Danube Sediment Management Guidance

Interreg
EUROPEAN UNION
Danube Transnational Programme
DanubeSediment

Project co-funded by European Union funds (ERDF, IPA)

Impressum

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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

Table of Contents

Overview and key recommendations

STATEMENT OF PROBLEMS AND NEEDS

- Socio-economic development has gradually altered the Danube River and its tributaries. The main drivers are flood protection, hydropower, navigation, water supply, land use (e.g. agriculture and urbanisation) and commercial dredging.
- In the Upper and Middle Danube, large-scale engineering transformed the formerly complex river morphology to a uniform channel over large stretches. The river length was reduced by 130 km, which means the Upper Danube was shortened by 11 % and the Middle Danube by 4 %. The average width of the river was reduced by 39 % in the Upper and by 12 % in the Middle Danube. In the Lower Danube River, the length was marginally reduced by around 1% and the average width by 4 %.
- Bank protection measures, in particular on the Upper and Middle Danube, and cut-off side channels and flood protection dykes hinder the lateral exchange of sediments.
- Transversal structures for hydropower use and water supply, like weirs and dams, interrupt sediment continuity to a large extent.
- 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, while the reduced energy slope in the impoundments leads to sedimentation.

SEDIMENT BUDGET AND RIVERBED CHANGES

- 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 (also see page 16).
- The interruption of river continuity also prevents the transport of bedload, which leads to a lack of those sediments that shape the river.
- In some river stretches, the dredging amounts exceeded the sediment supply from upstream.
- In total, about 733 river kilometres (rkm) (29 %) of the Danube River are dominated by erosion and 857 rkm (34 %) by sedimentation. In the Lower Danube, 670 rkm (27 %) show an erosional trend, but a lack of data hinders a detailed analysis. For example, local 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 page 18).

AIMS

- These numbers 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 bed forms and bed material.

SIGNIFICANT WATER MANAGEMENT ISSUE

- The DanubeSediment project concluded that the alteration of the sediment balance is a Significant Water Management Issue (SWMI) in the Danube River Basin. According to 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.
- Additionally, sediments, respectively sediment management, should be an integral part of the National River Basin and the Flood Risk Management Plans.

RECOMMENDATIONS FOR AN IMPROVED MONITORING AND DATA MANAGEMENT

- The project recommends establishing a harmonized transnational sediment quantity monitoring network and setting-up new monitoring stations.
- The most important sediment monitoring elements are: suspended sediments, bedload, bathymetry data, bed material, dredging and feeding and floodplain deposition.
- The sediment data should be stored in a centralised, Danube Basin-wide system or database, such as the Transnational Monitoring Network (TNMN) of ICPDR.

GENERAL RECOMMENDATIONS

- The project recommends to develop an integrated Danube River Basin sediment management concept that operates on a transboundary level. It must balance environmental and socio-economic values, operate on different spatial and temporal scales and include upstream–downstream relationships.
- Priority should be given to protecting and preserving the (nearly) undisturbed sediment regime within the remaining natural free-flowing river sections and tributaries. It is recommended to give attention to restoring/improving the sediment continuity by improving or removing existing barriers, avoiding additional interruptions and considering sediments when new structures are built. Restoration of the sediment continuity means to increase the sediment transport through structures with the aim to reduce the problems associated with a sediment surplus and deficit and to adapt the sediment budget to reach the best possible morphological conditions in the water bodies and further downstream.
- River reaches with a clear trend to sedimentation and erosion, especially impounded and free-flowing sections, should be improved with the aim of establishing a dynamic equilibrium in the riverbed.
- Where sediments are dredged, we recommend re-feeding them into the river at sections with a lack of sediments and to end or minimize the sand or gravel extraction.
- 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 gain acceptance of any sediment 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. We recommend that the stakeholder networks established by the DanubeSediment project be maintained on the transnational level.
- A holistic approach to sediment management must concern not only sediment quantity but also quality, to ensure that sediments do not pose a risk on the ecological and human water demands.

1 Introduction

The EU Water Framework Directive (WFD 2000/60/EC) has the purpose to establish a framework for the protection and enhancement of waters, including rivers, and to ensure a sustainable use of water resources. The main aim of the WFD is to achieve a good ecological and chemical status in all water bodies. Besides biological, chemical and physico-chemical quality parameters, the description of the ecological status also consists of hydromorphological elements. The WFD demands an assessment of the hydromorphological elements "hydrological regime", "river continuity" and "morphological conditions". The hydrological regime and the morphological parameters of the catchment are directly referenced in the WFD. These are essential for a functioning sediment transport and important for the development of morphological conditions. Sediment quantity in turn is for most of the classes of indirect importance via the Biological Quality Elements (BQE) and only mentioned directly in the WFD in connection with the high status as follows:

> *River continuity: The continuity of the river is not disturbed by anthropogenic activities and allows* ***undisturbed*** *migration of aquatic organisms and* ***sediment transport****.*
>
> *Morphological conditions: Channel patterns, width and depth variations, flow velocities,* ***substrate conditions*** *and both the structure and condition of the riparian zones* ***correspond totally or nearly totally*** *to* ***undisturbed conditions****.*

In the years following the adoption of the WFD, the International Commission for the Protection of the Danube River (ICPDR), in cooperation with sediment experts, worked on identifying the status of sediment transport and morphological conditions in the Danube River Basin District (DRBD). For the WFD Art. 5 Report 2004, ICPDR identified a sediment deficit in the Danube, naming dam construction and regulation works as the main pressures. In 2006, a Sediment Issue paper was prepared by the countries Austria, Hungary and Romania in cooperation with the ICPDR Secretariat addressing both sediment quality and quantity. Regarding sediment quantity, sediment accumulation and the need for sediment removal in dams were reported. In addition, the paper also identified sediment deficit and a lower sediment discharge after dams, leading to riverbed erosion downstream of hydropower plants (HPP) such as HPP Freudenau, HPP Gabčikovo and HPP Iron Gate. For the Upper Danube, no deficit of suspended sediments was reported. So, the issue of sediment deficit remained open.

Published in 2009 and 2015, the 1st and 2nd Danube River Basin Management Plan (DRBM Plan) concluded that the sediment balance of most large rivers within the Danube River Basin District (DRBD) can be characterised as disturbed or severely altered. Therefore, attention should be given to ensuring the sediment continuity, e.g. by improving existing transversal structures and avoiding additional interruptions. However, the availability of sufficient and reliable data on sediment transport is a prerequisite for any future decisions on sediment management in the DRBD. Further knowledge and investigations on potential measures are needed. Hence, in order to propose appropriate measures for improving the situation, ICPDR required a sediment balance and additional investigations to determine the significance of sediment transport on the Danube basin-wide scale.

To obtain a full picture, a transnational project on sediment management was needed. Therefore, a proposal for the project "DanubeSediment", focusing on the quantitative aspect of sediments, was elaborated and submitted for financing to the Interreg Danube Transnational Programme (DTP) in 2016. The preparation of the proposal and the implementation of this project were undertaken in close cooperation between the ICPDR, the European Strategy for the Danube Region (EUSDR) and its Flagship Project Danube River Research and Management DREAM as well as stakeholders involved in sediment management. The results of the project provide valuable input for the updates of both national and international River Basin Management (RBM) and Flood Risk Management (FRM) plans in the DRBD. One of the main outputs of this project is the document at hand, the "Danube Sediment Management Guidance" (DSMG).

ELABORATION PROCESS OF THE DSMG

The Danube Sediment Management Guidance (DSMG) was prepared based on the results of the DanubeSediment project. These results were obtained through a broad participative process with the involvement of all relevant stakeholders such as representatives from administration, flood risk management, hydropower, waterway authorities, ecological stakeholders (e.g. national parks) and NGOs as well as 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 Danube Sediment Management Guidance (DSMG) defines the baseline for future sediment management in the Danube Basin and major tributaries. It aims to improve the sediment continuity and to reduce the gap between surplus and deficit of sediments, thereby leading to a sustainable use and protection of the Danube River.

The DSMG is a strategic document that seeks to improve awareness on challenges related to sediment quantity. It suggests measures that can be implemented to reduce sediment-related problems in the Danube River Basin. Improving the sediment balance can benefit both humans and nature alike, for example by improving the ecological status and decreasing flood risk. This document provides a strategy for better sediment management and thereby directly contributes to transnational water management and flood risk prevention.

2 Statement of problems and needs

As a lifeline for both people and nature, the Danube River meets a wide range of needs: it provides drinking water, is a trans-European navigational corridor, serves tourism and local recreation, provides energy and ecosystem services, is home for many protected species and is essential for the natural environment. In order to make better use of this essential lifeline, the Danube and its tributaries and consequently the sediment regime have been gradually altered over the years, drastically over the last two centuries. Experts have identified the main drivers for the alteration of the sediment regime as flood protection, hydropower, navigation, water supply, commercial dredging, and agriculture. This human interference has led to a sediment deficit and an increased sediment transport capacity in the free-flowing sections, which in turn leads to riverbed incision as well as bank and coastal erosion. In impounded sections, on active floodplains and around groyne fields, a surplus of sediments dominates. This, for example, may increase flood risks, reduce navigation possibilities and hydropower production and negatively influence groundwater connections. Moreover, these alterations also affect river morphodynamics, which can cause a deterioration of habitats. In general, this may lead to severe impacts on the type-specific aquatic communities and water dependent terrestrial ecosystems and thus on the water status, putting the rich and unique biodiversity and river habitats along the Danube at risk.

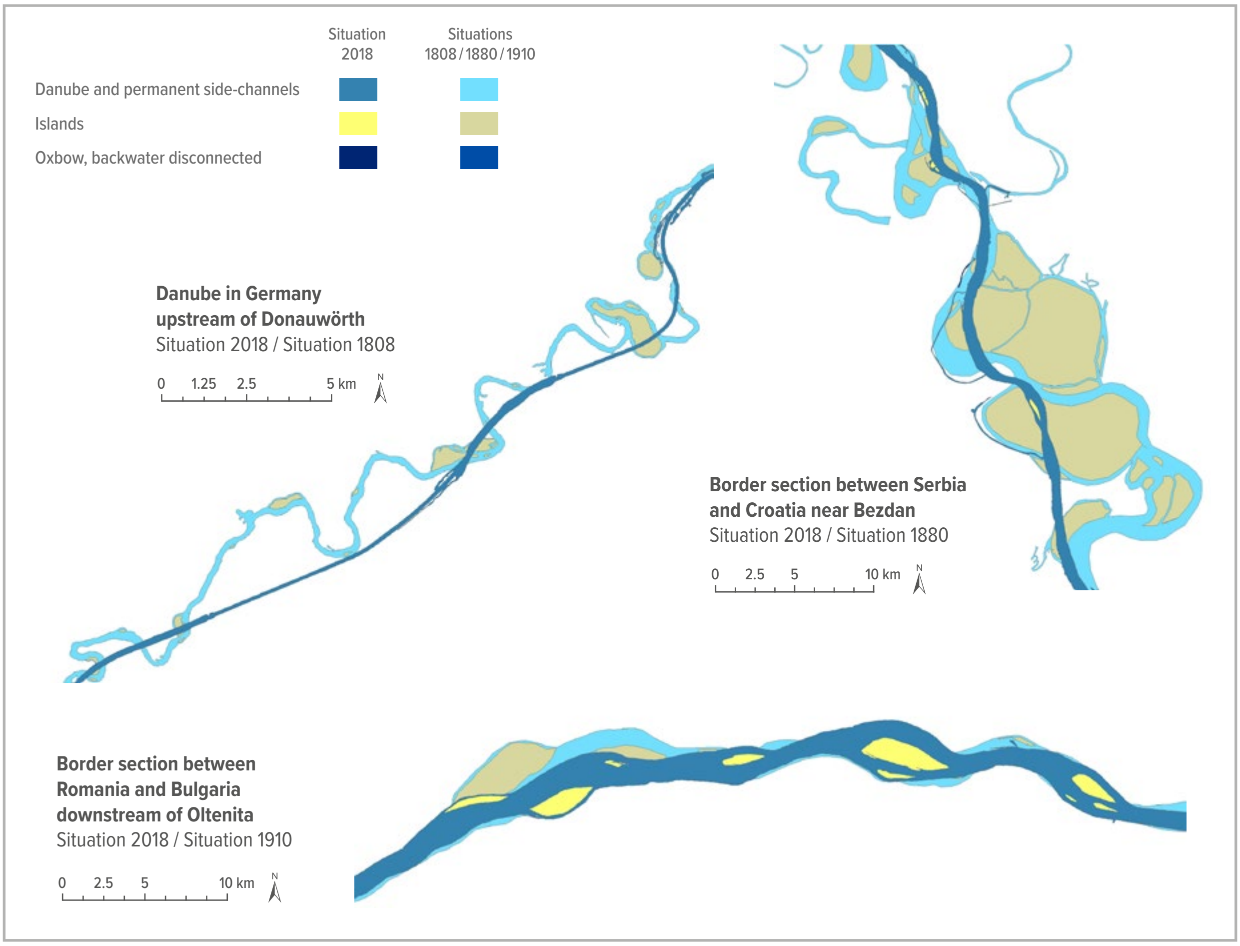

Figure 1: Top left: Danube in Germany upstream of Donauwörth. Top right: Border section between Serbia and Croatia near Bezdan. Bottom: Border section between Romania and Bulgaria downstream of Oltenita (based on data collected for the DanubeSediment Report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance").

