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Danube Transnational Programme
DanubeSediment

Long-term Morphological Development of the Danube in Relation to the Sediment Balance

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Sediments are a natural part of aquatic systems. During the past centuries, humans have strongly altered the Danube River. Riverbed straightening, hydropower dams and dikes 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.


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

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 Danube 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 (DRBMP) and the Danube Flood Risk Management Plan (DFRMP), 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.

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) Key Findings of the DanubeSediment Project
11) Danube Sediment Management Guidance
12) Sediment Manual for Stakeholders

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This report is a deliverable of the project **Danube Sediment Management** - Restoration of the Sediment Balance in the Danube River. DanubeSediment is co-funded by the European Union funds ERDF and IPA in the frame of the Danube Transnational Programme (Project reference number: DTP-1-1-195-2.1). The overall budget is 3 558 581.62 Euros, whereby the ERDF contributes 2 827 421.16 Euros and the IPA contributes 197 373.19 Euros.

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1. Introduction

The natural functioning of river systems has changed gradually over the centuries as a consequence of various human interventions. The fluvial dynamics of rivers have been disrupted by the extensive use of water in navigation, flood protection, energy production, agriculture and industry. The altered fluvial processes in regulated and dammed rivers have induced changes in the spatial distribution of river sediments, thus creating stretches with excessive bed aggradation (impoundments) or degradation (downstream of dams) and reducing the diversity of fluvial habitats and the lateral hydrological connectivity between the river channel and the floodplain. Isolated river and floodplain processes have resulted in successive morphological and ecological degradation in the ecosystems of rivers.

Since the beginning of the 19th century, the Danube River has changed dramatically as a result of systematic regulation works. Compared to its reference state (as at the end of the 19th century), the Danube channel has been narrowed and shortened to a considerable extent. The hard riverbank stabilisation have inhibited the channel’s lateral morphological development and reduced the degree of hydrological connectivity between the river and its floodplain. Hydropower dams built on the Danube have caused sediment continuity disruption, resulting in spatial and temporal changes in the sediment regime. In response to the altered sediment regime, the river bed has incised along the free-flowing stretches downstream of the dams, with sedimentation occurring within impoundments upstream of the dams. River-bed instability has been caused mainly by extensive commercial dredging (mostly in the period 1960-1990) and by the building of in-stream structures (groyne fields). Changes in the river’s morphodynamics have also led to variations in the habitat conditions over space and time. The combined effects of interventions in the Danube have caused successive morphological and ecological degradation in the river system and imposed challenging constraints on sediment management and sustainable river restoration.

The understanding of the spatial and temporal variations in the physical processes taking place in the Danube channel (flow and sediment regimes) is, therefore, considered to be fundamental for the preparation of:

- a reliable assessment of the hydromorphological changes in the river channel;
- a quantitative assessment of some components of the river’s sediment balance;
- a proposal for sediment management designed to preserve/improve the river’s water-management functions and to preserve/improve its ecological status.

The focus of this work package (WP 4.3 Long-term Morphological Development of the Danube in Relation to the Sediment Balance) is on identifying the morphological changes that have occurred in the Danube channel within various spatial and temporal scales, taking into account the main hydromorphological pressures (channel regulation, dredging, damming). This activity is described in the following chapters:

- Morphological characteristics of and physical processes in alluvial rivers – general knowledge (Chapter 3);
- Historical evolution of the Danube's river pattern (Chapter 4);
- Morphological development of the Danube channel as influenced by the main pressures (Chapter 5);
- Recommendations for long- term morphological monitoring (Chapter 6).

These chapters contain the knowledge and quantitative results that are needed to better understand the Danube River's behaviour in the context of disrupted sediment transport and other pressures affecting the sediment regime. Some quantitative results (from areas exposed to erosion/sedimentation, dredging) are used as input data for quantifying the Danube's Sediment Balance (WP 4.2 Sediment Balance Assessment) and other related activities (WP 5 Impacts and measures, WP 6 Sediment Management) of the DanubeSediment project.

2. Aims of the activity

A thorough understanding of the flow characteristics and their interaction with the river channel's geometry and planform is essential for any engineering, ecological, economic and management study involving rivers (Bathurst, 1997).

The main aims of this activity are to identify and quantify the morphological characteristics of the Danube channel and their variation within the given space (the Upper, Middle and Lower Danube, and the national river sections) and time scales (historical: from the 19th century to date (2017); long-term: from Period I (1920-1970) to 2017; mid-term: from Period II (1971-1990) to 2017; and short-term: over Period III (1991-2017) with regard to the main hydromorphological pressures (river regulation, hydropower dam construction, dredging). The river's response to these pressures (changes in the river processes) was identified and its main morphological characteristics (longitudinal profile, channel topography, river-bed sediments) assessed in quantitative terms in the context of sediment balance variation.

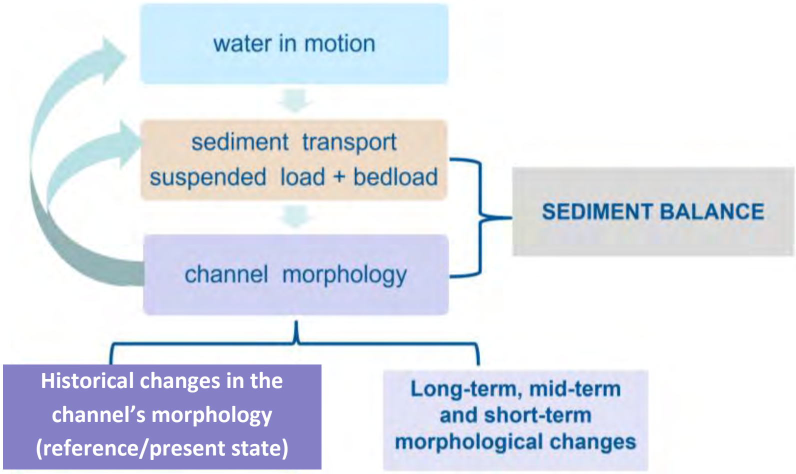

Fig. 2.1 Interconnections between the water flow, sediment transport and channel morphology in relation to the sediment balance

The interactions between the water flow, sediment (suspended load and bedload) transport and channel morphology in relation to the sediment balance are illustrated in Figure 2.1. Water and sediments form the shape of the river channel and create riverine habitats that are typical for that particular river type. The morphological changes in the river channel influence the sediment transport and flow dynamics, which are reflected in the sediment balance (aggradation – surplus, degradation – deficit) and, vice versa, any change in the sediment balance is reflected in the river channel's morphology.

Morphological changes were investigated for the following states of the Danube channel:

- ***Historical state*** – from the time before the river channel was regulated (the beginning of the 19th or 20th century) to the present time (2017). Changes in the morphological characteristics of the Danube (i.e. channel width, length, channel straightening, sinuosity index, meandering and anabranching) were analysed and quantified on the basis of historical maps depicting the reference conditions (some flood protection measures had already been implemented).

- ***Present state*** – covering **a** period of almost 100 years from the time when the first hydropower dams were built (1920) to the present time (2017); changes in the river channel's morphology were analysed for three sub-periods as ***long-term, mid-term*** and ***short-term*** changes caused by specific pressures.

Assessment of the morphological modification (hydromorphological quality of the river reaches) on the basis of an analysis of the channel-forming processes is of key importance for reliable determining of the ecological status of rivers. A thorough understanding of the river system's functioning is necessary mainly in the context of global issues associated with the climate change and the solution of ecological problems covered by implementation of the Water Framework Directive 2000/60/EC, the Nature Conservation Directives (Birds Directive

2009/147/EC, Habitats Directive 92/43/EEC, Natura 2000, Ramsar Convention), and of the Flood Directive (2007/60/EC).

The evaluation of the river's morphological evolution as a dynamic process (*process-based method*) has been recognised as an urgent need, particularly in the context of methods based on *physical habitat assessment* (static approach), which were used in many EU countries in the last decade to meet the requirements of the Water Framework Directive (WFD). In order to improve the quality of these methods and to increase their comparability between EU countries, the ECOSTAT (*WFD, CIS Working Group on Ecological Status*) has initiated activities to issue updates.

Within the scope of these activities, the revision of CEN standards on hydromorphological assessment (*EN 14614:2004, EN 15843:2010*) has commenced. The first standard on the hydromorphology of rivers (EN 14614:2004) has recently been revised and is awaiting approval via a formal voting procedure.

The evaluation of temporal and spatial changes in the Danube's hydromorphology carried out within as part of this activity provides a sound basis for assessing these changes in line with the requirements of the WFD and with the current activities of ECOSTAT.

The development of a 'process-based method' for assessing the Danube's hydromorphology was not included in the project objectives as it would have needed more time and sound knowledge of the geomorphological conditions. Therefore, only a slightly improved method based on an assessment of the '*physical habitat features'* (including some results from JDS3*)* was employed to identify the hydromorphological 'risks' in pilot stretches of the Danube (see Activity 5.2 Report *Risk Assessment Related to the Sediment Regime of the Danube*).

As the method of hydromorphological assessment used in this project leaves ***sediment transport and the related physical processes*** out of account, the following recommendations (Holubová et al, 2019) have been produced in respect of this matter (as part of Activity 5.2 *Risk Assessment Related to the Sediment Regime of the Danube*):

- A process-based method (covering sediment transport, erosion and deposition) for assessing the hydromorphological changes need to be developed; this method should provide a better understanding of the links between the river processes, their responses and the causes of hydromorphological changes, as well as a better understanding of the interactions between organisms and hydromorphological pressures;
- Appropriate spatial and temporal scales should be identified for the application of the hydromorphological assessment method developed and for the linking of processes within a hierarchical spatial framework (catchment scale approach);
- All components of hydromorphological assessment required by the WFD should be included in the process-based method applied: morphology, hydrology, physical and

riparian habitats, longitudinal continuity for both sediment transport and biota; in addition to these components, the river's floodplains should also be integrated into the hydromorphological assessment.

3. Morphological characteristics and physical processes in alluvial rivers – general knowledge

Rivers naturally adjust their shape and dimensions to the discharge and sediment load, and create habitats colonised by biota – invertebrates, macrophytes and fish that are characteristic of the particular river type (Hey et al. 1998). Biota also react to changes in the habitats as part of a continual mutual interaction. The behaviour of natural rivers described in terms of the characteristic physical processes is influenced by the type and degree of artificiality (human intervention), from the catchment area through the river valley to the river stretch concerned (catchment scale approach). A thorough understanding of these processes and responses makes it possible to diagnose the impacts and causes of the hydrological and morphological changes, thus enabling a better linkage between the biota responses. This is important for the preparation of a sound plan for sustainable restoration measures (as part of the Danube River Management Plan).

Rivers are effective erosion and sedimentation factors, playing a significant role in landscape formation over a certain time and geological period. Within the first phase of a river system's evolution, the morphological and sedimentation processes result from a complex interaction between its 'filling and emptying', while periods of stability are relatively rare. If the sediment supply available for transport decreases, the river system tends to create more stable regime conditions. During erosion and sedimentation, the characteristics of the flow regime and sediment transport vary systematically in response to spatial a temporal changes in the river channel's geometry and the grain size of bed sediments.

Rivers naturally adjust their shape and dimensions to the water discharge and sediment load. The habitats created are colonised by the invertebrates, flora and fauna (fish) that are characteristic of the particular river type, i.e. upland or lowland, sand or gravel, ephemeral or perennial river (Hey, 1997). Any change occurring in a river as a result of engineering works, or in its flow and sediment regimes as a result of land use or river regulation, may cause instability. This may lead to changes in the river channel's characteristics and may adversely affect nature conservation and the value of fisheries.

The morphological river types are determined by the type and size of bed sediments (D – sediment calibre) and by the river-bed slope (S – slope). The values of both characteristics decrease with the distance downstream (Leopold et. al., 1964). As a result of interaction between of the flow, bed sediments and river slope, a particular river type develops with characteristic bed sediments, velocity profile, sediment transport and channel roughness.

$$Qi \approx Q_s\, d_{50}$$

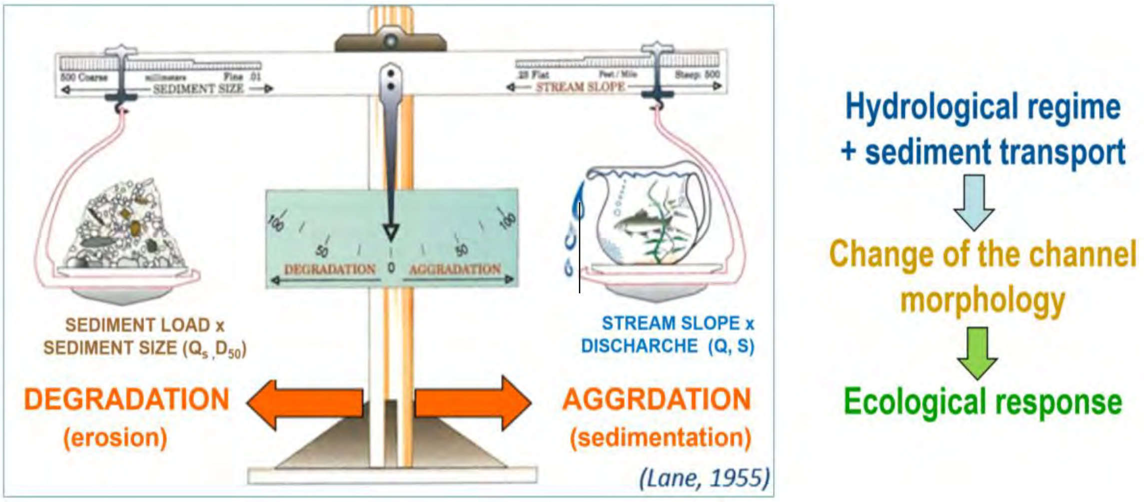

Figure 3.1 Relationship between the basic variables that determine the physical processes in rivers (Lane, 1955)

Lane (1955) proposed a generalised relationship for ‘stable channel balance’, which is illustrated in Figure 3.1. The relationship $Q_s.d_{50} \sim Qi$ indicates proportionality between the sediment load (Q_s), discharge (Q), sediment size (D_{50}) and the river-bed slope (S). A change in any one of these variables induces a series of mutual changes in the companion variables inducing a direct change in the morphological characteristics of the river.

For example, a change in sediment transport causes changes in the width, depth and bed slope of the river channel. These changes in the morphological and hydraulic characteristics affect the river’s flow capacity, as well as the capacity of sediment transport.

3.1 The flow and sediment regimes

The most important controls that determine the stability of a river channel over a certain period (years, decades) are the flow and sediment regimes. If any of these driving variables undergoes a sudden change, the river channel’s morphology may change considerably. The degree of these changes depends on the supply of sediments into the river channel from the hilly catchment area eroded by major floods.

The supply of sediments into a river channel may vary as a result of changes in the source areas: hillslopes, tributaries, or margins of the channel itself. In addition to major floods, most changes in the sediment supply relate to changes in land use within the catchment area, the most important of which are afforestation, urbanisation and mineral extraction (Werritty, 1997). In response to these anthropogenic interventions in the river system, the local sediment yields may increase by two or three orders of magnitude (Wollman & Schick, 1967).

The most significant inadvertent changes in a river’s flow regime arise from climate changes. These may have a profound impact on the river channel’s stability. Human interventions such as urbanisation and afforestation may also cause significant local increases in higher discharges with a potential impact on channel stability.

The potential impacts on short-term channel stability of changes in the flow and sediment regimes were described by Shumm (1977) in his concept of river metamorphosis. Eight possible combinations of changes in the water and sediment discharges and their impacts on channel morphology are summarised in Table 3.1.1.

In some cases, the change is accommodated by the river as part of its inherent variability. The negative feedback occurring in this case causes neither sustained channel instability nor irreversible channel changes. In other cases, the change exceeds the river's natural inherent variability and positive feedback occurs. This causes disturbance in the river channel, which leads to channel instability exceeding an extrinsic threshold. Under such conditions, river metamorphosis may occur (Shumm, 1977).

Table 3.1.1 Geomorphic impacts on river channels of changes in the flow and sediment regimes leading to river metamorphosis (Schumm, 1977)

Change	River bed morphology	Change	River bed morphology
Qs + Qw =	aggradation, channel instability, wider and shallower channel	Qs + Qw -	aggradation
Qs - Qw =	incision, channel instability, narrower and deeper channel	Q + Qw +	processes increased in intensity
Qw + Qs =	incision, channel instability, wider and deeper channel	Qs - Qw -	processes decreased in intensity
Qw - Qs =	aggradation, channel instability, narrower and shallower channel	Qs - Qw +	incision, channel instability, deeper, wider? channel

Qs – sediment discharge; Qw – water discharge; + increase; - decrease; = remains constant; ? – uncertain response.

In regard to the morphological variability of the river channel, the ***flood discharge, bankfull discharge or dominant discharge*** are of high importance. There is still ongoing discussion on whether medium-sized flows (up to bankfull discharge) occurring many times a year or very rare catastrophic floods are more effective as geomorphic agents.

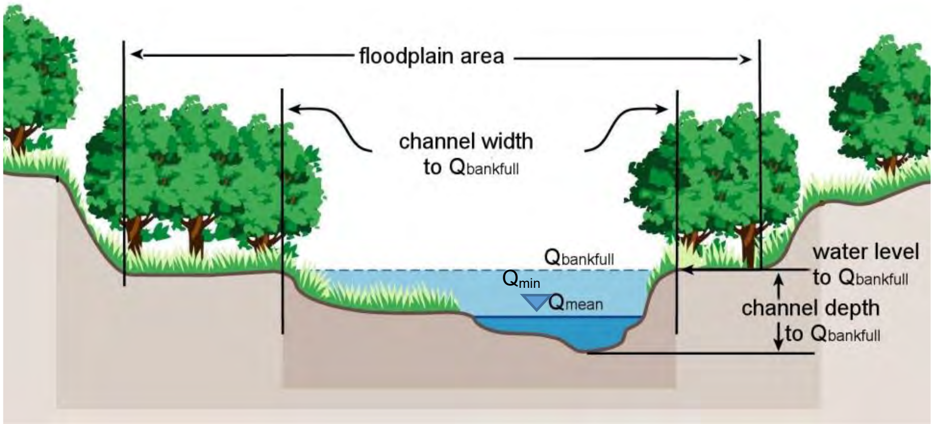

Figure 3.1.1 Delineation of the river channel for bankfull discharge (width, depth) and of the floodplain

Channel forming or dominant discharge is defined as water flow that cumulatively transports most sediments. The relations between the dominant discharge, most effective discharge and bankfull discharge were established by Knighton (1984). The dominant discharge flowing within the banks of the river channel is defined as the bankfull discharge. This discharge delineates the river channel for which the morphological parameters are estimated (width, depth – channel variability w/d). Changes in the bankfull discharge within a certain time period indicate changes in the channel's morphology (erosion/deposition), hence its value can be used as an indicator of hydromorphological changes.

In quantitative terms, bankfull discharge (Q_b) is usually defined as discharge with a return period of 1.5 to 2 years (Dunne & Leopold, 1978). This is, however, a simplified approach and the real value of bankfull discharge may differ considerably, depending on the river's physiogeographical and hydrological conditions. Therefore, precise quantification of the bankfull discharge requires a deeper insight into the river's hydrological regime, channel topography, and sediment transport.

Medium discharges with a high frequency of occurrence are more effective in the context of cumulative sediment transport than major floods with a low frequency (Wolman & Muller, 1960). This is illustrated in Figure 3.1.2, where the curves A and B are plotted separately, and then jointly (curve C). Thus, the two processes must be discussed individually:

- The ***sediment transport rate*** once the threshold of motion has been exceeded (typically a power function): ***magnitude***
- The frequency of occurrence of discharges of varying magnitude: ***frequency***

Where the threshold of motion is relatively low, the peak of the curve defining the product of magnitude and frequency (curve C) typically occurs at middle-range flows. This led Wolman & Miller (1960) to conclude that, low-magnitude events are more important than rare floods in terms of the cumulative magnitude of sediment transport. They identified some limitations, too.

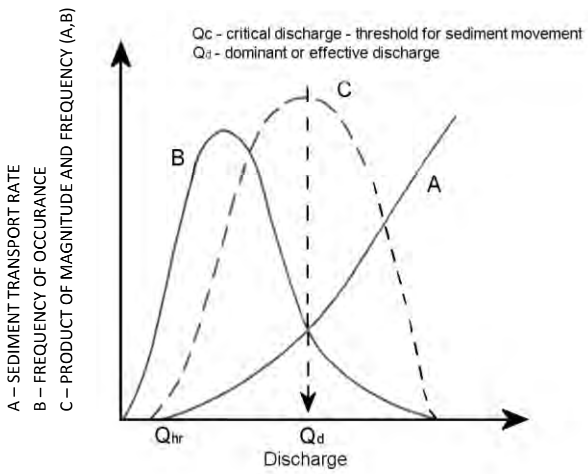

Figure 3.1.2 Hypothetical magnitude and frequency distribution curves showing the dominant role of middle-range flows (Kinghton, 1984)

The frequency and magnitude of flood discharges are very important, not only as geomorphic agents (changes in the river pattern, floodplain deposition) but also from the viewpoint of floodplain ecology. Periodic inundation and drought (flood pulse) support the lateral exchange of water, nutrients and organisms between the main river channel (or lake) and the connected floodplain (Junk et al., 1989). The annual flood pulse is the most important aspect and the most productive feature of a river´s ecosystem in biological terms, describing the movement, distribution and quality of water within that ecosystem and the dynamic interaction between water and land in the transition – aquatic/terrestrial transition zones.

A thorough understanding of the flow characteristics and their interaction with the river channel’s geometry and planform is essential for almost any engineering, ecological, economic or management study involving rivers. Through flow characteristics, such as average depth, maximum depth, mean velocity and secondary circulation, they are all determined by the channel’s properties such as cross sectional shape, long channel slope, river-bed and bank material size distribution, and riparian vegetation, while these properties are in turn modified by the flow characteristics (Bathurst, 1997).

3.2 Continuum of the channel pattern

River channel morphology – channel form (channel size, cross-sectional shape, longitudinal profile and channel pattern) is determined by geomorphological processes such as sediment transport, erosion and deposition, which take place within certain constrains imposed by the geology of the catchment area. Thus, the sediment regime of a river should be regarded as a continuum of sediment supply, transfer and storage, in both the *catchment area* and the relevant river stretch. Shear & Newson (1991, 1993) illustrate the ‘knock-on’ effect of a large sediment input in the uplands and the effect of increased sediment transport downstream.

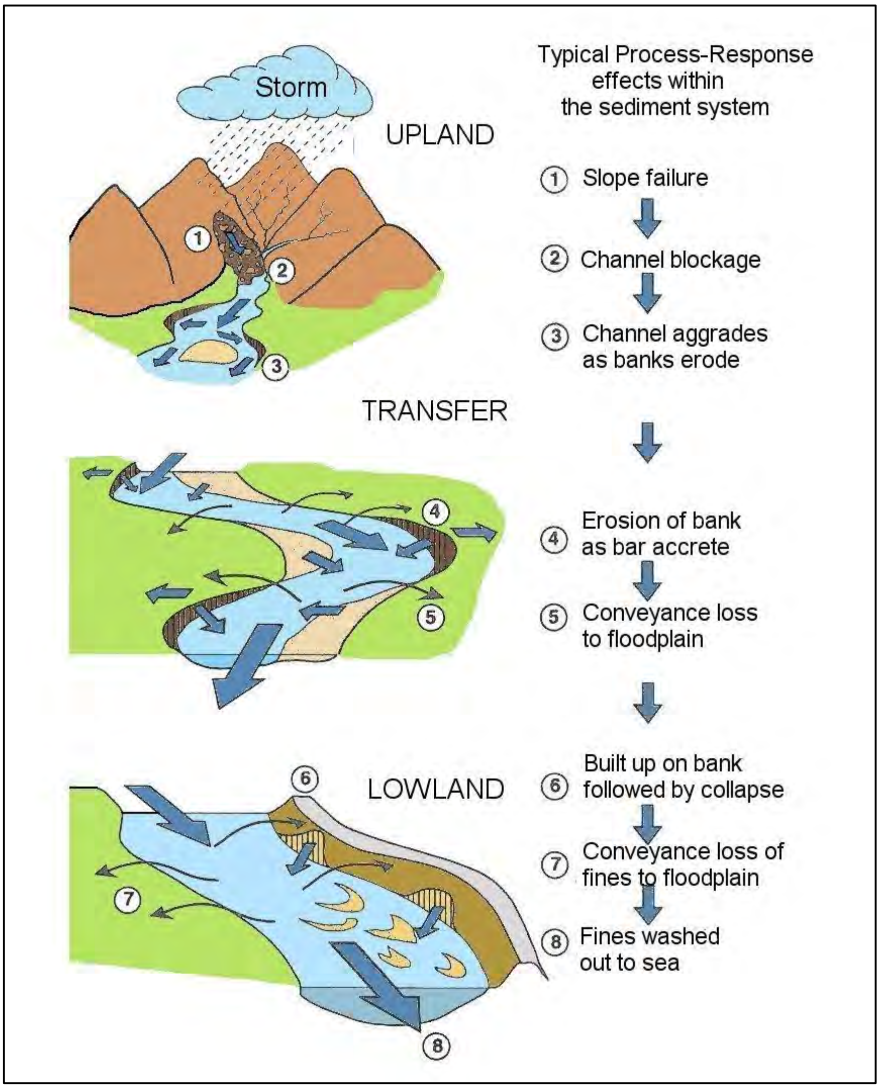

Figure 3.2.1 Typical process-response effects within a fluvial sediment system (Shear & Newson, 1993)

In Figure 3.2.1, Shear & Newson (1996) illustrate the effect of a large sediment input into the river system from the upland section and the response effects of increased sediment supply in the lower stretches. A large sediment input caused by slope failure (1) from the upland section creates channel blockage (2), the sediments are transported further downstream and the channel aggrades as a result of riverbank erosion (3). In the middle section, bars are formed by bank erosion (4) and the conveyance of fine sediments to the floodplain (5). In the lower section, the sediments built up on riverbanks are released into the channel in response to the bank's collapse and create islands/channel bars (6) and conveyed back to the floodplain (7). The finest sediments are transported into the sea (8).

The continuum of the channel pattern is also reflected in the geomorphological evolution of the river's longitudinal profile. Thus, the river processes taking place within the river system produce typical morphological characteristics for the river channel in its upper, middle and lower sections. Figure 3.2.2 illustrates the division of the river's longitudinal profile into three typical sections – the upper valley (close to the source), the middle transitional section, and the lower section (near the delta). The typical processes – responses within the sediment system are briefly described here but more details are available in the report: *Data analyses for the sediment balance and long-term morphological development of the Danube,* Chapter 2.1.

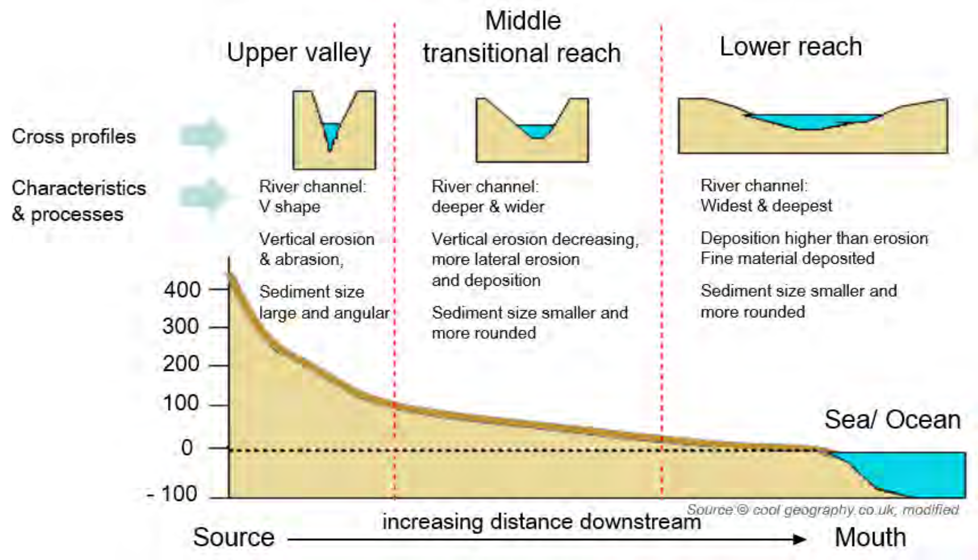

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Figure 3.2.2 Typical sections of an alluvial river's longitudinal profile and the corresponding channel shapes

Figure 3.2.3 Examples of river channels in the upper and lower sections

In the upper valley, vertical erosion dominates, creating a narrow, relatively shallow V-shaped channel cut into the ground, with a steep gradient. Large amounts of coarse sediments produced by erosion in the upper valley and in the channel itself, are transported downstream. Vertical erosion decreases, while lateral erosion and deposition in the river channel prevail in the middle transitional section, hence the sediment load is lower there. The river channel is wider and deeper with a moderate gradient. There are more balanced sedimentary conditions in the transitional section, hence the erosion and deposition processes are in dynamic equilibrium. A wide and deep river channel with a gentle gradient is typical for the lower section, where lateral erosion (bank erosion, collapse) and channel sedimentation (the formation of islands and bars) dominate in response to the reduced sediment transport capacity.

Thorne (1997) described the differences and interactions between the *driving variables, boundary conditions and channel forms* of river systems as follows: streams are constantly evolving and accommodating to the flow conditions (normal flow, flood flow, drought), which are associated with the regional climate, local weather and hydrological conditions. In this respect, the channel form can be explained rationally only if distinctions are made between the factors that drive the fluvial system ***(driving variables)*** in forming the river channel, those defining the physical boundaries within which the channel is established ***(boundary conditions),*** and those responding to the driving and boundary conditions to define the river channel's three-dimensional geometry ***(channel form)***.

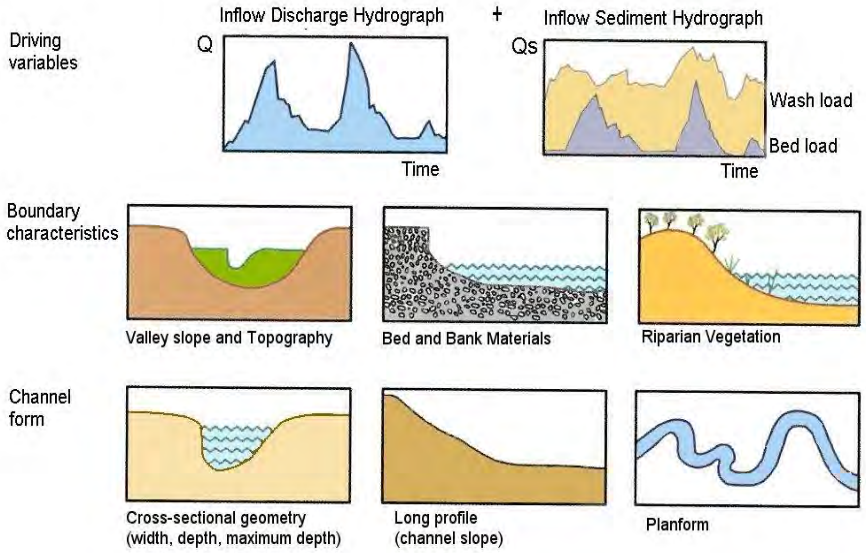


Figure 3.2.4 Interactions between the independent and dependent controls of channel form in a fluvial system (vertical and lateral), (Thorn, 1997)

- ***Driving variables: water flow and sediment transport*** *(bedload, suspended load),* i.e. variables determining the processes that form the river channel within the fluvial system
- ***Boundary characteristics – characteristics of the river channel:*** *valley slope and topography, river-bed and bank materials, riparian vegetation,* i.e. characteristics of the physical conditions in which the river channel is situated.
- ***Channel form:*** *cross-sectional geometry (width, depth, maximum depth), longitudinal profile (channel slope) and planform,* i.e. factors resulting from the interactions between the driving variables and boundary conditions, which shape the channel's spatial geometry.

The interactions between the driving variables within the boundary conditions produce the characteristics of channel morphology in unconfined alluvial rivers. Both inputs values, i.e. water and sediment, are highly variable in time. The balance between water and sediment inputs controls the channel aggradation or degradation tendencies. For the purpose of channel classification, both input values (water and sediment) can be considered as driving variables independent of the river channel's morphology.

Water and sediment interact with the landscape in forming the river channel. In this respect, the landscape can be defined in terms of the characteristics of the terrain and channel material (river-bed and bank sediments) in which channel is formed. These comprise ***valley topography, valley slope, bed and bank sediments, and riparian vegetation.***

River-bed and bank materials control the erodibility of the channel's boundaries. There is a significant distinction between channels formed in bedrock and those formed in alluvium. Channels formed in sediments that can be eroded, transported and deposited by the flow of water are classified as self-formed or ***alluvial.*** The nature and form of these channels are being constantly adjusted by the flow and their dimensions obey the laws of hydraulic geometry or regime theory, which are transferable to some extent between the fluvial systems of various scales and geomorphological locations (Thorne, 1997).

In characterising a river channel, a distinction should also be made between ***confined and unconfined channels***. A river flowing through a narrow valley tends to interact with the valley sides. Fluvial and hill-slope systems are closely connected. A considerable amount of debris from the valley-side processes is supplied into the river channel under these conditions, hence the channel's morphological evolution can be ***confined*** by the valley sides in two ways:

- In the case of channels formed in consolidated materials such as rock, the bed and banks of which are from erosion-resistant materials, morphological development is restricted by the rock valley.
- In the case of channels formed in unconsolidated materials such as rock fragments, mass failures may deliver large amounts of sediments that cannot be transported downstream and the channel's lateral development is restricted by the interaction between the valley sides.

Unconfined rivers flowing through wide alluvial valleys in channels the bed and banks of which are from unconsolidated erodible sediments do not interact with the valley sides but wander laterally within the floodplain, hence their morphological evolution is not restricted within the floodplain.

Where a river flows across a wide floodplain bounded by a rocky hill on one side of the valley, the lateral morphological development of the river channel is restrained by the rocky hill on one side, but the channel can move laterally within the unconfined floodplain. Such channels are defined as ***partly confined;*** they can wander from the confined side of the valley to the unconfined floodplain.

Floodplain and bank vegetation is an important factor determining the erodibility and stability of the channel's boundaries. It affects the balance between the erosive power of the water flow and the erodibility of the boundary materials that determine the rate and direction of channel changes and the ultimate, stable shape of the channel.

The action of the driving variables (i.e. water and sediment) on the boundary conditions given by the actual floodplain topography, bed sediments, bank materials, and by the riparian vegetation, determines the morphological characteristics of an unconfined alluvial channel.

3.3 Chanel morphology – channel pattern, river types

For the geomorphological classification of channel types, quantitative links have been established between the river processes and the shape and stability of river channels. Thus, the river pattern can serve as a good indicator of the river processes and of their intensity.

Various systems can be found in literature (Leopold & Wolman, 1957; Schumm, 1977; Rust, 1978) for classifying channel patterns according to their morphological characteristics. Most of them assume a continuum of planform patterns using various combinations of geomorphological features for the river channel and/or river processes (sediment load, channel stability) to classify the river type. The general relationship between sediment load and channel stability/shape was first defined by Schumm (1977). The classification shown in Figure 3.3.1 grades from straight, through meandering, to braided channels.

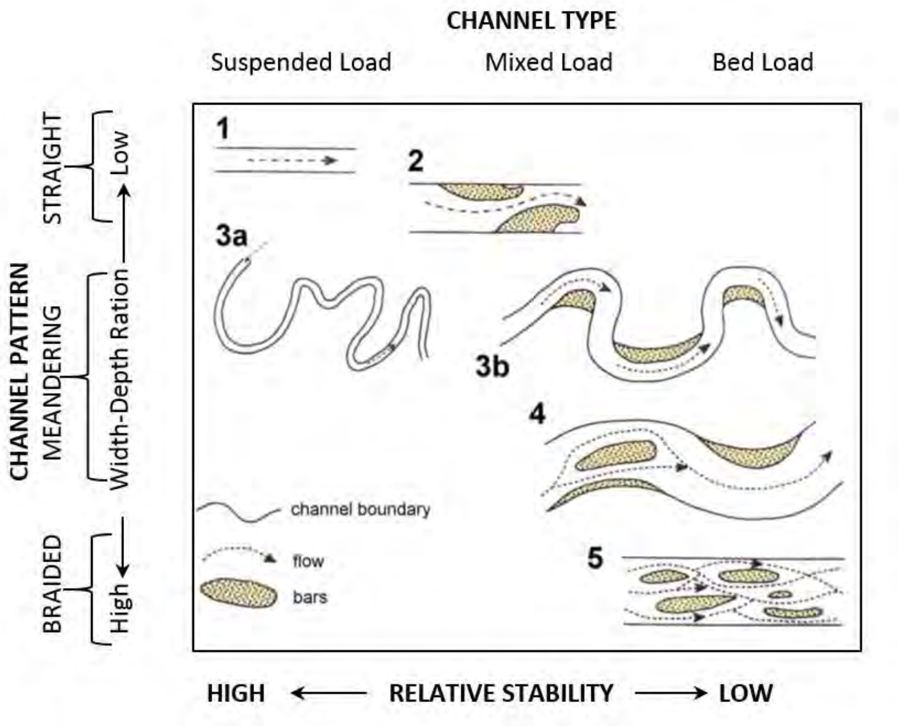


Figure 3.3.1 Classification of river types based on the relationship between sediment load and channel stability (Schumm, 1977)

Rust (1978) proposed another quantitative diagram for the continuum of channel patterns, using sinuosity and the degree of channel division as its axes and allowing divided rivers to be subdivided according to their sinuosity (Figure 3.3.2). The shapes and features of low- energy anastomosing river channels are currently regarded as sufficiently different from conventional high-energy braided river systems to merit separate classification (Nanson & Croke, 1992).

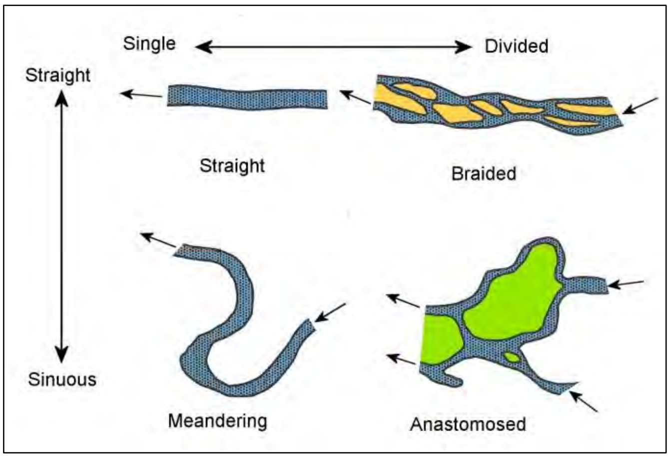


Figure 3.3.2 Classification of the channel pattern according to sinuosity and the degree of channel division (adopted from Rust, 1978)

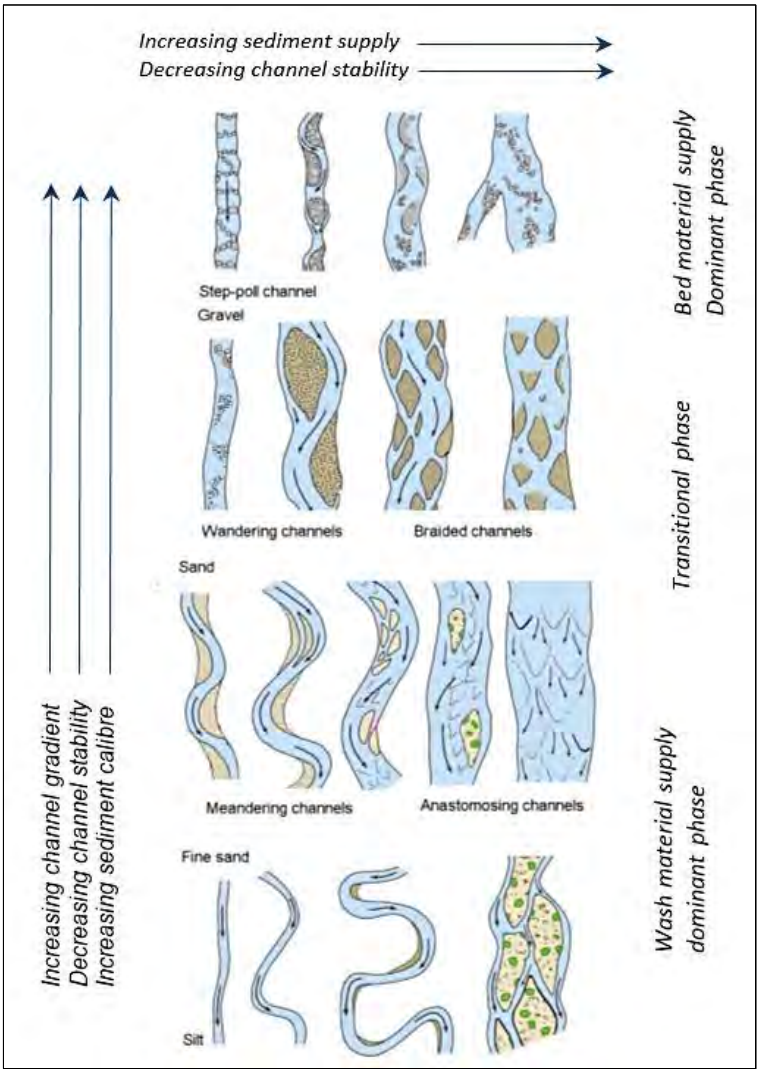


Figure 3.3.3 Channel types – diagram showing the relationship between the shapes of alluvial river channels and the main governing factors (Church 1992, modif ied in 2006), based on the concept by Mollard (1973) & Schumm (1985)

For a geomorphological analysis of alluvial river channels, it is useful to consider channels separately according to whether the channel at formative discharges is straight, meandering, braided or anastomosed. These four classes form a background for numerous other more extended stream classification systems (e.g. Mollard, 1973; Schumm, 1985; Church 1992; Rosgan 1994; Rinaldi et al. 2015). A classification system designed specifically for mountain rives by Montgomery & Buffington (1997) includes five categories: A – cascade; B – step-pool; C – plane bed; D – riffle-pool; E – dune-ripple.

A more comprehensive classification system for channel patterns was devised by Church (1985), on the basis of a concept developed by Mollar (1973) and Schumm (1985). This system classifies the types of rivers according the bed material, gradient, sediment supply, and the river channel's stability (Figure 3.3.3).

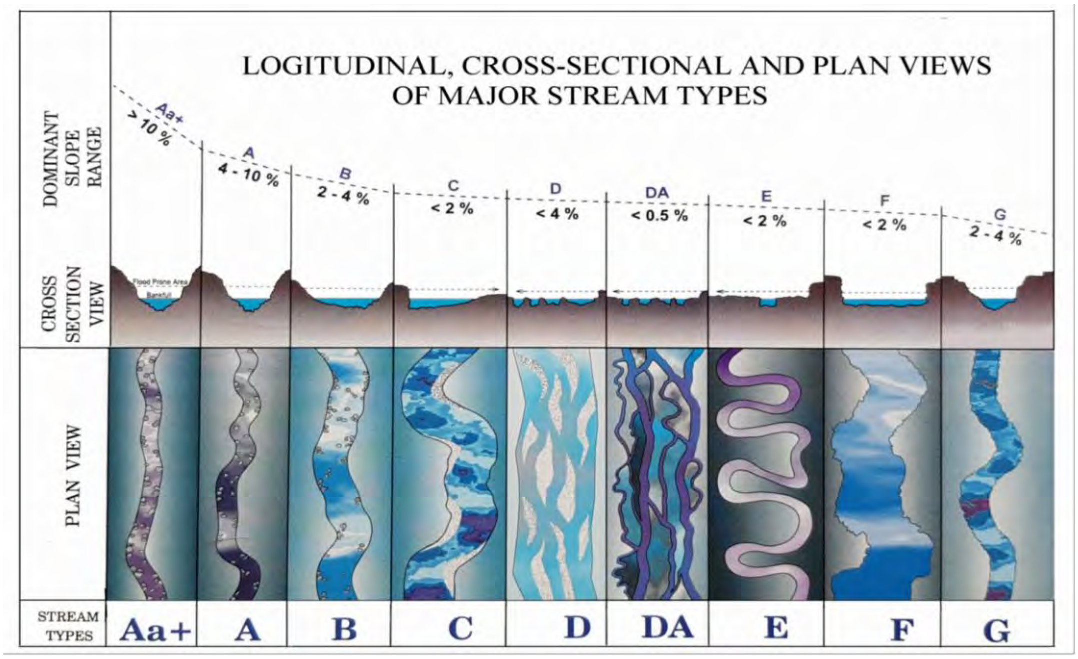


Figure 3.3.4 Rosen's morphological classification system – seven basic types of river channels and the corresponding morphological characteristics – gradient (modified by Rosgen, 1996)

The most comprehensive classification system developed by Rosgen (1996) divides rivers into seven basic types according to the degree of their entrenchment, gradient, width/depth ratio and sinuosity (Figure 3.3.4). In addition to these seven basic types, Rosgen divided each category into six subcategories according to the dominant type of bed and bank materials (94 subtypes in total). The result is a comprehensive classification system, but its proper application requires in-depth knowledge of the geomorphological conditions, as well as practical experience. Rosgen´s system of semi-quantitative holistic morphological classification incorporates all three dimensions of the river channel, and takes into account the differences in the channel-forming materials, too. This approach, combining a qualitative description with the quantitative parameters in the definition of channel types, represents, without doubt, the way forward. However, Rosgen´s method does not represent the final classification system.

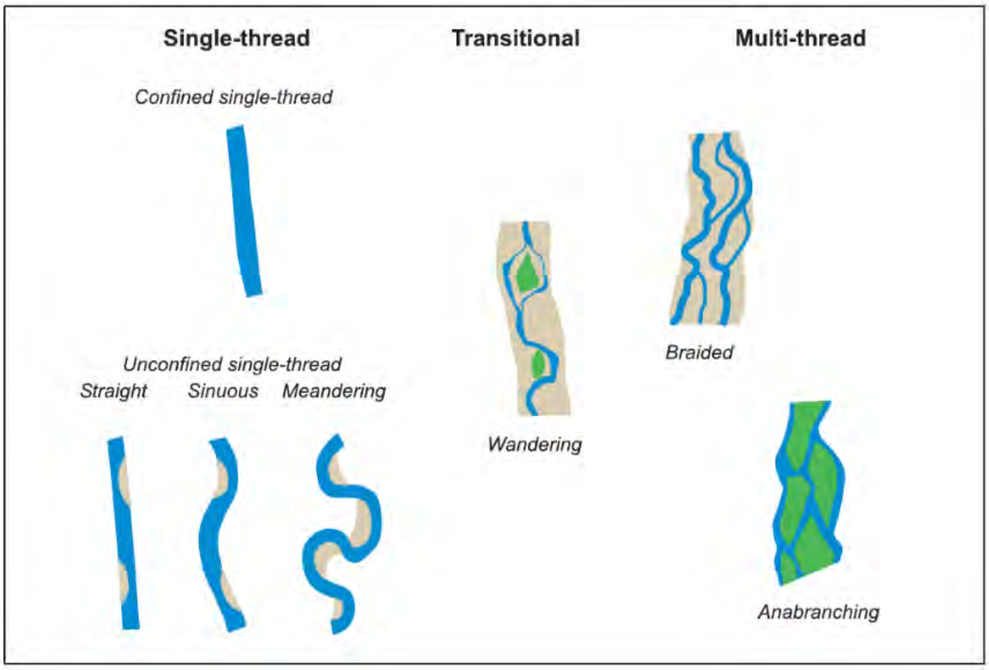


Figure 3.3.5 The seven main morphological types based on confinement and planform
(Rinaldi et al, REFORM, 2014)

A simple system for classifying rivers (Figure 3.3.5) according to the river channel's planform (number of threads and planform pattern), framed in the context of valley settings (degree of confinement), was presented within the REFORM project (2014). This channel typology defines seven basic river types. On the basis of this typology and the results of previous geomorphological surveys (Schumm,1985; Rosgen, 1995; Knighton & Nanson, 2013; Nanson & Knighton, 1996; Church, 1992), an extended river typology has been devised for practical application.

The extended typology covers the typical relationships between the channel pattern, bed sediment calibre and the geomorphic units, framed in context of different valley settings. This typology, based directly on the simple river classification system, provides more detailed information on the river stretch concerned. However, some of the river types are subdivided where there is a clear distinction within the same simple morphological type, reflecting different bed material calibre and/or morphological units (e.g. different bed material or bed configuration sub-types in confined single-thread river stretches; change from a straight/sinuous channel with continuous bars to a straight/sinuous channel with sporadic or absent bars).

There are twenty-two morphological river types plus one type (0) for greatly altered river stretches – artificial channel (Figure 3.3.6, Table 3.3.1), classified according to their confinement (confined, partly confined, unconfined), dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt), and planform (straight-sinuous, meandering, pseudo-meandering, wandering braided, island-braided, and anabranching).

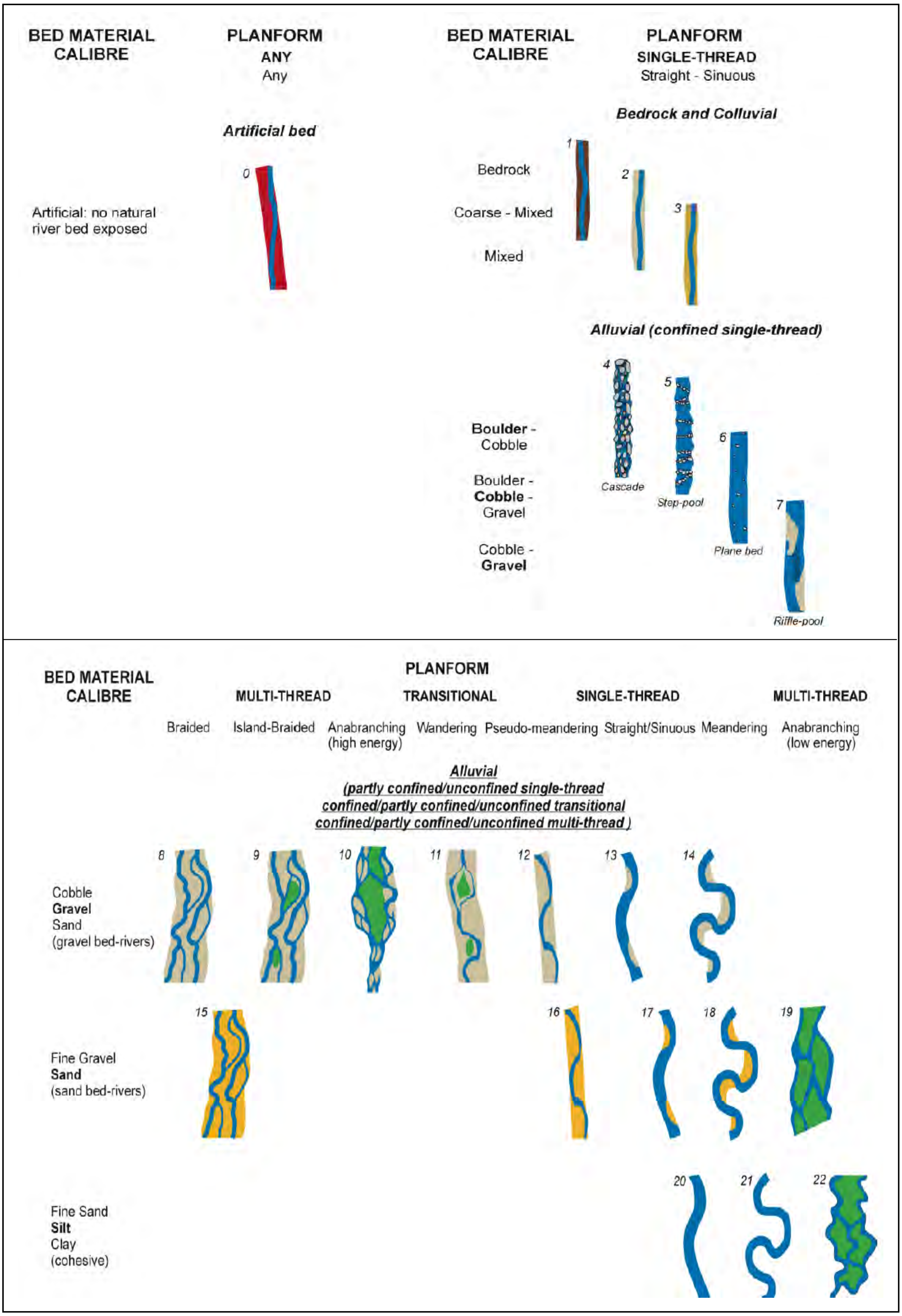


Figure 3.3.6 Extended morphological typology (22 river types) according to Rinaldi et al. (REFORM, 2015)

Table 3.3.1 Main characteristics of the 22 morphological river types identified on the basis of the extended river typology (ERT) and the corresponding basic river type (BRT); confinement: confined (C), partly confined (PC), unconfined (UC); and the typical bed slope

ERT (BRT)	**Confinement class**	**Bed material calibre**	**Planform**	**Typical slope (m.m^{-1})**
Bedrock and colluvial channels				
1 (1)	C	**Bedrock**	Straight-sinuous	Usually steep
2 (1)	C	**Coarse mixed**	Straight-sinuous	Steep
3 (1)	C	**Mixed**	Straight-sinuous	Lower than ERTs 1 and 2
Alluvial channels				
4 (1)	C	**Boulder**	Straight-sinuous	>> 0.04
5 (1)	C	**Boulder**, cobble	Straight-sinuous	> 0.04
6 (1)	C	Boulder, **cobble**, gravel	Straight-sinuous	> 0.02
7 (1)	C	Cobble, **gravel**	Straight-sinuous	> 0.01
8 (6)	C, PC, U	**Gravel**, sand	Braided	< 0.04
9 (6)	C, PC, U	**Gravel**, sand	Island-braided	< 0.04
10 (7)	C, PC, U	**Gravel**, sand	Anabranching (high energy)	< 0.01
11 (5)	C, PC, U	**Gravel**, sand	Wandering	< 0.04
12 (3)	C, PC, U	**Gravel**, sand	Pseudo-meandering	< 0.04
13 (2/3)	PC, U	**Gravel**, sand	Straight-sinuous	< 0.02
14 (4)	PC, U	**Gravel**, sand	Meandering	< 0.02
15 (6)	C, PC, U	Fine gravel, **sand**	Braided	< 0.02
16 (3)	C, PC, U	Fine gravel, **sand**	Pseudo-meandering	< 0.02
17 (1/2)	PC, U	Fine gravel, **sand**	Straight-sinuous	< 0.02
18 (4)	PC, U	Fine gravel, **sand**	Meandering	< 0.02
19 (7)	C, PC, U	Fine gravel, **sand**	Anabranching (low energy)	< 0.005
20 (2/3)	PC, U	Fine sand, **silt**, clay	Straight-sinuous	< 0.005
21 (4)	C, PC, U	Fine sand, **silt**, clay	Meandering	< 0.005
22 (7)	C, PC, U	Fine sand, **silt**, clay	Anabranching (low energy)	< 0.005

The following circumstances should be considered when the extended river typology is used:

- The river typology has been extended to cover the naturally functioning river types (reference or pristine conditions).
- Straight and sinuous river types are combined in the extended typology's definitions and descriptions, because both planform types are related to similar morphological units in the case of similar bed material and level of confinement.
- A new transitional river type has been added to the extended typology: that of pseudo-meandering rivers. This type is linked to straight or sinuous channels with large, alternate bars at low discharges. While a bankfull channel is a straight or sinuous channel as a rule, a low-flow channel is so heavily affected by the exposure of alternate bars that it can be classified as a meandering river channel, provided that the Si index meets the relevant criteria. Pictures on Figure 3.3.7 show some selected river types.

Figure 3.3.7 Examples of various morphological river types

Adjustment-based classifications differ substantially from morphology-based classification systems in that they require the person performing the classification to determine the current nature of the channel-adjusting processes. While historical records of the types, trends and rates of channel changes are very useful in determining the current situation, such information is not always available. Even in the case of ongoing changes in the catchment characteristics, alterations in the river channel’s management or complexity in response to the fluvial system often indicate that changes from the past are not representative of the current or future adjustments (Downs & Thorne, 1996). For these reasons, the practical application of the classification system requires engineers or scientists who are able to understand the channel-forming processes. Their evaluation requires careful observation combined with an insight into the links between these processes and their interpretation in qualitative terms (Thorne, 1997).

Summary: In morphological classification, adjustments may provide important information on the type and morphological parameters of a river channel (e.g. channel width, channel straightening) and on the prevailing river processes. This is particularly important as a basis for determining the current situation and the degree of channel modification (deviation from the natural functioning of the river system).

This approach was used to identify the channel types along the Danube. The channel types and rates of channel changes were evaluated on the basis of an analysis of the historical maps (pristine or reference conditions). The extended morphological typology was applied for this purpose (Rinaldi et al., 2015; Figure 3.3.6, Table 3.3.1).

A detailed analysis of the morphological characteristics needed for proper classification (e.g. confinement, sinuosity, degree of braiding or anabranching, and bed material calibre) was carried out prior to the classification of the channel types in different reaches of the Danube.

In line with the revised CEN standards for *Hydromorphological assessment (EN 14614:2004),* the following definitions of channel characteristics and methods of calculation were used:

Sinuosity: for **a** river reach with a single channel, sinuosity can be assessed by calculating the ***sinuosity index (SI),*** which is the ratio of length along the centre line of the river channel to the length of the broad river channel or river valley within a reach unit. Reach units can be delineated, for example, according to whether the channel is ***straight (SI < 1.05), sinuous (1.05 < SI < 1.5), or meandering (SI > 1.5).***

Degree of braiding: for a single channel or a network of many channels separated by small, often temporary (mostly gravel) islands called braid bars, the degree of braiding can be assessed by calculating the ***braiding index (BI),*** which is the average number of distinct channels counted at 10 equally-spaced cross sections of the river under low-flow conditions. River reach units can be delineated, for example, according to whether the channel has a ***single thread (BI = 1), wandering (1 < BI < 1.5), or multi-thread (BI > 1.5)*** pattern.

Degree of anabranching: for a river reach with more than one channel separated by fully vegetated areas rather than by bare or sparsely vegetated sediments, the degree of anabranching can be assessed by calculating the ***anabranching index (AI),*** which is the average number of distinct channels separated by islands, counted at 10 equally-spaced cross sections of the river under low-flow conditions. Multi-thread river reach units can be delineated, for example, according to whether or not the channel has an anabranching (*AI* > 1.5) pattern.

River-bed sediment size: River-bed sediments need to be characterised in terms of size for the use of the extended morphological classification. Geomorphic units need to be characterised, too, for the assessment of their functioning. The grain size of bed sediments represent another useful criterion for the delineation of the river reach concerned. The typical grain size of sediments found in the river bed can be used to delineate the reach units, according to whether they flow predominantly over bedrock, boulders, cobbles, gravel, sand, silt or clay.

The results of the Danube channel's classification for particular river reaches are included in Chapter 4 of this Report.

3.4 River bed sediments and their characteristics

Water flow and sediments in motion (suspended load and bedload) drive the fluvial system (driving variables) in forming the river channel and bed sediments characterise the physical boundaries within which this channel is established. Since transported sediments (suspended load and bedload) are defined and described in the final report from WP3: *"Analysis of Sediment Data Collected along the Danube"*, increased emphasis on bed sediments is placed only in this part of the report.

A variety of characteristics concerning bed sediments, bed features, longitudinal continuity disruption, and evidence of recent and contemporary changes provides a picture of the nature of the river bed, and where historical information can be obtained, makes it possible to construct the temporal trajectory of changes.

The key characteristics of the bed material in the river channel are as follows:

- Bed sediment size (bedrock, boulder, cobble, pebble, gravel, sand, silt, clay, peat);
- Bed sediment features/units – spatial arrangement of bed sediments, which act in some forms as a complex on the river bed (e.g. waterfall, boulder step, cascade, rapid, bar (mid-channel, point, counterpoint, scroll, etc.), chute, riffle, pool, dune;
- Bed sediment structure representing the composition of the river bed, which may indicate transport, sorting and deposition processes (e.g. armouring, infiltration by silt-clogging).

a) Boulder, cobble bed river *b) Coarse gravel bed river*

c) Medium and fine gravel bed *d) Coarse and medium sand bed*

Figure 3.4.1 Bed sediments in upland (boulders and cobbles), midland (gravel and sand) and lowland rivers (sand, clay)

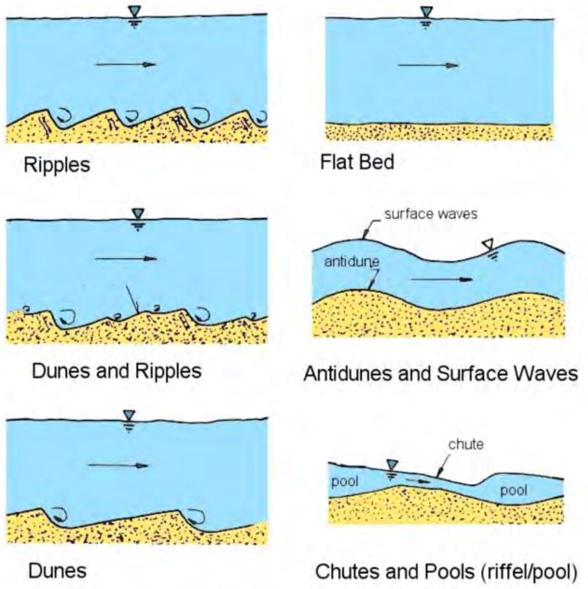
Downstream fining: The composition and arrangement of individual bed sediment particles form the river bed. Both the composition and arrangement of bed sediments vary systematically along the river in the downstream direction. Coarse sediments transported form the upper river valley become progressively finer in the downstream direction reaching a base-level. The downstream-fining 'law' was first formulated by Sternberg in 1875. Since that time, the importance of fining as a diagnostic tool used by geomorphologists in examining the fluvial processes has increased. Although this phenomenon is widely dissected in literature, there is still considerable controversy over the mechanisms of downstream fining. This is connected with the long-term nature of the processes involved and with our inability to establish records of suitable length and our incomplete knowledge of the ways in which sediments are transported downstream. The problem is compounded by the fact that the rate of downstream fining vary considerably between the channel types and in different geomorphological environments. Notwithstanding this, the rate of change in the calibre of bed materials has an important implication for downstream changes in flow resistance and sediment transport, hence it cannot be ignored in river management (Reid at al., 1997).

Armour layer: vertical variability that is characteristic of *gravel-bed river channels* has mostly local importance. Armouring occurs on the bed surface when selective entrainment of smaller, more unstable particles leave the river bed with an average surface gravel size larger than that of the underlying river bed. Thus, the armour layer, which may develop on the bed surface under specific flow and sedimentary conditions, is generally coarser than its substratum. The armour layer of the gravel bed consists of cluster formations, where small and medium-sized particles congregate around the larger particles to form more stable structures (Brayshaw et al., 1983). The armour layer is a layer of sediments with an average grain size larger than that of the underlying river bed. Not all the particles in the surface layer of the bed will be entrained at the same time, owing to flow turbulence, sediment grading, and the resulting fluctuation of hydrodynamic forces (Reid et al., 1997).

Armour layers that often develop in river reaches effected by degradation (downstream of barriers) create a river bed that is more stable and more resistant to disruption. Thus, bed sediments are set in motion by higher discharges (hydrodynamic forces) that disrupt the armour layer of the river bed, but then larger volumes of bed sediments are transported as the subsurface layer consists of finer sediments.

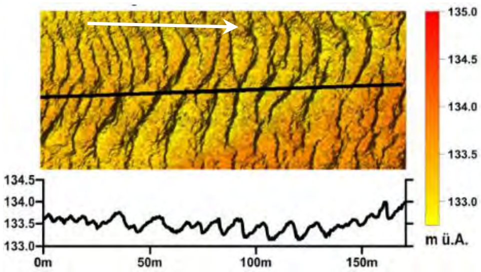
Infiltration of silt (clogging): after a prolonged period of no sediment transport, the bed material has time to become consolidated. The infiltration of fine, particularly cohesive sediments into coarser sediments may produce a powerful cementation effect. As a result of interaction between the surface and ground waters may be disconnected. Clogging usually occurs in river reaches exposed to sedimentation, in response to a decrease in the flow dynamics.

Microforms (bed forms): Free surface flow over an erodible sand river bed generates a variety of microforms (pebble clusters, dunes, ripples, antidunes) and configurations (arrays of bed forms). The type of bed configuration and the dimensions of bed forms are dependent on the flow and bed material characteristics. These have an impact on flow resistance and sediment transport. In gravel bed rivers, the most frequent microforms are pebble clusters and dunes, which may develop in large gravel bed rivers with intense bedload transport. Other repeating microforms are transverse ribs, clast dams and steps (Koster, 1978; Bluck, 1987; Whittaker & Jaeggi, 1982). The main microforms in sand bed rivers are ripples and dunes. Their formation depend on the flow characteristics and the grain size. All microforms have an impact on the water flow as they increase the roughness of the river bed. Increased flow resistance causes a certain decrease in the flow velocity and an increase in the water level. Bed forms increase the variability of channel habitats creating appropriate biological conditions for fish and other aquatic species (e.g. zones of accelerated or decelerated flow, spawning sites).



a) Bed forms (Manual, ASCE, Vanoni,edt, 1975)

b) Ripples in sand river bed



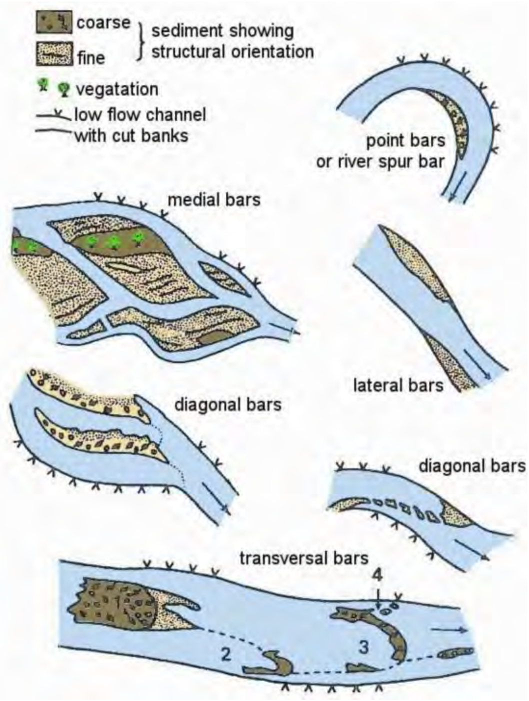
Picture by Gmeiner et al., 2016

c) Dunes in the Danube in Austria

Figure 3.4.2 River-bed forms: a) bed forms according to Vanoni (1975), b) sand river bed (ripples), c) gravel river bed of the Danube in Austria (dunes)

Selection of a sampling site: Bed sediments that act as isolated grains are characterised by their physical properties (grain size and shape), which are highly variable – both laterally and longitudinally. Therefore, the sampling sites should be pre-selected according to satellite images taking into account the river's type and typical features, as well as its tributaries. The final selection of the site should be refined in a field survey. Sediment sampling sites should be selected in view of the ongoing river processes and the morphological type of the river (bed material composition), so that sediment sampling is representative and covers the key sites of the river stretch concerned. Where possible, it is necessary to take samples not only from the top or side benches (surface and subsurface layers), but also from the stream (using a boat). An experienced fluvial morphologist is able to identify the bottom structure in a field survey, i.e. the cover layer (erosion) or the bottom's perpendicularity (sedimentation of fine-grained sediments) that directly identify the ongoing processes in the channel. If this information cannot be obtained directly in the field, details about the flow processes can be obtained by analysing the grain size distribution curves. The sampling method is chosen according to the specific options and output requirements. The methods of bed sediment sampling are described in more detail in WP 4.1. Report “*Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube”.*

Channel bars usually develop in river channels with excessive sediment load (gravel or sand), where the dominant process is aggradation. Various types of channel bars (Figure 3.4.3), including medial, transversal, longitudinal, crescentic and diagonal point bars, and the combinations thereof (Church & Jones, 1982), are typical for certain river types, particularly those with large sediment inputs, e.g. braided and anabranching rivers. Point bars formed on the inner sides of channel bends are also typical for meandering or sinuous rivers.



a) Types of channel bars (Lewin, 1978)

b) Diagonal gravel bar – Hron, Danube´s tributary

c) Longitudinal bar in the Danube at Štúrovo

Figure 3.4.3 Types of channel bars: a) according to Lewin (1978), b) diagonal gravel bar in the Hron River; c) longitudinal bar in the Danube at Štúrovo

Braided river systems have a higher slope, sediment supply, stream power, shear stress and bed load transport rate. Multiple stream channels of braided rivers are separated by braid bars, which are unstable and unvegetated in most cases, and they frequently change their shape and location.

Anabranching or anastomosing river channels also create channel bars, which are, however, vegetated as a rule, and are stable over a longer period then bars in braided rivers. A bar´s location is determined on the basis of the channel’s geometry and the flow conditions.

Specific channel bars occur at the confluences of rivers and their bifurcation into branches, where the channel curves and the bars have a range of forms with various patterns of sediment distribution, often complex, indicating the compound origin of the bars.

As some channel bars are typical for certain river types, their occurrence is used as an indicator or diagnostic tool to determine the river type. This, however, requires appropriate knowledge of and experience in applied geomorphology.

3.5 Disruption of lateral and longitudinal connectivity

River ecosystems form a continuum with gradual changes from the upper to lower reaches. Therefore, lateral and longitudinal connectivity disruption, accompanied by the ecosystem's fragmentation, represents one of the main human pressures on hydromorphology and ecology. River regulation (such as bank protection, the cutting-off of meanders and side arms), which separates the river and floodplain processes, leads to the reduction of lateral

a) Weir for river bed stabilisation on a small river
b) Dam with a reservoir on a large river

Figure 3.5.1 Examples of barriers on small and large rivers: a) weir and b) dam with a reservoir

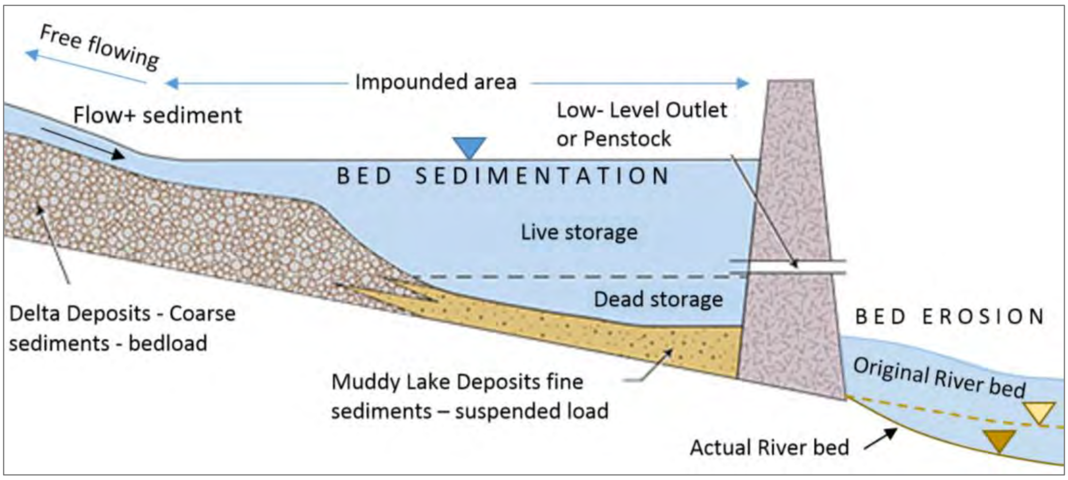


Figure 3.5.2 Typical Reservoir Sediment Profile – typical processes of sedimentation upstream of the dam and erosion downstream of the Dam. Adopted from Morris, G.L. and J. Fan, Reservoir Sedimentation Manual, McGraw-Hill. New York, 1998 – modified by Holubova

connectivity. This gives rise to morphological and ecological degradation in the river channel (river bed incision, loss of habitats) and floodplain (loss of biodiversity and habitats). The most significant impact on the river system's morphological evolution is connected with the disruption of longitudinal connectivity by transversal barriers such as dams, barrages, weirs and culverts (Figure 3.5.1). The impact of these structures on the sediment regime depends on their type (including location), size and shape.

