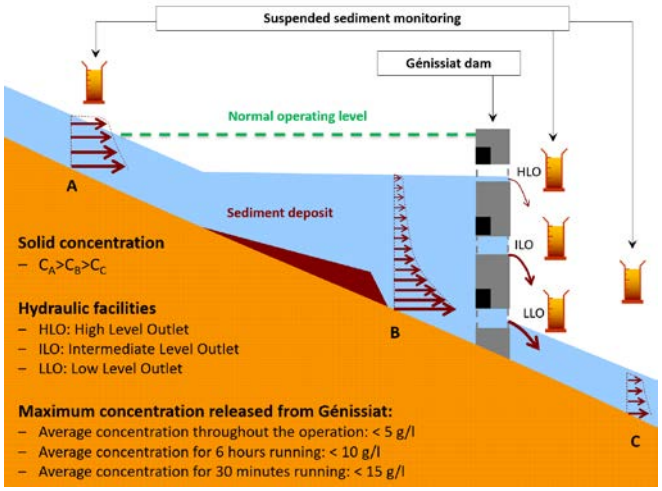
NEGATIVE

Excessive water level drawdown might cause high sediment concentration over a long time.



Examples

© Fruchard and Camenen, 2012



© Peteuil et al., 2016

Reference | Environmentally-friendly flushing at Genissiat dam on the Rhone River, France (Fruchard, F. and Camenen, B., 2012. Reservoir Sedimentation Different Type of Flushing – Friendly Flushing Example of Genissiat Dam Flushing. / Peteuil, C. et al., 2016. Feedbacks from Asia and Europe for designing sediment passing facilities in hydropower dam projects.)

8

HYDROPOWER — H 8

Measure	**Flood-conditioned flushing**
Location	Reservoirs and impoundments
Application	Existing and newly built reservoirs or impoundments
	Gravel and sand bed river
Main aim	Remove / remobilize sediments in a reservoir or impoundment to reduce sedimentation
Parameter	Sediment continuity, sediment transport capacity, discharge, flow velocity, shear stress, water level
Goals of measure – **Sediment**	Reduce sedimentation by lowering the water level to remobilize sediments
Ecology	Limit impact on downstream environment (flushing when concentration is already high during flood), supply gravel
Flood protection	Increase / maintain flood protection by reducing sedimentation
Hydropower	Ensure sustainable long term operability of the hydropower plant, maintain reservoir capacity

Effects (L Low / M Medium / H High)

Parameter	**Effects (upstream of the HPP)**	**Effects (downstream of the HPP)**
Hydro-dynamics – Water level	M decreased; depending on drawdown	L increased; depending on drawdown
Flow velocity	M increased; depending on drawdown	M increased; depending on drawdown
Shear stress	M increased; depending on drawdown	M increased; depending on drawdown
Sediment-dynamics – Transport capacity	M increased; depending on drawdown	M increased; depending on drawdown
Continuity	M increased; depending on drawdown	M increased; depending on drawdown
Morpho-dynamics – River morphology		L increased morphodynamics especially when gravel is supplied
Ecology – Habitat diversity / refugial habitats		L Concentration naturally high during floods; ideally also gravel is flushed

Type of measure		Non-recurring		Recurring	X
Categories	State of the art		X	Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale		X	Reach scale	Catchment scale
			X	Upstream effects	Downstream effects
Temporal	X Short-term			Mid-term	Long-term
Interrelation with	X Flood protection			Hydropower	
	X River basin management incl. Ecology			Navigation	

Assessment

Bathymetric surveys

Monitoring of bedload, suspended sediment concentration, oxygen and temperature during flushing

Assessment of the downstream habitats: grain sizes, deposition of the flushed fine material; abundance of aquatic species

Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

Flushing can strongly affect ecological conditions (e.g. long duration and high concentration of suspended sediments can have negative impacts on fish and macrozoobenthos like oxygen depletion, stress or mechanical damage / water quality is degraded).

Floods are a good opportunity to organize flushing since suspended sediment concentration is generally high. The measure may only be feasible in daily to weekly (short-term) reservoirs.

Availability of excess water and large capacity gates needed to discharge large flows and successfully flush sediments. Retrofitting of such gates is expensive. Therefore, a sediment management strategy should already be considered during the planning phase of the HPP.

Flushing can lead to sedimentation in the downstream reservoirs and therefore should be coordinated with all hydropower plants in the cascade.

The potential for excessive downstream sedimentation needs to be considered so that it does not hinder flood protection. In reservoirs with the purpose to attenuate flood waves, dam operations need to consider impacts on downstream water levels.

The effect and success also depends on the geometry of the reservoir and the degree of the water surface drawdown.

If flood flushing is the only measure, it might not be applied often enough. Therefore, the combination with other sediment management measures can be necessary.

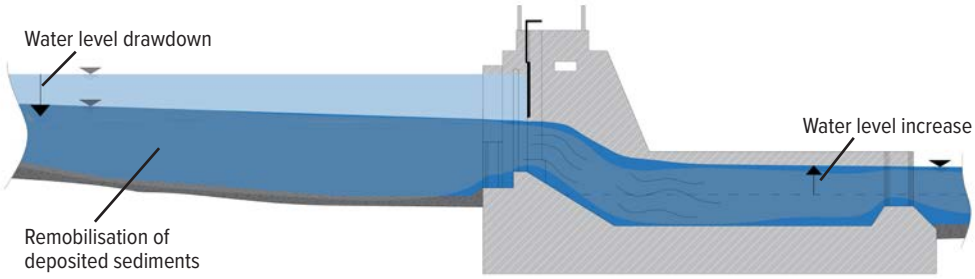
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, minimize fixed weir sill height, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules

HYDROPOWER — H 8

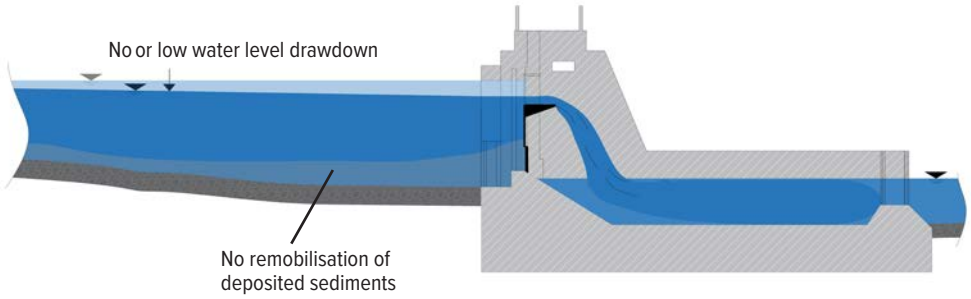
Measure	Flood-conditioned flushing

POSITIVE

Water level drawdown according to flood events.



NEGATIVE



Examples

© VERBUND

Reference	Hydropower plant Aschach, Danube River, AT (https://www.verbund.com) See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_R_H_D_P61.

9

HYDROPOWER — H 9

Measure	**Optimize flushing or sluicing strategies for dams in series**
Location	Reservoirs and impoundments
Application	Existing reservoir / dam Gravel and sand bed river
Main aim	Route or remobilize sediments at a chain of reservoirs / impoundments to reduce sedimentation and maintain transport
Parameter	River continuity, sediment transport capacity, water depth, flow velocity, shear stress, discharge, reservoir geometry
Goals of measure – **Sediment**	Reduce sedimentation and improve sediment continuity
Goals of measure – **Ecology**	Limit impact on downstream environment (flushing when concentration is already high during flood), supply gravel
Goals of measure – **Flood protection**	Increase / maintain flood protection by reducing sedimentation
Goals of measure – **Hydropower**	Ensure sustainable long term operability of the hydropower plant, maintain reservoir capacity

Effects (L Low, M Medium, H High)

Parameter	Effects (upstream of the HPP)	Effects (downstream of the HPP)
Hydro-dynamics – Water level	M decreased; depending on drawdown	L increased; depending on drawdown
Hydro-dynamics – Flow velocity	M increased; depending on drawdown	M increased; depending on drawdown
Hydro-dynamics – Shear stress	M increased; depending on drawdown	M increased; depending on drawdown
Sediment-dynamics – Transport capacity	M increased	M increased
Sediment-dynamics – Continuity	H increased	H increased
Morpho-dynamics – River morphology	M increased; depending on drawdown	M increased; depending on drawdown
Ecology – Habitat diversity / refugial habitats	M increased; depending on drawdown	M increased; depending on drawdown

Type of measure			Non-recurring	X	Recurring
Categories		State of the art	X	Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
			X	Upstream effects	X	Downstream effects
Scaling – **Temporal**	X	Short-term		Mid-term		Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology	X	Navigation		

Assessment

Bathymetric surveys

Monitoring of bedload, suspended sediment concentration, oxygen and temperature during flushing

Assessment of the downstream habitats: grain sizes, deposition of the flushed fine material; abundance of aquatic species

Impact on environment due to (changed) sediment management operation

Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

Harmonized operation of two or more dams to optimize sediment remobilisation and routing.

Flushing can strongly affect ecological conditions (e.g. long duration and high concentration of suspended sediments can have negative impacts on fish and macrozoobenthos like oxygen depletion, stress or mechanical damage / water quality is degraded).

Availability of excess water and large capacity gates needed to discharge large flows and successfully flush sediments. Retrofitting of such gates is expensive. Therefore, a sediment management strategy should already be considered during the planning phase of the HPP.

The potential for excessive downstream sedimentation needs to be considered so that it does not hinder flood protection. In reservoirs with the purpose to attenuate flood waves, dam operations need to consider impacts on downstream water levels.

Coordination with inland navigation to avoid potential conflict.

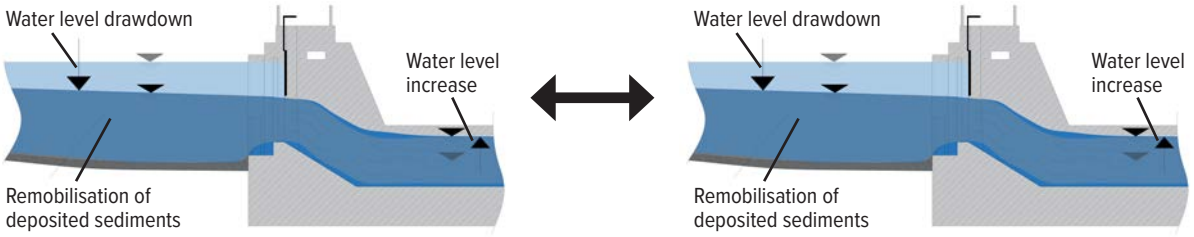
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, minimize fixed weir sill height, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules

HYDROPOWER H 9

Measure | **Optimize flushing or sluicing strategies for dams in series**

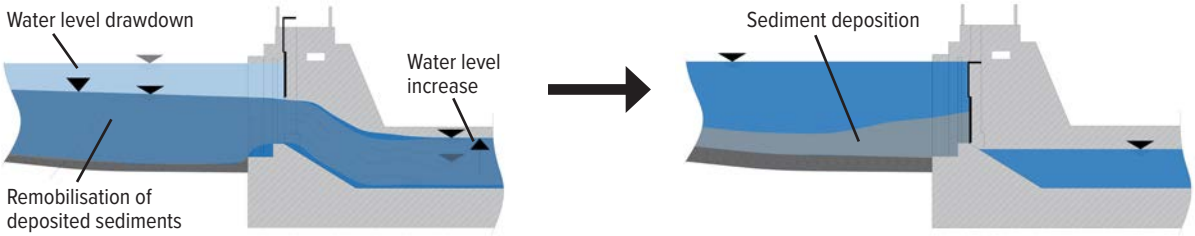
POSITIVE

Coordinated water level drawdown with adequate timing between two or more hydropower plants



NEGATIVE

Uncoordinated water level lowering might lead to depositions in the downstream reservoir



Examples

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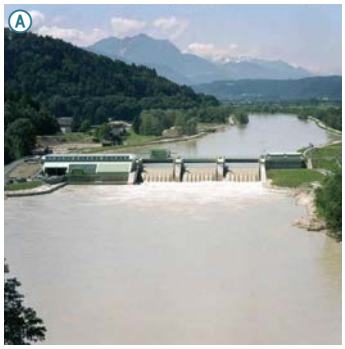
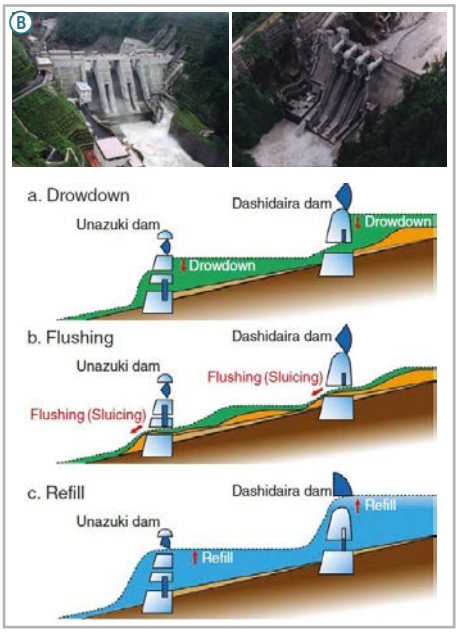


© Reindl/TIWAG



© Sumi et al., 2017

Reference

(A) Flushing MGMT at HPP Kirchbichl and Langkampfen at the Inn River, AT (https://bit.ly/mgmtinn) (Reindl, R., 2017. Fachtagung Sedimentmanagement 2017: Herausforderungen an das Sedimentmanagement bei den Flussstaukraftwerken des Tiroler Inn.) See DanubeSediment report „Sediment Management Measures for the Danube", factsheet code in annex 2: S_R_H_T_GP51

(B) Flushing and Sluicing operations at two dams in Japan (Sumi, T. et al. 2017. Reservoir Sediment Flushing and Replenishment Below Dams: Insights from Japanese Case Studies.)

10

HYDROPOWER — H 10

Measure	**Wet or dry dredging and reinsertion**

Location		Reservoirs and impoundments
Application		Existing reservoir
		Gravel and sand bed river
Main aim		Reduce sedimentation in the reservoir / impoundment and riverbed erosion in the downstream reach by refeeding
Parameter		Water levels at flood stage, bridge clearance at highest navigable discharge, grain sizes
Goals of measure	**Sediment**	Improve sediment continuity
	Flood protection	Increase / maintain flood protection by reducing sedimentation and flood water levels
	Hydropower	Remove accumulated sediments to maintain capacity and operability
	Navigation	Ensure water depth in the fairway at low navigable discharge and bridge clearance at highest navigable discharge

Effects	L Low / M Medium / H High	**Parameter**	**Effects (impoundment)**	**Effects (downstream of the dam)**
	Hydro-dynamics	Water level	H decreased water level / increased water depth	L increased water level / decreased water depth
		Flow velocity	no effects	no effects
		Shear stress	no effects	no effects
	Sediment-dynamics	Transport capacity	L Reduced at dredging location	
		Continuity		M Increased due to refeeding
	Morpho-dynamics	River morphology	Depends on amount and type of sediments (gravel or fines)	Depends on amount and if bedload supplied downstream
	Ecology	Habitat diversity / refugial habitats	Depends on mode of operation and suspended sediment concentrations	Depends on mode of operation and suspended sediment concentrations

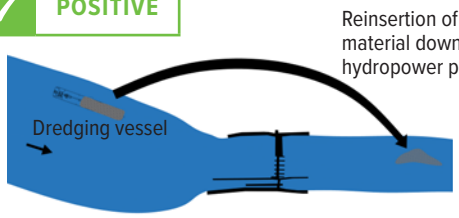
Type of measure			Non-recurring	X Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**	Local scale	X Reach scale		Catchment scale
			X Upstream effects	X Downstream effects
	Temporal	X Short-term	X Mid-term		Long-term
Interrelation with	X Flood protection		Hydropower		
	X River basin management incl. Ecology		X Navigation		

Assessment	Bathymetric surveys Water levels Quality of the sediments Monitoring of quantity excavated and reinserted (sediment volume)
Notes / Risks	Single solution or complements other sediment management methods No change of reservoir operations necessary for wet dredging or hydrosuction Costs depend on site-specific conditions Presence of contaminants can lead to very high disposal costs (no reinsertion of dredged material) Seasonal limitations can mitigate the impact on the ecology (e.g. fish) Continuous downstream discharge of dredged sediments can impact the environment; this can be mitigated by installing settling basins, where remobilisation takes place at higher discharges. Augmentation strategy to avoid impact on navigation or flood protection, e.g. feeding a large amount at places with higher water depths
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, minimize fixed weir sill height, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules

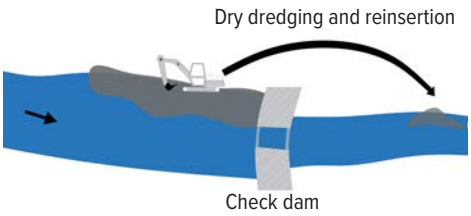
HYDROPOWER — H 10

Measure — **Wet or dry dredging and reinsertion**

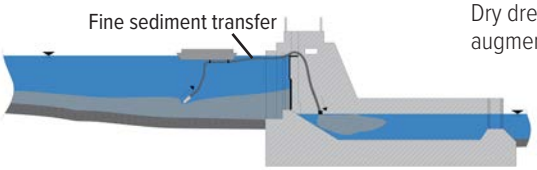
POSITIVE



Wet dredging with vessels and reinsertion downstream of the HPP

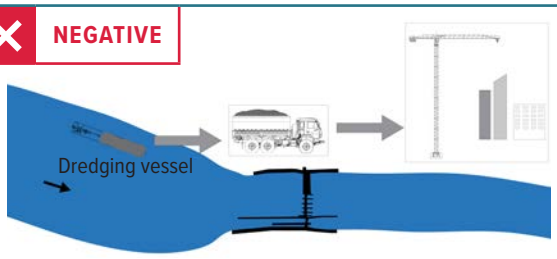


Dry dredging at check dams and augmentation downstream

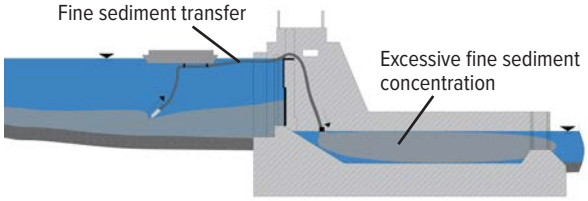


Wet dredging (hydrosuction) and transferring fine sediments to the downstream reach

NEGATIVE



Excessive dredging and selling on the market, especially in degrading river systems. Local disturbances for e.g. fish at dredging spot must be considered.



Excessive fine sediment concentration over a longer period during low flow discharge when continuously dredged.