INCREASE OF SEDIMENT TRANSPORT CAPACITY DUE TO RIVER REGULATION

With the beginning of the 19th century, systematic training works for flood protection and navigation were executed in large parts of the Danube River. Consequently, the morphology of the river was severely altered (Figure 1). 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 (Figure 2) and its floodplains was drastically reduced. According to ICPDR, 2009, the floodplains were reduced by 81 % since the 19th century. In the Upper Danube, the total river width was decreased on average by 39 % (the active width by 22 %) and in the Middle Danube by 12 % (the active width by 1 %). Additionally, the gradient of the Danube River was steepened by reducing the length of the river by about 100 km (−11 %) in the Upper Danube (e. g. Figure 1) and about 30 km (−4 %) in the Middle 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. Mainly in the Upper and Middle Danube the former complex river morphology with meandering and sinuous river types and several multi-thread anabranching reaches has changed to a single-thread sinuous river type. 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. At present, there are in total only 745 rkm of multi-thread anabranching (low energy) left in the Lower Danube; the multi-thread anabranching (high energy) type does not exist anymore. 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".

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 the project show that the lateral restrictions caused by river training are less severe in the case of the Lower Danube. The length of the Lower Danube was decreased by around 1 % and the mean total width was reduced by 4 %, with an active width increase of 1 %. (Figure 2).

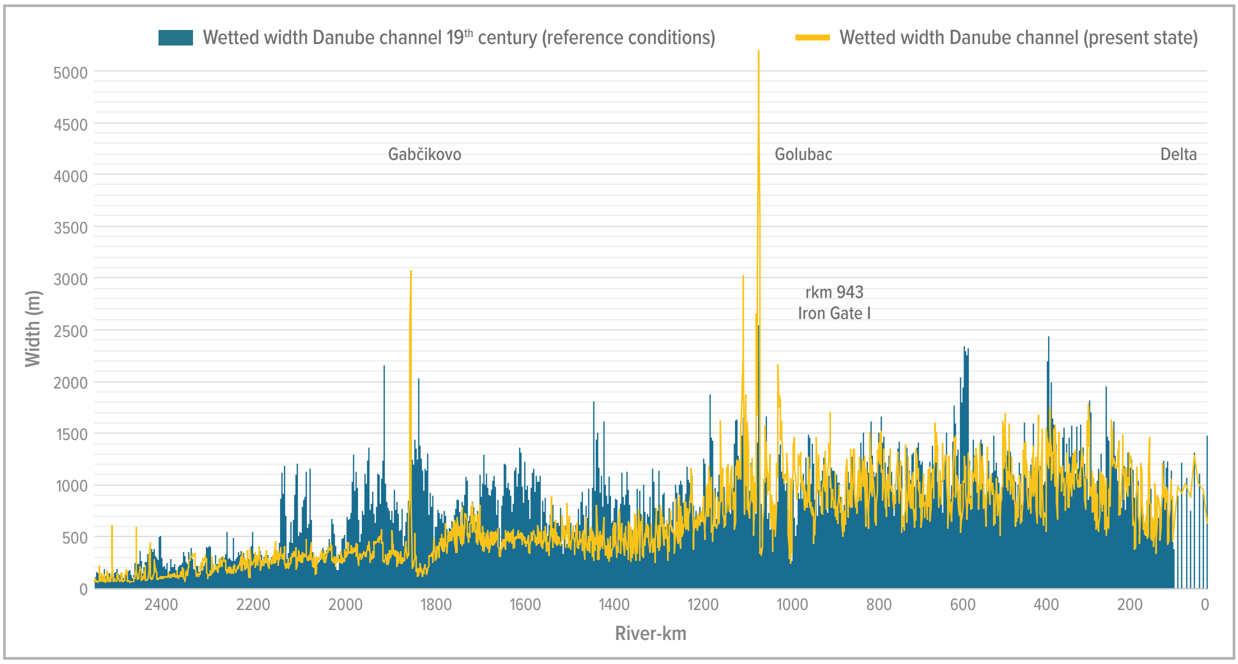

Figure 2: Change of the channel width of the Danube River: 19th century and current situation (from the DanubeSediment Report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance"). The significantly increased width in the present state at some locations is due to impoundments / reservoirs.

INTERRUPTION OF SEDIMENT CONTINUITY

At the end of the 19th century and the beginning of the 20th century, the first transversal structures (weirs, dams) were constructed for hydropower use and water supply as well as longitudinal structures for flood protection. Over time, more than 80 barriers of various sizes have been constructed along the entire Danube River main channel. For the whole Danube River Basin, a total number of 1030 barriers were reported in the DRBM Plan – Update 2015 (ICPDR, 2015). However, this number does not include all barriers in the entire basin. Many of these transversal structures were constructed for hydropower production and are mainly located in the catchment of the Upper Danube River (Figure 3).

Due to the reduced flow velocities, sedimentation occurs in the impoundments and reservoirs of the hydropower plants, resulting in a surplus of sediments (Figure 4). In case of major flood events, fine sediments can be remobilised. Such an event can lead to major problems for the river ecosystem, e.g. it may congest the respiratory system of fauna, clog spawning places, bury plants and increase the oxygen demand, as well as adding sediment to the floodplains (Figure 5). The sedimentation in the floodplain and settlements can significantly increase damages and thus floodrisk.

Figure 3: Spatial distribution of longitudinal sediment continuity interruptions on the Danube River and major tributaries selected in the project (from the DanubeSediment report "Interactions of Key Drivers and Pressures on the Morphodynamics of the Danube").

Figure 4: Huge sediment deposits in the Iron Gate I reservoir near Donji Milanovac, visible only during floods (Photo: ©IJC).

Figure 5: Floodplain sedimentation in Austria after the flood event in 2013 (Photo: ©Marktgemeinde Ardagger).

Downstream of hydropower plants, e.g. HPP Freudenau, HPP Gabčikovo and 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 on a lower riverbed level. 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 development between Iron Gate and Zimnicea (rkm 553).

The results of the DanubeSediment project clearly show the effects of sediment regime alterations from the Upper Danube through to the Danube Delta. Today, the Danube transports only about 20 million tons per year compared to the historic amount of about 60 million tons per year of suspended sediments into the Danube Delta. Around 15 million tons per year are transported to the Black Sea, compared to historic amounts of 40 million tons per year (for details see page 16). This is a reduction of more than 60 % (Figure 6). Between Ceatal Izmail and the Black Sea, the suspended sediment load decreases, although there are uncertainties about the data from the last monitoring stations due to the tidal influence.

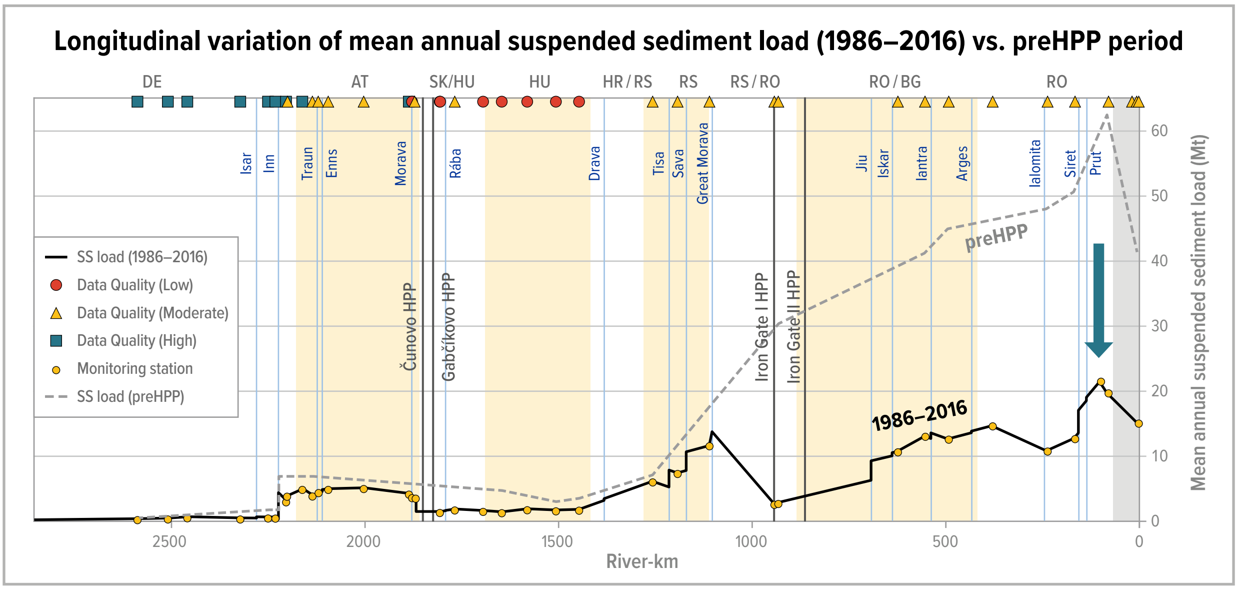

Figure 6: Suspended sediments along the Danube River: past and present. The arrow indicates a reduction of the suspended sediment input into the Danube Delta and the Black Sea of about 60 %. The data quality indicator only refers to the present situation: high data quality: good practices of suspended 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").

FURTHER ASPECTS

The above-mentioned impacts of alterations in the sediment regime can be intensified by increased agricultural use and deforestation in the catchment, which increases the sediment yield and consequently results in a loss of fertile soil (Habersack et al., 2016).

Changes in fine sediment transport, deposition and remobilization dynamics can also affect the transport of pollutants and nutrients from point and diffuse sources, as 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.

NEEDS WITH RESPECT TO SEDIMENT MANAGEMENT

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. A balanced sediment regime as well as improved morphodynamics are beneficial to type-specific aquatic communities and water dependent terrestrial ecosystems.

3 Sediment budget

A sediment budget provides an organising framework to relate the components and interacting variables of the sediment regime. It is an accounting of sediment sources, sinks, storage and transport terms (Eq. 1).

$$(I_u + I_l + I_t + I_a) - (O_d + O_{dr} + O_f + O_g + O_a) = \Delta S \qquad (1)$$

Variables presenting sediment inputs within the budget equation are for example upstream input (I_u), lateral input (I_l – e.g. groyne fields, river banks and floodplains), input from tributaries (I_t), artificial input (I_a – e.g. feeding) (Figure 7). Downstream transport (O_d), abrasion (O_a), dredging (O_{dr}), lateral outputs (e.g. groyne fields (O_g), river banks and floodplains (O_f)) for instance can be part of the sediment output of the system. Potential sediment storage (ΔS) includes the riverbed (bed level changes), banks, bars or floodplains.

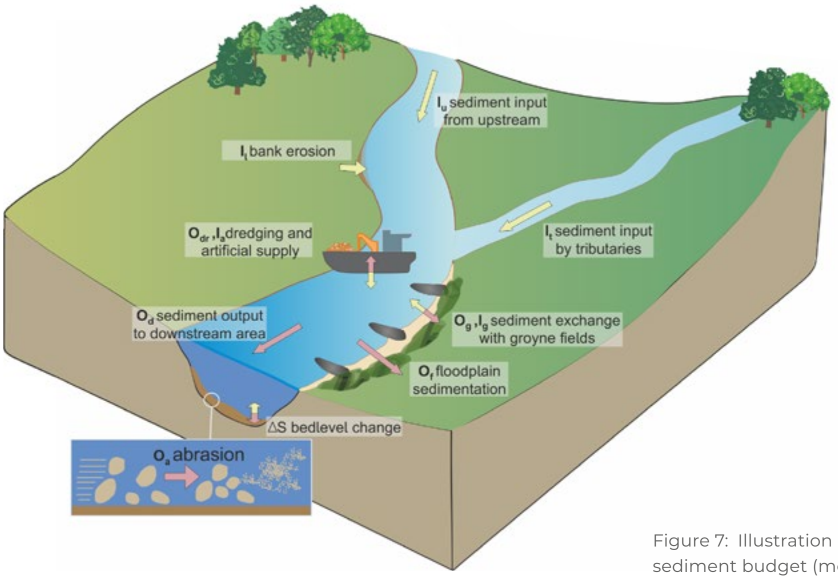

Figure 7: Illustration of input, output and storage terms of a sediment budget (modified after Frings et al, 2014).

SEDIMENT TRANSPORT

Based on the collected suspended sediment data, published in the DanubeSediment report "Sediment data analysis in the Danube River", a 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 8). 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 (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 important for the sediment balance was the Drava, however the data displayed in Figure 8 has already been influenced by first HPPs. 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 Gabčikovo 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 upstream and at tributaries. 60 % of the sediment input is deposited in the HPP Gabčikovo reservoir and 60–80 % of the sediment input in the HPP Iron Gate I reservoir (now less than at the beginning of the commissioning of the hydropower plant). This data is calculated by comparing monitoring stations upstream and downstream of the reservoirs as described in the DanubeSediment report "Sediment data analysis in the Danube River". The sedimentation rate of the 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 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 (see Figure 6), although there are also uncertainties at the last monitoring stations due to tidal influence from the Black Sea.