In relation to the sediment balance, barriers play a key role owing to their impact on sediment transport and the spatial redistribution of river sediments. The imbalance in sediment transport caused by barriers is reflected in changes of the channel's morphology. The disruption of flow and sedimentary conditions causes river bed aggradation upstream of barriers and degradation downstream. The scheme in Figure 3.5.2 illustrates the deposition processes upstream of a dam (impoundment and reservoir) and river bed degradation downstream of the dam. Thus, barriers built across rivers induce several negative impacts:

- River bed degradation (changes in bedload transport);
- Decrease in the surface and ground water levels;
- River bed aggradation (changes in the sediment regime – bedload and suspended load, clogging in the reservoir – disconnection of surface and ground waters);
- Loss of biodiversity and habitats;
- Eutrophication in the reservoirs;
- Water quality deterioration as a result of remobilisation of contaminants from suspended sediments into water.

In this context, the restoration of lateral and longitudinal connectivity represents a vital step not only for hydromorphology but also for the river's overall functionality and biodiversity.

4. Historical evolution of the Danube River pattern

River pattern is the spatial arrangement of river channels in the landscape. It is determined by the geological structure, downstream slope, bed load calibre, discharge regime, tendency towards erosion or sedimentation processes and by other factors. Compared to the reference conditions prior to human alterations of the Danube river for navigational or flood protection purposes, the river pattern has changed dramatically especially in the Upper and Middle Danube sections. Together with changes of the river lengths and widths having an effect on the river bed gradient, sediment balance has also been affected. Hence, our task was to document the evolution of the Danube River pattern by morphological classification of its river channel as well as by comparing several parameters at reference conditions and in present situation (river channel length, widths, sinuosity and anabranching indexes).

Historical maps collected within the project document the reference conditions of the Danube River from the period before major river training works, such as extensive flood protection measures (continuous flood dykes), mean water regulation (river channel training, closure of side channels) and low-flow water level regulation (groyne fields, lateral structures). Historical maps were used for identification of Danube river pattern and for analysing the river channel's morphological development. Mostly maps from the end of 19th century/beginning of the 20th century were analysed. For German and Austrian section of the Danube, maps from the beginning of 19th century were used, as most of the river regulation measures already existed in these sections at the end of the 19th century. Complete metadata about historical maps are listed in Table 3.9 in the Report *"Data analyses for the sediment balance and long-term morphological development of the Danube".*

4.1 The Danube river pattern

The extended typology of the REFORM project (Rinaldi et al., 2015) was applied to define the river types of the Danube in its individual river reaches. It is a process-based river reach typology reflecting a combination of valley confinement, river planform and bed material calibre. The typical slope of the river reach and the potential genetic floodplain type are also considered in this classification.

Twenty-two extended morphological types (Figure 4.1.1) are identified in REFORM extended typology according to the degree of confinement (confined, partly confined, unconfined), dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt) and planform (straight-sinuous, meandering, pseudo-meandering, wandering, braided, island-braided, anabranching). Transitional river types may also occur.

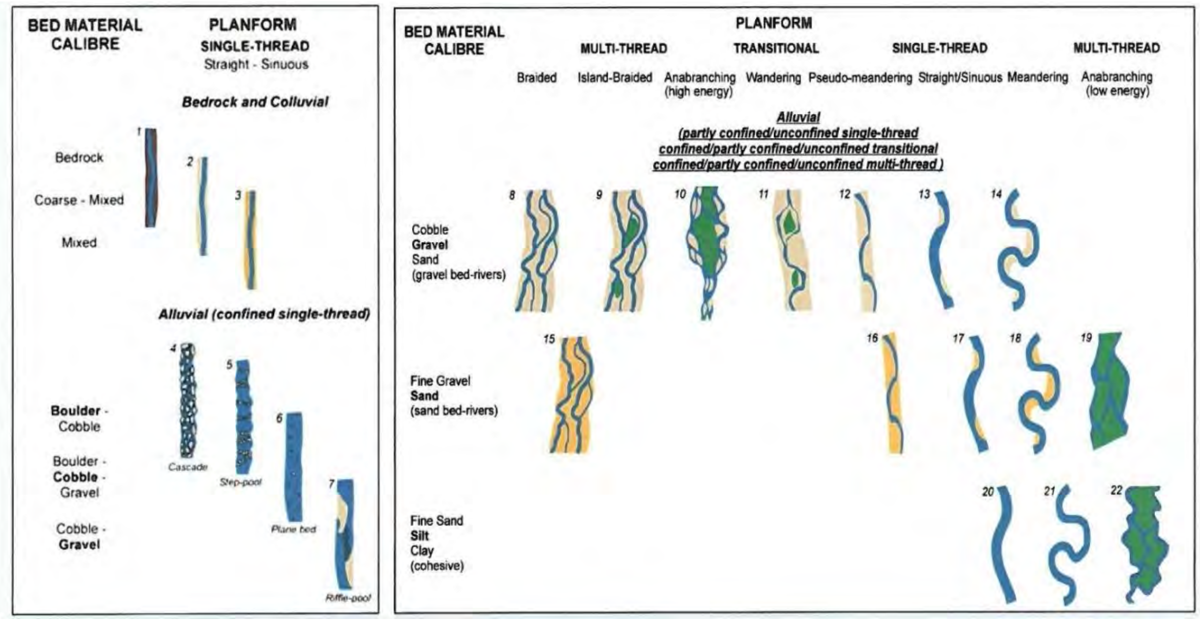


Figure 4.1.1 River types identified in the extended REFORM typology (Rinaldi et al., 2015)

DanubeSediment project attempted to categorise the Danube River channel according to the REFORM typology for the river's reference state as well as for the present state. At the very first step, confinement of the river segments had to be defined.

Confinement is the degree to which the lateral movement of a river channel is confined by the presence of valley sides or terraces. According to the approaches of Brierley and Fryirs (2005) and Rinaldi et al. (2015) a river channel's confinement can be defined as follows:

- ***Confined channel***: more than 90% of the river banks are directly in contact with hillslopes or ancient terraces. The alluvial plain is limited to some isolated pockets (< 10% bank length),
- ***Partly-confined channel***: river banks are in contact with the alluvial plain for between 10 and 90% of their total length,
- ***Unconfined channel:*** less than 10% of the river bank length is in contact with hillslopes or ancient terraces - the alluvial plain is virtually continuous, and the river has no lateral constraints to its mobility.

The Danube River mostly flows in unconfined conditions, whereas around 350 km of the river flows in confined channel (Germany, Austria, short reach at Vysegrad gate on the border between Hungary and Slovakia and Iron Gate gorge on the border between Romania and Serbia). In a less than 100-km long stretch, the river channel is partly confined (Figure 4.1.2).

Considering the confinement, longitudinal profile, riverbed slope, bed material calibre, channel pattern, floodplain and the morphological indexes, 9 river types were identified for the reference state and 4 types at the present state of the Danube River (Table 4.1.1 and 4.1.2). Longer sections of the Danube were categorised on the basis of short river reaches, which were identified in the first step – a certain level of generalisation was necessary in the context of the Danube river Basin's scale.

Figure 4.1.2 Confinement of the Danube River channel

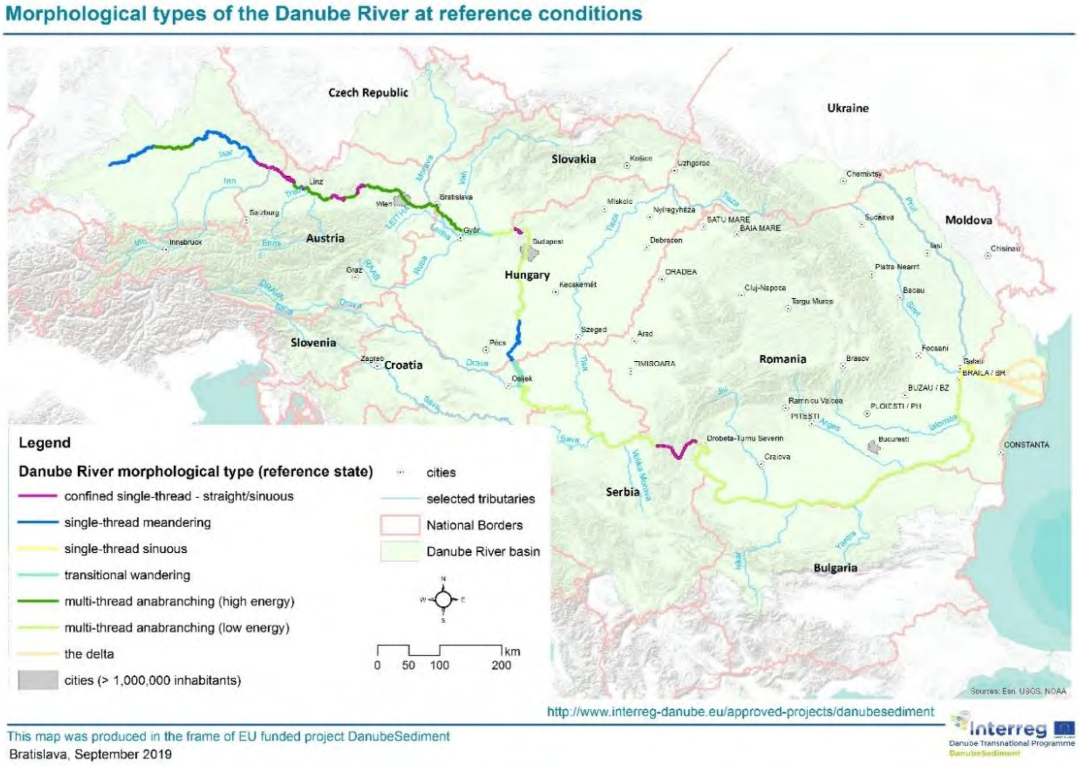


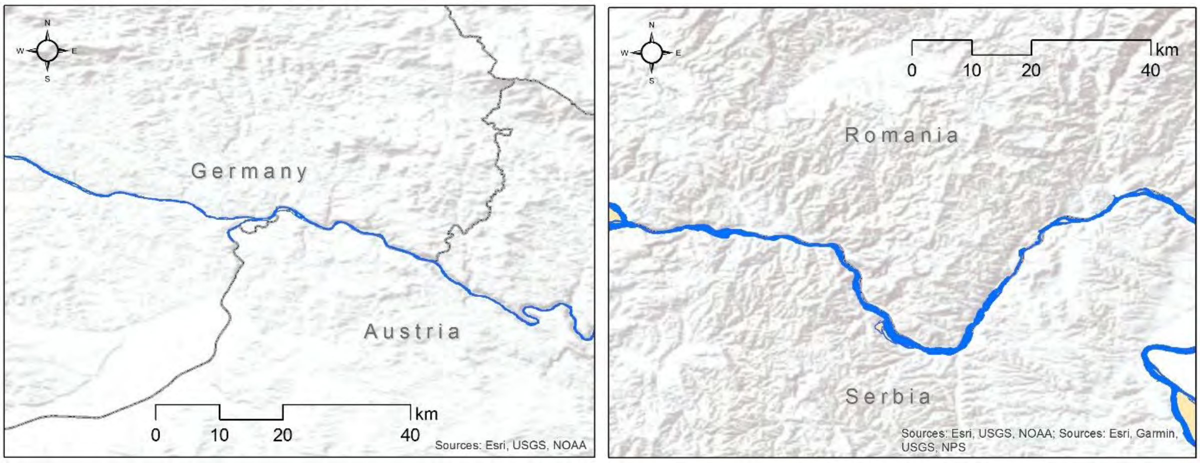
Figure 4.1.3 Morphological types of the Danube River at reference conditions

Table 4.1.1 Morphological types of the Danube River at reference conditions

section	from (rkm)	to (rkm)	river type (REFORM)
upper	2588	2498	single-thread meandering
	2498	2428	multi-thread anabranching (high energy)
	2428	2253	single-thread meandering
	2253	2160	confined single-thread - straight/sinuous
	2160	2144	multi-thread anabranching (high energy)
	2144	2136	confined single-thread - straight/sinuous
	2136	2082	multi-thread anabranching (high energy)
	2082	2050	confined single-thread - straight/sinuous
	2050	2030	multi-thread anabranching (high energy)
	2030	2005	confined single-thread - straight/sinuous
	2005	1880	multi-thread anabranching (high energy)
	1880	1802	multi-thread anabranching (high energy)
upper&middle	1802	1750	transitional wandering
middle	1750	1712	multi-thread anabranching (low energy)
	1712	1692	confined single-thread - straight/sinuous
	1692	1515	multi-thread anabranching (low energy)
	1515	1433	single-thread meandering
	1433	1383	transitional wandering
	1383	1040	multi-thread anabranching (low energy)
	1040	945	confined single-thread - straight/sinuous
middle&lower	945	375	multi-thread anabranching (low energy)
lower	375	170	multi-thread anabranching (low energy)
	170	80	single-thread sinuous
	80	0	the delta - Kilija - anabranching channels
	80	0	the delta - Sulina - single thread sinuous channels
	80	0	the delta - St.Gheorghe - meandering channels

As shown in the maps in Figure 4.1.3 and 4.1.8 and in the tables (Table 4.1.1 and 4.1.2,), the river types in the Lower Danube are the same as in the past – the multithread anabranching type still exists under the present conditions. On the other hand, the Upper and Middle Danube sections have rapidly changed due to regulation works such as river bank protection, cutting off the side channels, branches and the floodplain, channel damming and straightening, which have also caused the changes of the morphological river types.

Under the reference conditions, multithread anabranching reaches accounted for 1,685 kilometres of the Danube river and were identified in the Upper Danube in Germany, Austria, Slovakia and Hungary (high energy type) and in the Middle and Lower Danube in Slovakia, Hungary, Serbia, Bulgaria and Romania (low energy). In 19th century, the Danube river was highly meandering within river reaches in Germany, Hungary and Croatia/Serbia (transitional reach between meandering and anabranching type). Figures 4.1.4 - 4.1.7 show examples of spatial pattern of the identified Danube river types at reference conditions.



Sources: Esri, USGS, NOAA

Sources: Esri, USGS, NOAA; Sources: Esri, Garmin, USGS, NPS

Figure 4.1.4 Confined single-thread straight/sinuous channel in Germany and Austria (left) and in the Iron Gate gorge on the border between Romania and Serbia (right) at reference conditions

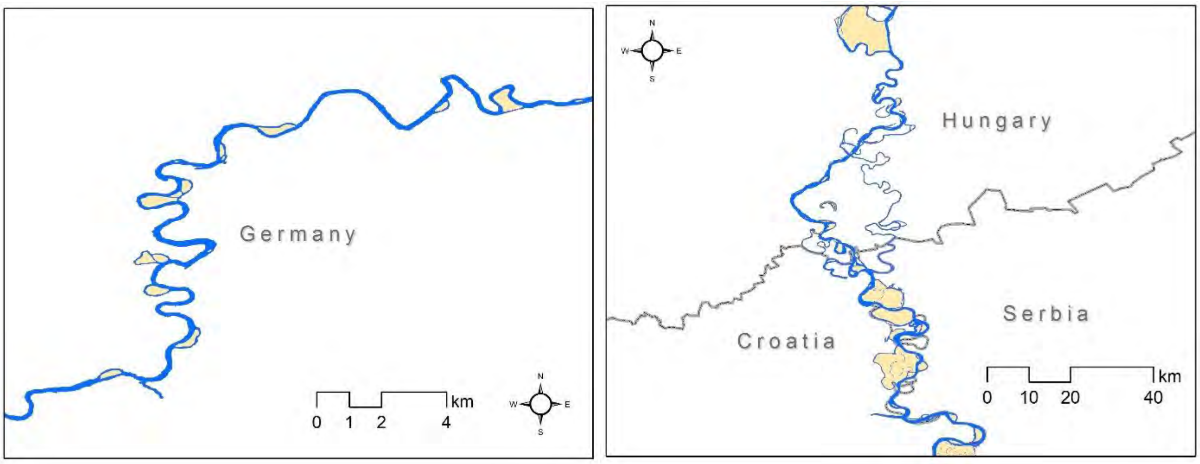


Figure 4.1.5 Single-thread meandering reach in Germany (left) and single-thread meandering reach in Hungary with transitional reach in Croatia and Serbia (right) at reference conditions

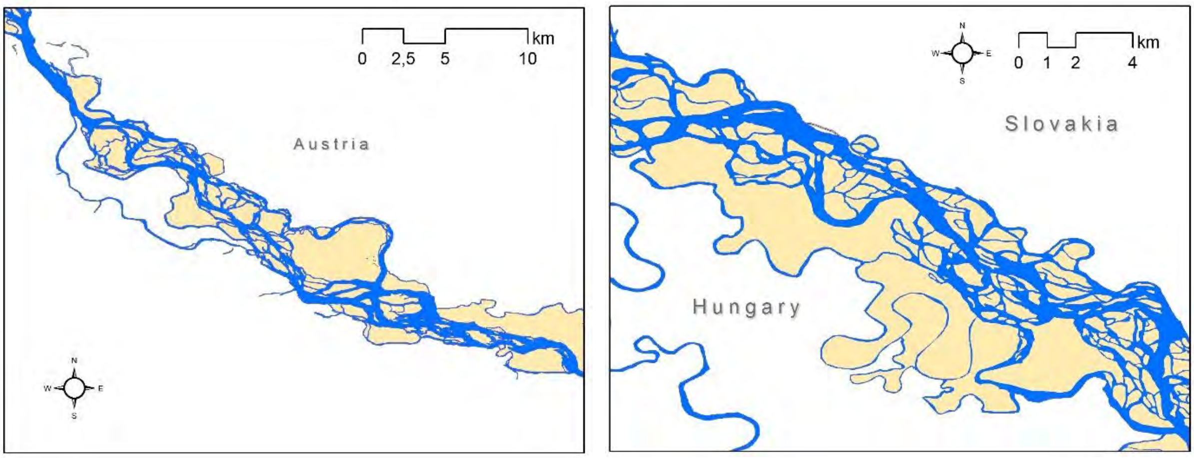


Figure 4.1.6 Multithread anabranching (high energy) reach in Austria (left) and on the border between Slovakia and Hungary (right) at reference conditions

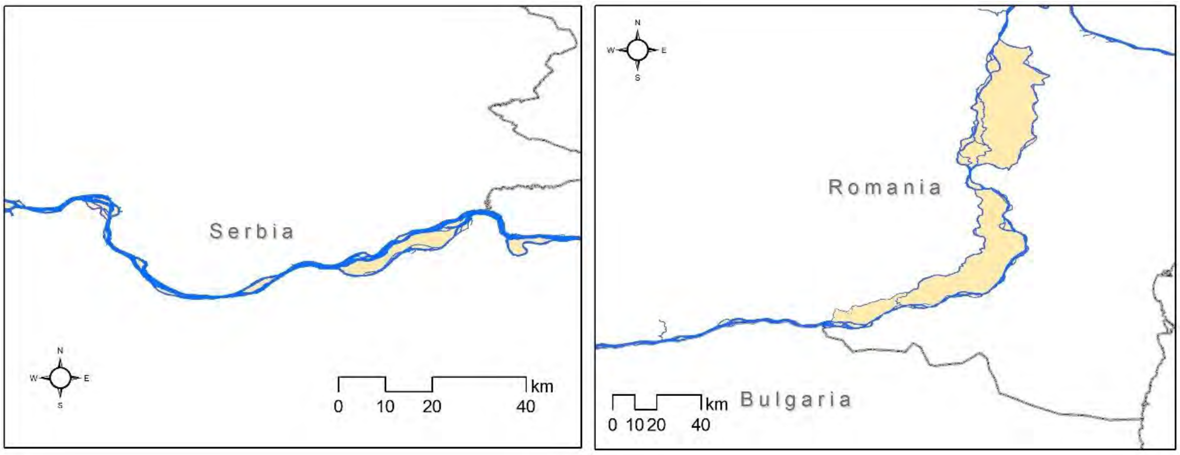


Figure 4.1.7 Multithread anabranching (low energy) reach in Serbia (left) and in Romania and Bulgaria (right) at reference conditions

Historically, the multithread anabranching river type used to cover 1,685 kilometres of the river (390 km - high energy and 1,295 km - low energy type) in the Upper, Middle and Lower Danube sections (see Table 4.1.1, Figure 4.1.3). At present, only a 745 kilometres long stretch of the Danube has a multithread anabranching (low energy) river pattern – only at the Lower Danube. The multithread anabranching (high energy) type is no longer represented (Table 4.1.2, Figure 4.1.8). As the regulated river channel has been separated from its branches, the greater part of the Upper and Middle Danube can be considered a single thread straight/sinuous river type at the present time. The river type of Danube in confined reaches have not changed owing to the geological conditions, under which single-thread straight/sinuous river type prevails. The Upper and Middle Danube sections have changed to the greatest extent – the meandering and sinuous river with several multithread anabranching reaches has changed into to single thread sinuous river (Table 4.1.2, Figure 4.1.8). The Lower Danube can still be considered a multithread anabranching low energy river because it has remained virtually unchanged compared with its natural state, with little anthropogenic interference and regulation works.

Table 4.1.2 Morphological types of the Danube River at present state

section	from (rkm)	to (rkm)	river type (REFORM)
upper	2580	2255	single thread straight/sinuous
	2255	2160	confined single-thread - straight/sinuous
	2160	2144	single thread straight/sinuous
	2144	2136	confined single-thread - straight/sinuous
	2136	2082	single thread straight/sinuous
	2082	2050	confined single-thread - straight/sinuous
	2050	2030	single thread straight/sinuous
	2030	2005	confined single-thread - straight/sinuous
upper&middle	2005	1712	single thread straight/sinuous

middle	1712	1692	confined single-thread - straight/sinuous
	1692	1040	single thread straight/sinuous
	1040	945	confined single-thread - straight/sinuous
	945	863	single thread straight/sinuous
lower	863	170	multi-thread anabranching (low energy)
	170	80	single thread sinuous
	80	0	delta -Kilija - anabranching channel
	80	0	delta - Sulina - single-thread sinuous channel
	80	0	delta -St. Gheorghe- meandering channel

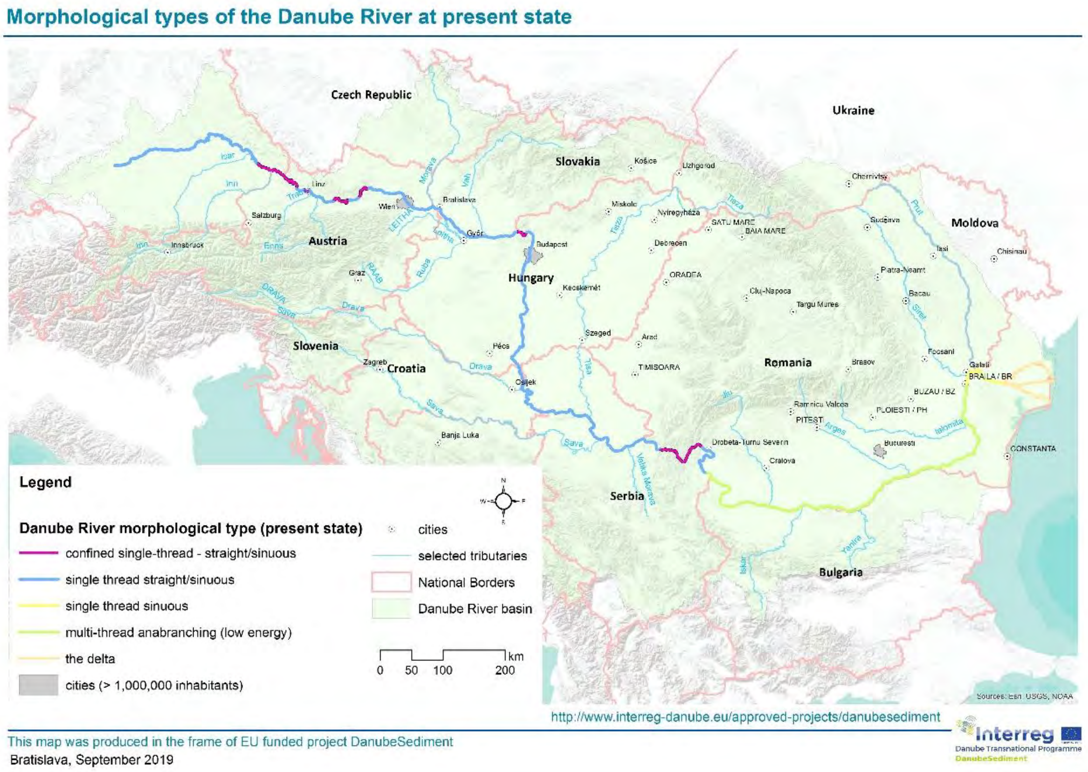


Figure 4.1.8 Morphological types of the Danube River at present state

The best documentation of the changed river pattern is provided when we overlap the maps of historical river channel with the present situation. These maps also show changes of the morphological parameters described in the following chapter (river length, width). As mentioned above, the most significant change of the river pattern happend in the Upper and Middle Danube where a complex river with a variety of river types changed into a uniform river channel with cut-offs or isolated side branches within reduced floodplain areas. Long segments of meandering channel were regulated into a single-thread sinuous channel in Germany (Figure 4.1.9), former multithread anabranching reaches changed to a single-thread sinuous river in Austria, Slovakia and Hungary (Figure 4.1.10 and Figure 4.1.11).

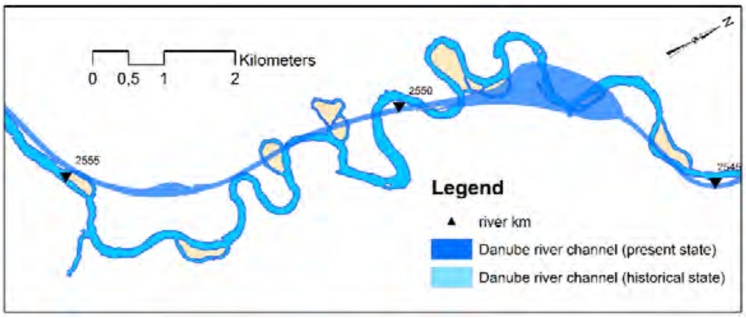


Figure 4.1.9 Historical and present Danube channel in Germany

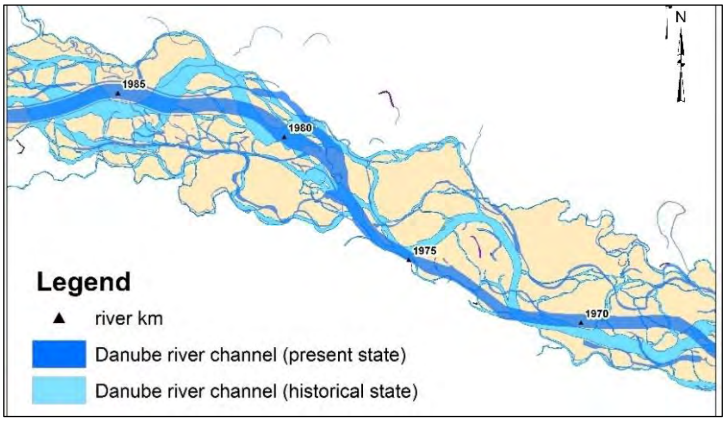


Figure 4.1.10 Historical and present Danube channel in Austria

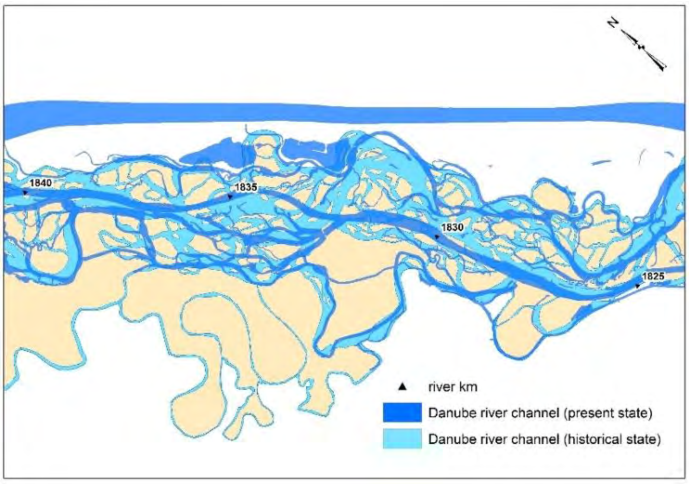


Figure 4.1.11 Historical and present channel of the Danube in Slovakia and Hungary

Further downstream in Hungary, Croatia and Serbia, multithread channels were also separated from the main channel and the Danube has a character of a single-thread river under present conditions (Figure 4.1.12, 4.1.13).

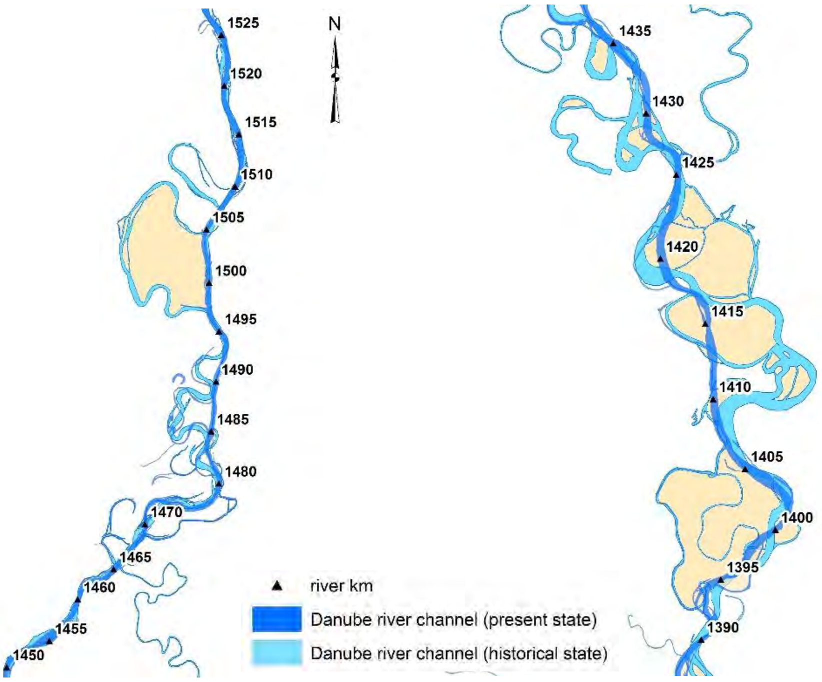


Figure 4.1.12 Historical and present Danube channel in Hungary (left) Croatia/Serbia right

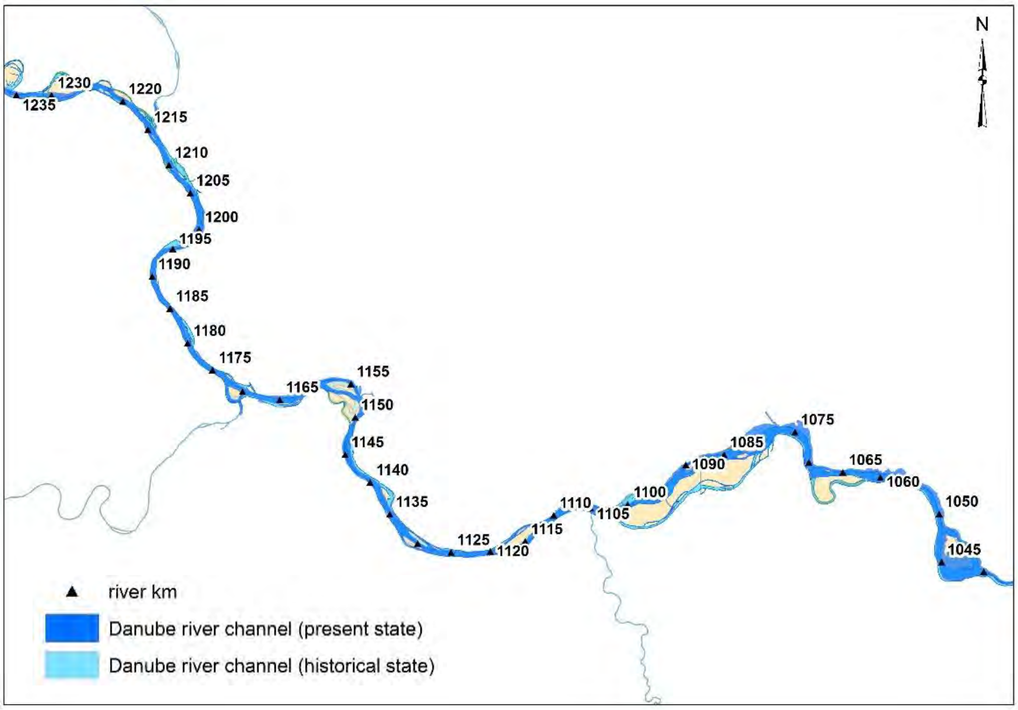


Figure 4.1.13 Historical and present Danube channel in Serbia

Lower Danube downstream of rkm 863 shows no change in the morphological typology under present conditions even though certain natural lateral movement has changed the river pattern comparing the present channel with historical maps (Figure 4.1.14). Side-arms are degrading and becoming more narrow than in the past (Figure 4.1.15). On the other hand, in some reaches, the river has become wider due to natural lateral movement and bank erosion (Figure 4.1.16).

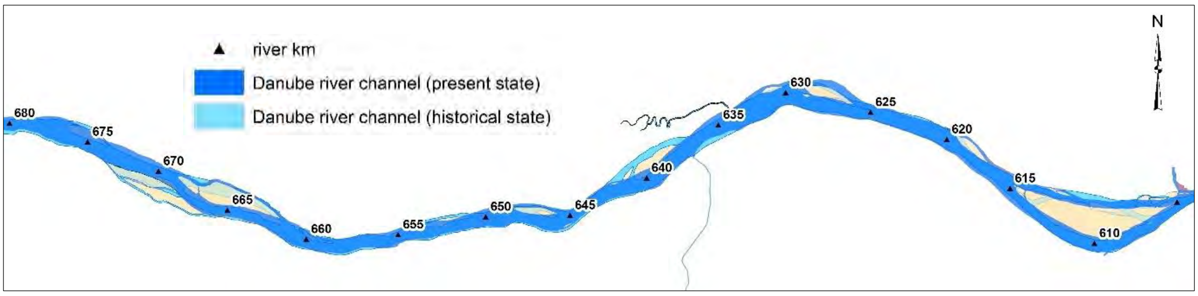


Figure 4.1.14 Historical and present Danube channel in Romania – Bulgaria

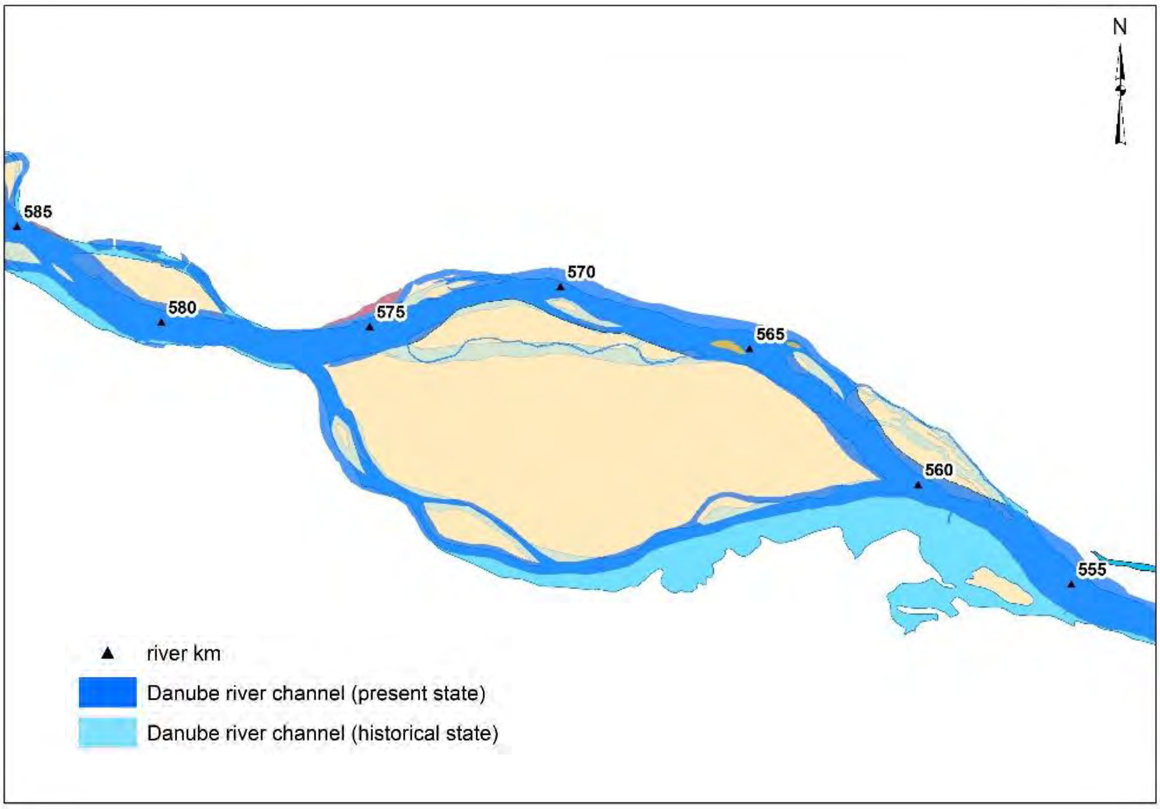


Figure 4.1.15 Historical and present Danube river channel in Romania - Bulgaria

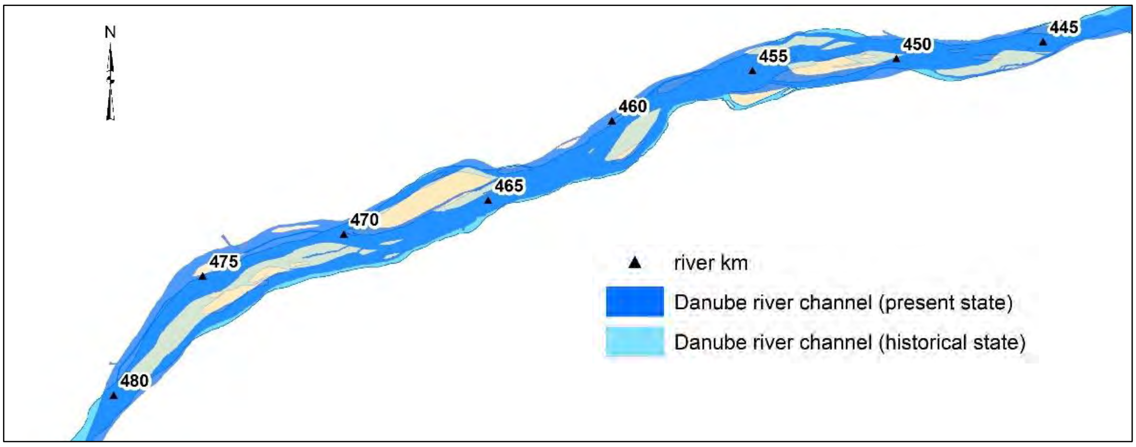


Figure 4.1.16 Historical and present Danube river channel in Romania - Bulgaria

4.2 Changes in the morphological characteristics of the Danube channel from reference conditions till present

Long-term changes in the morphological characteristics of the Danube can be described by using a GIS analysis to quantify the spatial changes of the river pattern, sinuosity, and in the length and the width of the river channel.

Georeferenced historical maps of the Danube at reference conditions (19-20th century) were used to digitise the polygons of the Danube channel. This enabled us to create a centreline of the Danube river channel (Figure 4.2.1). The historical centreline was compared with the present state centreline to describe the changes and quantify various morphological characteristics for comparison with the present conditions. Several indexes were calculated (sinuosity, anabranching) to document the changes of the river channel (shortening, straightening). Changes in the river channel width were documented on the basis of the historical and present polygons of the Danube river and then cross-section profiles were drawn every kilometre along the whole Danube.

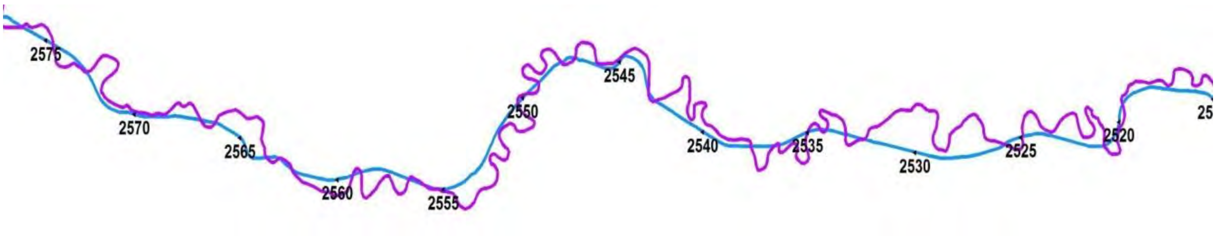


Figure 4.2.1 Historical (violet) and present (blue) channel centreline showing the Danube channel straightening in Germany

4.2.1 Channel length

In our analysis, we calculated the length of the river Danube channel starting from Ulm, Germany (river km 2,590), where the historical maps were available, down to rkm 80 where the Danube flows into the Delta. The reach upstream of rkm 2,590 was not evaluated because no historical maps were available.

As mentioned previously, river regulation works have caused straightening and shortening of the channel in many of the Danube reaches. The river channel has been shortened most significantly in the Upper Danube section, i.e. by almost 100 kilometres in total. The Middle Danube has been shortened by 31 km and the Lower Danube by 4 km compared with their lengths in the past (Table 4.2.1). In the Danube Delta, Sulina branch has been shortened by 13 kilometres, whereas the other two branches (Kilija and St. Gheorghe) are longer at present time owing to the outflow of the sediments into the Black sea forming the delta itself. Although the evolution of the delta in more time steps of the historical maps was not analysed, it is clear that the damming of the Danube River and its tributaries causes lack of sediments from the upstream sources to the delta, leading to the coastal erosion which is already present at some localities.

Table 4.2.1 Changes of the Danube river channel length from reference conditions till present

section	present river channel (km)	historical river channel (km)	change in length (km)	change in length (%)
Upper Danube	759	**857**	**-97,8**	**-11,4%**
Middle Danube	828	**859**	**-31,1**	**-3,6%**
Lower Danube*	**828**	**832**	**-3,6**	**-0,4%**
Danube delta: Kilija	120	**112**	**8,12**	**7,2%**
Danube delta: Sulina**	87	**100**	**-13,2**	**-13,1%**
Danube delta: St. Gheorghe**	**105**	**101**	**4,5**	**4,4%**

*without Delta, ** rkm from the Black sea calculated via Sulina

4.2.2 Channel widths

The widths of the Danube River were evaluated using a GIS analysis of the polygons created for the channel's wetted area from the historical maps (reference state) and present maps (national datasets 2007-2017). The authors are aware of various discharge conditions depicted at the time of mapping (low-flow, bankfull discharge etc.) especially on the historical maps. Anyway, the analysis of the river widths has revealed the general situation and trends of changes along the Danube from reference state till present. The widths of the river were measured in GIS using a set of cross-sectional profiles drawn at every river kilometre – for the reference and present states (Figure 4.2.2). The profiles were attributed the river pattern at each cross-section (D – Danube channel or I - island in case it is present in cross-section) and the length of each cross-section was exported. Where there are groin fields in the river, the channel width between the groins was also measured (see the green lines on Figure 4.2.2).

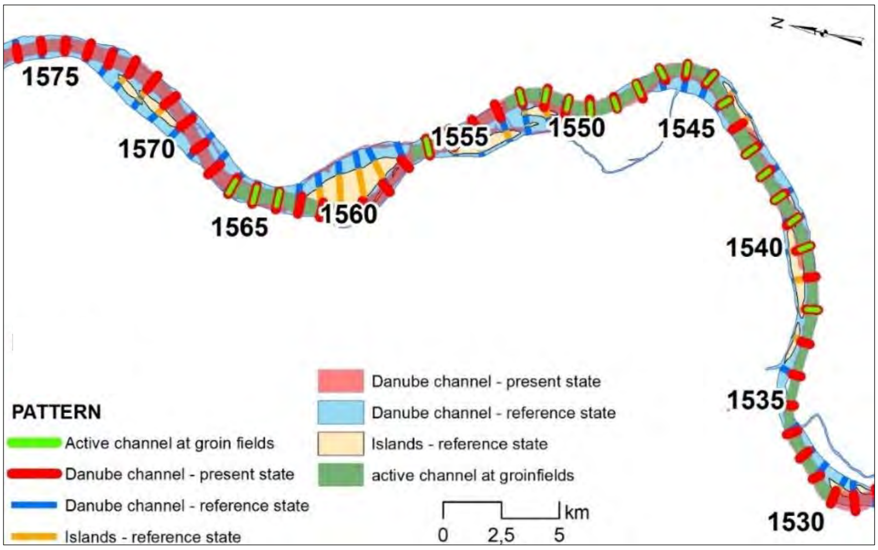


Figure 4.2.2 Estimation of the Danube river widths using a set of cross sections in GIS

Moreover, the river widths were evaluated for two cases:

- ***Active channel for bedload transport:*** the width of the assumed active part of the river system for bedload transport - the main channel (usually navigational channel) and its branches comparable in size, without side-arms, only islands in the channel and among the main branches were included;
- ***Full width of the river system***: covering the river channel/channels, branches and side arms, islands in the channel and within the whole river system; only side arms wider than 10% of the main channel were included.

An example how the Danube river widths were estimated for the whole river system and for the assumed active channel for bedload transport (reference state) is shown in Figure 4.2.3.

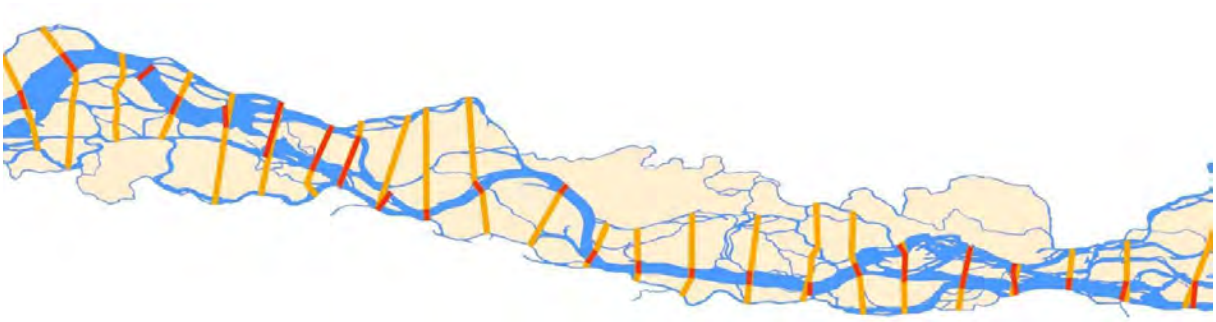


Figure 4.2.3 Estimation of the Danube river widths of the active channel (red colour) and of the river system (orange colour) for reference state

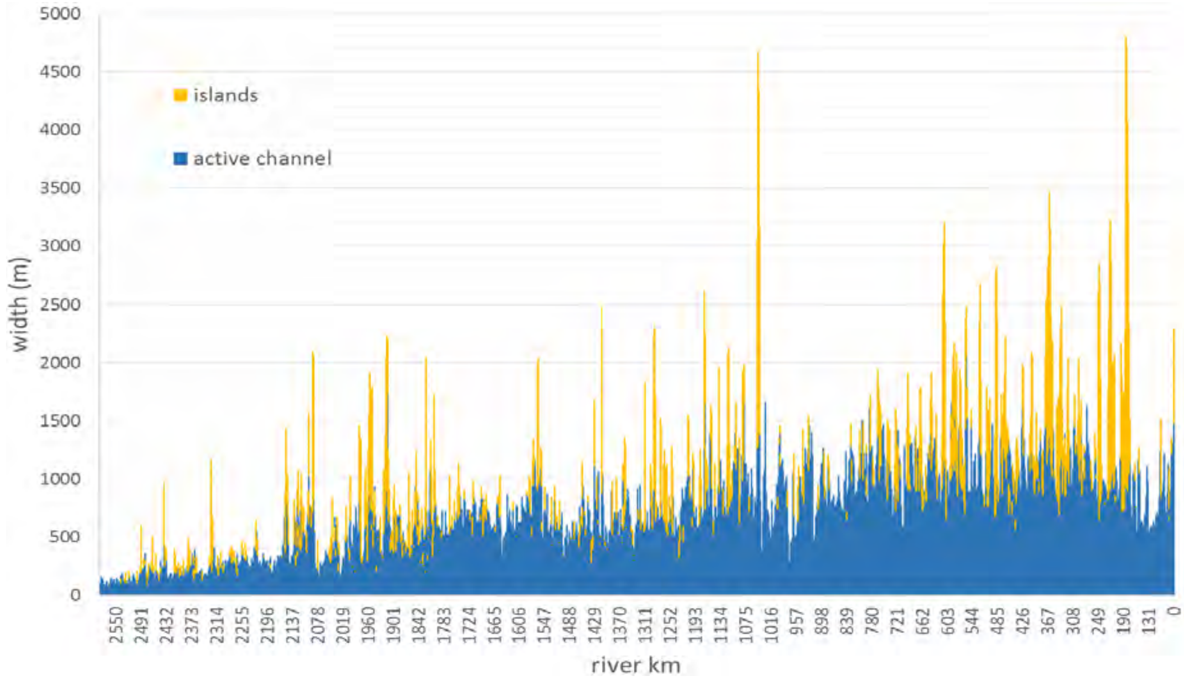


Figure 4.2.4 The widths of the assumed active channel for bedload transport at reference conditions - blue colour showing the total widths of the wetted areas and orange colour showing the total width of the islands at every cross-section

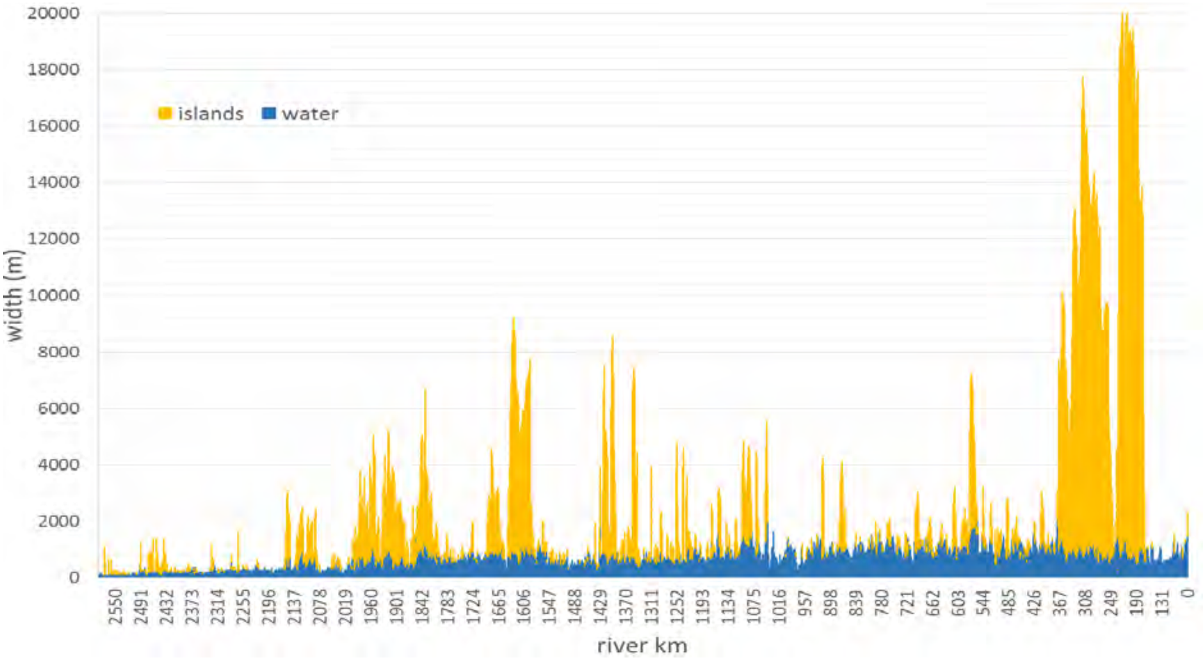


Figure 4.2.5 The full widths of the Danube river system at reference state – blue colour showing the total widths of the wetted areas and orange colours showing the total width of islands at every cross-section

Figures 4.2.4 and 4.2.5 show the total width of the wetted areas in each cross-section from Danube river kilometre 2590 down to the delta at reference conditions (19th century). Besides the width of the channels in cross-sections also the total width of the islands is depicted for both cases (active channel and the river system). Figures 4.2.6 and 4.2.7 show comparison of the channel widths at reference state (blue colour) and at present (red colour) for the two cases – active channel and the whole river system.

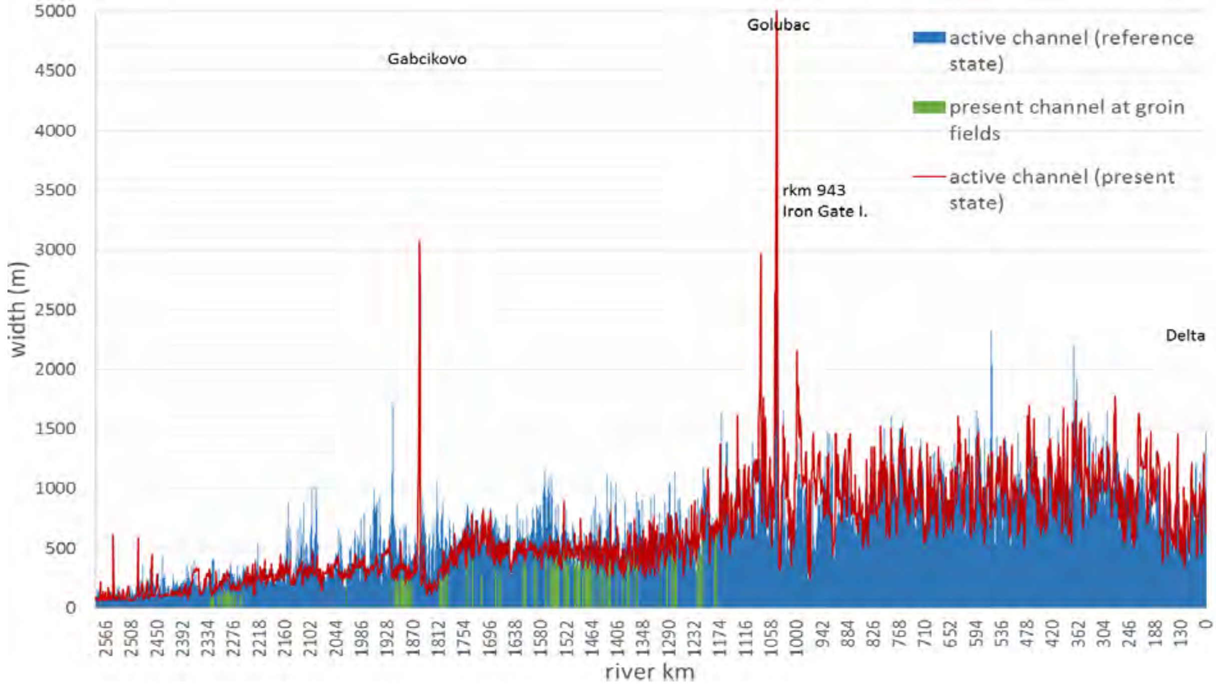


Figure 4.2.6 Comparison of the active channel widths of the Danube river at reference state (blue) and at present conditions (red) showing the total width of Danube channels (wetted area) in each cross-section

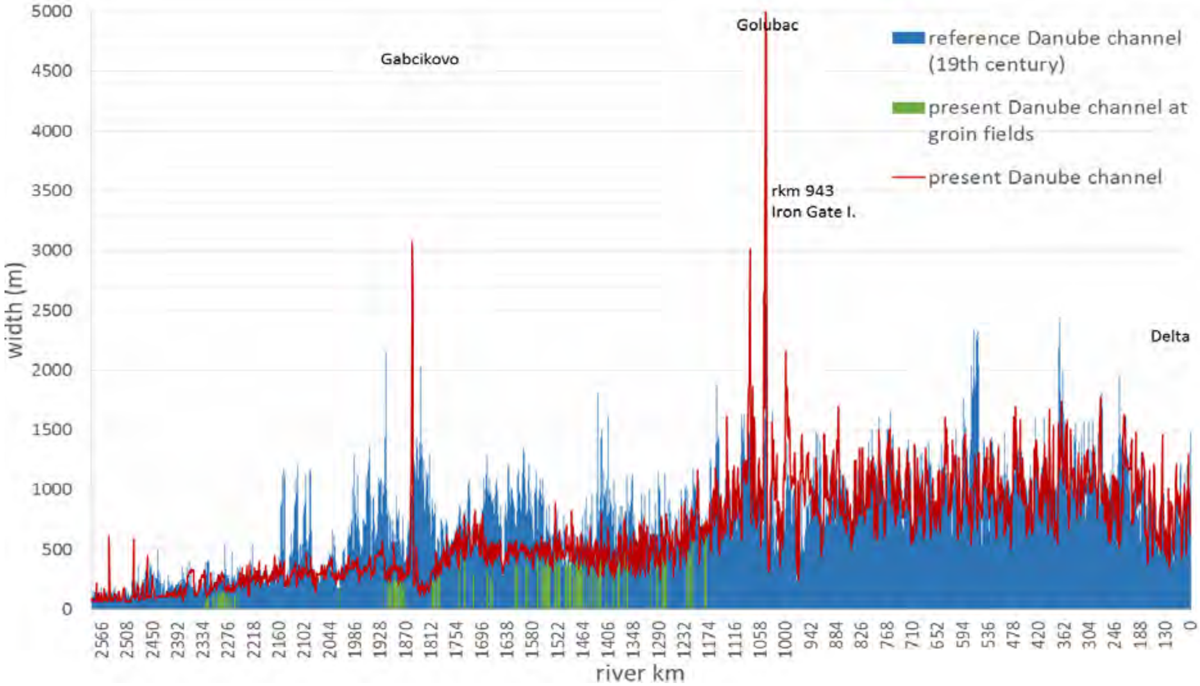


Figure 4.2.7 Comparison of the widths of the Danube river system at reference state (blue) and present (red) showing the total width of Danube channels (wetted area) in each cross-section

Green colour on Figures 4.2.6 and 4.2.7 show the channel widths at groin fields (present state). In average, in the Upper Danube the total width has decreased by 39% (the active width by 22%) and in the Middle Danube by 12% (the active width by 1%) (Table 4.2.2). Present active channel at groin fields is only a half of the original channel width (44% in the Upper Danube, 53% in the Middle Danube). The width of Lower Danube has changed very slightly in average (by 4%) and there are no groin fields in the present river channel. Figures 4.2.8, 4.2.9 and 4.2.10 show the changes in the active channel widths from reference state (blue) to present state (red) in the Upper, Middle and Danube section in more detail.

Table 4.2.2 Average width of the Danube river channel in Upper, Middle and Lower section and its change from reference conditions till present

		Whole River System				Active channel				Active channel at groin fields
		Width B (m)		Width Change (ΔB)		Width B (m)		Width Change (ΔB)		Width B (m)
River km	Section	Reference conditions	Present state	ΔB (m)	ΔB (%)	Reference conditions	Present state	ΔB (m)	ΔB (%)	Present state
2588-1790	**Upper**	**409**	**250**	**-159**	**-39%**	**319**	**250**	**-69**	**-22%**	**182**
1790-943	**Middle**	**753**	**660**	**-93**	**-12%**	**664**	**660**	**-4**	**-1%**	**403**
943-0	**Lower**	**1005**	**968**	**-37**	**-4%**	**958**	**968**	**10**	**1%**	**n.a.**

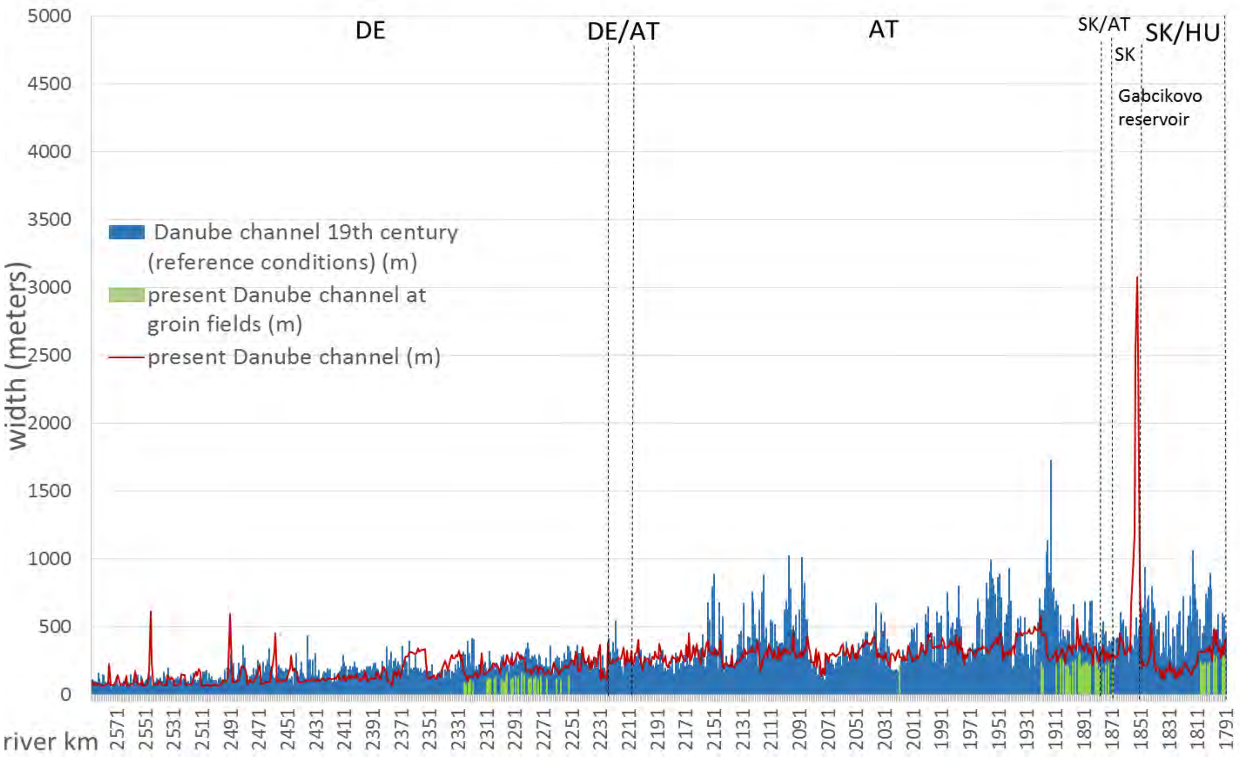


Figure 4.2.8 Comparison of the active channel widths of the Danube river at reference state (blue) and at present (red) showing the total width of Danube channels at every cross-section – Upper Danube

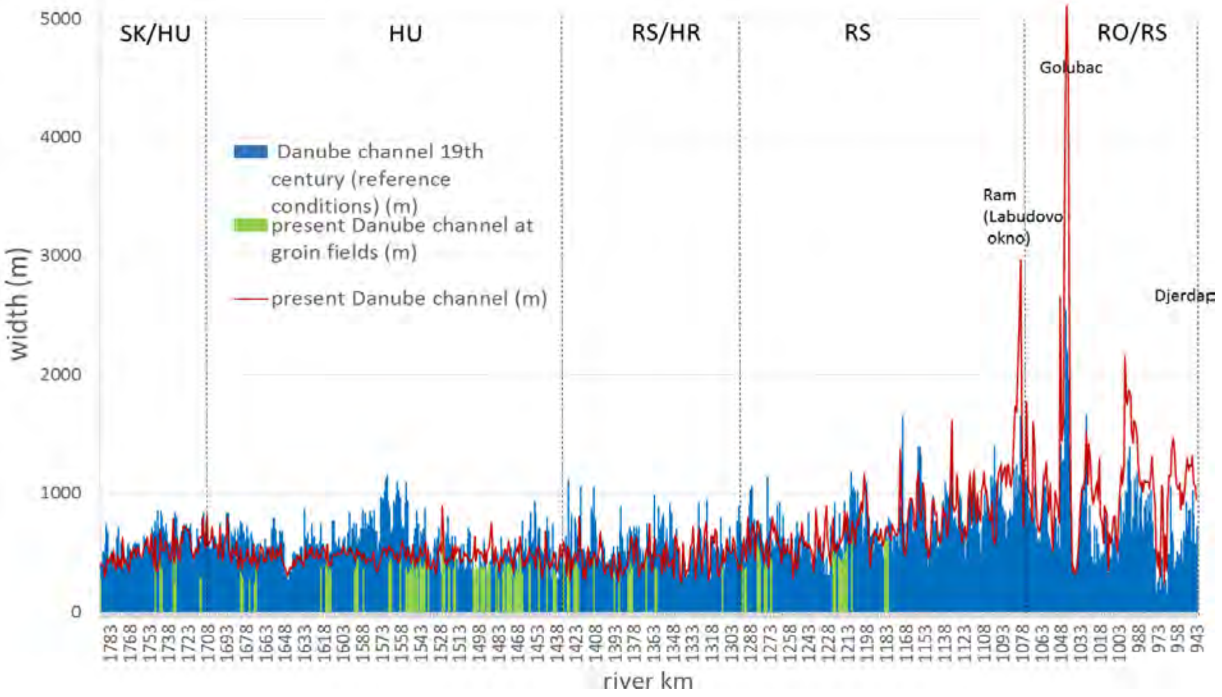


Figure 4.2.9 Comparison of the active channel widths of the Danube river at reference state (blue) and at present (red) showing the total width of Danube channels at every cross-section – Middle Danube

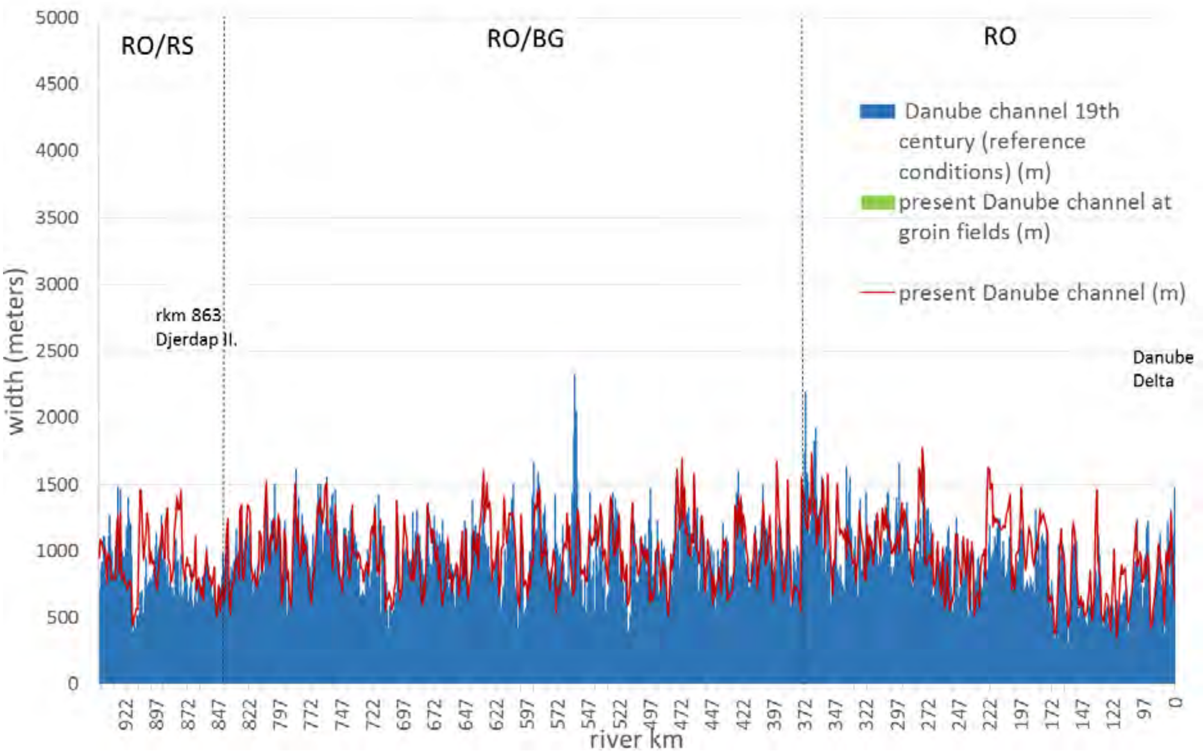


Figure 4.2.10 Comparison of the active channel widths of the Danube river at reference state (blue) and at present (red) showing the total width of Danube channels at every cross-section – Lower Danube

Figure 4.2.11 shows widening (+) and narrowing (-) of the Danube river channel from upstream to downstream. Significant narrowing and unification of the river channel in the Upper and Middle section was caused by river training (bank protection measures, longitudinal and lateral structures for navigational purposes, cutting-off side channels etc.) and its further consequences (e.g. reduced lateral connectivity and movement, incision of river bed causing further cutting-off the floodplain areas). Although damming of the river created wider sections (wetted areas) within the impoundments, river channel is only active in some part (low velocities and water surface slope causing sedimentation in reservoirs). Analysis of the active part of the channel width within reservoirs is beyond the scope of this project and was not evaluated.

On the other hand, alternating short reaches of widening and narrowing of the Lower Danube downstream of Iron Gate II. can be observed. Small degree of channel modification by human activites allows the natural dynamic processes to continue in such near to reference conditions, e.g. lateral movement and bank erosion, which enable regular widening and narrowing of the channel in short reaches.