Examples

© Remi Loire

© IWA/BOKU

© WWA Traunstein

© LfU (Bavarian Environment Agency)

Reference

Ⓐ Buech River, Saveur dam, FR (Remi Loire, Case study: restoring sediment continuity in the Buëch, IV CONVEGNO ITALIANO, SULLA RIQUALIFICAZIONE FLUVIALE, Hymocares session, Bologna, 22–26 ottobre 2018).
Ⓑ Danube River near Vienna, AT. Ⓒ Saalach River at Kibling, DE. Ⓓ Isar River (rkm 142.9), DE.
See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet codes in annex 2: E_R_H_T_GP24, S_R_H/FP_T_GP67. Further examples: E_R_H_T_GP25, S_R_H/FP_D_GP65, S_R_H_O_GP58

11

HYDROPOWER — H 11

Measure	**Bedload drift**
Location	Impoundment
Application	Existing reservoir / dam
	Gravel bed river
Main aim	Reduce / remove sedimentation in the reservoir and riverbed erosion in the downstream reach
Parameter	Bedload continuity, bedload transport capacity, water depth, flow velocity, shear stress
Goals of measure – **Sediment**	Increase bedload continuity
Goals of measure – **Flood protection**	Increase / maintain flood protection by reducing sedimentation and increasing discharge capacity
Goals of measure – **Hydropower**	Remove accumulated coarse sediments to maintain capacity and operability

Effects (L Low, M Medium, H High)

Parameter	Effects (upstream of the dam)	Effects (downstream of the dam)
Hydro-dynamics – Water level	M decreased	L increased
Hydro-dynamics – Flow velocity	H increased	L decreased
Hydro-dynamics – Shear stress	H increased	L decreased
Sediment-dynamics – Transport capacity	H increased	H increased
Sediment-dynamics – Continuity	H increased	H increased
Morpho-dynamics – River morphology	L increased morphodynamics	M improved morphodynamics by bedload supply
Ecology – Habitat diversity / refugial habitats	L de-colmation effects	H improved habitats on the long term by bedload supply

Type of measure			Non-recurring	X	Recurring
Categories		State of the art	X	Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
			X	Upstream effects	X	Downstream effects
Scaling – **Temporal**	X	Short-term		Mid-term		Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology		Navigation		

Assessment

Bathymetric survey of the river
Bedload measurements
Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules

Notes / Risks

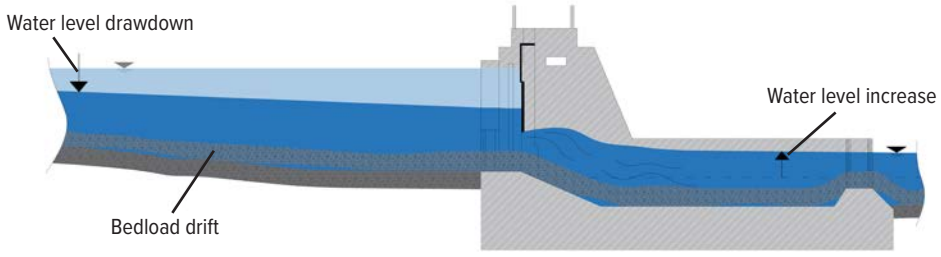
Weir gates are opened when a certain discharge is reached for a certain duration. The discharge can be induced by flooding or by upstream water supply. A protocol defines when gates are operated, i.e. discharge amount and duration.
Controlled slow water level drawdown to ensure the retention of fine sediments and protect upstream riverbanks and fish (in the referenced project: max. 60cm/h)
Bedload not transported with the drift must be dredged and reintroduced downstream.
Goal is to mainly transport bedload through the impoundment, while fine sediment remains settled.

Interrelation with other measures	Dry or wet dredging & reinsertion, environmentally-friendly flushing, flood-conditioned flushing

HYDROPOWER — H 11

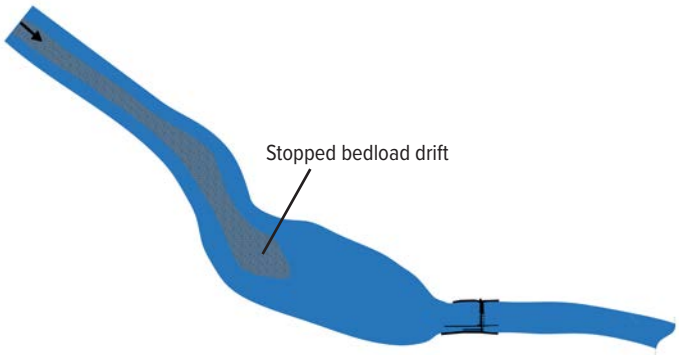
Measure	Bedload drift

POSITIVE



NEGATIVE

Stopped bedload drift due to insufficient time period of weir gate opening, excess river width or insufficient bed slope.



Examples

© LfU

Reference	Bedload drift at HPP Bad Tölz, DE (see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_R_H_T_GP54)

D.2.2 Measures in free-flowing sections

RIVER BASIN MANAGEMENT/FLOOD PROTECTION			RBM 6	F 4
Measure	**Enlarge morphological space of rivers**			
Location	Floodplain, riverbed and bank			
Application	Catchment			
	River-adjacent agricultural areas and grassland / undeveloped, unused land			
Main aim	Reduce riverbed erosion and damage potential			
Parameter	Riverbed level, river width, river morphology, side-erosion, sediment input			
Goals of measure – **Sediment**	Reduce of riverbed erosion by providing enough space for morphodynamic / side-erosion processes			
	Increase sediment input from the banks			
River basin management	Preserve undeveloped land for agricultural use and occasional flooding			
	Reduce damage potential by keeping the minimum morphological spatial demand of rivers free from settlements and infrastructure			
	Improve riverine habitats by morphodynamic processes			
Flood protection	Enhance flood protection by providing sufficient floodplain			

Effects (L Low, M Medium, H High)	**Parameter**	**Effects (main channel)**	
Hydro-dynamics	Water level	H	decreased at high flow
	Flow velocity	M	decreased
	Shear stress	M	decreased
Sediment-dynamics	Transport capacity	M	increased by side erosion
	Continuity	L	minor effects
Morpho-dynamics	River morphology	M	increased morphodynamics
Ecology	Habitat diversity / refugial habitats	M	improved habitats

Type of measure			X	Non-recurring		Recurring
Categories		State of the art		Tested (implemented at least once)	X	State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
			X	Upstream effects	X	Downstream effects
Temporal		Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology		Navigation		

Assessment	–
Notes / Risks	The minimum morphological spatial demand of rivers (MMSD) has positive effects on riverbed stability, since an enabled side-erosion reduces the hydraulic impacts on the riverbed. It also reduces the damage potential, if this area is kept free of buildings, infrastructure and other facilities. This measure is also important to ensure safe flood discharge and to have space available for flood protection measures. Implementing this measure could be problematic in areas with existing infrastructure.
Interrelation with other measures	Sediment management concept, improve or adjust land use and management, reduce surface runoff through infiltration and retention, minimize urbanisation and construction of buildings on sloped terrain

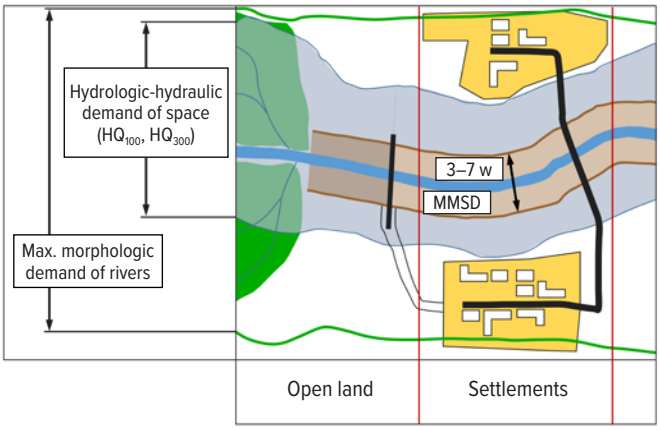
RIVER BASIN MANAGEMENT/FLOOD PROTECTION | RBM 6 | F 4

Measure | **Enlarge morphological space of rivers**

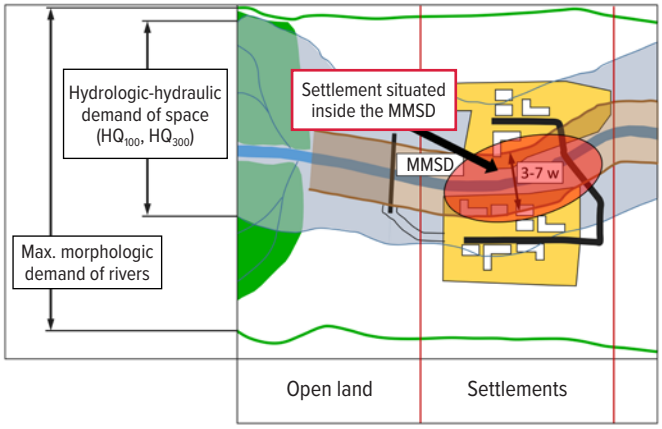
POSITIVE

MMSD = Minimum morphologic spatial demand of rivers
w = riverbed width between banks

Three to sevenfold the existing river width (3–7 w) should be kept free from buildings, infrastructure and other anthropogenic uses to have space available for morphological changes during major flood events



NEGATIVE



Examples

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© BOKU-IWHW

Reference

Habersack, H. et al. 2010. Neue Ansätze im integrierten Hochwassermanagement: Floodplain Evaluation Matrix FEM, flussmorphologischer Raumbedarf FMRB und räumlich differenziertes Vegetationsmanagement VeMaFLOOD.

Krapesch, G., Hauer, C., Habersack, H., 2011. Scale orientated analysis of river width changes due to extreme flood hazards. Nat. Hazards Earth Syst. Sci., 11, 2137-2147.

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 7	F 5

Measure	**River widening (artificial or self-forming)**	
Location	Near bank zone / floodplains	
Application	Free-flowing section	
	Gravel bed river	
Main aim	Reduce riverbed erosion	
Parameter	Sediment transport capacity, water depth / level, flow velocity, substrate, width, groundwater level	
Goals of measure – **Sediment**	Increase sediment input from riverbanks	
	Reduce riverbed erosion and consequently keep sediments longer in the river	
Goals of measure – **River basin management**	Recovery of typical river morphology and initiating morphodynamic processes	
	Sustainable improvement of the ecological conditions (particularly at the banks)	
Goals of measure – **Flood protection**	Enhance flood protection by increased runoff retention	

Effects (L Low / M Medium / H High)

Parameter		Effects		Note
Hydro-dynamics	Water level	M	decreased at high flow	
	Flow velocity	L	decreased at high flow	
	Shear stress	L	decreased at high flow	
Sediment-dynamics	Transport capacity	M	decreased	decreased in the river / increased at the riverbanks
	Continuity	M	decreased transfer	storage time of sediment in the system is increased
Morpho-dynamics	River morphology	M	increasing morphodynamics	higher variability of grain sizes
Ecology	Habitat diversity / refugial habitats	M	increased	

Type of measure			X Non-recurring		Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X Reach scale		Catchment scale
			Upstream effects	X	Downstream effects
Scaling – **Temporal**		Short-term	X Mid-term		Long-term
Interrelation with	X	Flood protection	Hydropower		
	X	River basin management incl. Ecology	X Navigation		

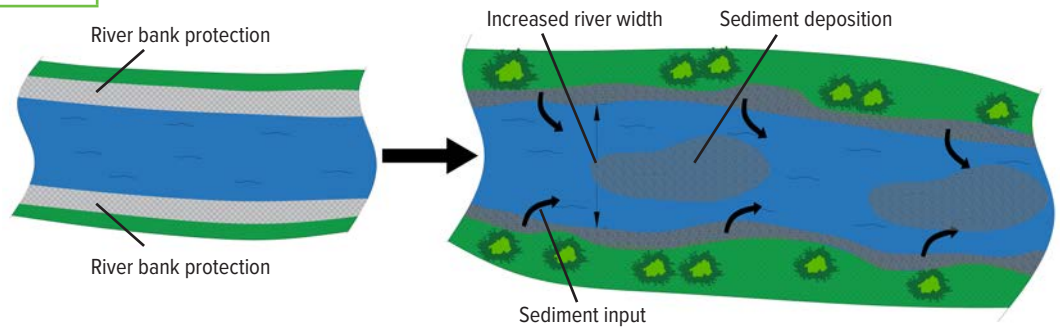
Assessment	Premonitoring (morphology, water level) Monitoring during implementation (side erosion-processes, morphology, water level) Postmonitoring (side-erosion processes, morphology, water levels, flow velocity)
Notes / Risks	The navigational conditions must not degrade as a result of the riverbed removal. Therefore, the low water level must be guaranteed by a combination of other measures (e.g. groynes). The bank areas can and should erode to a certain level. Limitations are given on the outer riverbanks through the removal of bank protections in the context of navigational conditions, flood protection and critical infrastructure. Removing of embankments shows a mid-term effect for the sediment regime, since it has an effect against riverbed deepening as long as bedload is available. In the long term, additional bedload input will be needed. In combination with other measures such as ramps (permitting fish migration) and the addition of coarse stones (armourstones), riverbed deepening can be counteracted. Without increasing the riverbed level, such a measure would lead to a decrease in the river water and groundwater level in the floodplain.
Interrelation with other measures	Riverbank restoration, reconnection of side-channels or enhance floodplain erosion, increase river length to reduce the slope, break-up of bed armouring (artificial flood or mechanical)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION

RBM 7 | F 5

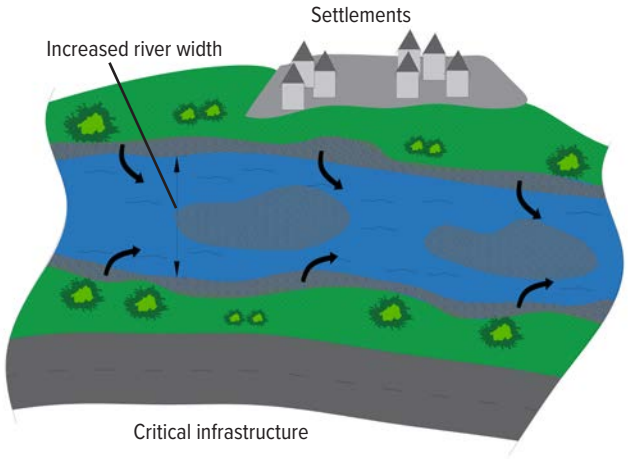
Measure | **River widening (artificial or self-forming)**

POSITIVE



NEGATIVE

Side erosion affecting nearby critical infrastructure. Lowered water level might also affect inland navigation.



Examples

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Reference

Widening of river Ybbs / Schönegg (https://www.ezb-fluss.at)

Further examples: see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_E_H_T_P68)

RIVER BASIN MANAGEMENT	RBM 8
Measure	**Riverbank restoration**

Location		Riverbanks
Application		Free-flowing section
		Gravel bed river
Main aim		Reduce riverbed erosion
Parameter		Shear stress, sediment transport capacity and continuity, water level, water depth, river width, substrate, habitat diversity
Goals of measure	**Sediment**	Increase of sediment input
		Reduction of riverbed incision by reducing shear stress
		Natural morphological development of bank zones (morphodynamics)
	River basin management	Restore the natural conditions before the river regulation
		Restoration of aquatic habitats (gravel banks, bays,..)
		Recovery of typical river morphology and initiating morphodynamic processes
		Increase groundwater level
		Enhance flood protection by increase of discharge cross-sections

Effects	L Low / M Medium / H High	**Parameter**	**Effects**	**Note**
	Hydro-dynamics	Water level	L decreased at high flow	
		Flow velocity	L decreased	
		Shear stress	L decreased	
	Sediment-dynamics	Transport capacity	L decreased	decreased in the river / increased at the riverbanks
		Continuity	L decreased transfer	storage time of sediment in the system is increased
	Morpho-dynamics	River morphology	H increasing morphodynamics	higher variability of grain sizes
	Ecology	Habitat diversity / refugial habitats	H increased	

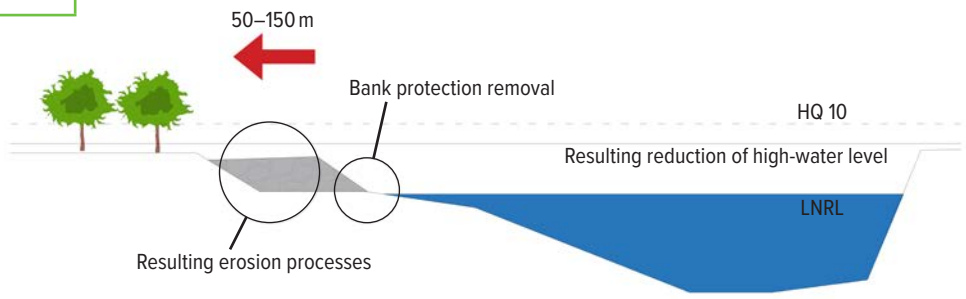
Type of measure			X	Non-recurring		Recurring
Categories	X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**	Local scale	X	Reach scale		Catchment scale
				Upstream effects	X	Downstream effects
	Temporal	Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection		Hydropower		
		River basin management incl. Ecology	X	Navigation		

Assessment	Premonitoring (morphology, water level) Monitoring during implementation (side erosion processes, morphology, water level) Postmonitoring (side erosion process, morphology, water levels, flow velocity)
Notes / Risks	Increased width due to lateral erosion reduces sediment transport capacity. The navigational conditions must not degrade as a result of the riverbank removal. Therefore, the low water level must be guaranteed by a combination of other measures (e.g. groynes). The bank areas can and should erode to a certain level – in this case the low water level. Limitations are given on the outer riverbanks through the removal of bank protections in the context of navigational conditions, flood protection and critical infrastructure. Sediment input is only temporarily effective. Riverbed incision remains in the long term, in case of no additional bedload supply.
Interrelation with other measures	River widening (artificial or self-forming), reconnection of side-channels or enhance floodplain erosion, increase river length to reduce the slope, break-up of bed armouring (artificial flood or mechanical)

RIVER BASIN MANAGEMENT — RBM 8

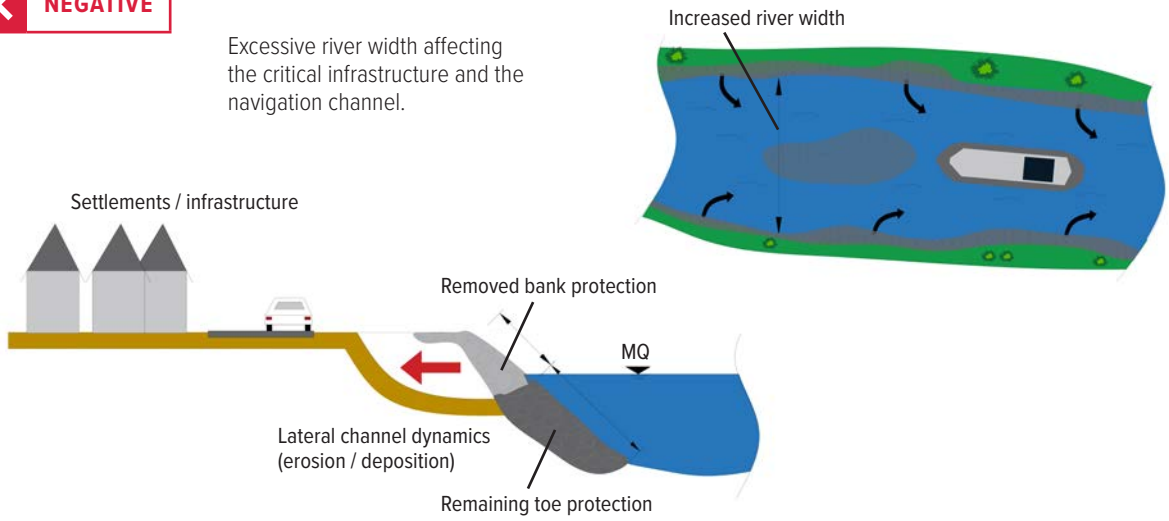
Measure	Riverbank restoration

POSITIVE



NEGATIVE

Excessive river width affecting the critical infrastructure and the navigation channel.