The data set for bedload in the Danube River is significantly smaller than the data set for suspended sediments. There is not sufficient data to create a bedload balance for the whole river system. 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 regulation but before construction of relevant hydropower plants. This value decreased to around 0.44 Mt/yr (or by 55 %) 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

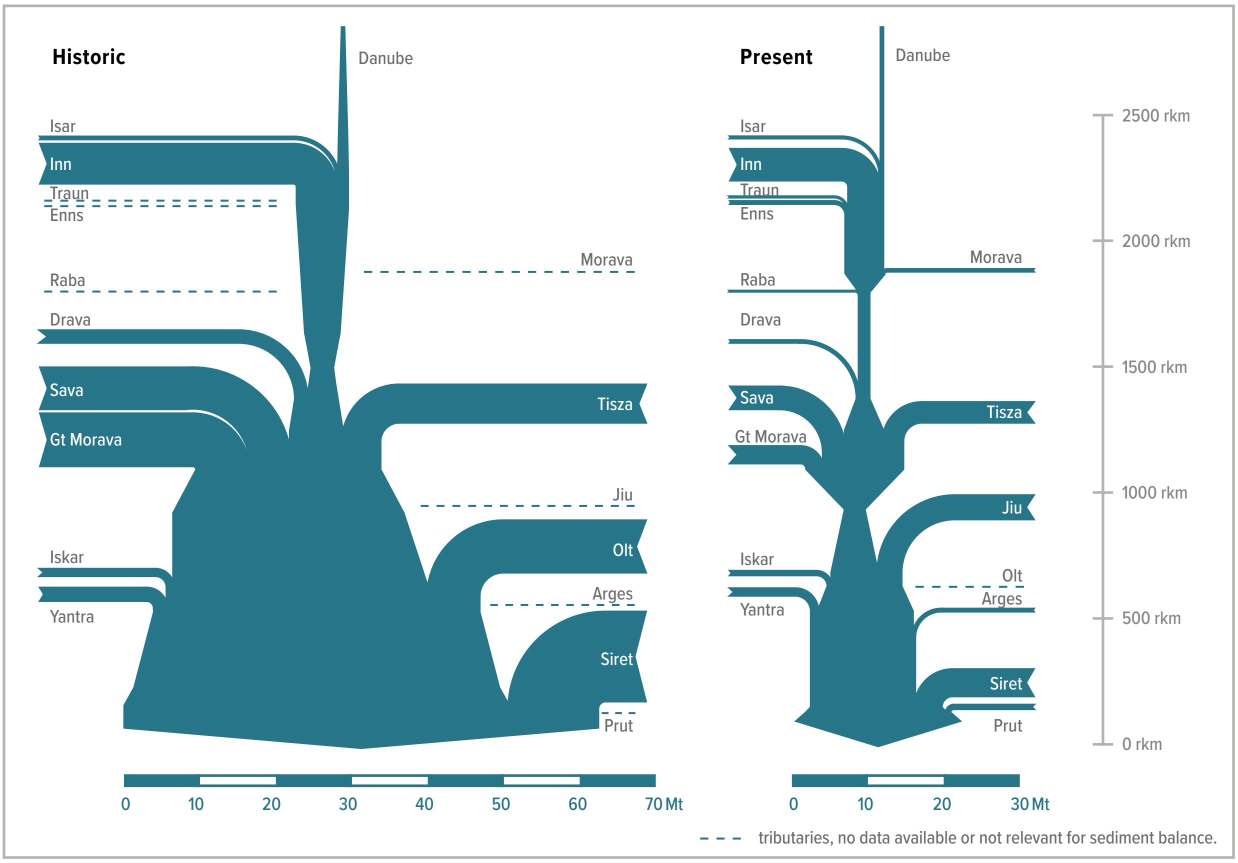

Figure 8: Suspended sediment balance along the Danube River and its major tributaries before (left) and after (right) HPP construction on the Danube River (dashed lines: tributaries, where no data is available or which are no longer relevant for the suspended sediment balance). The horizontal scale (Mt) applies for both the Danube River and its tributaries.

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. The load increased from 0.19 Mt/yr at rkm 1825.6 in the time period 1940–1960 to 0.55 Mt/yr at rkm 1795.58 after the HPP Gabčikovo was commissioned. Indeed, significant bed erosion was observed along the Upper Slovak-Hungarian Danube section after the commissioning of the HPP (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 from 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.

The contribution of the bedload transport to the total sediment transport indicates a clear dominance of the suspended sediment along the Danube River. For the few stations where both suspended sediment and bedload data were collected, ratios of bedload to the total load range between 5 and 10% in the Upper Danube and are around 5% at the Romanian reach. Immediately downstream of HPP Gabčikovo, a much higher ratio of more than 20% was determined. This can be explained by reduced suspended sediment transport due to sedimentation in the reservoir and erosion of bed material downstream of the hydropower plant. As highlighted, suspended sediments account for the higher mass fraction of sediment transport, but above all it is bedload transport that determines the river morphology, especially in free-flowing sections.

GRAIN SIZE DISTRIBUTIONS OF THE BED MATERIAL

Rivers are generally characterised by a downstream decrease in slope and grain size. Relevant factors are abrasion, size selective transport (i.e. different mobility of fine and coarse fractions), the increase in drainage area and discharge, input from tributaries and the formation of deltas.

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 in the Hungarian part of the Danube River. Further downstream, the riverbed mainly consists of sand, with short sections of gravel that is supplied by the tributaries, e.g. Great Morava.

The interruption of the sediment regime by hydropower plants exerts a strong control on the grain sizes of the riverbed, their transport mode (as bedload or in suspension) and transferability, as well as connectivity with the downstream reach. In the Upper Danube, the gravel fractions are present in the free-flowing sections. Also, in the sections directly downstream of hydropower plants, the riverbed consists of gravel, changing mainly to (fine) sand and silt, due to the increasing backwater influence of the next hydropower plant. Fine sediments also dominate in the reservoir of the HPP Gabčikovo, whereas downstream of the HPP Gabčikovo, the Danube riverbed largely consist of coarse and fine gravel. The sediment sizes gradually decrease as far as rkm 1420, where the Danube River changes from a gravel to a sand bed river. In the rest of the Middle Danube up to the confluence with the Great Morava, the riverbed mainly consists of fine and coarse sand. In the backwater of Iron Gate I, the grain sizes decrease, consisting of sand, silt and clay. The coarser grain sizes (gravel and coarse sand) in the Lower Danube occur in the section downstream of the Iron Gate II. The grain sizes further downstream 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.

DREDGING AND FEEDING

The amount of gravel and sand extracted from a river by dredging plays a crucial role in sediment budgeting. It helps to determine the contribution of dredging to riverbed erosion and the potential impacts in the upstream and downstream direction (e.g. upstream erosion or reduced downstream transport of certain or all grain sizes). Budgeting can also help to plan dredging and feeding strategies, such as upstream transfer and dumping, and can help to monitor their success in establishing a dynamic and balanced sediment regime.

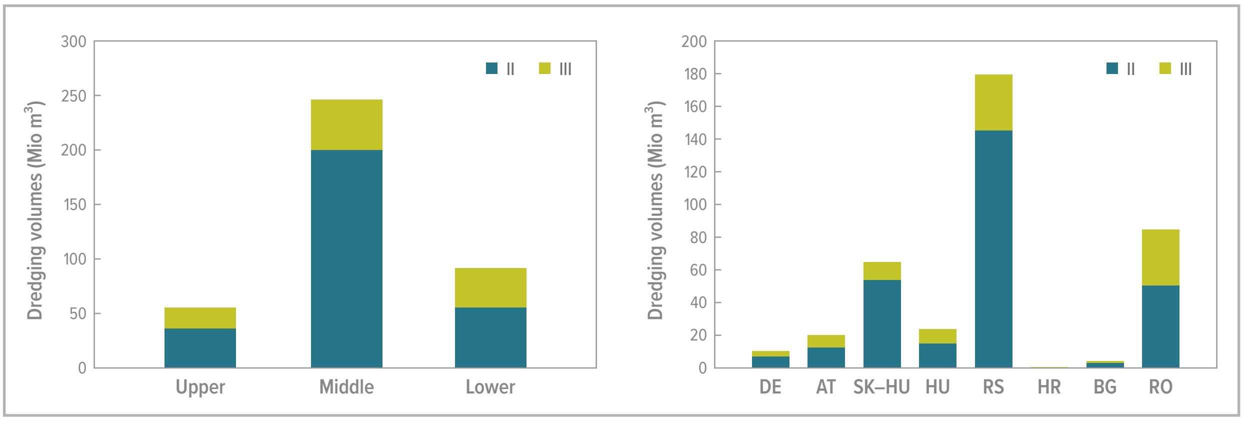

Figure 9: Dredging volumes divided in Upper, Middle and Lower Danube (left) and by country (right) for two different time periods (II: 1971–1990 and III: 1991–2016). Amounts for HR only consist of 3 years.

In the past, dredging in the Danube River was performed e.g. for commercial purposes, navigation, flood protection, river training, road constructions, land reclamation and during the construction of hydropower plants. The highest amounts of dredging occurred in the Middle Danube, especially in Serbia in the period 1971–1990 (Figure 9). In some river stretches, e.g. in some parts of Slovakia, Hungary and Serbia, dredging amounts even exceeded the bedload supplied from upstream. As most probably not all dredging amounts were covered within the project, the absolute figures are subject to uncertainty. More investigations and better monitoring of dredging amounts are needed to answer open questions on the long-term impact of dredging.

At present, dredging is undertaken mainly for navigation and flood protection as well as for in some cases emptying the impoundments of hydropower plants and for river restoration projects. Further dredging is done at the mouth of tributaries in impounded reaches, as well as in harbours and harbour entrances. In the Upper (DE and AT) and Middle (HU sections) Danube, commercial dredging (of gravel) is not performed/allowed anymore. In other parts of the Danube River, the situation is also changing towards more sustainable dredging. On the Danube River, gravel feeding only takes place in Austria, downstream of the HPP Freudenau (Vienna). The purpose is to compensate the impact of the hydropower plant on the gravel supply. The amount of gravel feeding was approximately 186,000 m^3/yr between 1996 and 2017. This amount was recently increased to 235,000 m^3/yr (BMNT, 2018).

BED LEVEL CHANGE

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". Mean bed level and 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 10).

The data shows that the general assumption of sedimentation occurring in impounded sections and erosion occurring in the free-flowing section is valid for a large extent of the Danube River. 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, Gabčikovo and Iron Gate I.

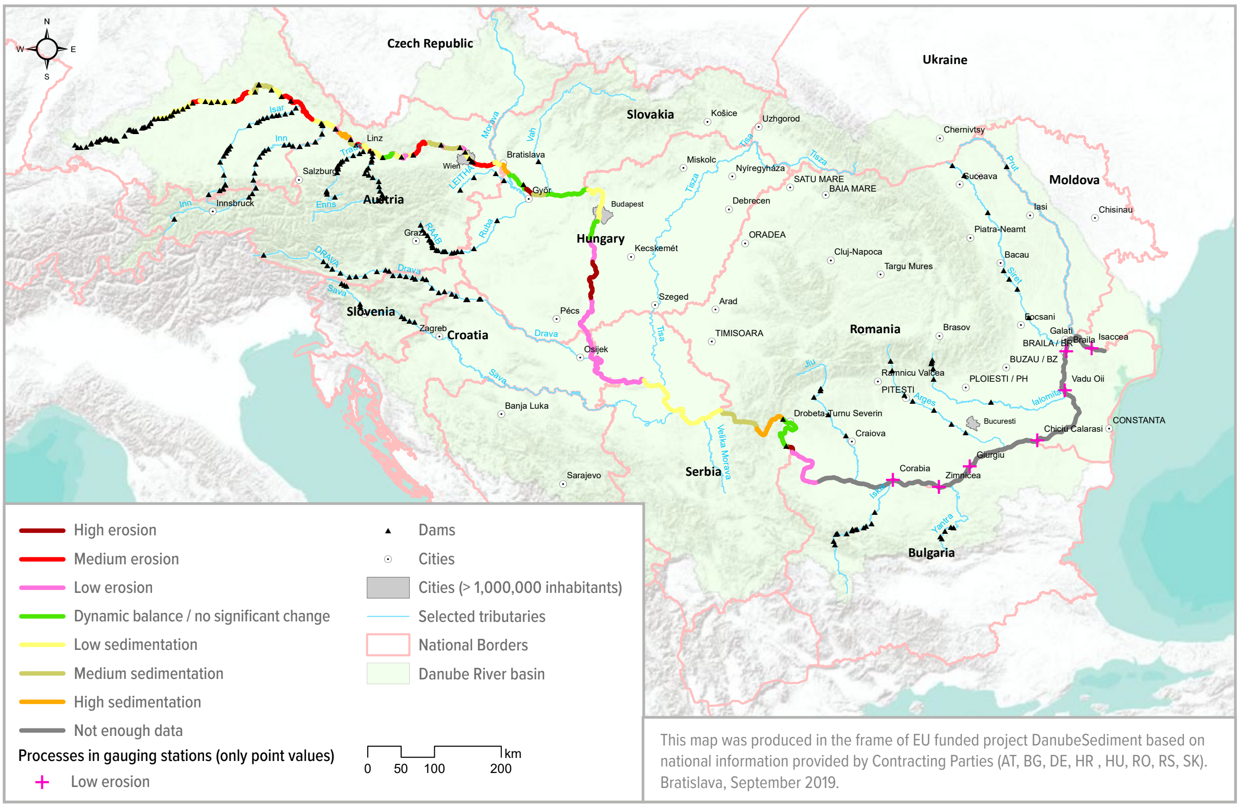

Figure 10: Reaches at the Upper, Middle and Lower Danube showing sedimentation and erosion (from the DanubeSediment report "Long-term Morphological Development of the Danube in Relation to the Sediment Balance").

For the greater part of the Lower Danube (670 rkm, from rkm 750 to 80), there was not enough data available for the period indicated above to evaluate 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 into the total numbers, ca. 56 % of the river length analysed in the project is facing erosional tendencies.