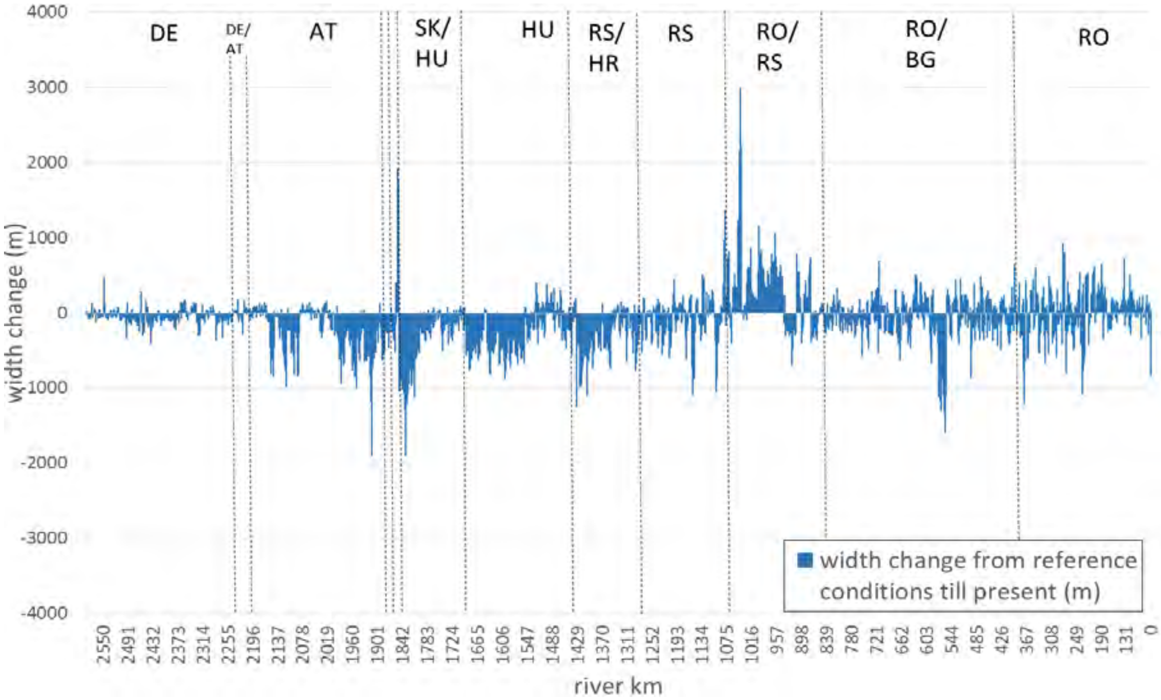


Figure 4.2.11 Widening (+) and narrowing (-) of the Danube river system from reference state till present

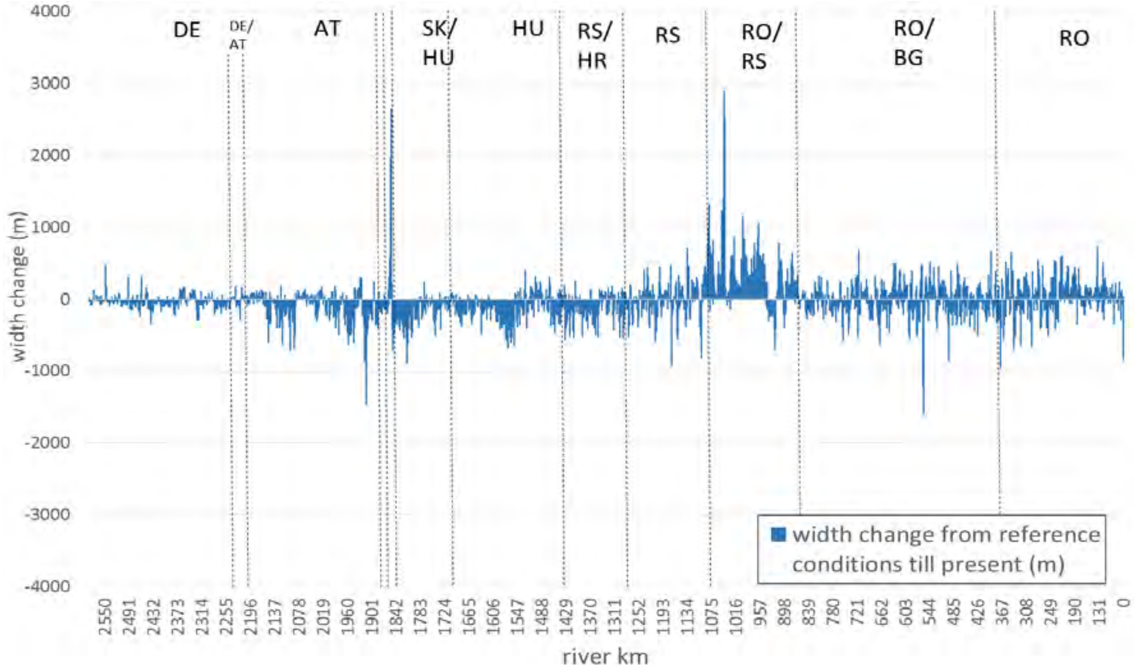


Figure 4.2.12 Widening (+) and narrowing (-) of the active Danube channel from reference state till present (note: active part within impoundments (reservoirs) was not evaluated)

4.2.3 River sinuosity and degree of anabranching

The sinuosity index (Si) is the ratio between the length of the centreline of the (main) channel and the length of the broad river or river valley course (or "meander belt axis" for single thread rivers). It is applicable for single thread rivers and based on the Si value, the river reaches are defined as follows:

- Straight reaches Si < 1,05
- Sinuous reaches 1,05 < Si <1,5
- Meandering reaches Si > 1,5

The anabranching index (Ai) is the number of active channels separated by vegetated islands at baseflow (Ai). Recommended method for estimating Ai is the average count of wetted channels separated by vegetated islands in each of at least 10 cross sections spaced no more than the maximum width of the outer wetted channels apart (Gurnell et al., 2014)

The braiding index (Bi) is the number of active channels separated by bars at baseflow. Recommended method for estimating Bi is the average count of wetted channels in each of at least 10 cross sections spaced no more than one braid plain width apart (Gurnell et al., 2014).

Within the DanubeSediment project, the sinuosity index was estimated for river reaches defined within the morphological classification of the reference state (Table 4.1.1). In anabranching reaches, the anabranching index was calculated according to the methodology mentioned above for the reference state. Due to lack of information on bars especially from the historical maps and the extend of work in the scale of the whole Danube river, the braiding index was not estimated.

In the past (reference state), in total 457 kilometres of the river had a meandering character (Si > 1.5) and 405 km were sinuous (1,05 < Si <1,5) (Table 4.2.3, Figure 4.2.13). The rest of the river (1,685 km) had a multithread anabranching character (Si value was not estimated). At present state, the Danube is a sinuous river almost along the whole Upper and Middle Danube with a short reach at the Lower Danube near Galati (Table 4.2.3, Figure 4.2.14). Sinuosity index is not applicable in multithread anabranching reaches of the river (where only anabranching index was calculated).

Complete overview of the changed river lengths and sinuosity indexes for reference state river reaches is given in Table 4.2.4.

Table 4.2.3 Sinuosity of the Danube River at reference state and present state

	reference state (km)	**present state (km)**
meandering	**457**	**0**
sinuous	**405**	**1653**
straight	**0**	**19**

Table 4.2.4 Length change and Sinuosity index (Si) of river reaches defined for the reference state and Si for the same reaches at present state

Section	From (rkm)	To (rkm)	River type (REFORM)	Length - reference state (km)	Length - present state (km)	Length change (km)	Sinuosity index (Si) reference state		SinuoSity index (Si) present state	
upper	2588	2498	single-thread meandering	126	86	-39	1,6	meandering	1,1	sinuous
	2498	2428	multi-thread anabranching (high energy)	80	67	-13	n.a.		1,1	sinuous
	2428	2253	single-thread meandering	175	159	-15	1,5	meandering	1,4	sinuous
	2253	2160	confined single-thread - straight/sinuous	90	91	0	1,3	sinuous	1,3	sinuous
	2160	2144	multi-thread anabranching (high energy)	15	15	-1	n.a.		1,3	sinuous
	2144	2136	confined single-thread - straight/sinuous	9	8	0	1,1	sinuous	1,1	sinuous
	2136	2082	multi-thread anabranching (high energy)	58	51	-7	n.a.		1,2	sinuous
	2082	2050	confined single-thread - straight/sinuous	31	31	0	1,4	sinuous	1,4	sinuous
	2050	2030	multi-thread anabranching (high energy)	19	19	0	n.a.		1,0	straight
	2030	2005	confined single-thread - straight/sinuous	24	24	0	1,4	sinuous	1,4	sinuous
	2005	1880	multi-thread anabranching (high energy)	134	121	-13	n.a.		1,1	sinuous
	1880	1802	multi-thread anabranching (high energy)	84	76	-8	n.a.		1,1	sinuous
upper&middle	1802	1750	transitional wandering	52	51	0	1,1	sinuous	1,1	sinuous
middle	1750	1712	multi-thread anabranching (low energy)	36	37	0	n.a.		1,1	sinuous
	1712	1692	confined single-thread - straight/sinuous	19	19	0	1,4	sinuous	1,4	sinuous
	1692	1515	multi-thread anabranching (low energy)	172	172	0	n.a.		1,1	sinuous
	1515	1433	single-thread meandering	92	80	-12	1,5	meandering	1,3	sinuous
	1433	1383	transitional wandering	65	49	-16	1,6	meandering	1,2	sinuous
	1383	1040	multi-thread anabranching (low energy)	339	336	-4	n.a.		1,4	sinuous
	1040	945	confined single-thread - straight/sinuous	92	93	0	1,3	sinuous	1,3	sinuous
middle&lower	945	375	multi-thread anabranching (low energy)	554	549	-6	n.a.		n.a.	
lower	375	170	multi-thread anabranching (low energy)	192	194	2	n.a.		n.a.	
	170	80	single-thread sinuous	87	87	0	1,2	sinuous	1,2	sinuous
							* in anabranching reaches Si is not aplicable			

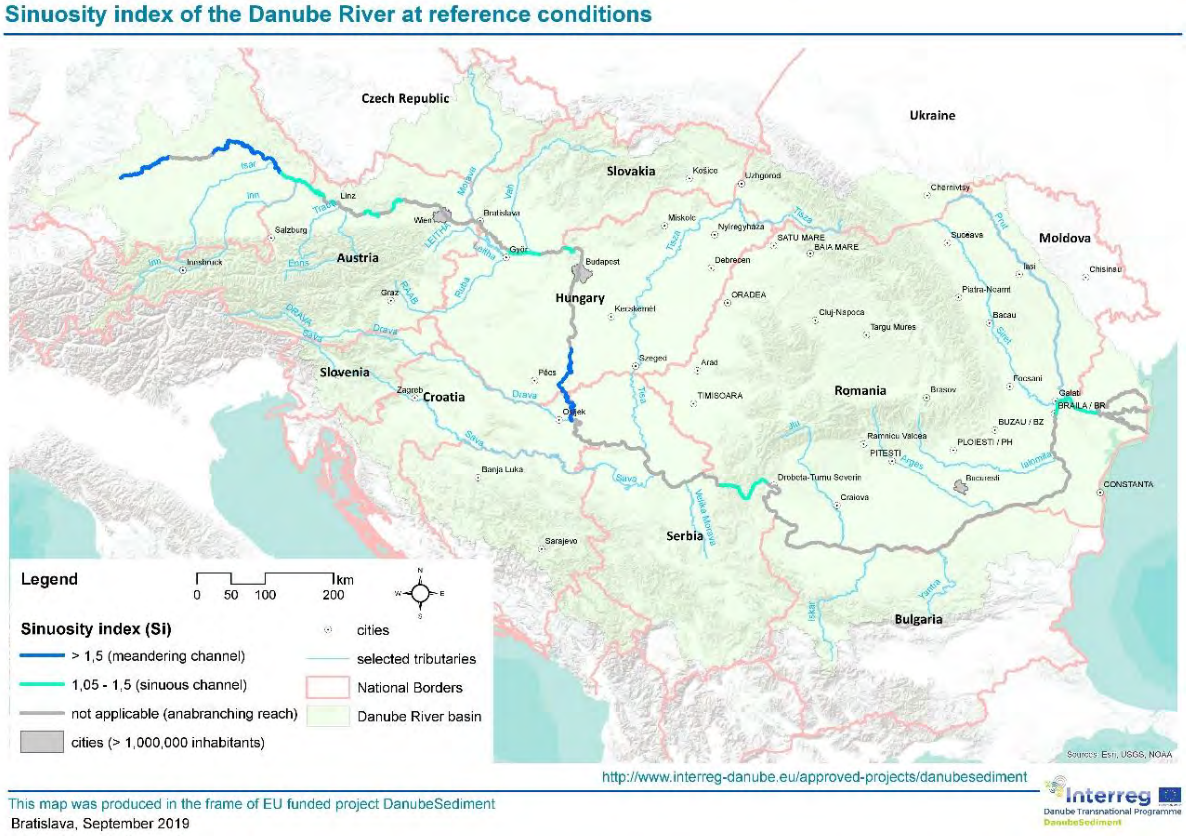


Figure 4.2.13 Sinuosity index of the Danube River at reference conditions

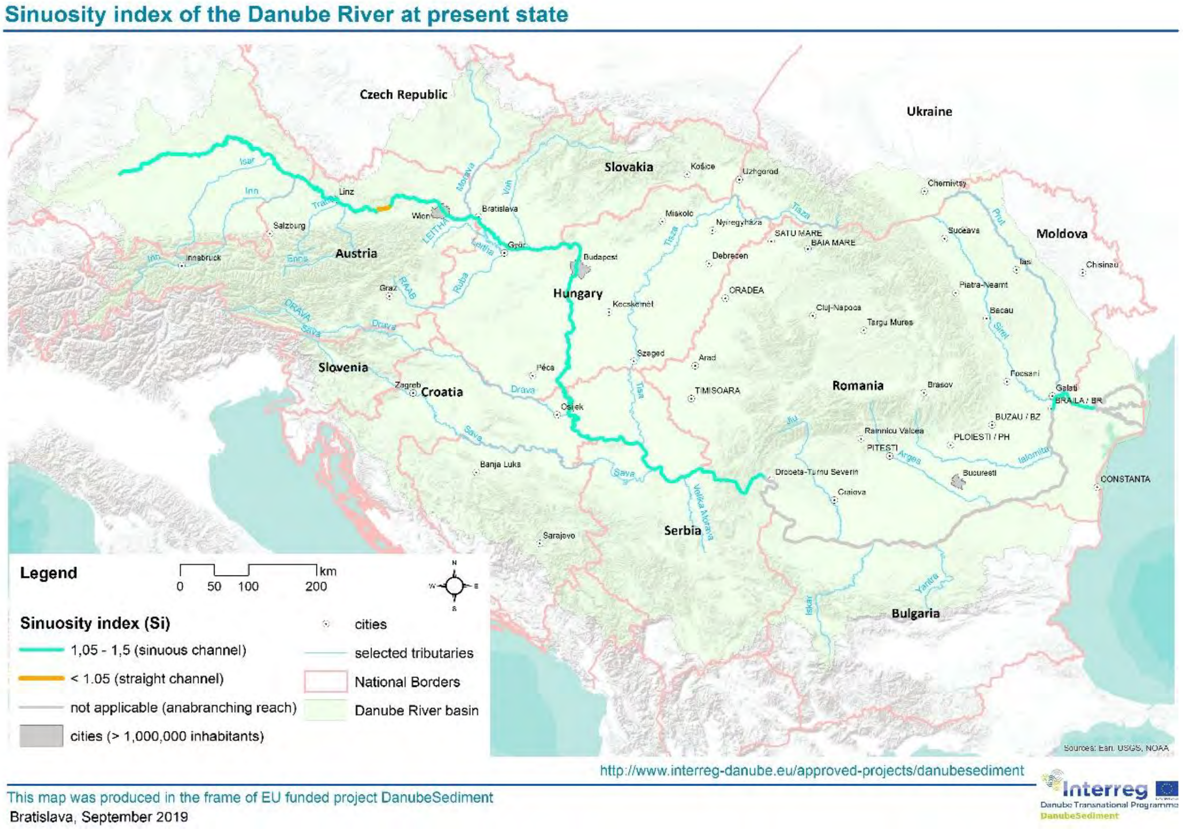


Figure 4.2.14 Sinuosity index of the Danube River at present state

The anabranching index was calculated according to the above mentioned methodology in anabranching reaches of the Danube River. Figure 4.2.15 shows anabranching character of the river in the Upper, Middle and Lower Danube with 1,5 up to 8 channels on average, estimated for 10 km long reaches (the average is based on 10 cross-sections).

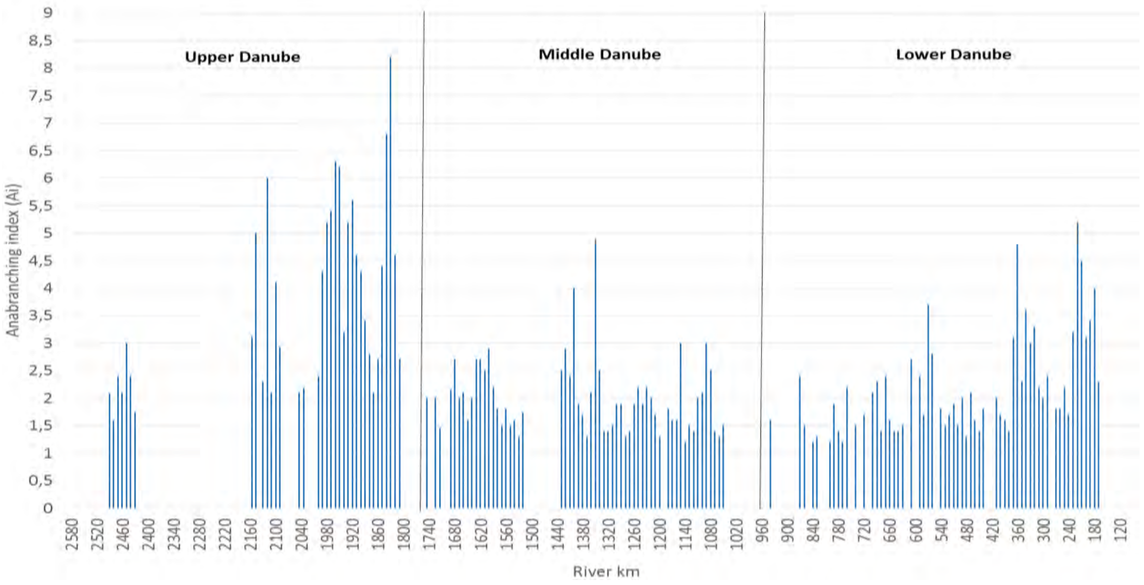


Figure 4.22 Anabranching index of the Danube River at reference state

4.3 Summary

The findings in Chapter 4 point to substantial changes in morphological characteristics of the Danube River from reference conditions till present. The wide and meandering river with many branches and side arms has changed into a uniform single-thread river especially in its upper and middle part. At reference state, the Danube used to be a multithread anabranching river along a 1685 kilometre long section. At present, only 745 kilometres of a multithread anabranching (low energy) river exist and it is only at the Lower Danube, and the multithread anabranching (high energy) type is no longer recognized.

At present, the Danube River is ***shorter*** (by approximately 130 kilometres), as a result of river regulation such as channel straightening, damming and building of bypass canals. Extensive flood protection measures, mean water regulation and low-flow water level regulation have also caused ***narrowing*** of the river system. On average, in the Upper Danube the total width has decreased by 39% (the active width by 22%) and in the Middle Danube by 12% (the active width by 1%). Groin fields in the channel have reduced the active width for sediment transport by another almost 50%. Even though the Lower Danube width has changed only slightly, (by an average of 4%), bank erosion is an ongoing process in many sections. Significant river channel narrowing, shortening and unification due to flood protection measures, hydropower generation or navigation purposes affect the river bed gradient, sediment transport and consequently, the sediment balance of the Danube River.

5. Morphological development of the Danube channel as a response to the main pressures

Rivers naturally adjust their shape and dimensions in response to the imposed discharges and sediment load. The habitats that are created in response to flow and sedimentary conditions are colonised by invertebrates, flora and fauna, which are characteristic of that particular river type (Hey, 1997). The balance between water and sediment inputs controls the aggradation or degradation tendencies of the channel. Any human intervention into the river system (flow and sediment transport regime) can cause instability of the river channel resulting in changes of the main channel characteristics. Morphology of the channel defined by its size, cross-sectional shape, longitudinal profile and planform pattern – is the result of processes of sediment erosion, transport and deposition operating within the constraints imposed by geology and terrain of the drainage basin (Thorne, 1997).

A river channel has a wide range of characteristics, which are variable in both time and space. They reflect the geographical conditions prevailing in the given catchment and fluvial system.

The results obtained within this chapter provide quantitative input data for the sediment balance and broad knowledge about the impact of the main pressures on the Danube channel morphology under specific flow and sedimentary conditions.

This chapter consists of three main parts focusing on the following areas: spatial and temporal river bed changes in the Danube; long-term changes of the longitudinal profiles caused by sediment continuity disruption and other pressures; and spatial and temporal variations in the grain size of river bed sediments.

5.1 Spatial and temporal variation of the Danube River bed in national reaches

The main objectives of this chapter are focused on identification and quantification of the river processes (erosion/ sedimentation) that prevailed on the particular river reaches along the Danube in response to disrupted sediment continuity and other hydromorphological pressures (dredging, gorynes, flow regulation). objectives were as follows: to cover areas as followes

- to provide some insight into the long-term, midterm and short-term morphological development of the Danube river bed for a better understanding of the river’s behaviour;
- to identify the erosion and/or sedimentation processes taking place in the national sections of the Danube River in the periods considered in this study;
- to quantify the river’s response to bed level changes in view of the ongoing process of erosion, sedimentation or dredging (feeding) along the national river sections;

- to provide input data and information for sediment balance assessment for the Danube (Activity 4.2), sediment management (WP6), and for other sediment-related issues.

Analyses and quantification of erosion and sedimentation in the Danube riverbed is based on channel bathymetry in relation to interruption of sediment continuity and dredging activities (amounts of bed sediments removed from the river).

Analyses of the river processes were performed with contribution of the project partners along their national reaches due to specific flow and sedimentary conditions, which are influenced by several different pressures.

The range of morphological analyses performed by project partners, depends on data availability in each country and mostly cover the second and third period.

Therefore, the main structure of this chapter consists of sub-chapters, focusing on the situation prevailing in the national sections of the Danube River.

5.1.1 Germany

Brief description of the national river reach

The Danube River originates in southern Germany in the Black Forest. The German reach of the Danube is divided into two administrative sections, the federal states of Baden-Württemberg and Bavaria. The length of the Danube in Baden-Württemberg is approximately 200 km, measured from its origin to the city of Ulm, which shares the Danube with the neighbouring Bavarian city of Neu-Ulm. The Bavarian Danube begins where the Iller flows into the Danube (rkm 2588) and ends shortly after the hydropower plant Jochenstein, where the Dandlbach enters the Danube (rkm 2201.8) at the border to Austria.

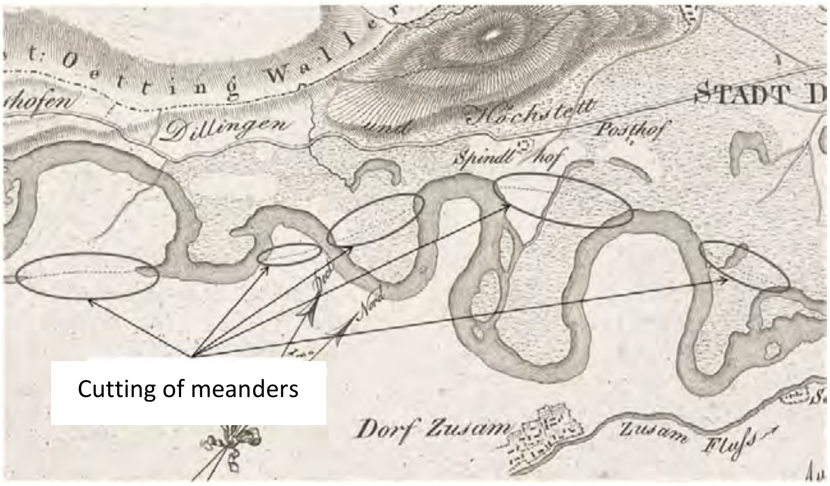


Figure 5.1.1 Historical river and planned cutting of meanders, after Skublics (2014)

The original historical Danube had a meandering, braided shape with wide inundation and retention areas. At the beginning of the 19th century, the Danube was still in a natural condition. The river could freely develop and was morphologically very active. However, widespread floods affected nearby cities and cultivated land, and caused diseases. Therefore, starting in 1806 to 1867, humans regulated the river to improve the situation for flood mitigation and land cultivation.

During this time, the meanders of the river were cut off to create a straight, channelized shape, riverbanks were protected and groynes were built. These measures caused a detachment of the natural floodplains and the river. The straight river course generated an additional benefit for navigation. Moreover, these measures initiated an ongoing riverbed deepening, which the engineers had planned in order to drain the floodplains. This made them suitable for agriculture and prevented diseases from swamps.

In the first part of the 20th century, flood protection dykes along the Danube were reinforced and extended, further reducing natural inundations. The deepening of the river continued over time, affected only by regulation of the tributaries. For instance, the important alpine tributaries Iller, Lech, Isar and Inn, which originally contributed great amounts of coarse gravel to the Danube, were also regulated and modified.

Around 1958, the negative consequences of riverbed erosion became apparent, and as a countermeasure, run-of-river hydropower plants were constructed along the river. Until 1992, twenty-two hydropower plants were built in Bavaria. Nowadays, these structures are forming a chain of impoundments, and only three short free-flowing sections remain. The modification of the river makes a stable water level possible, which makes the Danube into an international waterway enabling navigation from the Black Sea to the North Sea.

In summary, the anthropogenic changes to the Danube are significant. Over the last 200 years, the river course was severely changed and hydropower plants now regulate the flow. The lateral and vertical connectivity of the river is disturbed. The hydraulic, morphological and ecological conditions are certainly different today than they were before. However, the impact of the individual pressures and their consequences are unclear. This chapter addresses these issues and describes the morphological development over time.

Spatial and temporal variation of the Danube channel morphology

To understand and predict sediment behaviour of a river, a profound knowledge of the underlying processes is necessary. Therefore, a detailed analysis of the sediment transport processes for the river of interest was conducted. Most of the gauging stations at the Danube show an increasing trend of floods between 1951 and 2002. In addition, the discharge behaviour in the Danube is dominated by summer floods and gauges in the mountain ranges represent faster runoff regimes. The volumetric sediment data analysis for the German Danube (rkm 2,588 – 2,202) concludes 6 periods, that are discussed in the following chapters.

To get a better understanding of the sediment processes taking place in the German Danube, a variety of influences have to be considered. This includes effects of dams and tributaries as well as hydrological, hydrodynamic, and morphological effects and variations over the years.

Since sedimentation and erosion occur naturally in a river, this analysis will only focus on extreme events.

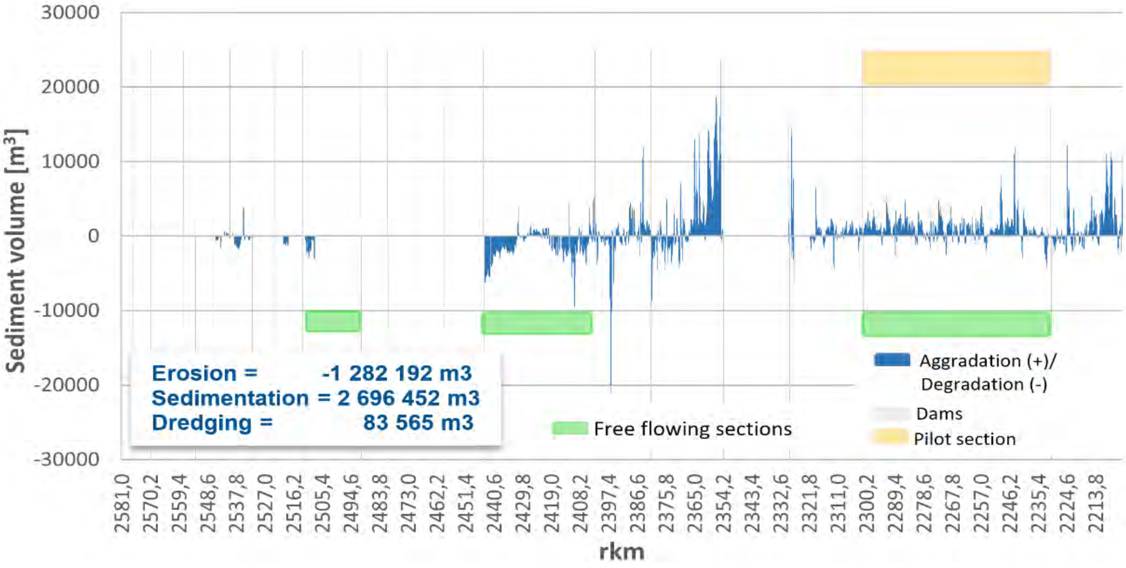


Figure 5.1.2 Riverbed changes in the Danube/ Germany period III. – 1990-1995

The first continuous suspended sediment measurements were carried out for a 5-year period between 1990 and 1995. Figure 5.1.2 shows the erosion and sedimentation volumes for this period and the total values of erosion, sedimentation, and dredging. The section in orange is the German pilot section “Kelheim to Geisling”, which was analysed in detail in another activity of the DanubeSediment project. Dams (marked with grey lines) have a big influence on sediment processes in the Bavarian Danube. One interesting event is the considerable amount of sedimentation in front of the ship locks Geisling (rkm 2354). A reason for this could be that the ship lock was built in 1980 and still had a larger influence on sedimentation during that period. For the other sections, there is either no suitable data available or erosion and sedimentation fluctuates in an acceptable range.

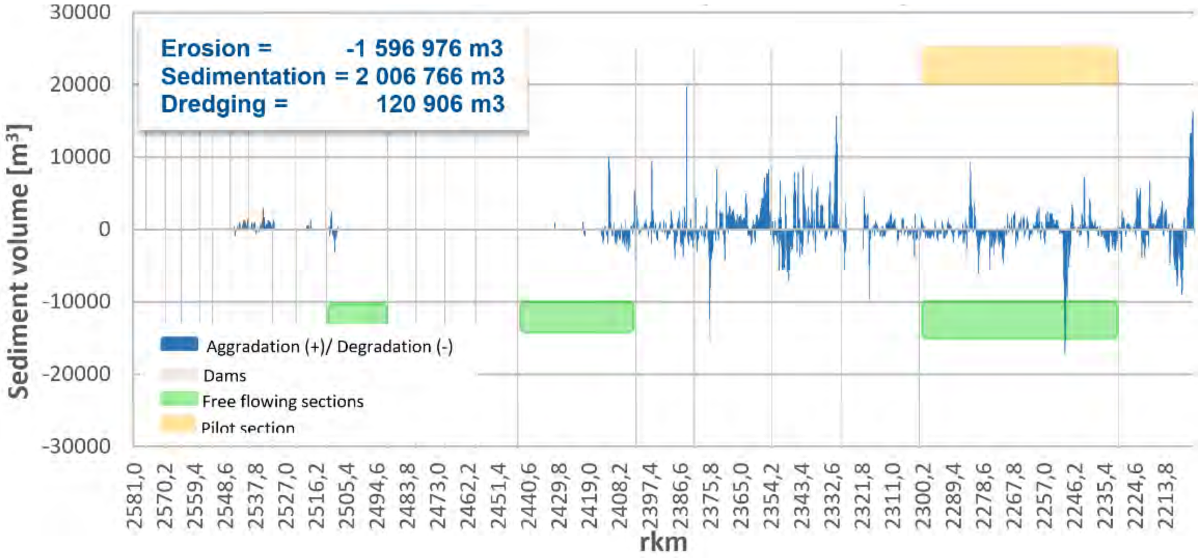


Figure 5.1.3 Riverbed changes in period III. (1995-2000)

In the period from 1995 to 2000, the so-called Pentecost Flooding occurred in 1999. This event is classified in the entire German Danube as an extraordinary event. Especially for the upper section, upstream of rkm 2400, the event was in the size of HQ_{100}. The big tributaries Isar (rkm 2281.7, ~HQ_{50}) and Inn (rkm 2225.3, ~HQ_5) showed also high discharge regimes. This event transported and remobilized great amounts of sediment, leading to developments in the riverbed, which are visible in the balance. The following table provides an overview of the flood event along the Danube with peak discharges and classification of the return period.

Table 5.1.1 Overview of flood discharges of Pentecost Flooding (1999) along the German section of the Danube

Station	rkm	Peak Discharge Q_{max} [m³/s]	Return period T_n
Neu-Ulm	2586.7	1020	30
Dillingen	2538.3	1030	10-20
Donauwörth	2508.1	1060	10
Tributary Lech	2496.5	1500	50-100
Ingolstadt	2458.3	2270	200
Kelheim	2414.8	2140	50-100
Oberndorf	2397.4	2180	50
Schwabelweis	2376.5	2280	10-20
Pfelling	2305.5	2350	10-20
Tributary Isar	2281.7	1180	50-100
Hofkirchen	2256.9	3300	20-50
Tributary Inn	2225.3	3500	2-5
Achleiten	2223.1	5400	5-10

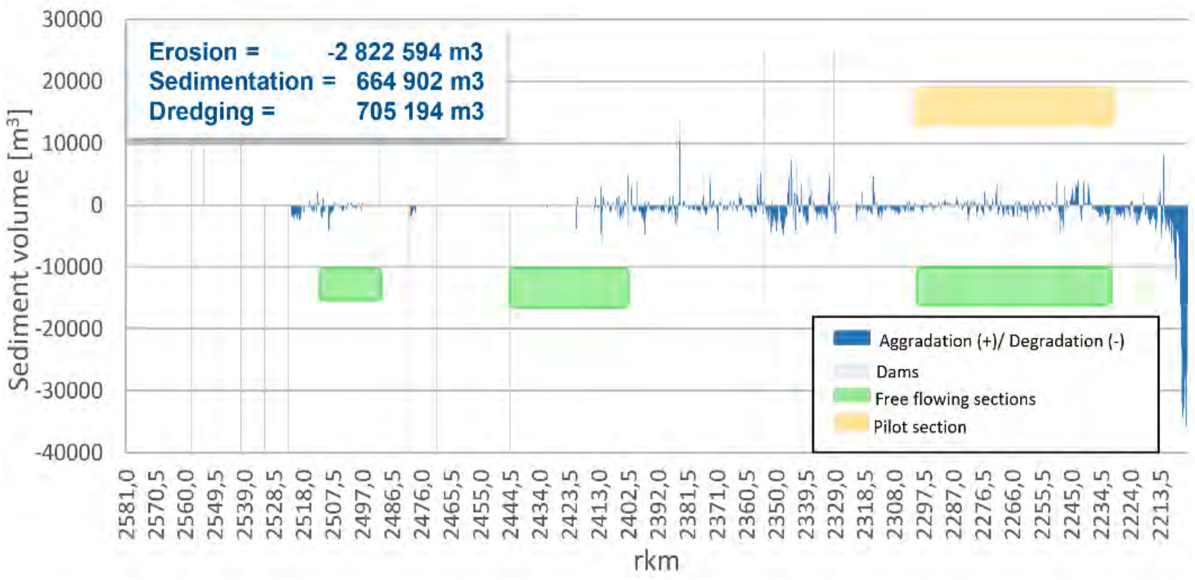


Figure 5.1.4 Riverbed changes in period III. (2000-2003)

Figure 5.1.4 shows, that during the period 2000 – 2003 high erosion with up to around 35000 m³ occurred between weir Kachlet (rkm 2230.8) and weir Jochenstein (rkm 2203.2). Figure 5.1.5 shows the corresponding monthly minimal and maximal discharges in the Danube at the gauging station Pfelling (rkm 2305.5). The main reason for the extreme erosion is the flood that occurred in 2002. This flood had a peak discharge of 2400 m³/s at the gauging station Pfelling (rkm 2305.5) in August 2002. During the flood one of the major tributaries, the Inn (rkm 2225.3), contributed a huge discharge to the Danube. The discharges of the Danube and the Inn summed up in Passau to approx. 7700 m³/s, which corresponds to a HQ_{50}.

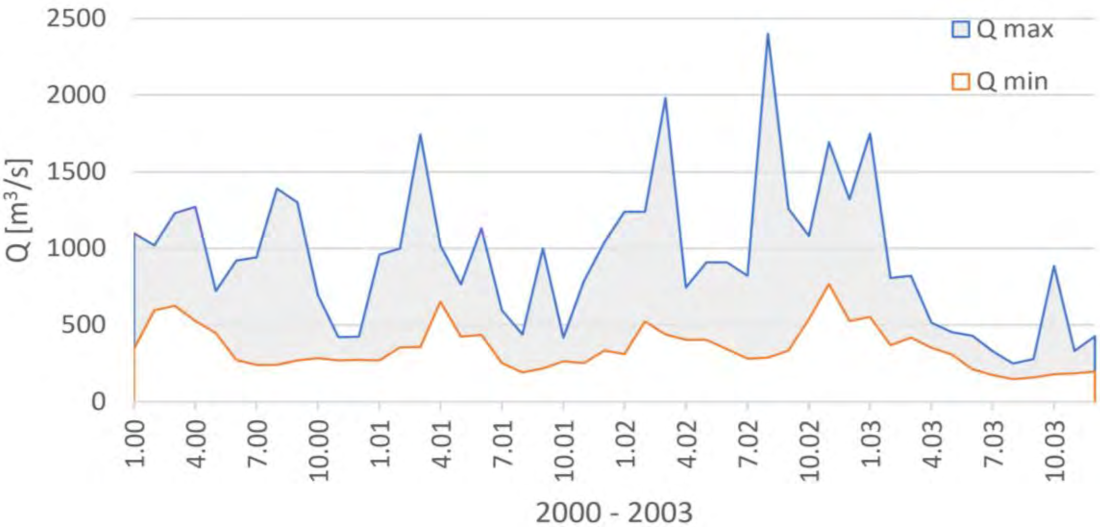


Figure 5.1.5 Monthly minimum and maximum discharges at gauging station Pfelling 2000-2003

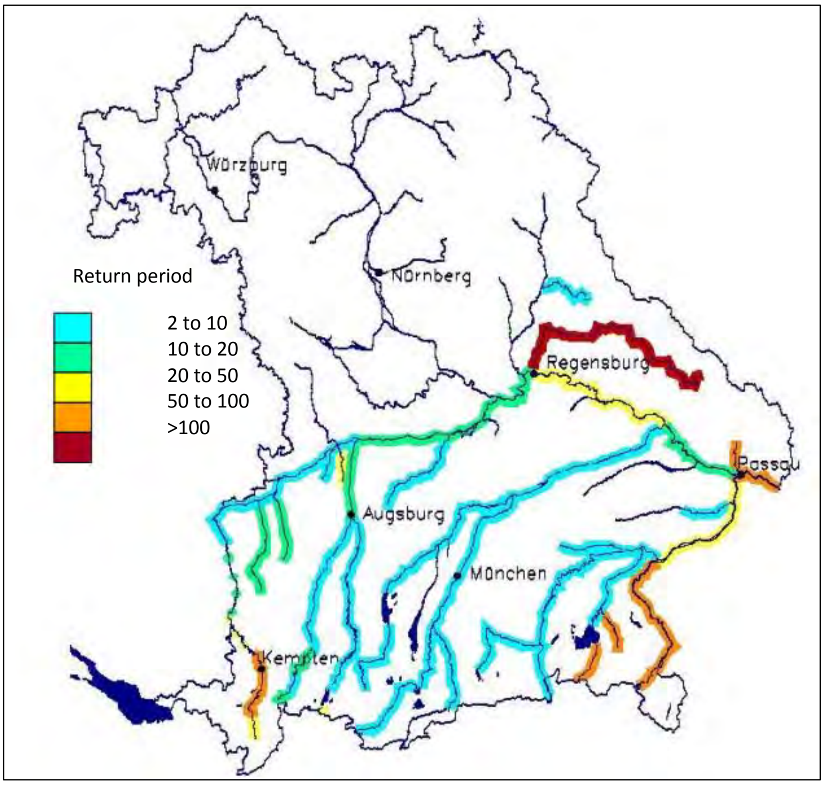


Figure 5.1.6 Overview of the return periods in the German Danube catchment for the 2002 flood event (after GKD, 2002).

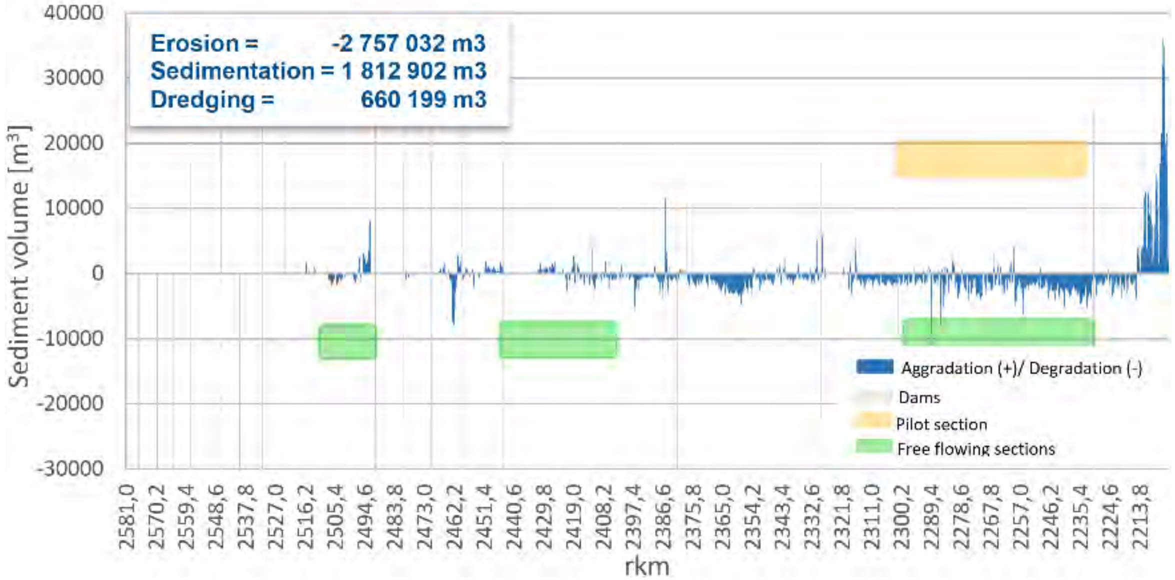


Figure 5.1.7 Riverbed changes in period III. (2003-2007)

Figure 5.1.7 shows that during the period 2003 – 2007 a low, but continuous erosion occurred along the measured section of the Danube. The flood in 2002 transported the sediment further downstream of weir Jochenstein (rkm 2203.2) and thereby offered space for sedimentation. In combination with the transported sediment in the Danube and the sediment contribution from the Inn (rkm 2225.3), this leads to a high sedimentation between the Inn tributary and weir Jochenstein.

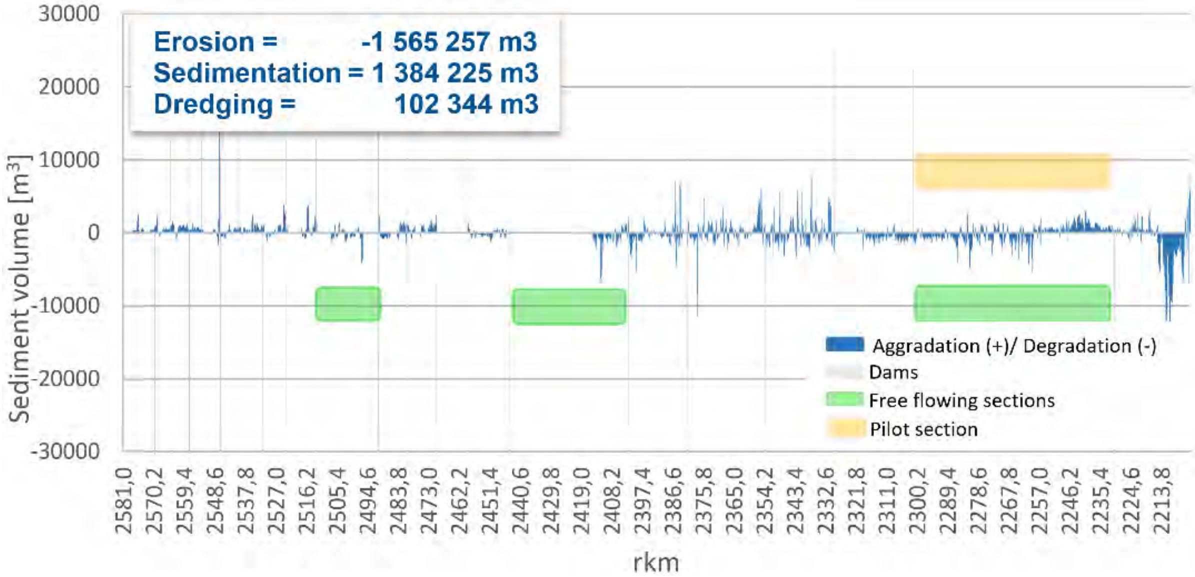


Figure 5.1.8 Riverbed changes along the Danube in Germany, period III, 2007-2010

During the period 2007 – 2010, no flood events occurred that led to greater erosion or sedimentation (see Figure 5.1.8). Figure 5.1.9 shows that a high amount of erosion occurred in the period 2010 – 2017 at the end of the German Danube. The main reason for this was the extreme flood in June 2013. Figure 5.1.10 shows the corresponding minimum and maximum monthly discharges at the gauging station Pfelling (rkm 2305.5) for this period. Here we can see that the Danube reached a peak discharge of 2880 m^3/s.

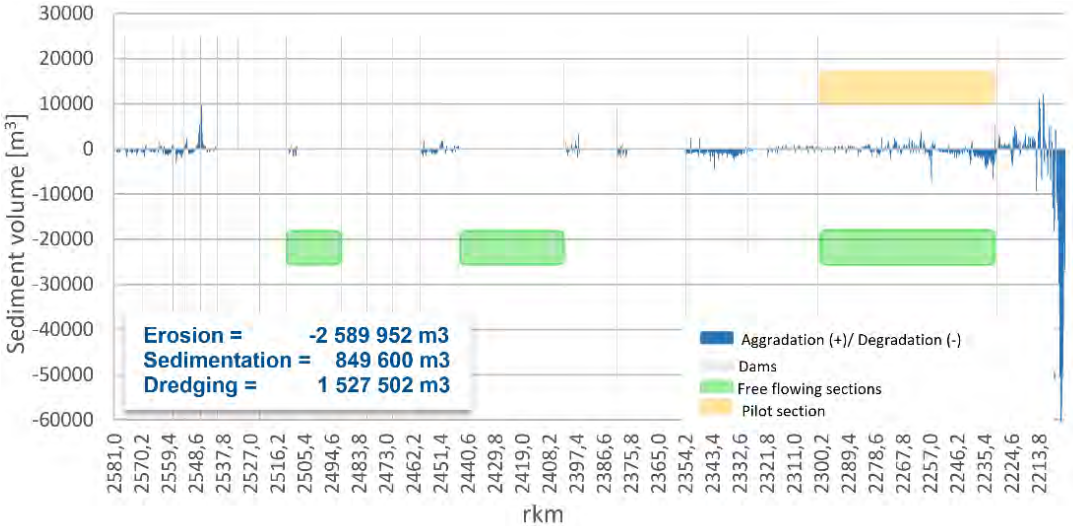


Figure 5.1.9 Riverbed changes along the Danube in Germany, period III, 2010-2017

The flood led to a high mobilization and transport of sediment. The main precipitation was distributed over two time blocks separated by only a few hours, which resulted in a single peak, with a long-duration flood wave along the Inn and subsequently, the Danube. At the confluence of the Bavarian Danube and the Inn in Passau, the discharges of both rivers sum up to a peak of approx. 10 000 m³/s leading to a discharge higher than a HQ_{100}. During the flood, the inundation level in the city Passau reached a peak of 12.89 m.

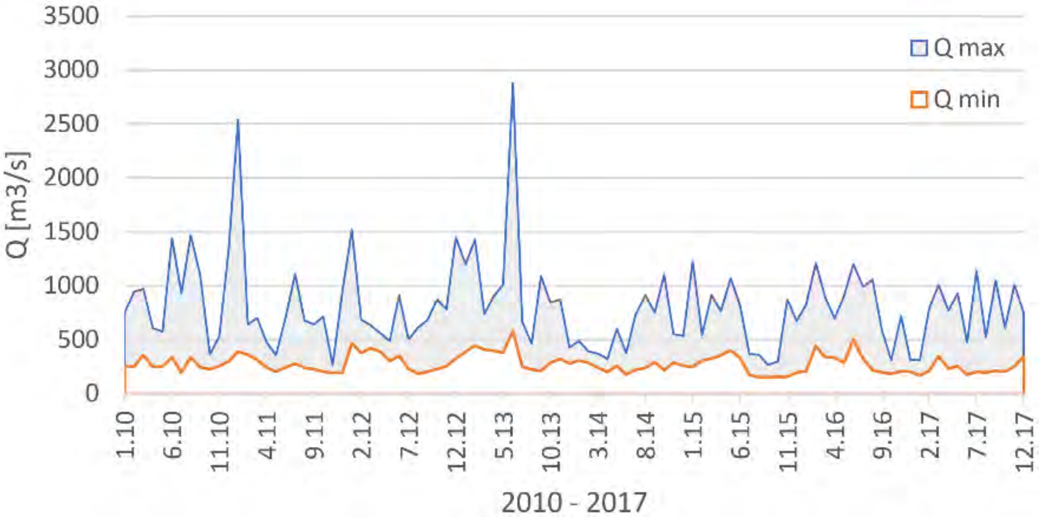


Figure 5.1.10 Monthly minimum and maximum discharges at gauging station Pfelling 2010-2017

Spatial analysis of mean riverbed development over time

Since the Bavarian Danube consists of twenty-two reservoirs, which cut the river into different sections, a sectional analysis of the mean riverbed development is possible. In the following, the mean riverbed elevations over time are plotted, starting from the section furthest upstream, going downstream. In addition, an approximated water surface level is visualized to identify the dams and reservoirs, and the names of the tributaries are indicated where they enter the Danube. Due to a lack of historical data, this detailed analysis is only possible for the newer decades. Nonetheless, the analysis correctly represents the current and ongoing processes in the German Danube sections.

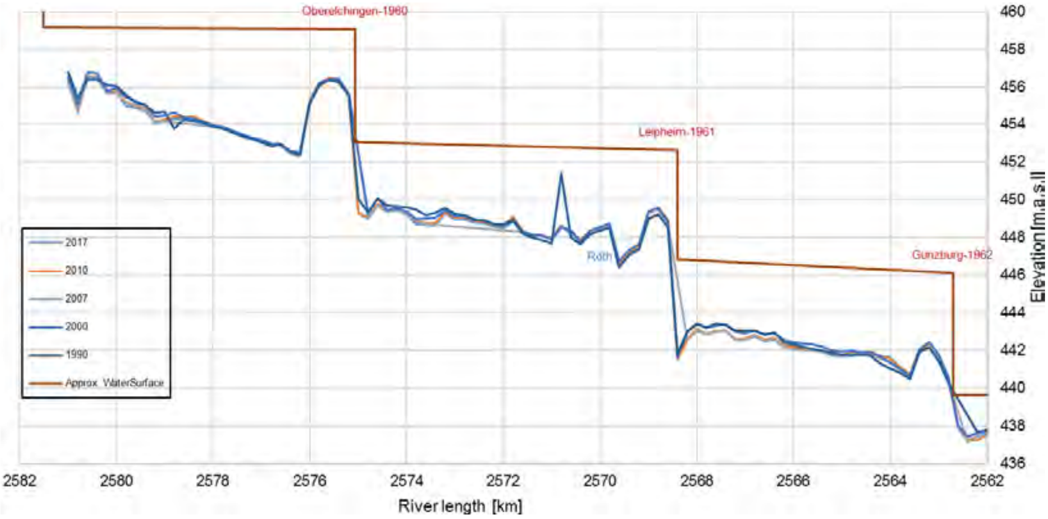


Figure 5.1.11 Development of longitudinal profile in section from rkm 2582 to rkm 2562

In the first section (Figure 5.1.11), the riverbed basically remains constant over time, altering only slightly. The effect of the construction of hydropower plants in 1960-1962 is almost over. The riverbed has adapted to the shape of the water surface in the reservoir and forms steps. A stable sedimentation in front of each reservoir can be detected as well.

The following section (Figure 5.1.12) shows identical characteristics.

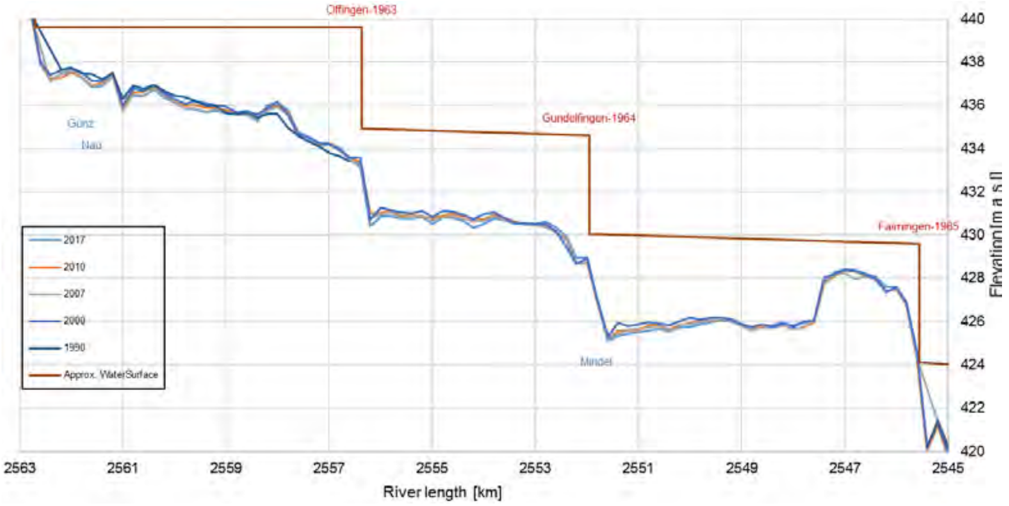


Figure 5.1.12 Development of longitudinal profile in section from rkm 2563 to rkm 2545

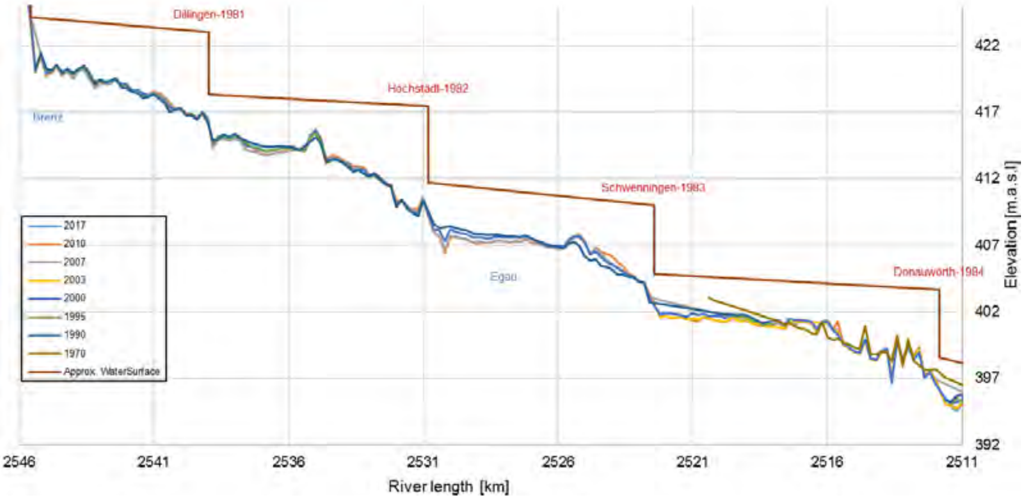


Figure 5.1.13 Development of longitudinal profile in section from rkm 2546 to rkm 2511

The third section (Figure 5.1.13) includes data from 1970, the time before hydropower plant construction, showing the original slope of the Danube. The powerplants in this section were built around 20 years later than the upstream ones. Therefore, we can see in the reservoir Schwenningen an ongoing erosion at the head of the reservoir and sedimentation close to the weir. This effect will probably stop in the next decades and a new equilibrium will be reached, like in the previous sections.

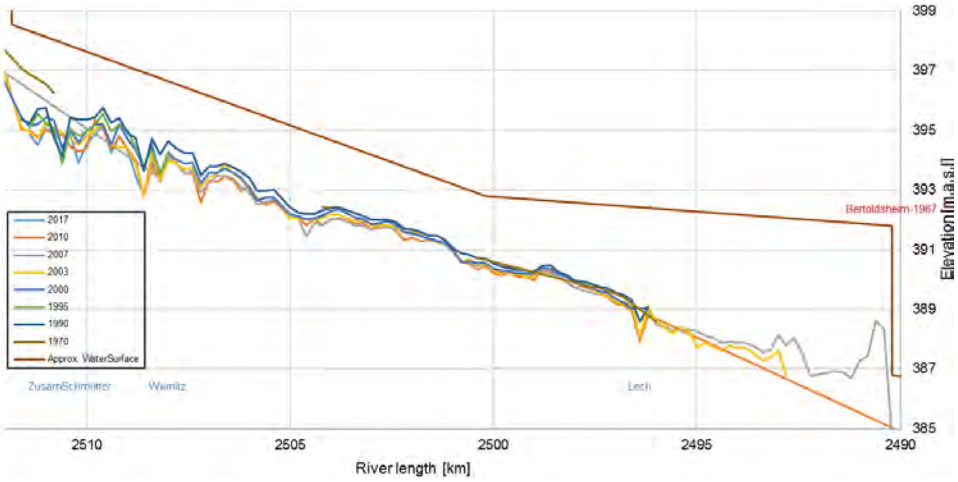


Figure 5.1.14 Development of longitudinal profile in section from rkm 2512 to rkm 2490

The section on Figure 5.1.14 includes a short free-flowing section, where an ongoing erosive trend can be detected. This is a consequence of the resservoir cascade above, where sediment is trapped.

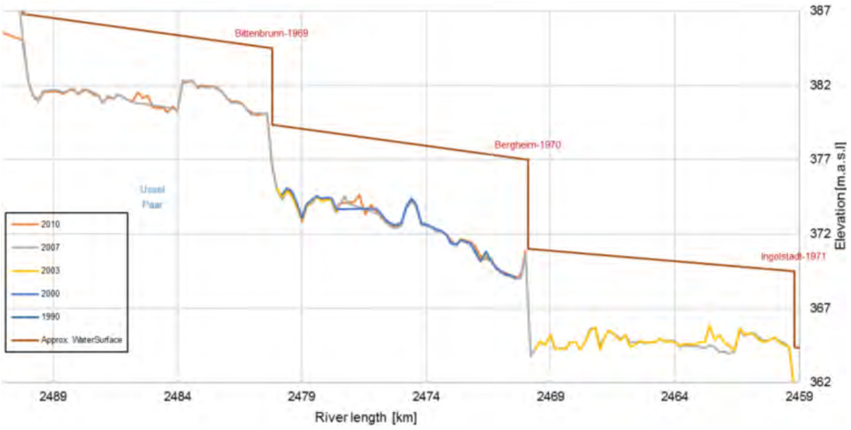


Figure 5.1.15 Development of longitudinal profile in section from rkm 2490 to rkm 2460

For the following three reservoirs (Figure 5.1.15), we do not have very much data, but the stepped shape of the riverbed is clearly visible and it runs almost parallel to the surface of the water level.

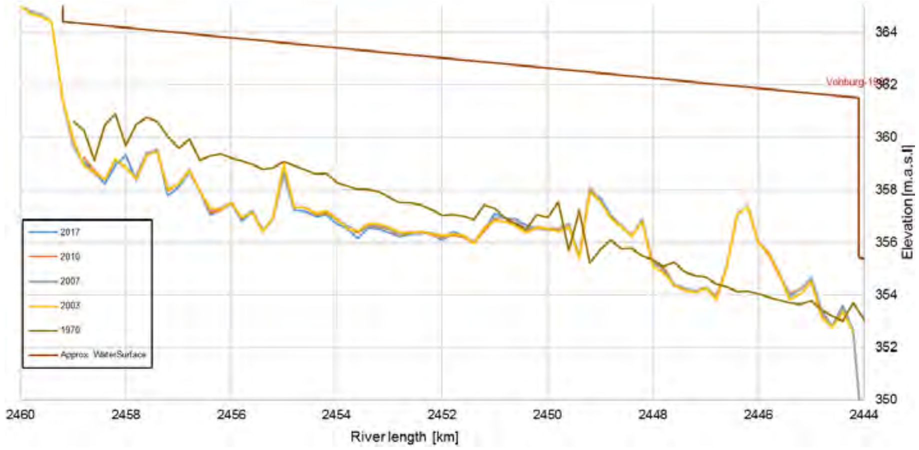


Figure 5.1.16 Development of longitudinal profile in section from rkm 2460 to rkm 2445

At the reservoir Vohburg, built in 1992, data from 1970 is available (Figure 5.1.16). The initial riverbed was around 1-2 m higher in the upstream part and consequently lower in the downstream part. In the meantime, quite stable conditions have already been reached, with only minor alterations.

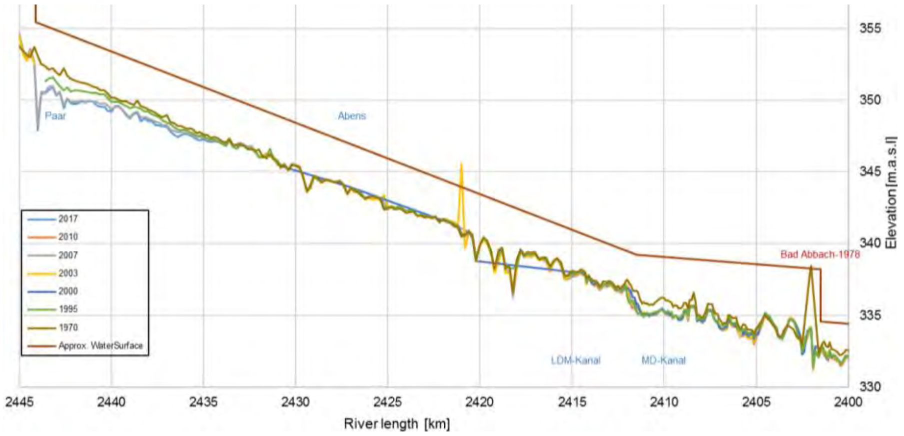


Figure 5.1.17 Development of longitudinal profile in section from rkm 2445 to rkm 2400

In section on Figure 5.1.17 the navigation of the Danube starts at rkm 2415. Here, the Main-Donau-Kanal connects the waterways of Main and Danube. In the upper section, free-flowing conditions exist and a slight erosive trend of the riverbed can be seen. In addition, the riverbed in the reservoir of Bad Abbach is also lower nowadays than in 1970.

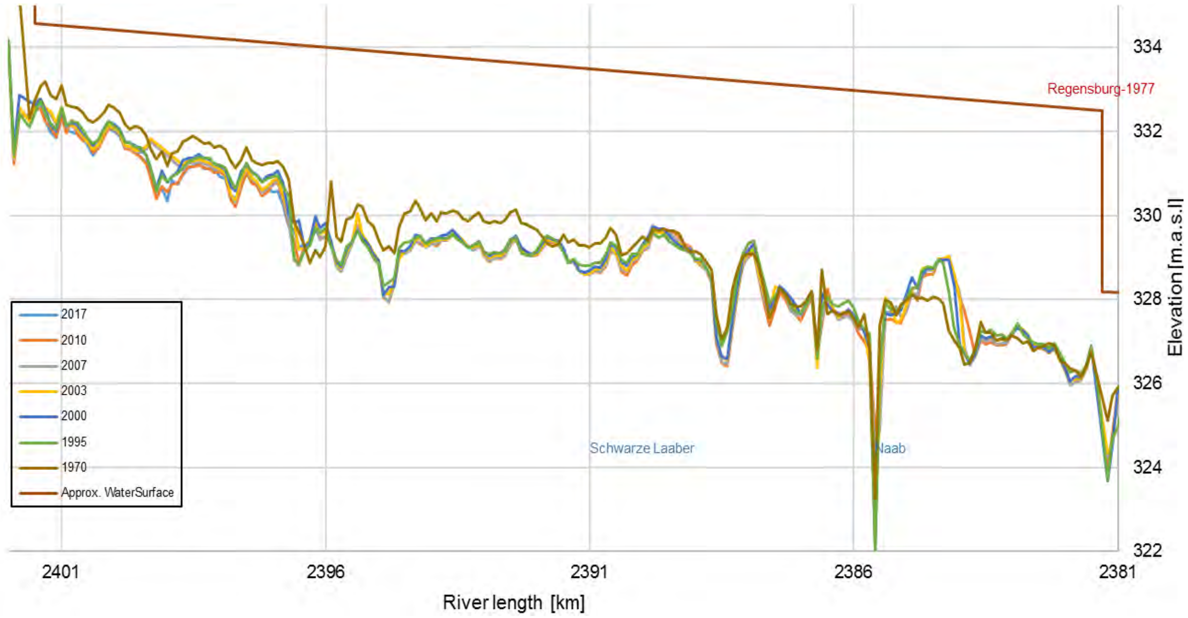


Figure 5.1.18 Development of longitudinal profile in section from rkm 2400 to rkm 2380

Figure 5.1.18 shows again the process of erosion and sedimentation in the reservoir. Alterations are generally low, also influenced by dreding and feeding to ensure a safe and stable waterway.

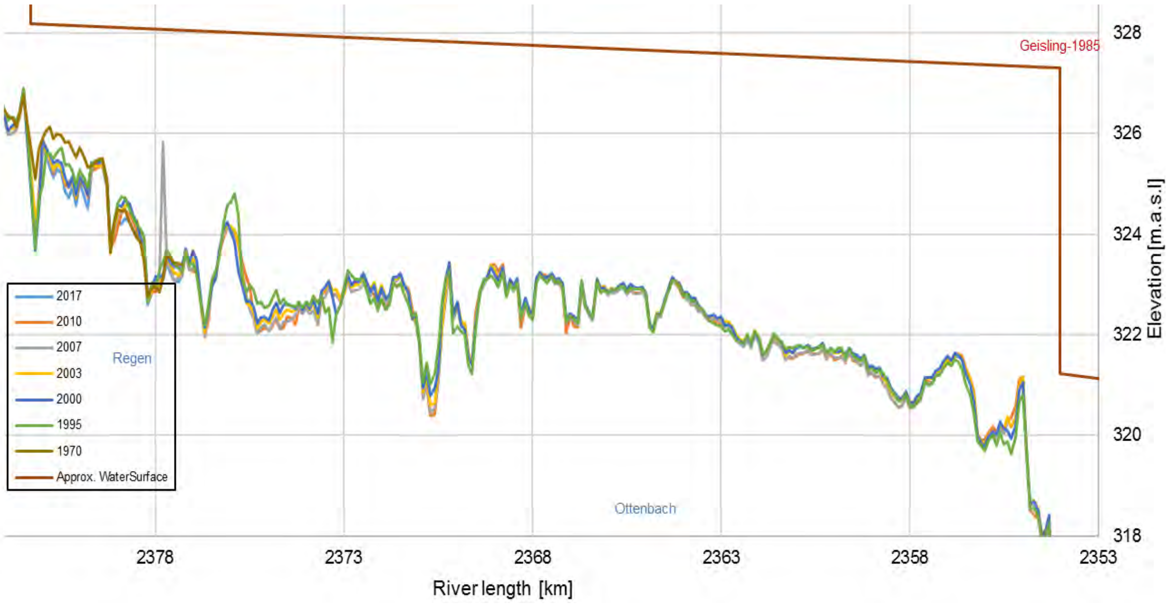


Figure 5.1.19 Development of longitudinal profile in section from rkm 2380 to rkm 2353

The section on Figure 5.1.9 has characteristics similar to the previous one.

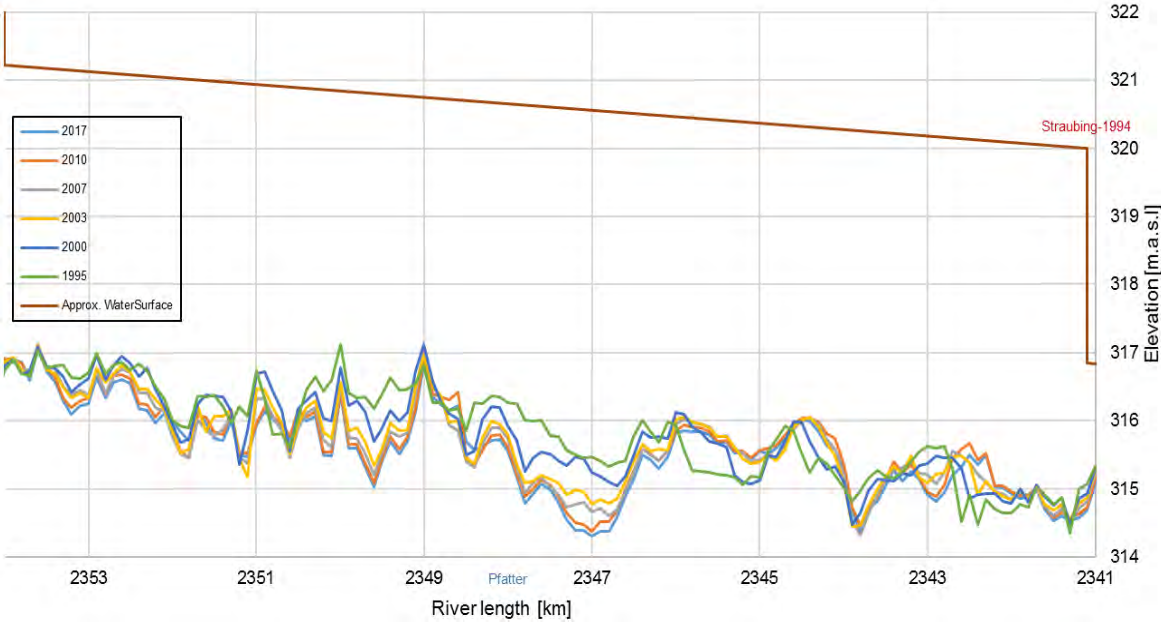


Figure 5.1.20 Development of longitudinal profile in section from rkm 2353 to rkm 2341

Short section on Figure 5.1.20 shows greater erosion. It might be a consequence of the lack of sediment from upstream, from dredging and flood events.

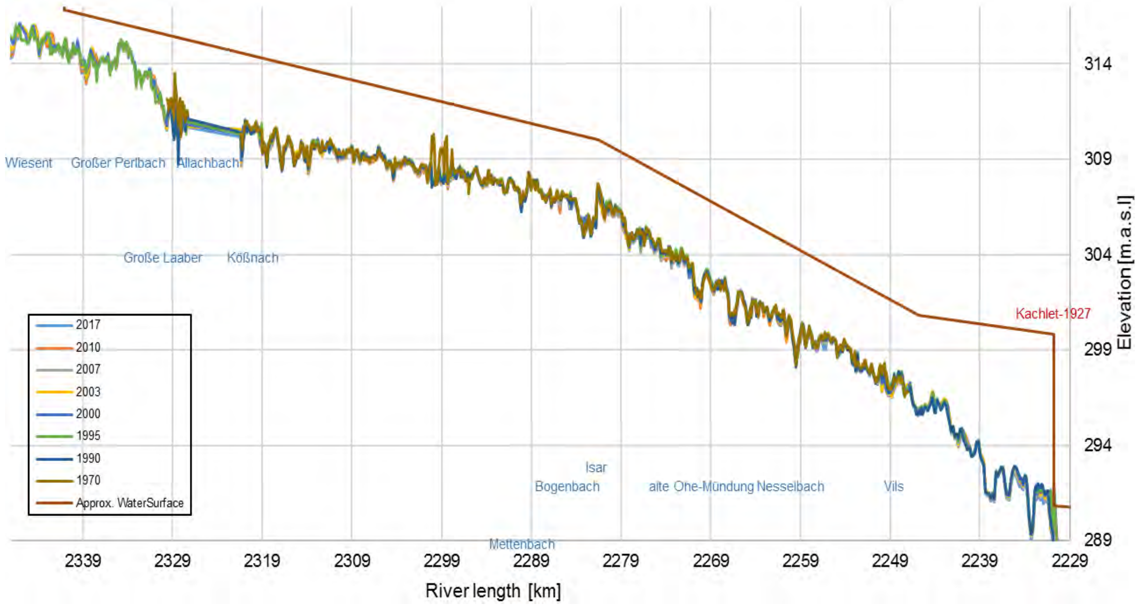


Figure 5.1.21 Development of longitudinal profile in section from rkm 2341 to rkm 2230

The largest free-flowing section of the Bavarian Danube is characterised by a change of slope at rkm 2281 (Figure 5.1.21). This is where the river Isar flows into the Danube. Historically, the Isar contributed large amounts of coarse gravel, forming a dumping cone at the confluence with the Danube. This contribution of gravel has stopped during the past years due to the construction of hydropower dams in the lower Isar. To ensure that the dumping cone keeps its stabilizing effect for both the riverbed and water level of the Danube, great efforts in sediment management are being undertaken. Otherwise, strong erosion would occur.