Examples

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Reference	Riverbank restoration at the Danube River at Witzelsdorf (see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_N_D_GP11 (https://bit.ly/irepat)) Further examples: Danube, AT (https://bit.ly/irepat) E_FF_N_D_GP14, Isar, GER (https://bit.ly/bankrestIsar) E_E_H/FP_T_GP33

RIVER BASIN MANAGEMENT/NAVIGATION — RBM 9 — N 1

Measure	**Increase river length to reduce the slope**
Location	Riverbed / riverbanks
Application	Free-flowing section of channeled rivers
	Gravel and sand bed river
Main aim	Reduce riverbed erosion
Parameter	Water level, flow velocity, sediment transport capacity, shear stress, habitat diversity, substrate
Goals of measure – **Sediment**	Stabilisation of the riverbed by decreased slope
	Sediment input from reconnected oxbows and meanders
	Initiating morphological processes in oxbows and meanders
Goals of measure – **River basin management**	Improve aquatic habitats
	Enhance flood protection by increased runoff retention

Effects (L Low / M Medium / H High)

Parameter		Effects	
Hydro-dynamics	Water level	L	eventually decreased
	Flow velocity	M	decreased
	Shear stress	M	decreased
Sediment-dynamics	Transport capacity	M	decreased
	Continuity	M	decreased
Morpho-dynamics	River morphology	M	increased morphodynamics
Ecology	Habitat diversity / refugial habitats	H	increased

Type of measure			X Non-recurring		Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X Reach scale		Catchment scale
			Upstream effects	X	Downstream effects
Scaling – **Temporal**		Short-term	Mid-term	X	Long-term
Interrelation with	X Flood protection		Hydropower		
	X River basin management incl. Ecology		X Navigation		

Assessment

Premonitoring (morphology, flow velocity, discharge, suspended sediments, bedload, substrate, fish)
Monitoring during implementation (morphology, flow velocity, discharge, suspended sediments, bedload)
Postmonitoring (morphology, flow velocity, discharge, suspended sediments, bedload, fish)

Notes / Risks

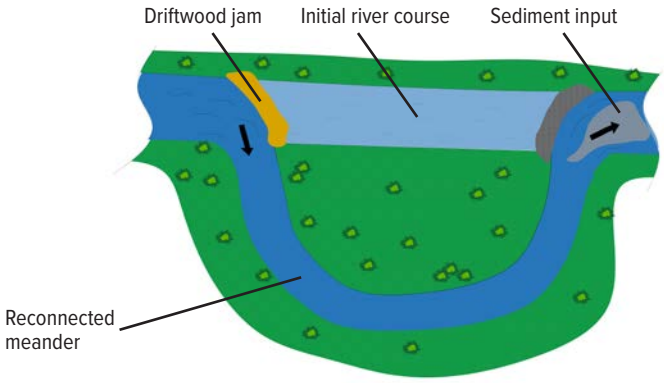
Findings of the referenced project: within a few years, the river re-meandered and widened by half of the width. In some places, the riverbed deepened mainly due to flood events. Bedload from the banks enabled a mid-term increase of sandbanks and gravel banks. This allowed for short-term growth of pioneer vegetation. Due to a lack of bedload from upstream (weir), this typical gravel bed vegetation has been replaced in the long-run by bushes and trees (willow, alder, spruce).
Without bedload supply from upstream morphodynamic processes will vanish and riverbed deepening will remain.
Need enough space to implement the measure. River type must be suitable and support a meandering plan form.

Interrelation with other measures	River widening (artificial or self-forming), riverbank restoration, reconnection of side-channels or enhance floodplain erosion, break-up of bed armouring (artificial flood or mechanical)

RIVER BASIN MANAGEMENT/NAVIGATION | RBM 9 | N 1

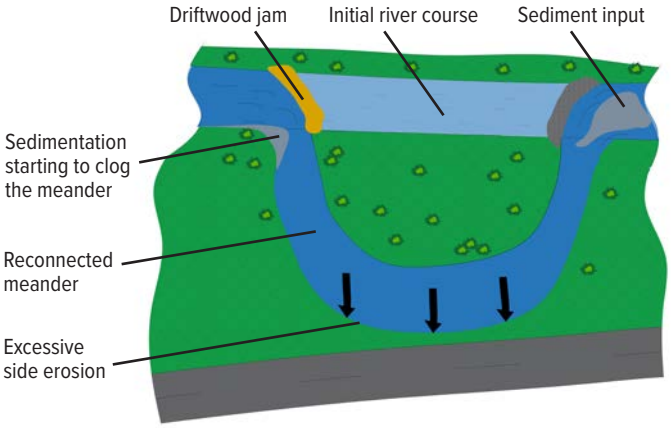
Measure | **Increase river length to reduce the slope**

POSITIVE



NEGATIVE

Excessive side erosion in the meander might affect critical infrastructure (e. g. streets) nearby.



Examples

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Reference | Reconnected meander at the river Thaya, AT (https://bit.ly/sedecothaya)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 10	F 6

Measure	**Reconnection of side-channels or enhance floodplain erosion**	
Location	Floodplains	
Application	Free-flowing section	
	Gravel and sand bed river	
Main aim	Reduce riverbed erosion	
Parameter	Water level, flow velocity, sediment transport capacity, shear stress, habitat diversity, substrate	
Goals of measure – **Sediment**	Reduced bed erosion in the main channel by decreasing shear stress and an increasing sediment input from the side-channel	
	Sustainable sediment budget in the side-channel by increasing sediment exchange with the main channel	
River basin management	Improvement of ecological conditions in the side-channel	
	Preferably permanent connection of side-channels at low-flow conditions	
	Permanent refugial areas, protection against vessel-induced waves	
Flood protection	Improve flood retention, lowered water level at high flow in the main channel	

Effects (L Low, M Medium, H High)

Parameter	**Effects (main channel)**	**Effects (side-channel)**
Hydro-dynamics – Water level	**L** decreased at high flow	**H** increased → permanent connection with main channel
Flow velocity	**L** decreased at high flow	**H** increased
Shear stress	**L** decreased at high flow	**H** increased, drift of macro-invertebrates to suitable habitats
Sediment-dynamics – Transport capacity	**L** decreased at high flow	**H** increased
Continuity	**L** slightly increased by sediment input from side-arms	**H** increased
Morpho-dynamics – River morphology	**L** minor effects	**M** increased morphodynamics
Ecology – Habitat diversity / refugial habitats	**L** minor effects	**H** increased

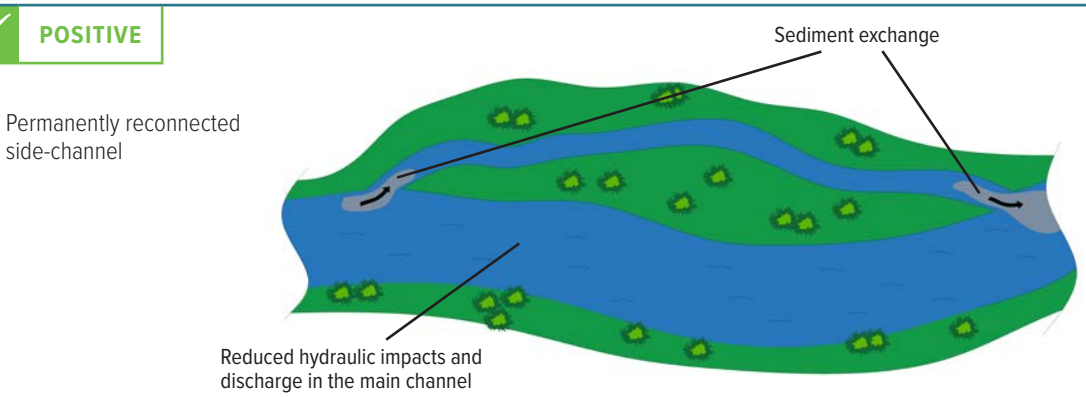
Type of measure		X Non-recurring	Recurring
Categories	X State of the art	Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale	X Reach scale	Catchment scale
		Upstream effects	X Downstream effects
Temporal	Short-term	Mid-term	X Long-term
Interrelation with	X Flood protection	X Hydropower	
	X River basin management incl. Ecology	X Navigation	

Assessment	Premonitoring (morphology, flow velocity, discharge, suspended sediments, bedload, substrate, fish) Monitoring during implementation (morphology, flow velocity, discharge, suspended sediments, bedload) Postmonitoring (morphology, flow velocity, discharge, suspended sediments, bedload, fish)
Notes / Risks	Potential sedimentation of the side-channels if not enough discharge and exchange with the main channel. Need enough discharge in the side-channel to have morphodynamics Potential cross flow at the mouth of side-arms Potentially negative effects on fairway depth at low-flow conditions
Interrelation with other measures	River widening (artificial or self-forming), riverbank restoration, increase river length to reduce the slope, break-up of bed armouring (artificial flood or mechanical)

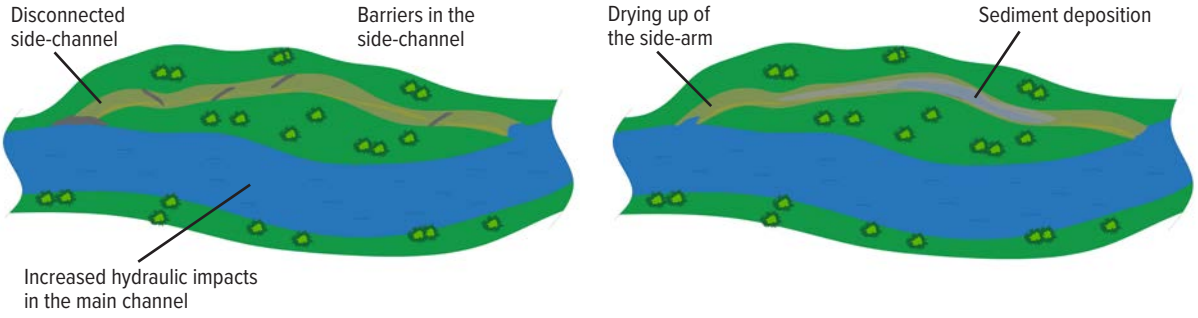
RIVER BASIN MANAGEMENT/FLOOD PROTECTION | RBM 10 | F 6

Measure | **Reconnection of side-channels or enhance floodplain erosion**

✓ POSITIVE



✗ NEGATIVE



Examples

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Reference

Pilot project Bad Deutsch-Altenburg (see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_FP/N_D_GP18 (https://bit.ly/irepat))

Further examples: Danube, AT (https://bit.ly/irepat) E_C_N_D_GP31, Danube, AT (https://bit.ly/lifewachau) E_FF_FP/N_D_GP15, E_FF_FP/N_D_GP16, Danube, SK S_FF_FP_D_GP38

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 11	F 7

Measure	**Opening or removal of flood dykes**	
Location	Floodplains	
Application	Free-flowing section	
	Gravel and sand bed river	
Main aim	Reduce riverbed erosion	
Parameter	Water level at flood stage, sediment transport capacity, shear stress, flow velocity	
Goals of measure – **Sediment**	Reduce riverbed erosion by decreasing shear stress at discharges above bankfull stage	
	Increase river – floodplain sediment exchange	
River basin management	Improve habitat diversity in the floodplain	
Flood protection	Enhance flood protection by increasing water retention and reducing peak discharge	

Effects

L Low / M Medium / H High	Parameter		Effects (main channel)		Effects (floodplain)
Hydro-dynamics	Water level	H	decreased (at high flow)	H	increased / higher diversity (at high flow)
	Flow velocity	M	decreased (at high flow)	M	increased / higher diversity (at high flow)
	Shear stress	M	decreased (at high flow)	M	increased / higher diversity (at high flow)
Sediment-dynamics	Transport capacity	M	decreased (at high flow)	M	increased (at high flow)
	Continuity	M	increased sediment exchange with floodplain (at high flow)	M	increased sediment exchange with main channel (at high flow)
Morpho-dynamics	River morphology	L	minor effects	L	increased morphodynamics
Ecology	Habitat diversity / refugial habitats		no effects	H	increased

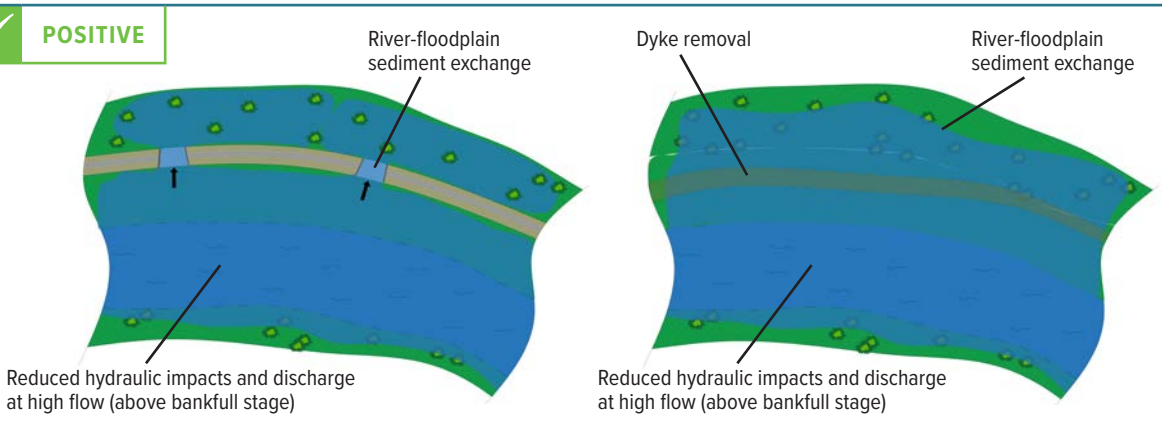
Type of measure				X	Non-recurring		Recurring
Categories		State of the art		X	Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale		X	Reach scale		Catchment scale
					Upstream effects	X	Downstream effects
Temporal		Short-term			Mid-term	X	Long-term
Interrelation with	X	Flood protection		X	Hydropower		
	X	River basin management incl. Ecology		X	Navigation		

Assessment	Hydrodynamic-numerical modelling Monitoring (discharge, sediment transport, habitats in the floodplain, etc.) Aerial and satellite images
Notes / Risks	Reduced hydraulic impacts on the main channel Increased river-floodplain sediment exchange Lowered peak discharge and water level by increasing water retention Increased habitat diversity in the floodplain Flood protection must not degrade. Attention must be paid to nearby critical infrastructure.
Interrelation with other measures	Removal of natural near-river levees (bank erosion or mechanical)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION | RBM 11 | F 7

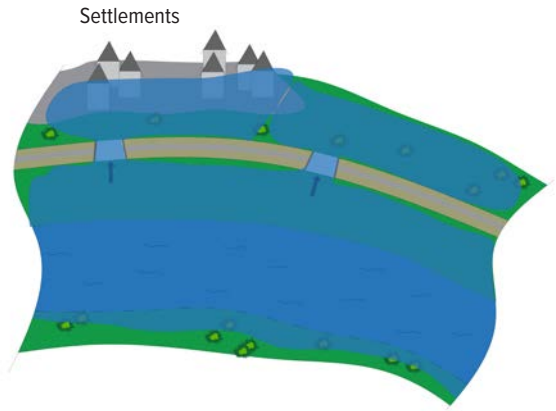
Measure | **Opening or removal of flood dykes**

POSITIVE

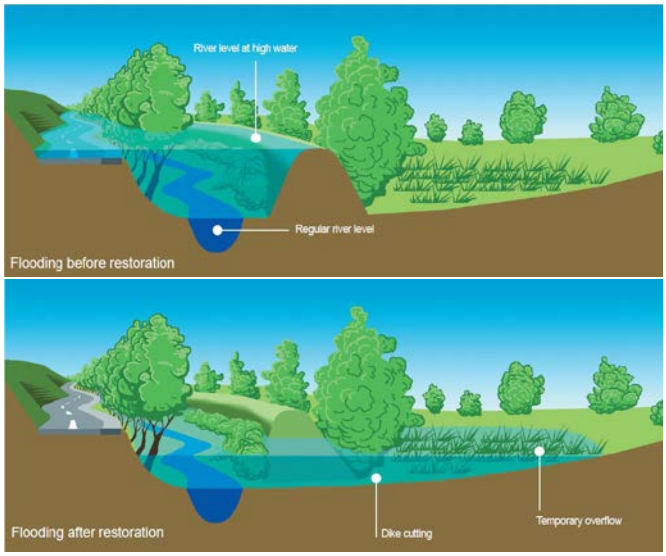


NEGATIVE

Flooding eventually endangers e.g. settlement areas situated near the flood dyke.



Examples



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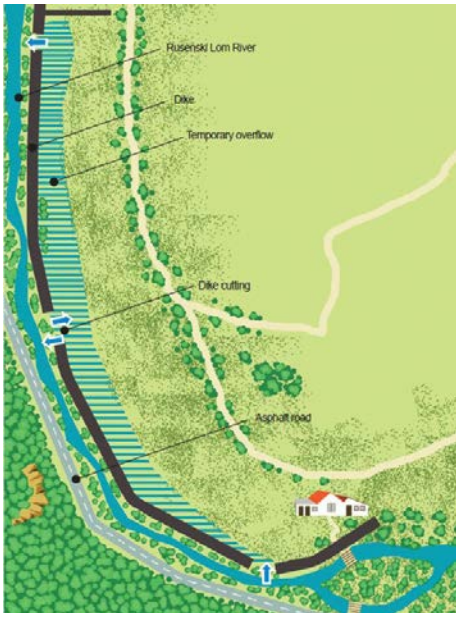


© Nikolov, Mihov and Hristov

Reference | Opening of a flood dyke at the Rusenski Lom River near Ivanovo, BG (Mihov, S., Hristov, I., 2011. River Ecology. WWF Booklet.)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 12	F 8

Measure	**Relocation or set-back of flood dykes**	
Location	Floodplains	
Application	Free-flowing section	
	Gravel and sand bed river	
Main aim	Reduce riverbed erosion	
Parameter	Water levels at flood stage, sediment transport capacity, shear stress, flow velocity	
Goals of measure – **Sediment**	Reduce riverbed erosion by decreased shear stresses at discharges above bankfull stage	
	Increase river – floodplain sediment exchange	
River basin management	Restore riparian ecosystems	
Flood protection	Enhance flood protection by increased water retention and reduced peak discharge	

Effects

L Low
M Medium
H High

Parameter	Effects (main channel)	Effects (floodplains)
Hydro-dynamics		
Water level	H decreased (at high flow)	H decreased (at high flow)
Flow velocity	M decreased (at high flow)	M decreased (at high flow)
Shear stress	M decreased (at high flow)	M decreased (at high flow)
Sediment-dynamics		
Transport capacity	M decreased (at high flow)	M increased (at high flow)
Continuity	M decreased (at high flow)	M increased (at high flow)
Morpho-dynamics		
River morphology	L minor effects	L minor effects
Ecology		
Habitat diversity / refugial habitats	L minor effects	L minor effects

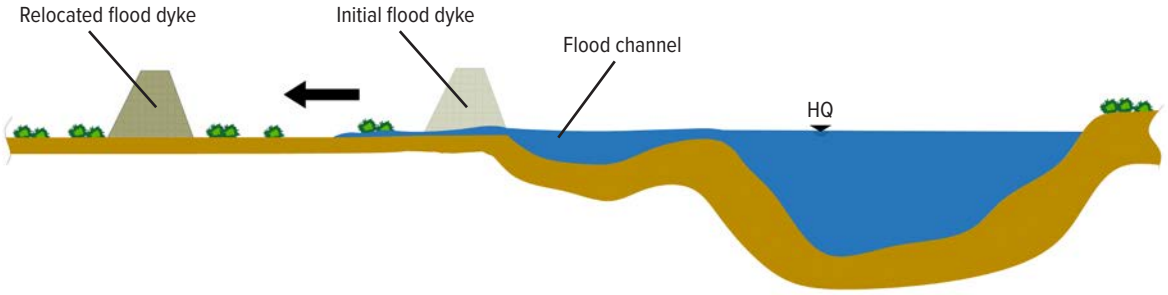
Type of measure			X	Non-recurring		Recurring
Categories	X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
			X	Upstream effects	X	Downstream effects
Temporal		Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection	X	Hydropower		
	X	River basin management incl. Ecology	X	Navigation		

Assessment	Hydrodynamic-numerical modelling
Notes / Risks	Reduced riverbed degradation by reducing shear stress and sediment transport capacity in the main channel Flood protection must not degrade. This measure is only feasible in areas with sufficient space available and in the absence of nearby critical infrastructure. The further from the river the dyke is moved, the smaller the required dyke height and the lower the risk of failure.
Interrelation with other measures	Opening or removal of flood dykes, removal of natural near-river levees

RIVER BASIN MANAGEMENT/FLOOD PROTECTION | RBM 12 | F 8

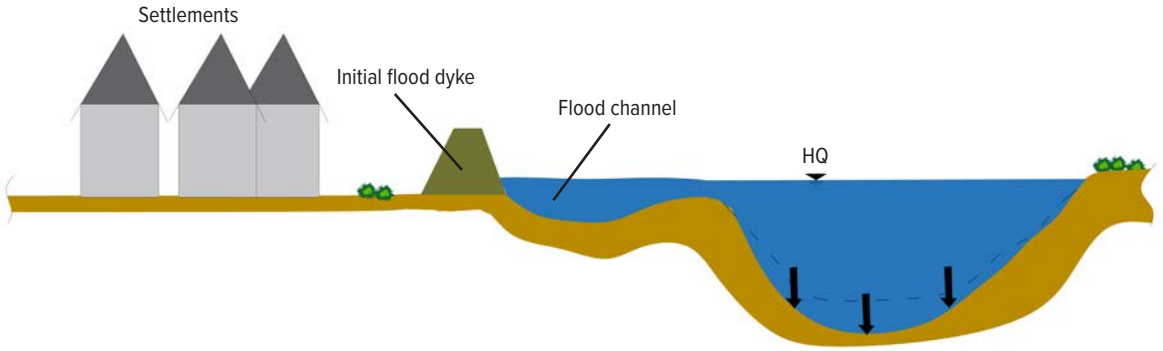
Measure | **Relocation or set-back of flood dykes**

POSITIVE



NEGATIVE

Reduced river width (at high flow) is causing riverbed incision.
Risk of failure due to higher flood heights and pressure on the dyke itself.
Increased damage potential for nearby settlements in case of dam break.