The spatial resolution of cross-sectional measurements 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.

NEED FOR COMPLETION OF SEDIMENT BALANCE

The data collected within the project DanubeSediment highlights that the current data base is too incomplete to be able to set up a sediment balance with all parameters for the entire Danube River. Unfortunately, not all the data described above were available for the whole river. Furthermore, when looking at the sediment balance equation (see equation 1, page 15), 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.

RISK ASSESSMENT

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 goal was to determine the influence of sediment alterations on the hydromorphological and biological quality elements and therefore the risk of failing the ecological aims of the WFD due to these alterations.

It is clear that there is a causal chain between sediment transport and river morphology and ecology. It is also clear that the 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 that influence the biological status, e.g. water quality, water temperature, invasive species or ship waves. 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. DanubeSediment 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 advanced hydromorphological assessments (CEN, 2018). They should also be set in correlation to the existing results and data pools of hydromorphological assessments and surveys done within the past decades.

4 Suggestions for an improved monitoring and data management

Sediment-related data are a prerequisite for appropriate planning and the evaluation of any sediment management measure. Sediment data are also an important input for sediment transport models and necessary for their calibration and validation. Long-term data that are measured regularly must be available to assess trends and long-term effects of sediment management measures and climate change. To gain deeper understanding of sediment-related problems, the establishment of a harmonized sediment monitoring network is proposed. This should take the following components of the sediment balance into account: sediment transport, bed material, bed level changes, dredging and feeding as well as floodplain and groyne field sedimentation. These measurements can be complemented by aerial mapping, taking photos of soil erosion, erosion of stream banks, landslides and mechanical movements. The measurements should especially be coordinated at border sections to enable the comparison of the results between the involved countries. Furthermore, comparing the results of different monitoring methods and setting up a sediment balance helps to verify the results of individual parameters.

SUSPENDED SEDIMENT AND BEDLOAD TRANSPORT

The monitoring of sediment transport comprises suspended sediments a well as bedload. Suspended sediment monitoring is already performed in all Danubian countries and also in a large number of the most important tributaries. Bedload monitoring however is only undertaken in some countries and often not on a regular basis, but only in the frame of monitoring campaigns.

The DanubeSediment recommendations to improve and harmonize monitoring systems (Figure 11) are described in detail in the project report "Sediment Monitoring in the Danube River" and the "Handbook on Good Practices in Sediment Monitoring". The recommendations for suspended sediment monitoring consist mainly of improving and harmonising the existing monitoring stations. For bedload, the project recommends to begin by setting up an initial monitoring network.

SEDIMENT MONITORING: Most important recommendations

- Harmonized monitoring system for suspended sediment taking the temporal and spatial variability of sediment transport into account
- Define standard bedload monitoring approach for the gravel bed and sand bed reaches of the Danube
- Improvement of existing monitoring stations
- Installation of new monitoring stations
- Measurements performed on a regular basis

SUSPENDED SEDIMENT: Most relevant elements

- High temporal resolution (e.g. 15 min) measurements of suspended sediment concentration (SSC) at one point in the cross-section: Optical or acoustic backscatter sensors (OBS or ABS)
- Calibration of OBS or ABS by isokinetic samplers
- Cross-sectional measurements by multipoint measurements applying isokinetic samplers and combined velocity measurements for sediment load calculations
- Combination of the measurements to calculate e.g. suspended sediment loads
- SSC and particle size distribution (PSD) analysis by laboratory facilities or laser diffraction-based instruments.

BEDLOAD: Most relevant elements

- Capture the temporal and spatial variability with the measurements
- Ensure suitability of the bedload sampler
- Defined hydraulic and sampling efficiency
- Cover full range of discharges (from initiation of motion to floods)
- Establishment of rating curves, i.e. discharge – bedload transport, shear stress – bedload transport relationships
- Surrogate techniques (e.g. acoustic based, sonar, tracer) can contribute → integrated approach

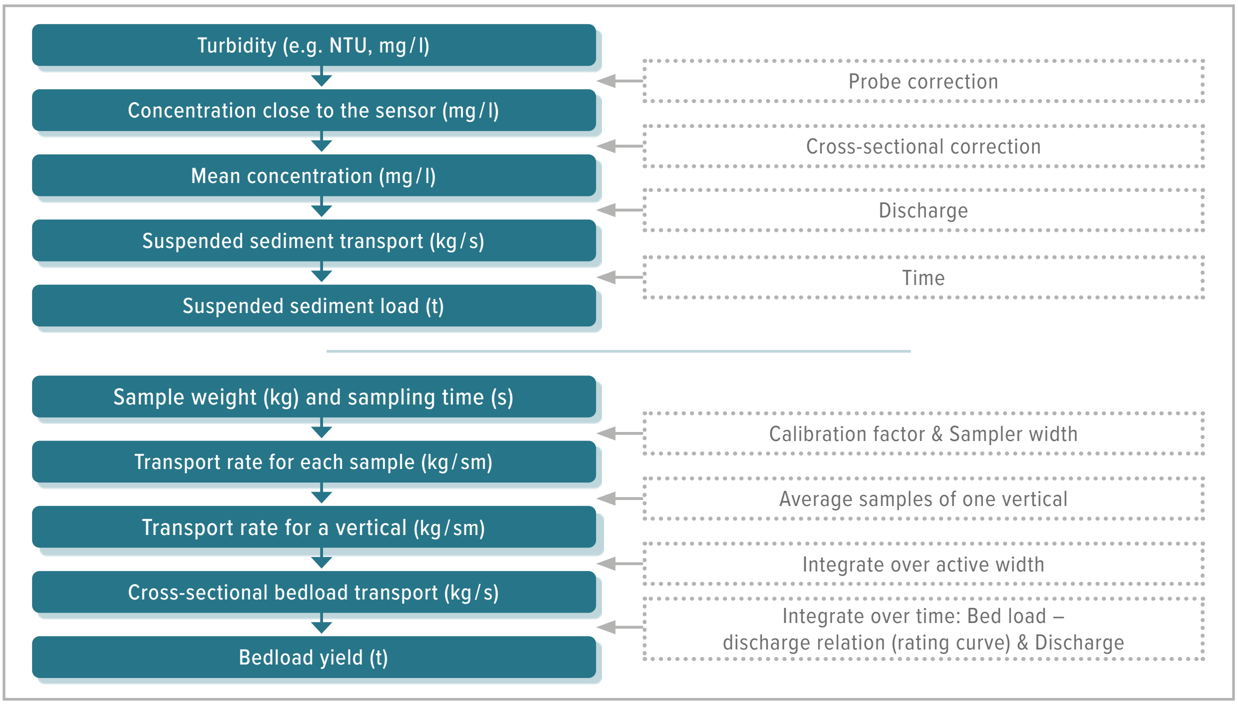

Figure 11: Scheme for suspended sediment monitoring (top) (modified after Habersack et al., 2013a) and scheme for bedload monitoring (bottom)

BED MATERIAL

Qualitative and quantitative analyses of sediment-related processes always require information about grain size fractions of the riverbed as well as from banks, bars and islands (Figure 12). As an important physical characteristic of the river, they are needed to describe the morphological conditions, respectively their changes. This information is needed to identify possible causes for these alterations. In addition, the quantity of the eroded, deposited and transported sediment is directly related to the size of the available sediments.

The substrate also provides one of the links in terms of physical habitat description of fish, phytobenthos, macrozoobenthos and macrophytes and directly supports the assessment of the biological quality elements (BQE) under the WFD.

The DanubeSediment recommendations for bed material sampling are described in detail in the project report "Long-term morphological development of the River Danube in relation to the sediment balance".

Figure 12: Volumetric bed material sample (left, photo: ©WRI) and freeze core sample (right, photo: ©IWA/BOKU).

BED MATERIAL: Most relevant elements

- Measurements in the main channel and on bars, banks and islands
- In gravel bed rivers: measurements of the surface and subsurface layers
- In a longitudinal resolution, consider the spatial conditions and local influences, e.g. up- and downstream of tributaries, longitudinal interruptions
- At least three samples per cross-section
- In a temporal interval of at least every five years, but considering conditions where significant changes can occur (e.g. implementation of measures)

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 13) 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, is not typically collected and published 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 to put an emphasis on the collection of the actual amount of all the dredging and feeding data in a high quality.

Figure 13: Dredging and feeding (photos: ©IWA/BOKU).

DREDGING AND FEEDING: Most relevant elements

- Measurements of dredged and fed amount (mass or volume), e.g. amount of filled barges or bathymetry measurement before and after dredging
- Documentation of the dredging and feeding location and extent, e.g. coordinates or rkm
- Representative sample (mass based on maximum grain size) to determine the grain size distribution

FLOODPLAIN SEDIMENTATION

Flood events along the Danube River showed that several meters of sedimentation can occur on the floodplains in case of inundation (Figure 14). 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.

Figure 14: Floodplain sediment depositions at the Danube River after the flood 2013 in Austria (left, photo: ©Verbund) and in Hungary (right, photo: ©ÉDUVIZIG).

FLOODPLAIN SEDIMENTATION: Most relevant elements

- Measurements of areal extent of the deposited sediment (e.g. field survey or aerial images) and the height of the deposition (the number of measurement points is dependent on the areal extent)
- Additional undisturbed samples taken in cross-sections perpendicular to the flow direction of the main and the side-channels, which need to be analysed in the lab (e.g. grain size, bulk and sediment density)

BATHYMETRY MEASUREMENTS

Bathymetry measurements that cover the whole width of the river (including bars and banks) are essential to be able to determine erosion or sedimentation tendencies (Figure 15). They are also required to determine morphological changes of river reaches or to be able to calculate a sediment balance.

So far, bathymetry measurements in some sections have only been undertaken to determine the fairway depth for navigation. These measurements often only cover the fairway or critical reaches for navigation. In other sections, bathymetry measurements are performed more regularly covering the whole cross-section or even have to be performed according to the law, for example in the Romanian-Serbian section of the Danube River.

The most complete picture of river morphology can be obtained by scanning the riverbed, e.g. with a multi-beam echo sounder. Therefore, these methods should be preferred. If only cross-sectional measurements can be performed, the spacing between the profiles should be appropriate for the river reach. To be able to analyse the riverbed development, a coherent data set is necessary. This means that measurements of cross-sections have to be performed at geodetically fixed profiles. Furthermore, systematic differences between different measurement systems need to be considered. In summary, bathymetry measurements should be performed in free-flowing as well as in impounded and critical sections taking the following specifications into account. The DanubeSediment recommendations for bathymetry measurements are further described in the project report “Long-term morphological development of the River Danube in relation to the sediment balance”.

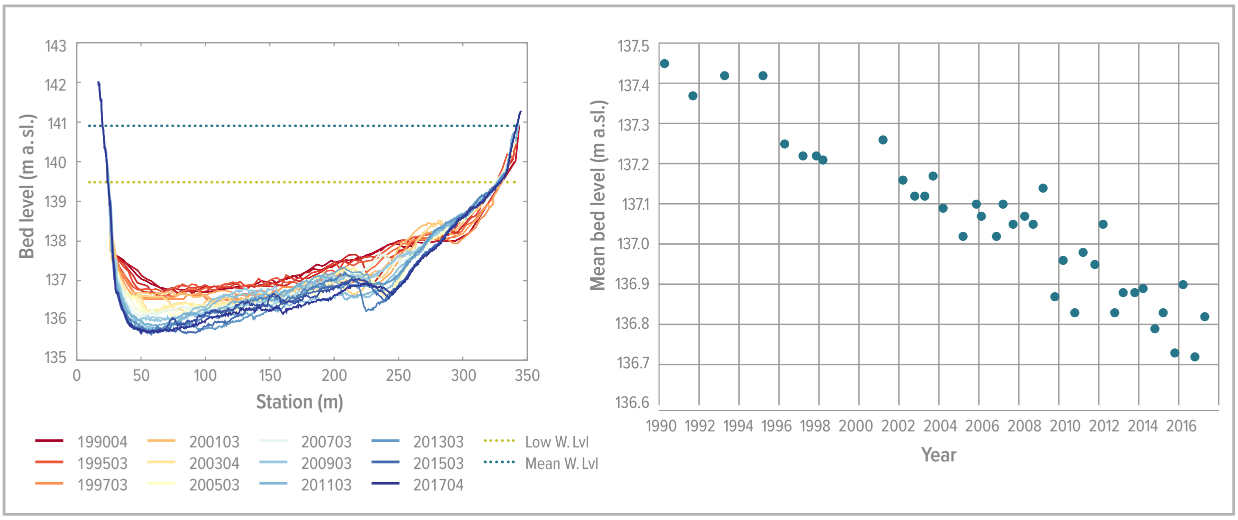

Figure 15: Exemplary cross-section showing riverbed erosion in a free-flowing part of the Austrian Danube (Data source: viadonau).

BATHYMETRY: Most relevant elements

- Measurements of the whole river width by areal scanning of the riverbed or in geodetically fixed profiles
- Spatial resolution of maximum 50/100/200/500 m cross section distance with higher densities in critical sections or tributaries
- Temporal interval of at least every three to five years, ideally coordinated along the whole Danube River
- Consider hydrological conditions, e.g. after major flood events, when severe changes can occur

DANUBE-WIDE SEDIMENT DATA MANAGEMENT

To date, sediment data is collected, stored and managed in different ways in the Danubian countries. In many countries, the sediment transport data, bathymetry measurements and bed material data are collected and stored by regional institutions and are not available for public use. Furthermore, in many cases there is no data exchange 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 the 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 in a centralised system, e.g. in the Danube GIS or to publish them in the yearbook of the Transnational Monitoring Network (TNMN). Sediment-related data often has to undergo a certain post-processing procedure and is therefore not suited for real time publishing, as is often the case for water stage and discharge. It is recommendable to make data available only after processing and validation.