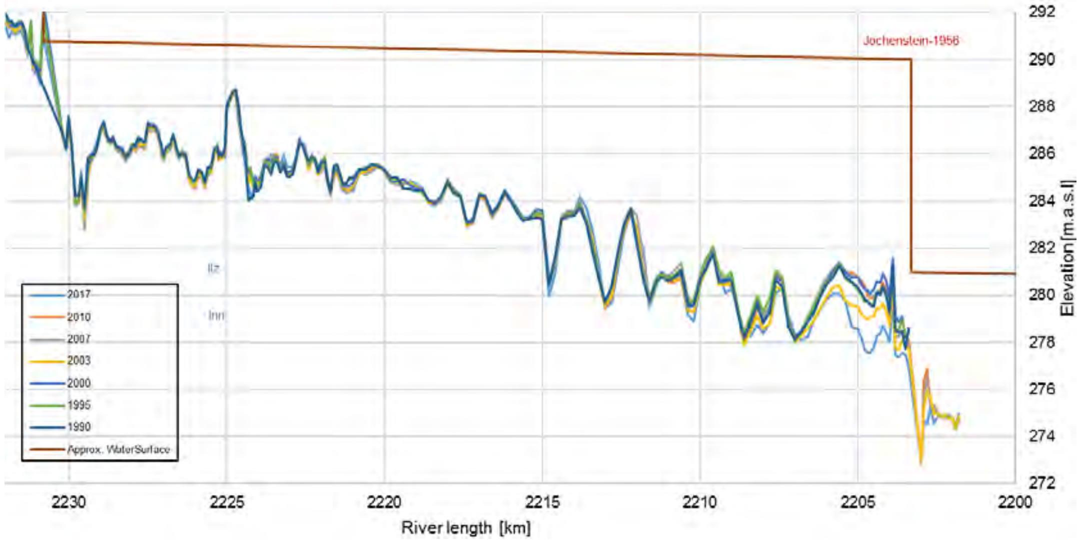


Figure 5.1.22 Development of longitudinal profile in section from rkm 2230 to rkm 2200

The last section on Figure 5.1.22 is highly influenced by the Inn River. During floods, this river can contribute higher discharges than the Danube itself. This is also the reason for erosion in the lower reservoir. During the 2002 and 2013 flood event, sediments from the reservoir were flushed out. However, after such events, sedimentation takes place again, e.g. as the 2010 data shows.

Pilot section Kehlheim (rkm 2415) to Geisling (rkm 2365)

Within DanubeSediment project, specific sites were selected as pilot regions to be studied in more detail. The German partners (LfU and TUM) selected a 50 km long reach of the Danube, where several drivers led to greater changes of the river (Figure 5.1.23).

In this section, there are two hydropower plants, namely Bad Abbach (rkm 2401.5) and Regensburg (2381,3). An analysis of the thalweg development between 1927/1943 until 2010 shows that the riverbed has clearly changed. In general, the chain of HPPs in the German Danube and in tributaries trap sediments, especially bedload. Also, in upstream sections of the impounded pilot region, a lack of sediment can be detected, leading to strong erosion and a deepening of the riverbed. However, close to the HPP at rkm 2385, this effect is not present. There, smaller particles (suspended load) and partially bedload is deposited, as they cannot pass the weir. Only in cases of flooding, are the weirs opened for a long time, allowing sediment to pass.

This erosive effect was strong in the first period, after construction. Since 1970, the erosion rate decreased and between 1990 and 2010 almost stopped as the system created a new morphological equilibrium. Nowadays, alterations of the riverbed are mainly induced by strong flood events such as the ones observed in 1999, 2002, 2005 and 2013. Significant dredging and feeding activities were not recorded in this region. A reason might be that the chain of HPPs along this reach of the Danube ensure the water level for navigation.

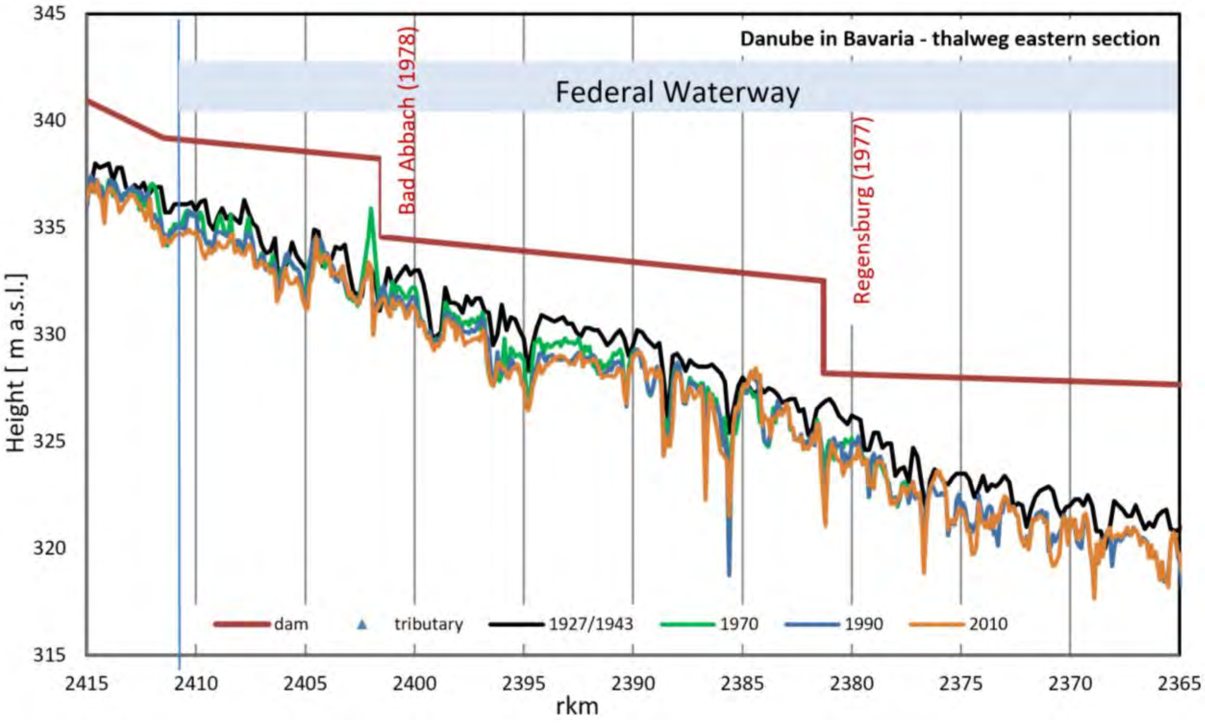


Figure 5.1.23 Development of longitudinal profile in pilot section Kehlheim (rkm 2415) to Geisling (rkm 2365)

Conclusion

The German Danube has clearly changed its shape over the years. The river was regulated and shortened in length and width (Skublics, 2014). The construction of a chain of HPPs along the Danube as well as important tributaries, interrupts the connectivity of the river, causing a disturbed sediment regime. In the reservoirs, sediment accumulates, which causes a deficit in downstream sections. However, the erosive trend seems to be decreasing in the last decades and a new kind of equilibrium situation has established in the impoundments. In the remaining free-flowing sections, for example between rkm 2,341 and 2,230, alternative management concepts have been established to ensure the quality of the near-natural system regarding hydraulics, morphology and biology. "Weak" concepts have tested, for example, the reinforcement of a natural bar to keep the water level high for navigation as well as to lower the flow velocities. In addition, a pilot study shows that the idea of "coarse gravel enrichment" is supposed to prevent erosion but requires a dense monitoring strategy.

5.1.2 Austria

Brief description of the Danube in Austria

The Austrian section of the Danube has a length of 350.5 km and the character of an alpine river. Around 96% or 80,565 km² of the national territory of Austria contribute to the overall catchment area of 801,463 km³ of the Danube River and to around 25% of the overall discharge into the Black Sea (BMLFUW, 2017). The section begins at the border with Germany (river-km 2,223.2) with a stretch forming the border between Germany and Austria from rkm 2,223.2 to rkm 2,201.77. The border between Austria and Slovakia stretches from rkm 1,880.1 to rkm 1,872.7. On its way across Austria, the Danube overcomes a height difference of around 157.3 m (at mean water level), corresponding to an average slope of around 0.45‰. The major alpine tributaries, the Inn, Enns and Traun, define the hydrological regime of the Austrian Danube. Influenced by these tributaries, the river's discharge peaks in spring/summer owing to the snowmelt in the Alps (Mader et al., 1996). A large part of the water volume in the Upper Danube comes from the Inn River, which has a mean annual discharge of 728 m³/s (recorded at the Schärding gauging station), slightly higher than that of the Danube itself. The Enns and Traun rivers have a mean annual discharge of 204 m³/s (gauge: Steyr (Ortskai)) and 130 m³/s (gauge: Wels-Lichtenegg) (BMNT, 2018a) respectively. Through its high bedload and suspended sediment input, the Inn River strongly influenced on the Austrian Danube's sediment regime in the past and still has a strong influence on it in terms of suspended sediments.

In a historical perspective, the development of the Austrian Danube can be broadly divided, in terms of its morphological changes and sediment regime, into four stages:

- Before 1850: Local measures for flood protection and navigation without greater influence on the river's morphology; the sediment regime (especially the suspended sediments) may already be changed as a result of deforestation/aforestation and altered land use.

- Between 1850 and 1955/1958: Systematic mean and low water regulation for flood protection and inland navigation, causing major changes in the river's morphology and sediment regime. Mean water regulation (implemented from 1850 until the beginning of the 20th century) caused the most significant changes, resulting in the Danube's confinement to a single channel with stabilised banks, exposed to permanent river-bed erosion; in addition the regulation activities and hydropower plants built in the tributaries further reduced the sediment supply into the Danube.
- Between 1955/1958 and 1997: Construction of a chain of hydropower plants in the Austrian section of the Danube, with the last one completed by end of 1997 (Freudenau).
- Since the middle of the 1990ies. Modified sediment management in the two free-flowing sections, leading to a gradual decrease of the amount of dredged (removed) sediments. The goal is now to retain the channel forming sediments in the fluvial system and to relocate the bedload upstream after dredging in order to feed it into the river later. The gravel feeding started in 1996 downstream of the Freudenau HPP, with the amount fed increasing recently. The implementation of river restoration measures started in the two remaining free-flowing sections and has continued to date. In some of the impoundments, the sediments are used to create bars and islands (e.g. Aschach).

Information on bedload transport in unregulated stretches of the Danube in Austria is based mostly on assumptions, as there are no (known) direct bedload transport measurements. Thus, we can give some rough estimates only. Schmautz et al. (2000), for instance, assume a bedload input of around 500,000 m^3/a into the Austrian Danube for the period before the major tributaries were regulated and dammed with hydropower plants. Based on various sources and own calculations, they assume an annual bedload supply of 330,000 m^3/a from the Inn River, 150,000 m^3/a from the Enns River, 10,000 to 15,000 m^3/a from the Traun River, and 5,000 to 15,000 m^3/a from the Ybbs River. In the period between 1880 and 1924, bedload input from the German Danube was already close to zero (~10,000 m^3/a) and was finally disrupted by the construction of the Kachlet HPP (rkm 2,230.8) (Bauer, 1965). Rosenauer (1947) assumes an annual bedload transport of around 300,000 m^3/a for the Austrian Danube near Linz (rkm 2135) and around 430,000 m^3 downstream of Mauthausen (the inflow of the Traun and Enns rivers) at rkm 2,111. He estimated the annual bedload supply from the Enns River at around 100,000 m^3/a and that from the Traun River at 38,000 m^3/a.

Gruber (1973) estimated bedload transport in the Danube at Linz to amount to 300,000 t/a (~170,000 m^3/a) between 1950 and 1957, without specifying how the values were determined. Ehrenberger (1931) estimated the volume of bedload transport at around

600,000 m³/a (~1,000,000 t/a) in Vienna on the basis of direct measurements. A comparable figure was obtained at Bad Deutsch-Altenburg in 1956/1957 by Bundesstrombauamt (the predecessor of viadonau). Both values are for the Danube in a regulated state. The Jochenstein HPP was already in operation at the time of the 1956/1957 campaign, but it is fair to assume that its influence had d not propagated that fast. It should be noted that the first HPPs on the Lower Inn had been put into operation 14 to 15 years earlier.

Using the estimates of Rosenauer (1947) and Schmautz et al. (2000), we have summarised, in Figure 5.1.24, the bedload inputs into the Danube prior to the implementation of major regulation measures.

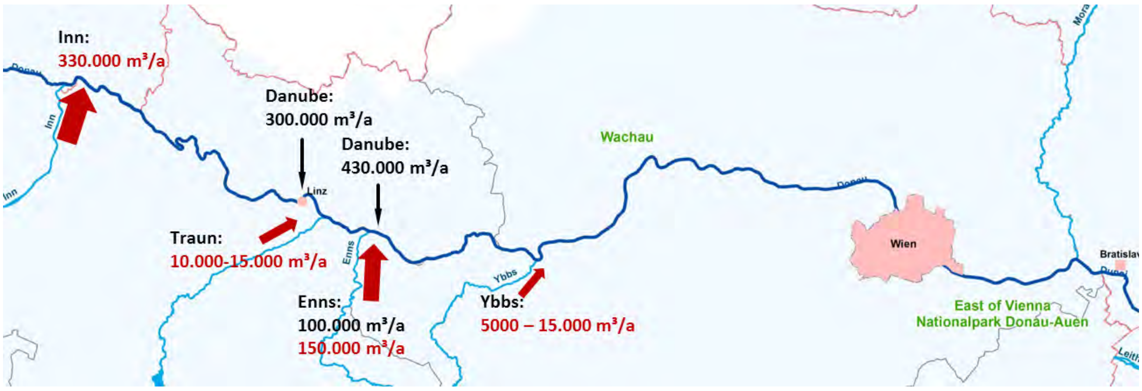


Figure 5.1.24 Estimates of the bedload inputs into the Danube from the tributaries prior to the implementation of major regulations measures and hydropower dams. The figures from Schmautz et al. (2000) are in red and those from Rosenauer (1947) are in black.

Comparing the present annual bedload in a free-flowing stretch East of Vienna (rkm 1,886.24) with measurements from 1956/1957 at Bad Deutsch-Altenburg (rkm 1,885.90), we can see that the annual bedload transport has decreased by over 50%. As already mentioned, the measurements from 1956/1957 represent the Danube in a regulated state, but before the chain of HPPs was constructed. At present, the bedload input into the Austrian Danube is close to zero. The input from the Inn River in 1965 was already smaller than 10,000 m³/a (Bauer, 1965). The mouth of the Traun River is influenced by the backwater of the Abwinden-Asten HPP and the remaining bedload is captured in a bedload trap. The same is true of the Enns River, which is influenced by the backwater of the Wallsee-Mitterkirchen HPP, and were the Enns harbour acts as a sediment trap.

From a geomorphological point of view, the Danube in Austria is characterized by changes in the break-through stretches (narrow incised valleys) and broad stretches in the wider basins with free anabranching reaches (Figure 5.1.25), were the Danube flows through postglacial alluvium. There are further very short break-through stretches, for example, the 'Linzer Pforte', the 'Wiener Pforte' where the Danube cuts through the foothills of the Alps, and the 'Thebener Pforte' at the Austrian-Slovak border.

Figure 5.1.25 Overview of the breakthrough stretches (red lines) and the wider basins (green lines) – modified according to Schmautz et al. (2000)

The two primary processes that made it possible for the Danube to incise into the hard crystalline rocks of the Bohemian Massif were epigenesis (the Danube was already fixed and slowly eroding into those rocks) and a slow local tectonic uplift (Jungwirth et al., 2014). One of the most striking features in this context is the Schlögener Schlinge (an incised double meander) in the narrow valley between Jochenstein and Aschach. The narrowest break-through valley of the Danube in Austria is situated in the Strudengau, which used to be a dangerous place for navigation in historical times and still a challenging one at the present time (Figure 5.1.26).

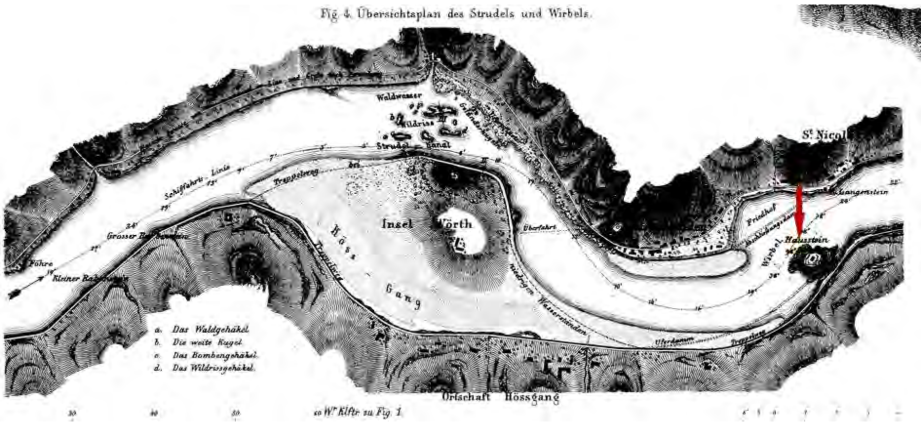


Figure 5.1.26 Historical map of the Struden (rkm 2078 – 2075) from 1771, with the Wörth Island splitting the Danube into Hössgang (right channel) and Strudenkanal (left channel). The red arrow marks the Hausstein. (Baumgartner, 1860).

While the wider basins were filled with quaternary sediments and were subject to a variety of morphodynamic processes, the sections in the narrow valleys served more as a sediment transfer zone, owing to the natural restriction of the river width. According to Hohensinner et al. (2016), the alluvial sections of the Danube in Austria show elements of a braiding / anabranching or a sinuous-meandering river system before the systematic river regulation started in the first half of the 19th century. The Danube usually had one or two dominant main stems, several smaller side arms and gravel bars, and point bars or mid-channel bars, with intense flow dynamics in some parts (Figure 5.1.27).

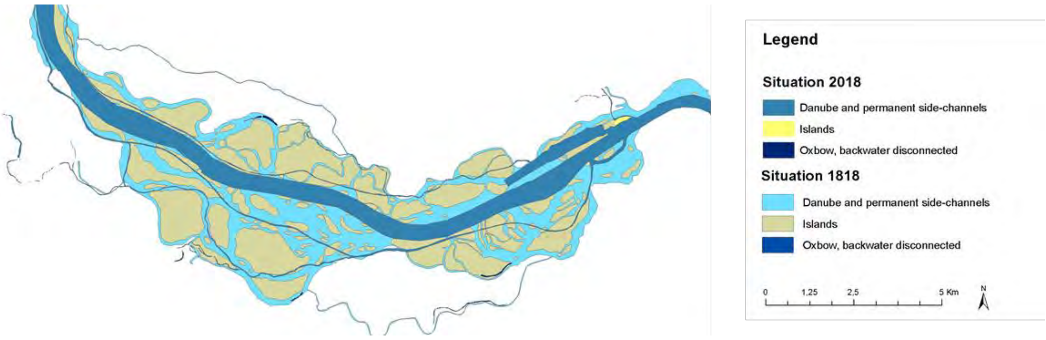


Figure 5.1.27 Eferdinger Becken (rkm 2,159 to rkm 2,144): the situation in 1818 and 2018

The transition between the anabranching and break-through sections is affected by backwater effects during flood events (these effects were stronger before the implementation of regulation measures), owing to the flow restrictions to which the Danube was exposed when entering a narrow valley (Haidvogl et al, 2003). The backwater effects were also responsible for the deposition of gravel and finer sediments in the surrounding fluvial landscape. Depending on the discharge, sediment supply and other characteristics, different sedimentation and erosion processes took place in the narrow stretch downstream (Jungwirth et al., 2014).

Within a short distance downstream of the break-through sections, the river-bed was in some places characterised by large boulders (so called ‘Kugeln’), having a volume of at least 2 m^3 and forming the so called ‘Kachlets’ (Schmutterer, 1959). The ‘Kachlets’ were shallow water sections with rocks protruding above the water surface or forming small island in some places. They usually constitute an erosion base level and are characterized by higher flow velocities and a higher gradient. The Aschacher Kachlet (Figure 5.1.28) for instance had a gradient between 2 and 5‰, which was much higher than the average gradient of the Austrian Danube at that time, i.e. 0.445‰ (Schmutterer, 1959). As they posed a threat to navigation, most of them were subject to regulation activities (e.g. 30,000 boulders were removed from the Aschacher Kachlet within 20 years) with special equipment (Figure 5.1.28).

It is not really possible to divide in time the Danube in Austria into a river in a (near) natural state and a modified river on the basis of information from a certain year. In 1848, for instance, around 70% of the Austrian Danube was already obstructed by bank protection measures (Schmautz et al., 2000) and, after 1850, the first nation-wide river regulation measure took place in Upper and Lower Austria. The measures implemented before 1850 did not follow a systematic regulation scheme but aimed at protecting human settlements and riverbanks against floods and ice drifts or jams, and at improving the conditions for inland navigation (Tschochner, 1957). The subsequent years saw the commencement of systematic mean and low water river regulation.

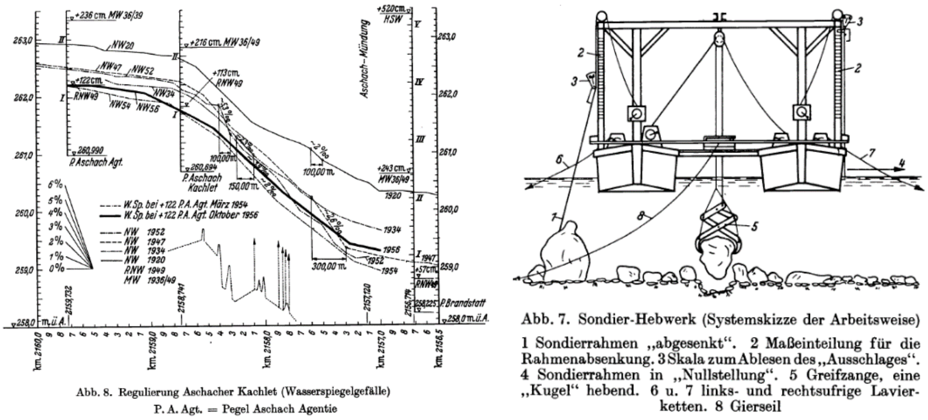


Abb. 8. Regulierung Aschacher Kachlet (Wasserspiegelgefälle)
P. A. Agt. = Pegel Aschach Agentie

Abb. 7. Sondier-Hebwerk (Systemskizze der Arbeitsweise)

1 Sondierrahmen „abgesenkt". 2 Maßeinteilung für die Rahmenabsenkung. 3 Skala zum Ablesen des „Ausschlages". 4 Sondierrahmen in „Nullstellung". 5 Greifzange, eine „Kugel" hebend. 6 u. 7 links- und rechtsufrige Lavierketten. 8 Gierseil

Figure 5.1.28 Left: Diagram showing the regulation of the Aschacher Kachlet (water surface slope); Right: Special equipment for lifting the boulders (Schmutterer, 1959)

According to Schmutterer (1959), the first measure of supra-local significance was the destruction (blasting) of the Hausstein (a rock in the Struden) at rkm 2076 in the period between 1853 and 1866 (Figure 5.1.26, Figure – red arrow). Systematic river regulation along the Danube in Austria began with the large-scale regulation works in Vienna (from rkm 1,935 to rkm 1,918) in the years 1870 to 1875. Thus, the regulation activities can be subdivided into stage dominated by local measures without greater influence on the river's morphology and a stage were the regulation works changed the morphological characteristics of the Danube in Austria to a greater extent.

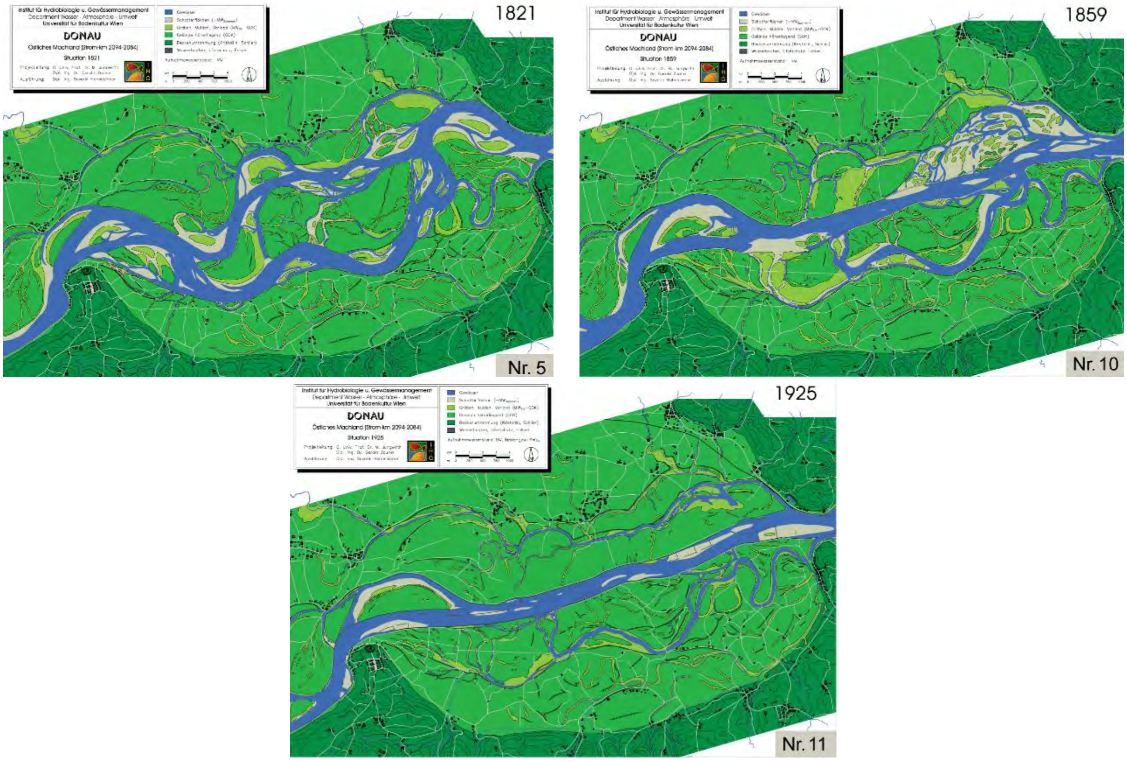


Figure 5.1.29 Situation in 1821 prior to river regulation, situation in 1859 after the intense regulation of the Danube in Eastern Machland, and the situation after the regulation was finished in 1925 (rkm 2,094–2,084). Hohensinner (2008)

This second stage started between 1850 and 1860 in Upper Austria, around 1860 in Vienna, and around 1880 in Tullnerfeld and Marchfeld, up- and downstream of Vienna. Although some of the regulation measures date back to the 1820ies, one of the first cut-offs in Upper Austria with a length of around 2.9 km was made around 1825, approximately at rkm 2,107 (K.K. Technisches Departement Linz, 1909) and the mean water regulation of the Aschacher Kachlet started in 1829 (Schmutterer, 1959). The systematic mean water regulation measures aimed at creating a uniform single threaded river bed by closing off side branches, creating cut-offs, constructing guiding walls and bank protection (Tschochner, 1957). An example of those regulation measures was a complex river system transformed into a single channel, which can be seen in Figure 5.1.29. It shows the reconstruction of Eastern Machland (from rkm 2,094 to rkm 2,084) by Hohensinner (2008) in t 1821 before the river regulation started, in 1859 at the end of the intense regulation period, and in 1925 after the regulation was finished but before the construction of hydropower plants.

The mean water regulations increased the Danube’s sediment transport capacity in the basin to a significant extent, owing to its reduced width, and caused a state of constant erosion (Schmautz et al., 2000). At the beginning of the 20th century, most of the mean water regulations were in place but they did not satisfy the needs of inland navigation in terms of fairway depth and width (Geitner, 1967). The fairway was not stable, but was oscillating between the river banks owing to the wandering gravel bars and had a lot of shallow sections. Therefore, the low water regulation as a sort of ‘fine tuning’ (Geitner, 1967) of the existing regulation measures started at the end of the 19th century, to establish fairway conditions that are adequate for the ever expanding inland navigation. In 1956, around 91 km of the Austrian Danube were low water regulated, one HPP was put into operation (Jochenstein) and another one (Ybbs-Persenbeug) was almost completed (Tschochner, 1957). The construction of the chain of hydropower plants on the Austrian Danube basically marks the beginning of the next period in terms of human modifications. The hydropower plants were built in rapid succession within fairly short time periods in the free-flowing sections downstream of the HPPs. The reduced bedload transport capacity at the head of the impoundments led to bedload sedimentation and stopped the gravel supply into the downstream section.

During the construction of the HPPs at Ybbs-Persenbeug (November 1958), Wallsee-Mitterkirchen (May 1968) and Altenwörth (May 1976), the Danube was free-flowing over a distance of 143,66 and 80 km. Another major influence on the bed levels and the amount of sediments was exerted by tail water dredging during the construction of the HPPs. For the Aschach and Freudenau HPPs, no tail water dredging was performed. For the Jochenstein, Ottensheim-Wilhering, Abwinden-Asten, Wallsee-Mitterkirchen, Ybbs-Persenbeug, Melk, Altenwörth and Greifenstein HPPs, tail water dredging was done over a length of 5 to 10 km. This reduced the water surface slope to a considerable degree in these sections. Dredging for the Ybbs-Persenbeug HPP was performed mostly after the Melk HPP was put into operation, with the aim of removing a large amount of boulders. During tail water dredging for the

Ottensheim-Wilhering, Wallsee-Mitterkirchen, Ybbs-Persenbeug, Melk and Greifenstein HPPs, the underlying rock was cut to some extent. In the impoundments of Abwinden-Asten (near the city of Linz over 3 km) and Wallsee-Mitterkirchen (section Au to Mauthausen over 4 to 5 km), dredging was performed to lower the bed level for flood protection. After the HPPs were put into operation, gravel started to be dredged at the head of the reservoirs for flood protection and inland navigation. This had a variable influence on river-bed erosion and deposition. (Prazan, 1990).

Currently, the Danube passes a chain of 10 hydropower plants (including Jochenstein) and the two remaining free-flowing sections (Wachau and East of Vienna), while it flows across Austria. Around 78% of the Danube in Austria are affected by impoundments, while only 22% or 77 km are free-flowing sections (NEWADA duo, 2014).

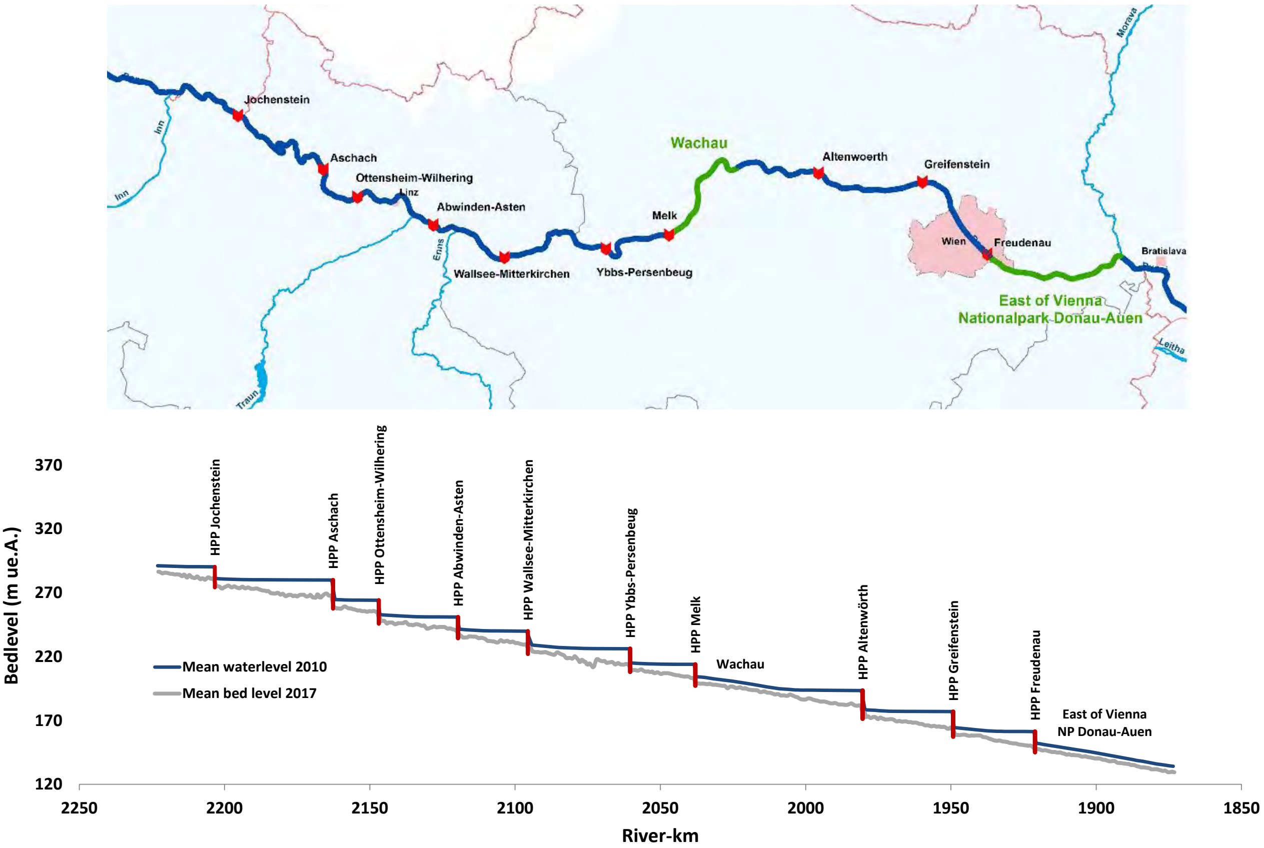
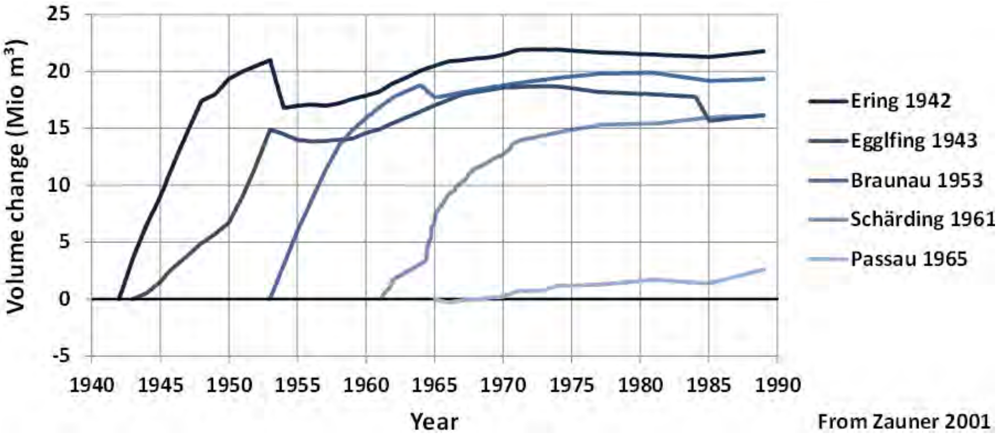


Figure 5.1.30 The Danube River in Austria: Locations of the hydropower plants and the free-flowing sections (bed levels: VHP and viadonau; water levels and locations of the hydropower plants: viadonau (2012)).

The chain of hydropower plants (HPPs) along the Austrian section of the Danube consists of 10 HPPs (including the Jochenstein HPP) (Figure 5.1.30). Of these ten hydropower plants, nine were put into operation between 1955 (HPP Jochenstein) and 1984 (Greifenstein HPP), and the Freudenau HPP was completed in November 1997. The length of the impoundments varies from 16 to 41 km (VHP, 2013b) and the HPPs have a hydraulic head between 9.1 and 15.4 m at mean water level (viadonau, 2012). The reaches influenced by impoundments can be further divided into a central part (water level fluctuation between the low navigable water level /LNWL/ and the mean water level /MWL/ are smaller than 0.3 m, excluding the weir operation tolerance), which makes up around 197 km, and the head of the reservoirs with a length of 72 km (Zauner et al., 2016), which behave to some extent like short free-flowing sections.

Owing to the construction of several hydropower plants on the tributaries, the current bedload input into the Austrian Danube is close to zero. According to Bauer (1965), the input from the Inn River in 1965 (when the Passau-Ingling HPP was put into operation) was smaller than 10,000 m³/a. The mouth of the Traun River is influenced by the backwater of the Abwinden-Asten HPP and the remaining bedload is captured in a bedload trap. The mouth of the Enns River is influenced by the backwater of the Wallsee-Mitterkirchen HPP and, according to VERBUND (1998), only small amounts of gravel, if any, enter the impoundment after the extension of the Enns harbour, which acts as an additional sediment trap.

As regards the suspended sediment regime, one of the main influences was the construction of the HPPs on the tributaries. Especially the ones on the Inn River, for instance, have a marked influence on the amount of suspended sediments supplied into the Danube River. Zauner (2001) assessed the accumulated volume of sediments for the five run off river hydropower plants on the Lower Inn (Figure 5.1.31).



From Zauner 2001

Figure 5.1.31 Sedimentation at the HPPs on the Lower Inn (Zauner, 2001).

He concluded that the sedimentation process at each HPP lasted for around 10 years and that after about 30 years an equilibrium was achieved at the beginning of the 1970ies. The overall volume of sediments deposited at those 5 HPPs until the end of the 1990ies was around 80 million m³ and the degree of silting was high – 57% at the Ering HPP, for example.

The overall land use in Austria is an other relevant factor affecting the sediment input into the rivers. As from 1830, there is an apparent increasing trend in the size of settlements and forest areas, while that of agricultural land and grassland areas shows a decreasing tendency (according to the data published for the EU Volante project). Therefore, the volume of sediments accumulated since that time cannot be easily derived from the total land use. The intensity of areas used for agriculture and forestry has changed, too (the increase in forested areas is not equally distributed, it is concentrated in the mountainous region). The intensive land use had reduced the forested areas a minimum (to 2% in 1850), before the industrial revolution relieved its pressure on forests (Kaplan, 2009). Since that time, the forests have recovered even in the intensively used areas (the increase in forested areas was due mainly to afforestation and the reuse of abandoned land in the mountainous region). Furthermore, there is a significant loss of grasslands (e.g. in Upper Austria[1]), which can be attributed to their conversion to arable land or forests (Eurostat 2015). Summer et al (1996) assessed the trends in soil erosion cause by agriculture in the alpine basin of the Austrian Danube for the period from 1950 to 1990. They concluded that the sediment yield increased by 32% over a period of 40 years, to around 780,000 t/a in 1990. According to Summer at al. (1996), one of the main factors behind this significant increase was the expansion of maize production in hilly unprotected areas, causing strong erosion (its rate increased from 4% in 1950 to 16% in 1990).

Spatial and temporal variations in the Danube channel's morphology

It is rather difficult to use a certain period to characterise the development of the Austrian Danube after the construction of the hydropower plants commenced. Frequent bathymetry measurements covering longer parts of the Danube started to be made during the construction of a hydropower plant in the given section. Another reason is that hydropower plants were built in rapid succession within relatively short time periods in the free-flowing sections downstream of the HPPs. In addition, two major flood events occurred in 2002 (HQ10 to HQ100) and 2013 (HQ100 to HQ200) (BMLFUW, 2004; BMLFUW, 2014), causing intense sediment remobilization in some of the reservoirs. Therefore, the measurements available for each impoundment and for the free-flowing sections had been analysed by 2001. The only exception is the impoundment from the Freudenau HPP. As this HPP had been put into operation by end of 1997, the morphological changes in this section are shown from 1998 to 2016.

In Figure 5.1.32, the erosion and sedimentation volumes for a 500 m-long river section are shown for the period beginning when the first bathymetric measurement was made in the given section and ending in 2001. Also indicated are the locations of the relevant dredging and feeding activities. Figure 5.1.33 shows the general trends observed in the Austrian section of the Danube, i.e. erosion (red) and sedimentation (green). Grey indicates areas were no clear erosion or sedimentation pattern was distinguishable in the impoundment from the Ybbs-Persenbeug HPP, which is situated downstream of the Strudengau. The classification in this case is again based solely on bathymetric measurements.

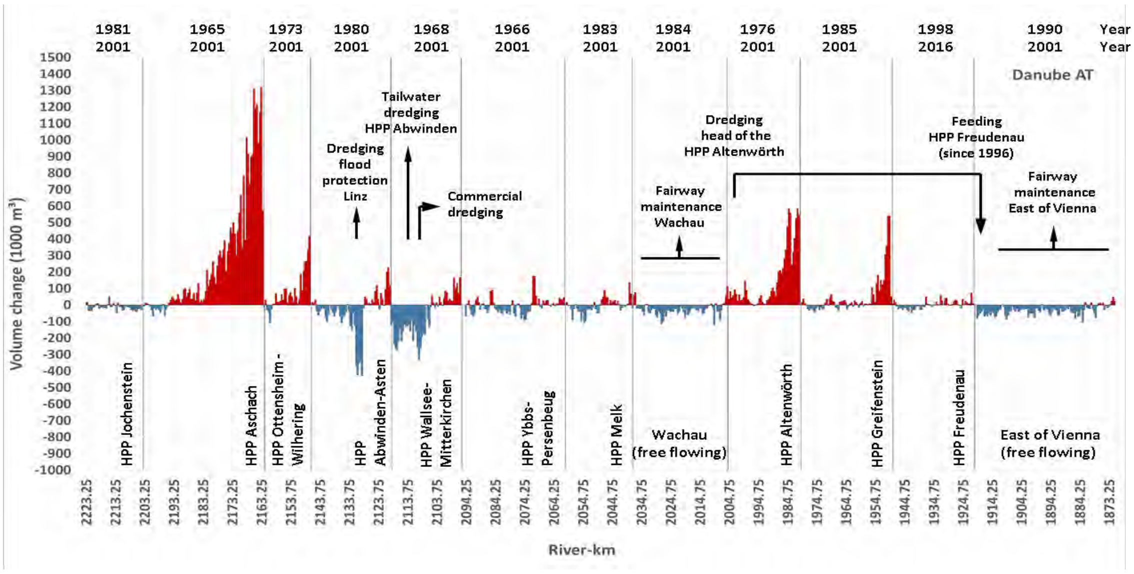


Figure 5.1.32 Bathymetry: Erosion and sedimentation in 500 m-long sections from the first measurement to 2001. For the Freudenau HPP since 1998.

Figure 5.1.33 Classification of erosion and sedimentation in different parts of the Danube in Austria. Based on bathymetric measurements. For segments from the first measurement up to 2001. For the segment of the Freudenau HPP since 1998.

The two free-flowing sections, Wachau and East of Vienna, are subject to erosion. The same is true of the stretch between the Greifenstein HPP and the not yet operating Freudenau HPP. Sedimentation prevails only in the AT-SK border section East of Vienna, which is influenced by the backwater of the Gabčikovo HPP. Except for the Jochenstein HPP with its oscillating erosion and sedimentation patterns and the Freudenau HPPs not yet operating at that time, all the reservoirs show sedimentation at least along the first few kilometres upstream of the dam and erosion in the head of the impoundment. The only exception is the Altenwörth HPP, which is situated downstream of the free-flowing section Wachau and is supplied with bedload from that section. The largest volume of accumulated sediments in the Austrian Danube can be found at the Aschach HPP and the second largest volume at the Altenwörth HPP. The intensity of sedimentation upstream of these HPPs varies considerably and depends mainly on the height of the dam and its location within the chain of hydropower plants. The Aschach HPP is the biggest hydropower plant in the Austrian section of the Danube, in terms of weir height, reservoir volume and reservoir length. It is situated at the upstream end of the

Austrian Danube and is directly influenced by the suspended sediment regime of the Inn River. Therefore, the entering suspended sediment concentration is higher than in the case of other HPPs and the reservoir acts like a settling basin (see Klicpera and Prazan, 2000). In the case of Abwinden-Asten and Wallsee-Mitterkirchen, another factor is the large amount of dredged sediments, which implies erosion.

A comparison of the results of bathymetry measurements and the amounts of dredged sediments (gravel in this case) changes the above picture, mainly in respect of the Abwinden-Asten and Wallsee-Mitterkirchen HPPs (Figure 5.1.34 and Figure 5.1.35).

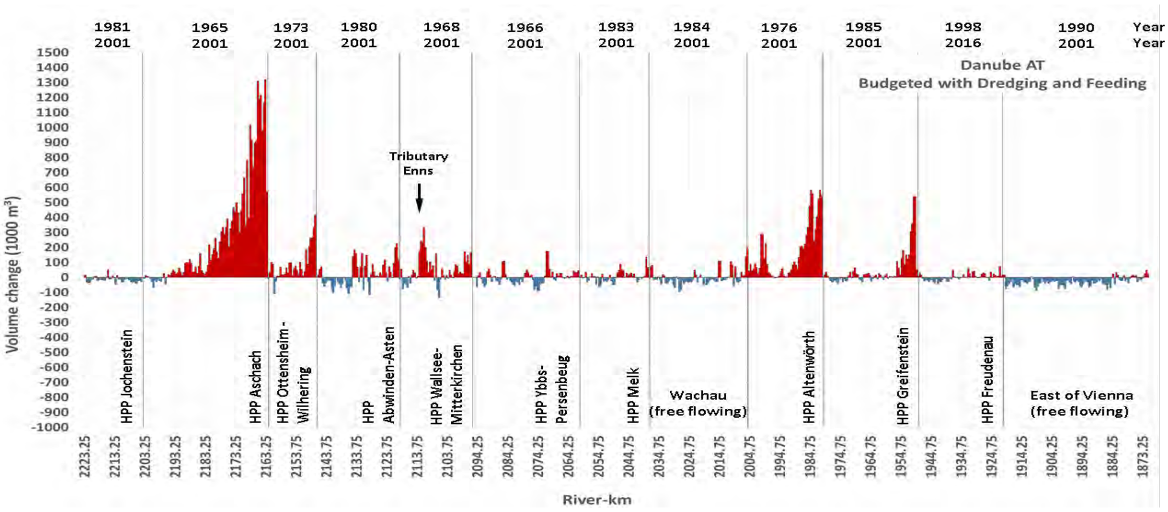


Figure 5.1.34 Bathymetry, including dredging and feeding: Erosion and sedimentation in 500 m-long segments from the first measurement to 2001. For the Freudenau HPP since 1998.

Figure 5.1.35 Classification of erosion and sedimentation in different parts of the Danube in Austria. Bathymetry, including dredging and feeding. Segments from the first measurement to 2001 for the Freudenau HPP since 1998.

The zone of sedimentation stretches over a longer part of the impoundments, but there is still some erosion visible at the tail of the upstream HPPs. As regards the Ybbs-Persenbeug HPP, the zone of erosion is currently located in the narrowest part of the Struden, were gravel is still mobilized and transported farther down into the backwater area (see Prazan, 1990). In the Wachau valley, sedimentation now extends further upstream. This is due to the fact that sediments for fairway maintenance were dredged mostly from the Danube (see Schmautz et al., 2000).

The spatial and temporal sedimentation and erosion processes, during large floods in particular, do not show a distinct pattern between the HPPs, which means that they are not directly transferable between the reservoirs (see Klicpera and Prazan, 2000). A more comprehensive picture is provided by the river's longitudinal profile showing increased sedimentation a few kilometres upstream of the dams, less intense sedimentation in the central part of the impoundments, and erosional trends in the upper part of the impoundments. In terms of the transported grain sizes and the transport mode (bedload or suspended), the impounded sections have changing patterns depending on the discharge and the longitudinal position within the impoundment (Nachtnebel at al., 1998). Thus, the sand fraction makes up 40% of the deposited sediments in the impoundments.

On the long run, the HPPs act as a sediment sink: they reduce the concentration of suspended sediments in the downstream direction, compared with the unaffected state. Only large floods coupled with the now necessary drawdowns are expected to remobilize the fine sediments to some extent. In short time periods lasting for a few days only, the suspended sediment load in the domain of the HPPs and downstream of them increases temporarily. The amount of remobilized fine sediments during extreme floods accounts for 50% of the overall suspended sediment load (see BMLFUW, 2015; Bock et al, 2019). Between large flood events, the accumulation of sediments in the reservoirs may theoretically reach an equilibrium, which has hardly been achieved so far, owing to the repeated remobilization of sediments during those large floods.

The following chapters provide the reader with a detailed overview of how the sediment regimes in the 12 different reaches of the Austrian Danube have hanged over the past decades and of how they were affected by the floods in 2002 and 2013. First the changing dredging volumes and the changing approaches to sediment handling are summarized, for they have – in some reaches – a marked influence on the sediment regime.

Dredging

The locations and volumes of dredging in the Danube in Austria have changed over the years, owing mainly to construction and/or finalisation of low and mean water regulation measures and 10 HPPs between 1955 and 1997. During these years, considerable amounts were dredged for the river regulation works and for the river maintenance, as well as for HPP and road construction (Schmutterer, 1952; Tschochner, 1957; Geitner, 1969; Geitner, 1978).

Figure 5.1.36 shows the amounts of dredged gravel based on usage for the period from 1936 to 2016. Overall, not all the dredged material shown in Figure 5.1.36 (red bars) was extracted; a certain (unknown) amount was kept in the main stream of the Danube and another part was used for river training works.

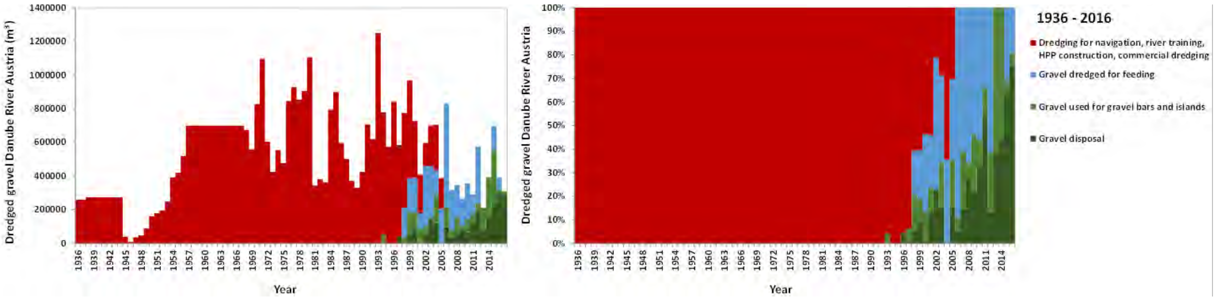


Figure 5.1.36 Amounts of gravel in m³ and % dredged in the Austrian Danube, based on usage. Time period: from 1936 to 2016. Sources: Danube Commission, Geitner (1968 und 1979), Mühlbauer (2017), Schmautz et al. (2000), Schmutterer (1952), Tschochner (1957), VHP, viadonau.

In the mid-1990s, the amount of dredged (removed) gravel decreased gradually. A paradigm shift took place at that time. Instead of being removed for fairway maintenance, the dredged gravel was either used for the construction of gravel bars and islands (e.g. since the beginning of the 21st century in the Wachau valley – see Mühlbauer, 2017) or was stored in the main stream (mainly East of Vienna) (Figure 5.1.36 and Figure 5.1.37 – green bars).

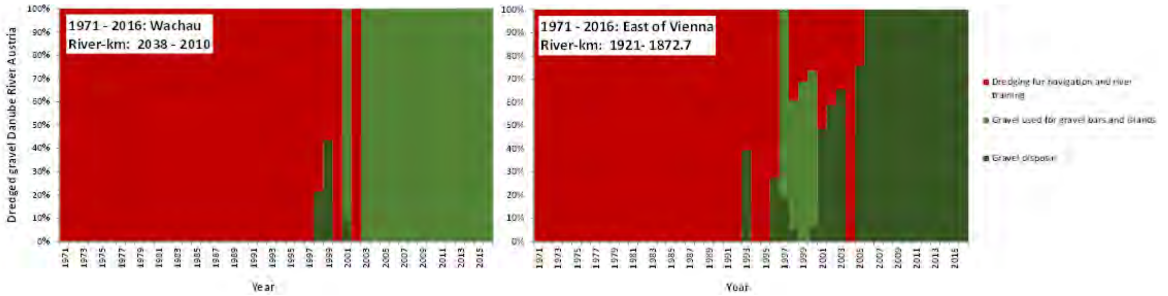


Figure 5.1.37 Amount of dredged gravel in % in the two free-flowing reaches, Wachau and East of Vienna, in the Austrian Danube, based on usage. Time period: from 1971 to 2016. Sources: Danube Commission, Mühlbauer (2017), Schmautz et al. (2000), viadonau.

The management of dredged material for fairway maintenance in the free-flowing section East of Vienna has undergone several stages over the last 20 years. According to Simoner (2018), between 1996 and 2005, approx. 50% of the sediments were fed back into the main stream, 30% were extracted, and 20% used for the construction of gravel structures. From 2006 on, all the dredged material was fed back into the main stream, first downstream and from 2009 on upstream of the dredging location. Finally, from 2015 on, the upstream transfer distance was considerably increased, to around 11 km (Simoner, 2018).

The gravel dredged at the head of the impoundment from the Altenwörth HPP, which is transported from the free-flowing Wachau section to this backwater area, is not removed but transferred downstream of the Freudenau HPP as material for gravel feeding (Figure 5.1.38 – blue bars). The dredging works take place between approx. rkm 2,003 and rkm 1,999.5, with the aim of ensuring the necessary bridge clearance at the highest navigable discharge and lowering the flood water level near the city of Krems (VHP, 2013a). The amount of gravel fed downstream of the Freudenau HPP into the maintenance reach between rkm 1,921 and rkm

1,910 was approx. 186,000 m³/a in the period from 1996 to 2017. This amount has recently been increased to 235,000 m³/a (BMNT, 2018b).

Figure 5.1.38 gives an overview of the amount (in m³) and location (river-km) of the dredging activities for the period from 1971 to 2016. Besides dredging for fairway maintenance in the two free-flowing sections and dredging at the head of the impoundment form the Altenwörth HPP, there are two additional sections in which increased dredging is performed. One is located near the city of Linz in the impoundment from the Abwinden-Asten HPP, with around 2.5 million m³ dredged for flood protection between rkm 2,134 and rkm 2,128 (see VHP, 2014).

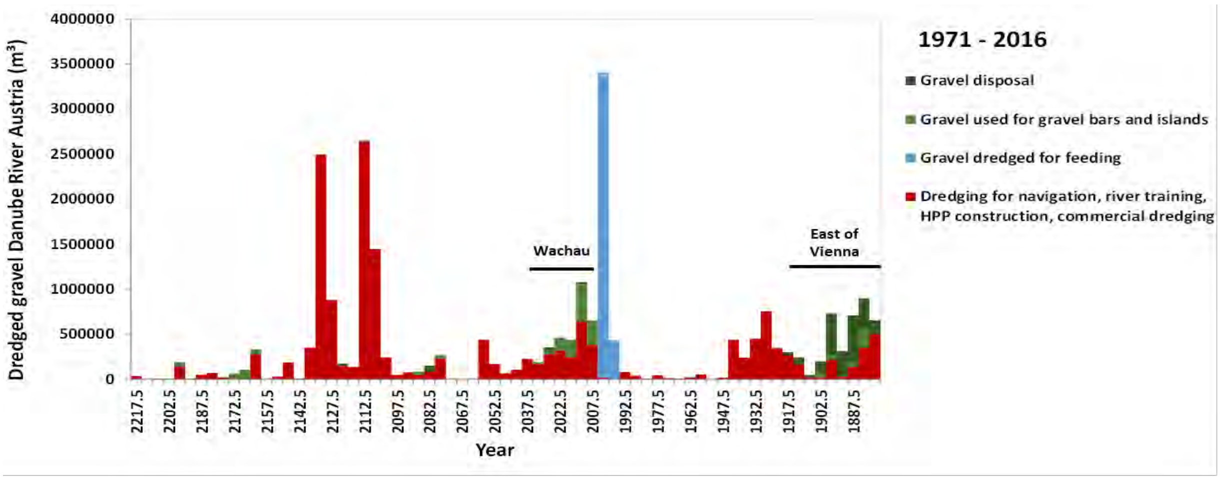


Figure 5.1.38 Amounts of gravel dredged in 5 km-long sections of the Austrian Danube between 1971 and 2016. Sources: Danube Commission, Mühlbauer (2017), Schmautz et al. (2000), VHP, viadonau.

The other section is located in the impoundment of the Wallsee-Mitterkirchen HPP. Here around 1.9 million m³ was dredged between rkm 2,119.5 and rkm 2,112, during the construction of the upstream Abwinden-Asten HPP (1977 – 1980). Tail water dredging is used to lower the river bed downstream of a hydropower plant to increase the hydraulic head (see Prazan, 1990). This was a common measure used during the construction of HPPs in the Austrian section of the Danube. The rest of dredging in the impoundment of the Wallsee-Mitterkirchen HPP was done mainly for commercial purposes between rkm 2,110 and rkm 2,104 (see Schmautz et al., 2000, and VHP, 2014).

The Jochenstein HPP

Compared with the other HPPs on the Austrian Danube, the Jochenstein HPP is the only one situated upstream of the Aschach HPP, which is of central importance for the suspended sediment regime within the chain of hydropower plants (see Prazan, 1990 and Bock et al., 2019). Therefore, it is the only HPP under the direct influence of the Inn River's suspended sediment regime, which is a major factor in this regard.

The Jochenstein HPP shows slight erosion, but the first 26 years representing the initial filling stage are missing in the data set. Until 1981, around 2.8 million m³ of sediments were deposited (Prazan, 1990). In the subsequent years, the impoundment shows alternating phases of erosion and sedimentation with volume changes of +/- 1 million m³ (Figure 5.1.39).

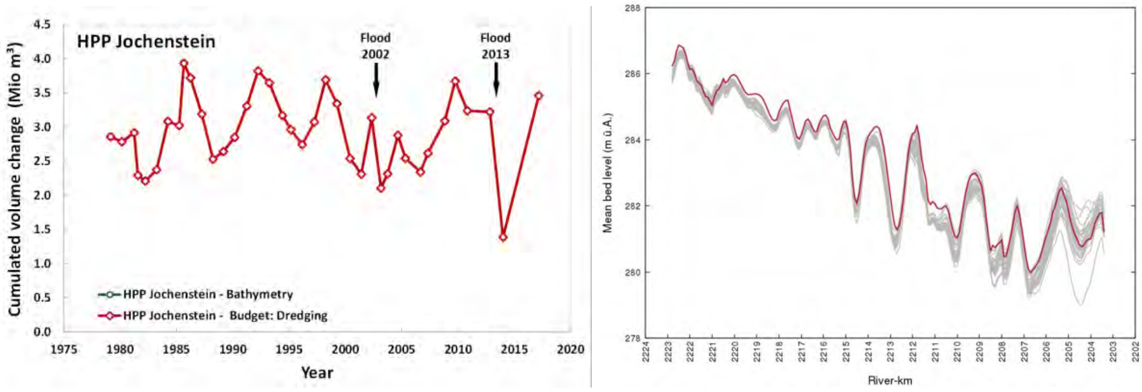


Figure 5.1.39 Left: Cumulated volume changes at the Jochenstein HPP between 1981 and 2017. Right: Changes in the mean bed level. The red line shows the present situation. (Source: viadonau).

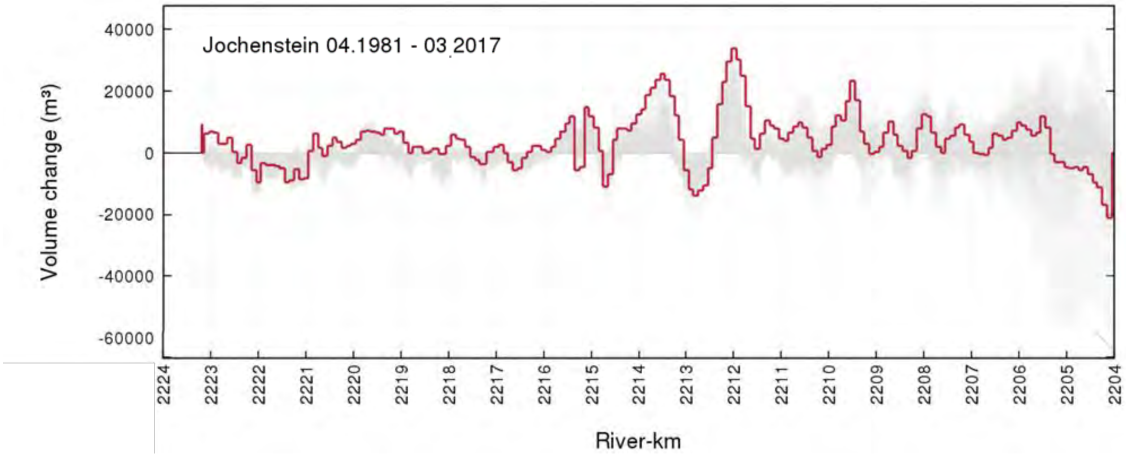


Figure 5.1.40 Distribution of sedimentation and erosion (100 m-long sections) over the length of the reservoir between 1981 and 2017. The grey shading indicates the volume changes that took place during the period under review and the red line shows the result of comparison of the first and last available measurements (Database: viadonau).

In the impoundment of Jochenstein, the largest deposits of fine sediments can be found around 3 km upstream of the dam (Figure 5.1.40), their volume decreases with the increasing distance upstream (Prazan, 1990). In the upper part of the reservoir, a natural change in the sediment regime (either erosion or sedimentation) is visible. According to Klicpera and Prazan (2000), only suspended sediments are deposited downstream of the Jochenstein HPP (rkm 2,210) in the long term.

Fine sediment deposition increases towards the HPP. In the impoundment of Jochenstein, the floods in 1985 (HQ10) and 1991 (HQ8) led to sediment accumulation, with a steady decline of the volume of accumulated sediment in the following years. After the lowest sedimentation in 1996, the accumulated volume increased again over the next three years. The floods in 2002 and 2013 in turn caused sediment remobilization, followed by sediment accumulation in the years after the flood events. It seems that the accumulation of fine sediments follows an 'oscillating' equilibrium somewhere between 2 and 3.5 million m³. This oscillation seems to match the extreme flood events but not necessarily the smaller floods (see Prazan, 1990).

The Aschach HPP

The Aschach HPP is the largest hydropower plant in the Austrian section of the Danube in terms of weir height, reservoir volume and reservoir length. Aschach is the first HPP with a notable weir height (~15.3 m) in Austria, which means that the concentration of the entering suspended sediments is higher than in other impoundments and the reservoir acts like a settling basin (see Klicpera and Prazan, 2000). Furthermore, it is situated at the downstream end of the narrow 'Oberes Donautal valley', a break-through of the Danube through the Bohemian Massif, with a sinuous and meandering planform.

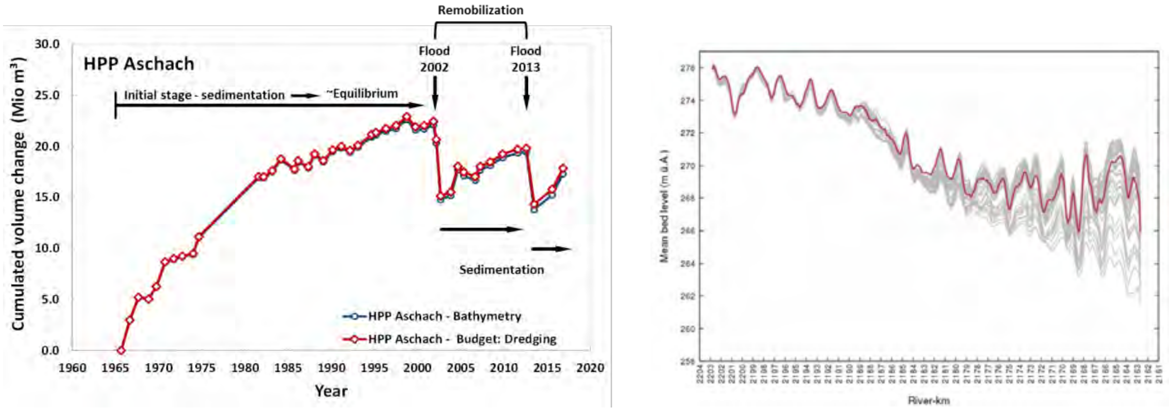


Figure 5.1.41 Left: Cumulated volume changes at the Aschach HPP between 1965 and 2016. Right: Changes in the mean bed level at the Aschach HPP. The red line shows the present situation. (Database: VHP and viadonau).

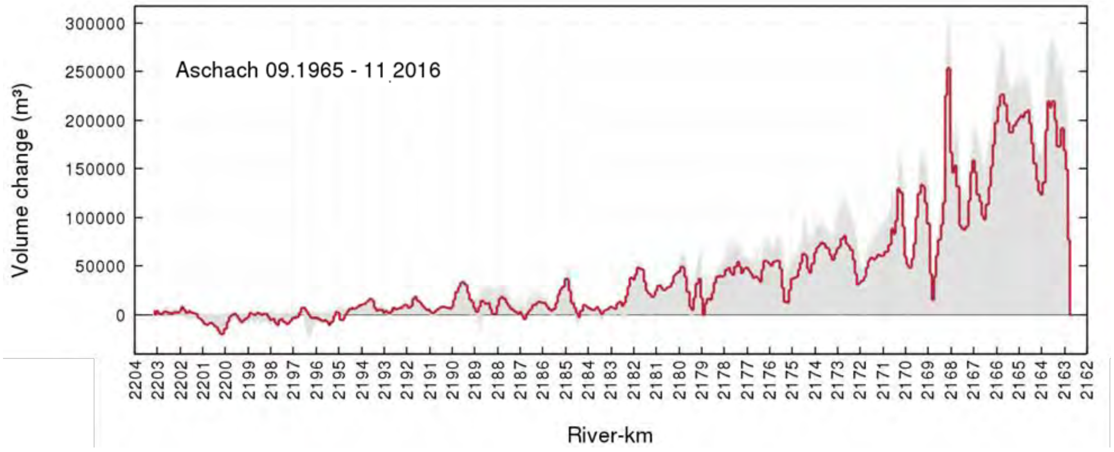


Figure 5.1.42 Distribution of sedimentation and erosion (100 m-long sections) over the length of the reservoir from 1965 to 2016 (after the floods in 2002 and 2013). The grey shading indicates the volume changes that occurred during the period under review and the red line shows the results of comparison of the first and last available measurements. (Database: VHP and viadonau).

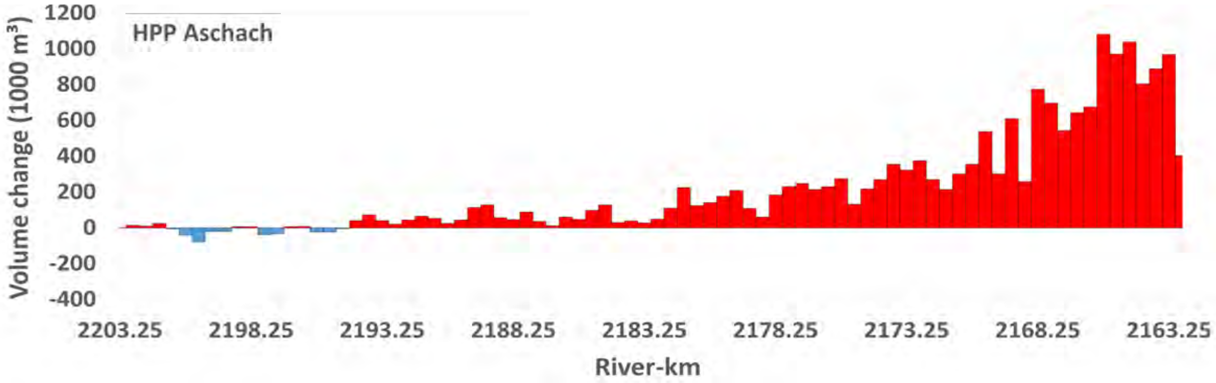


Figure 5.1.43 Distribution of sedimentation and erosion (500 m-long sections) over the length of the reservoir from 1965 to 2016 (after the floods in 2002 and 2013) – bathymetry (Database: VHP and viadonau).

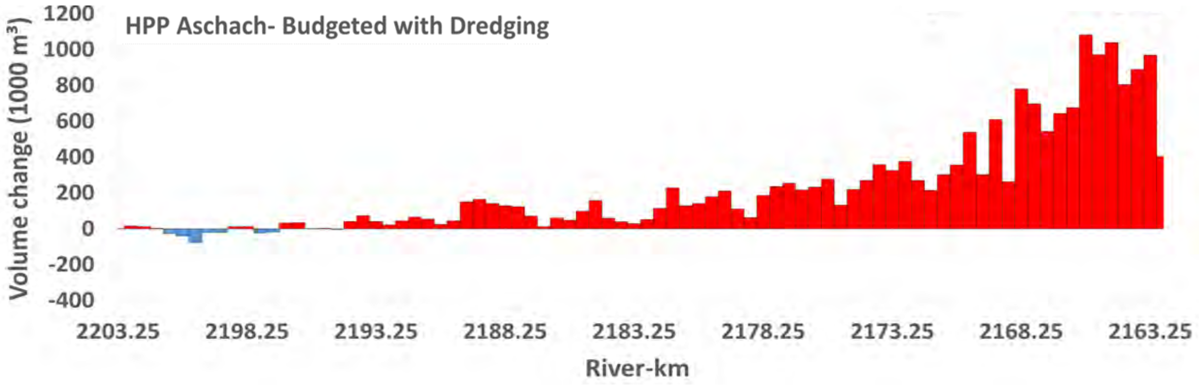


Figure 5.1.44 Distribution of sedimentation and erosion (500 m-long sections) over the length of the reservoir from 1965 to 2016 (after the floods in 2002 and 2013) – bathymetry, including dredging (Database: VHP and viadonau).

This planform, combined with the significant reduction in the flow velocities, creates backwater zones downstream of the inner bends were a significant amount of suspended sediments is deposited. In the impoundment of Aschach, fine sediments are mostly deposited close to the dam (within approx. the first 5 km); their volume then decreases gradually up to rkm 2,183/2,182 (Figure 5.1.41 – right panel, Figure 5.1.42 and Figure 5.1.43).

This means that downstream of rkm 2183/2182 only suspended sediments are deposited in the long term. The height of sedimentation ranges from 10 to almost 20 m in this part of the reservoir. The grain size composition of the sediments deposited in the lower third of the impoundment in Figure 5.1.45 shows that silt represents the main fraction, with equal amounts of clay and sand (Kralik and Augustin-Gyurits, 1994).

Further upstream, gravel deposits are interleaved with layers of fine sediments and visible fine sediment accumulations can be found up to rkm 2,190 (Prazan, 1990). The impoundment of Aschach showed signs of rapid sedimentation in the first 20 years after the HPP was put into operation. Subsequently, the rate of sedimentation slowed until an equilibrium was reached at around the turn of the millennium (Figure 5.1.41 – left panel), with about 23 million m³ of accumulated sediments. During the two floods in 2002, over 7 million m³ of sediments was remobilised from the reservoir (Figure 5.1.46 – left panel). This remobilisation was due to a large flood combined with the necessary water level lowering by about 5 m (Bock et al., 2019).

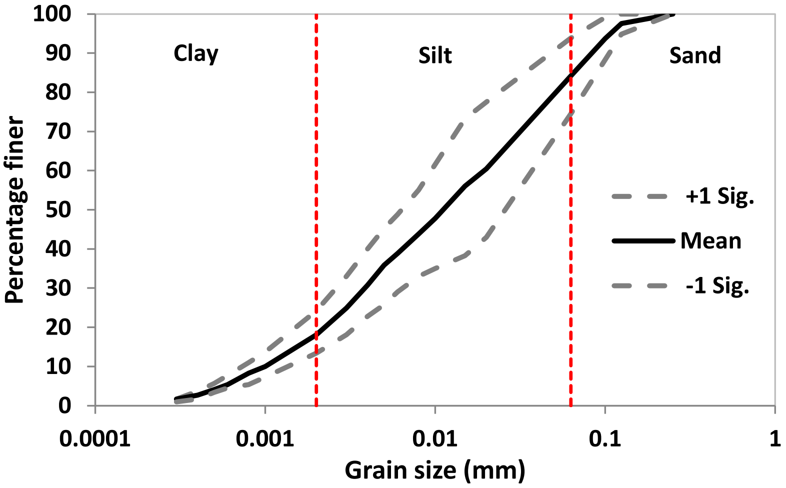


Figure 5.1.45 Grain sizes of sediments deposited in the lower third of the impoundment of Aschach (Kralik and Augustin-Gyurits, 1994)

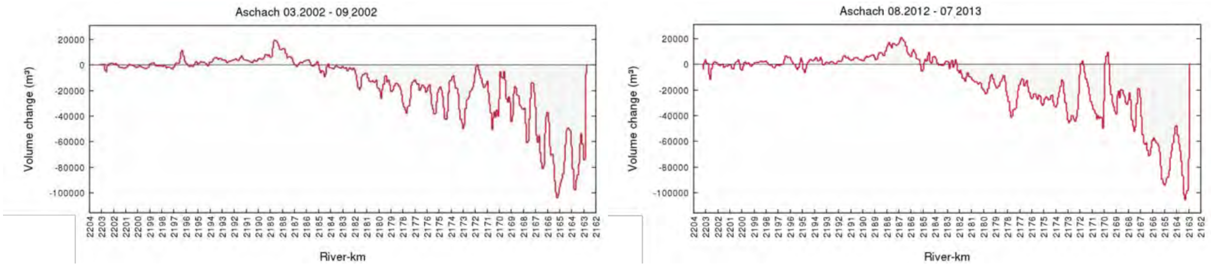


Figure 5.1.46 Left: Sediment remobilisation caused by two floods in 2002. Right: Sediment remobilisation during the flood in 2013. (Database: VHP and viadonau).