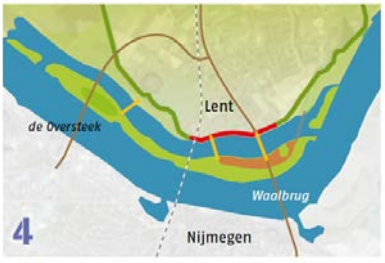


Examples

The initial siutation with the existing dike.

The dike was moved 350 metres inland.

An ancillary channel is to be dug in order to give the river more room. This will create an elongated island.



Bridges across ancillary channel.

Reference | Relocation of a flood dyke at the river Waal near Nijmegen, NL (tributary of Rhine River) (www.uu.nl)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 13	F 9

Measure	**Removal of natural near-river levees (bank erosion or mechanical)**	
Location	Riverbanks	
Application	Free-flowing section	
	Gravel and sand bed river	
Main aim	Reduce riverbed erosion and sedimentation at the riverbanks	
Parameter	Water level at flood stage, flow velocity, shear stress, sediment transport capacity	
Goals of measure – **Sediment**	Increase of sediment input from the riverbanks	
	Reduce riverbed incision by decreasing shear stress	
	Natural morphological development of bank zones (morphodynamics)	
River basin management	Improve the lateral connectivity between the main channel and floodplain	
Flood protection	Improve flood protection by increasing discharge capacity	

Effects (L Low, M Medium, H High)

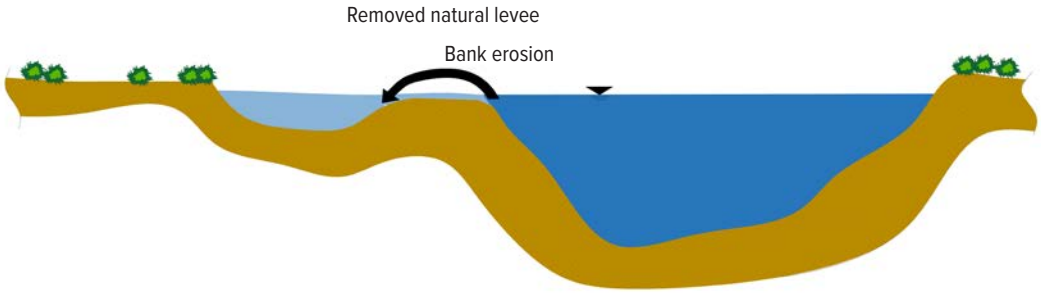
Parameter	Effects (main channel)	Effects (riverbanks/floodplain)
Hydro-dynamics – Water level	M decreased (above bankfull discharge)	M earlier floodplain inundation
Flow velocity	M decreased (above bankfull discharge)	M increased (above bankfull discharge)
Shear stress	M decreased (above bankfull discharge)	M increased (above bankfull discharge)
Sediment-dynamics – Transport capacity	L eventually decreased	M increased
Continuity	L increased sediment exchange with the floodplain	M increased sediment exchange with the main channel
Morpho-dynamics – River morphology	L minor effects	M increased morphodynamics
Ecology – Habitat diversity / refugial habitats	L minor effects	L increased habitat diversity

Type of measure		Non-recurring	X Recurring
Categories	State of the art	X Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale	X Reach scale	Catchment scale
		Upstream effects	X Downstream effects
Temporal	Short-term	X Mid-term	Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	X Navigation	

Assessment	Hydrodynamic-numerical modelling Aerial and satellite images Digital elevation model (e.g. terrestrial laser scanning, laserscan, photogrammetry)
Notes / Risks	Removal can either be done mechanically or by removing the bank protection to enable lateral erosion. Improved lateral connectivity between main channel and floodplain High costs may occur if levees are mechanically removed.
Interrelation with other measures	Opening or removal of flood dykes, relocation or set-back of flood dykes

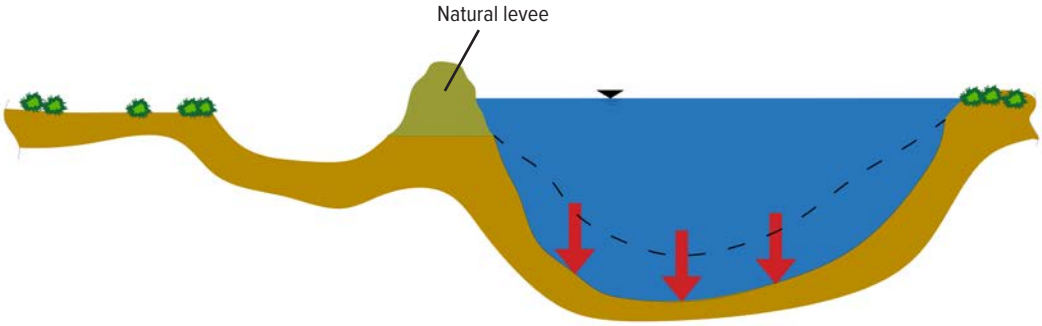
RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 13	F 9
Measure	**Removal of natural near-river levees (bank erosion or mechanical)**	

POSITIVE



NEGATIVE

Reduced river width (at bankfull discharge) is causing riverbed incision.
Reduced water retention.
Increased water level.



Examples

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Reference	Removal of natural near-river levees at the Danube River (Rkm 2429 to 2430) (https://bit.ly/removelevee) See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_A/H_D_GP34

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 14	F 10

Measure	**Restore wetlands**	
Location	Floodplains	
Application	Free-flowing section	
	Gravel and sand bed river	
Main aim	Reduce riverbed erosion	
Parameter	Water level, flow velocity, sediment transport capacity, shear stress, habitat diversity, substrate	
Goals of measure – **Sediment**	Reduce excessive fine sediment input in to rivers by decreasing flood peaks	
River basin management	Re-mobilize and re-establish characteristic wetland habitats	
	Improve the connectivity between main river channel and wetlands	
	Enhance aquatic habitats and water quality by creating artificial or constructed wetlands in urban areas	
Flood protection	Improve flood retention by reactivating former wetlands	

Effects (L Low, M Medium, H High)

Parameter	Effects (main channel)		Effects (wetlands)	
Hydro-dynamics – Water level	L	decreased at high flow	H	increased and higher diversity at high flow
Flow velocity	L	decreased at high flow	M	increased and higher diversity at high flow
Shear stress	L	decreased at high flow	M	slightly increased at high flow
Sediment-dynamics – Transport capacity	L	decreased at high flow	H	increased at high flow
Continuity	L	minor effects	H	increased at high flow
Morpho-dynamics – River morphology	L	minor effects	M	increased morphodynamics at high flow
Ecology – Habitat diversity / refugial habitats		no effects	H	increased

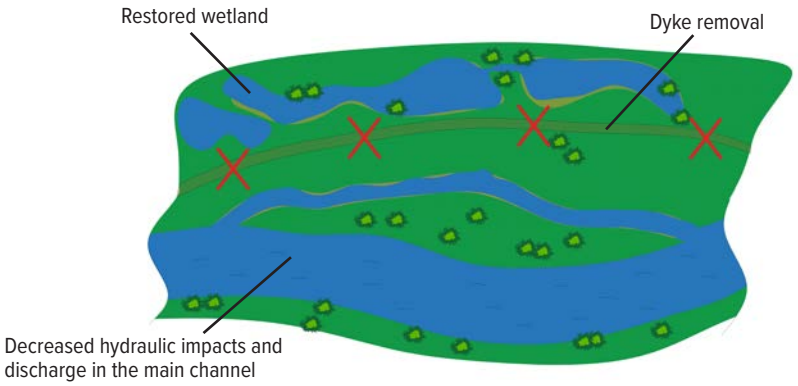
Type of measure			X	Non-recurring		Recurring
Categories	X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
				Upstream effects	X	Downstream effects
Temporal		Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology	X	Navigation		

Assessment	Pre- and postmonitoring (morphology, flow velocity, discharge, suspended sediments, substrate, fish)
Notes / Risks	Restored / improved lateral connection of a river system (riverine-riparian-floodplain) Reduced flood peaks through the increased retention capacity Aquatic habitats are restored and wetland vegetation can reestablish Artificial / constructed wetlands in urban areas can contribute to flood attenuation, water quality improvement and habitat and landscape enhancement.
Interrelation with other measures	River widening (artificial or self-forming), riverbank restoration, reconnection of side-channels or enhance floodplain erosion, increase river length to reduce the slope, break-up of bed armouring (artificial flood or mechanical)

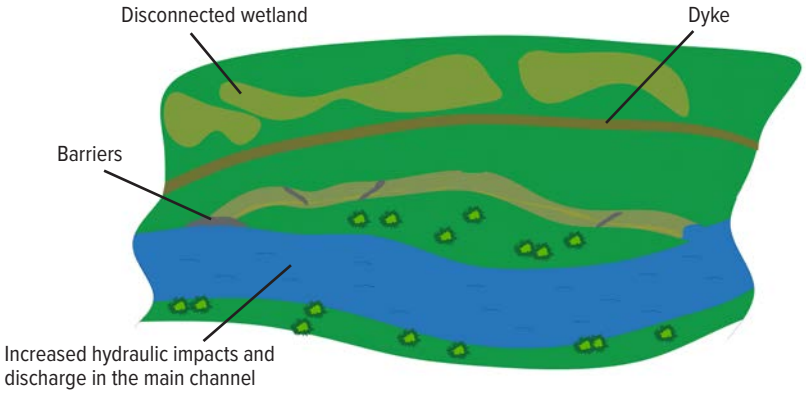
RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 14	F 10

Measure — **Restore wetlands**

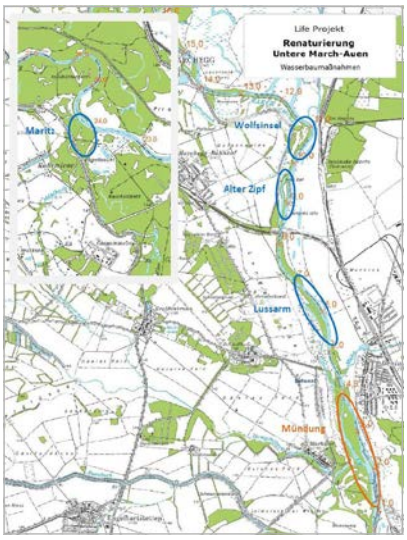
POSITIVE



NEGATIVE



Examples



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Reference	LIFE+ Untere March Auen (http://www.life-march.at/sk-en.html) Further example: see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_FF_D_T_GP47

RIVER BASIN MANAGEMENT/NAVIGATION	RBM 15	N 2

Measure	**Coarse particle feeding (granulometric bed improvement)**	
Location	Riverbed / fairway	
Application	Free-flowing section	
	Gravel bed river	
Main aim	Reduce riverbed erosion	
Parameter	Sediment transport capacity, (critical) shear stress, riverbed incision, grain size	
Goals of measure – **Sediment**	Sustainable riverbed stabilisation (stop riverbed erosion) by increasing critical shear stress	
	Reduce maintenance works (less ford dredging)	
	Increase of low-water level	
	Implementation of dynamic equilibrium	
Goals of measure – **River basin management**	Ensure stable water levels	

Effects

L Low / M Medium / H High	Parameter	Effects	
Hydro-dynamics	Water level	L	slight increase due to added sediment at low / mean flow
	Flow velocity	L	eventually minor changes
	Shear stress	M	changed shear stress due to higher roughness
Sediment-dynamics	Transport capacity	H	decreased due to increase of critical shear stress
	Continuity	M	sediment is kept longer in the system, when the added and the present material are mixing
Morpho-dynamics	River morphology	M	increase of surface grain sizes on the riverbed
Ecology	Habitat diversity / refugial habitats	L	minor changes; local disturbance

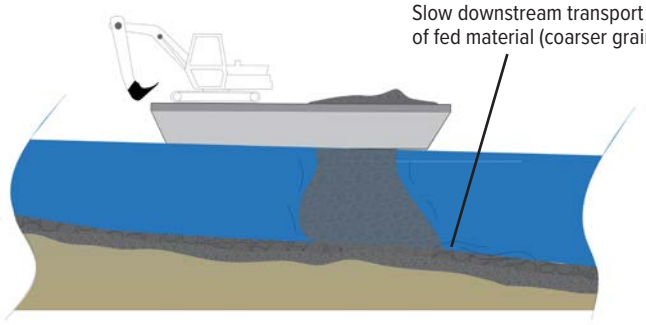
Type of measure			Non-recurring		Recurring
Categories		State of the art	X Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X Reach scale		Catchment scale
			Upstream effects	X	Downstream effects
Scaling – **Temporal**		Short-term	Mid-term	X	Long-term
Interrelation with	X	Flood protection	Hydropower		
	X	River basin management incl. Ecology	X Navigation		

Assessment	Before implementation: Hydrodynamic-numerical modelling, physical model tests, premonitoring (sediment transport, grain size distribution, shear stress, initiation of motion via radio-tracer, underwater pictures of the riverbed, connectivity to the groundwater, clogging, bathymetry; Biotic: fish and makrozoobenthos) During implementation: Abiotic: sediment transport measurements, freeze core and volumetric sampling, radio-tracer, bathymetry After implementation: Postmonitoring (sediment transport, grain size distribution, shear stress, initiation of motion via radio-tracer, underwater pictures of the riverbed, connectivity to the groundwater, clogging, bathymetry; Biotic: fish and makrozoobenthos)
Notes / Risks	Pilot studies have shown a higher mobility of the sediment than theoretically calculated. Sensitivity to grain size of added material Mixing with subsurface material benefits natural morphodynamics Availability of material (i.e. sediment in the necessary grain size) might be a decisive factor
Interrelation with other measures	River widening (artificial or self-forming), riverbank restoration, increase river length to reduce the slope, reconnection of side-channels or enhance floodplain erosion

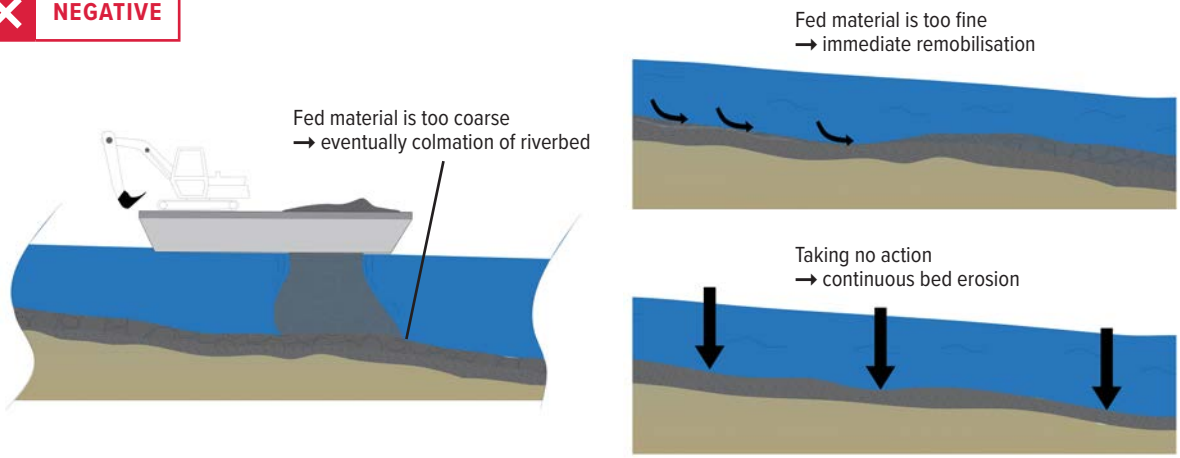
RIVER BASIN MANAGEMENT/NAVIGATION | RBM 15 | N 2

Measure | **Coarse particle feeding (granulometric bed improvement)**

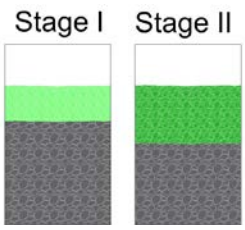
POSITIVE

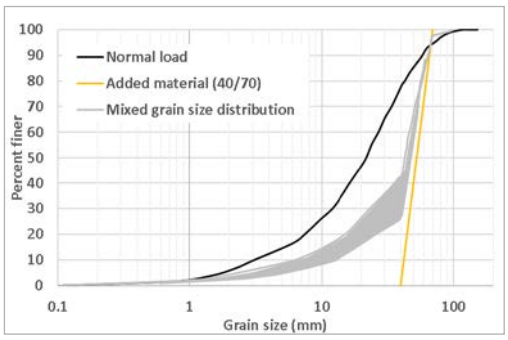


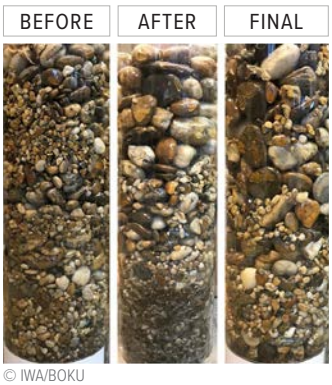
NEGATIVE



Examples







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Reference | Pilot project Bad Deutsch-Altenburg, AT (https://bit.ly/irepat)
See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet codes in annex 2: E_FF_N/H_D_GP22, E_FF_N/H_D_GP23

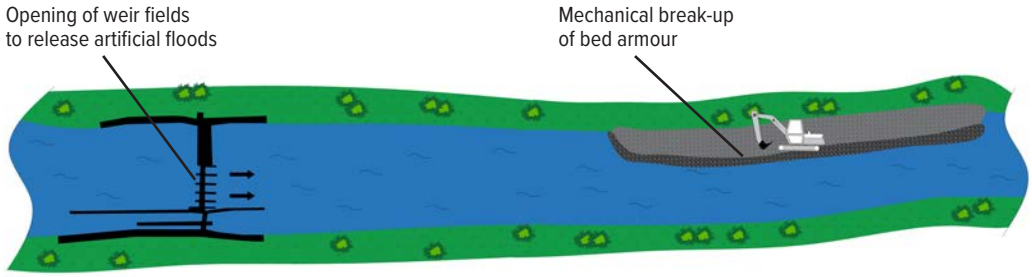
RIVER BASIN MANAGEMENT								RBM 16
Measure								**Break-up of bed armouring (artificial flood or mechanical)**
Location								Riverbed
Application								Free-flowing section
								Gravel and sand bed river
Main aim								Reduce riverbed erosion
Parameter								Riverbed level, sediment transport capacity, sediment continuity (fine sediments), substrate
Goals of measure	**Sediment**							Restore (fine) sediment continuity by breaking up of clogged riverbed
	River basin management							Maintain / restore aquatic habitats with adequate oxygen levels
Effects	L Low M Medium H High	**Parameter**		**Effects**				
	Hydro-dynamics	Water level		M	decreased			
		Flow velocity		M	increased (by artificial flooding)			
		Shear stress		M	increased (by artificial flooding)			
	Sediment-dynamics	Transport capacity		M	increased (fine sediments)			
		Continuity		M	increased (fine sediments)			
	Morpho-dynamics	River morphology		M	increased morphodynamics			
	Ecology	Habitat diversity / refugial habitats		M	enhanced habitat conditions			
Type of measure					Non-recurring	X	Recurring	
Categories		X	State of the art		Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**		Local scale	X	Reach scale		Catchment scale	
				X	Upstream effects	X	Downstream effects	
	Temporal	X	Short-term		Mid-term		Long-term	
Interrelation with		X	Flood protection	X	Hydropower			
			River basin management incl. Ecology		Navigation			
Assessment		Bathymetric survey of the riverbed before and after implementation Monitoring of suspended sediment concentration, oxygen and temperature during implementation						
Notes / Risks		The bed armour can either be broken up by artificial floods (increased water outflow from an upstream reservoir) or mechanically via dredging. If there is not enough bedload available to be mobilized, bedload augmentation with external sediments. Improved vertical connectivity to the ground water Positive effect on the hyporheic zone (interstitial water filled space beneath riverbeds) and thus for aquatic habitats, whilst ensuring adequate oxygen levels						
Interrelation with other measures		River widening (artificial or self-forming), riverbank restoration, reconnection of side-channels or enhance floodplain erosion, increase river length to reduce the slope						

RIVER BASIN MANAGEMENT — RBM 16

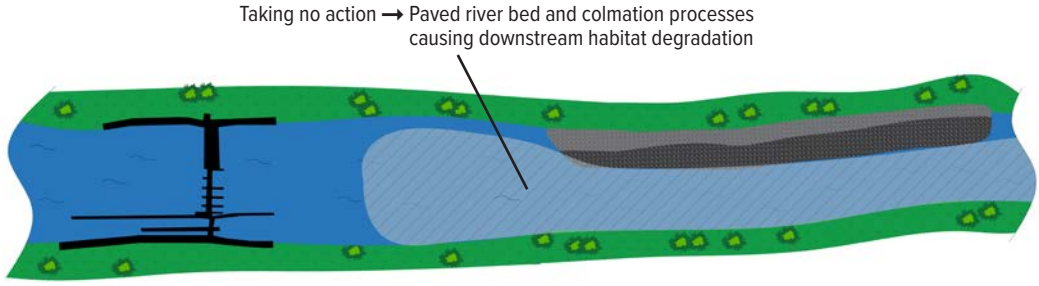
Measure	**Break-up of bed armouring (artificial flood or mechanical)**

POSITIVE

Break-up of bed armouring helps to remobilise consolidated sediments.