SEDIMENT DATA MANAGEMENT: Most relevant elements

- 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: volume, 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)

SEDIMENT TRANSPORT MODELLING

Numerical sediment transport models can be implemented as prognostic or planning tools. For example, 1D sediment transport models can be applied for longer river reaches and times scales (decades and more) and individual 2D and 3D sediment transport models for shorter or critical river reaches and shorter times scales (years to events). Therefore, models should be considered as important supplements to monitoring data. They can also be used to close data gaps in measurements or for the spatial and/or temporal inter- and extrapolation of sediment data. In addition, for specific sediment-related measures, physical, large-scale models are recommended. Examples for the application of numerical and physical models in the DRB were collected by the DanubeSediment project and made available in the document “River Model Network”.

5 Practical measures

SELECTION OF SUITABLE MEASURES

When approaching any sediment-related problem, it is important to understand the system and to identify the cause of the problem. Rather than only treating the symptoms, the source of the sediment problem must be addressed. 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 river basin boundary conditions. Such conditions could be alterations in the sediment regime due to climate change-related issues such as glacier retreat or land use changes (for agriculture and urbanisation). Therefore, it is recommended to follow a set of criteria for the selection of suitable measures. 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.

To support this decision-making process, DanubeSediment has collected an array of measures in the "Sediment Manual for Stakeholders". 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 (Figure 16). Keeping this in mind also aids to set the scale of the measures in proportion to the problem. Furthermore, the effects of the measure need to be assessed, e.g. on the hydrodynamics, water level, sediment-dynamics, morphodynamics and ecology. In addition, one also needs to take the impacts of a measure on different users, such as hydropower, flood protection, nature protection or water supply into account.

Once an 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 and 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 should consist of monitoring before, during and after the implementation. This will help to evaluate the success of the measure and give the chance to adapt the measure, if necessary, and to learn from the implementation for future measures.

Figure 17 illustrates the possible steps from the system understanding to an identification of a set of measures to address sediment related issues.

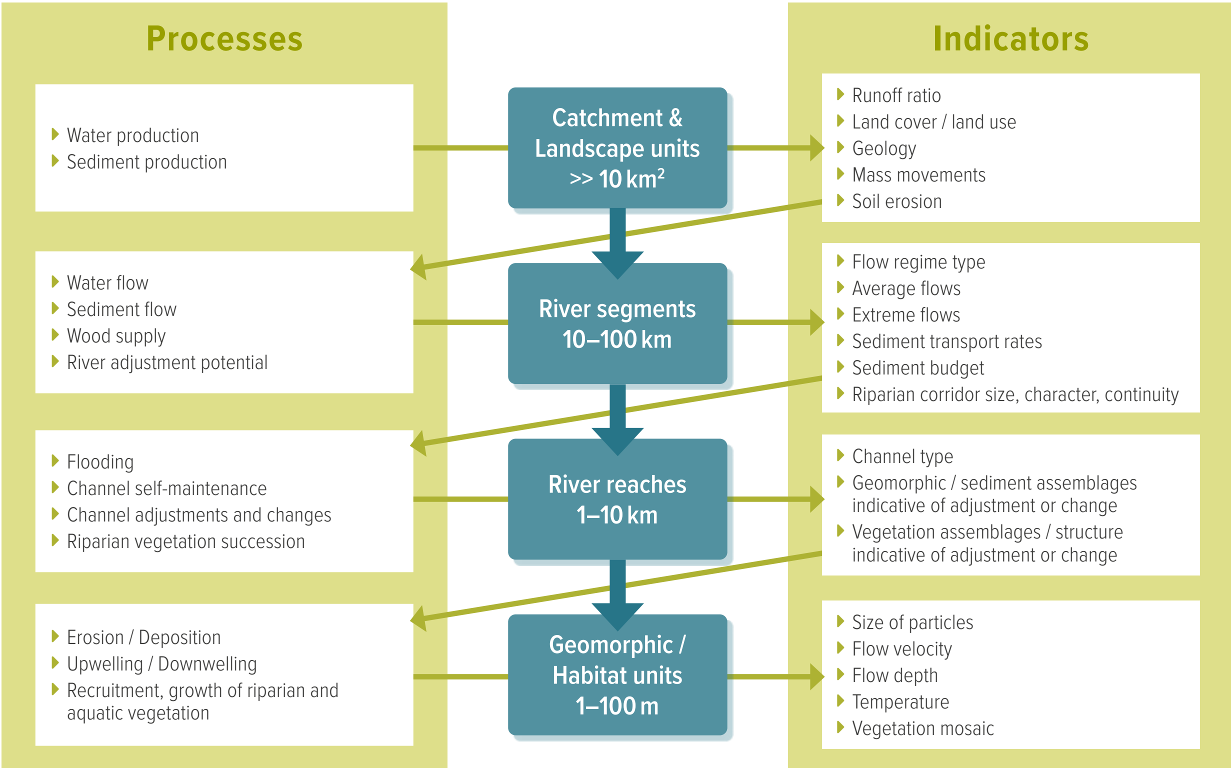

Figure 16: At each spatial scale the indicators represent specific processes. They provide indications how the different processes at one scale influence processes at smaller scales (modified after Gurnell et al., 2014).

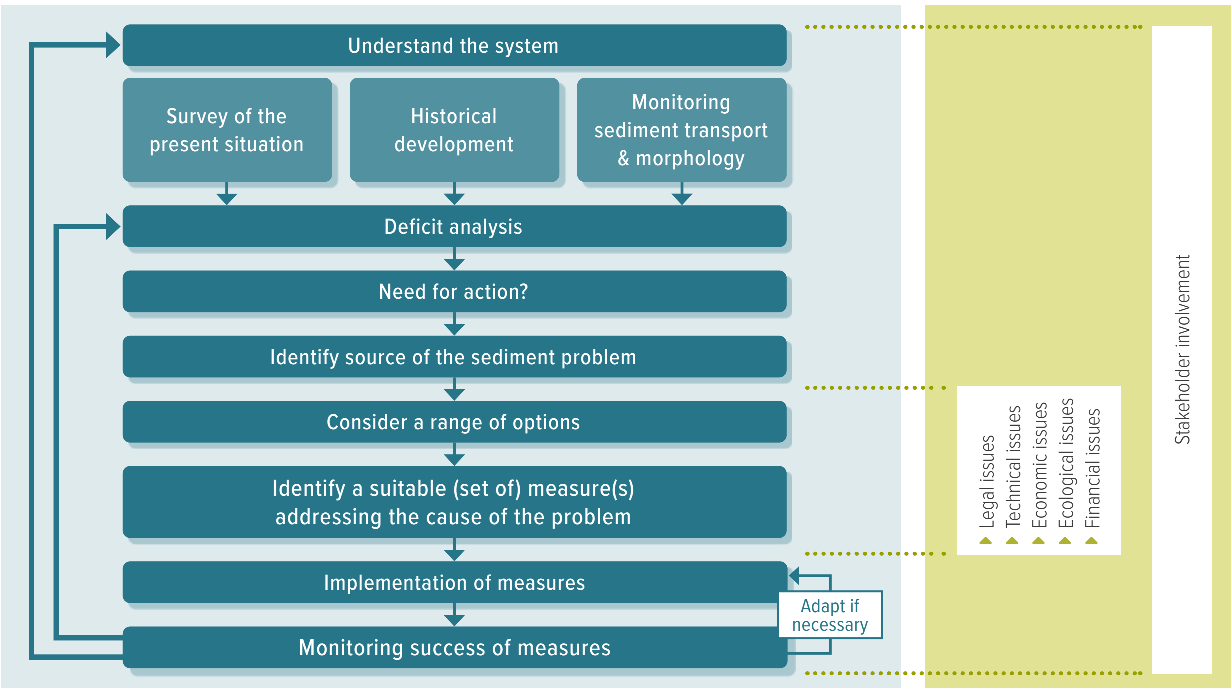

Figure 17: Scheme for sediment management

TYPES OF MEASURES

Figure 18 shows potential measures against riverbed erosion in free-flowing sections. To stop bed erosion in reaches with sediment deficit, the emphasis must be placed on increasing the sediment supply in this river reach. When the sediment deficit originates from sediment removal (e.g. commercial dredging), these extractions should be stopped or brought to a minimum and only be performed for safety reasons (e.g. flood protection, navigation). These extracted sediments should then be relocated to other locations in the river where erosion occurs and where sediment input is needed.

If a change of sediment retention by transversal structures such as dams and weirs is the reason for the sediment deficit, the sediment regime can be changed by increasing the sediment continuity of fine and coarser material through the barrier (e.g. adapting existing transversal structures or flushing). Measures to change the sediment regime and improve the sediment balance are more effective when they cover longer river stretches. The increased sediment input can either be achieved by activating the natural input (e.g. side erosion, input from upstream by providing the continuity from sources, torrents to hydropower plants) (Figure 19) or by adding sediments artificially (feeding). By adding coarser material than the natural bed material in the river reach (but still in the range of the natural spectrum), the bed resistance of the river can be increased additionally. By reducing the energy slope and minimizing the bed shear stress, the transport capacity of rivers is reduced. For example, this can be accomplished by optimizing hydraulic structures (Figure 20) or river widening.

Potential measures addressing sedimentation in impoundments and reservoirs are shown in Figure 21. To reduce accumulation in impoundments and reservoirs, potential options include changing the sediment regime, routing sediments, increasing the energy slope or the shear stress. The sediment regime can be changed by decreasing the sediment input from the catchment, e.g. with agricultural/silvicultural or with hydro-engineering measures. Routing sediments can be done by sediment bypassing or by passing sediments through the impoundment or reservoir, e.g. turbidity currents. By increasing the energy slope and the bed shear stress, the transport capacity can be enhanced and sedimentation of fine sediments in the impoundments and reservoirs can be reduced. For example, this can be accomplished by adding or altering hydraulic structures in existing impoundments and reservoirs or by optimizing the geometry of newly constructed ones. Flushing, respectively a drawdown of the water surface, can be performed to remobilize deposited sediments.

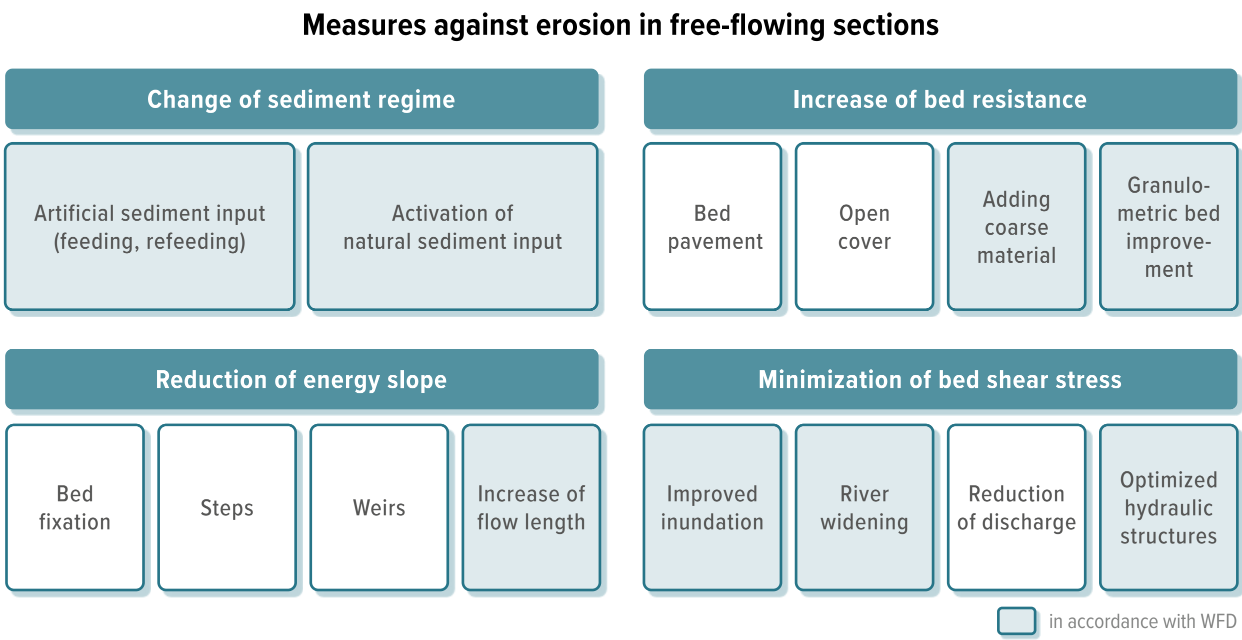

Figure 18: Sediment management measures to stop bed erosion (modified after Habersack et al., 2013b); measures in accordance with the WFD are highlighted with a light blue background.

Figure 19: Left bank of the Danube River at Witzelsdorf before (left) and after (right) riverbank restoration (photos: ©viadonau).

Figure 20: Hydraulic structures before (left) and after (right) optimization (groyne modification) (photos: ©viadonau).