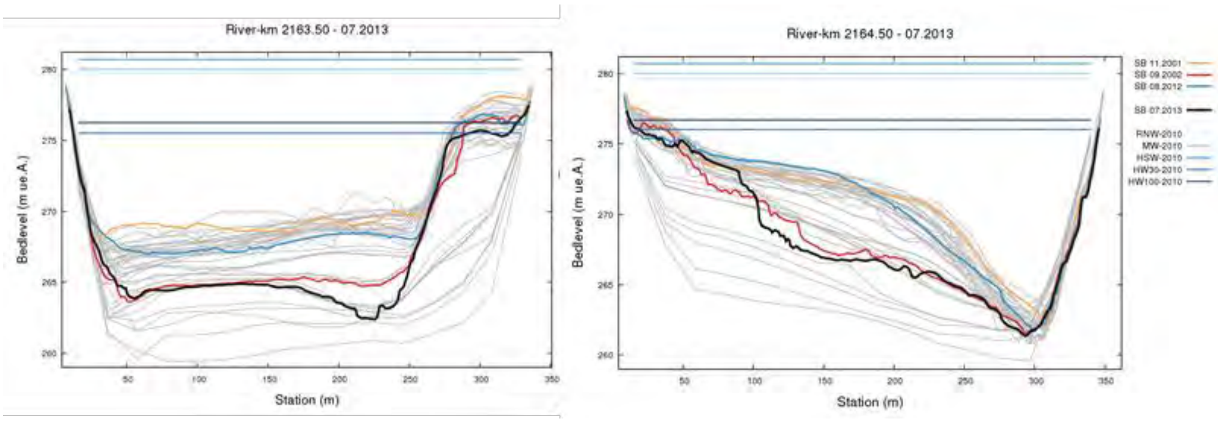


Figure 5.1.47 Example of sediment remobilization during the floods in 2002 and 2013. Red line: Bed level after the floods in 2002. Black line: Bed level after the floods in 2013.

Sediment remobilization took place mostly along the first 9 km upstream of the dam, up to rkm 2,182 (around 19 km upstream of the dam). The sediments were deposited further upstream were the Danube enters a narrower break-through section (near Schloegen). After the equilibrium was reset, the sedimentation process continued and, in the following years until 2012, around 5 million m³ of sediments was trapped in the reservoir. The flood in June 2013 remobilized over 5.5 million m³ of sediments, restoring the reservoir volume to the level of the late 1970ies (VHP, 2014) and causing sediment deposition in the amount of about 600,000 m³ upstream of rkm 2,185. The remobilization and sedimentation patterns are in general comparable to the floods in 2002 (Figure 5.1.46 – right picture). Figure 5.1.47 shows an example of the bed level changes (ranging from -5 to -6 m) that occurred in the lower part of the impoundment during the floods.

According to BMLFUW (2015), the remobilization was responsible for around 71% (in 2002) and 58% (in 2013) of the suspended sediment load in the Danube directly downstream of the Aschach HPP.

After 2013, a new sedimentation cycle started with around 3.5 million m³ of sediments accumulating within the impoundment over the next few years, with the total volume of accumulated sediments reaching about 18 million m³.

The sediments resulting from sediment transport within the impoundment and deposited upstream of rkm 2,185 (Figure 5.1.46 – right picture) were dredged in the subsequent years for flood protection purposes. The sediments were transported upstream and used to build gravel bars and islands in the upper part of the impoundment.

The Ottensheim-Wilhering HPP

Upstream of the Ottensheim-Wilhering HPP, suspended sediments are deposited close to the dam, along the first 4 km up to rkm 2,151 (Figure 5.1.47). Further upstream (from rkm 2,155 to rkm 2,157), sedimentation takes place mostly near the river banks (see Prazan, 1990 and VHP2014).

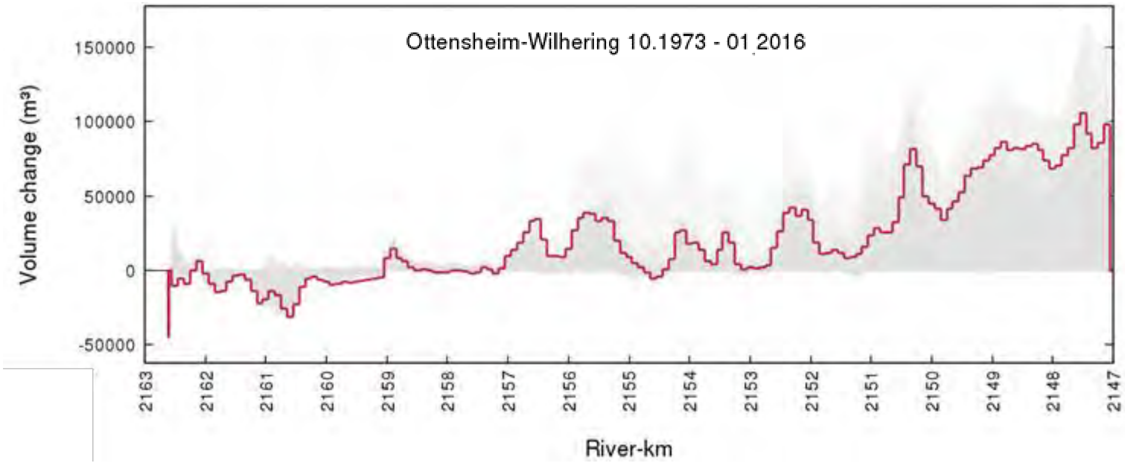


Figure 5.1.48 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir from 1973 to 2016 (after the floods in 2002 and 2013). The grey shading indicates the volume changes that took place over the period under review and the red line shows the results of comparison of the first and last available measurements. (Database: VHP and viadonau).

From rkm 2,159 to the Aschach HPP, the total volume of eroded sediments reached roughly 300,000 m³, whereof about 250,000 m³ were due to gravel dredging from a gravel bar (‘Aschacher Haufen’). From the time when the HPP was put into operation to 2001, steady growth was observed in the volume of accumulated sediments, i.e. an increase of around 2.7 million m³ (excluding the sediments dredged) (Figure 5.1.49).

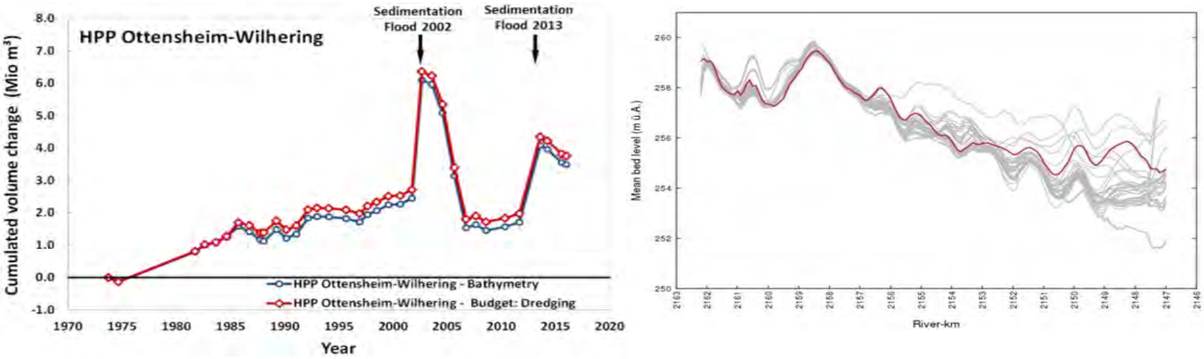


Figure 5.1.49 Left: Cumulated changes in the volume of sediments at the Ottensheim-Wilhering HPP between 1973 and 2016. Right: Changes in the mean bed level at the Ottensheim-Wilhering HPP between 1973 and 2016. The red line shows the present situation. (Database: VHP and viadonau).

During the floods in 2002, 3.7 million m³ of sediments were deposited in the impounded river section. Over the next four years, sediments were remobilized and transported out of the impoundment in the amount of roughly 4.6 million m³. The left panel of Figure 5.1.50 shows the deposition of sediments after the flood in 2002, while the right panel of Figure 5.1.50 shows the situation 2 years later after the sediments had been transported downstream to the dam and, in part, out of the reservoir.

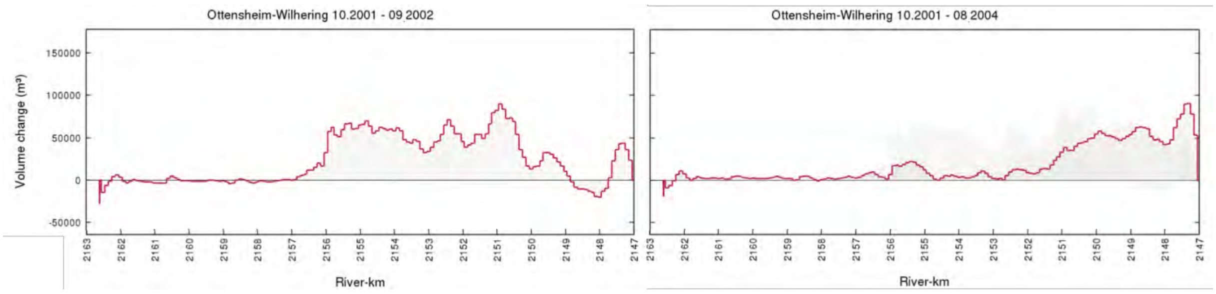


Figure 5.1.50 Distribution of sedimentation (100 m-long sections) along the length of the reservoir directly after the flood in August 2002 (left panel) and two years later (right panel) – showing the sedimentation after the flood and the remobilization and transport of sediments through and out of the reservoir in the following years. The red line shows the differences in volume between sedimentation before the flood and in the year under review. (Database: VHP and viadonau).

During the flood in June 2013, another 2.4 million m³ of sediments were deposited within the impoundment, markedly less than during the floods in 2002. During the flood in August 2002, around 0.31 million m³ were deposited in the flood plain (Eferdinger Becken) between rkm 2158 and rkm 2,145 and around 0.56 million m³ during the flood in 2013 (BMLFUW, 2015). The sediment deposits were recorded by joint commissions and represent the upper bound of the deposited volumes. The commissions overestimated the volumes to some extent, as either the maximum heights of the deposits were used or the mean values were rounded up (BMLFUW, 2015), which means that they are subject to a certain degree of uncertainty. Sediment remobilisation took place after the flood, but at a slower pace, with about 0.6 million m³ of sediments transported out of the reservoir over the course of 2.5 years. Overall, around 3.7 million m³ of deposits have been deposited since the HPP was put into operation.

The Abwinden-Asten HPP

Situated downstream of the city of Linz, the impoundment of the Abwinden-Asten HPP is heavily influenced by the consequences of sediment dredging for flood protection from the past. The amount of dredged sediments surpasses their total volume accumulated within the impoundment (Figure 5.1.51 – left panel: blue line).

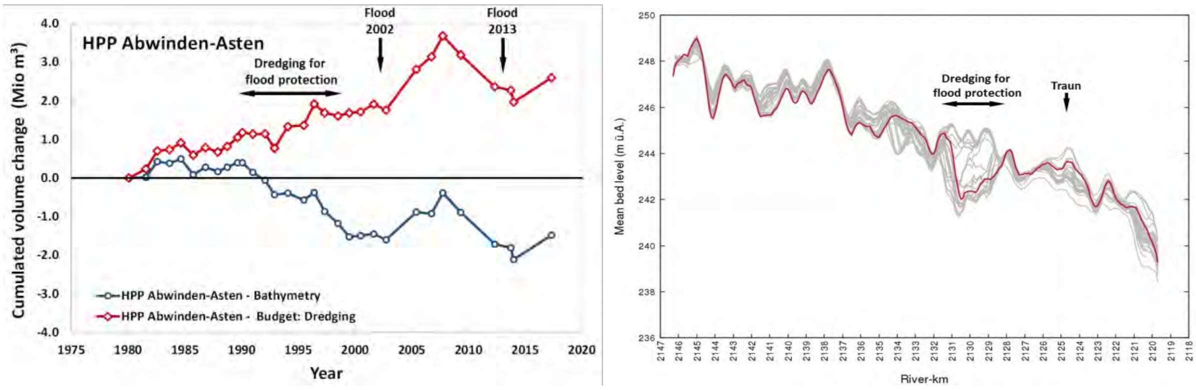


Figure 5.1.51 Left: Cumulated changes in the volume of sediments at the Abwinden-Asten HPP between 1980 and 2017. Right: Changes in the mean bed level at the Abwinden-Asten HPP between 1980 and 2017. The red line shows the present situation. (Database: VHP and viadonau).

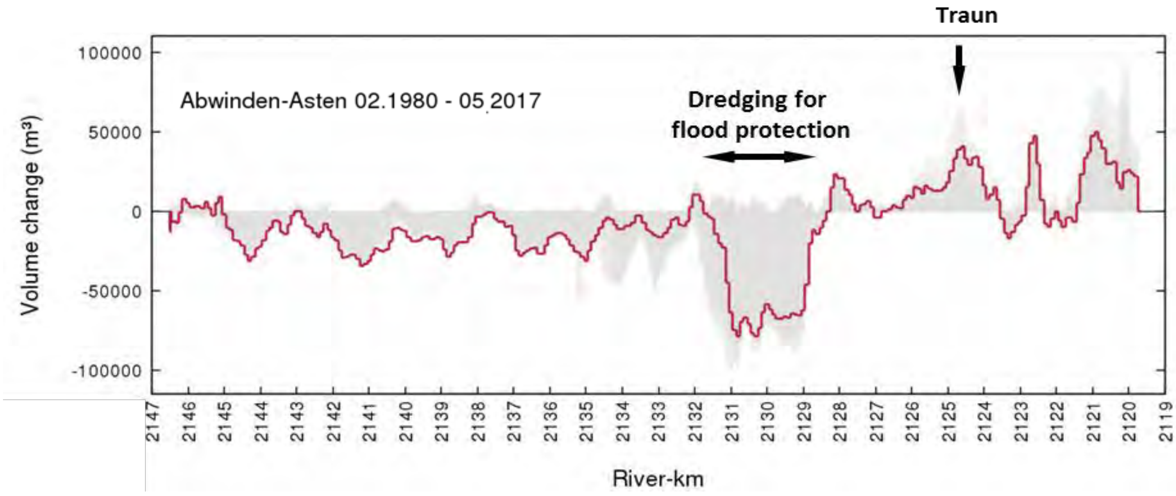


Figure 5.1.52 Distribution of sedimentation and erosion (100 m-long sections) along the reservoir between 1980 and 2017 (after the floods in 2002 and 2013). The grey shading indicates volume changes that occurred during the period under review and the red line shows the differences between the first and last measurements. (Database: VHP and viadonau).

The accumulation of fine sediments in the reservoir is offset in large part by the dredging activities. The Traun River flowing into the impoundment of the Abwinden-Asten HPP has a small annual suspended sediment load (an annual average of roughly 0.08 million tons between 1985 and 2016) and the gravel is intercepted in a bedload trap. In the 1980ies, dredging activities were performed mostly at rkm 2,133 (see Prazan, 1990). A reduction of about 2.5 million m³ in dredging between rkm 2,132 and rkm 2,129 (Figure 5.1.52 and Figure 5.1.53) resulted from sediment dredging for the city of Linz in the 1990ies, for flood protection purposes (see VHP, 2014).

Overall, about 3 million m³ of sediments were dredged in the impoundment of the HPP under review. The erosion upstream of rkm 2,138 is more or less the result of a natural erosion process, as the river is still able to transport a certain amount of gravel (see Prazan, 1990). However, some backward erosion is also visible upstream of rkm 2,135, owing to dredging directly downstream (see VHP, 2014).

Fine sediments tend to accumulate close to the HPP under review and near the mouth of the Traun tributary (Figure 5.1.52 and Figure 5.1.54). Considering the amount dredged, a steady

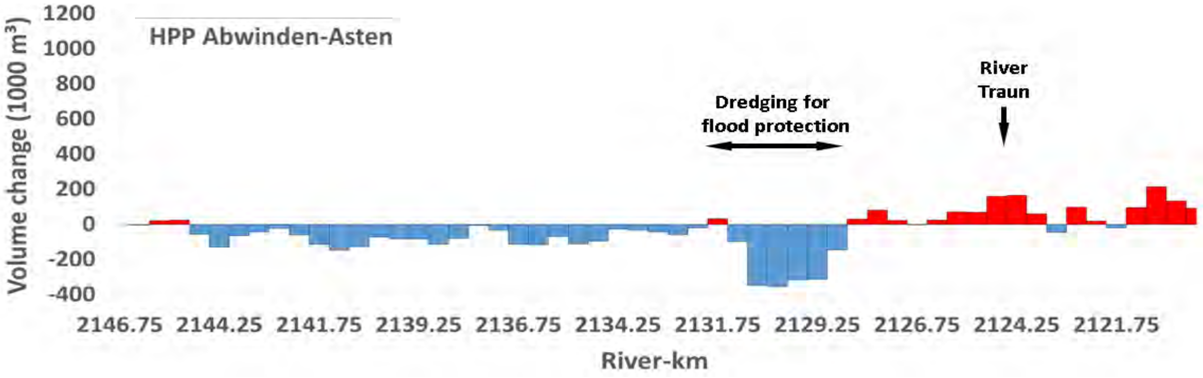


Figure 5.1.53 Distribution of sedimentation and erosion (500 m-long sections) along the reservoir between 1980 and 2017 – bathymetry (after the floods in 2002 and 2013). (Database: VHP and viadonau).

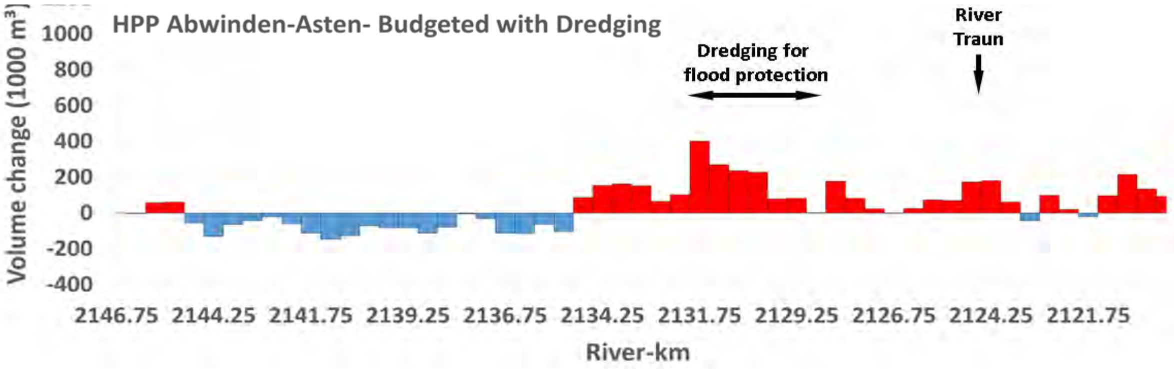


Figure 5.1.54 Distribution of sedimentation and erosion (500 m-long sections) along the reservoir between 1980 and 2017 – bathymetry, including dredging (after the floods in 2002 and 2013). (Database: VHP and viadonau).

increase of around 2 million m³ in the volume of accumulated sediments was observed until 2001, from the time the HPP was put into operation (Figure 5.1.51 – left panel: red line). The floods in 2002 and 2013 caused comparable net changes. In 2013, for example, sediments were remobilised in the amount of roughly 500,000 m³ near the left river bank, in the vicinity of the ship lock that was open during the flood event (VHP, 2014). Combined with sedimentation in the upstream section, river-bed erosion occurred during this flood in the amount of around 100,000 m³. More notable was the sedimentation process that started after the flood in 2002 and reached its maximum at the end of 2007. It was followed by steady sediment remobilisation lasting until the end of 2012. The remobilised sediments were probably deposited in the reservoir upstream of Ottensheim-Wilhering during the floods in 2002 and then transported through and out of the reservoir of the Abwinden-Asten HPP. By the end of 2017, around 2.9 million m³ of fine sediments had been accumulated in this reservoir. Based solely on bathymetric data, the impoundment currently shows a sediment deficit of about 1.5 million m³.

The Wallsee-Mitterkirchen HPP

Like the impoundment of the Abwinden-Asten HPP, that of the Wallsee-Mitterkirchen HPP was also influenced heavily by dredging in the past. In this case, around 1.9 million m³ of sediments came from tail water dredging performed between rkm 2,119.5 and rkm 2,112 in the period from 1977 to 1980, when the Abwinden-Asten HPP was built (Figure 5.1.55 and Figure 5.1.57). The rest of dredging took place in the impoundment between rkm 2,110 and rkm 2,104 and was intended mostly for commercial purposes (see Schmautz et al., 2000 and VHP, 2014). The amount of dredged sediments exceeds the total volume of sediments accumulated in the impoundment (Figure 5.1.44 – left panel: blue line). Which means that the accumulation of fine sediments in the reservoir – mostly at the mouth of the Enns River – is masked by the dredging activities.

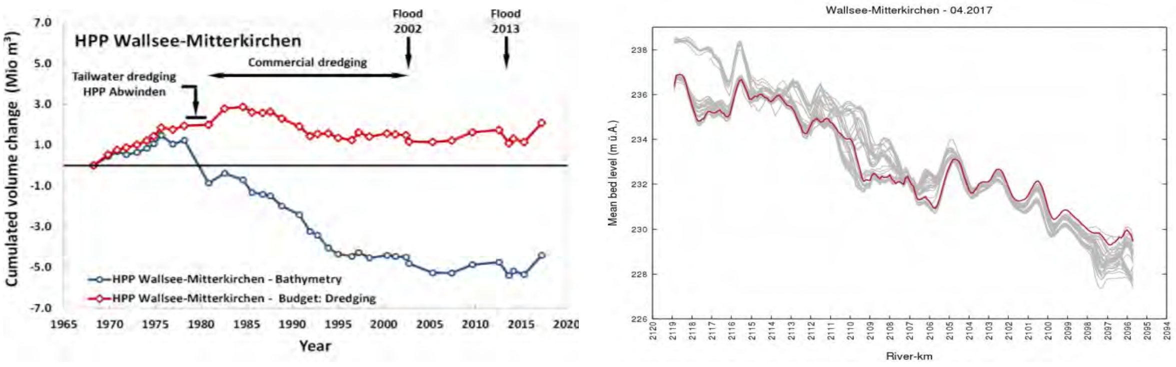


Figure 5.1.55 Left: Cumulated volume changes at the HPP Wallsee-Mitterkirchen between 1968 and 2017. Right: Changes in the mean bed level at the HPP Wallsee-Mitterkirchen from 1968 and 2017. The red line shows the present situation. (Database: VHP and viadonau).

The River Enns flowing into the impoundment has, compared with the Danube, a rather small annual suspended sediment load (an annual average of about 0.30 million tons between 1985 and 2016). Before the construction of a chain of HPPs (the Staning HPP was commission as first in 1946), the Enns River was – besides the Inn River – one of the major tributaries in terms of bedload (see Rosenauer, 1947). The mouth of the Enns is currently influenced by the backwater of the Wallsee-Mitterkirchen HPP and only small amounts of gravel, if any, enter the impoundment owing to the extension of the Enns harbour (VERBUND, 1998), which acts as an additional sediment trap. According to Dieplinger (2010) and Zauner et al. (2011), apart from fine sediments, around 1 million m³ of gravel have been dredged in this section of the Enns since the 1970ies, mainly to maintain the fairway depth in the Enns harbour.

In the period before the construction of the upstream Abwinden-Asten HPP commenced in 1976, a sedimentation trend is visible in Figure 5.1.55, with the volume of accumulated sediments reaching around 1.8 million m³ bat the end of 1975. The main sediment deposits were formed along the first 2-3 km upstream of the dam and in a wider section (rkm 2,112 to rkm 2,109.5) downstream of the mouth of the Enns tributary (Figure 5.1.56 and Figure 5.1.58). The sedimentation in this wider section is not visible in Figure 5.1.45, owing to commercial dredging in this part of the impoundment. Since the beginning or middle of the 1990ies, the sedimentation volume has been virtually unchanged.

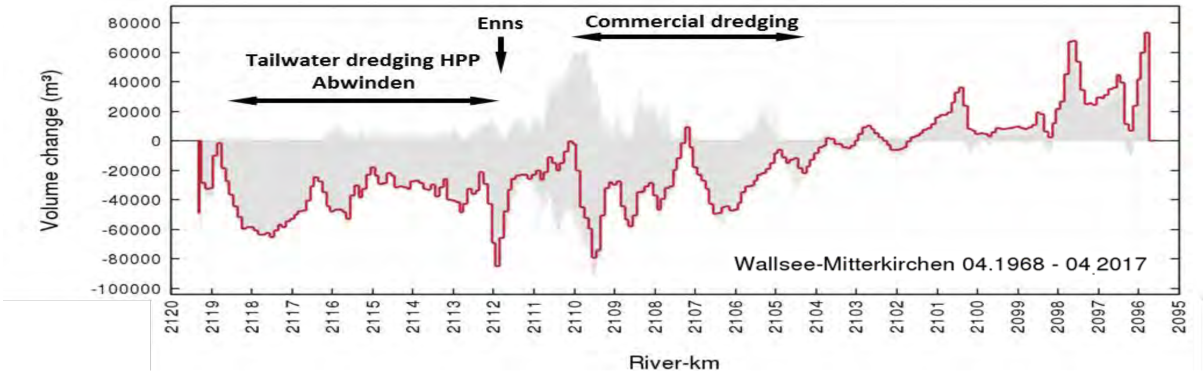


Figure 5.1.56 Distribution of sedimentation and erosion (100 m-long sections) along the reservoir between 1968 to 2017 (after the floods in 2002 and 2013). The grey shading indicates the volume changes that took place during period under review and the red line shows the result of comparison of the first and last measurements available. (Database: VHP and viadonau).

The floods in 2002 and 2013 caused sediment remobilization in the amount of 0.4 to 0.6 million m³, which took place close to the HPP (in 2013, the ship locks were opened). During the flood in August 2002, around 0.56 million m³ of sediments were deposited in the flood plain (at Wallsee) between rkm 2,112 and rkm 2,100, and around 0.96 million m³ during the flood in 2013 (BMLFUW, 2015). In the Norther Machland section (rkm 2,100 to rkm 2,085), 1.7 million m³ of sediments were deposited in 2002, and 1.11 million m³ in 2013 during the flood (BMLFUW, 2015). In the Southern Machland section (rkm 2093 to rkm 2083), 0.95 million m³ were deposited in 2002 and 1.41 million m³ during the flood in 2013 (BMLFUW, 2015). These volumes were recorded by joint commissions and thus they represent the upper bound of the volumes deposited. These are overestimated to some extent, as either the maximum height of the deposits were used or the mean values were rounded up (BMLFUW, 2015), which indicates a certain degree of uncertainty.

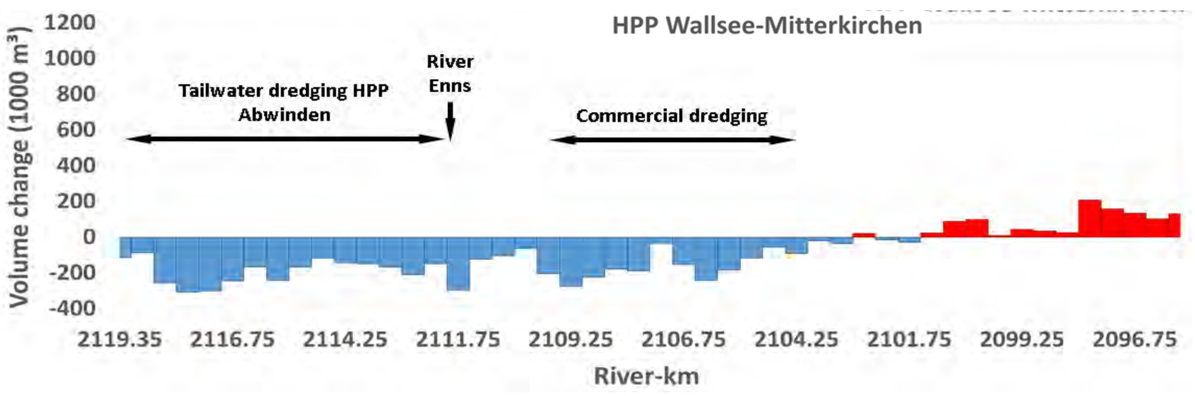


Figure 5.1.57 Distribution of sedimentation and erosion (500 m-long sections) along the length of the reservoir between 1968 and 2017 – bathymetry (after the floods in 2002 and 2013). (Database: VHP and viadonau).

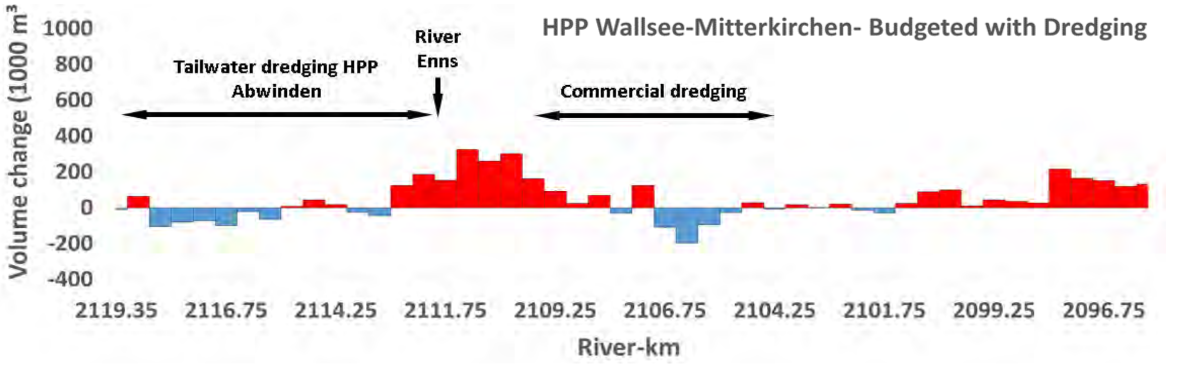


Figure 5.1.58 Distribution of sedimentation and erosion (500 m-long sections) along the length of the reservoir between 1968 and 2017 – bathymetry, including dredging (after the floods in 2002 and 2013). (Database: VHP and viadonau).

Like in the case of the upstream Abwinden-Asten HPP, the bed level at the head of the reservoir of the Wallsee-Mitterkirchen HPP is subject to erosion. This is mainly visible in the narrower section between rkm 2,118 and rkm 2,116, where erosion has prevailed since the HPP was put into operation (Figure 5.1.55). Based solely on bathymetric data, the impoundment has a sediment deficit of around 4.4 million m³. According to the data on dredging, around 2.1 million m³ of sediments have been deposited in the reservoir since the HPP was put into operation.

The Ybbs-Persenbeug HPP

The Ybbs-Persenbeug HPP is the second oldest HPP in the Austrian section of the Danube (in operation since in 1958). It is situated more or less in the middle of the Austrian Danube. This means it was significantly affected by bedload transport along the Austrian Danube up to the Wallsee-Mitterkirchen HPP. The distance to the next HPP upstream was around 143 km

(Gruber, 1969). This distance also includes the narrow break-through of the Struden, which used to be a dangerous section for inland navigation in the past.

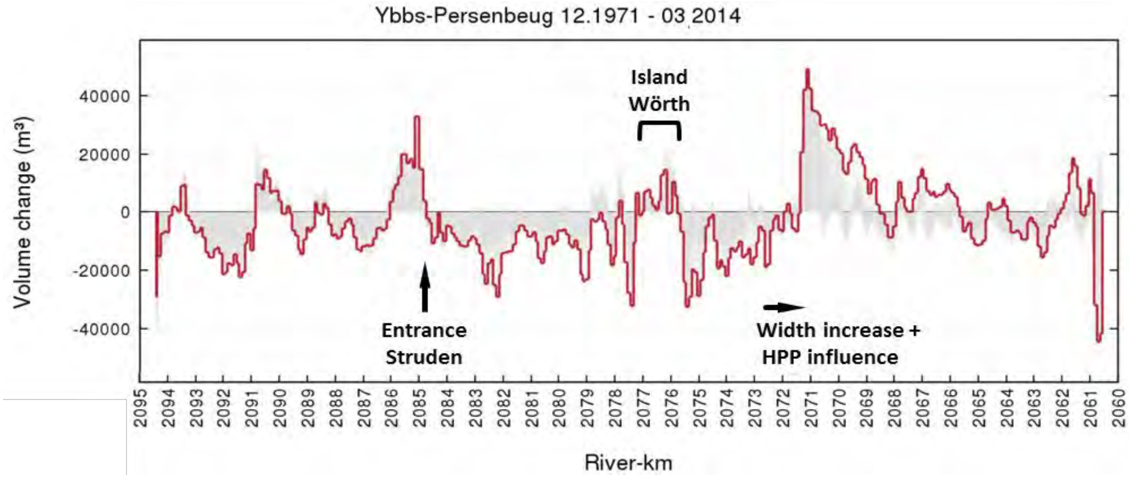


Figure 5.1.59 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir between 1971 and 2014. The grey shading indicates the volume changes that took place during the period under review and the red line shows the differences between the first and last available measurements. (Database: VHP).

The zone of erosion is more or less located in the narrowest part of the Struden, were gravel is still mobilized and transported farther downstream into the backwater. During the flood in 2013, sediments were deposited along the first 10 km upstream of the HPP in the amount of around 480,000 m³. Overall, the volume of sediments deposited since the putting into operation of the Ybbs-Persenbeug HPP is rather small (Figure 5.1.60).

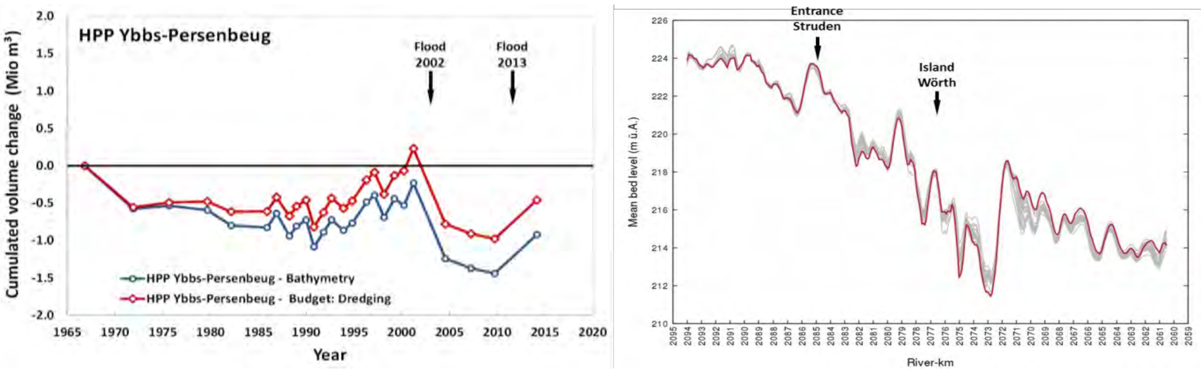


Figure 5.1.60 Cumulated volume changes at the Ybbs-Persenbeug HPP between 1966 and 2014. Right: Changes in the mean bed level at the Ybbs-Persenbeug HPP between 1966 and 2014. The red line shows the present situation. (Database: VHP).

For the impoundment of the Ybbs-Persenbeug HPP, no bathymetry measurements were available for the first few years. Schmutterer (1961) assumes that bedload sediments amounted to around 457,000 m³ in 1959 (the first year after the HPP was put into operation). Kobilka and Hauck (1982) investigated the sedimentation process in the impoundment and concluded that, in the first four years, around 1.4 million tons (~0.8 million m³) of bedload sediments were deposited in the reservoir, but most of them were dredged. According to Tschochner (1964), 750,000 m³ of gravel were dredged from the backwater of the Ybbs-

Persenbeugin HPP’s impoundment in 1960 and 1961. According to Schmutterer (1961), twice the mean bedload discharge is transported in the impoundment. He concludes that if any bedload is transported through the dam, it may be a relatively small amount.

Fine sediment deposits can be seen mainly in the lower third of the reservoir, close to the dam (see Prazan, 1990; VHP, 2014). The clearly visible deposits between rkm 2,171.5 and rkm 2,169 are composed of gravel forming the river bed and are influenced by an increase in the river’s width, coupled with the backwater effect of the HPP (Figure 5.1.59).

The Melk HPP

There were only minor fine sediment deposits at the Melk HPP (Figure 5.1.61). The deficit between rkm 2,059 and rkm 2,053 was mainly the result of gravel dredging (Figure 5.1.62, Figure 5.1.63 and Figure 5.1.64).

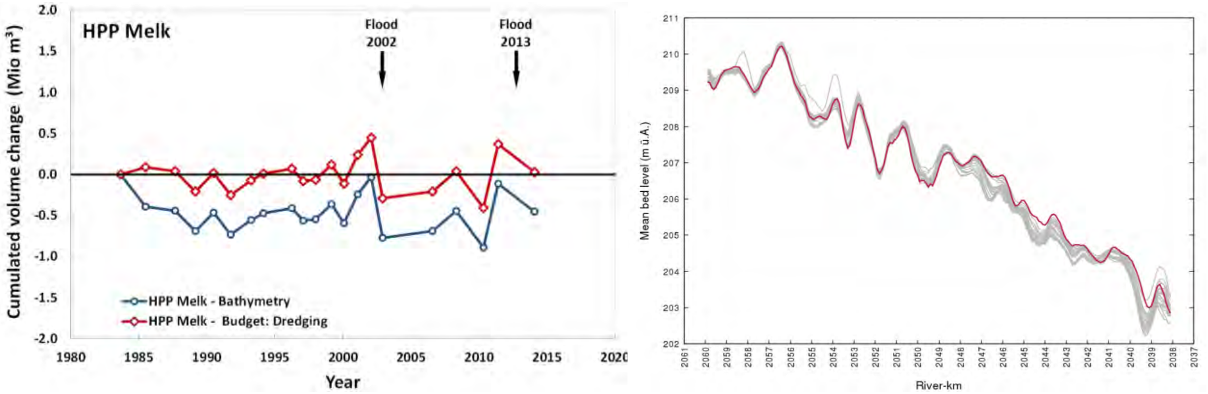


Figure 5.1.61 Left: Cumulated volume changes at the Melk HPP between 1983 and 2014. Right: Changes in the mean bed level at the Melk HPP between 1983 and 2014. (Database: VHP).

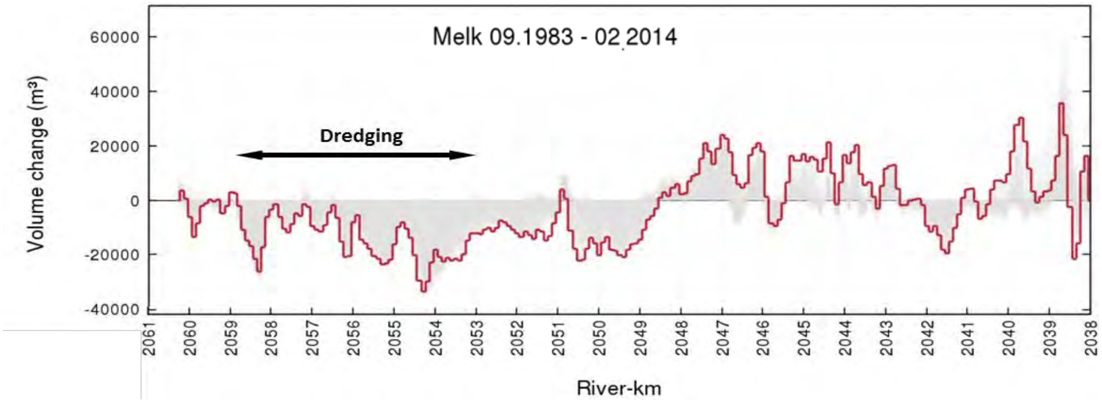


Figure 5.1.62 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir between 1983 and 2014. The grey shading indicates the volume changes that took place during the period under review the red line shows the differences between the first and last available measurements. (Database: VHP).

According to VHP (2014), sediment remobilization during the flood in 2013 took place close to the dam (approximately 250,000 m³) and was attributable to the open weirs and ship locks.

With the volume dredged taken into account, sedimentation in net terms has been close to zero since the HPP was put into operation.

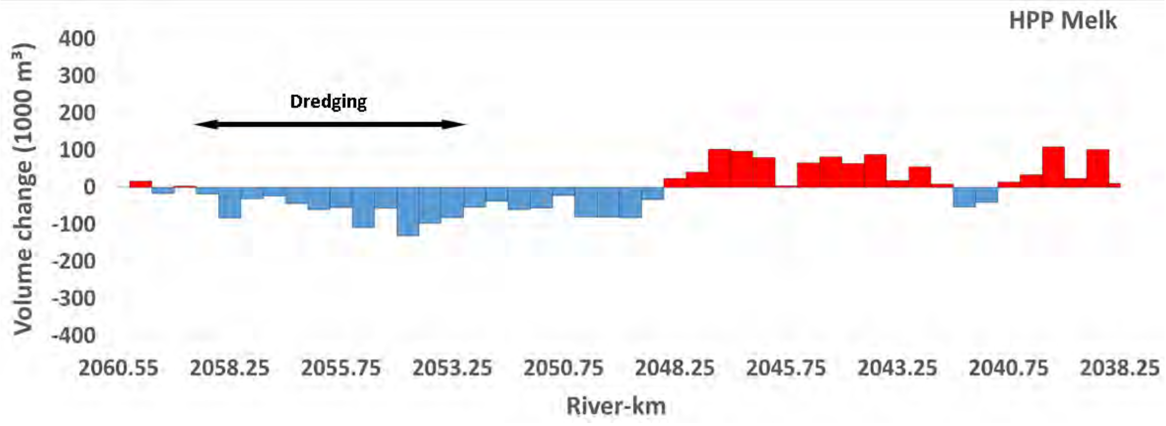


Figure 5.1.63 Distribution of sedimentation and erosion (500 m-long sections) along the length of the reservoir between 1983 and 2014 - bathymetry. (Database: VHP).

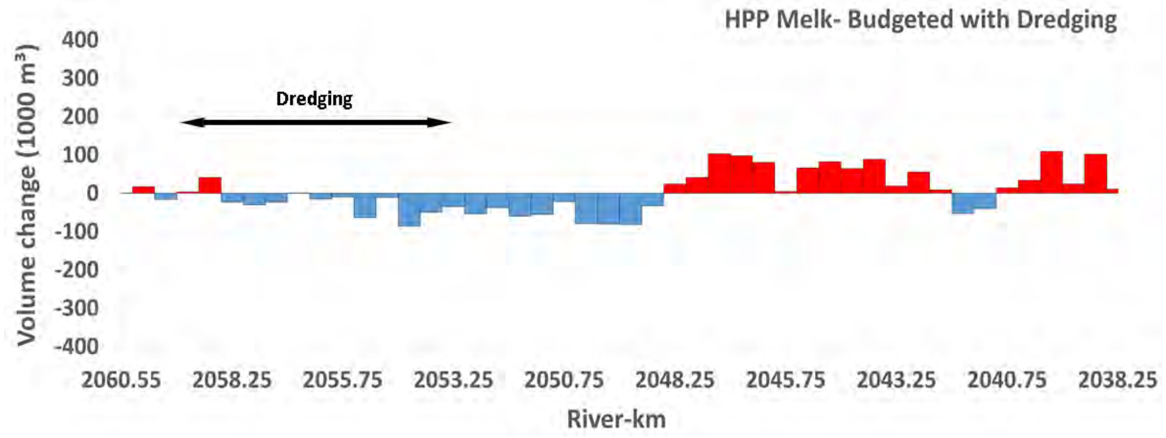


Figure 5.1.64 Distribution of sedimentation and erosion (500 m-long sections) over the length of the reservoir between 1983 and 2014 – bathymetry, including dredging. (Database: VHP).

Wachau

The Wachau is one of the two remaining free-flowing sections in the Austrian Danube. It is situated in a break-through section of the Danube. Prior to the river training activities, the most up- and downstream reaches were characterized by somewhat wider channels. Besides river training, additional pressures were exerted by the construction of the Melk HPP, followed by tail water dredging and maintenance measures (dredging) for inland navigation. Compared with the free-flowing section East of Vienna, no gravel was fed into the river channel downstream of the HPP and consequently the river bed was eroded gradually (Figure 5.1.65 – right panel).

The restoration of type-specific morphologies commenced at the end of the 1990ies, within in the scope of ecologically motivated projects. By 2014, gravel bars and island with a functional length of 6.5 km and side channels with a length of 8.5 km had been created as part of those projects. A consequence of the creation of gravel bars and islands in terms of the river’s sediment regime was that the sediments dredged were not removed from the Danube, but were used to build aforementioned morphological features.

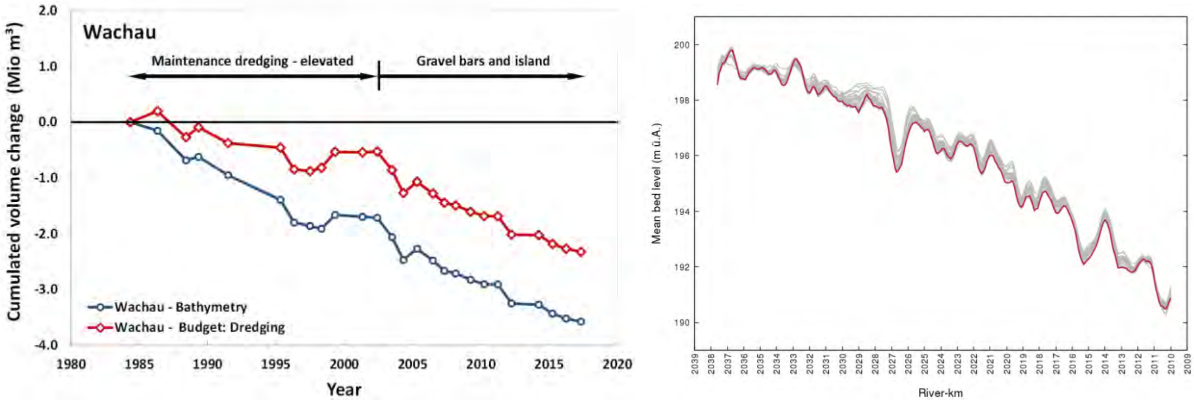


Figure 5.1.65 Cumulated volume changes in the free-flowing section Wachau between 1984 and 2017. Right: Changes in the mean bed level in the free-flowing section Wachau between 1984 and 2017. The red line shows the present situation. (Database: viadonau)

The free-flowing section of Wachau was exposed to gradual erosion (Figure 5.1.66), but, after the maximum erosion rate was reached, a slight decrease was visible around 2002. From that time, the gravel was no longer removed from the river channel. The erosion rate ranged from 1.0 to 1.4 cm/a (+/- 0.3) (Figure 5.1.66). The mean bed level was below minimum navigable water level (LNWL)) or below the mean water level (MWL).

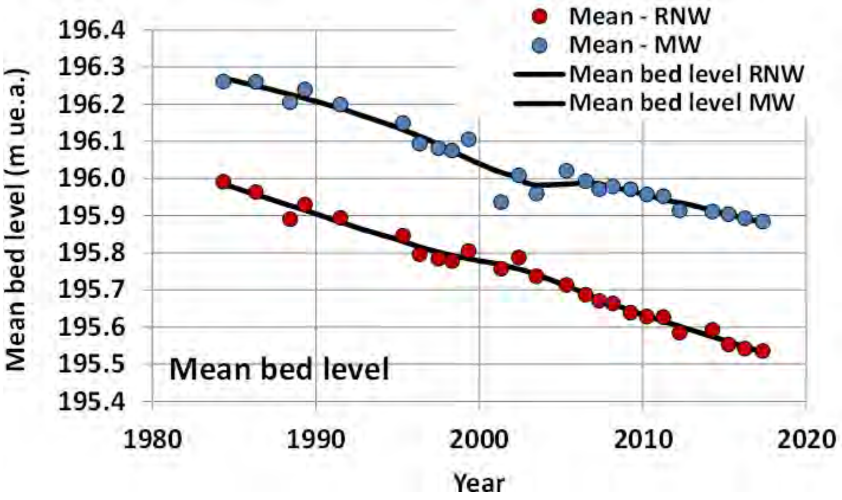


Figure 5.1.66 Changes in the bed level in the Wachau until 2017. Red dots: Mean bed level below the LNWL; Blue dots: Mean bed level below the MWL. The black lines indicate the overall trend after smoothing. (Database: viadonau)

The sediment deficit amounts to 100,000 m³/a (+/- 25,000 m³/a). This value is comparable with the assessment made by VHP (2013a), which calculated the output from Wachau into the backwater of the Altenwörth HPP from a budget based on bathymetry and a dredging volume of 113,000 m/a for a period of 15 years.

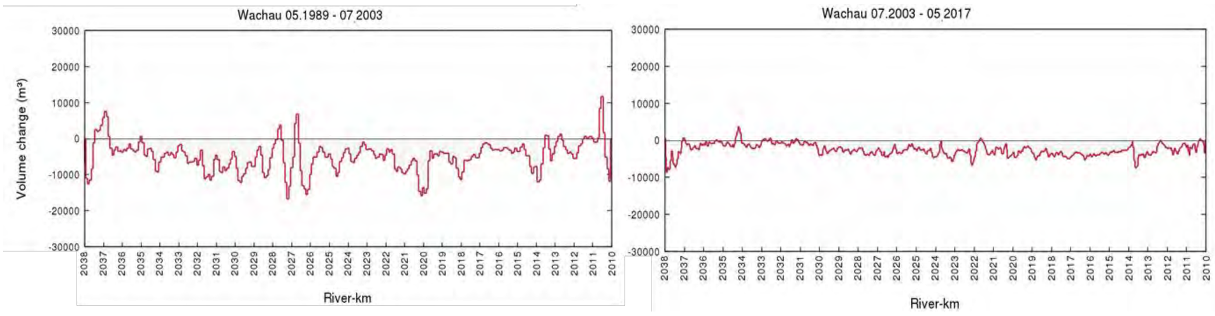


Figure 5.1.67 Distribution of sedimentation and erosion (110 m-long sections) along the free-flowing section from 1984 to 2003 (left) and from 2003 to 2017 (right). The red line shows the differences between the respective measurements. (Database: viadonau).

The Altenwörth HPP

The Altenwörth HPP is situated downstream of the free-flowing section of Wachau and therefore has a backwater with considerable sedimentation. The Altenwörth HPP has the second greatest weir height and reservoir volume of the HPPs on the Austrian Danube (see Nachtnebel et al., 1998). It is the second HPP in terms of the volume of fine sediment accumulation (the first is the Aschach HPP). In the reservoir of the Altenwörth HPP, a large volume of suspended sediments has accumulated along the first 5 km upstream of the dam. The volume of sedimentation gradually decreases until rkm 1,995. The (former) accumulation near rkm 2,000 results from bedload transport along the Wachau reaching the backwater of the impoundment (Figure 5.1.68 – left panel, Figure 5.1.69 and Figure 5.1.71) and was subject to dredging.

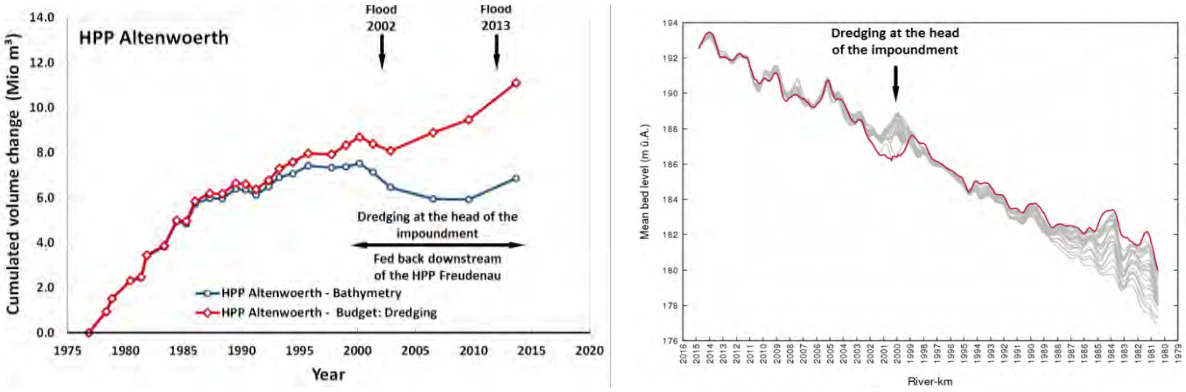


Figure 5.1.68 Cumulated volume changes at the Altenwörth HPP between 1976 and 2013. Right: Changes in the mean bed level at the Altenwörth HPP between 1976 and 2013. The red line shows the present situation. (Database: VHP)

Dredging took place approximately between rkm 2,003 and 1,999.5, with the aim of ensuring the necessary bridge clearance at the highest navigable discharges and to lower the flood water level near the city of Krems (VHP, 2013a) (Figure 5.1.68 – right panel, Figure 5.1.69 and Figure 5.1.70). The volume dredged between 1998 and 2016 amounted to around

3.8 million m³ (VHP, 2018) and the sediments dredged were used for feeding downstream of the Freudenau HPP to supply the free-flowing section East of Vienna.

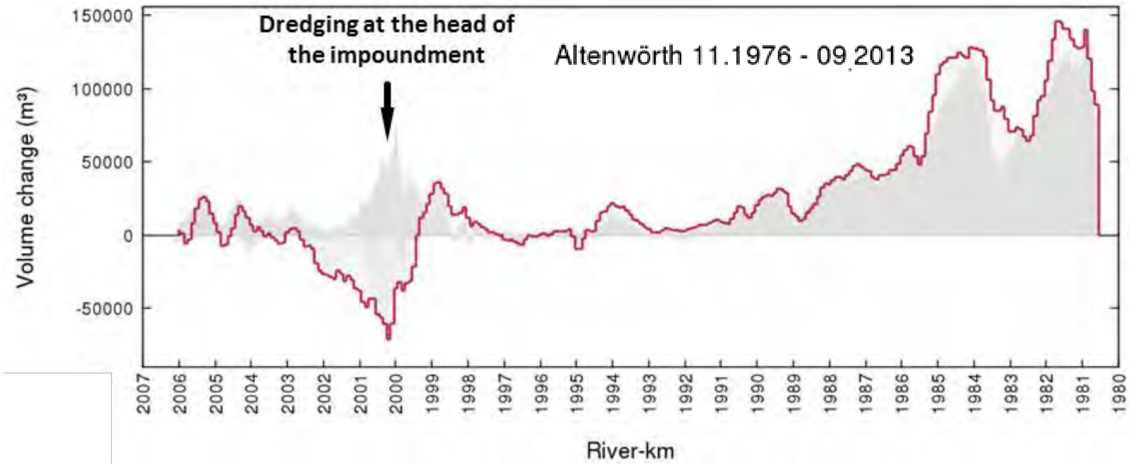


Figure 5.1.69 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir between 1976 and 2013. The grey shading indicates the volume changes that took place during period under review and the red line shows the difference between the first and last available measurements. (Database: VHP).

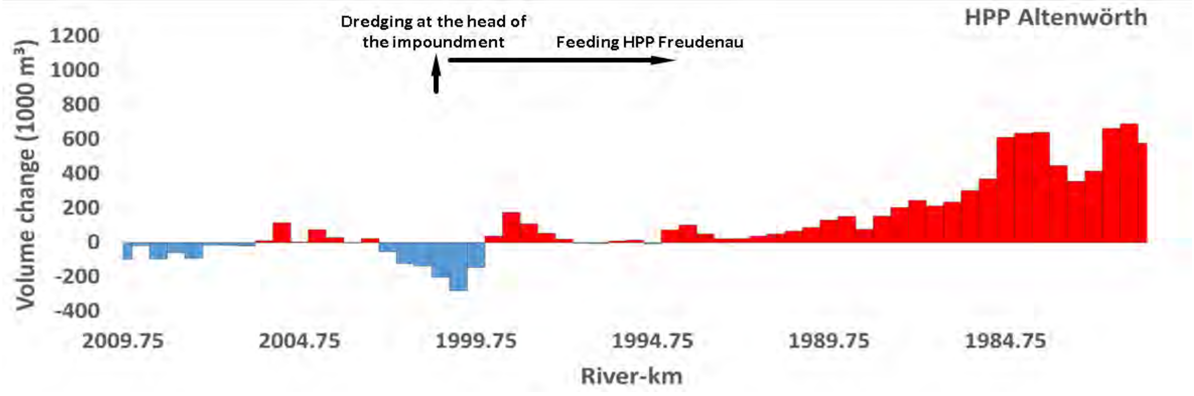


Figure 5.1.70 Distribution of sedimentation and erosion (500 m-long sections) along the length of the reservoir between 1976 and 2013 – bathymetry (Database: VHP).

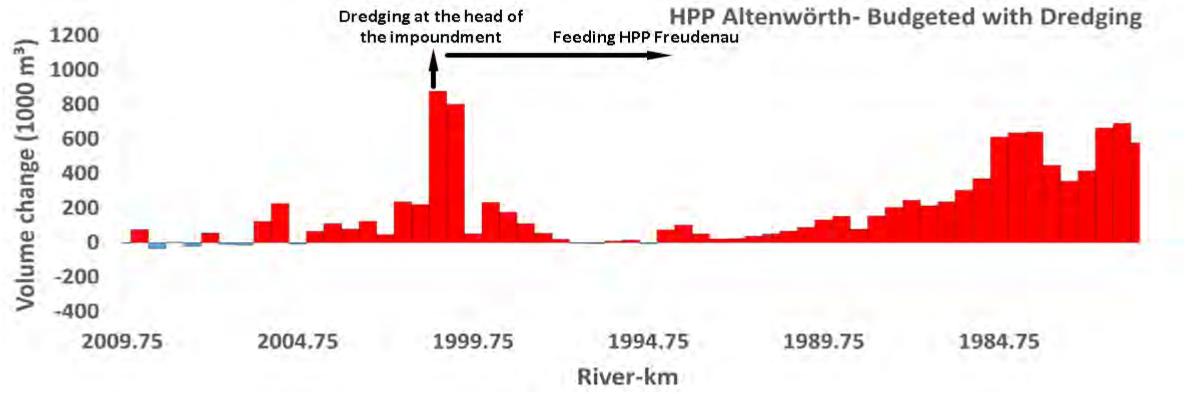


Figure 5.1.71 Distribution of sedimentation and erosion (500 m-long sections) along the length of the reservoir between 1976 and 2013 – bathymetry, including dredging (Database: VHP).

Summer and Nachtnebel (1989) compiled a longitudinal distribution of the grain sizes across the impoundment of Altenwörth, showing that the volume of deposited sediments consists of sand and silt (Figure 5.1.72). Gravel fractions in the river bed can only be found at the head of the impoundment (upstream of rkm 1,994). Figure 5.1.72 illustrates that – starting from the dam – the grain sizes are steeply increasing in the upstream direction and that the accumulated sediments have a high percentage of sand. Only along the first 4 to 5 km upstream of the dam were large amounts of sediments deposited (Figure 5.1.68 – right panel and Figure 5.1.69), with silt fractions starting to dominate the river bed.

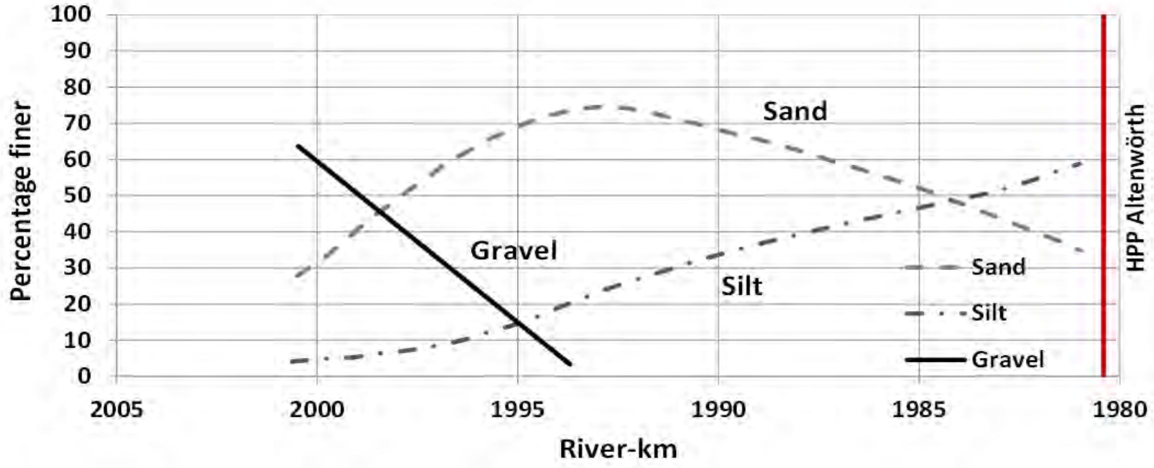


Figure 5.1.72 Longitudinal distribution of the grain sizes in the impoundment of Altenwörth (Summer and Nachtnebel, 1989)

When comparing the grain sizes in Figure 5.1.72 with those at the Aschach HPP, we can see a certain degree of sediment coarsening in the downstream direction (from Aschach to Altenwörth). This was also noted by Kralik and Sager (1986), who showed that the grain sizes of the sediments accumulated in the impoundments are increasing in the downstream direction, i.e. from Aschach to Greifenstein.

Over the first ten years after the Altenwörth HPP was put into operation, the volume of deposited sediments rapidly increased (Figure 5.1.68). Subsequently, the rate of sedimentation decreased and then remained broadly unchanged until the turn of the millennium. The subsequent reduction until 2006 was caused mainly by the dredging activities that started in 1998 at the head of the reservoir (Figure 5.1.68, blue line – right panel) (see VHP, 2013a), and around 0.5 million m³ were remobilized during the floods in 2002 downstream of rkm 1,996. The flood in June 2013 in turn resulted in sedimentation of around 1.3 million m³ in net terms, in the lower part of the reservoir. The last available measurement before the flood was made in 2009, so some sedimentation might have occurred already before the flood in 2013. Budgeting the sediment volume in the impoundment with the amount dredged in the reservoir (Figure 5.1.68, red line – right panel) indicates that around 1.4 million m³ of sediments were deposited between the end of 2002 and 2009. Half of these sediments were fine sediments, the other half came as a bedload input from Wachau into the backwater of the Altenwörth HPP. Since the HPP was put into operation, fine sediments have accumulated downstream of rkm 1995 in the amount of 7.3 million m³.

The Greifenstein HPP

After the Aschach and Altenwörth HPPs, the Greifenstein HPP has the third largest impoundment in the Austrian section of the Danube. In the reservoir of the Greifenstein HPP, most sediments were deposited along the first 2.5 km and then their volume decreased until rkm 1,956 (Figure 5.1.73).

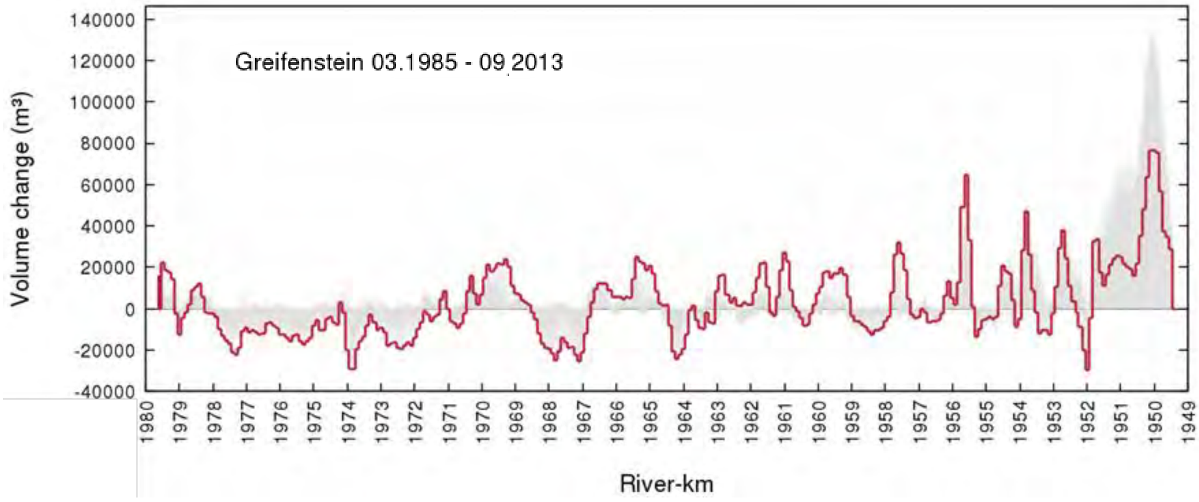


Figure 5.1.73 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir between 1985 and 2013. The grey shading indicates the volume changes that took place during the period under review and the red line shows the differences between the first and last available measurements. (Database: VHP).

From its putting into operation in 1984 to 2002, the reservoir had a more or less constant sedimentation rate, which was interrupted only by the flood in 1991 (Figure 5.1.74). Overall, around 3 million m³ of sediments were trapped over a period of 18 years. The floods in 2002, mainly the one in August 2002, caused sediment remobilization in the amount of almost 2 million m³, mainly over the first 5 to 6 km upstream of the dam. Until 2010, sedimentation prevailed with a volume of approximately 700,000 m³, downstream of the area where sediments were remobilised in 2002. In 2013, only 200,000 m³ of sediments were remobilized during the floods. Flood plain sedimentation at Tullnerfeld (from rkm 1,972 to rkm 1,945) is subject to a high degree of uncertainty, because the volumes of sediments deposited are not recorded values but estimates based on the known amounts of deposits, i.e. 1.25 million m³ for the 2002 flood and 1.81 million m³ for the 2013 flood (BMLFUW, 2015). Until 2017, around 600,000 m³ of sediments had been deposited in the impounded river stretch. This indicates that around 2.1 million m³ had been trapped since the day when the reservoir was put into operation.

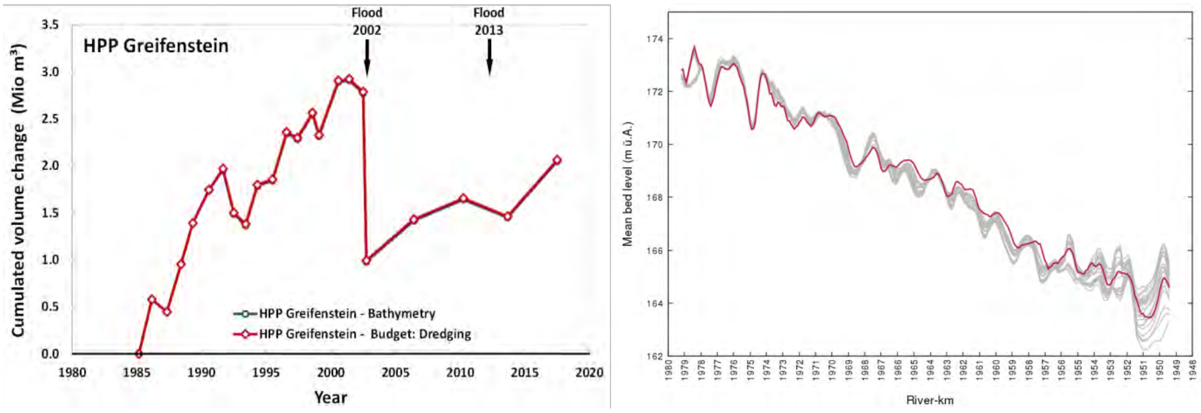


Figure 5.1.74 Cumulated volume changes at the Greifenstein HPP between 1985 and 2017. Right: Changes in the mean bed level at the Greifenstein HPP between 1985 and 2013. The red line shows the present situation. (Database: VHP).

The Freudenau HPP

The Freudenau HPP is situated in Vienna, were the Danube has been channelized since the great Danube regulation in Vienna (from rkm 1,935 to rkm 1,918), which took place between 1870 and 1875. Another big regulation project was the dredging of the 'Neue Donau' and the construction of the 'Donau Insel' in the period from 1972 to 1988 for flood protection. This means that, during flood events, the Danube in Vienna now flows through two separate channels.

The Freudenau HPP is the last hydropower plant that was put into operation (at the end of 1997) on the Danube in Austria (its construction started in 1992). Until the partial inundation in 1996, the East of Vienna section had been supplied with bedload from an additional 28 km-long stretch. Until the start of construction works, the river bed had been subject to erosion. According to BMNT (2018b), bedload transport from the stretch between the Greifenstein and Freudenau HPPs was assumed to amount to about 160,000 m³. This amount was also used as a baseline for gravel feeding downstream of the Freudenau HPP.

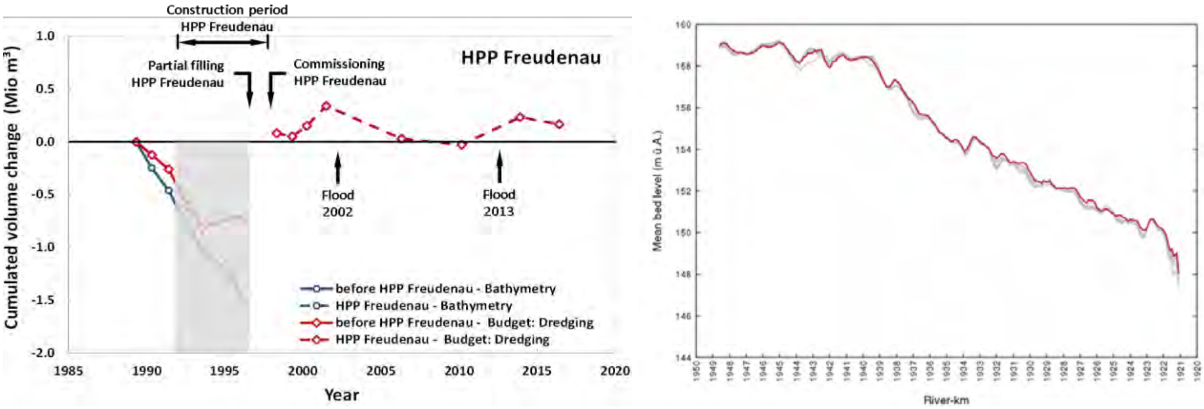


Figure 5.1.75 Cumulated volume changes before and after the Freudenau HPP was put into operation at the end of 1997. Right: Changes in the mean bed level at the Freudenau HPP between 1998 and 2016. The red line shows the present situation. (Database: VHP)

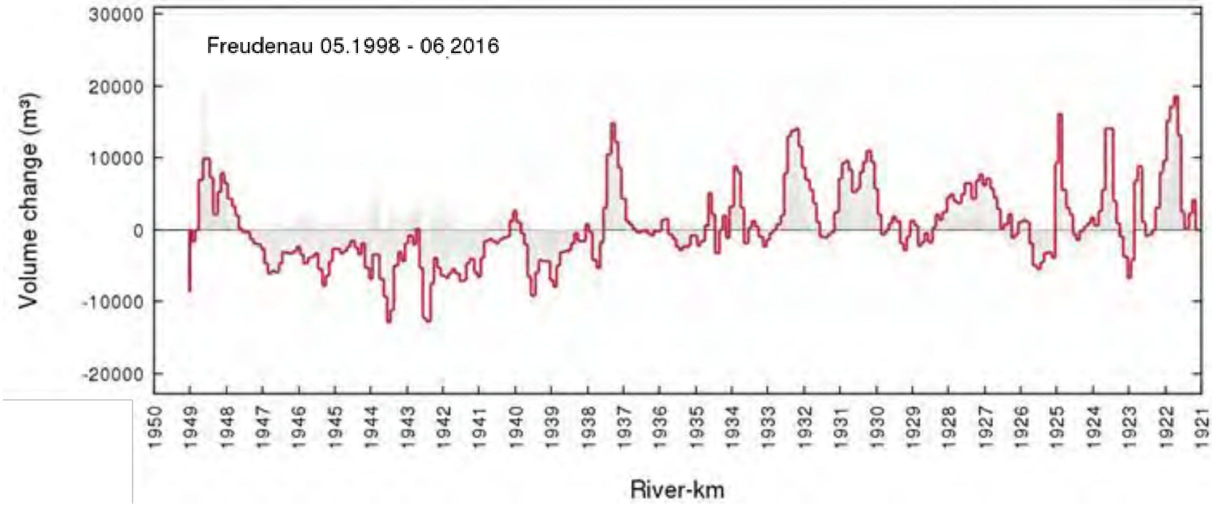


Figure 5.1.76 Distribution of sedimentation and erosion (100 m-long sections) along the length of the reservoir between 1998 and 2016 (after the Freudenau HPP was put into operation). The grey shading indicates the volume changes that took place during the period under review and the red line shows the differences between the first and last available measurements. (Database: VHP).