NEGATIVE



Examples

© HSE Invest d.o.o.

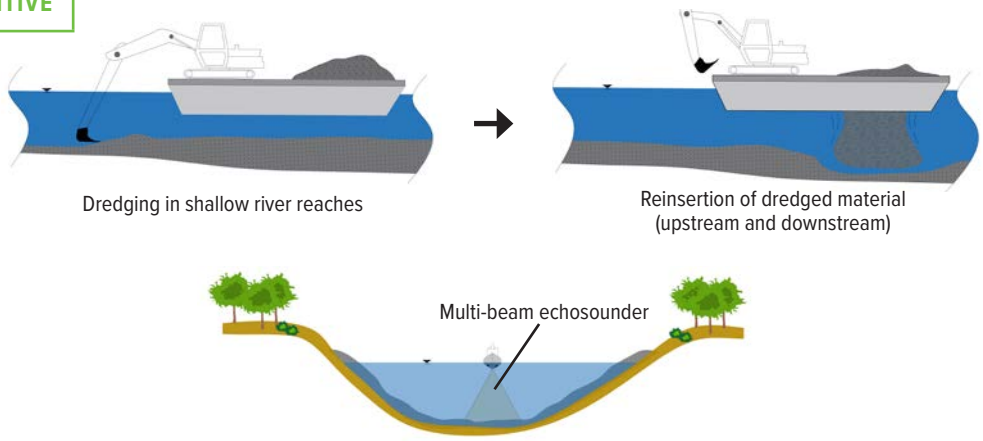
Reference	Break-up of bed armouring downstream of the HPP Melje at the Drau River (http://www.dem.si) See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_FF_D_T_GP45, S_FF_D_T_GP46

NAVIGATION								N 3
Measure			**Intelligent dredging and feeding management**					
Location			Riverbed / fairway					
Application			Free-flowing section					
			Gravel bed river					
Main aim			Both reduction of sedimentation and erosion, since the dredging itself aims to reduce sedimentation in the fairway, while the reinsertion of the dredged material upstream aims to reduce bed erosion by keeping the sediments in the system.					
Parameter			Water depth, riverbed level, flow velocity, shear stress, sediment transport capacity					
Goals of measure	**Sediment**		Reduce riverbed erosion via upstream transfer and dumping of the dredged sediments					
			Dynamic stabilisation of the riverbed					
	Navigation		Maintain fairway depths for low water level conditions in the navigation channel					
Effects	**L Low** **M Medium** **H High**		**Parameter**		**Effects**		**Note**	
	Hydro-dynamics		Water level		**M**	increased	depends on the state of the shallow	
			Flow velocity		**L**	decreased	depends on the state of the shallow	
			Shear stress		**M**	decreased	depends on the state of the shallow	
	Sediment-dynamics		Transport capacity		**M**	decreased	depends on the state of the shallow	
			Continuity		**M**	decreased	decreased after dredging; positive effect when the goal is not to lose sediment in the downstream direction; negative when the downstream section requires sedi-ments (e.g. no impoundment downstream)	
	Morpho-dynamics		River morphology		**L**	grain sizes	Higher trapping efficiency for larger grains; smaller grains might pass (depends on the extend of dredging)	
	Ecology		Habitat diversity / refugial habitats		**L**	minor changes, local disturbance	Depends on the time of the dredging (e.g. spawning season) and the amount of fine sediment release	
Type of measure						Non-recurring	X	Recurring
Categories		X	State of the art			Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**		Local scale	X		Reach scale		Catchment scale
				X		Upstream effects	X	Downstream effects
	Temporal		Short-term	X		Mid-term		Long-term
Interrelation with		X	Flood protection	X		Hydropower		
		X	River basin management incl. Ecology			Navigation		
Assessment			Premonitoring (bathymetry of the riverbed and detailed measurements at dredged areas, monitoring of water depths) Monitoring during implementation (dredged cubature) Postmonitoring (bathymetry of the riverbed and detailed measurements at dredged areas, monitoring of water depths)					
Notes / Risks			The overall goal is to keep the sediments in the system. The additional upstream transport of the dredged sediments compensates for the downstream transport and loss of the sediments in the upstream reach. Adding external coarser sediments can intensify the effects and counteracts abrasion. Bedload trap can be part of this measure, in order to gain coarse sediments for refeeding. The measure comes with a high maintenance effort and is cost-intensive.					
Interrelation with other measures			Sediment feeding, install bedload traps					

NAVIGATION N 3

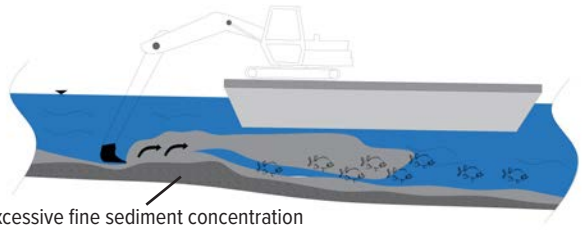
Measure	Intelligent dredging and feeding management

POSITIVE

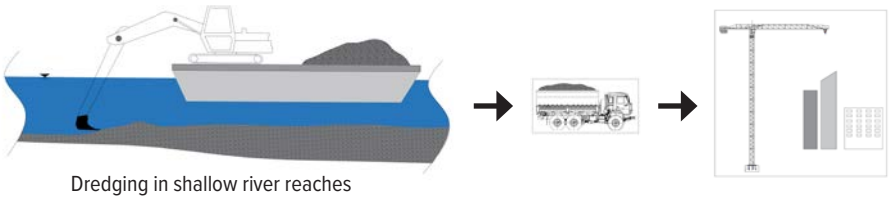


NEGATIVE

Dredging during spawning time



Taking the dredged material out of the river system



Examples

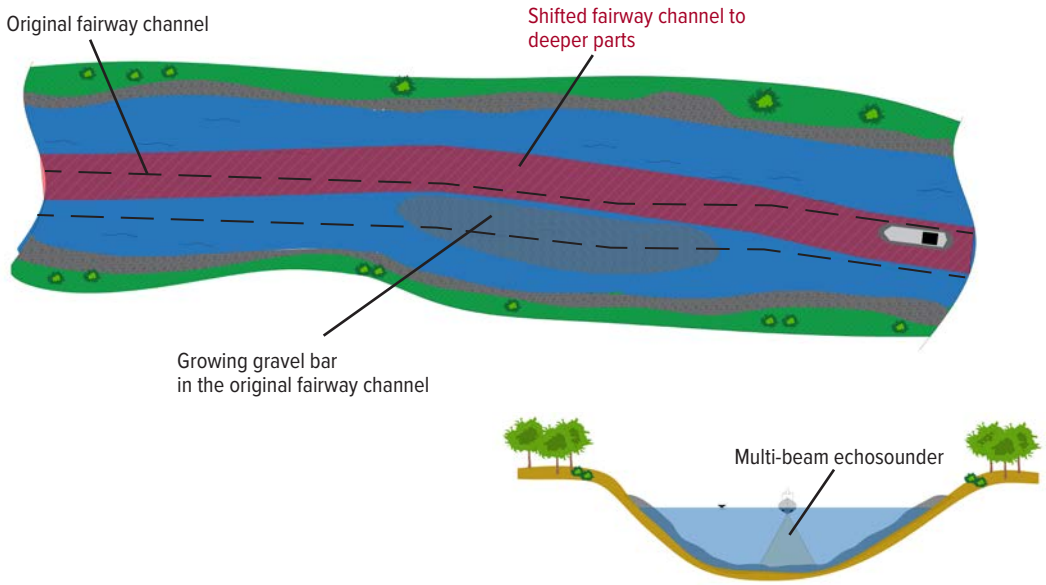
© IWA/BOKU

Reference	Catalogue of Measures for the Danube East of Vienna / Maintenance dredging works - WAMS (Waterway asset management system) (https://bit.ly/comeastvienna) See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_FF_N_D_GP40

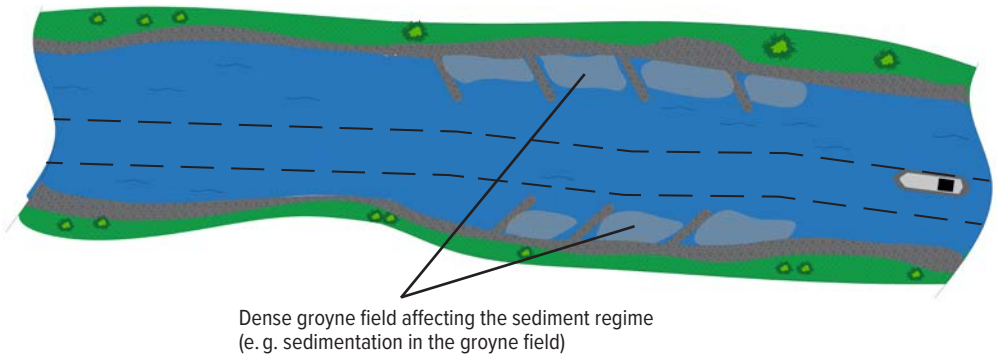
NAVIGATION								**N 4**
Measure			**Fairway shifting or narrowing**					
Location			Riverbed / fairway					
Application			Free-flowing section					
			Gravel / sand bed river					
Main aim			Ensure sustainable fairway conditions					
Parameter			Fairway depth / width, riverbed level					
Goals of measure	**Sediment**		Allow more natural morphodynamics and river patterns					
			Reduce river training and maintenance works (e.g. dredging)					
	Navigation		Maintain fairway depth and width in critical sectors					
Effects	L Low M Medium H High		**Parameter**		**Effects (fairway)**			
	Hydro-dynamics		Water level	M	increased water depth			
			Flow velocity		no effects			
			Shear stress		no effects			
	Sediment-dynamics		Transport capacity		no effects			
			Continuity		no effects			
	Morpho-dynamics		River morphology	L	allowing more morphodynamics			
	Ecology		Habitat diversity / refugial habitats	M	improved aquatic habitats (less disturbances by e.g. dredging)			
Type of measure					Non-recurring	X	Recurring	
Categories			State of the art	X	Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**		Local scale	X	Reach scale		Catchment scale	
					Upstream effects		Downstream effects	
	Temporal		Short-term	X	Mid-term		Long-term	
Interrelation with			Flood protection		Hydropower			
		X	River basin management incl. Ecology		Navigation			
Assessment			Regular riverbed surveys					
Notes / Risks			Applicable in river stretches with sufficient width Low impact on river, usually cheaper and easier/faster to implement Similar operational measure: fairway narrowing (dredging only a narrow part of the fairway instead of the full width)					
Interrelation with other measures			Bathymetric survey, minimize or stop commercial dredging					

NAVIGATION	N 4
Measure	**Fairway shifting or narrowing**

POSITIVE



NEGATIVE



Examples	–
Reference	–

Optimisation of river engineering structures to reduce erosion (© IWA/BOKU)

D.3 LOCAL / POINT SCALE

Figure 38 shows sediment management measures on the local or point scale at the dam and in free-flowing sections. The ones highlighted in bold are described in the following factsheets.

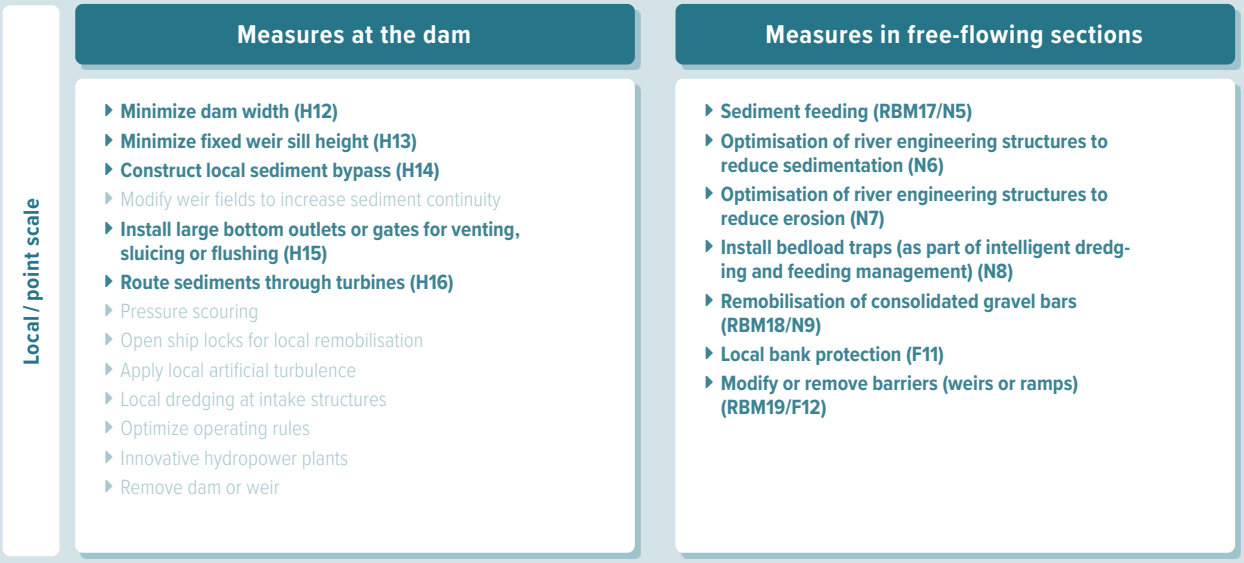


Figure 39: Overview of sediment management measures on the local/point scale at the dam and in free-flowing sections; measures that are described in a factsheet are highlighted in bold

D.3.1 Measures at the dam

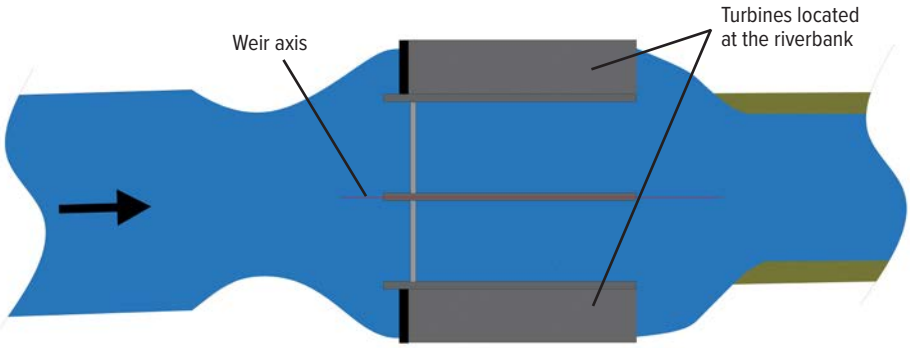
12

HYDROPOWER								H 12
Measure								**Minimize dam width**
Location								Dam / weir
Application								Existing and newly built reservoir / dam
								Gravel and sand bed river
Main aim								Reduce sedimentation in the reservoir and riverbed erosion in the downstream reach
Parameter								Shear stress, sediment transport capacity, flow velocity, water level/depth, bed slope
Goals of measure	**Sediment**							Improve sediment continuity by increasing shear stress and sediment transport capacity near the dam
	Flood protection							Increase / maintain flood protection by reducing sedimentation and flood water levels
	Hydropower							Reduce maintenance works and ensure safe operability of the hydropower plant
Effects	L Low M Medium H High	**Parameter**		**Effects (at the dam)**				**Effects (downstream of the dam)**
	Hydro-dynamics	Water level		M	decreased at high flow		M	increased at high flow
		Flow velocity		H	increased		M	increased
		Shear stress		H	increased		M	increased
	Sediment-dynamics	Transport capacity		M	increased		M	increased
		Continuity		M	increased		M	increased
	Morpho-dynamics	River morphology		L	increased morphodynamics		M	increased morphodynamics especially when gravel is supplied
	Ecology	Habitat diversity / refugial habitats		L	increased (reduced colmation)		L	improved, when gravel supplied downstream
Type of measure					X	Non-recurring		Recurring
Categories			State of the art		X	Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**	X	Local scale			Reach scale		Catchment scale
					X	Upstream effects	X	Downstream effects
	Temporal		Short-term			Mid-term	X	Long-term
Interrelation with		X	Flood protection			Hydropower		
		X	River basin management incl. Ecology			Navigation		
Assessment		Bathymetric surveys of the riverbed Bedload transport Water levels						
Notes / Risks		This is a construction measure that enhances sediment transfer and remobilisation, since it increases shear stress in the close range of the hydropower plant. Hydroelectric generating components of the hydropower plant (e.g. turbines) are positioned at the left and right side of the river by the riverbank. This is basically an option for newly built hydropower plants; high implementation effort at existing hydropower plants.						
Interrelation with other measures		All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, install large bottom outlets or gates, minimize fixed weir sill height, open ship locks for local remobilisation, optimize operating rules						

HYDROPOWER H 12

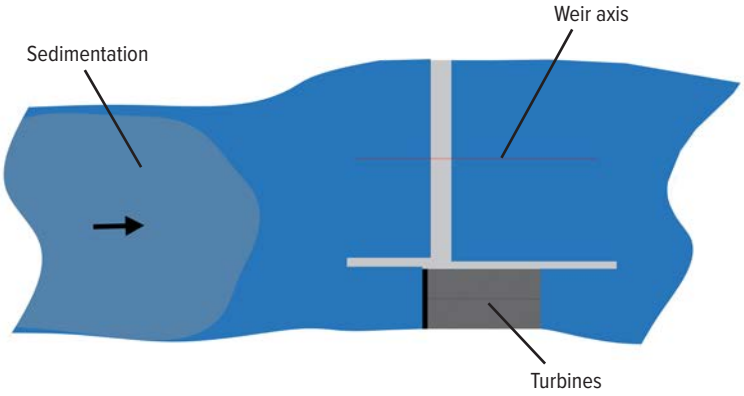
Measure	Minimize dam width

POSITIVE



NEGATIVE

High reservoir width near the dam/weir causing sediment deposition.



Examples

Reference	Salzburg AG. VERBUND. 2019. Strom aus der Salzach. Das Kraftwerk Gries. Residenz Verlag. ISBN 9783701734863.