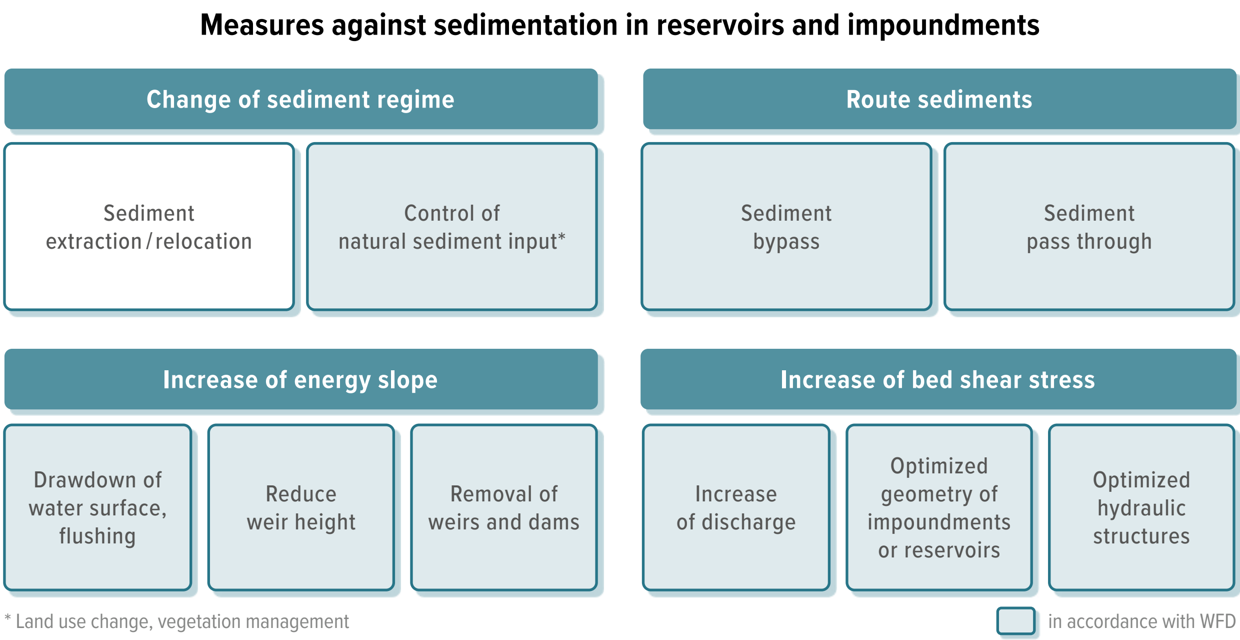

Figure 21: Sediment management measures addressing sedimentation; measures in accordance with the WFD are highlighted with a light blue background.

An overview on managing options and examples of good practice on sediment management measures from inside and outside the Danube region are provided in the DanubeSediment report "Sediment Management Measures for the Danube". These measures are also described in detail in the Sediment Manual for Stakeholders (SMS). Thus, this document only provides a condensed list of measures (Figure 23), subdivided in different spatial scales (Figure 22).

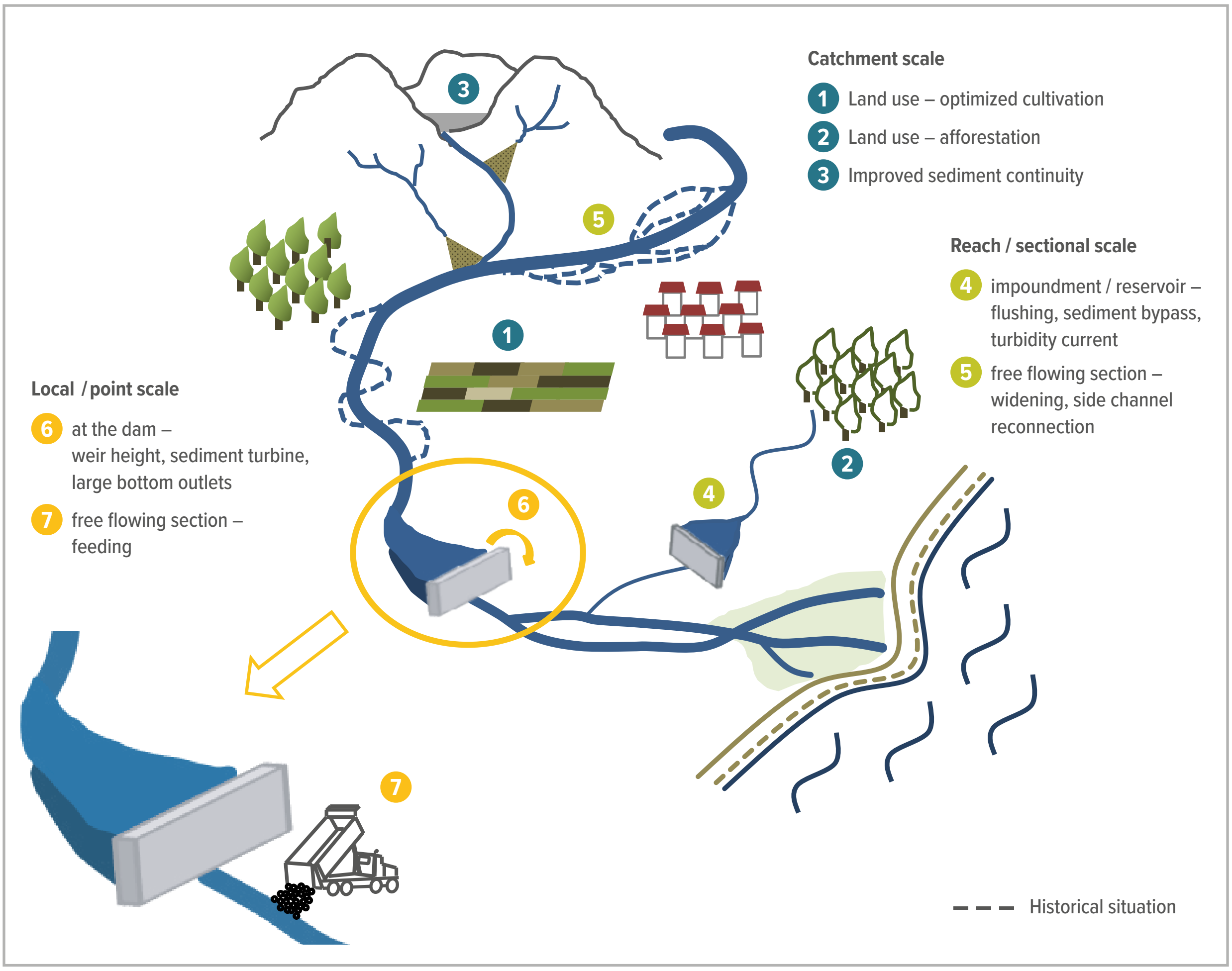

Figure 22: Location of selected measures within the basin.

Catchment scale

Measures in the catchment

- Sediment management concept
- Raise awareness and capacity building
- Minimize urbanisation and construction of buildings on sloped terrain
- Minimize anthropogenically caused excessive debris flow, mass movements and land slides
- Improve or adjust land use and management
- Reduce surface runoff by infiltration and retention
- Reduce undesired (fine) sediment input
- Controlled sediment transfer at barriers (improve sediment continuity)
- Adapt to impacts of climate change

Reach / sectional scale

Measures in reservoirs or impoundments

- Minimize width of the impoundment or reservoir (by hydraulic structures)
- Sediment bypass (tunnel, channel)
- Off-stream reservoirs
- Sluicing
- Venting of turbidity currents
- Environmentally friendly flushing
- Flood conditioned flushing
- Optimize flushing or sluicing strategies for dams in series
- Prevent sedimentation by artificial turbulence (jet screens)
- Wet or dry dredging and reinsertion
- Bedload drift

Measures in free-flowing sections

- Enlarge morphological space of rivers
- River widening (artificial or self-forming)
- River bank restoration
- Increase river length to reduce slope
- Reconnection of side-channels or enhance floodplain erosion
- Opening or removal of flood dykes
- Relocation or set-back of flood dykes
- Removal of natural near-river levees (bank erosion or mechanical)
- Restore wetlands
- Coarse particle feeding (granulometric bed improvement)
- Break-up of bed armouring (artificial flood or mechanical)
- Intelligent dredging and feeding management
- Fairway shifting or narrowing

Bathymetric survey
Minimize or stop commercial dredging

Local / point scale

Measures at the dam

- Minimize dam width
- Minimize fixed weir sill height
- Construct local sediment bypass
- Modify weir fields to increase sediment continuity
- Install large bottom outlets or gates for venting, sluicing or flushing
- Route sediments through turbines
- Pressure scouring
- Open ship locks for local remobilization
- 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
- Optimisation of river engineering structures to reduce sedimentation
- Optimisation of river engineering structures to reduce erosion
- Install bedload traps (as part of intelligent dredging and feeding management)
- Remobilisation of consolidated gravel bars
- Local bank protection for objects
- Modify or remove barriers (weirs or ramps)

Figure 23: Overview on sediment management measures

6 Key question – Significant Water Management Issue

Pressures acting on the water environment that most threaten the achievement of the environmental objectives of the WFD are called Significant Water Management Issues (SWMIs). Issues may arise from on-going human activity, historic human activity and new developments.

In the DRBD, four Significant Water Management Issues (SWMIs) were already identified in the 1st DRBM Plan 2009 and its update 2015 for surface waters:

- Organic pollution,
- Nutrient pollution,
- Hazardous substances pollution and
- Hydromorphological alterations.

The SWMI "Hydromorphological alterations" is further divided into

- Hydrological alterations
- Interruption of river continuity
- Morphological alterations
- Future infrastructure projects

In the 1st DRBM Plan 2009 and its update 2015, conclusions regarding sediment management in the DRBD were outlined including respective actions for the upcoming RBM and FRM cycles. However, sediments were not addressed as a Significant Water Management Issue.

The DanubeSediment project was asked by the ICPDR to clarify and provide scientific evidence as to whether the alteration of the sediment balance shall be identified as Significant Water Management Issue (SWMI) in the Danube River Basin. Based on their investigations the project consortium concluded that the alteration of the sediment balance should become a SWMI.

To date, the SWMI "Hydromorphological alterations" already addressed many sediment-relevant aspects, such as the interruption of river continuity, morphological alterations as well as the disconnection of adjacent floodplains or wetlands. The interruption of river continuity was mainly related to fish migration, but the continuity for sediments was not mentioned. Although sediments are needed for morphodynamics and habitat quality, and thus for the ecological status, they were not directly included in the SWMI and thereby the issue was missing.

For the reasons mentioned above, it did not seem necessary to define the alteration of the sediment balance as a SWMI. Instead, the project recommended that the sediment balance alteration, as an integral part of hydromorphology, be listed as sub-SWMI under the existing SWMI "Hydromorphological alterations."

The results of the project and their conclusions pertaining to the sediment balance alteration as being a SWMI, were presented by the DanubeSediment consortium at several ICPDR meetings. 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". The results of the project are used for the description of the issue and the preliminary identification of actions and coordination requirements for the basin-wide level. Following several discussions, the text now reads as follows:

Sediment balance alteration

The aspect of sediment quantity in the Danube River Basin was already mentioned in the 1st DRBMP 2009 and considered as potential Significant Water Management Issue in 2013. Based on key findings of the DanubeSediment project (Danube Sediment Management – Restoration of the Sediment Balance in the Danube River) the alteration of the sediment balance is now identified as new sub-item of the Significant Water Management Issue "Hydromorphological alterations". First results of the project are used for the description of the issue and the preliminary identification of actions and coordination requirements for the basin-wide level. The results of the project will be further discussed under the umbrella of the ICPDR with the aim to fully integrate them into the development of the 3rd DRBMP Update 2021.

THE ISSUE

The sediment balance is disturbed in particular by interruption of sediment transport caused by transversal structures (such as weirs or dams due to e.g. hydropower use, water supply or flood protection). The sediment balance is furthermore impacted by river regulation works for flood protection and navigation (river strengthening and building dykes often leading to cut-off meanders and shortening of the river length), as well as commercial dredging, land use (e.g. agriculture and urbanisation) on the entire catchment and other infrastructure projects. These measures reduce the river width, increase the riverbed slope whereas bank protection measures prohibit side erosion. This leads to a sediment deficit and increased sediment transport capacity in the free-flowing sections as well as to coastal erosion. In impounded sections, floodplains and groin fields a surplus of sediments is dominating. Disturbed morphodynamics cause a deterioration of type-specific habitats and may cause a lowering of groundwater levels. In general this may lead to severe impacts on the type-specific aquatic communities and groundwater dependent terrestrial ecosystems and thus on the water status.[1]

VISION

The ICPDR's basin-wide vision is a balanced sediment regime and an undisturbed sediment continuity. Type-specific natural bed forms and bed material as well as a dynamic equilibrium between sedimentation and erosion are provided. The balanced sediment regime enables the long-term provision of appropriate habitats for the type-specific aquatic communities and groundwater dependent terrestrial ecosystems.

PRELIMINARY IDENTIFICATION OF ACTIONS AND COORDINATION REQUIREMENTS FOR THE BASIN-WIDE LEVEL

- The objective of the EU funded DanubeSediment project (2017–2019) is to improve water and sediment management as well as the morphology of the Danube River. Following the DPSIR (Drivers, Pressures, States, Impacts and Responses) approach the key drivers and pressures in the Danube River Basin that act on the sediment regime were identified and their impacts were described.
- The DanubeSediment project identified a sediment imbalance for the Danube River, revealing areas with erosion and sedimentation being a risk for achieving the environmental objectives of the WFD.
- To gain deeper understanding of sediment quantity related problems, the establishment of a harmonized sediment quantity monitoring network will be discussed in the frame of the TransNational Monitoring Network (TNMN)[2] and under the supervision of the Hydromorphology Task Group (HYMO TG), Monitoring and Assessment Expert Group and Flood Protection Expert Group.
- The Danube Sediment Management Guidance will provide recommendations towards the 3rd DRBM Plan Update 2021 for an improved sediment balance.
- The Manual for Stakeholders will offer assistance for sediment related actions in the Danube River Basin and future programmes of measures.
- A catalogue of measures in order to mitigate the impacts is available to support targeting measures to improve the sediment balance and continuity; the catalogue will need to be updated in the future.