Since the HPP was put into operation, the volume and bed level changes have been rather small (Figure 5.1.75). Sedimentation is currently concentrated in the lower half of the impoundment, while erosion takes place in its upper half (Figure 5.1.76). The flood in June 2013 caused sedimentation in the amount of roughly 330,000 m³ in the lower half of the impoundment, while the area between rkm 1,942 and rkm 1,936 was exposed to erosion. The volume of eroded sediments amounted to 80,000 m³ (VHP, 2014). Since the partial inundation in 1996, a net output of around 260,000 m³ has been recorded, while, since the time when the HPP was put into operation (the end of 1997), sedimentation in the amount of roughly 170,000 m³ has been observed (Figure 5.1.75).

The Danube East of Vienna

The Danube east of Vienna is one of the two remaining free-flowing stretches of the Danube in Austria, situated in the 'Donau-Auen' National Park within the 'Marchfeld' basin. The Freudenau HPP is located in the upstream part of the East of Vienna reach of the Danube. Downstream of this HPP, gravel is fed into the river channel. At its downstream end, the river reach is influenced by the backwater of the Gabčíkovo HPP (in operation since 1992). In terms of sediment management, the free-flowing section under review has undergone several stages over the last 30 years.

An important event was gravel feeding downstream of the Freudenau HPP, arranged by the hydropower company VERBUND. The feeding started in 1996 and the amount of gravel fed into the maintenance reach downstream of the Freudenau HPP, between rkm 1,921 and rkm 1, was roughly 186,000 m³/a in the period from 1996 to 2017. This amount has recently increased to 235,000 m³/a (BMNT, 2018).

In addition, several measures have been implemented for the Danube east of Vienna with the aim of stabilising the surface and ground water levels, maintaining and improving the habitats in the Danube floodplains, and improving the waterway infrastructure for inland navigation. These integrated measures comprise integrated sediment management, optimized river training, side channel reconnection, bank protection removal, and scour protection. These measures are designed to keep the sediments longer in the system, reduce the transport capacity of the main channel, prevent a river bed break-through, and to improve the ecological situation (viadonau, 2018).

In terms of fairway maintenance (Simoner, 2018), roughly 50% of the sediments dredged between 1996 and 2005 were fed back into the main stream, 30% were extracted and 20% used for the construction of gravel structures. From 2006 on, all the dredged material was fed back into the main stream, first downstream and from 2009 on upstream of the dredging site. Finally from 2015 on, the upstream transfer distance was considerably increased, to around 11 km (Simoner, 2018), to keep the sediments longer in the system. In addition, a bedload trap was installed at around rkm 1,888 in 2017 and the dredged sediments are now transported about 20 km upstream.

As regards river training and/or river restoration, the following pilot projects have been implemented by *viadonau* over the last 20 years:

- River bank restoration at Thurnhaufen (2006), where bank protection was removed along a length of 2.85 km and the Danube was allowed to widen again.
- Groyne field reconfiguration and optimisation (modified shape, larger spacing and reduced height) near Witzelsdorf (at around rkm 1,892.5), combined with height reduction of the upstream guiding wall and bank protection removal (finalised in 2015).
- Groyne field reconfiguration and optimisation (modified shape, larger spacing and reduced height) near Bad Deutsch-Altenburg (between rkm 1,887.5 and rkm 1,884.5), combined with bank protection removal (finalised in 2017). Part of this project was a so-called ‘Granulometric Bed Improvement’ test, on the basis of which coarser stones (but still within the natural grain size spectrum) were placed on the river bed to reduce the river’s bedload transport capacity.
- Side channel reconnection (e.g. the Haslau-Regelsbrunn, Orth, Schönau and Johler side arms have been reconnected) and the reconnection of the Spittelauer side arm, which is currently under implementation.

Pessenlehner et al. (2016) assessed the influence of two pilot projects aimed at groyne field modification (different shape, larger spacing and reduced height) in order to identify the influence of these measures on the sediment balance of the Danube east of Vienna. In the stretch where the Bad Deutsch-Altenburg pilot project was implemented (after 2009), aggradation was observed in the period from 2001 to 2015. In the stretch further upstream at Witzelsdorf, higher bed levels can be seen (Figure 5.1.66 – left panel). Figure 5.1.77 shows the influence of the Gabčíkovo HPP's backwater downstream of rkm 1,880, were the bed levels appear to be stable. For the period from 2009 to 2015, Pessenlehner et al. (2016) calculated an annual average bed level change in the stretch in which the Bad Deutsch-Altenburg pilot project was implemented (+2.2 cm/a), compared with the extent of erosion (-0.6 cm/a) measured along the whole East of Vienna reach (Figure 5.1.77 – right panel). They concluded that the restoration measures may reduce the ongoing river bed erosion to some extent and that the measures proposed should be optimised if the reduced degradation and navigational requirements are to be met.

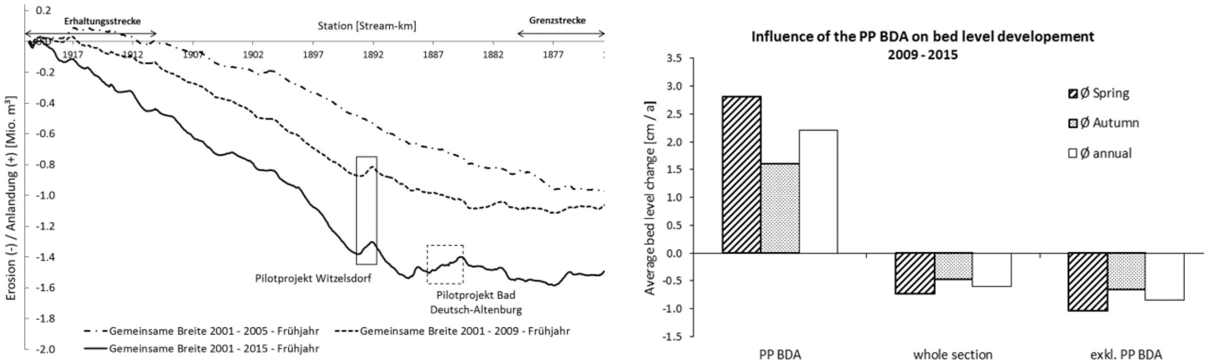


Figure 5.1.77 Left: Cumulated bed level changes the Danube between the Freudenau HPP and the Slovak border (from rkm 1,920.6 to rkm 1,872.7) for the periods 2001 to 2005, 2001 to 2009 and 2001 to 2015 (Habersack et al., 2017). Right: Influence of the Bad Deutsch-Altenburg pilot project on the average annual bed level change for the common width and the period 2009 to 2015. (Pessenlehner et al., 2016)

Regarding the bed level changes and the degree of erosion in recent years, several different values can be found in the literature. They have been derived from calculations of bed level changes and volumes made for different time periods and different lengths. Klasz et al. (2016) calculated an annual erosion of -2 cm/a for the stretch between rkm 1,916 and 1,893 for the period from 1996 to 2015. They calculated an erosion volume of 151,000 m³/a for the stretch between rkm 1921 to rkm 1,880 for the period from 1996 to 2011. Simoner and Berger (2016) calculated an erosion volume of 124,000 m³/a for the period from 1996 to 2016; 165,000 m³/a for the period from 1996 to 2006; and 92,000 m³/a for the periods from 2006 to 2016, for the stretch between rkm 1,920 and rkm 1,880. They also calculated the volume change for a shorter time period (from 2009 to 2016), resulting in an erosion volume of 73,000 m³/a and an erosion rate of -1 cm/a based on the mean water levels in the years 1996 and 2015. BMNT (2018) calculated an erosion rate of around -1.5 cm/a for the period from 1996 to 2010, based on the changes in the LNWL. An erosion rate of -1 cm/a for the period from 2001 to 2015 can be found in Habersack et al. (2017) and -1.16 cm/a for the period from 2001 to 2009.

What all the cited sources have in common is that, if the last roughly 20 years are compared with last 10 years, the erosion rates and/or the eroded volumes show a decreasing trend. This trend is also apparent when the volume changes between 1990 and 2017 (Figure 5.1.78 – left panel: blue line) are compared with the changes in the mean river-bed levels (Figure 5.1.79 – left panel). The longitudinal profile in Figure 5.1.78 (right panel) shows an erosional trend, mainly upstream of rkm 1893 or rkm 1889, with a more stable or slightly aggrading river bed in the downstream part.

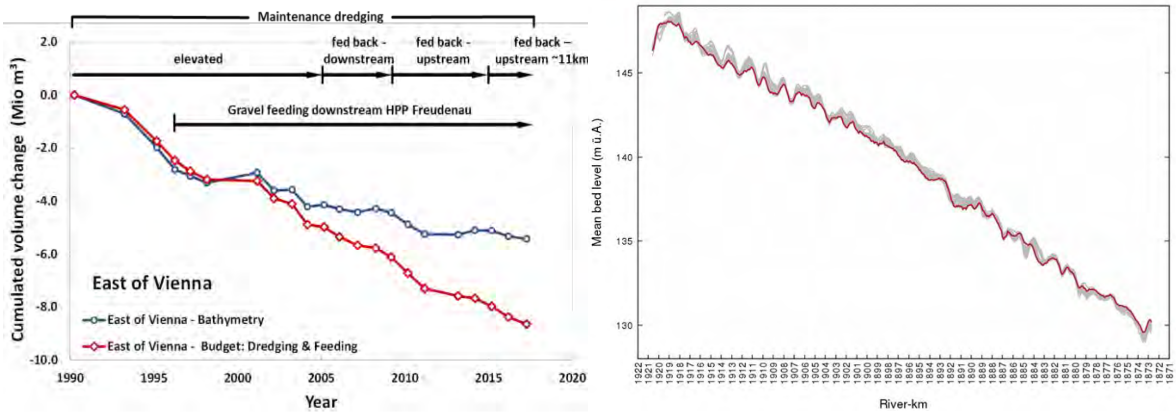


Figure 5.1.78 Cumulated volume changes in the free-flowing East of Vienna reach between 1990 and 2017. Right: Changes in the mean bed level of the East of Vienna reach between 1990 and 2017. The red line shows the present situation. (Database: viadonau)

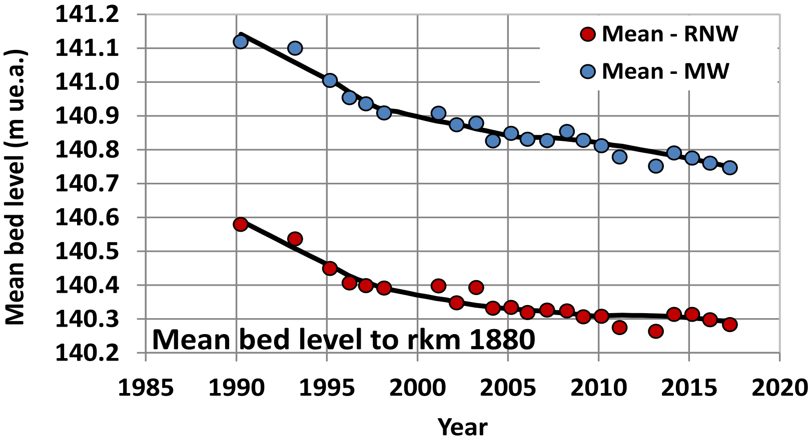


Figure 5.1.79 Left: Changes in the bed level of the East of Vienna reach between rkm 1,920 and rkm 1,880 (excluding the border reach) until 2017. Red dots: Mean bed level below LNWL. Blue dots: Mean bed level below MWL. The black lines indicate the overall trend after smoothing. Right: Bed level changes in cm/year calculated for overlapping 7 year periods. Red: Mean bed level below LNWL; Blue: Mean bed level below MWL. Shading indicates uncertainty based on an assumed random measurement error of +/- 2 cm. (Database: viadonau)

A significant effect in this regard is exerted by gravel feeding downstream of the Freudenau HPP. During the period from 1996 to 2010, for example, gravel feeding in the amount of 193,000 m³/a reduced the erosion rate by about 1.9 cm/a along a length of 40 km between the HPP and the confluence with the Morava River (BMNT 2018b). During the period from 2009 to 2017, gravel feeding in the amount of 175,000 m³/a (2009 to 2017) reduced the erosion rate by about 1.5 cm/a along a length of roughly 47 km. The difference between the two values stems mainly from the different amounts of gravel fed per year and the different lengths of the river reach under review.

The effect of the erosion rate in the case of maintenance dredging was assessed by BMNT (2018a) to account for around 0.4 cm/a (along a 40 km-long stretch) for the period from 1996 to 2010, which means that around 20% of the bed level degradation was due to the fact that the sediments were not fed back into the river channel. Currently, the gravel dredged for maintenance is fed back in full. To see what would happen in terms of the erosion rate if the gravel dredged were removed, we assumed that the gravel dredged in the period between 2009 and 2017 was fully removed. In this case the erosion rate would be much higher (1.5 cm/a along a 47 km-long stretch). This means that keeping the sediments in the river channel has a measureable downward effect on the erosional trend.

The data on bathymetry, dredging and feeding shows that the amount of gravel excavated from the river channel ranges from 290,000 to 330,000 m³/a for the period after 2001. Not included is the amount lost as a result of abrasion. The sediment transport measured at rkm 1,886.24 for the period from 2009 to 2017 amounts to 420,000 t/a (+/- 20,000 t/a) or about 240,000 m³/a (see Gmeiner et al., 2016 and Liedermann et al., 2018). BMNT (2018a) calculated a net volume change (including abrasion) of 340,000 m³/a (+/-20,000 m³/a) for the period until 2010.

Thalweg

When looking at the longitudinal profile of the Danube in Austria (Figure 5.1.80), including the Thalweg from 1902 (2km, moving average), it shows no continuous decline in the river's gradient. This is due to the geomorphological conditions described earlier, with changes between the break-through sections and the wider basins (see also Kresser et al., 1978).

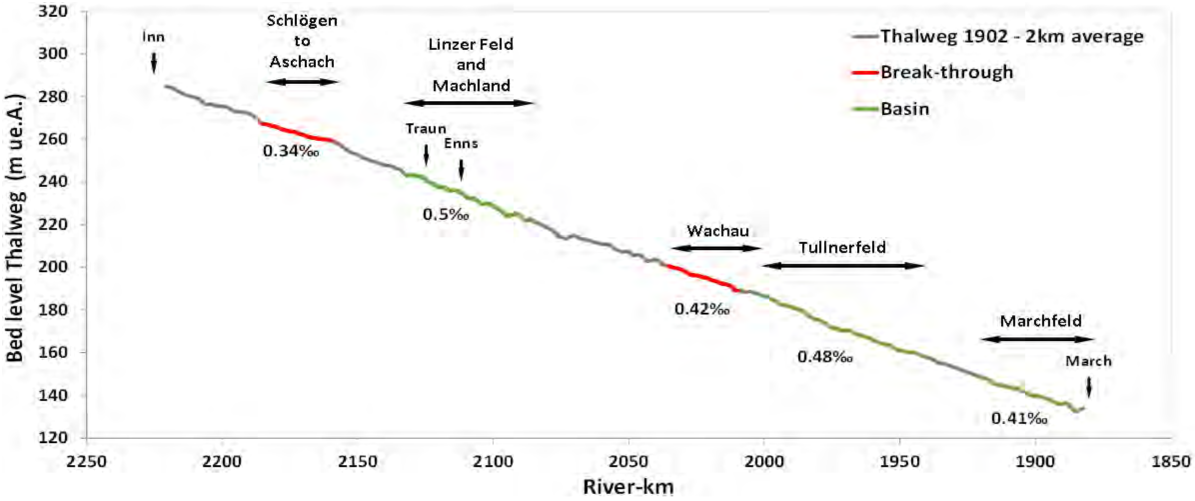


Figure 5.1.80 Thalweg 1902: Longitudinal profile. Thalweg smoothed with a moving average of over 2 km. Red lines: Narrow valleys (break-through sections); Green lines: Basins.

The slopes of most of the wider sections shown in Figure 5.1.80 (e.g. Linzer Feld and Machland with a slope of 0.5‰ and Tullnerfeld with a slope of 0.48‰) are higher than the slopes of the break-through sections (e.g. Schlögen-Aschach with a slope of 0.34‰ and Wachau with a slope of 0.41‰). Only the Marchfeld (East of Vienna) section has a mean slope of about 0.41‰. This is due probably to the subsidence of this region over the past millions of years (Grupe and Payer, 2014; Hohensinner and Jungwirth, 2016). It should be noted that the Thalweg from this period is already influenced by at least the mean water regulation. But according to Hohensinner and Jungwirth (2016), the water surface slope in the Eastern part of Machland (from rkm 2,094 to rkm 2,084) varied between 0.47‰ and 0.59‰ in the years from 1775 to 1817. This means that despite the river regulation, the slope had not changed to a significant extend by 1902. The cause of this slope difference between the basins and the valleys seems to be the difference in the wetted channel's width. Assuming a sediment regime with a dynamic equilibrium after the last ice age, the narrow single threaded parts of the break-through sections need to have a lower gradient to be able to transport the same amount of sediments than the wider and shallower parts of the Danube (see Schmautz et al. 2002). A comparison of the thalweg from 1902 with the present one (Figure 5.1.81) shows that the most significant changes occurred downstream of the HPPs, where tail water dredging was applied to lower the river bed.

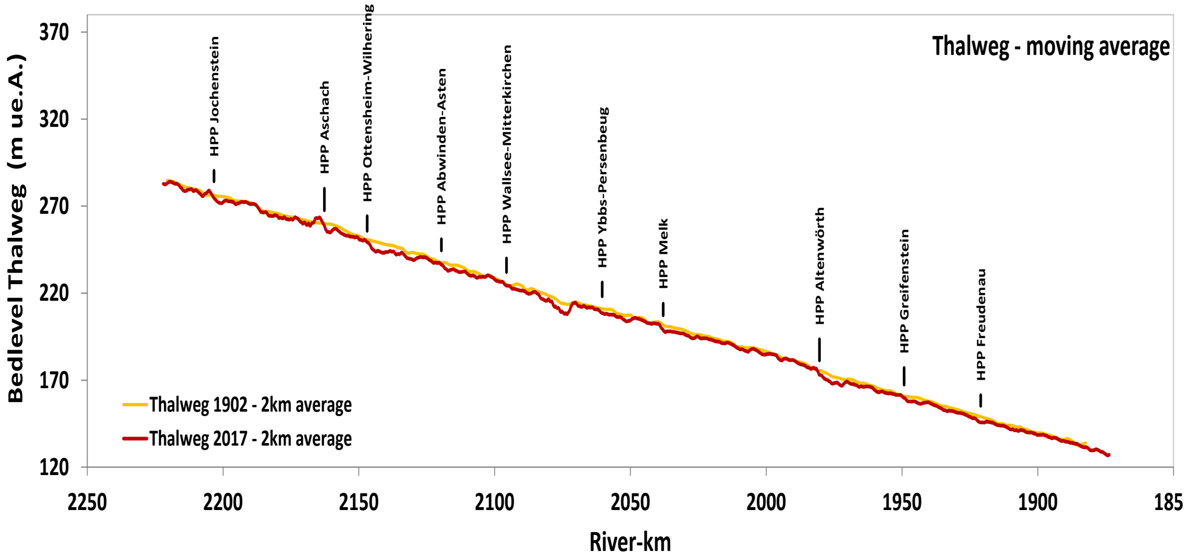


Figure 5.1.81 Comparison of the thalweg from 1902 with the thalweg from 2017 for the Danube in Austria

The accumulation of sediments is also illustrated, but overall the thalweg is not the best indicator, mainly where the accumulated sediments are concentrated at one side of the river channel (see Figure 5.1.47 – right panel), with only small height changes in the thalweg. Also, the thalweg in the two free-flowing sections is now smaller than it was in the past by around 0.08‰ (Wachau, rkm 2,035 to rkm 2,011) and 0.03‰ (East of Vienna, rkm 1,920 to rkm 1,884) (Figure 5.1.82). This slope of the East of Vienna section was calculated only up to rkm 1,884, because the thalweg further downstream was not available. The present thalweg of the upstream part of Wachau is to some extent influenced by tail water dredging for the Melk HPP. However, a calculation of the thalweg slope between rkm 2,028 and rkm 2,011 leads to the same result.

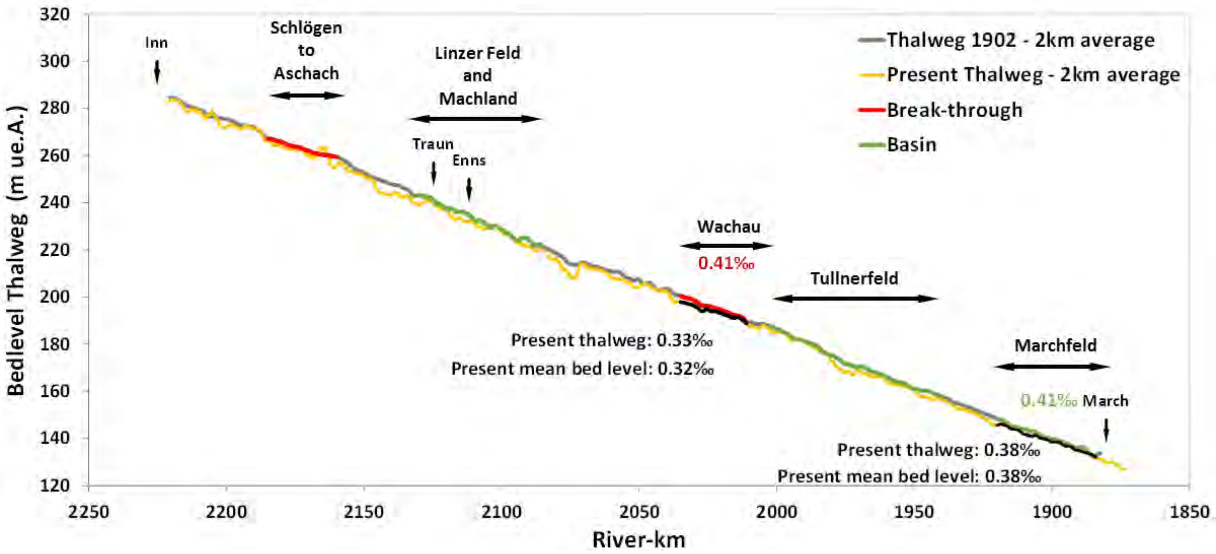


Figure 5.1.82 Comparison of the thalweg from 1902 with the thalweg from 2017 for the Danube in Austria. Also indicated is the bed slope for the present mean bed level.

As there were no mean bed levels for the historical data available, the slope difference between the thalweg and the mean bed level (2 km on average for both) was assessed for the current situation, to get an idea of the extent to which they may differ. The slope for the mean bed level was calculated for the river bed delimited by the LNWL of 2010. There is no difference for the East of Vienna stretch (rkm 1,920 to rkm 1,884) and the slope of the thalweg in Wachau (rkm 2,035 to rkm 2,011) is 0.01‰ higher than the slope of the mean bed level.

5.1.3 Slovakia

Brief description of the Danube in Slovakia

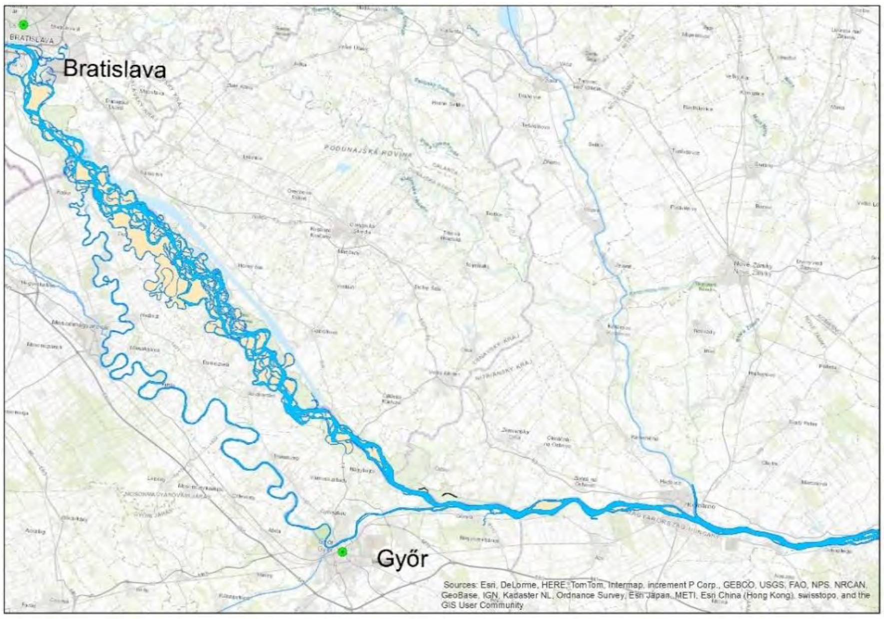
The river’s morphology is determined by the natural conditions prevailing in the given physical and geographical environment, which is modified by human interventions and engineering activities successively implemented into the river system (river training measures, dams, etc.). The resulting morphological changes in the river channel greatly influence the level of food protection, the shipping conditions, and hydropower generation. This chapter contains a spatial-temporal analysis of the morphological changes occurring in the river bed (across the territory of Slovakia) in relation to the sediment balance and the main hydromorphological pressures.

The Slovak section of the Danube begins at the mouth of the Morava River (rkm 1,880) and ends at the mouth of the Ipel River (rkm 1,708). Within its total length amounting to 172 kilometres, the Danube consists of a Slovak-Austrian stretch (from rkm 1,880 to rkm 1,873) and of a Slovak-Hungarian stretch (from rkm 1,851.75 to rkm 1,708). Four of its tributaries flow into the Danube from the left side (i.e. Morava, Váh, Hron and Ipel) and two from the right side (i.e. Rába and Mosoni Duna). In the Slovak – Hungarian stretch, the mountainous character of the Upper Danube is changing into that of a lowland river between Kližská Nemá (SK) and Gönyű (HU), from rkm 1,790 downstream (Middle Danube).

Since the end of 19th century, the natural character of the Danube channel has been modified successively by river training works, mostly for navigation and flood protection purposes. These works continued until the first half of the 20th century. Over the next decades, sediment transport (supply) along the Danube across the territory of Slovakia was also affected by a chain of hydropower plants built on the Upper Danube (in Austria and Germany). However, their impact on the flow and sedimentary conditions in the Danube channel was connected with the construction and operation of the Gabčíkovo hydropower plant (1992).

Spatial and temporal changes in the river channel's morphology

In the past, the Danube River created a very dynamic fluvial system downstream of Bratislava (Figure 5.1.83). Large amounts of sediments (gravel, sand) transported from the upper parts of the Danube accumulated downstream of the '*Devín Gate*' (at the mouth of the Morava River), forming extensive deposits in response to a major drop in the river bed gradient. The dynamic evolution of the river system resulted in a massive alluvial fan – today's Žitný ostrov (Zitny Island) and Szigetköz, which are bounded by the Small Danube on the Slovak side and Mosoni Duna on the Hungarian side.



Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 5.1.83 Layout of the Danube River's pattern corresponding to the reference conditions, illustrated in a topographic map (Esri, 2019)

With the Danube flowing at the top of this alluvial fan where, owing to the specific morphological conditions, a unique anastomosing river stretch developed gradually between Bratislava and Sap (rkm 1,810). This highly diversified anabranch system is referred to as *the Danube Inland Delta* (Figure 5.1.83).

The river pattern then changes from a *multi-thread anabranching (high energy)* pattern into a *transitional wandering (rkm 1,802–1,750)* pattern and downstream of Dunaalmás (rkm 1,750) into *multi-thread anabranching (low energy)* pattern.

The period of *'free meandering'* had prevailed until the beginning of the 19th century. The morphological development was affected by frequent floods, which caused changes in the river's main course and channel pattern. In this period, lateral morphological evolution prevailed in the Danube. Initially, flood protection measures were implemented only locally, for the nearest towns and villages (until the 13th century). Later, the flood protection system was gradually improved and extended to form continuous flood protection lines on both sides (by the 19th century). Thus, a floodplain of irregular width was formed by the dikes, with the anabranch system being part of this floodplain.

In the second half of the 19th century, river training works started to be implemented in the Danube channel for medium discharges. This is documented by a map from the 3rd military mapping (1869–1897). Hence, the state of the Danube from the period just before the beginning of systematic river regulation can be considered the last *unregulated state,* which corresponds to the ***reference conditions*** (Figure 5.1.84).

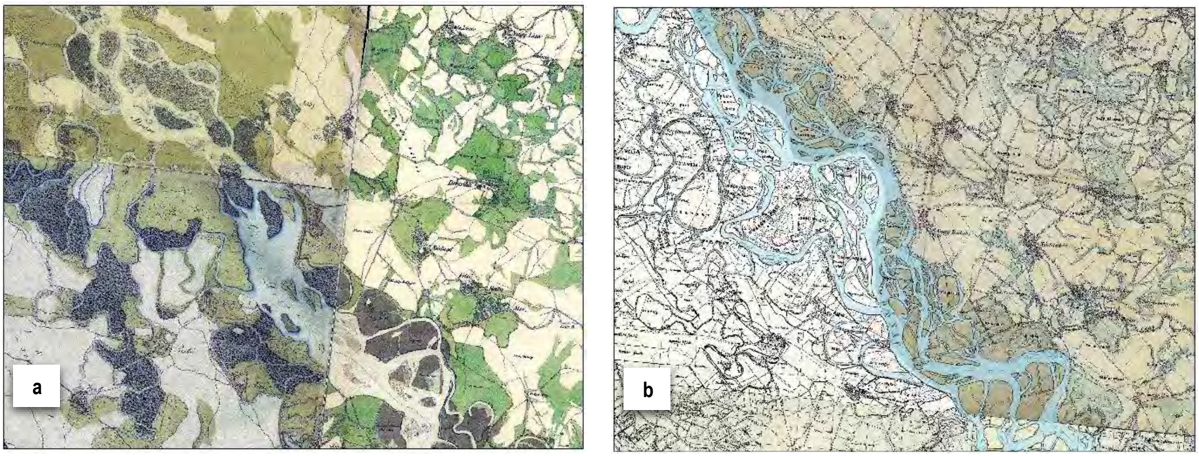


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Figure 5.1.84 The Danube River channel (Bodiky-Baka) in maps from different historical periods:
a) 2nd military mapping (1806-1869) and b) 3rd military mapping (1869-1897) – reference conditions

The morphodynamic changes in the Danube's river pattern downstream of Bratislava are illustrated by maps from the 2nd and 3rd military mapping (Figure 5.1.84 a,b). The intense river training for navigation and flood protection purposes continued throughout the 19th century. The dikes concentrated the floods and high discharges in the floodplain, but medium and low discharges were distributed among the river's numerous side branches. Starting from the middle of the 19th century, the development of shipping required a single channel to be created for navigation. The main Danube channel for *'medium discharges'* (up to the bankfull discharge) was formed in the period from 1886 to 1896. This is already partially indicated in the map from the 3rd military mapping (Figure 5.1.84b). The new regulated river channel crossed the side branch system in numerous places, but the interaction between the main channel and the branches remained unrestricted at that time. In order to keep the water in the side branches, rocky dams were built gradually to cut off the branches from the main channel.

Later, within the scope of low-flow regulation, groynes and deflective structures were built in the main Danube channel to ensure the required shipping conditions during low discharges. As a result of these measures, the lateral development that had been a characteristic feature of the Danube before the creation of a single channel, has stopped completely. With the riverbanks having been stabilised by hard riprap, the morphological evolution of the river channel could continue only vertically – in the form of river-bed aggradation or degradation. Thus, hydrological connectivity has been reduced considerably, too.

PERIODS I–II (1920-1990) – before the Gabčíkovo HPP was put into operation

The Danube channel in the territory of Slovakia was exposed to conflicting trends in the 20th century. As the lateral movement was already stopped completely in that period, the river's morphological development was oriented only vertically (river bed aggradation / degradation). The alternation of longer periods of aggradation and degradation affected mostly the surface and ground water-level regimes in this area (Holubová, Capeková, Szolgay, 2004). Since the 1960ies, the natural aggradation of the river bed that had previously prevailed in the Danube downstream of the Morava River's mouth (rkm 1,880) for a longer period, has been replaced by river bed degradation. The flow and sedimentary conditions in the Danube have changed substantially in response to the river training works and the cascade of hydropower plants built on the Upper Danube (DE, AT). These interventions into the river system have isolated the river and floodplain processes. This has led to the morphological and ecological degradation of the anabranching river system, which is illustrated in Figure 5.1.85.

Figure 5.1.85 Satellite images of anabranching section of the Danube between Bodíky -Baka from 1950 and 2017 illustrate a successive degradation of the anabranch system (SK-HU area) (Source: GEODIS SLOVAKIA, s.r.o., © Topografický ústav Banská Bystrica, © EUROSENSE, s.r.o., © TU Zvolen)

The satellite images in Figure 5.1.85 show an anabranching section of the Danube between Bodiky and Baka from 1950, when a large number side branches were still connected with the main channel in contrast with the situation in 2017, when the side branches were completely isolated from the main channel.

In the ‘60s and ‘70s, large amounts of bed sediments (Figure 5.1.86) were dredged downstream of Bratislava to improve flood protection and to provide construction material (for commercial purposes). Excessive dredging in the Danube caused dramatic changes in the river bed, which led to progressive decline in the water levels upstream and downstream of Bratislava. Thus, river bed dredging is one of the main driving forces that determine the morphological development of the Danube in the long term.

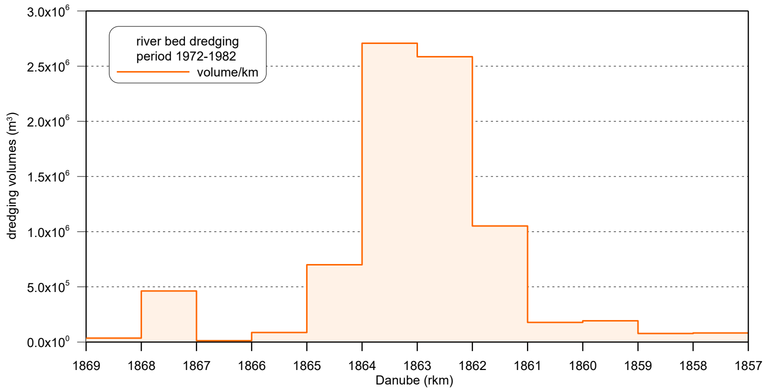


Figure 5.1.86 Volumes of the river bed dredging along the Danube downstream of Bratislava over the period 1972 – 1982 (according Szolgay, 1982)

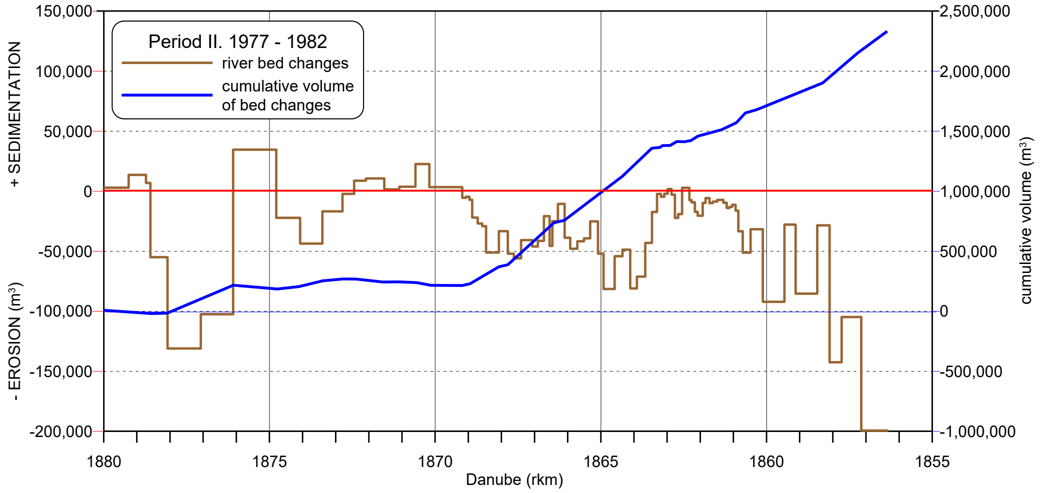


Figure 5.1.87 Changes in the river bed caused by extensive dredging downstream of Bratislava, including the cumulative volumes of river bed changes (Szolgay, 1982)

In the ‘50s and ‘60s, river bed sediments were dredged to ensure flood protection in the vicinity of Bratislava, but later (in the ‘70ies and ‘80ies) commercial dredging prevailed. During the period from 1972 to 1977, gravel was dredged from the river bed in the total amount of 3.94 million m^3 along a relatively short stretch of the Danube between rkm 1,857 and rkm

1,869. This caused river bed degradation between the mouth of Morava (rkm 1,880) and Rusovce (rkm 1,856). Thus, a 24 km-long stretch of the Danube was affected by river bed erosion.

The process of river bed degradation was further strengthened by commercial dredging in the next few years. During the period from 1978 to 1982, further 4.22 million m^3 of bed sediments were dredged from the same locality. In total, 8.17 million m^3 were extracted in 10 years from 12 stretches of the Danube. The distribution of the amounts dredged downstream of Bratislava is shown in Figure 5.1.86. The largest amount of gravel was dredged from a very short stretch of the Danube (4 km, see Figure 5.1.75) within a relatively short time. The impact of excessive dredging on river bed degradation in the second dredging period (1977-1982) is shown in Figure 5.1.89, which also shows the cumulative volumes of eroded bed sediments.

The annual amounts of extracted bed sediments highly exceeded the bedload transport capacity of the Danube. As a result, river bed incision occurred not only locally. River bed degradation moved upstream and downstream from the dredging site. The incised river bed caused marked decreases in the water levels for discharges up to the bankfull discharge. A fall in the low-flow water level (minimal water level for navigation – LNWL) was observed not only in the dredging locality, but also in the river stretches upstream of the Morava River's mouth (Austrian Danube) and downstream of Rusovce (Old Danube, SK-HU).

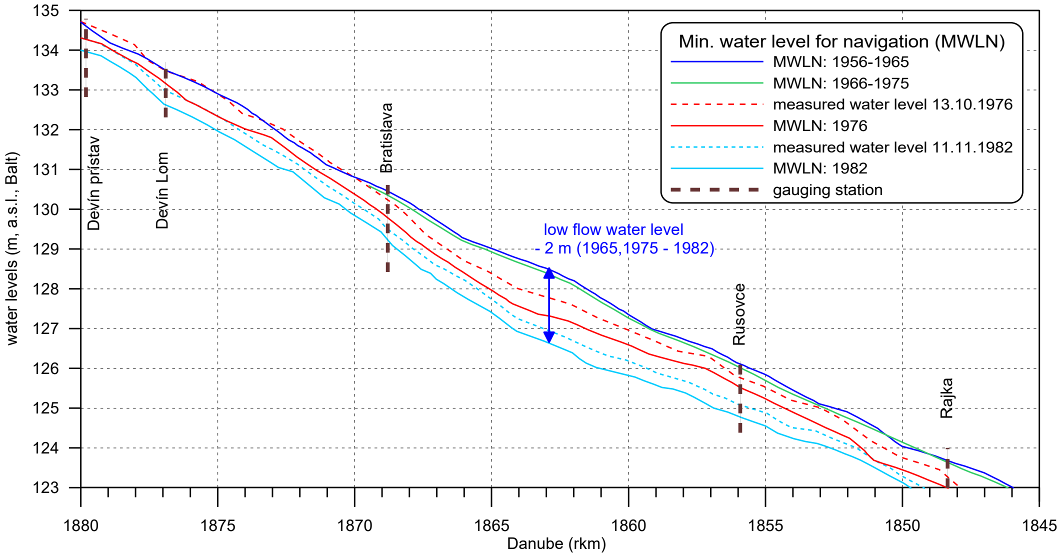


Figure 5.1.88 Changes of low flow water levels in response to commercial dredging of the river bed performed over the period 1956 (1965) - 1982

The changes in the minimum water level for navigation (Low navigable water level - LNWL) that occurred in the period from 1956(65) to 1982 are shown in Figure 6. An overall fall in LNWL´82 was recorded along the whole river stretch between rkm 1,880 and rkm 1,850. A comparison with the situation from 1956-1965 shows a maximum fall in LNWL´82 of about 200 cm in Bratislava (rkm 1,863), 70 cm at the Morava River's mouth (rkm 1,880), and 100 cm further downstream at the lower edge of the Danube in Slovakia (rkm 1,850).

An analysis of the morphological changes in the river bed carried out by Szolgay (1982) revealed that river bed degradation induced by dredging was equal in volume to around half of the total volume of dredged sediments (between 1977 and 1982). Excessive river bed dredging within a short river stretch may destabilise the river bed to a significant extent. For instance, the excavation of 200,000 m^3 of gravel within 4 months resulted in river bed degradation, which was four times higher in volume than dredging.

During two dredging periods, the annual volumes exceeded the Danube's transport capacity more than twice (V_{dred} ~ 657,000 m^3/year between 1972 and 1977, and V_{dred} ~ 845,000 m^3/year between 1978 and 1982). Although the volume of river bed dredging had been reduced considerably, the impact of the aforementioned river bed incision was observable in the Danube for a long time. In fact, river bed aggradation was re-established here after the Danube was dammed at Čunovo (1992). The impact of excessive river bed dredging was reflected in the changes that occurred in the longitudinal profiles.

The longitudinal profile of the Danube between the mouths of the Morava and Ipel rivers is fixed by natural bottom sills situated at: Devin–Lom (rkm 1,872.5–1873.5; Nergyesújfalu (rkm 1,732–1,735); Štúrovo–Esztergom (rkm 1,721–1,725); and Helenba (rkm 1,709–1,711) (Figure 5.1.89). These natural bottom sills consist of sediments that are resistant to erosion so the short stretches between them fix the vertical position of the longitudinal profile. These stretches have been stable for a long time (Figure 5.1.89, Figure 5.1.95). They restrain the river bed erosion from spreading to the neighbouring stretches.

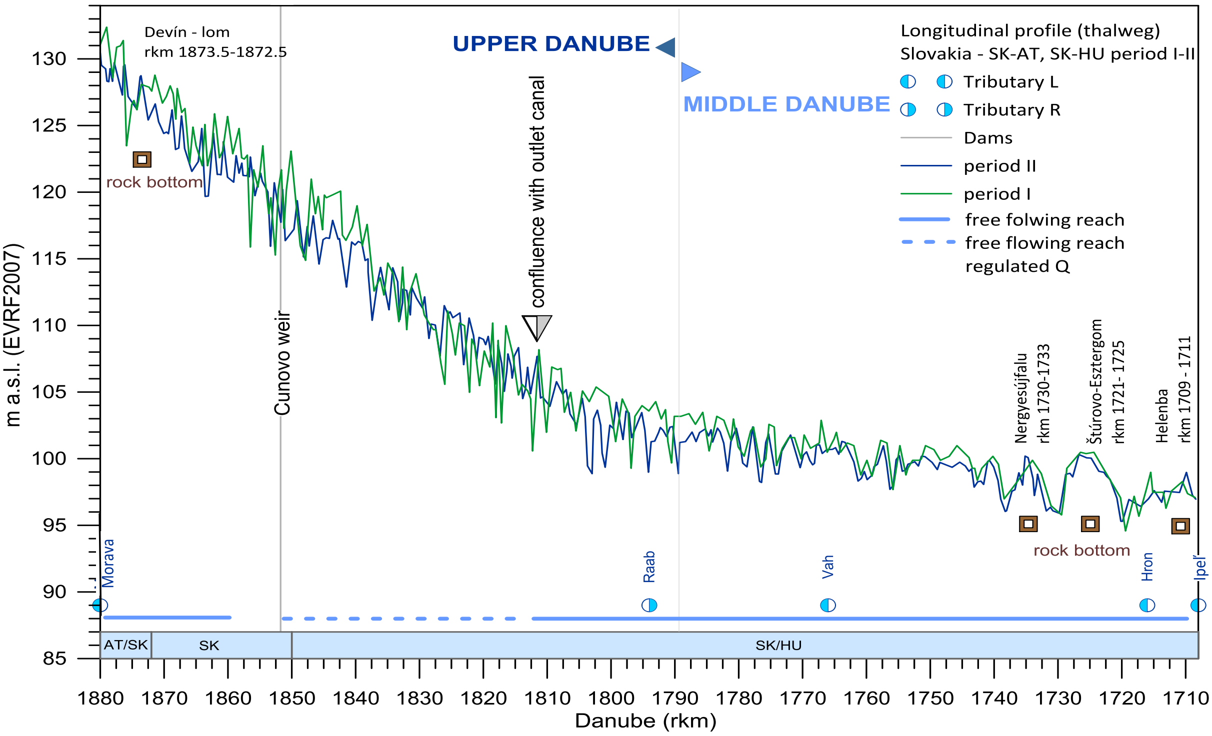


Figure 5.1.89 Comparison of the longitudinal profiles of the Danube (along the thalweg) between the mouths of the Morava and Ipel rivers in Period I (1910) and Period II (1971)

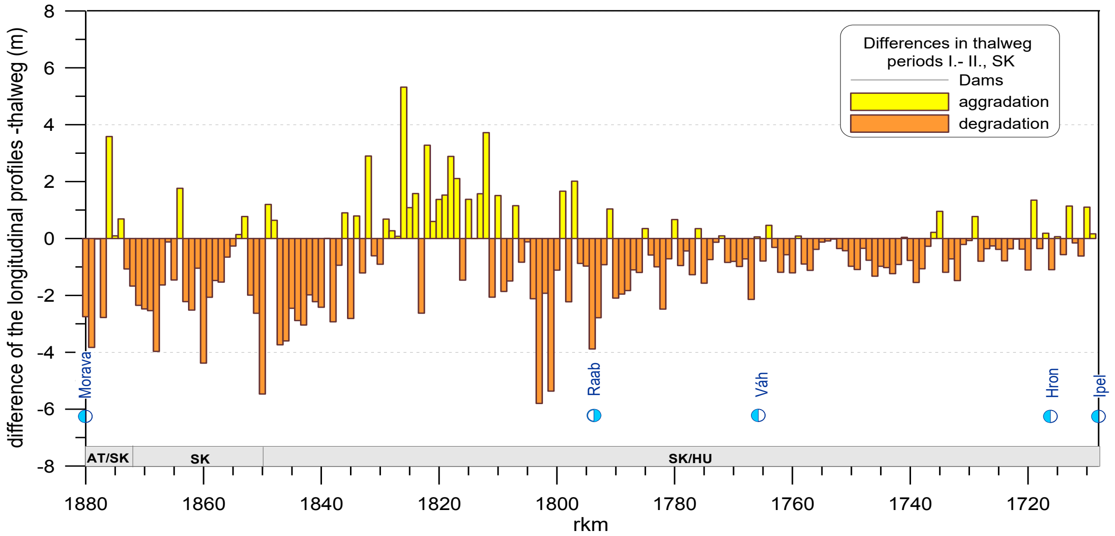


Figure 5.1.90 Differences in the river bed level (thalweg) between the longitudinal profiles of the Danube between the mouths of the Morava and Ipel rivers, periods I and II

The river bed slope of the Danube between the mouth of the Morava (rkm 1,880) and the lower end of the Upper Danube (rkm 1,790) rose from 0.31‰ (1910) to 0.35‰ (1971) as a consequence of river training and sediment dredging. A slight fall in the river bed slope downstream of Kližská Nemá – Gyönyű (rkm 1,790) was caused by excessive dredging (from 0.11‰ in 1910 to 0.10‰ in 1971). The differences between the Danube's longitudinal profiles from periods I and II (Figure 5.1.90) show prevailing river bed degradation along the whole river stretch under review, except for a shorter stretch between rkm 1,830 and rkm 1,810, where there were more stable conditions (only low sedimentation). The longitudinal profile from 1971 did not reflect the impact of extreme dredging as it was performed later. This is better documented by changes in the low-flow water level (Figure 5.1.88) and by the channel bathymetry (Figure 5.1.92), because the data used for evaluation covered the period of commercial dredging along the whole Danube section under investigation.

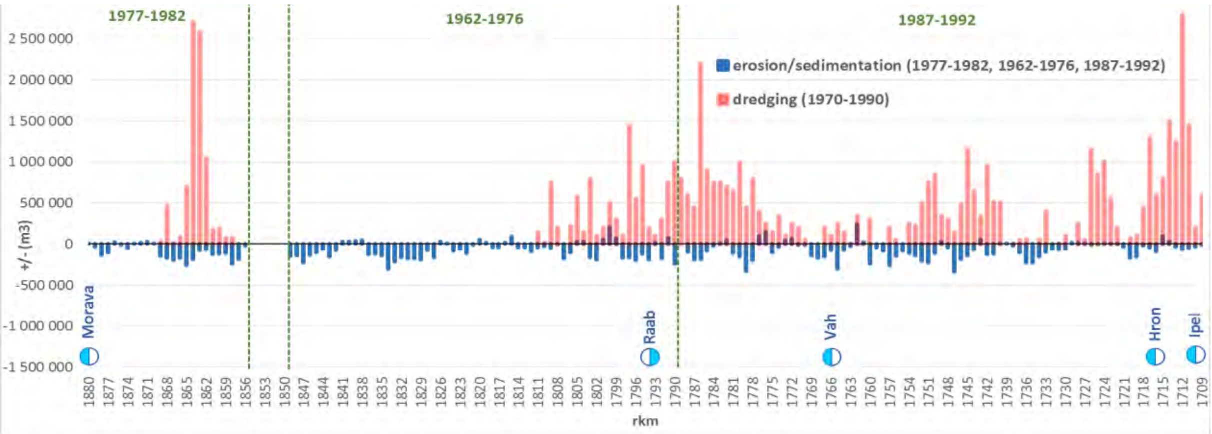


Figure 5.1.91 Spatial changes of the river bed based on channel bathymetry (erosion/sedimentation) recalculated for 1 km-long stretches of the Danube (rkm 1,977–1,982, rkm 1,962–1,976, rkm 1,987–1,992) and the total volumes of dredging, Period II (1970-1990)

River bed changes evaluated on a basis of the channel bathymetry from different years of Period II (cross sections: 1977-1982, 1962-1976, 1987-1992), recalculated for 1 km-long stretches, are shown in Figure 5.1.91, including the total dredging volumes recorded in Period II. The areas of erosion and sedimentation shown in Figure 5.1.91 do not correspond to the amounts of sediments dredged (different years). To better understand the relation between dredging and river bed degradation, we recalculated the total volumes of dredging (from the years 1970 to 1990) into annual average volumes and then assigned them to the periods of bathymetric data.

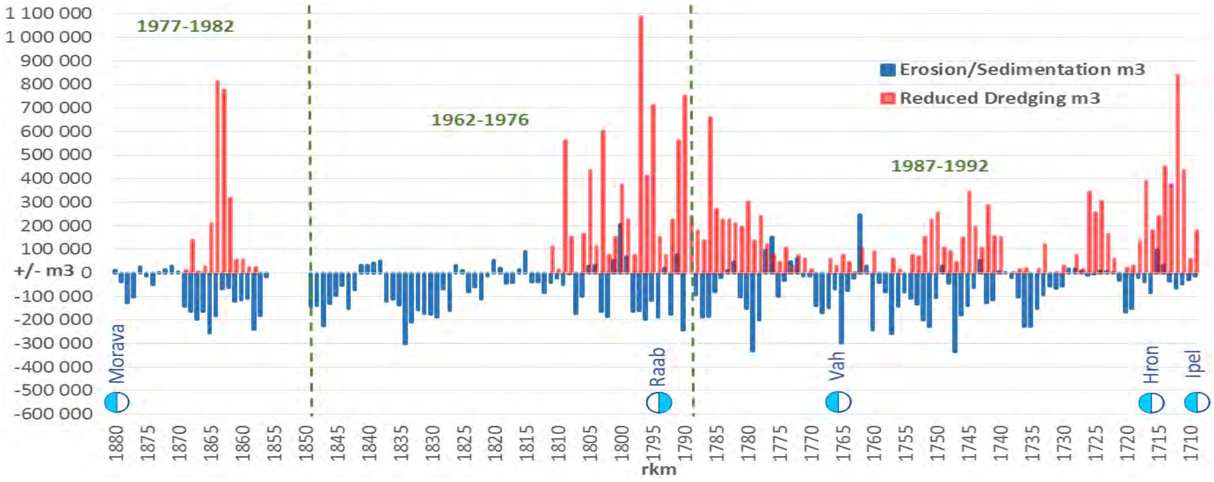


Figure 5.1.92 Spatial changes of the river bed based on channel bathymetry (erosion/sedimentation) recalculated for 1 km-long stretches of the Danube and the corresponding volumes of dredging - Period II

The results of an analysis of river bed changes, shown in Figure 5.1.92, illustrate the impact of river bed dredging on the degradation of the river bed along the Danube in Slovak territory. The areas of erosion and sedimentation, including the volumes of dredging in Period II are shown in Figure 5.1.92. It is evident that river bed dredging in excessive amounts was preformed not only downstream of Bratislava but also along the whole Slovak–Hungarian river section (the dredging data do not cover the section between rkm 1,855 and rkm 1,810). The highest volumes of dredging were concentrated upstream and downstream of a major change in the river bed slope (rkm 1,790), where large amounts of sediments transported from upstream accumulated as a result of a decrease in the river’s bedload transport capacity.

Although the data on dredging and the bathymetric data are not complete, the total calculated volumes of erosion, sedimentation and dredging summarized in Table 5.1.2 document the river processes that prevailed along the Danube (SK, SK-AT, AK-HU) during Period II. The results of analyses demonstrate strong river bed degradation along the whole Danube section under investigation, resulting in a total sediment deficit of ~ 33 million m^3 in periods I and II.

Minor effects of river bed dredging on bed sediment fining can also be identified in comparison with the bed material size (D_{50}) for two periods (Figure 5.1.93). Bed sediment fining can also be seen along the Middle Danube, but the data available for the Upper Danube section do not allow similar conclusions to be drawn.

Table 5.1.2 Total volumes of erosion, sedimentation and dredging, including the sediment deficit in Period II

rkm	Data	Erosion (m^3)	Sedimentation (m^3)	Dredging (m^3)	Deficit – or surplus + (m^3)
1,880-1,709	SK, SK-HU	-14,412,989	+ 1,930,789	-20,664,223	**- 33,146,423** m^3

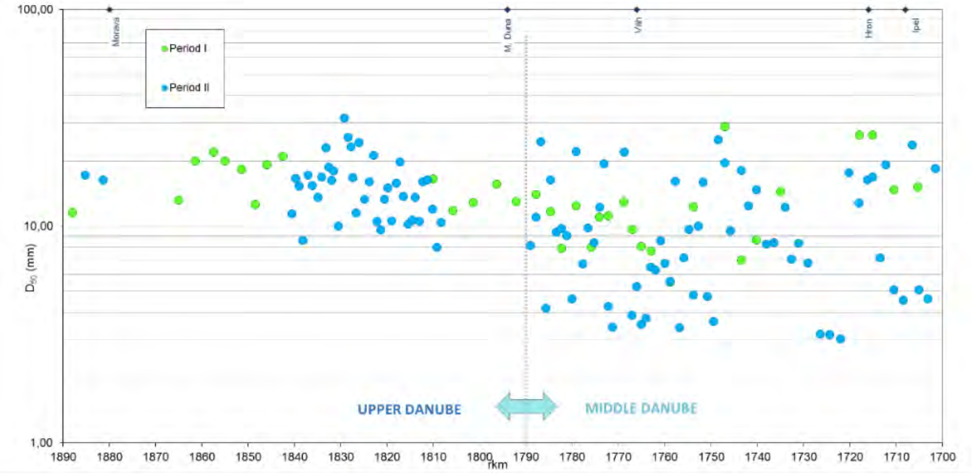


Figure 5.1.93 Comparison of the bed sediment size – median D_{50} for two periods at the Danube along the Slovak territory

A comparison of the river's longitudinal profiles (Figure 5.1.89, Figure 5.1.90), as well as an analysis of the channel bathymetry (Figure 5.1.91, Figure 5.1.92), demonstrate several causes that affected the Danube's sediment balance and consequently its channel morphology in the periods I and II:

- While the river bed degradation that prevailed in the Danube during ***the first period*** (Figure 5.1.89, Figure 5.1.90) was principally caused by ***river training works*** (implementation of measures for the formation of a low-flow channel, e.g. groyne fields, side arms closures, deflective structures) and partly by dredging performed for flood protection improvement;
- ***Excessive commercial dredging***, which started in ***the second period*** (during the '70s and '80s and continued until the '90s) was the key factor that determined the morphological evolution of the river for a long period, causing further river bed degradation, mainly in longer stretches upstream and downstream of Bratislava.

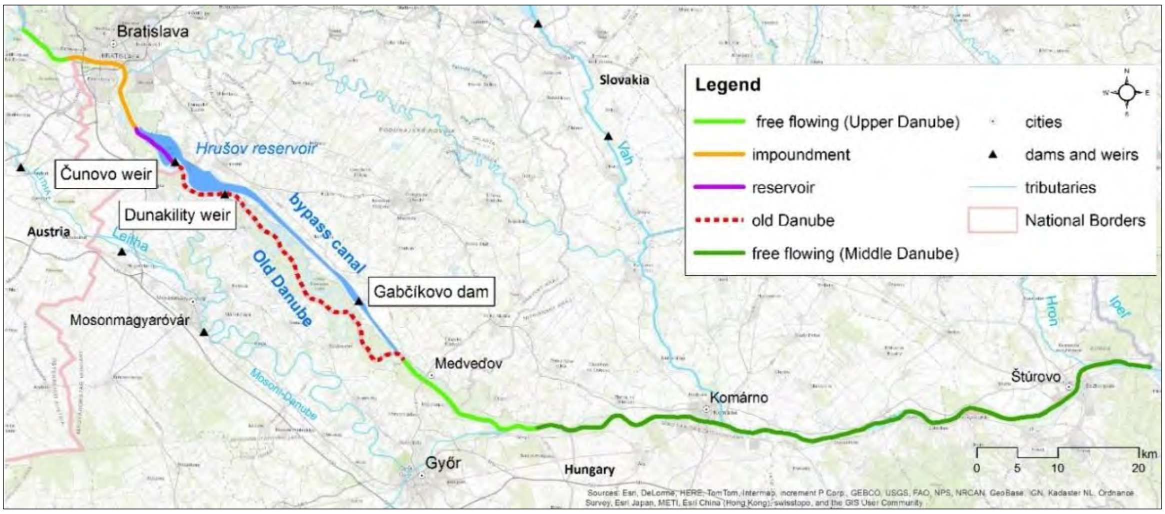
Sediment balance at that time was strongly influenced by the systematic river training works aimed at improving flood protection and ensuring adequate shipping conditions (channel adjustment for medium and low discharges), the chain of hydropower plants built in Austria and Germany, and by intense river bed dredging along the whole Danube section under review. These interventions into the river system caused widespread river bed degradation, which resulted in a total sediment deficit of ~ 33 million m^3 (between rkm 1,880 and rkm 1,708). The river and floodplain processes became isolated in consequence of river bed degradation. This led to morphological and ecological degradation in the anabranching river system. Thus, the natural functioning of the river system has changed substantially.

PERIOD III – after the Gabčíkovo and Freudeanou HPPs were put into operation

During the next period, the Danube channel was modified substantially in connection with the construction and operation of the Gabčíkovo hydropower plant (built on a by-pass canal), which greatly altered the flow conditions and the sediment balance along the whole national river section. The disruption of sediment continuity by the system of weirs at Čunovo and the hydropower plant at Gabčíkovo has caused sediment retention in the Hrušov reservoir and sediment deficits in the downstream sections, giving rise to extensive river-bed erosion in the Danube.

This period saw the construction of the last hydropower plant on Danube in Austria, i.e. the Freudenau HPP (rkm 1,921.05, 1997). In order to stabilize the eroded river bed along one of last two free-flowing Danube stretches in Austria, bedload feeding was applied downstream of Freudenau. As river bed stability was not achieved by this measure alone, more complex restoration measures were implemented to improve the channel morphology, including the sediment balance, navigation conditions and ecological status (within the scope of the 'East of Vienna' project). Some of the measures implemented in this river stretch affected, to some extent, the Danube downstream of the Morava River's mouth, too.

Taking into account the current sedimentary and flow conditions, as well as the river's morphological characteristics, the Slovak section of the Danube can be split into 5 major stretches (see Figure 5.1.94).



Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 5.1.94 The Danube in Slovak territory divided into 5 stretches according to the differences in the river's morphological conditions, sediment continuity and flow regime

1. **Free-flowing stretch** – the river stretch between the mouth of the Morava River and the end of impoundment upstream of the Gabčíkovo dam (rkm 1,880–1,873); it reflects the impact of increased bedload transport from the upstream river stretch (artificial bedload supply from Freudenau, AT) and that of finer sediments transported from the Morava River (fine gravel and sand).

2. **Impounded stretch** – the river stretch affected by the disruption of sediment continuity upstream of the Gabčíkovo HPP; it includes the impounded area and the Hrušov reservoir, both affected by sedimentation. Coarse sediments (bedload) are deposited in the upper impoundment (rkm 1,873–1,758) and fine sediments (suspended load, i.e. sand, silt and clay) are deposited within the reservoir (rkm 1,758–1,751.75) and the inlet canal.

3. **Free-flowing stretch (Old Danube)** – the river stretch (bypassed by the inlet/outlet canal of the Gabčíkovo HPP) between the Čunovo weir and the confluence with the outlet canal near Sap (rkm 1,810). The trapping effect of the reservoir and the regulated discharges (mostly 600 m^3/s) have caused a major change in sediment transport in this stretch. The main discharges are diverted into the inlet canal. Bedload transport has been stopped almost completely and suspended load reduced to a significant extent. Sediment transport is re-established only at high flood discharges ($Q_{Devin} > 6,000\ m^3/s$). Hence, the river bed is mostly in dynamic balance. The right-side tributary, the Raab, enters the Danube at rkm 1,794.

4. **Free-flowing stretch (Upper Danube)** – the river stretch between Sap (rkm 1,880) and Kližská Nemá–Gönyű (rkm 1,790). Downstream of the confluence with the outlet canal, there is a major river bed incision between rkm 1,810 and rkm 1,798, followed by moderate sedimentation near a major change in the river bed slope.

5. **Free-flowing stretch (Middle Danube)** – the river stretch ranging from the border between the Upper and Middle Danube sections (rkm 1,790) to the mouth of the Ipel River (rkm 1,709). This stretch is affected by sedimentation caused by a change in the river bed slope. The river bed sediments in the Danube channel are changing from coarse gravel to fine gravel, with a higher volume of sand. The Váh and Ipel tributaries transport fine sediments (sand and silt) into the Danube, while the Hron supplies coarse gravel and thus causes local changes in the river channel (bed sediment fining or coarsening).

Under the current flow and sedimentary conditions in the Danube between the mouths of the Morava and Ipel rivers, the sediment balance is affected by the following factors:

- Bedload feeding – increased volumes of bedload are transported from a free-flowing stretch of the Danube in Austria into the river stretch downstream of the Morava

River's mouth as a consequence of artificial sediment supply downstream of Freudenau (this will decrease after the river bed is stabilized).

- Impoundment upstream of the Čunovo weir.
- Sediment deficit downstream of the Čunovo weir and downstream of the Old Danube's confluence with the outlet canal (downstream of the Gabčíkovo HPP).
- Systems of groyne fields and deflective structures narrowing the river channel and cutting off the side branches.
- River-bed sediment dredging for maintenance purposes (navigation and flood protection).

Under the present conditions, when the river banks of the Danube are stabilized by riprap, the river's morphological evolution may proceed only in the vertical direction. Thus, only river bed erosion or sedimentation can be considered an indicator of morphological evolution taking place in the Danube channel.

The morphological changes occurring in the river bed were analysed on the basis of data derived from the longitudinal profiles and an analysis of the bathymetric data:

- Longitudinal profiles (thalweg) from different years were evaluated separately, as well as in relation to changes in the low-flow water level, which corresponds to the minimum water level for navigation (LNWL);
- Bathymetric data on changes in the cross-sectional areas and the volume of these changes (+deposition/-erosion) were evaluated at low-flow navigable water levels (LNWL), while the reliability of volume changes depended on the distances between the cross sections and on the precision of their location in the case of repeated measurements.

Long-term morphological development: An analysis of the longitudinal profiles may contribute to a better understanding of the past and present river processes, which can be better quantified in smaller scales using bathymetric data. Except for the knowledge of basic trends in the evolution of the river bed, an analysis of the longitudinal profiles provides important information about the river bed slope and its variation over a longer period.

The comparison of the longitudinal profiles of the Danube (along the thalweg) shown in Figure 5.1.95 provides an overview of the long-term changes in the river bed for a period of more than one hundred years. It is clear that the changes in the longitudinal profiles (along the thalweg) reflect the long-term trends in the river processes – bed erosion or deposition, which were induced by a variety of pressures. Except in the short stretch between rkm 1,810 and rkm 1,830, the river bed elevation fell considerably along the whole river stretch in response to the regulation measures, which were performed over the past one hundred years of channel regulation, including dredging for commercial purposes and the construction of the Gabčíkovo HPP. The range of bed level changes is indicated by the differences in the longitudinal profiles shown in Figure 5.1.96. The river bed elevation fell by - 2 meters on average, locally by - 4 meters and maximum by -10 meters.

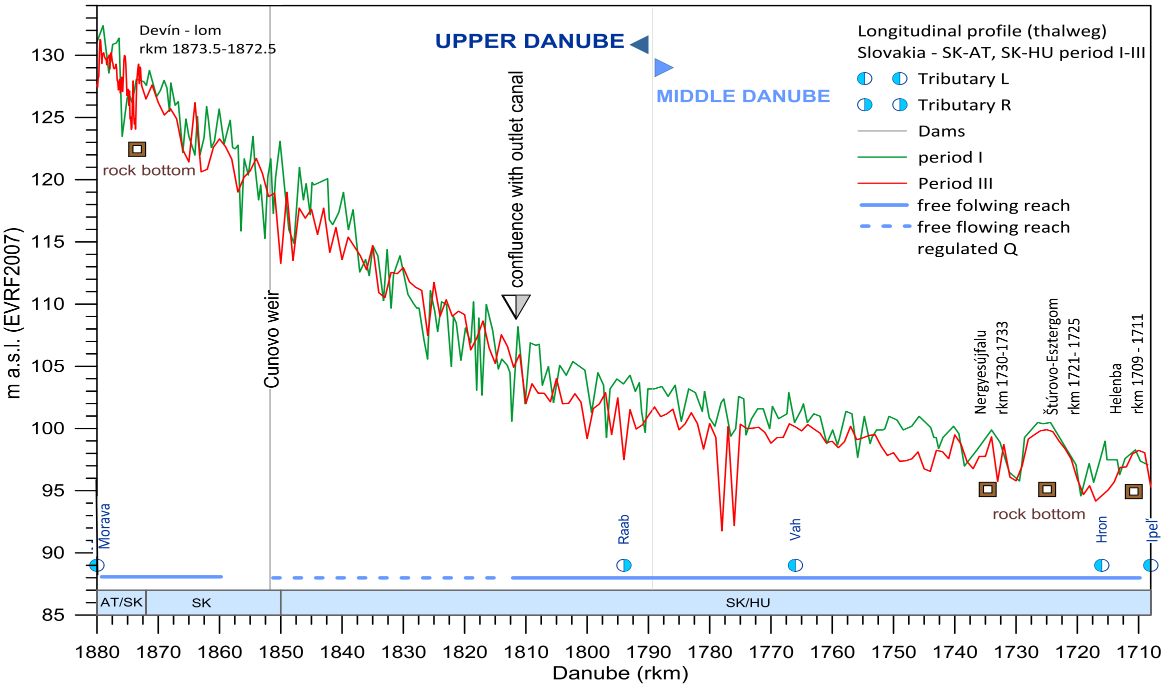


Figure 5.1.95 Comparison of the longitudinal profiles of the Danube (along the thalweg) between the mouths of the Morava and Ipel rivers for Period I (1910) and Period III (2013)

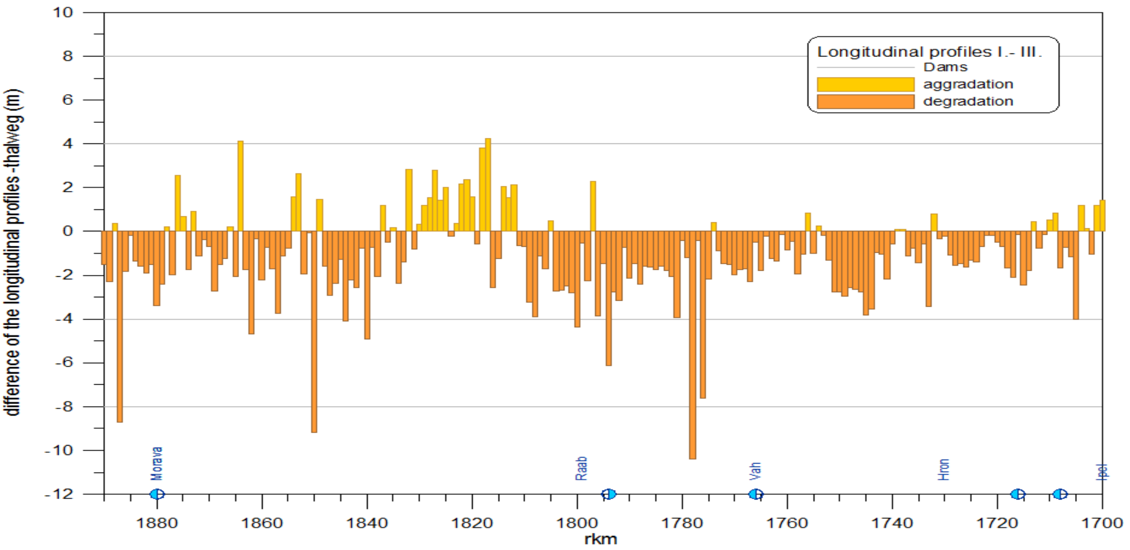


Figure 5.1.96 Differences in the longitudinal profiles of the Danube (along the thalweg) for periods I and III

Midterm morphological development: changes in the river bed elevation can be identified by comparing the longitudinal profiles from 1971 and 2013 (Figure 5.1.97). This period includes the final phase of river channel training, commercial dredging and, in particular, more than 20 years with the Gabčíkovo HPP in operation, which had a profound effect on the morphological evolution of the river bed upstream and downstream of the dam. A comparison of the longitudinal profiles in Figure 5.1.97 shows that the river stretch downstream of Sap (rkm 1,810) is exposed to river bed degradation, while the river bed upstream of the Gabčíkovo dam is influenced mostly by sedimentation (the impact of impoundment). These trends have been confirmed by the differences in the longitudinal profiles of the Danube (along the thalweg) for Period II (1971) and Period III (2013) shown in Figure 5.1.98. A comparison with periods I and II (Figure 5.1.90) indicates that the intense river bed degradation has moved from the area downstream of Bratislava to the stretch downstream of Sap (Gabčíkovo). Although the intensity of erosion and sedimentation along the Danube decreased in this period (III), these processes were strengthened locally. These results have confirmed the dominant effect of the Gabčíkovo HPP on the sediment balance and channel morphology of the Danube in the third period.