13

HYDROPOWER — H 13

Measure	**Minimize fixed weir sill height**

Location		Dam / weir
Application		Existing and newly built dam / weir
		Gravel and sand bed river
Main aim		Reduce sedimentation in the reservoir and riverbed erosion in the downstream reach
Parameter		Bedload transport, sediment transport capacity, sediment continuity, bed slope, water level (flood stage)
Goals of measure	**Sediment**	Prevent bedload deposition at the dam / weir, improve transport capacity through the impoundment / reservoir
	Flood protection	Enhance flood protection by maintaining the original riverbed levels and thus securing the high water levels
	Hydropower	Reduce maintenance works and ensure safe operability of the hydropower plant, increase slucing / flushing efficiency
		Maintain reservoir volume

Effects — L Low / M Medium / H High

Parameter	**Effects (upstream of the dam/weir)**	**Effects (downstream of the dam/weir)**
Hydro-dynamics		
Water level	M decreased at flood discharge	M increased
Flow velocity	H increased	M increased
Shear stress	H increased	M increased
Sediment-dynamics		
Transport capacity	H increased	M increased
Continuity	H increased	M increased
Morpho-dynamics		
River morphology	L minor effects	M increased morphodynamics especially when gravel is supplied
Ecology		
Habitat diversity / refugial habitats	L minor effects	L improved, when gravel supplied downstream

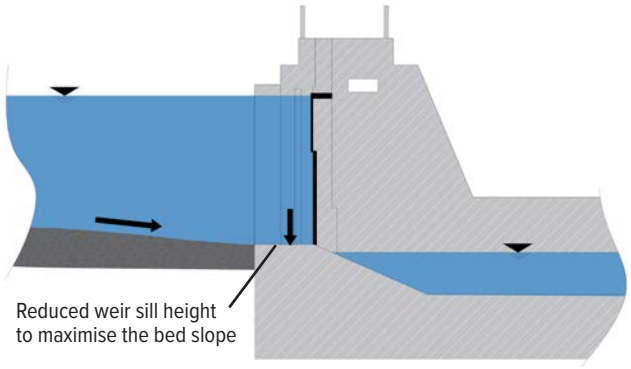
Type of measure			X Non-recurring		Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling — **Spatial**	X Local scale		Reach scale		Catchment scale
			X Upstream effects	X	Downstream effects
Temporal		Short-term		X	Long-term
Interrelation with	X Flood protection		Hydropower		
	X River basin management incl. Ecology		Navigation		

Assessment	Bathymetric surveys of the riverbed Suspended sediment and bedload transport Impact on environment due to (changed) sediment management operation Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules
Notes / Risks	Increases efficiency of sediment routing (e.g. sluicing) or removal (e.g. flushing) operations. Higher and movable gates / weirs are needed Incorporate into design phase of the hydropower plant, since retrofitting might be costly or not feasible
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules

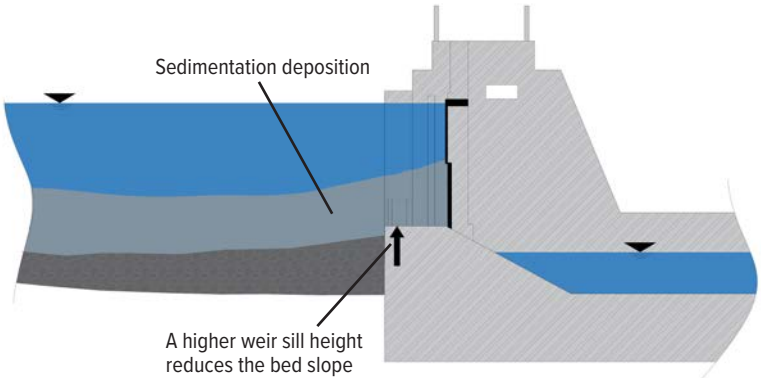
HYDROPOWER — H 13

Measure | **Minimize fixed weir sill height**

POSITIVE



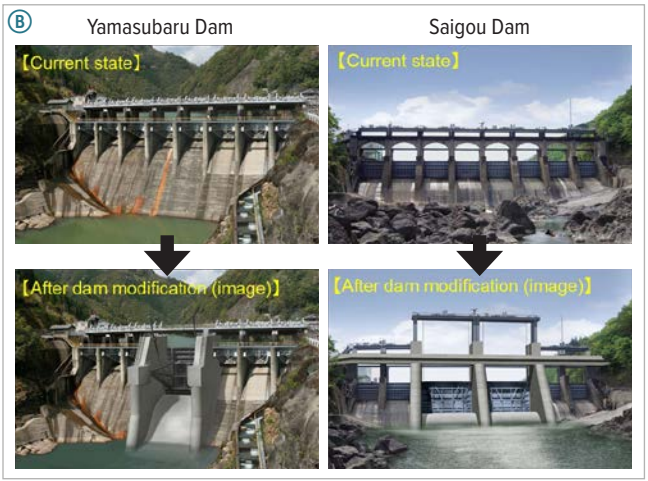
NEGATIVE



Examples

Physical model test:
① Lowering of weir fields
② Extension of the existing guiding wall
③ Construction of a new guiding wall
④ Scour protection with large stones

© BAW-IWB



© Sumi, 2016

Reference

Ⓐ Adapting the existing weir system at the HPP „Sohlstufe Hallein“, river Salzach, AT (https://bit.ly/sohlstufehallein) (see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_R_H/FP_T_GP66)

Ⓑ Retrofitting works of the Yamasubaru and the Saigou dams, JP (Sumi, T., Kantoush, S. A., 2016. Sediment Management Option by Sediment Sluicing in the Mimi River. Japan.)

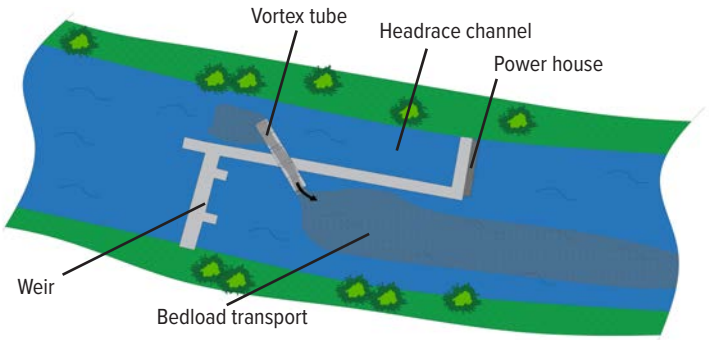
14

HYDROPOWER								H 14
Measure			**Construct local sediment bypass**					
Location			Dam / weir					
Application			Existing and newly constructed reservoir with the weir placed behind the turbine water channel (turbine water channel and residual flow channel are separated by a side weir)					
			Rivers with high bedload transport					
Main aim			Reduction of bedload deposition in the headwater channel and riverbed erosion in the residual flow reach					
Parameter			Substrate, bedload continuity, discharge					
Goals of measure	**Sediment**		Improving bedload continuity					
	Flood protection		Maintaining / improving of flood discharge capacity without further structures (e.g. longitudinal dams)					
	Hydropower		Prevent sedimentation and keep intakes free					
Effects	**L** Low **M** Medium **H** High		**Parameter**		**Effects (headwater channel)**		**Effects (downstream reach)**	
	Hydro-dynamics		Water level		**L**	eventually decreased at high-flow	**L**	eventually increased
			Flow velocity		**L**	minor effects	**L**	minor effects
			Shear stress		**L**	minor effects	**L**	minor effects
	Sediment-dynamics		Transport capacity		**H**	increased		
			Continuity		**H**	increased bedload transport	**H**	increased amount of bedload material
	Morpho-dynamics		River morphology		**L**	increased morphodynamics	**L**	increased morphodynamics
	Ecology		Habitat diversity / refugial habitats		**L**	minor effects	**M+**	increased
Type of measure					X	Non-recurring		Recurring
Categories				State of the art	X	Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**		X	Local scale		Reach scale		Catchment scale
					X	Upstream effects	X	Downstream effects
	Temporal			Short-term	X	Mid-term		Long-term
Interrelation with			X	Flood protection		Hydropower		
			X	River basin management incl. Ecology		Navigation		
Assessment			Physical model tests before implementation Bedload and suspended sediment measurements Bathymetric surveys					
Notes / Risks			Functionality mainly depends on difference in energy head and the location of the vortex tube relative to the zone of active bedload transport. The energy head between the higher and the lower situated channel should always be larger than approx. 1m. Choice of vortex tube diameter should be adapted to grain size (Rachelly, 2019)					
Interrelation with other measures			All measures in the catchment; minimize width by hydraulic structures, sluicing, flood-conditioned flushing, optimized flushing and sluicing strategies for dams in series, wet or dry dredging & reinsertion, bedload drift, minimize fixed weir sill height, install large bottom outlets or gates, open ship locks for local remobilisation, optimize operating rules					

HYDROPOWER — H 14

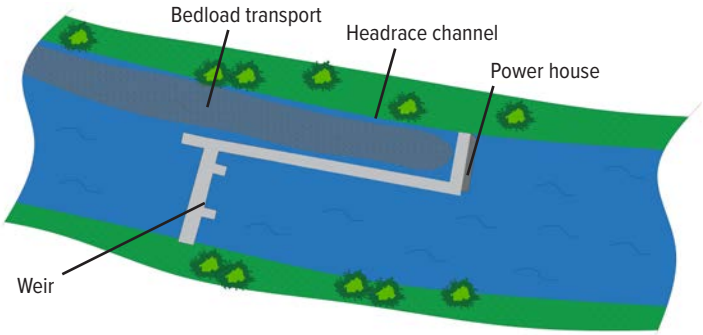
Measure | **Construct local sediment bypass**

POSITIVE

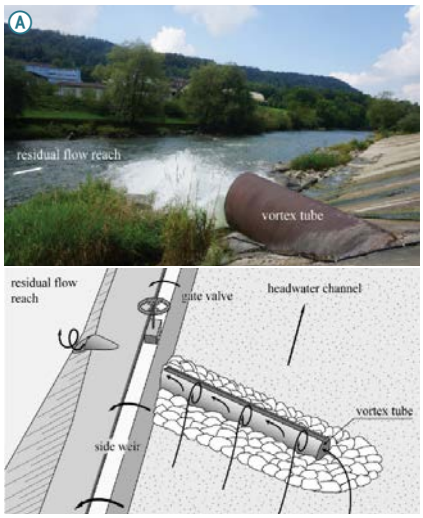


NEGATIVE

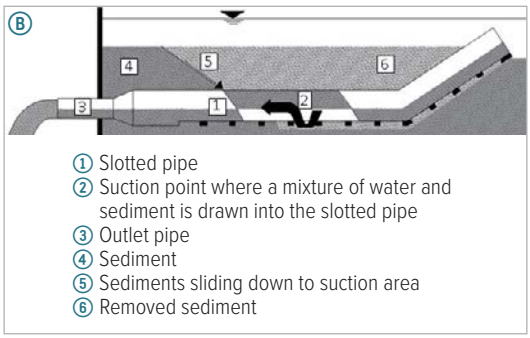
If there is no local bypass (vortex tube), bedload might deposit near the weir or dam, causing the water intake to clog.



Examples



© Rachelly et al., 2019



① Slotted pipe
② Suction point where a mixture of water and sediment is drawn into the slotted pipe
③ Outlet pipe
④ Sediment
⑤ Sediments sliding down to suction area
⑥ Removed sediment

Modified after Jacobsen, 1997

Reference

Ⓐ Vortex tube at Limmat River, CH (Rachelly, C. et al., 2019. Bed-load diversion with a vortex tube system. 10.3929/ethz-b-000370865.) See DanubeSediment report „Sediment Management Measures for the Danube", factsheet code in annex 2: S_FF_H_O_GP37

Ⓑ Slotted Pipe Sediment Sluicer (SPSS) (Jacobsen, T., 1997. Sediment problems in reservoirs. Control of sediment deposits. Doctoral thesis.)

15

HYDROPOWER — H 15

Measure	**Install large bottom outlets or gates for venting, sluicing or flushing**

Location		Dam / weir
Application		Existing and newly built reservoir / dam
		Gravel and sand bed river
Main aim		Reduce sedimentation in the reservoir and improve continuity; increase efficiency of venting, sluicing and flushing
Parameter		Sediment continuity, sediment transport capacity, water depth, flow velocity, shear stress, flood discharge
Goals of measure	**Sediment**	Prevent / reduce sedimentation in the reservoir / impoundment
		Improve sediment continuity
	Ecology	Limit impact by improving efficiency of sediment management during floods when concentration is naturally high
	Flood protection	Increase / maintain flood protection by reducing sedimentation
	Hydropower	Ensure sustainable long-term operability of the hydropower plant, maintain reservoir capacity

Effects

L Low · M Medium · H High

Parameter	Effects (upstream of the dam)	Effects (downstream of the dam)
Hydro-dynamics		
Water level	depends on management (flushing, sluicing or venting)	L minor effects
Flow velocity	depends on management (flushing, sluicing or venting)	M increased near the outlet
Shear stress	depends on management (flushing, sluicing or venting)	M increased near the outlet
Sediment-dynamics		
Transport capacity	M increased	M increased
Continuity	M increased	M increased
Morpho-dynamics		
River morphology	L minor effects	M increased morphodynamics especially when gravel is supplied
Ecology		
Habitat diversity / refugial habitats	depends on management (flushing, sluicing or venting)	M transport during flood were load is naturally high

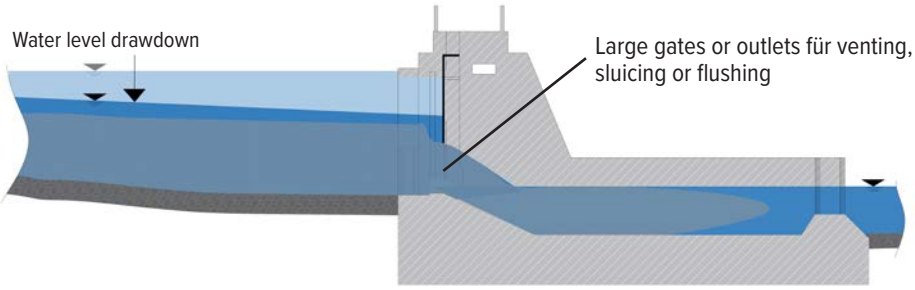
Type of measure		X Non-recurring	Recurring
Categories	State of the art	X Tested (implemented at least once)	State of science (no field test yet)
Scaling — **Spatial**	X Local scale	Reach scale	Catchment scale
		X Upstream effects	X Downstream effects
Temporal	Short-term	Mid-term	X Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	X Navigation	

Assessment	Bathymetric surveys Monitoring of bedload, suspended sediment concentration and grain sizes Impact on environment due to (changed) sediment management operation Physical or numerical models to plan and assess the functionality in terms of sediment transport and to obtain optimal operation rules
Notes / Risks	Improves efficiency of flushing, sluicing and venting Incorporate into design phase of the hydropower plant, since retrofitting might be costly or not feasible The bottom outlets need to be reinforced due to high flow velocities and risk of damage due to abrasion from bedload
Interrelation with other measures	All measures in the catchment; minimize width by hydraulic structures, sluicing, venting, flood-conditioned flushing, optimised flushing or sluicing strategies for dams in series, minimize fixed weir sill height; bathymetric survey

HYDROPOWER H 15

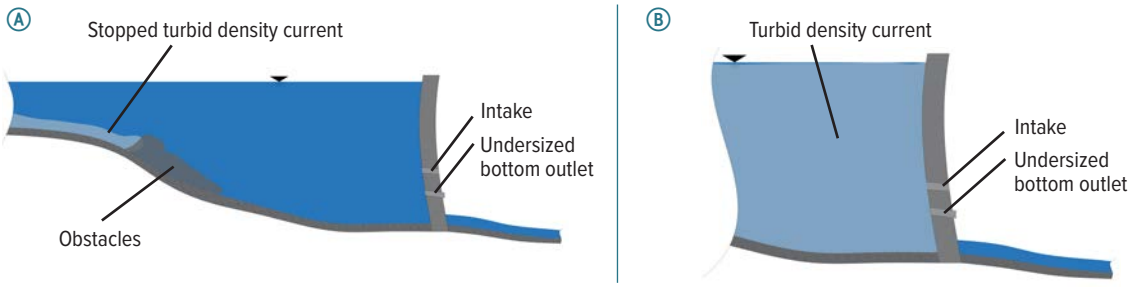
Measure | **Install large bottom outlets or gates for venting, sluicing or flushing**

POSITIVE



NEGATIVE

The turbid density current might be stopped by obstacles or barriers in the reservoir (A). An undersized low-level outlet might lead to premature depositions and clogging of the outlet (B).



Examples

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Reference | Rimasco dam, IT (ICOLD proceedings. 2018. question 100. report 18. 26th congress. Vienna 2018.)

16

HYDROPOWER — H 16

Measure	**Route sediments through turbines**
Location	Intake
Application	Existing reservoir / dam
	Gravel and sand bed river
Main aim	Reduce sedimentation in the reservoir and improve continuity
Parameter	Sediment continuity (fine sediments), sediment transport capacity, grain sizes, petrography
Goals of measure – **Sediment**	Reduce sedimentation by passing sediment-laden water through turbines
Goals of measure – **Flood protection**	Maintain flood protection by reducing sedimentation
Goals of measure – **Hydropower**	Reduce sedimentation – complementary measure

Effects (L Low / M Medium / H High)

Parameter	Effects (upstream of the dam)	Effects (downstream of the dam)
Hydro-dynamics – Water level	M decreased	depends on turbine operation
Hydro-dynamics – Flow velocity	M increased	depends on turbine operation
Hydro-dynamics – Shear stress	M increased	depends on turbine operation
Sediment-dynamics – Transport capacity	M maintained (fine sediment)	M maintained (fine sediment)
Sediment-dynamics – Continuity	M increased (fine sediment)	M supplied (fine sediment)
Morpho-dynamics – River morphology		Effect depends on concentration of fines
Ecology – Habitat diversity / refugial habitats		Effect depends on concentration of fines

Type of measure		Non-recurring	X Recurring
Categories	State of the art	X Tested (implemented at least once)	State of science (no field test yet)
Scaling – **Spatial**	Local scale	X Reach scale	Catchment scale
		X Upstream effects	X Downstream effects
Scaling – **Temporal**	X Short-term	Mid-term	Long-term
Interrelation with	X Flood protection	Hydropower	
	X River basin management incl. Ecology	Navigation	

Assessment

Bathymetric surveys
Monitoring of suspended sediment concentration and particle sizes
Monitoring of sediment transport in head race
Physical or numerical models to plan and assess the functionality

Notes / Risks

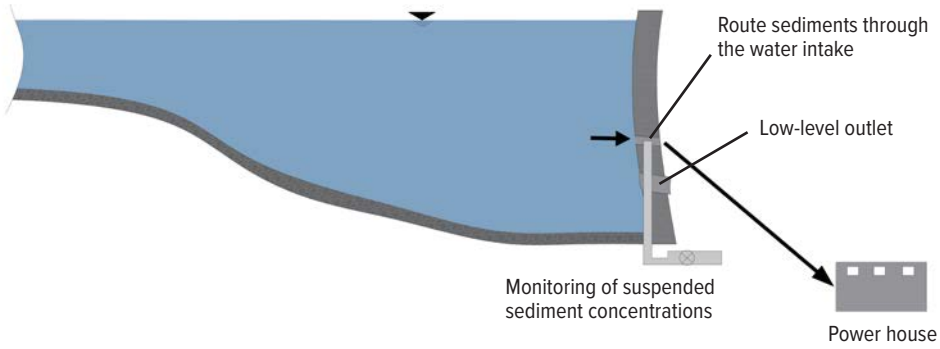
Size of sediments and petrography of the catchment can limit applicability
Limited to fine sediments, coarse material should not enter the turbines
Hard coating of turbines to reduce damage by abrasive processes (special turbines may be required)
Might cause excessive fine sediment concentrations with adverse effects on ecology.
Complementary sediment management measure

Interrelation with other measures	All measures in the catchment; venting of turbid density currents, sediment bypass (tunnel, channel), sluicing, flood-conditioned / environmentally-friendly flushing, prevent sedimentation by artificial turbulence, wet or dry dredging and reinsertion, install large bottom outlets or gates, apply local artificial turbulence;

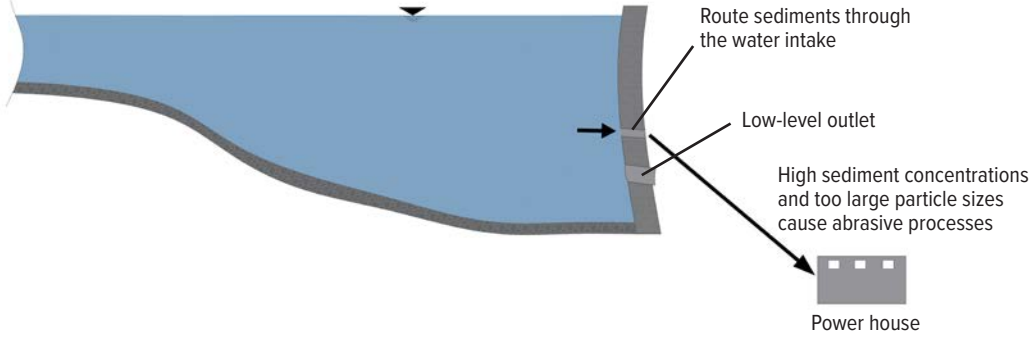
HYDROPOWER	H 16
Measure	**Route sediments through turbines**

POSITIVE

Eventually in combination with artificial turbulence (jet screen) to route the turbid density current to the water intake.