1 Article 1a Water Framework Directive.
2 https://www.icpdr.org/main/activities-projects/tnmn-transnational-monitoring-network.

7 Recommendations

GENERAL RECOMMENDATIONS

The following recommendations apply to the Danube River and its tributaries.

Development of a basin-wide sediment management concept

We recommend 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 an element of uncertainty.

Improvement of legal regulations and governance

The aspect of sediment quantity in the Danube River Basin was already mentioned in the 1st DRBM Plan 2009 and considered as potential Significant Water Management Issue in 2013. Based on key findings of the project, the sediment balance alteration has been identified as a new sub-item of the Significant Water Management Issue "Hydromorphological alterations".

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). Additionally, we recommend for the Danube countries' authorities, HPP operators and bilateral commissions to initiate an in-depth investigation of sediment issues, to set new management rules and include them into the operational procedures.

Preservation of the sediment continuity and the morphology

In the Danube River Basin, the protection and preservation of the (nearly) undisturbed sediment regime that still exists within the remaining natural free-flowing river sections and tributaries, should be of utmost priority, reflecting 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, respectively rivers.

Restoration / improvement of the sediment continuity and river morphology

There is a need to restore / improve the sediment continuity of the Danube River and its tributaries where it is interrupted, and / or impacted. Restoration of the sediment continuity means to increase the sediment transport through structures with the aim to reduce the problems associated with a sediment surplus and deficit and to adapt the sediment budget to achieve the best possible morphological conditions in the water bodies and further downstream. Attention should be given to improving sediment continuity at existing barriers and impoundments and to avoiding additional interruptions. If transversal structures are newly constructed or existing ones are reconstructed, not only the possibility for fish migration but also measures to enable sediment continuity have to be taken into account.

The project does not recommend to remove all existing barriers, but when the operation is no longer profitable or technically feasible, the decommissioning and the controlled removal of the dam/barrier should be considered as an option.

Reduction of surplus and deficit reaches

The number of river reaches with a clear trend in sedimentation and erosion shall be reduced with the aim of establishing a dynamic equilibrium and morphodynamics. This should be done by restoring sediment continuity on the one hand and by river restoration on the other hand.

At stretches with sediment deficit, the river can be restored by e. g. side-channel reconnection or removal of bank protection. Such measures help to decrease the sediment transport capacity by river widening and to increase the lateral sediment exchange. Lateral erosion shall be allowed at locations where this has no significant negative effects, e. g. for flood protection of settlements.

At impounded reaches with a sediment surplus, measures to increase the transport capacity and sediment continuity need to be implemented, taking care of the downstream and upstream consequences and the overall sediment regime.

Development and implementation of sediment-related measures addressing navigation, hydropower and flood risk management

Water and sediment are the fundamental elements of a fluvial system, therefore water and sediment need to be managed together. Neglecting sediments in the planning process can result in undesired outcomes of the planned “solution”. An integrated planning process needs to consider how the sediment regime is affected and which problems can occur. Those problems can be either be ones that already exist or potential ones that can arise when ignoring sediments.

Therefore, it is crucial that measures implemented by relevant stakeholders such as hydropower, floodrisk management and navigation consider sediment transport in a harmonized and integrated way. For example, in order to increase the water depth for navigation, the river width might be decreased. This in turn intensifies sediment transport processes that lead to riverbed erosion, which affects the ecosystem and flood risk. The same is true for flood risk measures that lead to a disconnection between river and floodplain e. g. when dykes are built close to the river. These measures also increase erosional tendencies during higher discharges. Hydropower schemes disrupt the sediment continuity, leading to sedimentation upstream and erosion downstream, thus affecting navigation, flood risk and ecology. In turn, river restoration measures, for instance, can have consequences for navigation infrastructure or flood risk, when too much aggradation or lateral erosion is occurring. In simple terms: a measure planned for one sector can influence other sectors, too. This shows, that an inter-sectoral process is essential when planning measures in the river. It is important to take advantage of stakeholder expertise and of synergies between stakeholders of all different sectors. This will help to avoid potential future conflicts amongst users of the river.

Defined refeeding of the dredged material

In general, it is recommended to keep the sediments in the river system and, if possible, to stop or minimize the extraction of sand or gravel. If dredging cannot be avoided due to safety reasons, like flood protection or fairway maintenance, the sediments should be reinserted into the river at sections with a significant lack of sediments. Most preferably, the reinsertion of dredged material should take place upstream in free-flowing sections and downstream of the barrier in impoundments. In cases of dredging in impounded reaches, the sediments can be fed back downstream of the barrier to compensate sediment deficit. The dredged material, 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. As long as a sediment deficit exists, all dredged sediments from the Danube and the tributaries should be reinserted, regardless if fine or coarse sediments. However, the sediment quality and other ecological boundary conditions, e.g. duration and maximum concentrations due to feeding, have to be considered.

Catchment-related measures

Since sediment related problems should rather be treated at the source of the problem, measures implemented in the catchment area might be the right choice in some 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. Additionally, by reducing the output from agricultural areas, the input of nutrients into the river system can be reduced. In cases of bed material deficit, the amount of bedload entering the river should be increased, for example, by modifying torrent barriers to allow bedload to pass into the river system, taking flood risk management into account.

Establishment of harmonized sediment monitoring network and data management

On a basin-wide scale, there are still several sediment data-related issues that need to be addressed. This requires a harmonized sediment monitoring using the same methodology on a transboundary level (see details in chapter 4). Sediment monitoring should consist of sediment transport, bed material, bed level changes, dredging and feeding as well as floodplain and groyne field sedimentation. These measurements can be complemented by aerial mapping, taking photos of soil erosion, stream bank erosion, landslides and mechanical movements. The measurements should especially be coordinated at border sections to enable the comparison of the results between the involved countries. Furthermore, comparing the results of different monitoring methods and setting up a sediment balance helps to verify the results of individual parameters. These sediment monitoring activities should be closely interlinked with the regular hydromorphological assessments based on the European Standard "Water quality – Guidance standard for assessing the hydromorphological features of rivers" (EN 14614; CEN, 2018) and described by e.g. Gurnell et al. (2016). This would support the recognition of ongoing processes and planning targets for larger, often transboundary, river reaches.

The establishment of a harmonized monitoring system should be coordinated on a high, transnational level, for example via the ICPDR. The recommendations for good practice sediment monitoring should be included in a future sediment management concept for the entire Danube River Basin. Sediment monitoring activities during flood situations need to be prioritised in water management tasks. For sediment management to be successful on the DRB level, long-term sediment data should be stored in well-managed databases in the respective countries. It should also be provided to a central database, for example at an established institution such as the ICPDR. Stakeholders should have access to the non-classified data. The collected data and information would serve as a support for analyses, forecasts, predictions, resource optimization and – generally – in reaching management decisions in water management. The data could further be implemented in a Decision Support System (DSS) to assist decision makers.

Sediment quality needs to be included

The project DanubeSediment only dealt with sediment quantity but not with sediment quality. Thus, no detailed recommendations concerning the monitoring of sediment quality can be provided. However, information regarding the topic is available from the Joint Danube Surveys and the SIMONA project. Nevertheless, in the project consortium's opinion, a holistic approach concerning sediment quality and quantity should be pursued since contaminated sediments pose a risk to ecological and human water demands.

Sediment-related risk analysis

Another important aspect for a follow-up project should be to analyse the risk of failing the good ecological status or potential due to sediment-related problems along the Danube River and the tributaries. Furthermore, we recommend to performing a risk analysis at the national levels in connection with the national river basin management plans.

Stakeholder involvement and interdisciplinary planning

To gain an overall acceptance of any sediment management measure, be it maintenance of existing or implementation of new measures, all relevant stakeholders should be included in the process as early as possible. This provides the option to integrate all relevant perspectives into river management and to raise synergies and avoid conflicts between different aims. Furthermore, sediment issues should be tackled by (inter-)national stakeholder networks, such as the ones set up in DanubeSediment project. After the project, we recommend that the ICPDR maintains this network and continues to involve stakeholders, for example through the development of a Danube-wide sediment management concept. On the national level, the project will provide a list of national contacts for interested stakeholders. Stakeholders can provide their expertise and practical experience with sediment management measures, thereby giving crucial information and support for selecting adequate measures to improve the sediment balance.

Adaptive implementation of measures and accompanying monitoring

When realising any measure it has to be ensured that an adaptive and holistic planning process is implemented to confirm that the most practically efficient, environmentally friendly and cost effective option is selected, considering the socio-economic needs and constraints. All effects of the measure and the feasibility need to be analysed in the decision and planning process including the possible need for hydraulic adjustments of the downstream river sections (see chapter 5).

It is necessary to implement an accompanying sediment monitoring during the realisation of sediment management measures in order to monitor and assess the effects of these measures and – if relevant – to be able to adapt them.

To support the Danube-wide planning and decision-making process for sediment management measures, we recommend that the measures collected, described and evaluated in this project (see Sediment Manual for Stakeholders) be updated regularly. In general, sediment research should be intensified in the Danube River Basin. For a follow-up project, we recommend the implementation and monitoring of sediment management measures at pilot sites in cooperation with relevant stakeholders, such as water administration, hydropower companies and nature protection.

RECOMMENDATIONS FOR THE DIFFERENT RIVER SECTIONS

The following recommendations apply to the Danube and the lower parts of its tributaries. Although the recommendations are divided according to the river sections, in the long-term, sediment management should not only focus on the local situation but needs to consider the whole river basin to avoid overcompensation or deterioration elsewhere.

Recommendations for the Upper Danube

The recommendations to improve the sediment regime in the Upper Danube need to be differentiated between free-flowing and impounded sections.

Free-flowing sections
In the free-flowing sections, where erosion occurs, it is recommended to apply a mixture of different measures for short to mid-term improvements of the sediment regime. In areas where a risk of riverbed break-through exists, i.e. the river cuts into the fine marine or lake deposits, counter measures need to be given a high priority.

To improve the sediment balance, river restoration measures such as planform rehabilitation, e.g. side-arm reconnection and islands, as well as removal of bank protection and restoration of natural banks should be continued. Lateral erosion shall be allowed at locations, where it has no negative effects, e.g. on navigation or flood protection. Lateral erosion may still be possible in flood risk areas, if alternative options to ensure flood protection are considered. Besides having a positive effect on flood protection, floodplain reconnection also reduces the sediment transport capacity. To further reduce the sediment transport capacity and the degradation of the riverbed, the optimization, respectively reduction, of existing river training structures such as groynes and guiding walls, should be continued. All the above-mentioned measures have significant positive ecological benefits.

In the Upper Danube, the extraction of coarse sediments is not performed anymore and dredging is only performed for specific reasons, e.g. for navigation or flood protection. It is recommended to limit dredging to a minimum and to continue the now common practice of keeping the dredged material in the river system. This can be done either by reinsertion of the material further upstream or the construction of instream structures such as islands and gravel bars. To compensate sediment continuity interruptions caused by hydropower dams and other barriers in the upstream section, or to compensate an increased transport capacity due to river regulations, additional material should be fed into the river.

Impounded sections
In impounded sections, sediments are trapped due to low flow velocities and reduced water surface slopes leading to a reduced transport capacity. While finer sediment is only partially trapped in the impoundments or reservoirs, coarse sediment transport is frequently completely interrupted. With respect to the sedimentation rate within the impoundment or reservoir, an improvement of the sediment regime by restoring the sediment continuity is one of the main sediment management issues in the Upper Danube. Sedimentation processes can usually not be eliminated but they can be reduced. For this purpose, a combination of effective measures is recommended. Studies should be done to show whether fine sediments, and in some impoundments even coarser sediments, can be remobilized by artificial or flood induced flushing. This flushing causes a temporal shift of the sediment transport; meaning a large amount of sediment is transported within a short time period. This can lead to increased sedimentation of fine material on floodplains and gravel bars. Any releases of fines should be done in a controlled/planned and ecologically compatible manner, understanding that sediment control during large floods will almost not be possible. In the long term, it is recommended to place emphasis on a more continuous and natural

sediment regime by preventing either sediment settling or more frequent remobilisation. This might be achieved by e.g. more frequent opening of the gates, sluicing, optimized or innovative technologies such as sediment bypass. Also, deflective structures to improve hydraulic conditions for sediment transport are recommended, as well as targeted maintenance dredging in some localities with downstream re-insertion, particularly within the navigation channel. Where possible, the impoundments should in the mid to long-term be reshaped, e.g. by groynes, to achieve maximum shear stresses to transport material during floods. Where the coarse material cannot be transported through the impoundment or reservoir, we recommend dredging in the impoundment or reservoir and feeding the material downstream of the hydropower dams in the short to mid-term.

In the long-term, it is recommended to improve the sediment continuity in the Danube River and its tributaries. Therefore, further research is needed to develop innovative approaches and measures, e.g. sediment bypass or sluicing, especially for coarse material.