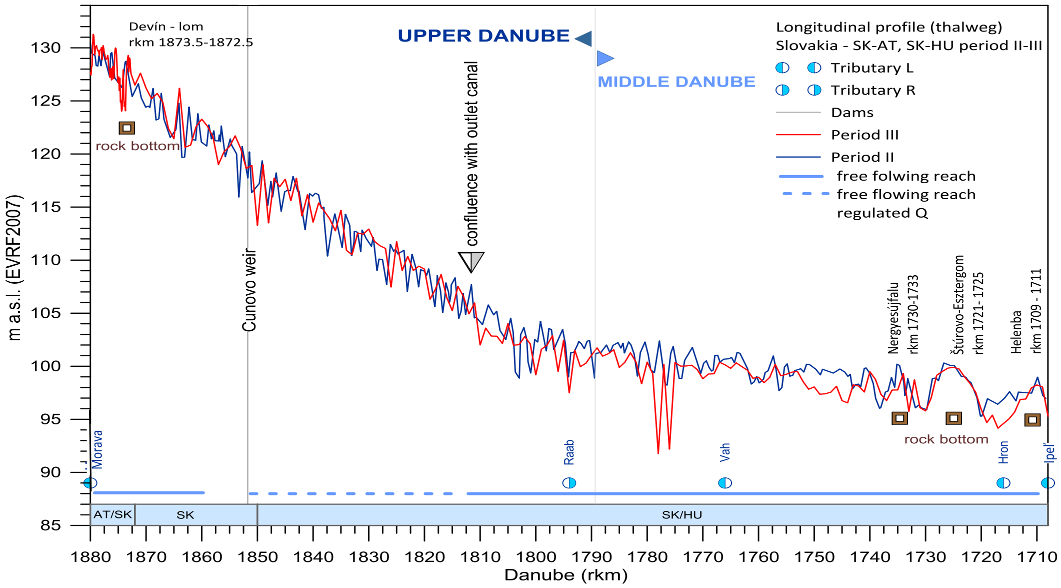


Figure 5.1.97 Comparison of the longitudinal profiles of the Danube (along the thalweg) between the mouths of the Morava and Ipel rivers for Period II (1971) and Period III (2013)

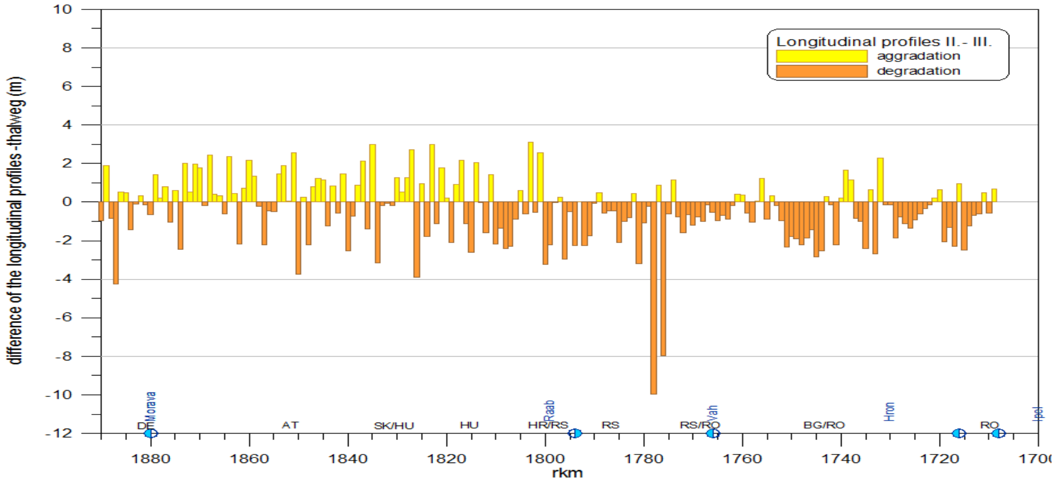


Figure 5.1.98 Differences in the longitudinal profiles of the Danube (along the thalweg) for periods II and III

Short-term morphological development: An analysis of the river channel's bathymetry in smaller scales provides a deeper insight into the river bed erosion and sediment deposition processes and into their impact on river bed morphology. The changes in river bed erosion / sedimentation recalculated for 1 km-long stretches of the Danube and the corresponding volumes of dredging for Period III (1992–2013) are shown in Figure 5.1.99. Bathymetric data on the Hrušov reservoir (rkm 1,863–1,851.74) are not available

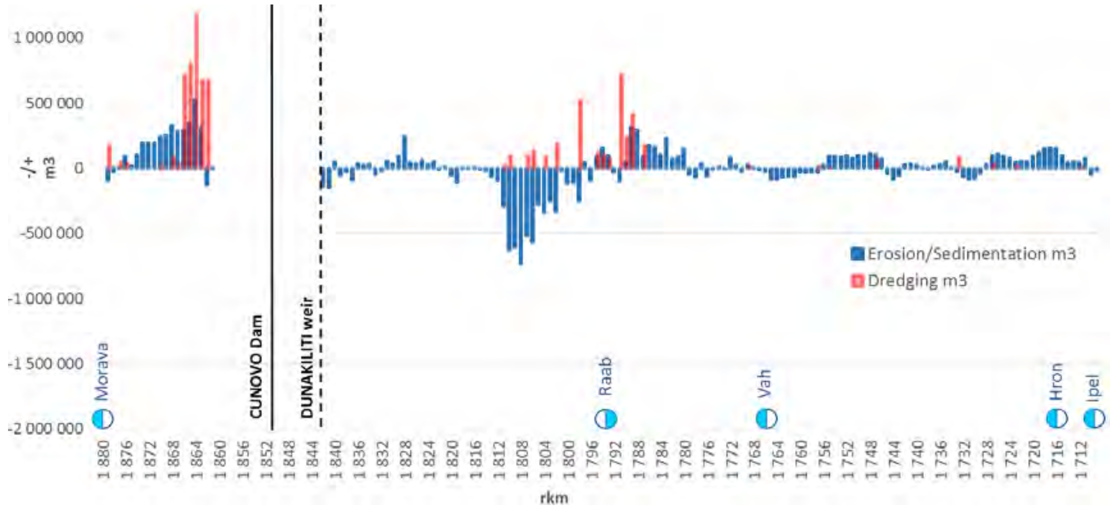


Figure 5.1.99 Spatial changes of the river bed based on channel bathymetry (erosion / sedimentation) recalculated for 1 km-long stretches of the Danube and the corresponding volumes of dredging in Period III

The river bed upstream of the Gabčíkovo HPP reflects the impact of the impoundment. Except in a short stretch downstream of the Morava River's mouth (rkm 1,880–1,877), which is affected by the moderate erosion and intense sedimentation processes prevailing along the impoundment and the Hrušov reservoir. Although sediment dredging from the Danube was reduced in the third period for maintenance purposes, still large amounts of river bed sediments are dredged in the upper part of the impoundment (Figure 5.1.99). Deposits of coarse sediments (bedload), transported from the Austrian Danube, are to be excavated in order that the required conditions for navigation and flood protection are ensured.

Since the Gabčíkovo HPP was put into operation, huge amounts of fine sediments (sand and silt) have been deposited in the Hrušov reservoir. The extension of sedimentation upstream and the grain size distribution curves of the sediment deposits are shown in Figure 5.1.100. Although complete bathymetric data for evaluating the sedimentation rate in the Hrušov reservoir are not available, the total volume of sediment deposits (~20 million m^3) has been published by the Slovak Water Management Enterprise (SWME).

Since the Danube's discharges were diverted into a bypass canal leading to the Gabčíkovo HPP, the hydrological conditions in the **abandoned** Old Danube channel have changed considerably. The reduced, mostly uniform discharges (~400–600 m^3/s) and the resulting sediment deficit have caused a decrease in the Old Danube's morphodynamics. As a result, the river bed has remained broadly unchanged, except in a short stretch (between rkm 1,812 and rkm 1,810) close to the confluence with the outlet canal, which is affected by erosion (Figure 5.1.99).

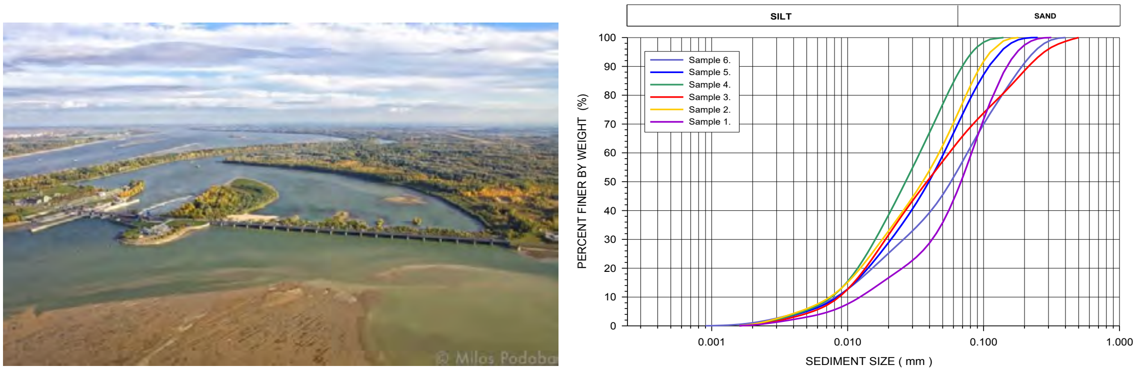


Figure 5.1.100 Extension of sedimentation from the Hrušov reservoir upstream of the Gabčíkovo HPP and the grain size distribution curves of reservoir deposits (left photo: Miloš Podoba)

As Figure 5.1.99 shows, major river bed incision took place in the Danube within the third period, downstream of the confluence with the outlet canal (from rkm 1,810 to rkm 1,798). Large amounts of eroded bed sediments are transported downstream and deposited within the stretch located near the major change in the river bed slope. Downstream of this slightly deposited river stretch (between rkm 1,798 and rkm 1,778), the river bed is more balanced, except in a stretch between rkm 1,766 and rkm 1,740, where slight erosion is taking place.

The calculated volumes of river bed erosion, sedimentation and dredging are shown in Table 5.1.3. It is evident that the Gabčíkovo dam is the key factor in the sediment balance and hydromorphology of the Danube (Period III). Major sedimentation is taking place upstream of the Gabčíkovo dam and erosion downstream of the dam. Currently, dredging is performed only for maintenance purposes – to ensure the required conditions for navigation and flood protection. It is performed in shorter sections:

- Upstream of the Gabčíkovo dam – in the upper part of the impoundment (dredging of gravel deposits).
- Downstream of the Gabčíkovo dam – downstream of the highly eroded river stretch near a major change in the river bed slope (dredging of gravel deposits).

Dredging is concentrated in areas that are exposed to sedimentation. These areas have been formed by the main pressures (except for an area affected by a change of the river bed slope). The sum of the total volumes of erosion, sedimentation and dredging calculated for the whole Danube section under investigation represents a total sediment surplus +13.93 million m^3. This surplus reflects the intense sedimentation in the Hrušov reservoir and the impounded river stretch upstream. However, the Gabčíkovo HPP split the Danube into two different parts as it was mentioned above. Hence, the sediment balance has also been calculated for the stretches upstream and downstream of the Čunovo weir and Gabčíkovo respectively (see

Table 5.1.3). Sedimentation in the total amount of +19.92 million m^3 prevails upstream of the Čunovo weir and erosion in the total amount of - 5.99 million m^3 prevails downstream of Sap (Gabčíkovo).

Table 5.1.3 Total volumes of erosion, sedimentation and dredging, including the sediment deficit or surplus from Period III

Danube rkm	Data source	Erosion (mil.m^3)	Sedimentation (mil.m^3)	Dredging (mil.m^3)	Deficit – or surplus + (mil.m^3) 1992-2013
1,880–1,708	SK, SK-HU	-7. 52	+ 9. 07 + 20.0 (reservoir)	-7.62	**+ 13.93**
1,880–1,751.75	SK, SK-HU	-0.23	**+ 3. 35 + 20.0** (reservoir)	-3.20	**+ 19.92**
1,751.75 – 1,708	SK, SK-HU	**-7. 29**	+5.72	-4.42	**- 5.99**

Sedimentation in the reservoir and river bed degradation downstream of the Gabčíkovo dam (Sap) are the main sediment management issues in Slovakia. The river bed changes in the Danube and the corresponding dredging volumes shown in Figure 5.1.88 illustrate only the final situation in 2013 (after 21 years). Hence, they cannot provide all the necessary information about the progress of river bed erosion. As this is important for the proposal of restoration measures to re-establish the sediment balance, a brief overview of the changes detected in the river bed downstream of Sap (rkm 1,810) is provided in this chapter.

The evolution of river bed changes downstream of the Gabčíkovo dam (Sap) is illustrated in Figure 19 for the periods 1993–2006 and 2006–2013, including the impacts of the extreme flood from 2013 (Holubová et al., 2015).

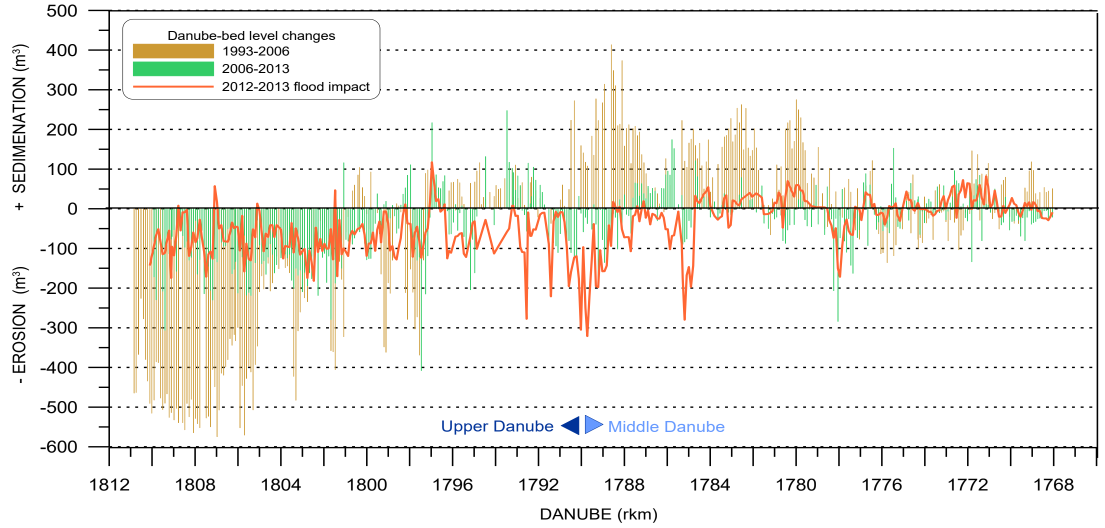


Figure 5.1.101 Spatial changes of the Danube bed based on channel bathymetry (erosion/sedimentation) between Gabčíkovo and Sap in the periods 1993–2006 and 2006–2013, including the 2013 flood

The sediment deficit downstream of the confluence of the outlet canal and the Old Danube (Sap, rkm 1810) induced a high degree of river bed instability. The most intense bed erosion was observed in the river stretch between Sap and Medveďov (rkm 1,806) during the first years of the Gabčíkovo HPP (1992–1996), when the average depth of erosion was -6 m and its maximum reached -8 m. During the next decade, when a major flood occurred in 2002, river bed erosion moderated in depth to an average -5 m but moved further downstream to rkm 1,801 (Figure 5.1.101). It subsequently weakened in intensity with its average depth decreasing to -2m (down to rkm 1,797). The bed sediments transported from eroded river stretches downstream of a major change in the river's gradient were deposited in the stretch between rkm 1790 and rkm 1778.

The river bed changes that occurred in the next period (2006–2013) also reflect the impact of the extreme flood from 2013 (as indicated by the bathymetric data from 2012 and 2013). Although this period is shorter than the previous one, it is evident that river bed erosion shows a decreasing tendency, but is still moving further downstream (Figure 5.1.101). The erosion process shifted to an area (rkm 1,784) that was formerly affected by sedimentation, was strengthened by the 2013 flood. Examples of river bed changes within cross sections covering the areas of erosion and deposition in the period from 1992 to 2013, are shown in Figure 5.1.102 (Holubová et al., 2015).

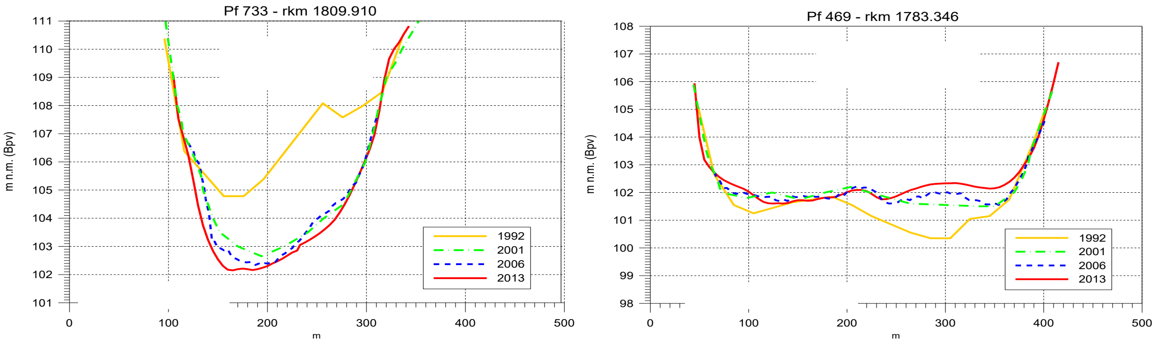


Figure 5.1.102 Morphological changes in the river bed illustrated by cross sections covering the areas of erosion and sedimentation in the Danube downstream of Sap (the Gabčíkovo dam)

The overall impact of the sediment deficit on the morphological development of Danube's river bed downstream of the Gabčíkovo dam in the period between 1992 and 2013 is shown in Figure 5.1.103. Since the Gabčíkovo HPP was put into operation, the river bed morphology has been affected by two big floods (2002 and 2013) with a peak discharge of around ~Q_{100}. An analysis of the changes in the river bed downstream of the Gabčíkovo dam clearly shows that river bed degradation has extended over the recent years. This process was strengthened by the extreme flood in 2013, which also contributed to the deepening of the river bed downstream of Sap (to max. -8 m or -9 m) compared with its previous level, corresponding to the first years of the Gabčíkovo HPP.

Although erosion has decreased in intensity over the last decade, river bed degradation is still moving downstream towards the area between Gönyű and Kližská Nemá (rkm 1,780, where the bed slope changes), causing problems for navigation, flood protection and ecology (loss of habitats). These problems were worsened by two severe floods and by the consequences of bed sediment dredging, which was reduced in the last decades but is still performed in areas exposed to erosion. River bed degradation caused a fall in the low-flow water level (LNWL) and major changes in the river bed slope.

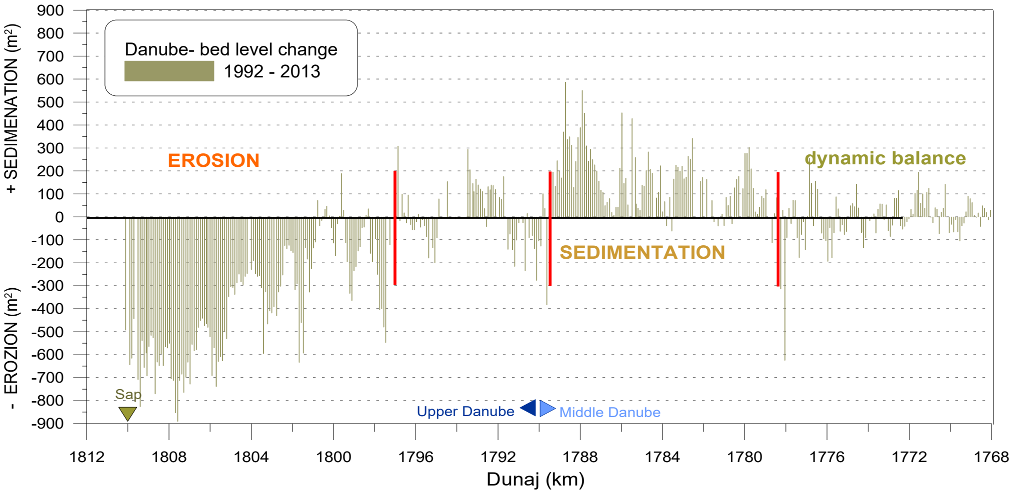


Figure 5.1.103 Overall impact of disrupted sediment continuity and dredging on the river bed of the Danube: stretches exposed to erosion and sedimentation downstream of Gabčíkovo in Period III (1992–2013)

The gradual fall in the low-flow water level during the period 1974–2013 and the changes in the river bed slope caused by river bed degradation are illustrated in Figure 5.1.104. The most significant changes occurred in the stretch between Sap and rkm 1,804, as a consequence of river bed degradation. They caused a fall in the water level downstream between Gönyű and Kližská Nemá. Over the period from 1984 to 1990, the water level fell by only -20 cm. From 1990 to 2003, it dropped by -150 cm and then, from 2003 to 2013, it decreased by a further 50 cm. Thus, from the putting into operation of the Gabčíkovo HPP to 2013, the low-flow water level (LNWL) fell by a total of 200 cm, just downstream of Sap (Holubová et al., 2015).

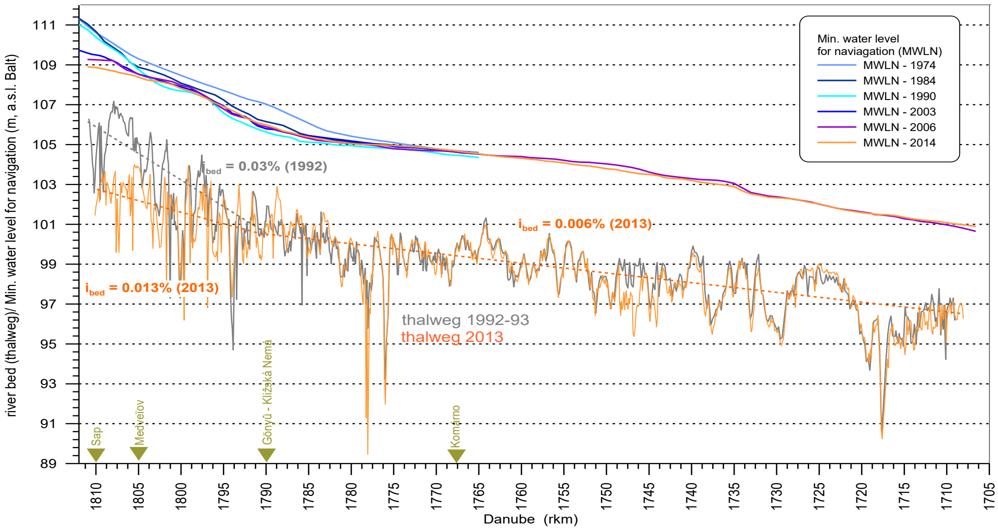


Figure 5.1.104 Changes in the low-flow water level (LNWL, 1974-2013) in relation to river bed changes (1992-2013) in the Danube, downstream of the Gabčíkovo HPP (at Sap) period

A comparison of the longitudinal profiles of the Danube (river bed) from 1992–1993 and 2013 illustrated in Figure 5.1.104 shows a change in the river bed slope, which has decreased from

0.3‰ to 0.13‰ and is gradually levelling with the markedly lower slope downstream of Gönyű–Kližská Nemá (0.06‰). This situation may have an unfavourable impact on the conditions for flood protection and navigation (ford formation).

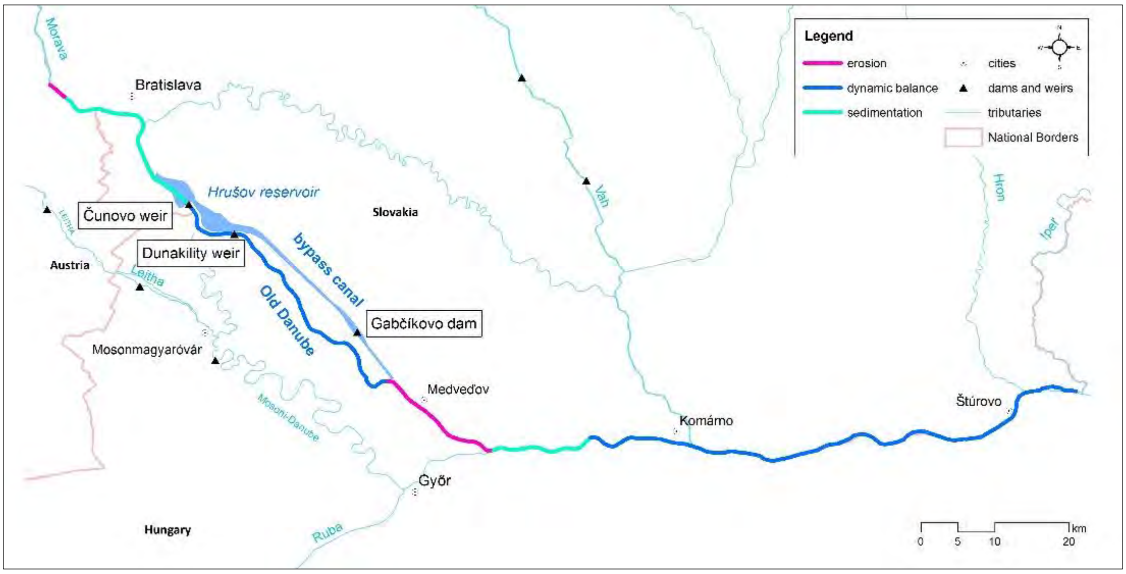


Figure 5.1.105 River stretches exposed to erosion and sedimentation identified on basis of bathymetric changes in the river bed of the Danube in Slovakia – Period III

The impact of river bed degradation on the Danube's water level regime and longitudinal profile along the river bed also stressed the need to implement effective restoration measures and formulate appropriate sediment management for this section of the Danube River.

Using the results of an analysis of river bed changes within the third period, river stretches exposed to erosion or sedimentation and stretches with a dynamic balance (no significant changes in the river bed) were identified along the Danube in Slovak territory (Figure 5.1.105).

Variations in the grain size of river bed sediments: river training works (e.g. dredging and groyne fields) and structures in the river channel, designed to modify the flow and sedimentary conditions, affect the composition of river bed sediments in many ways. A detailed analysis of the bed material from the Upper, Middle and Lower Danube is included in Chapter 5.3. In this chapter, the variations in the grain size of bed sediments are put into the context of morphological changes in the river bed along the Danube in Slovak territory. The variations in the grain size of bed sediments (D_{50}) in relation to the disruption of sediment continuity in the Danube over three periods are shown in Figure 5.1.106. A comparison of the D_{50} values from Period I and Period II revealed no significant or systematic changes in the river bed sediments. Some changes linked to river bed coarsening and fining can be observed when the D_{50} values from Period I and Period III are compared.

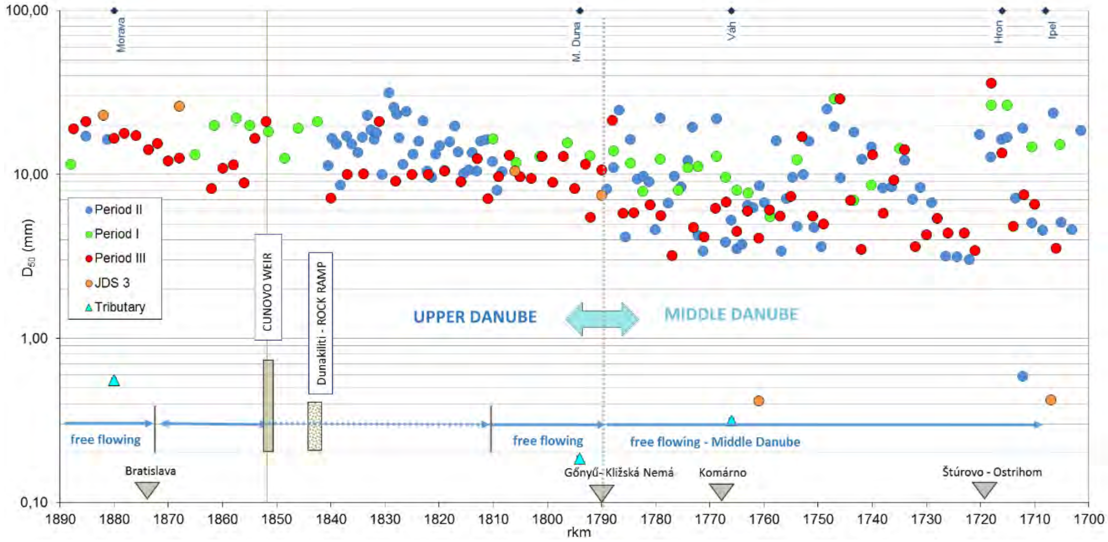
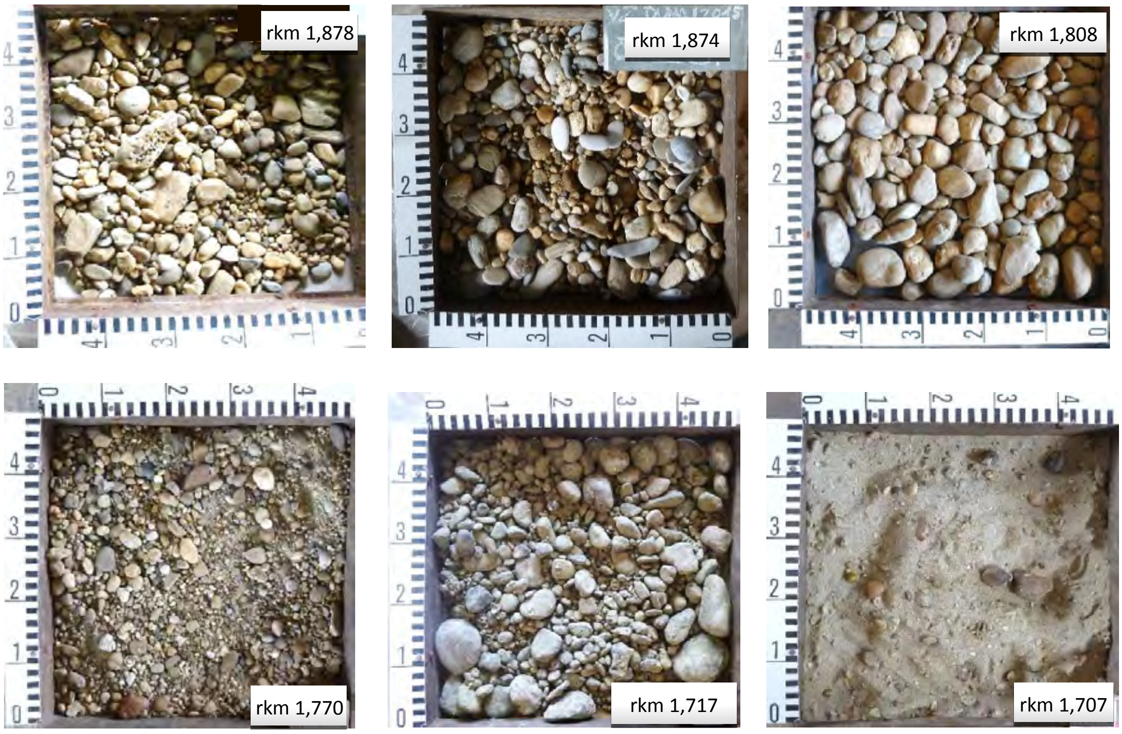


Figure 5.1.106 Variations in the grain size of bed sediments (D_{50}) in relation to sediment continuity disruption in the Danube in Slovak territory over three periods

The bed material in the Danube changes from the coarse gravel (D_{50} ~37 mm) to fine gravel (D_{50} ~3 mm) in the stretch between the mouths of the Morava and Ipeľ rivers. The same typical bed material samples that document the composition of the Danube's river bed in Slovak territory are shown in Figure 5.1.107.



Photos © WRI, Petrisko

Figure 5.1.107 Pictures of bed material samples representing the typical bed sediments in selected sites in the Danube channel between the mouths of the Morava and Ipeľ rivers

Bed sediment coarsening, which can be observed downstream of the Morava River (D_{50} ~ from 16 mm to 28 mm), extends as far as the beginning of the impounded river stretch, where bed sediment fining occurs as a consequence of a velocity decrease. Very fine sediments (silt and clay) deposited within the reservoir can induce river bed clogging with a negative impact on the interaction between the surface and ground water levels. The grain size of bed sediments also decreased in the Old Danube (D_{50} ~ from 18 mm to 9 mm) and downstream of the Danube's confluence with the outlet canal (D_{50} ~ from 12 mm to 6 mm). The main causes of bed sediment fining are dredging, which has disrupted the naturally coarser surface of the gravel bed, and the bedload deficit in both river stretches.

The sediment deficit and groyne fields in the river channel have increased the river's transport capacity, and thus affected the composition of the bed material in the Danube stretch downstream of Sap (Gabčíkovo HPP). As a result, bed sediments are well-sorted (Figure 5.1.107, rkm 1,810), indicating that the fractions of fine sediments are missing in the bed material. Therefore, in an eroded river stretch extending as far as Komárno (rkm 1,768), the bed sediments are rather homogenous (D_{50} ~ 4 mm – 6 mm) Further downstream, the range of variations in the grain size of bed sediments is wider (Figure 5.1.106), reminding us of the natural conditions (D_{50} ~ from 3 mm to 37 mm).

The composition of the river bed is locally influenced by sediments transported from the left-side tributaries (Váh, Hron and Ipeľ). The Váh and Ipeľ rivers transport fine-grained sediments (sand and silt) into the Danube. Their impact on the bed material can be observed in shorter river stretches (Figure 5.1.106, rkm 1,707). By contrast, the Hron River, being a gravel-bed river, has a river-bed coarsening effect on the Danube through the course-grained sediments it carries.

Summary: Since the reference conditions, through periods of systematic river regulation, excessive commercial dredging and hydropower plant construction and operation along the Upper Danube (including the Gabčíkovo HPP), the morphological character of the Danube channel has changed fundamentally in response to the modified flow and sedimentary conditions. The disrupted sediment continuity has substantially destabilised the Danube by forming areas exposed to erosion and sedimentation. The sediment balance of the Danube in Slovak territory has highlighted the need to propose and implement systematic restoration measures to minimise the negative impact of the Gabčíkovo HPP on the river's sediment balance and to formulate a sediment management strategy for this section of the Danube in the context of the Danube River Basin.

5.1.4 Hungary

For a long-term analysis of the morphological changes, a detailed quality check of the available data from bathymetric measurements had to be done and some years had to be excluded. In the end, data from the following years were considered reliable and suitable for use in estimating the volumes of sedimentation and deposition in the Hungarian section of the Danube: 1953, 1996, 2004, 2013 and 2016.

The longitudinal variations in the bed levels were calculated for these years as follows:

- for 1953, official monitoring sections (called VO sections in Hungary) were used to analyse the morphological changes detected in the cross sections;
- for the years from 1996, bathymetric data were used and cross sections analysed every 1 km;
- the mean bed levels were calculated in cross sections; the mean value was calculated for the channel width for which ALL data from geometry measurements were available. This width is narrower than the main channel, but wider than the navigational channel.

The Danube's longitudinal profiles depicted in the graphs are based on thalweg data, because most of the countries used only thalweg data (rather than data on the mean river bed). The longitudinal profiles of the Hungarian section of the Danube for 1959 and 2016 are shown in Figure 5.1.108.

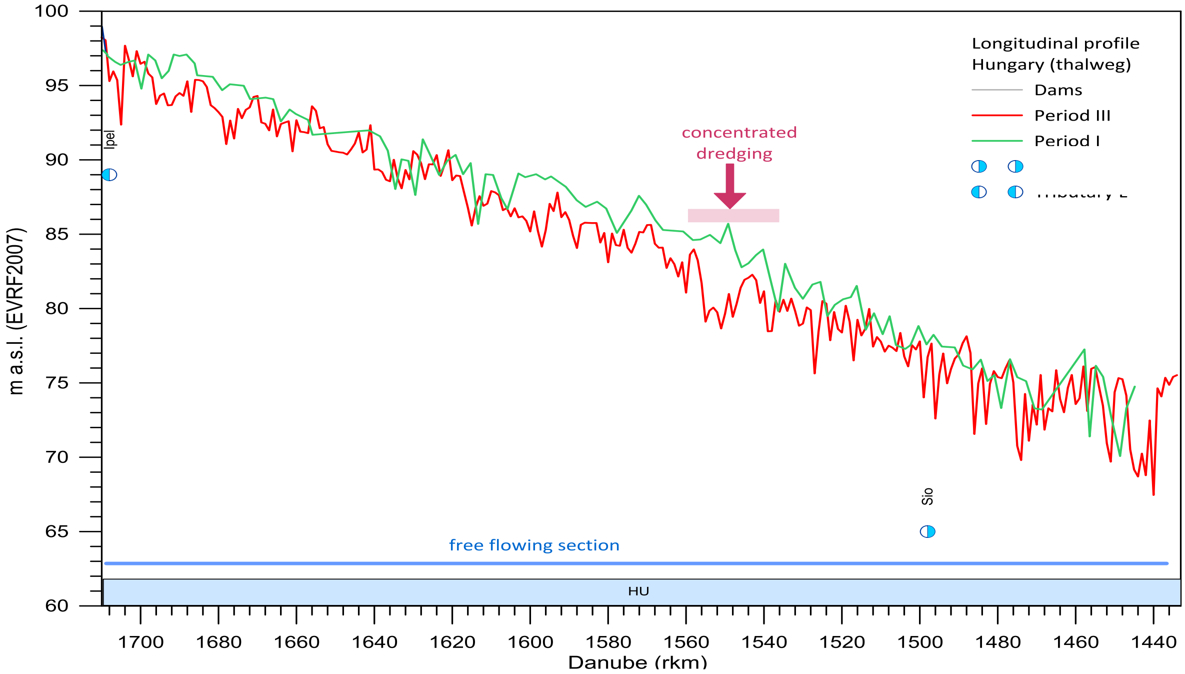


Figure 5.1.108 Longitudinal profiles of the Danube's river bed in Hungary for Period I (1959) and Period III (2016)

In connection with the recent changes in the Danube channel in Hungary, we calculated the volume changes in the stretch between rkm 1,709 and rkm 1,433 on the basis of bed geometry measurements from 1996, 2004, 2013 and 2016 (data from 2007 were not used owing to low data quality). The dredging volumes were separated for these years and are illustrated in the longitudinal profiles, too. The volume changes were calculated for the river stretches for which data were available from all the four years. An explanatory map is shown in Figure 5.1.109.

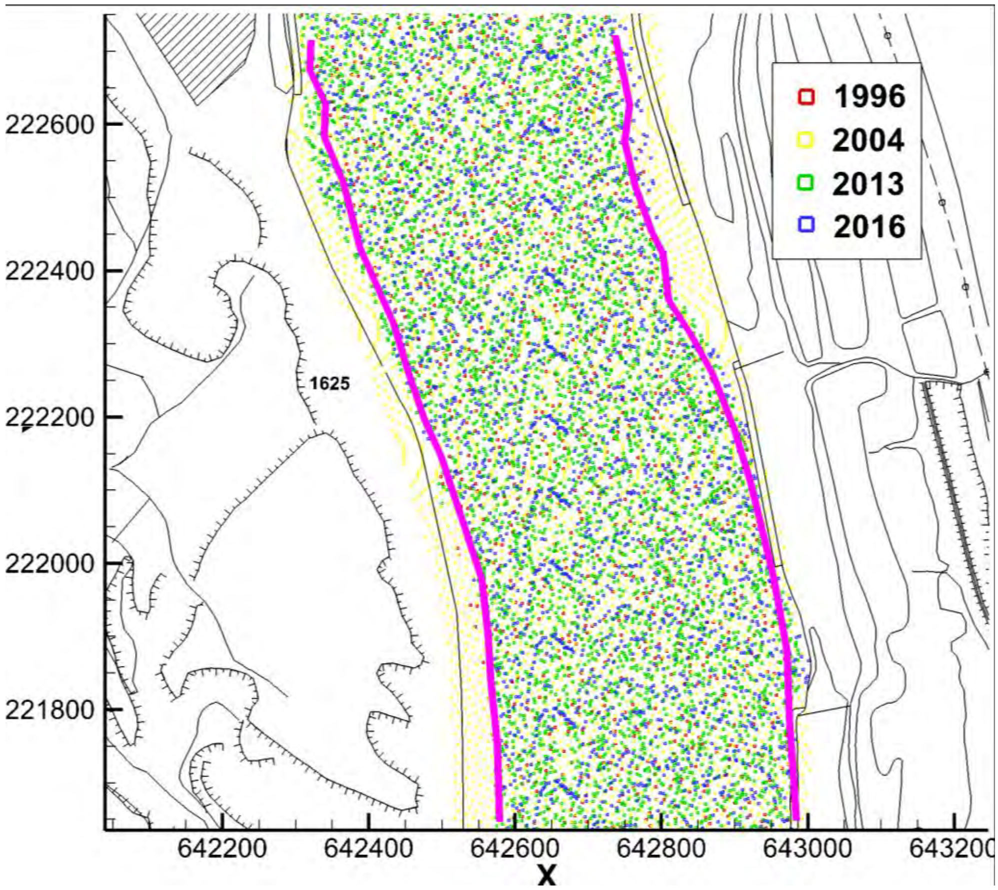


Figure 5.1.109 Bed geometry measurements from different years (dots) and the width of the main channel used for morphological assessment – overlapping zones of the four surveys (purple line)

Significant bed incision (~1.6 cm/year) took place in the river stretch between rkm 1,605 and rkm 1,525, whereas more stable stretches can be found upstream (-0.28 mm/year) and downstream (-0.8 mm/year).

Three stretches with different patterns of behaviour can be distinguished. Between rkm 1,709 and rkm 1,605, the Danube has a relatively stable river bed with minor incision between rkm 1,996 and rkm 2,004, a stabilizing river bed between 2004 and 2013, and a river bed exposed to sediment deposition after 2013. It should be noted that the bathymetry surveys in 2013 were carried out after a historical flood event. The stretch between rkm 1,605 and rkm 1,525 is exposed to erosion. This, however, can partly be explained with the intense dredging activities between 1996 and 2013. Very few dredging data are available outside the stretch between rkm 1,558 and rkm 1,535, so river bed incision upstream and downstream of this stretch is either the result of natural morphodynamic processes or of data gaps. On the other hand, the period between 2013 and 2016 saw sediment deposition almost along the full length of the Danube in Hungary (note that data for the stretch between rkm 1,605 and rkm 1,556 are missing owing to quality reasons). The 2013 flood had considerable erosion effects, which manifested themselves in the period between 2004 and 2013. After that historical flood event, the eroded areas were slowly but permanently refilled.

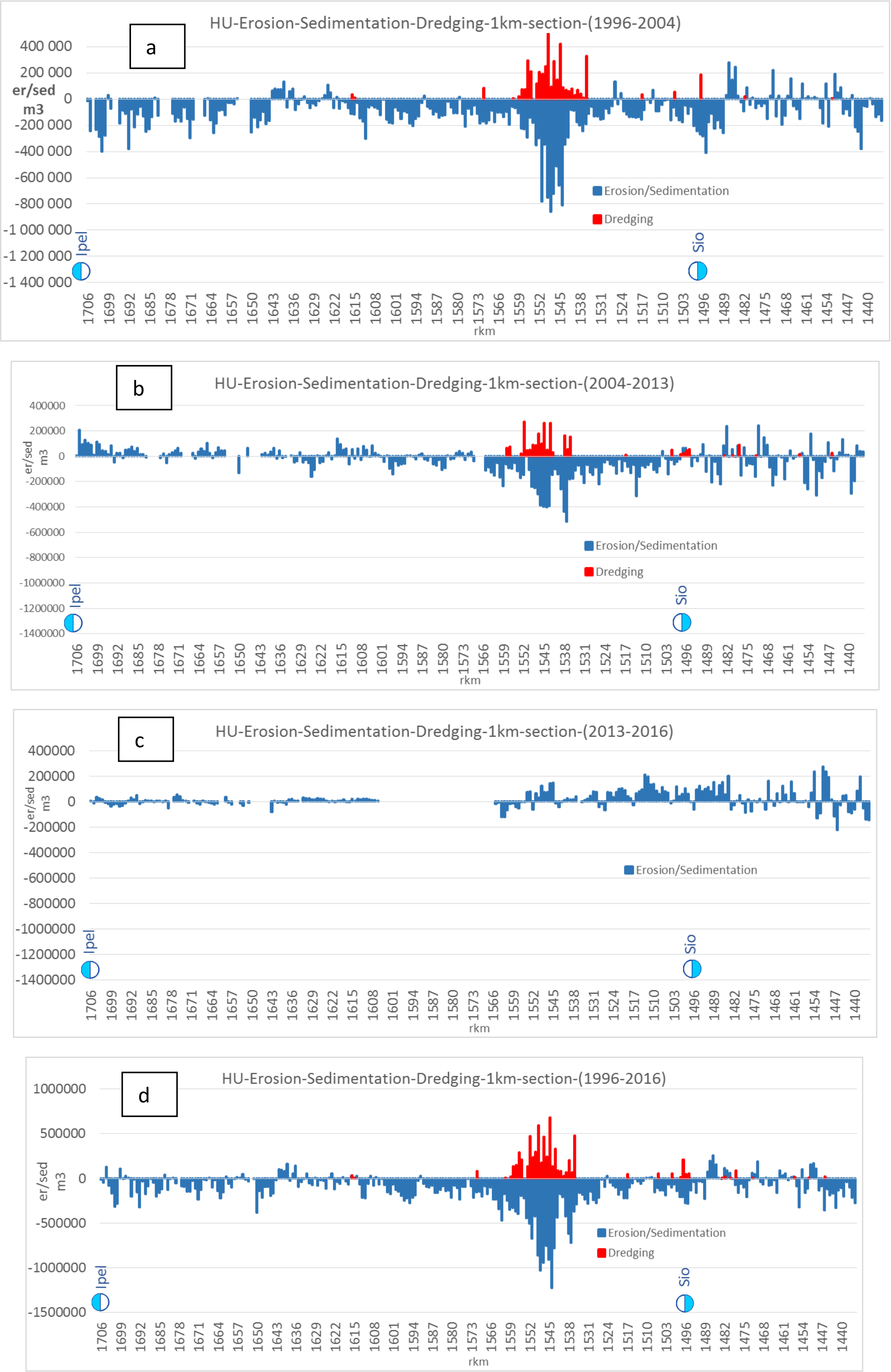


Figure 5.1.110 River-bed changes in the Hungarian Danube in the periods a) 1996-2004, b) 2004-2013, c) 2013-2016, d) 1996-2016, and the dredging volumes in the respective years and stretches

For illustrating the zones with deep river bed incision (rkm 1,551–1,542) and the more stable reaches (rkm 1,471–1,458), different maps were prepared, showing the river bed elevation changes for the periods 1996–2004, 1996–2013 and 1996–2016.

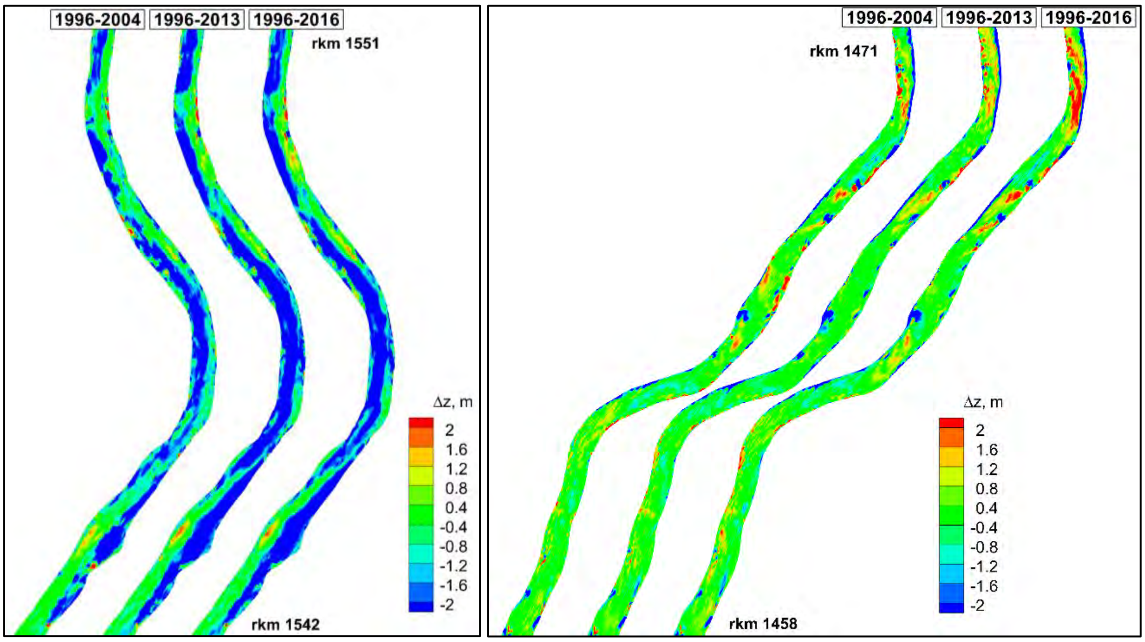


Figure 5.1.111 Examples of river-bed changes since 1996 in the stretches rkm 1,551–1,542 and rkm 1,471–1,458

5.1.5 Croatia

Brief description of the Danube in Croatia

The total area of the Danube Basin in Croatia, excluding the Sava and Drava river basins, is 2,120 km^2. The Croatian section of the Danube is 138 km-long. The river's major tributaries in Croatia are the Drava, Baranjska Karašica, and Vuka rivers. The Danube's average discharge in Croatia ranges from approx. 2,300 m^3/s at the border with Hungary to approx. 2,900 m^3/s at the border with Serbia. The average maximum annual discharge ranges from 4,800 m^3/s to 5,400 m^3/s.

The Danube enters Croatia from Hungary upstream of Batina (rkm 1,433) in Baranja, becoming after a few kilometres a border river that forms the state border with the neighbouring Serbia all the way to Ilok (rkm 1,295).

The Danube in Croatia is part of the Middle or Pannonian Danube; it has the characteristics of an alluvial river, with a low gradient.

The biggest tributary of the Danube is the Drava River, which significantly contributes to the water flow and sediment transport in the Danube.

Spatial and temporal changes in the river channel's morphology

Since there are not enough data on the sediment regime of the Danube in Croatia, the changes in the Danube channel observed in cross sections at the hydrological stations (HS) were analysed on the basis of data measured at such cross sections along the Danube and the changes depicted in Q-H curves, which had been compiled for hydrological stations only in the last 10 years.

Over the period under analysis since 2006, the river bed elevation of the Danube has been lowered by approx. 20 cm in the low-water domain at the locations of hydrological stations (Aljmaš, Dalj, Vukovar and Ilok) and by an average of approx. 30 cm in the mean water domain (by maximum 50 cm at HS Batina).

The systematic measurement of suspended sediments in the Danube channel has started only recently. There is no bedload measurement for the time being.

The data and the results of their analyses cannot be used to draw conclusions in respect of changes in the river bed, because measurements are available for a relatively short period only. Moreover, local erosion or deposition are often observed owing to the vicinity of certain hydraulic structures or of the passage of high waters before the hydrographic surveys were made. That is why the estimates presented here need to be taken as rough values.

The sediment transport regime has been greatly affected by the river regulation works done so far. The most comprehensive regulation works had been carried out before 1918. Between the two world wars and in the post-war period (until 1965), only the most essential interventions were made in the Danube channel.

The state of the Danube channel in Croatia in selected stretches:

- The Batina (Bezdan) stretch (rkm 1,426–1,433) – the river stretch along the border with Hungary, enabling two-way navigation day and night (the river regulation works have been mostly completed).
- The Čivutski Rukavac stretch (rkm 1,400–1,394) – one of the most difficult stretches of the Danube in Croatia. The regulation works done have stabilized the navigable waterway and ensured the required navigation parameters.
- The Aljmaš stretch (rkm 1,383–1,380) – the stretch at the mouth of the Drava River. The navigable waterway has been stabilized, the navigation parameters ensured and the conditions for entry from the Danube to the navigable Drava waterway improved up to Osijek. However, immediately upstream of the Drava River's entry into the Danube (at the village of Bijelo Brdo), it is necessary to regularly remove large quantities of suspended sediments that are transported in the Drava and deposited immediately upstream of its mouth.

- The Staklar stretch (rkm 1,377–1,373) – the construction of underwater weirs in this river stretch has stopped the deepening of the river bed. With the remnants of a demolished hydraulic structure removed and the left bank secured, the navigation conditions have been significantly improved.
- The Erdut (Bogojevo) stretch (rkm 1,369–1,360) – the construction of a system of regulation structures in this river stretch has prevented the formation of sand bars in the navigable waterway and has ensured the navigation parameters.
- The Dalj stretch (rkm 1,359–1,350) – this river stretch is known for a sharp bend where, at low water levels, the navigable waterway does not have the required breadth, and thus visibility is reduced considerably. The completed river regulation works have increased the breadth of the navigable waterway; however, this stretch requires constant maintenance and development.

With the construction of a system of regulation structures, the water flow has been concentrated into the main channel. In this way, the required navigation parameters have been ensured, but, on the other hand, the sediment balance has been adversely affected along the waterway.

The Danube waterway (E-80) is, along its entire length in Croatia (from Batina to Ilok, i.e. from rkm 1,433 to rkm 1,295), capable and marked for day and night navigation. Its parameters satisfy the requirements imposed on a Vic-class European inland waterway.

Summary: The transport of river sediment in the Danube River in Croatia is an important component of the natural hydromorphological regime. Due to various anthropogenic impacts, the natural processes of river sediment transport have been heavily modified, sometimes with significant consequences for the stability of the riverbanks and the river channel.

The consequences are multiple, reflected most often in the modification of the hydrological regime, habitat degradation, an increased flood risk, restricted navigation, etc. Improving the knowledge about the sediment and relevant processes (sediment deposition, transport and exploitation) is essential to achieve sustainable river sediment management. The monitoring of river sediment on the Croatian section of the Danube River has been established only recently. On the Drava River as the largest tributary of the Danube in Croatia, the existing monitoring needs to be additionally extanded and improved.

5.1.6 Serbia

Brief description of the Danube in Serbia

The Serbian section of the Danube is 588 km-long, and thus represents the second longest section (20.6% of the total length). It begins at the border with Hungary (rkm 1,433) and ends at the mouth of the Timok River, at the border with Bulgaria (rkm 845). It forms Serbia's border with Croatia along a length of 138 km (from rkm 1,433 to rkm 1,295) and Serbia's border with Romania along a length of 130 km (from rkm 1,075 to rkm 845). The geomorphology and alluvial tributaries of the Danube in Serbia contribute significantly to the river's sediment balance.

Three type-specific stretches can be distinguished along the Serbian section of the Danube:

- The stretch from the border with Hungary at rkm 1,433 to Golubac at rkm 1,042 is part of the Middle or Pannonian Danube. It shows the features of an alluvial river, with a low gradient, sandy river bed and, consequently, highly variable morphological characteristics (meandering, distortable and bifurcating course; numerous branches, islands and sandbars; and varying river bed width and depth). All three conventional types of geometric forms can be seen along this river stretch: micro-scale forms (ripples), mezzo-scale forms (sandbars) and macro-scale forms (meanders). The variety of geometric bed forms is consistent with the dynamics of morphological processes. As the natural channel of the Danube is incised into its own sediments, morphological changes are taking place continually. In the course of morphological changes in the river bed, intermittent erosion and sediment deposition processes are taking place, resulting in variable thicknesses and grain-size compositions in the alluvial strata. A geological cross section of the river channel shows marked stratification, typical of an alluvial substrate.
- The Iron Gate stretch of the Danube (from Golubac at rkm 1,042 to Kladovo at rkm 931) is situated in the deep and narrow Iron Gate Gorge, with steep, occasionally vertical sides, which rise to 200-300 m (even 500 m in several locations) above the water level in the river. The gorge consists of three smaller gorges, incised into the South Carpathian limestone. In its natural state, it was known as an extremely dangerous river stretch for navigation, owing to the steep gradients and high flow velocities. The natural river bed of this stretch was composed of coarse sediments and rocks.
- The most downstream stretch (from Kladovo at rkm 931 to the mouth of the Timok River at rkm 845) belongs to the Lower Danube.

The Danube in Serbia has numerous tributaries, which contribute greatly to the volume of water flowing in the river, as well as to its sediment balance. The Drava, Sava, Velika Morava, Mlava, Pek, Porečka and Timok rivers are the Danube's major left-side tributaries, and the

Tisa, Tamiš and Nera rivers are its major right-side tributaries. The Tisa and the Sava are the most significant tributaries in the entire Danube Basin. The Tisza River is the longest tributary (966 km) of the Danube and its sub-basin is the largest one in the Danube Basin (157,200 km²). The Sava River, with its mouth in Belgrade (at rkm 1,170), is the largest Danube tributary in terms of discharge and the second largest in terms of catchment area (95,400 km²). The Velika Morava is the largest Serbian river (38,000 km^2). The genesis of floods along the Danube in Serbia depends, to a large extent, on the coincidence of high flows in the Danube and in its major tributaries (primarily the Tisza and Sava rivers).

Sediment monitoring has revealed that the average annual suspended load in the Iron Gate stretch originates from the upstream Danube (ca 41%), the Tisa (26%), the Sava (21%), and the Velika Morava (12%). The sediment inflow from the Velika Morava was reduced from 6 to 2 million tons per year, between 1964 and 1994, owing to large scale anti-erosion works.

Presently, the Iron Gate 1 reservoir with a volume of 3.5 km^3 under average hydrologic conditions, has the most significant influence on the Danube's sediment regime. The hydropower plant operates as a run-of-river facility, providing only daily or weekly flow regulation (at low flows). The reservoir has a variable length, backwater magnitude and volume, depending on the water inflow.

The operating mode of the Iron Gate 1 HPP addresses the sediment transport and deposition phenomena: the sluice gates of the dam are fully opened and water levels are reduced prior to the arrival of flood waves (at Q>11,000 m^3/s) in order to enable the passage of sediment-loaded water. Nevertheless, sediment deposition in the reservoir is considerable and has substantial environmental and water management impacts, both within the reservoir and in the downstream stretches of the Danube. As a result of the impoundment, layers of gravel or sandy gravel downstream from the mouth of the Velika Morava are covered by sand and mud deposits.

The Iron Gate 2 reservoir is the smaller part of the Iron Gate system, with practically no impounding effect (it serves only as a lower compensation basin for the system).

Spatial and temporal variations in river channel's morphology

Period I – the situation before the IG's construction: Along the river stretch between the Hungarian border (rkm 1,433) and the mouth of the Sava River (rkm 1,170), the shipping conditions in the Danube's natural channel were inadequate owing to the insufficient dimensions of the waterway at low water levels, the sharp river bends and frequent ice jams. A systematic approach to river regulation in this stretch of the Danube, for navigation purposes, began with the development of an Investment Programme in 1965, which specified the river stretches which required river training works, the types of works, the stages of implementation, and the timeframe. Extensive river training projects carried out during the next two decades (including meander cut-offs and the construction of various structures in the river bed, as well as on the riverbanks) have markedly improved the shipping conditions and had a favourable impact on river-bed stability, flow conditions, sediment transport, and ice transport.

The bottom of the Danube channel is generally composed of sand, while gravel is found downstream of the Velika Morava River's mouth. Sand and gravel were dredged for various purposes, e.g. for building riverbank structures and levees, raising the altitudes of certain riverside areas (especially the Belgrade area), maintaining the waterway (upstream of Belgrade), and for commercial purposes (when the dredging locations are selected according to the properties of sediments and the local demands). The total amounts of sediments dredged in 1km-long stretches along the Middle Danube over the periods I and II (RS data) are shown in Figure 5.1.112. The largest amounts for commercial purposes were excavated in the area around the mouth of the Sava River and downstream of the Velika Morava River's mouth (between rkm 1,106 and rkm 1,048).

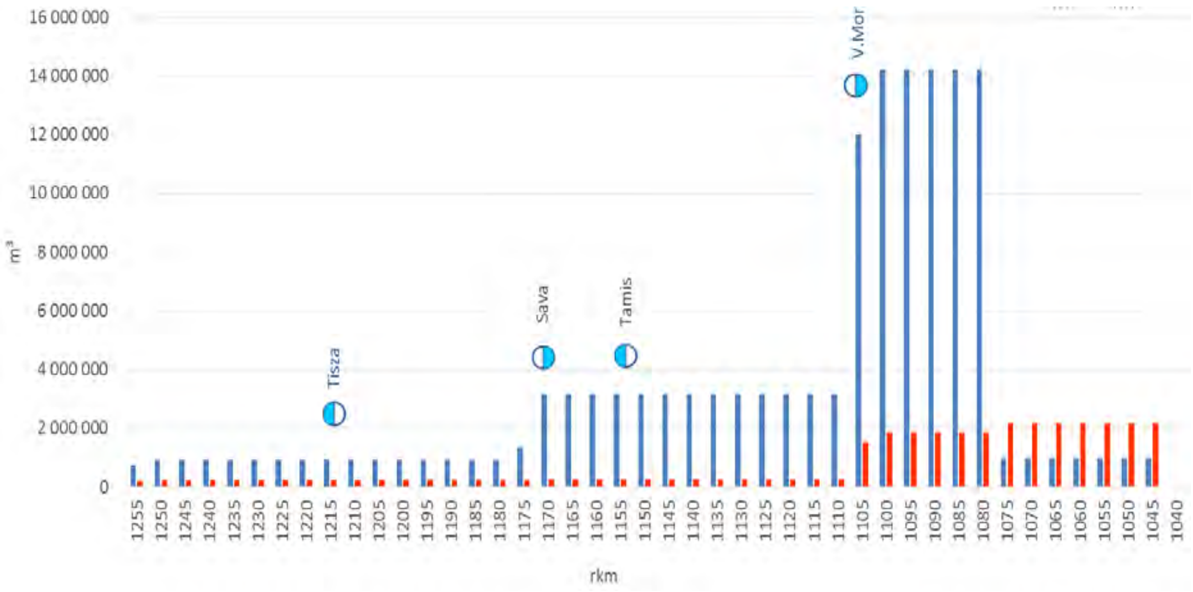


Figure 5.1.112 Amounts of the river bed sediments dredged in 1 km-long stretches along the Middle Danube over the periods I and II (RS data)

Sediment dredging from the Iron Gate reservoir is encouraged, for it partially reduces the negative impact of sediment deposition on the level of flood protection. The average quantity of sediments dredged within first 20 years of reservoir operation was 6 million m^3 per year. The most intensive dredging (an average of 3.4 million m^3 per year) took place between the Velika Morava and Nera rivers (rkm 1,105 to rkm 1,075,), where high quality gravel and sand can be found.

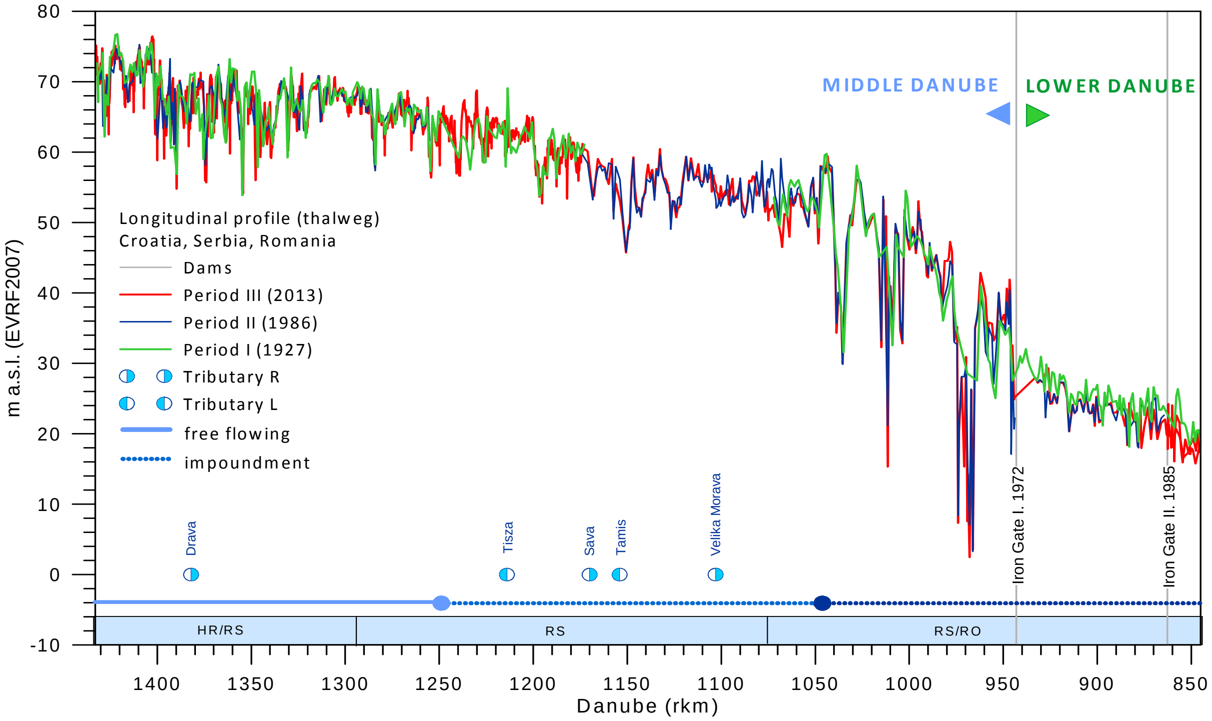


Figure 5.1.113 Longitudinal profile of the Danube (along the thalweg) in the Serbian/Croatian – Serbian - Serbian/Romanian stretch in Period I (1927), Period II (1986) and Period III (2013)

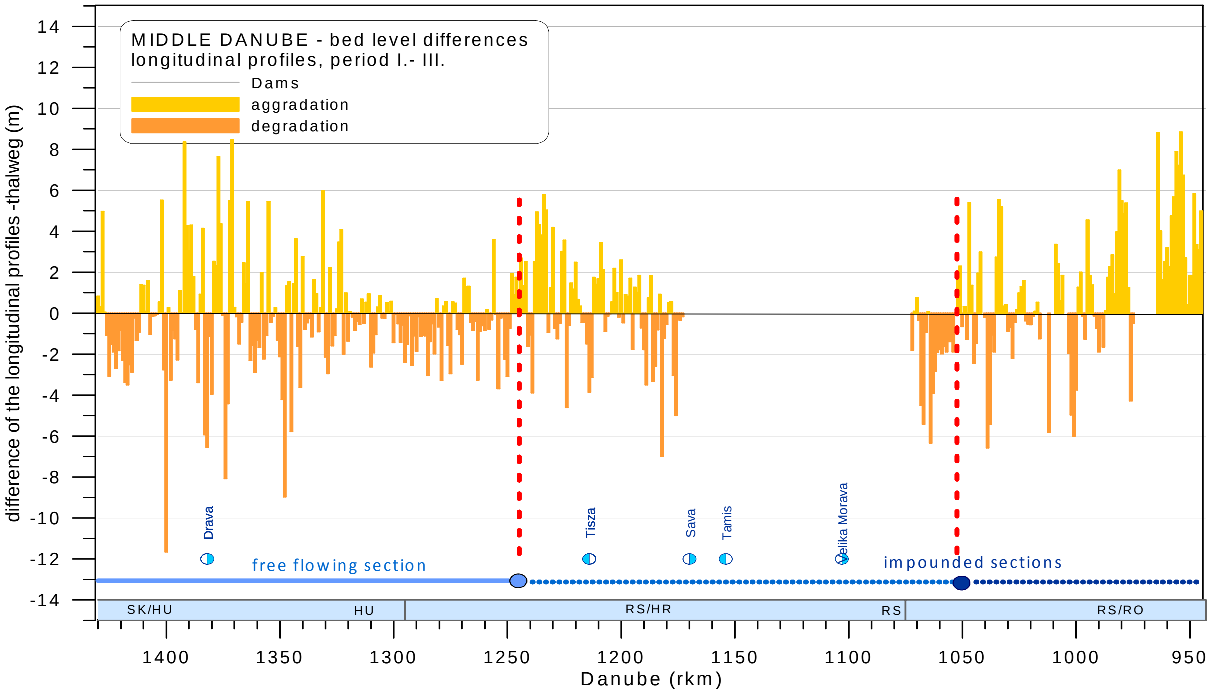


Figure 5.1.114 Differences in river bed levels between the longitudinal profiles (thalweg) of the Middle Danube for periods I and III

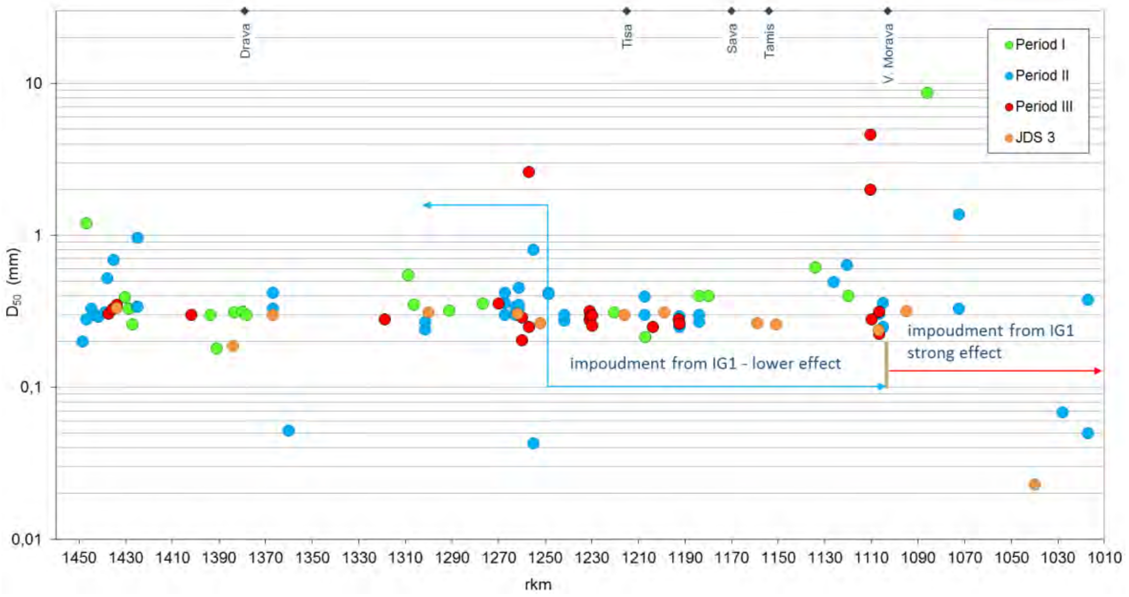
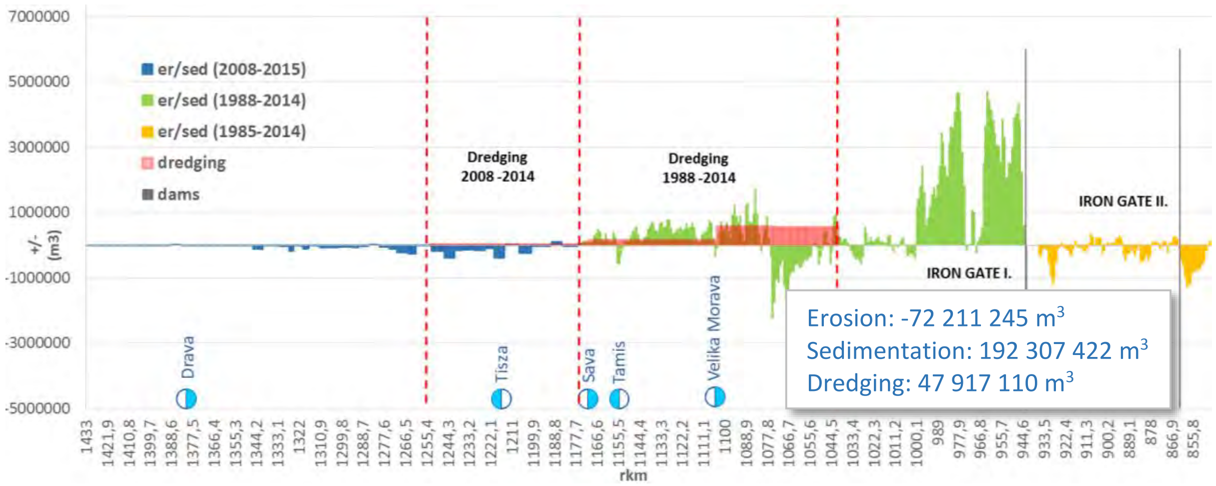


Figure 5.1.115 Comparison of the grain size of bed sediments (D_{50}) for three periods showing the possible impact of impoundment on the river bed composition upstream of the Iron Gate 1 HPP

A comparison of the river bed levels (thalweg) in the longitudinal profiles compiled for three periods is shown in Figure 5.1.113. The calculated differences in river bed levels between the longitudinal profiles illustrated in Figure 5.1.114 reflect the main tendencies of the river processes in the long term (from 1927 to 2013). The changes in the Danube channel in the long term (Figure 5.1.114) indicate strong erosion downstream of rkm 940 and sedimentation between rkm 940 and rkm 1,050. The strong erosion between rkm 940 and 850 reflects the situation before the Iron Gate 2 HPP was built. The river stretch influenced by sedimentation reflects the river's aggradation within the reservoir (Iron Gate 1) but only partially. However, the longitudinal profile cannot reflect adequately the sedimentation processes taking place in the reservoir, because it shows the level of the river bed in the deepest points (thalweg) of the navigational channel and sediments are deposited in the wider parts of the reservoir – along both sides of the river channel.