NEGATIVE



Examples	–
Reference	–

D.3.2 Measures in free-flowing sections

RIVER BASIN MANAGEMENT/NAVIGATION	RBM 17	N 5

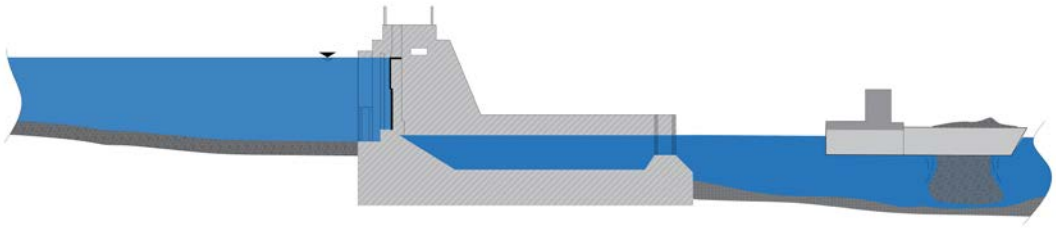
Measure	**Sediment feeding**							
Location	Main channel							
Application	Free-flowing section							
	Gravel bed river							
Main aim	Reduce riverbed erosion							
Parameter	Water level, sediment transport capacity, sediment supply, substrate (sediment size)							
Goals of measure	**Sediment**	Stabilize riverbed level (reduced erosion)						
		Improve sediment continuity by artificial gravel supply						
	Ecology	Reduce water level reduction and prevent floodplains from draining						
Effects	L Low M Medium H High	**Parameter**		**Effects**		**Note**		
	Hydro-dynamics	Water level		M	reduce decrease	Feeding reduces the riverbed erosion and therefore the lowering of the water levels		
		Flow velocity		L	minor effects			
		Shear stress		L	minor effects			
	Sediment-dynamics	Transport capacity		H	increased			
		Continuity		H	increased			
	Morpho-dynamics	River morphology		M	increased morphodynamics			
	Ecology	Habitat diversity / refugial habitats		M	improved aquatic habitats	There might be a disturbance of the habitats at the feeding site, but this measure counteracts bed degradation in the downstream section, thus benefitting ecology.		
Type of measure					Non-recurring	X	Recurring	
Categories	X	State of the art			Tested (implemented at least once)		State of science (no field test yet)	
Scaling	**Spatial**	X	Local scale	X	Reach scale		Catchment scale	
					Upstream effects	X	Downstream effects	
	Temporal		Short-term		Mid-term	X	Long-term	
Interrelation with	X	Flood protection		X	Hydropower			
	X	River basin management incl. Ecology		X	Navigation			
Assessment	Bathymetric monitoring before, during and after implementation Grain size							
Notes / Risks	Besides aiming to stabilize the riverbed, the measure achieves positive effects for side-arm systems, since it reduces previous water level decrease. Substrate availability is increased, i.e. coarser material/gravel may be available to improve the riverbed and for ecology.							
Interrelation with other measures	Remobilisation of consolidated gravel bars							

RIVER BASIN MANAGEMENT/NAVIGATION | RBM 17 | N 5

Measure | **Sediment feeding**

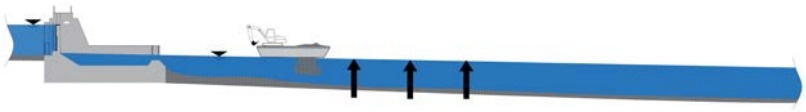
POSITIVE

Dumping of sediments in local pool areas to stabilize riverbed levels.
Feeding is not perfomed during spawning season.

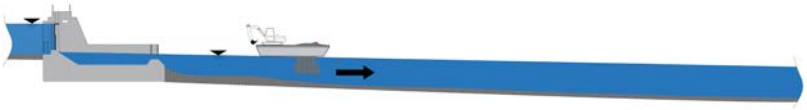


NEGATIVE

Feeding too much sediment or material that is too coarse might prevent transport and thus might increase flood risk.



Inappropriate material, e.g. grain sizes that are too small, might have no positive local effect, as it is immediately transported downstream



In case no action is taken, riverbed incision is likely to occur.

Examples

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Reference

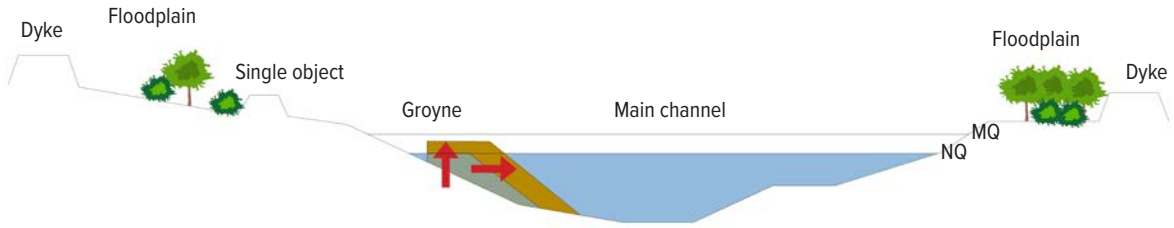
Gravel nourishment at the Danube River, downstream of the HPP Freudenau (https://www.verbund.com)
Further examples: see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet codes in annex 2: E_FF_H_D_GP01, E_R_H_T_GP24, E_R_H_T_GP25, S_R_H/FP_T_GP67, E_FF_FP-N_D_P21

NAVIGATION								**N 6**
Measure				**Optimisation of river training structures to reduce sedimentation**				
Location				Riverbanks / near bank zone				
Application				Free-flowing section				
				Gravel and sand bed river				
Main aim				Reduce sedimentation				
Parameter				Water level, water depth, flow velocity, shear stress, sediment transport capacity and continuity				
Goals of measure	**Sediment**			Reduce sedimentation by increasing shear stress in the main channel				
				Increase sediment continuity				
	Navigation			Improve navigational conditions (increase water depth at low discharges, reduce maintenance dredging)				
				Fixation of the navigation channel / fairway				
				Protection of banks at outer curves				
Effects	L Low M Medium H High		**Parameter**		**Effects (main channel)**		**Effects (groyne field, banks)**	
	Hydro-dynamics		Water level		M	increased	L	decreased
			Flow velocity		M	increased	M	decreased
			Shear stress		M	increased	M	decreased
	Sediment-dynamics		Transport capacity		M	increased	M	decreased
			Continuity		M	increased	M	decreased
	Morpho-dynamics		River morphology		H	increased morphodynamics	M	decreased morphodynamics
	Ecology		Habitat diversity / refugial habitats			no effects	M	decreased habitat diversity
Type of measure					X	Non-recurring		Recurring
Categories			State of the art		X	Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**	X	Local scale			Reach scale		Catchment scale
						Upstream effects	X	Downstream effects
	Temporal		Short-term			Mid-term	X	Long-term
Interrelation with		X	Flood protection			Hydropower		
		X	River basin management incl. Ecology			Navigation		
Assessment	Numerical modelling of hydrodynamic and sediment transport Monitoring of sediment transport, bathymetry, morphology, side erosion, flow velocity after implementation Grain sizes							
Notes / Risks	River training structures (e.g. groynes, guiding walls) are constructed in a river to modify the hydraulic flow and sediment response of a river. Length, spacing, height of these structures determines the effects Orientation and design of structures such as groynes must be adapted to river conditions, in order not to obtain unwanted effects (too much erosion) Scouring effects							
Interrelation with other measures	Optimisation of river training structures to reduce erosion, local bank protection							

NAVIGATION — N 6

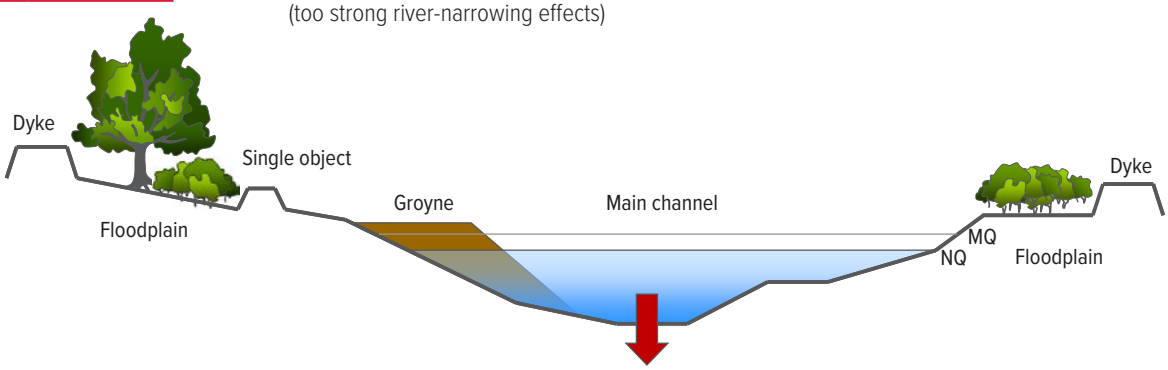
Measure | **Optimisation of river training structures to reduce sedimentation**

POSITIVE



NEGATIVE

Riverbed incision because of overdesigned groynes
(too strong river-narrowing effects)



Examples

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Reference

IREP – Integrated River Engineering Project on the Danube to the East of Vienna (https://bit.ly/irepat)

Further examples: Danube, GER (https://bit.ly/optimizinggroynes), see DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: S_FF_N_D_GP43

NAVIGATION								**N 7**
Measure				**Optimisation of river training structures to reduce erosion**				
Location				Riverbanks / near bank zone				
Application				Free-flowing section				
				Gravel and sand bed river				
Main aim				Reduce riverbed erosion				
Parameter				Water level, water depth, flow velocity, shear stress, sediment transport capacity and continuity				
Goals of measure	**Sediment**			Reduce bed erosion by decreased shear stress in the main channel				
				Less sedimentation in the groyne field				
				Increase sediment input by side erosion in combination with bank restoration				
				Increase hydromorphological dynamics at the banks				
	Ecology			Enhance ecological conditions (improvement of aquatic habitat diversity by near bank flow)				
Effects	L Low M Medium H High			**Parameter**		**Effects (main channel)**		**Effects (groyne field, banks)**
	Hydro-dynamics			Water level	M	decreased	L	increased
				Flow velocity	M	decreased	M	increased variability
				Shear stress	M	decreased	M	increased
	Sediment-dynamics			Transport capacity	M	decreased	M	increased
				Continuity	M	eventually decreased	M	increased sediment input
	Morpho-dynamics			River morphology	L	decreased morphodynamics	H	increased morphodynamics; more natural grain size distribution
	Ecology			Habitat diversity / refugial habitats		no effects	M	improved meso and micro habitat diversity
Type of measure					X	Non-recurring		Recurring
Categories				State of the art	X	Tested (implemented at least once)		State of science (no field test yet)
Scaling	**Spatial**			X Local scale		Reach scale		Catchment scale
						Upstream effects	X	Downstream effects
	Temporal			Short-term		Mid-term	X	Long-term
Interrelation with				X Flood protection		Hydropower		
				X River basin management incl. Ecology		Navigation		
Assessment				Numerical modelling of hydrodynamic and sediment transport Monitoring of sediment transport, bathymetry, morphology, side erosion, flow velocity after implementation				
Notes / Risks				Length, spacing, height of these structures determines the effects Scouring effects Side erosion of riverbanks Potential depositions in the fairway				
Interrelation with other measures				Optimisation of river training structures to reduce sedimentation, local bank protection				

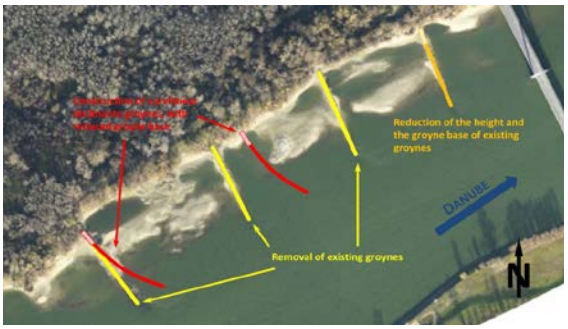
NAVIGATION — N 7

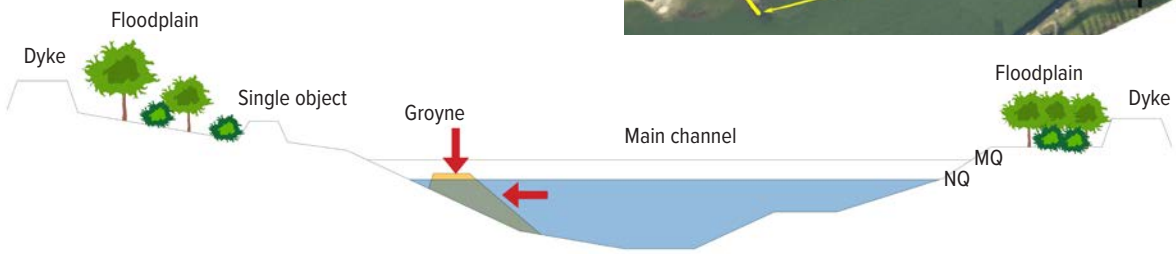
Measure | **Optimisation of river training structures to reduce erosion**

POSITIVE

Variation of groynes:

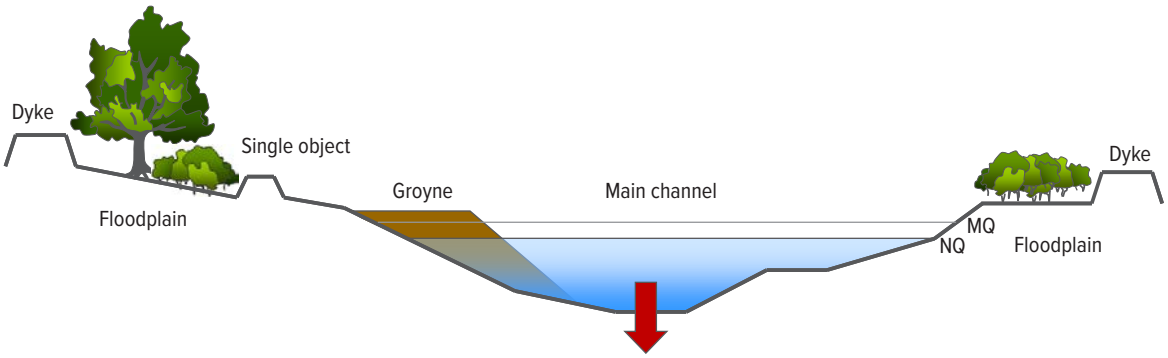
- shortening
- lowering
- change of orientation
- increase of spacing





NEGATIVE

Overdesigned river training structures benefit riverbed incision



Examples

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Reference

IREP – Integrated River Engineering Project on the Danube to the East of Vienna (https://bit.ly/irepat)
See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_N_D_GP11

8

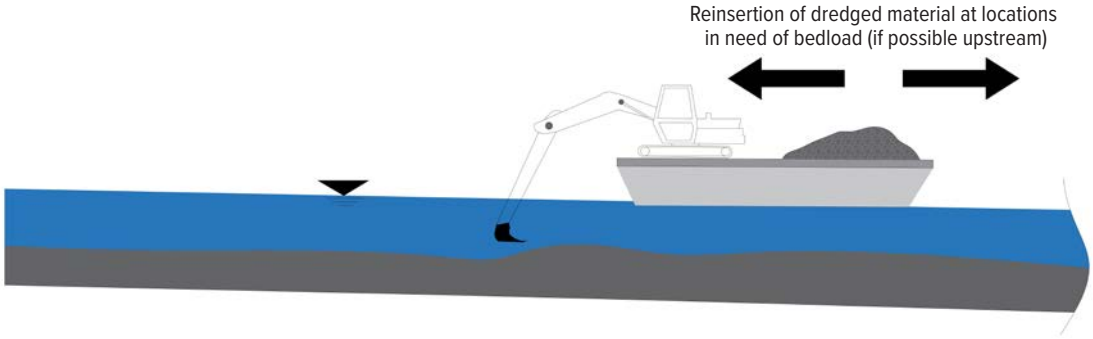
NAVIGATION								N 8
Measure								**Install bedload traps (as part of intelligent dredging and feeding management)**
Location								Riverbed / fairway
Application								Free-flowing section Gravel bed river
Main aim								Both reduction of sedimentation (control the location of deposition) and erosion (prevent sediments from leaving the system in the downstream direction)
Parameter								Water depth, bedload transport, location of fine sediment layers / the thickness of the gravel layer
Goals of measure	**Sediment**							Dynamic stabilisation of the riverbed Refeed dredged sediment in upstream parts to reduce the ongoing riverbed incision
	Ecology							Improve local aquatic habitats
	Navigation							Maintain water level conditions in the navigation channel
Effects	**L Low** **M Medium** **H High**	**Parameter**		**Effects**				**Note**
	Hydro-dynamics	Water level		**H**	increased			Depends on the filling stage of the trap
		Flow velocity		**M**	reduced			Depends on the filling stage of the trap
		Shear stress		**M**	reduced			Depends on the filling stage of the trap
	Sediment-dynamics	Transport capacity		**M**	reduced			Depends on the filling stage of the trap
		Continuity		**M**				Reduced when trap is filling; positive when the goal is to not lose sediments in the downstream direction; negative when the downstream section also needs sediments (e.g. no impoundment downstream)
	Morpho-dynamics	River morphology		**L**	grain sizes			Higher trapping efficiency for larger grains; smaller grains might pass the trap (depends on the size of the trap)
	Ecology	Habitat diversity / refugial habitats		**L**	minor changes; local disturbance			Depends on the time of the dredging (e.g. spawning season)
Type of measure					Non-recurring		X	Recurring
Categories			State of the art		Tested (implemented at least once)	X		State of science (no field test yet)
Scaling	**Spatial**		Local scale		Reach scale	X		Catchment scale
					Upstream effects		X	Downstream effects
	Temporal		Short-term		Mid-term	X		Long-term
Interrelation with		X	Flood protection	X	Hydropower			
		X	River basin management incl. Ecology		Navigation			
Assessment		Premonitoring (bathymetry of the riverbed and detailed measurements at dredging and refeeding locations, grain size analysis) Monitoring during implementation (bathymetry of the riverbed and detailed measurements at dredging and refeeding locations, grain size analysis) Postmonitoring (bathymetry of the riverbed and detailed measurements at dredging and refeeding locations, grain size analysis)						
Notes / Risks		The thickness of the gravel layer must be large enough after dredging the trap, especially in case finer sediments is present below the gravel layer. Those fine sediments are more easily erodible, which means reaching this layer when dredging the trap needs to be prevented. Downstream effects must be considered (e.g. sediment deficit)						
Interrelation with other measures		Sediment feeding, remobilisation of consolidated gravel bars, install bedload traps						

NAVIGATION — N 8

Measure — **Install bedload traps (as part of intelligent dredging and feeding management)**

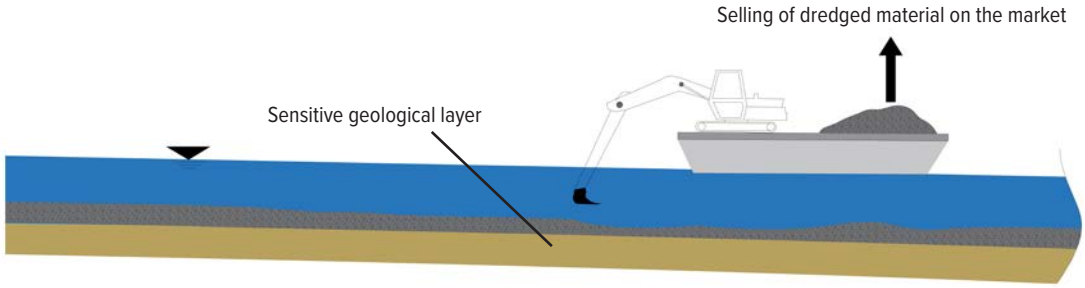
POSITIVE

Bedload traps should be designed appropriately (size, depth, ...).