Recommendations for the Middle Danube

In some sections of the Middle Danube, very little sediment monitoring is systematically implemented. Besides the different degrees of monitoring in the Danube basin, there is also a lack of integration between scientific investigations and river basin or sediment management. Furthermore, different institutions and stakeholders only collect certain types of data according to their specific interest. However, the majority of them require detailed spatial and temporal data. This indicates a clear need for the harmonization of sediment measurements and a monitoring network, as described in chapter 4. In transboundary basins, it is necessary to coordinate the measurement methods to enable the comparison of results.

In order to improve the sediment balance, some of the measures described for the free-flowing sections in the Upper Danube can also be applied on the upper part of the Middle Danube, i.e. the SK–HU section. Due to significant changes of the riverbed slope, sedimentation of the riverbed prevailed in some river reaches in the long-term and continues until the present. Thus, if no other measures are possible, minimal dredging to maintain navigation conditions is recommended. Sediment volumes dredged within the navigation channel should be relocated within the river channel, if possible upstream, to contribute to point bars development. This river reach has degraded on the long-term but indicates a dynamic balance during the recent years. To improve the sediment balance, we recommend applying some measures, e.g. removal of bank protection, optimization or reduction of existing river training structures and reconnection of the side-channels. Generally, an emphasis should be placed on the combination of measures to achieve an improvement of the sediment regime. Implementation of only one of these measures cannot provide the expected improvement, moreover, the length of the restoration reach is also important.

According to recent geophysical surveys, the riverbed of the Hungarian sand-gravel sections has reached a hard-to-erode layer at many sections, which, as of now, seems to prevent further bed incision. Nevertheless, the future behaviour of these layers of different compositions, e.g. silt, marl, sandstone, etc. is not entirely known. It might for example be eroded by bedload transport. This calls for further research to reveal the interaction mechanisms between the flow field and the riverbed. Although these hardly erodible layers might prevent further bed incision, these layers do not represent the alluvial bed material. That means, structures such as bars and islands cannot naturally develop. Thus, the supply of sediments, especially bed-forming sediments, into this reach should be increased. Considering the high number of navigational bottlenecks along the sand-gravel section, there is a strong intention to improve the characteristics of the navigational channel with local measures at the critical points. Thus, it is important that these measures take the sediment regime into consideration.

Keeping in mind that habitat conditions along the Danube are continuously being reduced, these future measures must also improve the diversity of hydromorphological conditions at the same time. In order to resolve these complex and often contradictory interests, different measures can be considered. For example, cutting through the near bank zones of conventional groyne fields to increase flow velocities along the critical fish spawning sites; lowering, rearranging, modifying the spacing of and even reshaping existing groynes; creating natural like gravel bars to vary the flow conditions; fixing the deepest parts of the cross-sections by e.g. feeding coarser bed material or constructing bendway weirs.

As to the clear sand bed section in the Hungarian Danube, where the bed morphology seems to be in a dynamic equilibrium, it is rather the fixing of the actual riverbed which needs to be maintained. From a navigational point of view, however, a few problematic sections can still be found in this reach of the Danube. At such locations, instead of implementing new engineering measures it is suggested to reconsider the width of the navigational channel, e.g. by decreasing the prescribed 150 m width to 90 m. Besides improving the sediment related issues of the main channel, we recommend improving the ecological status of the formerly disconnected side-channels. Reopening these branches in combination with the destruction or modification of the existing river training, e.g. weirs, cross dykes, traverses, and the inlet and outlet sections, and dredging of the riverbed, should lead to improved habitat conditions. However, these measures require in-depth planning that must consider the geometry, flow and sediment transport capacity in the side-channels. This has to be well established using state of the art, scientifically-based investigation methods, such as computational simulations or physical models.

Downstream of the Hungarian border to Backa Palanka, where the state border between Croatia (right bank) and Serbia (left bank) is not yet determined, a number of navigation bottlenecks have been identified and plans are being made to improve navigational conditions in the future. In order to preserve and improve the sediment balance, material that has been dredged shall only be relocated, if possible reinserted upstream, and not removed from the river. In this border reach, it is recommended that all measures should be closely coordinated by the two countries. The following downstream section until Novi Sad, where both banks are Serbian, is characterised as unstable sandy riverbed, with similar characteristics as the upstream section. Keeping in mind the dynamics of this river section, maintenance of navigation conditions is needed. We recommend that all future measures should be in line with the "Joint Statement on Inland Navigation and Environmental Sustainability in the Danube River Basin" (ICPDR, 2007) with the main goal of preserving the sediment balance and improving the environmental status of the river. At these two sections, different measures were done in the past, which resulted in increased velocities and the depletion of sediment. All future activities need to preserve the sediment balance, while in addition planning measures that increase the connectivity of water bodies, such as reconnection of side-channels and floodplains, as part of planned activities.

Further downstream, the impounded stretch of the Middle Danube River begins at Novi Sad. It can be split into four stretches:

- Novi Sad to Belgrade: this stretch is under the influence of the Iron Gate reservoir only during low waters, which makes it very unstable from a navigational point of view. Constant maintenance is required in order to provide necessary fairway conditions, while preserving the sediment balance of the river.
- Belgrade to the mouth of the Nera River: this is the shallow part of the reservoir, where a low rate of sedimentation is present.
- Mouth of the Nera River to Golubac: this alluvial reach is part of the reservoir and forms the state border between Serbia and Romania along the Danube River. Here sedimentation occurs and increases the risk of flooding.
- Golubac to the dam: the Iron Gate gorge builds the deep part of the reservoir with permanent sediment deposition. The state border between Serbia and Romania follows the Danube River. Sediment flushing through the dam is performed only during floods.

The impoundment in the Middle Danube is a very central point for the overall budget of the Danube River since sediment deposition occurs in significant amounts. Thus, there is a need to improve the sediment budget in the Middle Danube. This shall be done by improving the sediment continuity through applying a set of measures. The depositions have to be removed for the purpose of flood protection. It should be the aim to reinsert dredged material downstream of the hydropower plants in order to minimise the sediment deficit in the free-flowing Lower Danube River. A study should be performed to investigate possible further measures to reduce sedimentation, e.g. groynes or other guiding structures to increase the transport capacity, especially during flood conditions and especially in the shallow part of the reservoir. Flushing, which is already partially performed at overflow predictions nearing the value of 11,500 m^3/s, is another positive option to increase sediment continuity, if it is done in an ecologically-friendly way. Possibilities on how to improve the flushing process, e.g. timing and constructions in the reservoir, should be investigated. In a follow-up project, other potential options should be studied that improve sediment continuity and thus reduce the downstream sediment deficit.

At the same time, better knowledge of the sediment regime in the reservoirs Iron Gate I and Iron Gate II is important and we recommend to continuing the common Romanian-Serbian monitoring of the river morphology within the two reservoirs.

Recommendations for the Lower Danube, Delta and Coast

In the Iron Gate II reservoir, located between rkm 943 and 862, no sediment management measures are planned, as there is no sedimentation. However, any sediment remobilization measures performed in the upstream reservoir, e.g. flushing during high water conditions, should be performed in coordination with dam operation of this HPP to avoid sedimentation in this reservoir.

In the Lower Danube River downstream of the Iron Gate II dam, not enough data on the cross-sections is available to determine the long-term development of the riverbed. The cross-sectional analysis (starting in the 1980s and 1990s) of the development at the gauging stations shows that overall, low riverbed erosion is dominating. However, the short-term analysis, relying on more than 300 cross-section profiles for the period 2008–2017, shows deposition in relation to an overall erosion on many sectors of the Lower Danube. However, two time steps are not sufficient to come to a conclusion about erosion or deposition in detail. In addition, the flood of 2006 influenced the first time step. Thus, first of all a comprehensive specific monitoring (see chapter 4) is necessary to be able to analyse erosion and sedimentation reaches. Measures to improve the sediment regime can only be undertaken based on a profound analysis and understanding of the processes. Meanwhile, it is recommended to manage fords and bottlenecks for navigation with the least possible technical impact and to regard the overall erosional tendency. Such measures include monitoring of the riverbed and minimum dredging with a reinsertion of the sediments. It is recommended that construction measures are only taken where absolutely necessary. Every project should regard the slight erosion tendency of the riverbed with the aim to stop the erosion. An increase of the riverbed erosion would lead to enhanced side erosion and increase the pressure for river bank protection, which would affect the ecological status.

The reach downstream of the Iron Gate II dam, until the confluence of the Timok River, is unstable from a navigational point of view. This is due to the high velocities coming out of the dam and an insufficient supply of available sediment. No hard measures are planned for the future, only soft measures in form of fairway relocation and dredging, if necessary.

Further downstream, the Lower Danube flows across a wide plain and the river becomes shallower and broader, with several major islands, and the current slows down considerably. The anthropogenic interventions have impacted the river course causing physical degradation of the riverbed by erosion, increasing the number of islands and secondary branches by sedimentation. The river widens due to bank erosion, decreasing the river depth under the action of deposition processes. Several stretches along the left and the right banks of the Danube River are eroded.

In the free-flowing sections, where bank erosion occurs, different measures are recommended to be applied for short to mid-term improvements of the sediment regime. The main aim should be to stop riverbed erosion, which might enhance river bank erosion. River bank erosion contributes substantially to the sediment budget, a limitation might further increase the sediment deficit and thus increase the bed erosion. This means, riverbed and river bank development have to be thought together. In the light of the European Water Framework Directive, it is recommended to minimize bank protection, stop erosion of the riverbed and, if necessary, to apply more environmentally-friendly bank protection measures for the waterways, so-called "technical-biological bank protections" (bioengineering methods). They prevent other negative impacts from the vessel-induced flow and wave field. For this, better knowledge and good practices about the existing technical biological bank protections measures is necessary. Where needed, further measures to mitigate lateral erosion processes, always in consideration of the overall riverbed erosion and sediment deficit trend, and to improve river morphology downstream of the dam, shall be investigated.

In the free-flowing sections, where bottlenecks for navigation exist at certain locations, we recommend integrated approaches that include the overall sediment deficit and riverbed erosion as main boundary conditions. Thus, dredging should be limited and sediments re-inserted after dredging, if possible upstream. Between rkm 931 and 375, the number of islands formed and developed along the river has been increasing and the high number of fluvial islands is due to local control factors. It is recommended to perform a morphological study to investigate the island development in detail and to relate this process to bank erosion and riverbed erosion. Only such a study enables the understanding of the causes and effects of navigation bottlenecks and allows for the right conclusions to be derived. From a navigational point of view, a minimal navigation depth is necessary over the Lower Danube stretch. We recommend limiting the necessary remedial actions such as dredging to a minimum extent, keeping dredged material in the river system by moving it from one place to another. Recommendations undertaken by all Danube countries in the frame of Joint Statement on Guiding Principles - Development of Inland Navigation and Environmental Protection in the Danube River Basin should be considered in the frame of navigation projects. It is highly recommended that any navigational project that intends to improve the bottle neck situation must consider the sediment deficit and riverbed erosion. It is also important to record sediment budget changes.

On the long-term, we recommend improving the sediment continuity of the Danube River, which is no longer fed with coarser channel-forming material, except maybe from the embankments and the last kilometres of the tributaries before they enter the Danube. It is recommended to obtain better knowledge, good practices, light house projects and studies about how to increase the sediment input from the tributaries. This should be based on a regular sediment monitoring program, including bedload monitoring performed at least on the last kilometres of the tributaries. On the short- to mid-term, sediment feeding might be necessary, whereas on the long-term a study should be performed on how to optimize continuity in the impoundments and reservoirs on the main tributaries, for example by flushing, sluicing or bypassing.

Concerning the delta and coast it is recommended to increase the sediment input again by improving the upstream sediment continuity and thereby minimizing the erosion of the riverbed in the canals and the coastal erosion (GeoEcoMar, 2019). This needs to be integrated and harmonized with an optimization of engineering structures implemented in the delta at the connections between canals and natural meanders as well as at the outlet of the canals into the sea to improve the lateral distribution of the sediments.

LIST OF ABBREVIATIONS

ABS	Acoustic Backscatter Sensor
AT	Austria
BG	Bulgaria
BOKU	University of Natural Resources and Life Sciences, Vienna (Austria)
BQE	Biological Quality Element
DE	Germany
DFRM Plan	Danube Flood Risk Management Plan
DRB	Danube River Basin
DRBD	Danube River Basin District
DRBM Plan	Danube River Basin Management Plan
DSMG	Danube Sediment Management Guidance
DSS	Decision Support System
DTP	Danube Transnational Programme
ÉDUVIZIG	Észak-dunántúli Vízügyi Igazgatóság (Hungary)
ERDF	European Regional Development Fund
EUSDR	EU Strategy for the Danube Region
FRM	Flood Risk Management
HPP	Hydropower plant
HQE	Hydromorphological Quality Element
HR	Croatia
HU	Hungary
HYMO TG	Hydromorphology Task Group
ICPDR	International Commission for the Protection of the Danube River
IJC	Jaroslav Černi Institute for the Development of Water Resources (Republic of Serbia)
IPA	Instrument for Pre-Accession Assistance
IWA	Institute of Hydraulic Engineering and River Research (Austria)
NGO	Non-Governmental Organization
OBS	Optical Backscatter Sensor
PP	Project Partner
PSD	Particle Size Distribution
RBM	River Basin Management
RO	Romania
RS	Republic of Serbia
SK	Slovakia
SMS	Sediment Manual for Stakeholder
SSC	Suspended Sediment Concentration
SWMI	Significant Water Management Issue
TNMN	Transnational Monitoring Network
UNESCO	United Nations Educational, Scientific and Cultural Organization
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 Morphodynamics 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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