NEGATIVE

Bad practice would be to use the dredged material for commercial purposes. Attention must be given to potentially sensitive geological layers below the bedload trap to avoid a riverbed breakthrough.



Examples

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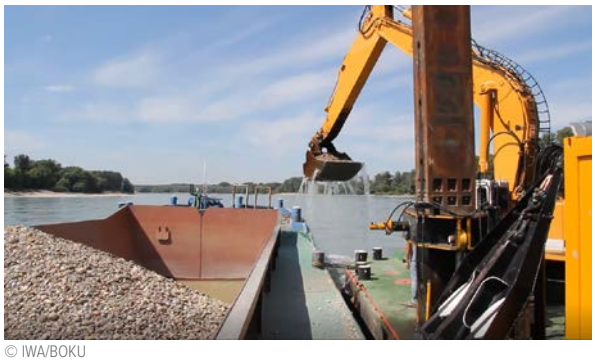

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Reference

IREP – Catalogue of Measures for the Danube East of Vienna / Bedload trap (integrative bedload management) (https://bit.ly/comeastvienna)

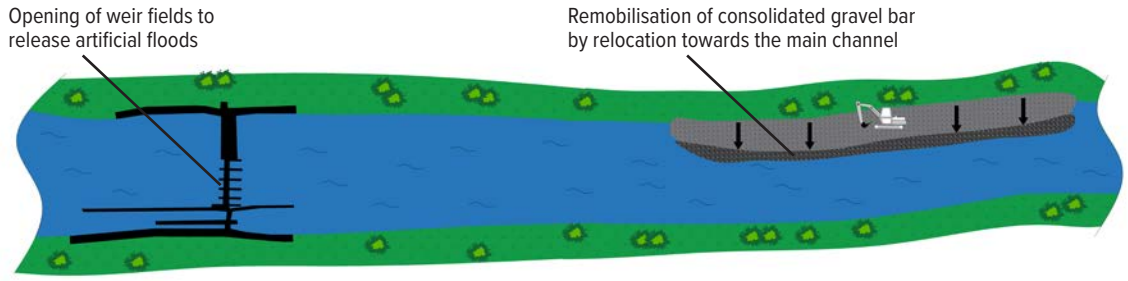
See DanubeSediment report „Sediment Management Measures for the Danube“, factsheet code in annex 2: E_FF_N_D_GP13, further example: Inn, AT (https://bit.ly/bedloadtrapinn) S_R_H_T_GP52

RIVER BASIN MANAGEMENT/NAVIGATION			RBM 18	N 9
Measure			**Remobilisation of consolidated gravel bars**	
Location			Near bank zone	
Application			Free-flowing section Gravel bed river	
Main aim			Reduce riverbed erosion	
Parameter			Water level, sediment transport capacity, sediment supply, substrate (sediment size)	
Goals of measure	**Sediment**		Stabilize riverbed level (reduced erosion) Improve sediment continuity by remobilising sediments	
	Ecology		Maintain / restore aquatic habitats with adequate oxygen levels	
Effects **L** Low **M** Medium **H** High		**Parameter**	**Effects**	**Note**
	Hydro-dynamics	Water level	**M** reduce decrease	
		Flow velocity	**L** minor effects	
		Shear stress	**L** minor effects	
	Sediment-dynamics	Transport capacity	**H** increased	
		Continuity	**H** increased	
	Morpho-dynamics	River morphology	**M** increased morphodynamics	
	Ecology	Habitat diversity / refugial habitats	**M** improved aquatic habitats	There might be a disturbance of the habitats at the feeding site, but this measure counteracts bed degradation in the downstream section, thus benefitting ecology.
Type of measure				Non-recurring: ☐ Recurring: ☒
Categories		☒ State of the art	☐ Tested (implemented at least once)	☐ State of science (no field test yet)
Scaling	**Spatial**	☒ Local scale	☒ Reach scale	☐ Catchment scale
			☐ Upstream effects	☒ Downstream effects
	Temporal	☐ Short-term	☐ Mid-term	☒ Long-term
Interrelation with		☒ Flood protection	☒ Hydropower	
		☒ River basin management incl. Ecology	☒ Navigation	
Assessment		Bathymetric monitoring before, during and after implementation		
Notes / Risks		Implementation is done by breaking-up clogged and consolidated (fine) sediments on the top of the riverbed. The bed armour can either be broken up through artificial floods (increased water outflow from an upstream reservoir) or mechanically via dredging. Sediments can also be relocated towards the main channel to make them more readily available for transport. Improved vertical connectivity to the ground water Positive effect on hyporheic zone (interstitial water-filled space beneath riverbeds) and thus maintains aquatic habitats The remobilisation of consolidated gravel bars requires flood discharge. In case of flood absence, gravel bars will start to increase again.		
Interrelation with other measures		Sediment feeding		

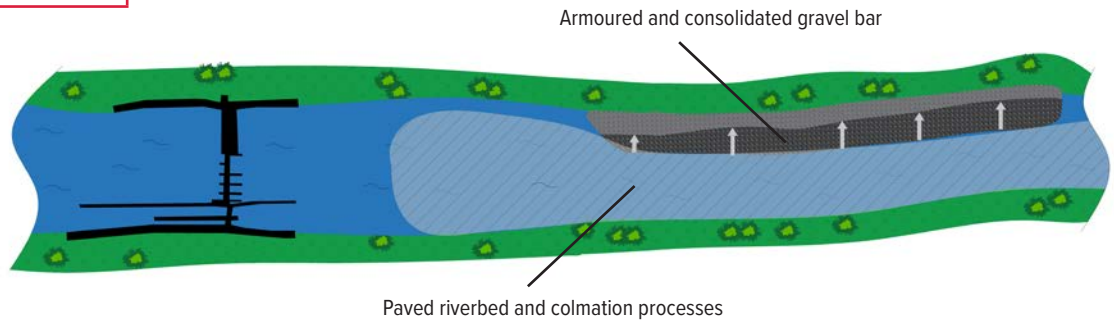
RIVER BASIN MANAGEMENT/NAVIGATION	RBM 18	N 9

Measure | **Remobilisation of consolidated gravel bars**

POSITIVE



NEGATIVE



Examples

© LfU (Bavarian Environment Agency)

Reference | Isar, near Lenggries, GE, LfU Bayern (https://www.lfu.bayern.de)

FLOOD PROTECTION — F 11

Measure	**Local bank protection**

Location		Riverbanks
Application		Free-flowing section
		Gravel and sand bed river
Main aim		Reduce riverbed erosion
Parameter		Sediment transport capacity, substrate, flow velocity, water level, shear stress
Goals of measure	**Sediment**	Stabilisation of the riverbed
		Reduced sediment input from riverbanks
	Flood protection	Enhance flood protection by protecting local riverbanks from erosion

Effects

L Low
M Medium
H High

Parameter	**Effects (main channel)**	**Effects (riverbanks)**
Water level	L increased	L increased
Flow velocity	L increased	L increased
Shear stress	L increased	L increased
Transport capacity	M increased	M decreased
Continuity	M increased	M decreased
River morphology	M riverbed lowering, decreased sediment input from the banks	M decreased morphodynamics and side-erosion
Habitat diversity / refugial habitats	no effects	H degradation of aquatic habitats

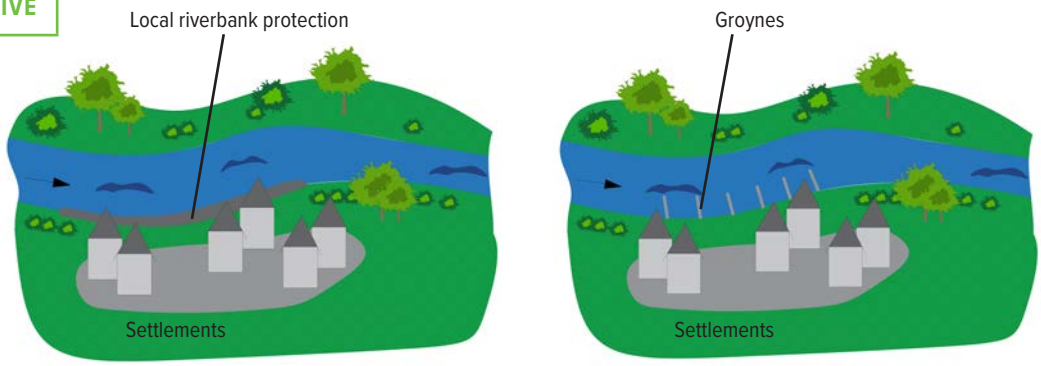
Type of measure			X Non-recurring		Recurring
Categories	X State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling — **Spatial**	X Local scale		Reach scale		Catchment scale
			Upstream effects	X	Downstream effects
Temporal	Short-term		Mid-term	X	Long-term
Interrelation with	Flood protection		Hydropower		
	X River basin management incl. Ecology	X	Navigation		

Assessment	Bathymetric surveys of the riverbed and banks before and after implementation Grain size
Notes / Risks	Riverbank protection as a measure to increase flood protection for nearby areas stops side-erosion but also increases hydraulic impacts on the main channel. Adverse effects on riverbed level and aquatic ecology must be prevented. Should only be done where needed, preferably using bio-engineering techniques. If feasible, an alternative is also to shift the nearby infrastructure, e.g. roads or dykes.
Interrelation with other measures	Optimisation of river training structures to reduce erosion, optimisation of river training structures to reduce sedimentation

FLOOD PROTECTION F 11

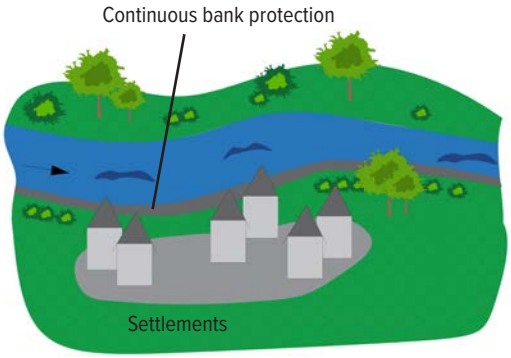
Measure	Local bank protection

POSITIVE



NEGATIVE

River-narrowing effects as a result of bank protection measures might cause riverbed incision.



Examples

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© Google maps

Reference	Local bank protection at the river Danube (Johler-Arm), AT

RIVER BASIN MANAGEMENT/FLOOD PROTECTION	RBM 19	F 12

Measure	**Modify or remove barriers**	
Location	Riverbanks / near bank zone	
Application	Existing and newly built reservoir	
	Gravel and sand bed river	
Main aim	Reduce sedimentation	
Parameter	River continuity, water level, flow velocity, shear stress, riverbed level, fish migration	
Goals of measure – **Sediment**	Prevent sedimentation by increasing sediment continuity	
Goals of measure – **Flood protection**	Enhance flood protection by preventing sedimentation	

Effects (L Low, M Medium, H High)

Parameter		Effects	
Hydro-dynamics	Water level	L decreased	
	Flow velocity	M increased	
	Shear stress	M increased	
Sediment-dynamics	Transport capacity	M increased	
	Continuity	M increased	
Morpho-dynamics	River morphology	L increased morphodynamics	
Ecology	Habitat diversity / refugial habitats	H improved fish migration	

Type of measure			Non-recurring	X	Recurring
Categories	X	State of the art		Tested (implemented at least once)		State of science (no field test yet)
Scaling – **Spatial**		Local scale	X	Reach scale		Catchment scale
				Upstream effects	X	Downstream effects
Scaling – **Temporal**		Short-term		Mid-term	X	Long-term
Interrelation with	X	Flood protection		Hydropower		
	X	River basin management incl. Ecology		Navigation		

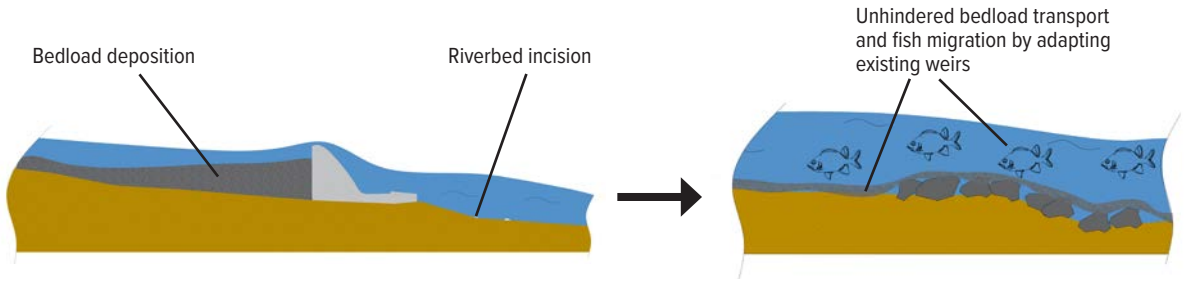
Assessment	Bathymetric monitoring before, during and after implementation
Notes / Risks	One must consider that this measure may cause too much erosion. For example, the construction of a ramp might be necessary in order to prevent excessive bed erosion. Fish migration is restored.
Interrelation with other measures	Minimize width (by hydraulic structures), prevent sedimentation by artificial turbulence (jet screens)

RIVER BASIN MANAGEMENT/FLOOD PROTECTION | RBM 19 | F 12

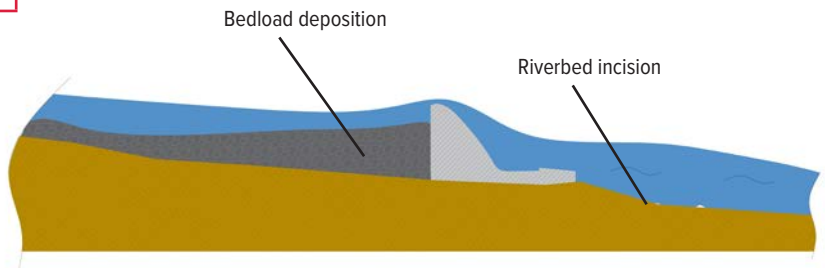
Measure | **Modify or remove barriers**

POSITIVE

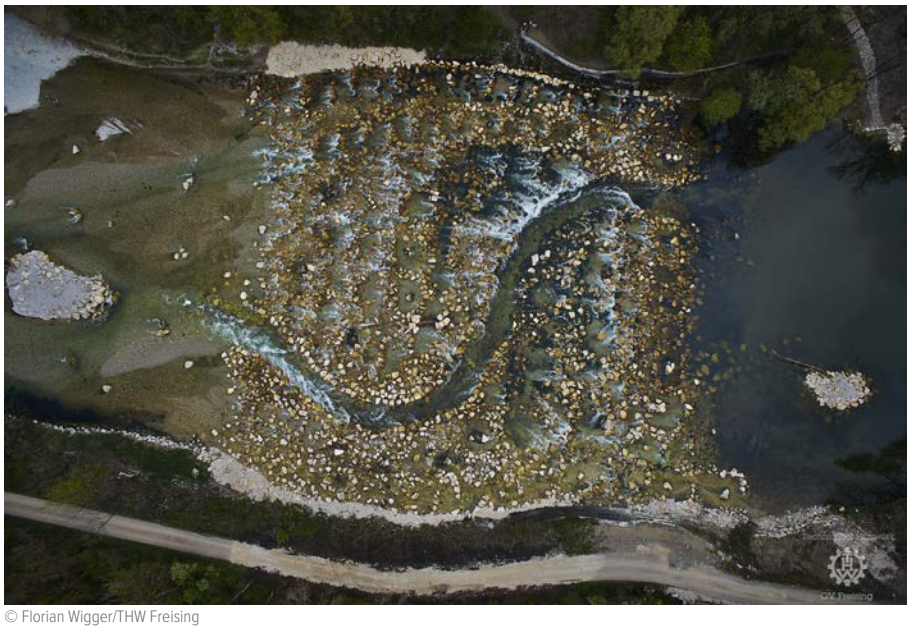
The construction of a ramp might be necessary in order to prevent excessive bed erosion.



NEGATIVE



Examples



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Reference

Modification from weir to river bottom ramp at the river Isar, GER (https://bit.ly/modifyweir)
See DanubeSediment report „Sediment Management Measures for the Danube", factsheet code in annex 2: E_FF_FP_T_GP08

Appendix

LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AT	Austria
BG	Bulgaria
BOKU	University of Natural Resources and Life Sciences, Vienna (Austria)
BQE	Biological Quality Elements
CEN	European Committee for Standardization
DC	Danube Commission
DE	Germany
DFRM Plan	Danube Flood Risk Management Plan
DRB	Danube River Basin
DRBM Plan	Danube River Basin Management Plan
DSMG	Danube Sediment Management Guidance
DTP	Danube Transnational Programme
EC	European Commission
EIA	Environmental Impact Assessment
ENC	Electronic Navigational Charts
ERDF	European Regional Development Fund
EU	European Union
F	Flood protection (factsheet identifier)
GES	Good Environmental Status
GNS	Good Navigation Status
H	Hydropower (factsheet identifier)
HPP	Hydro Power Plant
HR	Croatia
HU	Hungary
ICPDR	International Commission for the Protection of the Danube River
IMH	Institute of Meteorology and Hydrology (Romania)
IPA	Instrument for Pre-Accession Assistance
IPCC	Intergovernmental Panel on Climate Change
IWA	Institute of Hydraulic Engineering and River Research (Austria)
MMSD	Minimum Morphological Spatial Demand
MSFD	Marine Strategy Framework Directive
Mt	Million tons
N	Navigation (factsheet identifier)
NARW	National Administration “Romanian Waters”
NGO	Non-governmental Organization
OBS	Optical Backscatter Sensor
PP	Project Partner
PSD	Particle Size Distribution
RBM	River Basin Management
rkm	river kilometre
RO	Romania
RS	Republic of Serbia
SedNet	European Sediment Network
SK	Slovakia
SMS	Sediment Manual for Stakeholders
SPAs	Special Protection Areas
SSC	Suspended Sediment Concentration
SWME	Slovak Water Management Enterprise (Slovakia)
SWMI	Significant Water Management Issue
TEN-T	Trans-European Transport Network
TNMN	Transnational Monitoring Network
UNESCO	United Nations Educational, Scientific and Cultural Organization
VHP	VERBUND Hydro Power
WFD	Water Framework Directive
WRI	Water Research Institute (Slovakia)

PROJECT REPORTS

The DanubeSediment project was structured into six work packages. The main project publications are listed below.

A detailed list of all project activities and deliverables is available on our project website:

- www.interreg-danube.eu/approved-projects/DanubeSediment/outputs

1. Sediment Monitoring in the Danube River
2. Analysis of Sediment Data Collected along the Danube
3. Handbook on Good Practices in Sediment Monitoring
4. Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube
5. Assessment of the Sediment Balance of the Danube
6. Long-term Morphological Development of the Danube in Relation to the Sediment Balance
7. Interactions of Key Drivers and Pressures on the Morpho-dynamics of the Danube
8. Risk Assessment Related to the Sediment Regime of the Danube
9. Sediment Management Measures for the Danube
10. Danube Sediment Management Guidance
11. Sediment Manual for Stakeholders

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