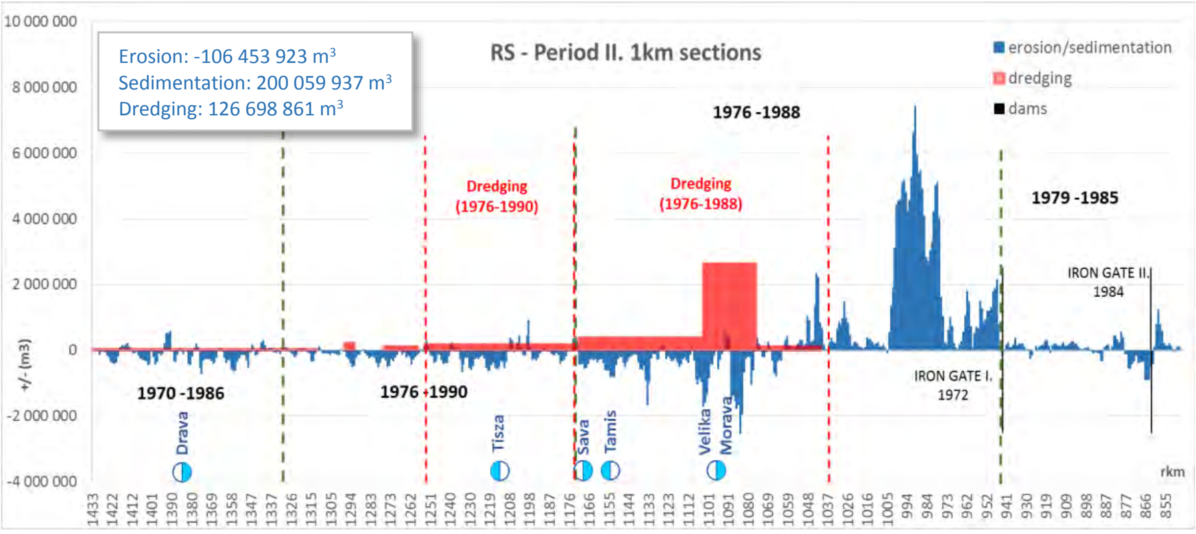
The river section upstream of rkm 1,050 indicates a more or less balanced situation as no significant erosion or sedimentation can be observed in the longitudinal profiles. However, the relative river bed balance (stability) is the result of extensive river bed dredging, which was performed along this river stretch over a long period (Figure 5.1.112). This situation has also been proved also by an analysis of the river channel's bathymetry for periods II and III (Figure 5.1.116, Figure 5.1.117).

The intensive sedimentation process that took place in the reservoir during Period II (Figure 5.1.117) moderated in the next period, i.e. Period III (Figure 5.1.116). The sedimentation process in the Iron Gate reservoir and the changes in that process are described and analysed in detail in the following part of this chapter.



Erosion: -72 211 245 m^3
Sedimentation: 192 307 422 m^3
Dredging: 47 917 110 m^3

Figure 5.1.116 Erosion/sedimentation and dredging volumes in the Middle Danube's Serbian/Croatian, Serbian, and Serbian/Romanian stretches –Period II -III



Erosion: -106 453 923 m^3
Sedimentation: 200 059 937 m^3
Dredging: 126 698 861 m^3

Figure 5.1.117 Erosion/sedimentation and dredging volumes in the Middle Danube's Serbian/Croatian, Serbian, and Serbian/Romanian stretches – Period I -II

The sediment regime and morphological development of the Iron Gate 2 reservoir are specific. Namely, a large portion of the sediments carried by the Danube is deposited in the upstream reservoir, while only a small amount of very fine sediments passes over the Iron Gate 1 dam. The transport capacity of the river is larger than the amount of the sediments supplied. Therefore, the variable water flow regime causes the small particles to move. This results in river bed erosion in the reservoir.

Development of the Iron Gate reservoir in terms of sedimentation

Since its construction in 1970, the Gate 1 HPP has, though its backwater regime, the most significant artificial influence on sediment transport and deposition in the Danube. The extent and magnitude of the backwater, which vary according to the Danube's hydrological regime, play an important role in the sediment transport and deposition processes taking place within the Iron Gate reservoir (Figure 5.1.118). Hence, a few relatively homogeneous spatial units can be found within the reservoir.

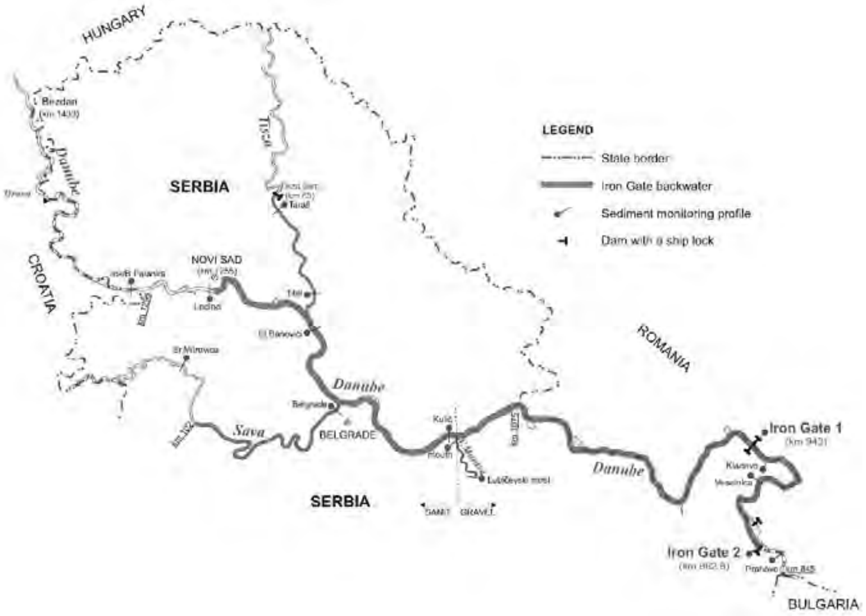


Figure 5.1.118 Iron Gate 1 reservoir with sediment monitoring profiles.

The reservoir is formed by the stretch of the Danube between the Iron Gate 1 dam and the mouth of the Nera River at the border with Romania (rkm 1,075). In this zone, the Danube's natural regime changed completely as soon as the reservoir had been filled. However, the subsequent modifications of the HPP's operating mode did not have a major impact on the sedimentary conditions in this part of the reservoir, and thus the character of the processes has remained unchanged.

The sediment transport capacity of the Danube is substantially lower than that of the Danube's natural regime. This has led to intensive sediment deposition. River-bed surveys (Figure 5.1.119) indicate that the largest sediment deposits have been formed between rkm 970 and rkm 1,003 of the Danube (near the town of Donji Milanovac), where a channel expansion in the gorge acts as a sediment trap.

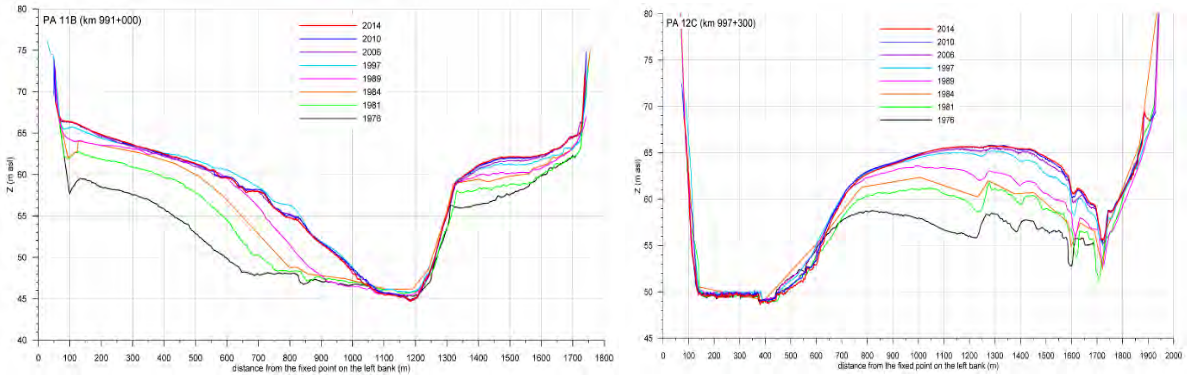


Figure 5.1.119 Evolution of sediment deposits in the Iron Gate 1 reservoir near (1976–2014)

In the upstream stretches of the Danube, affected by the backwater of the Iron Gate 1 dam, the sediment transport and deposition processes differ from those taking place in the reservoir. The backwater extends to Novi Sad (rkm 1,255) only during low flows in the Danube, while the hydraulic conditions, which are similar to those of the Danube's natural regime, are established during flood events. Therefore, changes in the sediment regime occur only during low flows in the Danube, but the decrease in the river's natural sediment transport capacity is relatively small and cannot lead to significant sediment deposition. During high flows, sediment transport is the same as under natural conditions. It is important to emphasize here that the mouths of the major tributaries represent contour conditions for sediment transport.

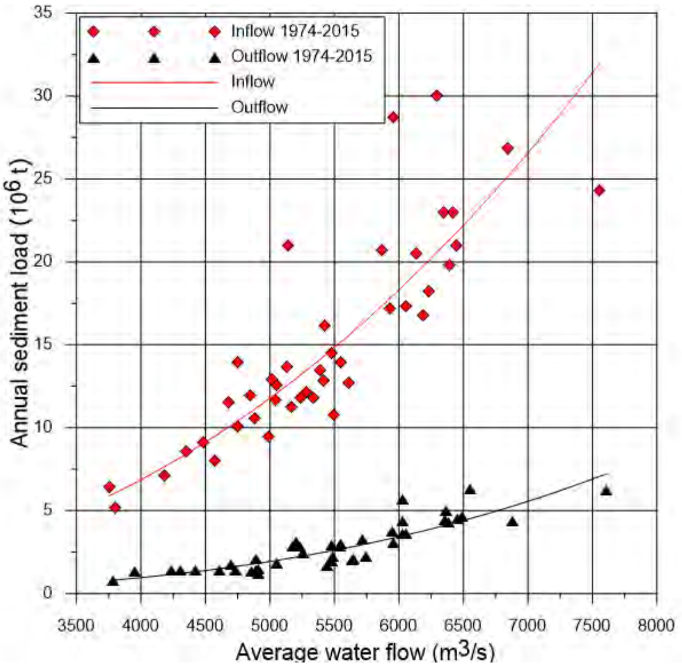


Figure 5.1.120 Correlation between the annual sediment inflow and outflow, and the average water flow through the Iron Gate 1 dam

A total of 663.87 million tons of sediments entered the Iron Gate 1 reservoir between 1974 and 2015 (approximately 16.2 million tons per year). The annual sediment inflow ranged from 7.9 (1990) to 30.7 million tons (1974). Some 118.6 million tons of sediments (or 2.9 million tons per year) passed through the turbines and over the spillways of the Iron Gate 1 dam. The annual sediment outflow depended directly on the water flow through the dam (Figure 5.1.120), and varied between 0.7 (in the dry years 1990 and 2003) and 6.3 million tons (in the wet year 1981).

Between 1974 and 2015, the entire reservoir retained approximately 520.5 million tons of sediments (or 12.7 million tons per year on average). As expected, the largest volumes of sediments were deposited within the reservoir during the first three years (Figure 5.1.121). In the following years, the ratio of the total volume of deposited sediments to the total sediment inflow into the reservoir (trap efficiency) varied according to the water inflow from the catchment area and the HPP's operating mode. During the entire period of operation, approximately 80% of the incoming sediments were deposited within the reservoir.

Along the 160 km-long stretch of the reservoir between the dam and the mouth of the Velika Morava, some 505.1 million tons have been deposited (90% of all deposits in the reservoir). No significant siltation trend was observed in the upstream stretches of the Danube and its tributaries within the reservoir range (on average, 370,000 tons of sediments were retained every year). A curve of the cumulative storage loss in the Iron Gate 1 reservoir over the period 1974–2015 (rkm 943–1,100) is shown in Figure 5.1.122.

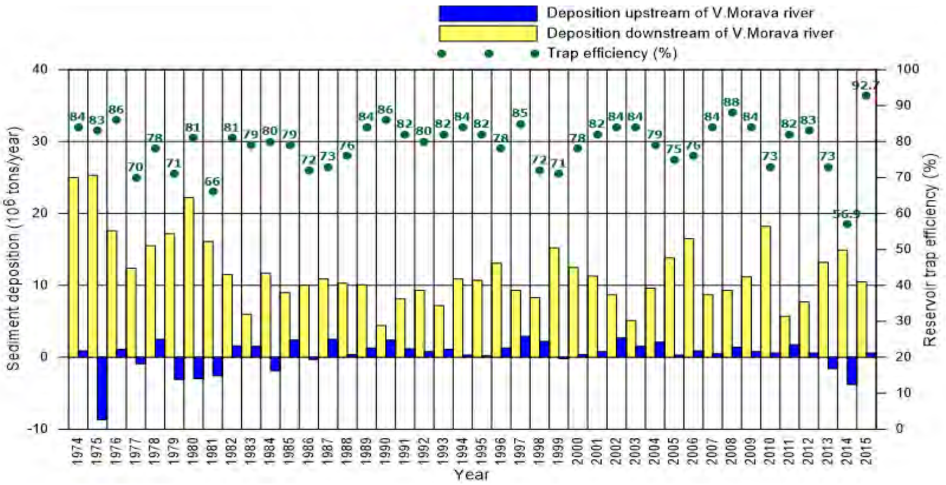


Figure 5.1.121 Sediment deposition upstream / downstream of the Velika Morava (1974-2015).

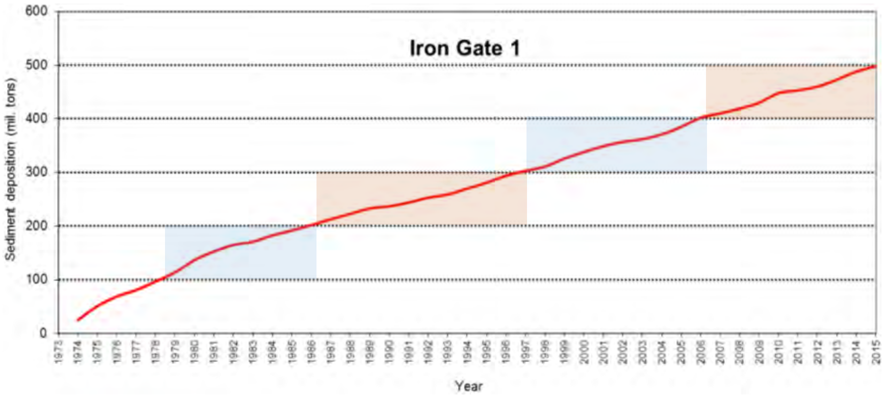


Figure 5.1.122 Cumulative storage loss in the Iron Gate 1 reservoir over the period 1974–2015 based on data shown in figure 5.1.121 (rkm 943– rkm 1,100); indication of deposits increase of intervals 100 mil.t and corresponding time interval (years)

The impact of floods

Although the HPP's operating mode implies water level lowering at the dam and a restored quasi-natural flow regime during the passage of floods, a major portion of the sediment load remains in the reservoir. Sediment transport data for the 2006 flood, which was an extreme hydrological event in the entire Danube River Basin, confirm that claim. In April 2006, peak flows in the Danube and its tributaries in Serbia occurred almost simultaneously. The return period of peak flows in the Danube stretch downstream of the Tisa River (Q_{max}= 11,325 m^3/s) and at the Iron Gate dam (Q_{max} = 16,260 m^3/s) was estimated to be 100 years. In April 2006, sediment transport in the Danube was equivalent to the annual sediment transport in dry years (7 million tons flowing into the reservoir and 1.6 million tons flowing out).

The rate of sediment deposition in the reservoir is changing in time. River-bed surveys indicate that, in the period 1976–1997, the largest sediment deposits were formed between rkm 970 and rkm 1,003 of the Danube (the Donji Milanovac zone). In an expanded part of the channel within the gorge, which was acting as a sediment trap, up to 10 m high sediment deposits were formed (Figure 5.1.123).

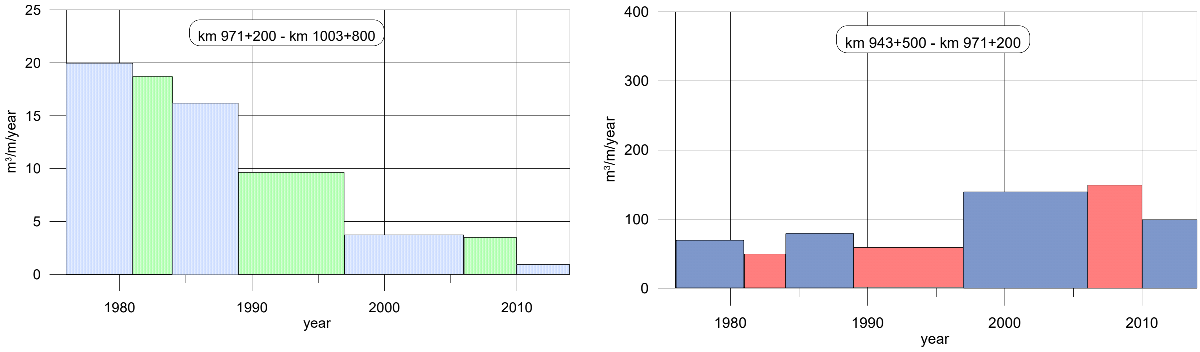


Figure 5.1.123 Sediment deposition immediately upstream of the Iron Gate 1 reservoir

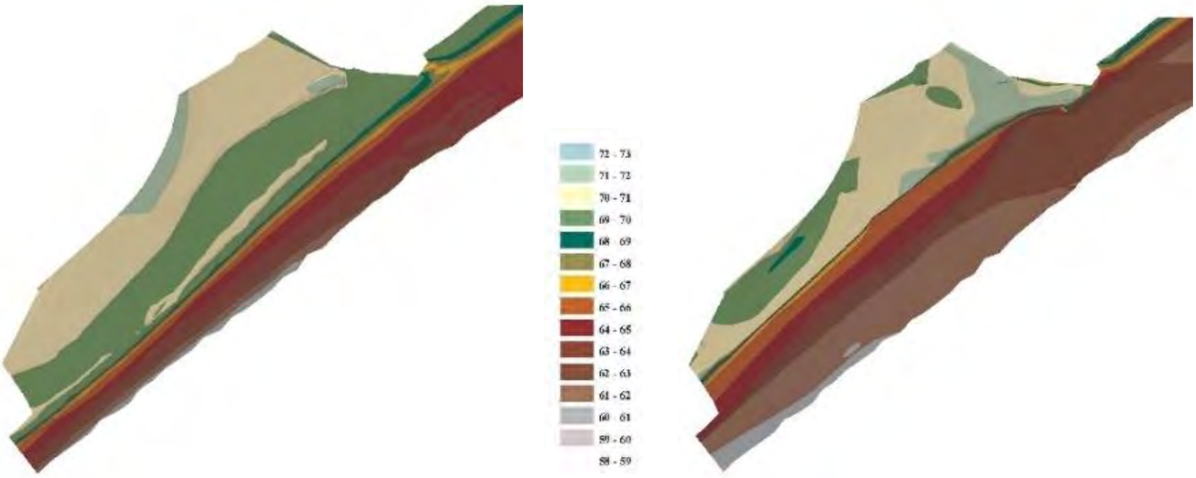
However, recent surveys of the river-bed (carried out in 2006, 2010 and 2014) indicate that the area near Donji Milanovac cannot retain more sediments, because the rate of sedimentation decreased from 320 m^3/m/year in the earliest 5 years of reservoir operation to 10 m^3/m/year in the most recent period. This may indicate that this natural sediment trap is now filled up. On the other hand, the sedimentation process in the most downstream part of the reservoir (between rkm 971.2 and the dam) intensified in the same period.

The impact of sedimentation in groyne fields on the river channel's morphology

In general, all groyne fields along the Danube are filled with sand and, in many places, the natural river bank cannot be recognized. An example of a successful groyne field, built to reduce the width of the Danube channel approximately 10 km upstream of the Sava River's mouth, is shown in Figure 5.1.124a.

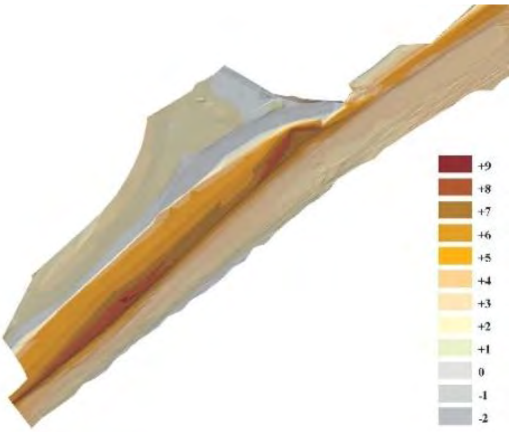
The rate of sedimentation in a groyne field was estimated for a T-shaped groyne built at rkm 1,108+500 (upstream of the Kovin winter shelter, marked orange in the picture) in the mid-60ties (Figure 5.1.124b). The siltation process was intense and the area behind the structure is now completely filed with sand, up to the average water level. Based on a 3D model of the area (Figure 5.1.125 a,b,c) from the period before the T-groin was built (1963), it is estimated that 1,9 million m^3 of sand accumulated behind the structure over the course of roughly 50 years. It should be noted that this area is currently under the influence of the Iron Gate 1 dam, and this may enhance the sedimentation process.

Figure 5.1.124 a) Groyne field built 10 km upstream of the Sava River's mouth; b) T-shaped groyne built at rkm 1,108+500 of the Danube (upstream of the Kovin winter shelter)



a) 1963

b) 2012



c) Difference (2012–1963)

Figure 5.1.125 Examples of sedimentation behind groynes. Pictures: a) situation in 1963, b) situation in 2012, c) amount of sediments deposited over 49 years (1963–2012)

In its present state, the sandbar consists of two parts – the part towards the dike is between 70 and 71 metres above the Adriatic, and the part towards the water between of 69 and 70 m.a.A. This means that the lower part is submerged all over the year, while the higher part is dry at low and medium water levels.

5.1.7 Romania and Bulgaria

The Lower Danube

The Lower Danube Basin covers an area of 240.000 km^2. The main tributaries of the Lower Danube are the Timok, Jiu, Iskar, Olt, Iantra, Arges, Ialomita, Siret, and Prut rivers. There are two large dams in this section of the Danube, i.e. Iron Gate I (rkm 943) built in 1971 and Iron Gate II (rkm 863) built in 1985 for generating electricity and facilitating navigation along the Iron Gate gorge, which crosses the Carpathian Mountains.

Downstream of the Iron Gates, the Lower Danube flows across a wide plain; the river channel is shallower and broader, the water flow is slower, and there are several major islands here. The tributaries entering the main channel in this river stretch, i.e. the Iskar, Olt, Yantra, Siret and Prut rivers, are relatively short – they account for only a modest increase in the water flow in the Lower Danube.

The river stretch ranging from the Timok River’s mouth (rkm 844) to km 375 has a total length of 471 km, of which about 244.1 km are eroded (mostly the river banks). Between rkm 931 and rkm 375, the number of islands emerging in the river channel is continuously increasing: there were 93 islands in 1934 (with a total length of 283 km) and 135 islands in 1992 (with a total length of 353 km).

The hydrographical basin of the Lower Danube along the border between Romania and Bulgaria is asymmetric, being more developed on the left side. This characteristic is also reflected in the morphological aspect of the riverbank, the right side is taller and has the appearance of a plateau rising locally up to 200 m. The left bank is lower and looks like a stretched plain comprising a lot of branches, lakes and ponds.

The river bed, at mean water levels, has a width of 950 m to 1,000 m. There is a wide river meadow on the left-side floodplain, characterized by a lower slope that ensures the dominance of sedimentation and the formation of islands and floodplains that require protection measures. A characteristic feature of the river stretch between Călăraşi and Brăila is the formation of ponds, where the Danube splits into branches forming meadows between them, called *Balta Ialomiţei* (or Borcea Branch) and *Balta Brăilei*. The stretch between Braila and Ceatal Izmail (rkm 80.5) has a width of 0.4 km to 1.7 km. The Danube flows in a channel having a depth of up to 20-34 m and making few elbows. Owing to its great depth, the river bottom is below the sea level and, in some places, below the bottom of the Danube at its Delta.

The common Bulgarian–Romanian river section: The Bulgarian section of the Danube starts at the Timok River's mouth and ends at the town of Silistra, and is 470 rkm-long. The Danube River Basin is intersected by two mountain ranges, which divide it into three parts – the Upper, Middle and Lower Danube. The Lower Danube stretches from Turnu Severin (rkm 931) to the mouth of the Sulina River (rkm 0), and includes the Bulgarian section of the river. Along its full length, the Lower Danube flows across the southern part of the Lower Danube Plain. In its lower stretches, the river flows into a swampy delta, divided by dense mesh girders and swamps.

The nature of the river valley, the river bed and the water regime indicate that the Lower Danube is a typical lowland river. The river valley is about 497 km wide, its width ranges from 7 to 10 km, while the downhill valley is 8 to 20 rkm wide. The right-side bank is higher than the left-side one, which is low and flooded. The river bed is slightly curved; it is made up of smooth curves and overlapping rectilinear plots. Along its entire length, the river is divided into multiple secondary branches, some of which are floating. In the expanded parts, there are numerous islands, composed of coastal and medium sand and silt. The width of the river bed varies between 400 and 1,200 m. Its depth at the thresholds is 1.50 to 2.00 m at low water levels, and -9 m in the deep stretches. The river slope evenly decreases along the river channel, from 0.05 ‰ at the beginning of the river stretch to 0.01 ‰ at the river mouth.

Romanian tributaries: The Jiu River has a catchment area of 10,080 km^2, including four relief units: Mountain (35%), Hills and Getic Plateau (around 65%) and Plain (10%). The river has a length of 206 km and an average width of 60 km in its upper part and 20 km in its lower part. A characteristic feature of the river basin is its elongated shape, combined with an average slope of 5‰. The altitude of the catchment area varies between 1,649 m in the north and 24.1 m at the river mouth, reflecting the diversity of landforms, geology and soil (dominated by clay and loamy textures), and of the land cover (mostly arable land – 49%). The Jiu River's lowest stretch, which is in a plain area, represents a build-up for accumulation. The terrace deposits consist of sand and gravel with very sharp permeability, which causes the superficial waters to infiltrate into the groundwater. In the Jiu River Basin, there are 61 reservoirs used for supplying drinking and industrial water, energy generation and flood protection, with a useful volume of 944,904 million m^3. The river is regulated along a total length of 712.1 km, including embankments with a total length of 511.3 km. Sediment transport into the Danube is influenced by the performance of hydraulic engineering works, such as sediment accumulation prevention, river regulation, and shore and embankment protection.

The Arges River has a catchment area of 12,550 km^2. Its lower section (flowing in a plain) is characterized by a large valley, with numerous meanders, where gravel and loess prevail. The loess layers are thin and are easily eroded. The river's flow and sediment regimes are significantly influenced by the 38 reservoirs built for different purposes, such as flood protection and power generation. Most of these reservoirs are arranged in a cascade, which amplifies the alluvial sediment retention process within the hydrographic network.

The Ialomiţa River has a length of 400 km and a catchment area of 9,431 km². The river is located in the southern part of the country and is the main tributary of the Danube in the stretch between Chiciu Silistra and Braila. In general, mostly gravel, sand, marne and clay can be found in the plain area of the river basin. There are both natural lakes and reservoirs in the basin. The former are used for fishing and therapeutic purposes; the latter play an important role in sediment retention.

The Siret River is a tributary of the Danube with the third largest catchment area. The river has an extensive reception basin (44,871 km^2), of which 96.5% is in Romanian territory. It is situated east of the Carpathian Mountains. The Siret flows from its source in the Ukraine and is joined along the way by numerous sub-tributaries. It has a length of 559 km in Romanian territory, from its entry into the country to its mouth where it flows into the Danube. The Siret River Basin has the highest hydropower potential and is the greatest fresh water supply in Romania. There is a cascade of hydropower dams along the Siret (with 31 reservoirs), which impose considerable hydromorphological pressures on the river and its tributaries. Over the last 50 years, a large part of the wetlands situated along the river have changed in character after the river was dammed, causing a water level rise in the floodplain and erosion in the river channel.

The Prut River is the second longest river in Romania (953 km) and the last major tributary of the Danube, with its confluence located immediately upstream of the Danube Delta. Its source is in the forests of the Ukrainian Carpathians (the first 211 km of the river are in Ukrainian territory, then a 31 km-long stretch forms the border between Romania and the Ukraine). Further downstream, the Prut forms the border between Romania and Moldova and the remaining 711 km represent a natural border between the two countries. The river's reception basin in Romanian territory covers an area of 10,999 km^2 and is asymmetric in shape, being wider in the north (80–85 km) and narrower in the south (15–20 km), at the river's confluence with the Danube). Owing to its location within the extra Carpathian region, away from the influence of air masses coming from the Atlantic Ocean, but wide open to continental air masses from the east, northeast and north, the Prut Basin receives rainfall in moderate quantities. The hydrological regime of the floodplain has been modified anthropogenically by the implementation of flood protection measures (e.g. longitudinal dikes built in the '70s and 26 reservoirs, including the Stânca Costesti reservoir in operation since 1978, having a total capacity of 1,400 million m^3 and playing an important role in flood protection, water supply and hydropower generation) and amelioration works (draining and irrigation). As a result of these arrangements, the protected and ameliorated agricultural area has increased. The river's hydrological regime is also influenced by the terrain's morphological and hydrogeological features, as well as by the climate. The floodplain is very well individualized –

it is located along the axis of the river basin within a very large alluvial plain, with a width of 3 to 6 km (up to 10 km) and a slope of up to 0.6 ‰, and functions as a regulator of the river's hydrological regime during a natural flow regime. There are numerous oxbows and old abandoned meanders within the Prut floodplain.

The Danube's tributaries in Bulgaria: The Iskar River is the longest river in Bulgaria (368 km-long). It has a catchment area of 8,646 km^2, representing 1.1% of the overall catchment area of the Danube. Its highlands and tributaries originate from the circular lakes situated at Rila at an altitude of 2,500 m above sea level. The river flows along a 86 km-long gorge, within a narrow and deep canyon valley having steep, vertical sides. In its lower section, the Iskar River has the characteristics of an alluvial river, flowing in relatively thick quaternary alluvial deposits. The river has 60 tributaries, which contribute significantly to its sediment balance.

The river's sediment regime is influenced most significantly by the operation of more than 20 hydroelectric power plants in the valley. In recent years, a cascade of 9 hydroelectric power plants has been built in the gorge of the river. At high water levels, the gateways of this cascade are opened almost fully to ensure that the sludge deposited flows into the lakes.

In the lower section, the river's morphology and natural sediment regime are influenced by a significant reduction in its length, caused by the cut-off of the natural meanders.

In the period when morphological changes were detected in the river bed in the lower part of the river, periodic sediment erosion and deposition were identified on the basis of the regular geodetic measurements made at the last gauging station near the town of Oryahovo (see the figures below). The left figure shows the transverse changes in the river bed (2007-2017) and right figure shows the changes in the elevation of the river bed in midstream.

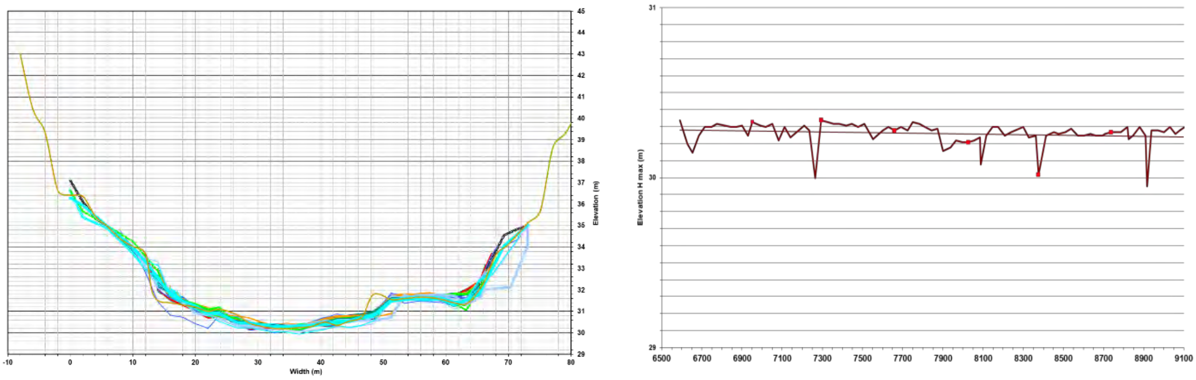


Figure 5.1.126 Iskar River (left) – transverse changes in the river bed at the town of Oryahovo (2007-2017); Right – changes in the elevation of the river bed in midstream

The Yantra River springs from the Stara Planina mountain at an altitude of 1,220 m. It is 285 km-long and has a catchment area of 7,861.6 km^2. The river flows almost entirely in a karst area. In its upper section, the river runs along a narrow, deeply drained valley having a very long longitudinal slope and steep bank slopes. In its middle stream, the river passes through gorges and enters the Danube plain, where it forms large meanders (with a meander ratio of 3.1 – the highest in Bulgaria).

The Yantra River has 14 tributaries that contribute to its sediment balance. It is characterized by one of the most intense transport of suspended sediments in the country. The river's sediment regime is influenced by the 12 hydropower plants operating in the valley. The morphological processes taking place in the river are characterized by periodic sediment erosion and deposition. The morphological processes show no long-term trends indicating river bed variability.

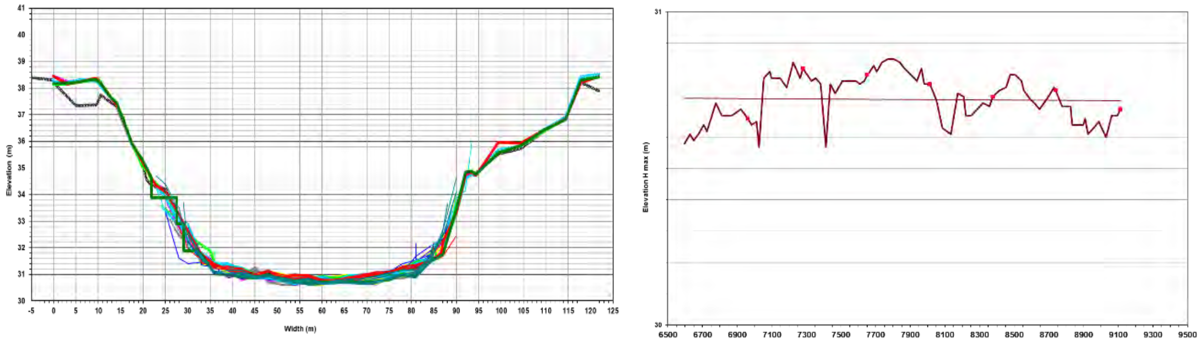


Figure 5.1.127 Yantra River (left) – transversal changes in the river bed at the town of Karantzi (2007-2017); Right – changes in the elevation of the river's midstream

Morphological development of the Danube channel

River-bed variability: Anthropogenic interventions in the Danube have affected the river channel causing ***river bed degradation through erosion.*** The anthropic impact on the river's hydrological regime is very complex. The most important hydraulic engineering works done were river regulation, riverbank reinforcement, and the construction of hydropower dams (Iron Gate 1 and Iron Gate 2) and other hydraulic structures, including the Danube–Black Sea Channel, hydraulic structures in harbours, irrigation works, water intakes, dredging works, irrigation systems, shipyards, and river bed smoothing in tributaries. The evolution of the river channel can be divided into four stages: 1) stage of natural regime – until 1834–1837, when measures for improving the shipping conditions started to be implemented in the river channel ; 2) stage of semi-natural regime – until 1964, when the floodplain embankments started to be adjusted and further river training works were done in the Sulina branch and along the border between Romania and Bulgaria; 3) stage of transitional regime – from 1964 to 1985, when the embankments continued to be adjusted and the construction of the Iron Gate 1 and 2 dams and of the Danube-Black Sea Channel was completed; 4) stage of actual regime – after 1965, when the regulation of the Saint George branch was completed.

Hydrologically, the water discharges in the Danube, excluding the average discharge, with significant increases during the year (~50–60%), can represent two extreme flow regimes: *the high flow regime* (or maximum discharge regime), which occurs mostly in the spring and summer months owing to the overlapping effects of snow melting and rainfall across the entire river basin and generates floods in the Danube, and *the low flow regime* (or minimum discharge regime), which occurs mostly in the autumn and winter months.

The morphology of the river bed on the Romanian side was evaluated in river stretches between 11 gauging stations, selected specifically for this project:

Between rkm 931 and rkm 858.3, the construction of the Iron Gate II reservoir (1985) necessitated river-bed adjustment, owing to a decrease in the volume of sediments deposited over the years. It should be noted here that no important lateral contribution is made by this stretch of the river.

Between rkm 858.3 and rkm 624.2, under the influence of the Danube reservoirs, there is practically no alluvial sediment transport along a 234 km-long stretch of the Danube, which is exposed to continuous sedimentation and flood peaks during major floods (1987, 1992, 1996 and 2010). The alluvium almost permanently increases the dimensions of the inlet structures and, in other stretches, the unprotected shores, without vegetation, are in a different stage of erosion.

Between rkm 624.2 and rkm 553.2, the variability of sediment transport is influenced by the Olt River Basin, in which more than 40 reservoirs have been built, of which those located near the waterfall on the Olt River, cause major changes in the transport of sediments.

Between rkm 553.2 and rkm 493, the transport of sediments and, in particular, the rates of erosion and sedimentation, show similar variability as the same processes in the upstream stretch, because the supply of sediments from the Vedea (Romania) and Yantra (Bulgaria) rivers is small in this river stretch. The protection measures implemented on the Bulgarian side have been improved, by means of groynes built in 1991.

Between rkm 493 and rkm 379.6, the variability of the river bed has been maintained, but near the Chiciu Calarasi – Island (nodal point), where the bifurcation of the Old Danube begins at the Borcea Branch, the river's flow velocity, slope and mean width have decreased, the latter from 890 m to 650 m for the Danube and 170 m for the Borcea Branch, indicating that there are conditions for the sedimentation process.

Between rkm 379.6 and rkm 238, the Danube is divided into the Old Danube and the Borcea Branch; this stretch is characterised by a continuous decrease in the mean flow velocity, enabling intense sedimentation with a gradual reduction in the sediment load downstream.

Between rkm 238 and rkm 167, downstream of the Vadu Oii gauging station, the Danube flows in a single channel along a ~3 km-long stretch; it is then divided into two major branches, i.e. the Old Danube (Macin Branch) and the Cremenea Branch. In the Macin Branch, the river bed is subject to some important alluvial processes, which show a gradually weakening tendency downstream. In addition, there are numerous shore collapses, including the emergence of sand banks at low water levels. In this respect, navigation is coordinated along the Cremenea Branch, in which a reasonable water depth is maintained for navigation (12–15m).

Between rkm 167 and rkm 100.2, the two important tributaries, the Siret and Prut rivers, contribute significantly to the growing volume of sediment loads in the Danube, especially during large floods.

Between rkm 100.2 and rkm 80.5, the dominant process is river-bed erosion (since 1995), owing to the commencement of construction works in the Reni harbour (Ukraine) and the Giurgiulesti harbour (Moldova).

Evaluation of river bed changes on the basis of bathymetric data

Periods I and III: The long-term morphological development of the river bed in the Lower Danube was analysed using bathymetric data (from cross sections along the thalweg) from the period before the Iron Gate 1 dam was built (1962) and current data from 2017. A comparison of the longitudinal profiles of the river bed in the Lower Danube shown in Figure 5.1.128 provides an overview of the long-term changes that occurred in the river bed along the two river stretches (for which data are available) over a period of 55 years. Figure 5.1.128 also shows a short stretch of the Middle Danube to provide a more comprehensive overview of the river bed changes in the Lower Danube.

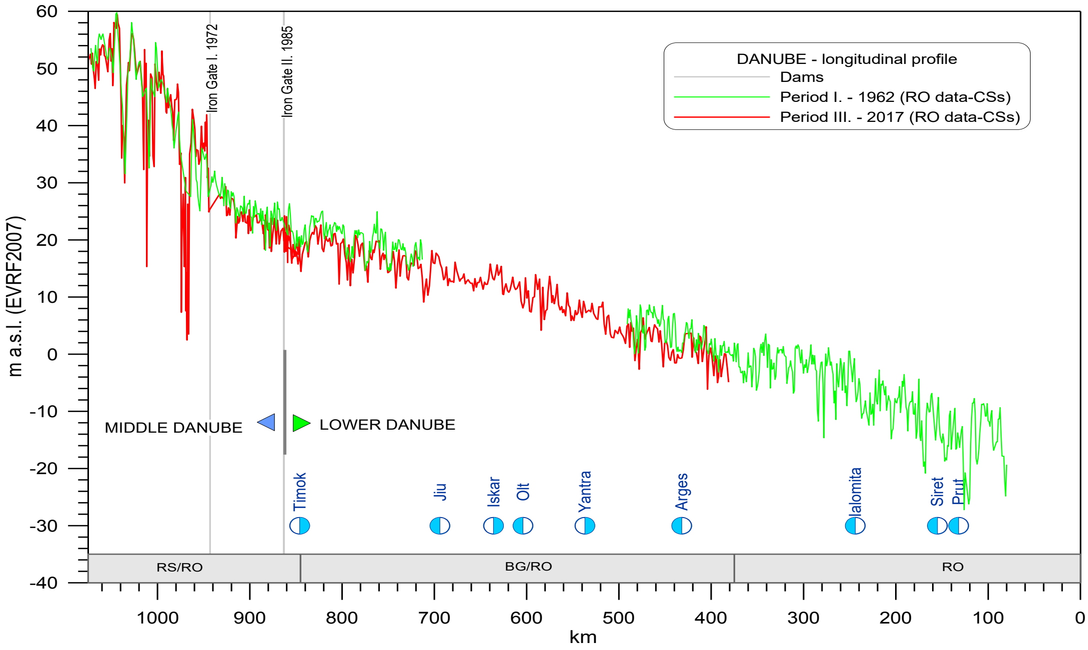


Figure 5.1.128 Long-term development of the Lower Danube’s longitudinal profile, including a short stretch of the Middle Danube, during the periods I and III (1992–2017)

Although the data available are incomplete (they do not cover the whole Lower Danube), the changes in the longitudinal profile (which can be clearly identified) indicate the long-term trends in the river processes – river-bed erosion and sediment deposition. A comparison of bed level changes along two river stretches for which such data are available (Figure 5.1.128) indicates systematic major river-bed degradation. The range of bed level changes is documented by the differences in thalweg between the longitudinal profiles in Figure 5.1.129. The river bed has sunk by -3 meters on average, locally by -5 m or -6 m, with a maximum of -9 m along the upper river stretch (rkm 863 – rkm 715). In the stretch between rkm ~500 and rkm 380, the bed level decrease has reached an average of -4 meters with local values of up to -6 m to -8 m. It needs to be stressed again that the longitudinal profiles show the river bed levels in the thalweg (the deepest points), so the results indicate the main trends in the evolution of the river bed.

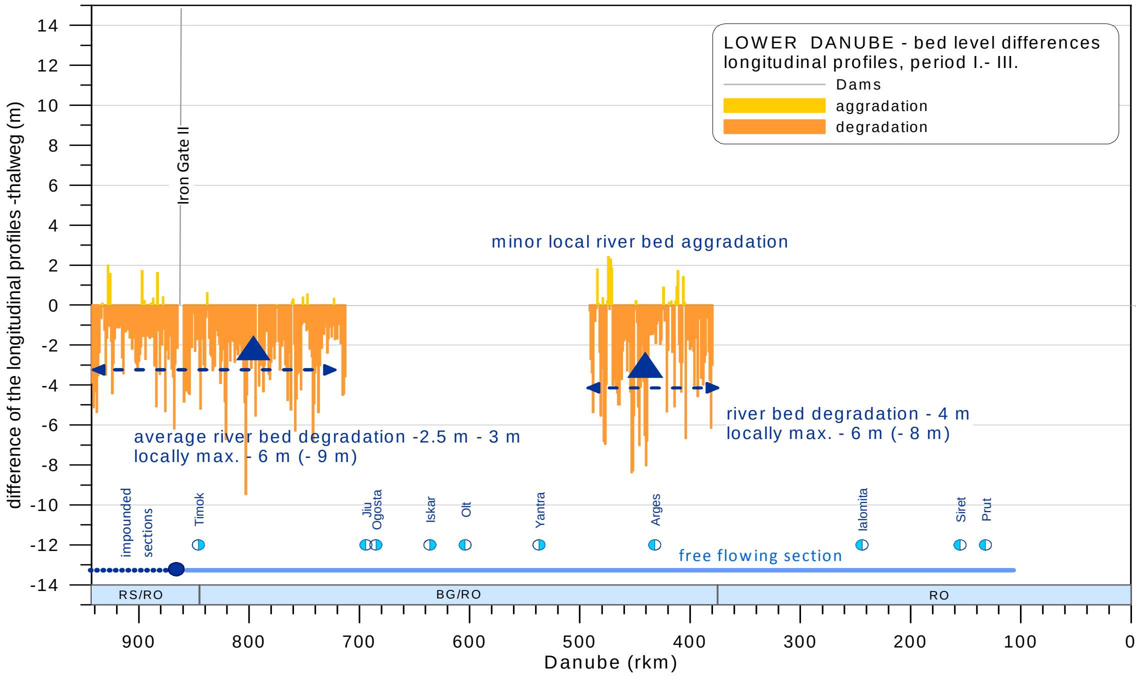


Figure 5.1.129 (5.2.24) Differences between the longitudinal profiles (along the thalweg) of the Lower Danube for periods I and III

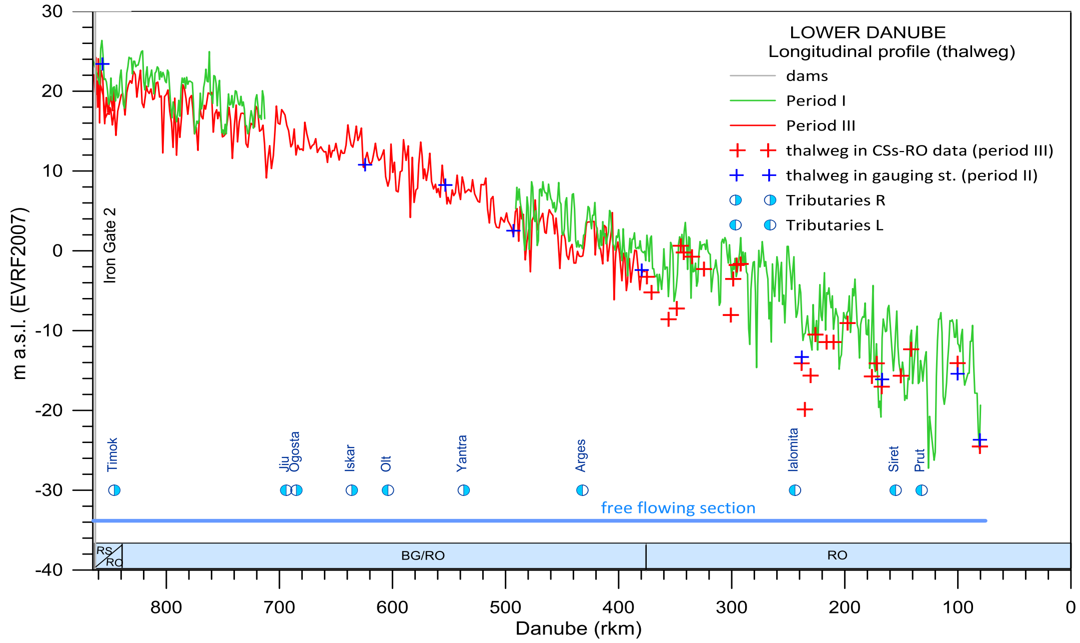


Figure 5.1.130 Comparison of the longitudinal profiles of the river bed in the Lower Danube (periods I and III), including data from the gauging stations (periods II and III)

River bed changes in the Danube are strongly influenced by the disrupted sediment continuity at the Iron Gate 1 and 2 dams, which has resulted in a sediment deficit in the Lower Danube. Apart from the Iron Gate 1 and 2 dams, the chain of hydropower plants built on the Lower Danube's tributaries also contributes to the growing sediment deficit. River bed incision was also affected considerably by excessive dredging during the periods II and III (Figure 5.1.132, Table 5.1.4).

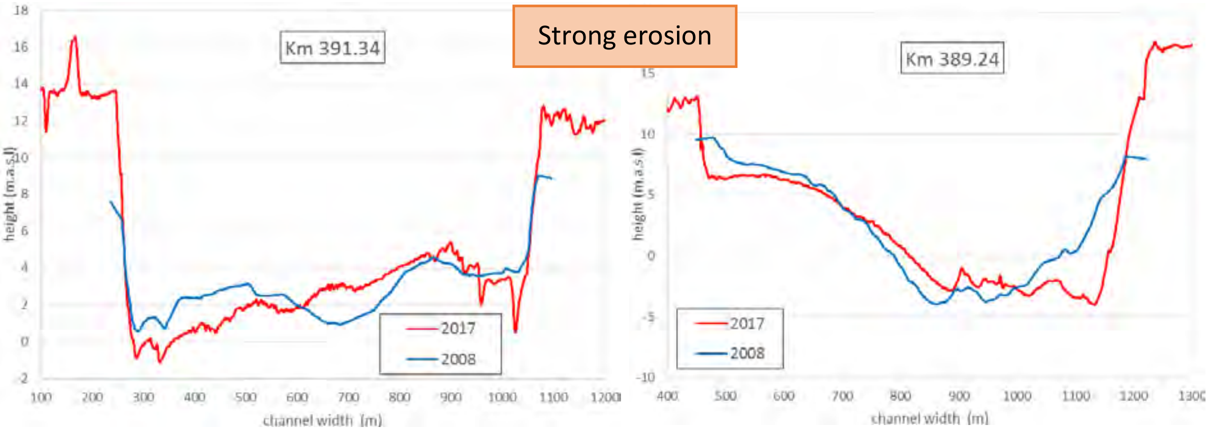
Table 5.1.4 Amounts of bed sediments dredged from the Lower Danube by the Romanian and Bulgarian River Authorities over the periods I and III, including the number of years covered

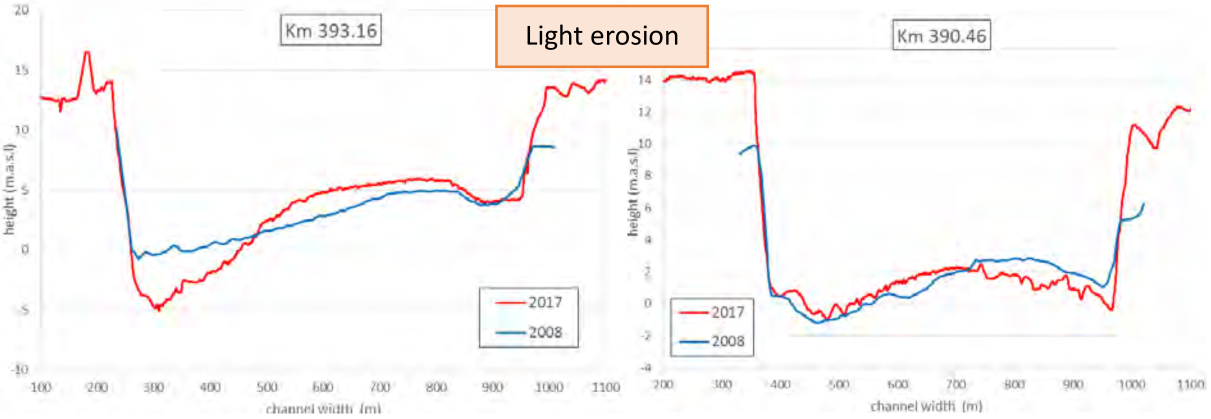
Country Danube rkm 940-80	**Period I**		**Period II**		**Period III**		**Total volume (mil. m³)**
	Total volume (mil. m³)	**Years covered**	**Total volume (mil. m³)**	**Years covered**	**Total volume (mil. m³)**	**Years covered**	
BG	1,509	15	2,768	17	1,048	20	5,325
RO	1,107	3	52,248	20	35,307	21	88,663
BG+RO	**2,616**	**15**	**55,016**	**20**	**36,355**	**21**	**93,988**

The longitudinal profiles of the river bed in the Lower Danube, which also include data obtained from the gauging stations for periods II and III are shown in Figure 5.1.130. Bathymetric data from 2008 could not be used for an analysis of the erosion/sedimentation processes, mainly because the cross sections were surveyed with longer distances between them (2 km on average or, in some cases, more than 20 km, max. 40 km). However, a comparison of the cross sections from 2008 and 2017 can provide useful information about the areas of erosion and sediment deposition in the river stretches under review. Figure

5.1.131 provides several examples showing areas of intense or slight erosion and areas where no significant changes have occurred in the river bed.

The anabranching river channel of the Lower Danube has a highly variable shape with numerous islands and several types of channel bars. Moreover, river bank erosion, which occurs on unprotected river banks, also contributes to the complexity of the river channel's morphological development. Hence, increased attention should be paid to the distribution of cross sections along the river channel, before field measurements are performed. The spatial distribution of cross sections must respect the channel's variability and the distances between them must be shorter (max. 500 m) so that reliable data are obtained for morphological analyses. The field campagien to perfom this range of bathymetric measurments, should be done regularly once in a 5 – 8 years or after a high flood. Even though measurements of 1,500 cross sections within 750 km river length seems to be demanding but with regard to time period it should be feasible. Regular monitoring of the river channel is highly needed as the river channel of the Lower Danube is more variable (bed changes, bank changes), influenced by natural river processes and also by human interventions. The methods of data acquisition and processing are also of high importance; they need to be harmonized between the Danubian countries.





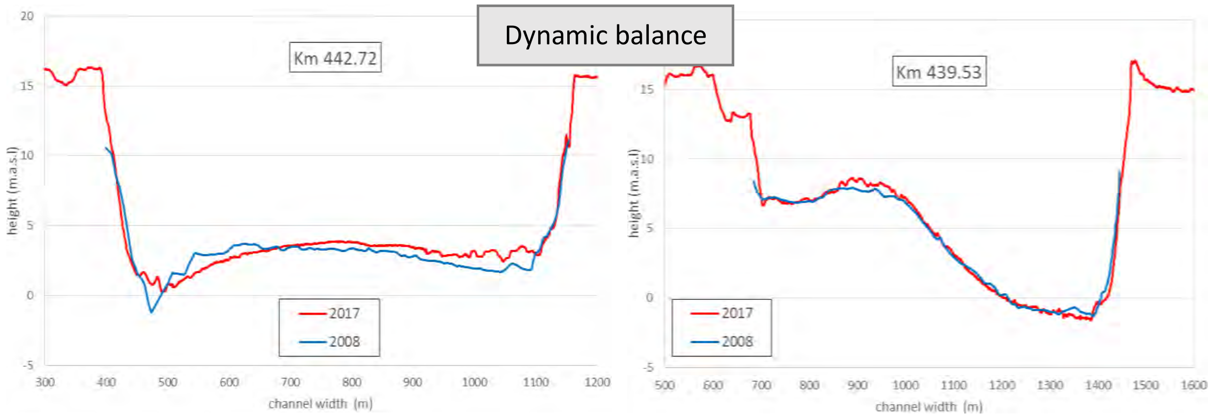


Figure 5.1.131 Examples of cross sections comparison obtained within two campaigns - period III (2008 and 2017) representing areas of strong and light erosion and cross section where no significant changes of the river bed occurred

The river's morphological development is evaluated mostly on the basis of its longitudinal profiles (1962, 2017). The data obtained from long-term bathymetric observations recorded at the gauging stations are presented in Figure 5.1.133 and data on sediment dredging performed over the periods under review are shown in Figure 5.1.132 (Table 5.1.4). All these data are used to identify the main trends in the and short-term and midterm processes of erosion and sediment deposition in the Lower Danube.

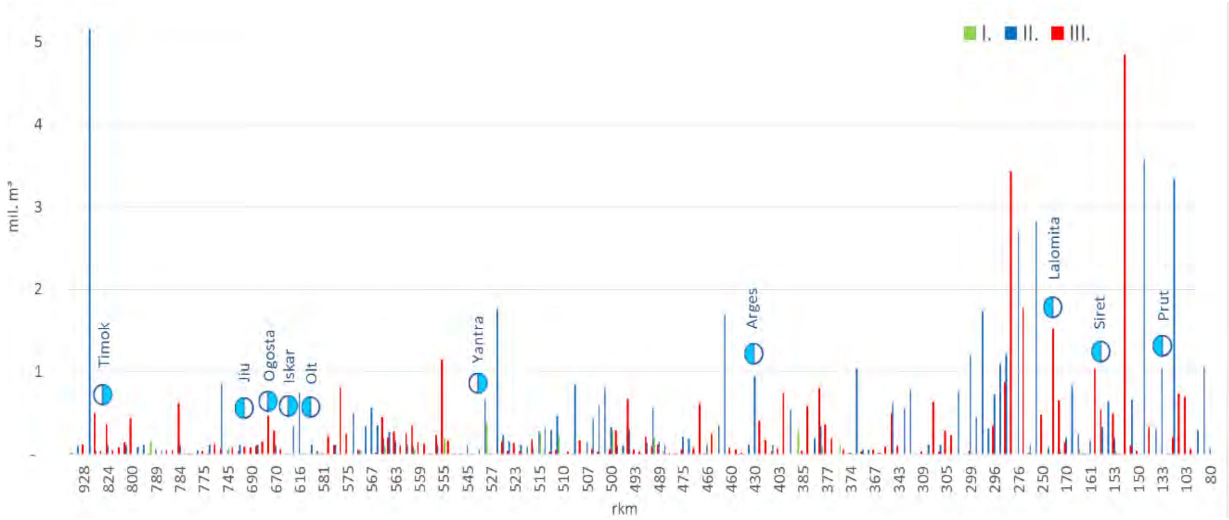


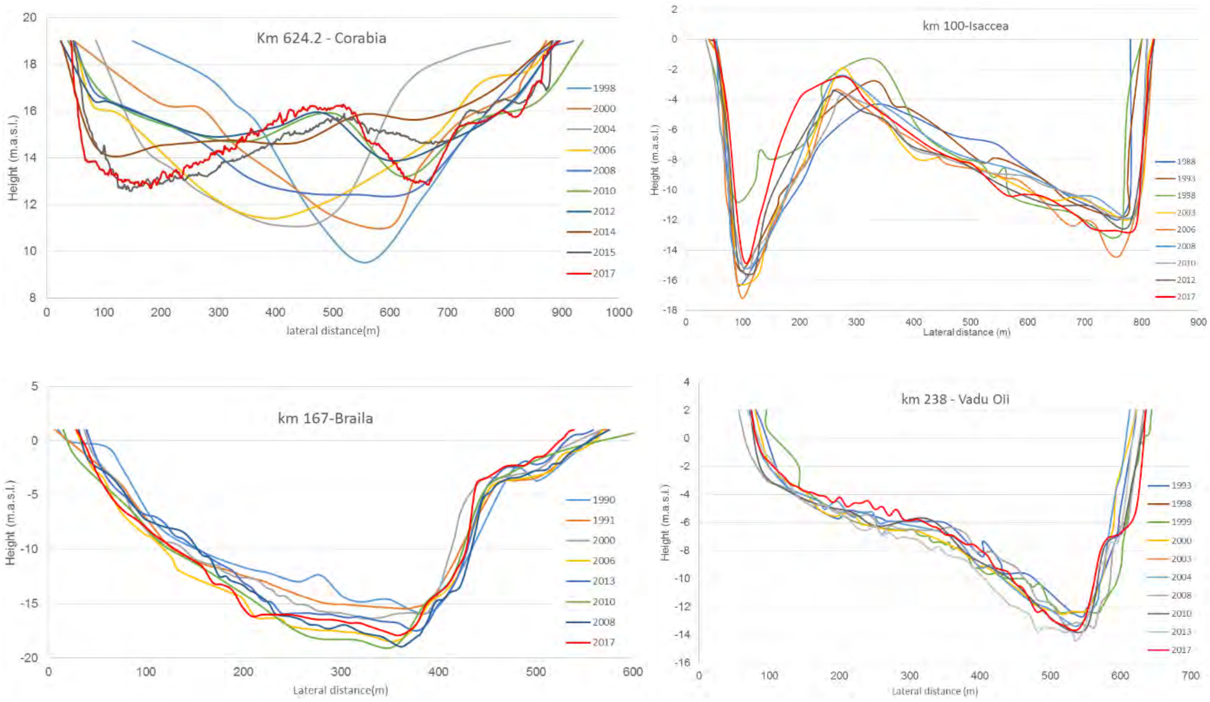
Figure 5.1.132 Amounts of riverbed sediments excavated in the Lower Danube over the three periods

Between the Iron Gate 2 dam (rkm 863) and rkm 847 downstream, strong river-bed erosion has been detected on the basis of Serbian bathymetric data and the calculated values of changes in the river bed (see Figure 5.1.116). A trend analysis of changes in the cross sections carried out by BOKU for Romanian gauging stations indicates light erosion at these localities (some of them are shown in Figure 5.1.133).

Taking into account the sediment deficit caused by the Iron Gate 1 and 2 dams, the long-term changes in the longitudinal profiles (Figure 5.1.130), and the results of the trend analysis made on the basis of data recorded at the gauging stations (BOKU), we may assume that the river stretch between rkm 847 and rkm 750 is subject to light erosion. The river processes downstream are indicated only locally in the cross sections of gauging stations, on the basis of the aforementioned trend analysis (BOKU). Thus, between rkm 750 and rkm 240, the changes in the river bed observed at the gauging stations indicate a midterm trend towards light erosion. The process of river bed erosion within this river stretch is supported by a sediment supply deficit from the tributaries – the Jiu, Iskar, Olt, Yantra and Arges rivers (caused by the damming of these rivers). This does not mean, however, that the river bed is eroded along the whole stretch. There may be places with light sedimentation and places without significant river bed changes between the eroded river stretches.

Although the volume of dredging along the Lower Danube decreased by ~34% in Period III, compared with the figures for periods II and III (Table 5.1.5), the actual amounts dredged in some localities are still too high (Figure 5.1.132). For instance, 3.4 million m^3 were dredged near rkm rkm 291 and almost 5 million m^3 near rkm 151. The impact of these extremely large volumes of sediments has caused a further sediment deficit in the river channel, which considerably contributed to the evolution of the river bed, mainly downstream of rkm 300.

Excessive volumes of river bed dredging have caused major river bed degradation along the whole Danube. Effects of river bed dredging can also be seen in the Lower Danube.



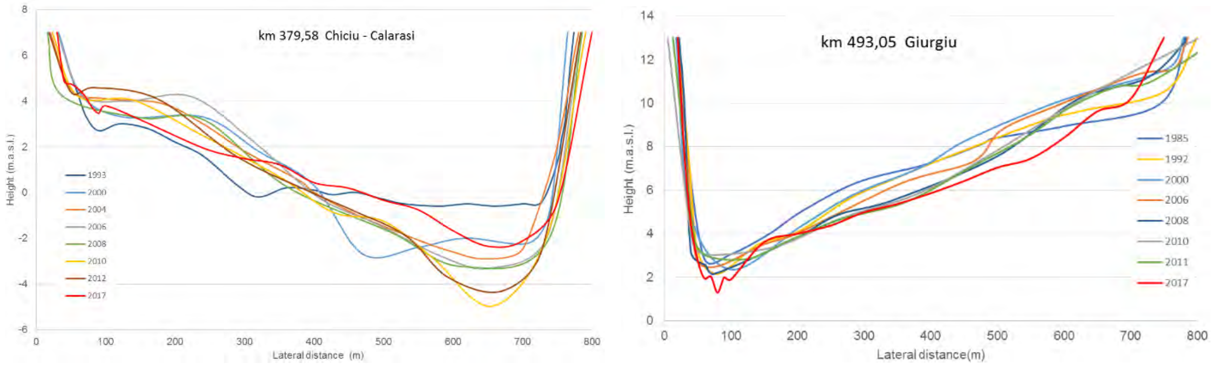
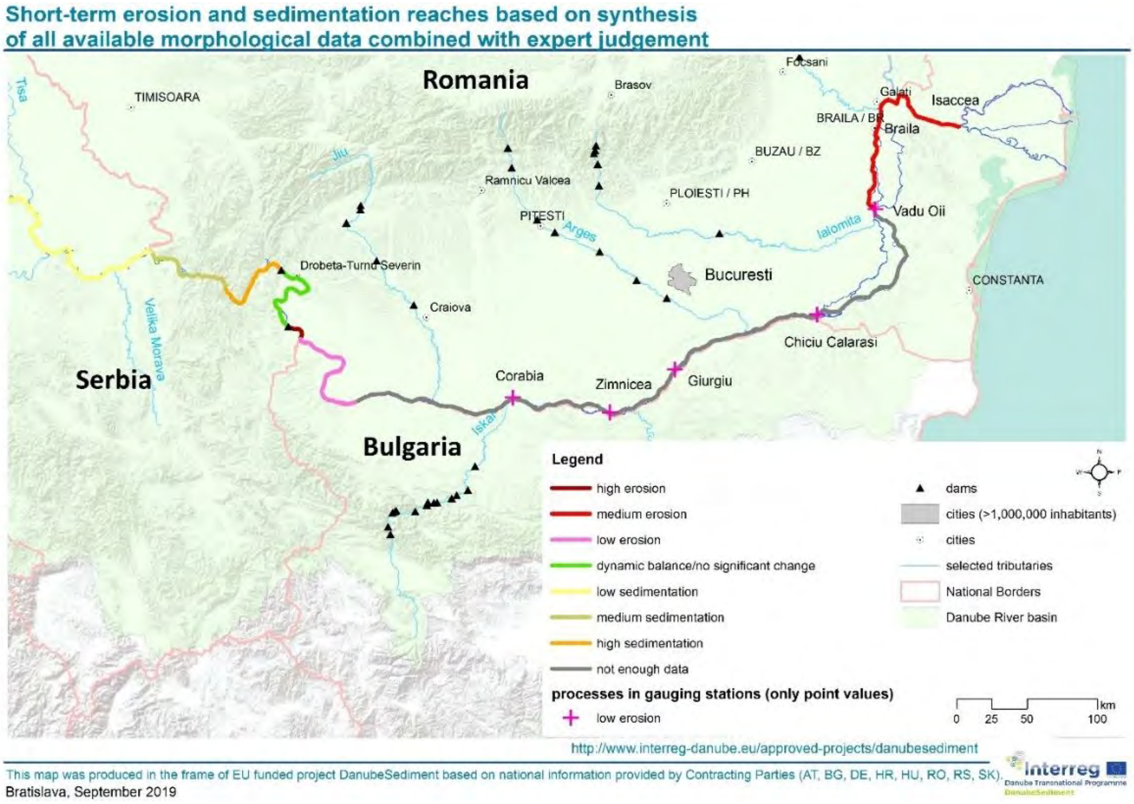


Figure 5.1.133 Examples of the channel development in the localities of some gauging stations (RO data)

River bed dredging in the Lower Danube was concentrated in the stretch between rkm 300 and rkm 80 in both periods (II and III). The total amounts of sediments dredged, broken down by the place of dredging (rkm 862 – 300; rkm 300 – 80) and the corresponding time period are summarized in Table 5.1.5. The values in Table 5.1.5 indicate that 51% of the total dredging volume was concentrated within a shorter river stretch between rkm 300 and rkm 80 in both periods (II and III). The impact of dredging, coupled with the concentration of excessive amounts of sediments in short sites (Figure 5.1.132), caused river bed degradation downstream of rkm 240 (up to rkm 80). Moderate erosion along this stretch of the Lower Danube was also indicated by data obtained from the relevant cross sections – thalweg (see Figure 5.1.130).

Table 5.1.5 Total amounts of sediments dredged in two stretches of the Lower Danube (rkm 862 – rkm 300; rkm 300 – rkm 80) over the three periods under review

Danube section rkm/ length (km)	Total volumes of dredging downstream of the Iron Gate 1 period / % of total volume (m^3)						**∑ of** total volume (m^3)
	I.		**II.**		**III.**		
80 -300 **(220)**	103 000	**4**	25 392 031	**51**	18 368 191	**51**	43 863 222
300-862 (**562**)	2512572	**96**	24 345808	**49**	17 369 861	**49**	44 228 241
∑	**2 615 572**	**100**	**49 737 839**	**100**	**35 738 052**	**100**	**88 091 463**



Short-term erosion and sedimentation reaches based on synthesis of all available morphological data combined with expert judgement

This map was produced in the frame of EU funded project DanubeSediment based on national information provided by Contracting Parties (AT, BG, DE, HR, HU, RO, RS, SK).
Bratislava, September 2019

Figure 5.1.134 Map of the main trends of the river processes (erosion/sedimentation) prevailing along the Lower Danube

Generally, it can be stated that the long-term development of the river bed along the Lower Danube indicates river bed degradation along the whole length of the river, owing to a sediment supply deficit from upstream (caused by the Iron Gate 1 and 2 dams) and excessive bed material dredging. The process of river bed incision still continues, though its intensity is decreasing. The minor erosion prevailing in the Lower Danube has been strengthened by the decreased sediment supply from the tributaries and the increased sediment dredging. However, the eroded stretches can alternate with shorter stretches exposed to sediment deposition or stretches without any major changes in the river bed. The data available did not enable us to detect and quantify erosion or sedimentation more accurately within the scope of this project. Therefore, the results illustrated in the map below (Figure 5.1.134) indicate the main trends in the short-term evolution of the river bed in the Lower Danube on the basis of the data available, supported by theoretical and practical knowledge gained from the other Danube stretches and by expert opinion.

Variation of erosion/sedimention processes along the Danube– GIS interperetation

Assessment of rivebed changes done by project partners from bathymetric measurements in various years resulted in quantification of morphological changes within the evaluated timescale. Methodology for such assessment was described in Report *"Data analyses for the sediment balance and long-term morphological development of the Danube"* and the results are part of Report *"Assessment of the Sediment Balance of the Danube".* Calculations of riverbed changes together with all available morphological data (dredging/feeding, bed material composition, longitudinal profile) and expert judgement considering measures/pressures such as longitudinal interruptions of sediment continuity, have led to identification of prevailing processes (erosion or sedimentation) in the Danube reaches within the investigated period (1991-2017). Categories of low, medium and high erosion/sedimentation indicate the intensity of the process. Map on Figure 5.1.135 shows the identified processes along the Danube from rkm 2,582 to rkm 750. Section downstream of rkm 750 was not covered by detailed data on morphological development of the riverbed (only two years from bathymetric measurements were available, profiles were too distant for quantification). Thus only point values with more frequent bathymetric measurements in gauging stations show the trend towards low erosion in these stations (more details can be found in Chapter 5.1.7).

In total, erosion is a prevailing process within 733 rkm of the Danube River, whereas 857 rkm is affected by sedimentation. Along 241 rkm of the Danube, dynamic balance prevails or no significant change occurs. High erosion dominates downstream of Gabcikovo and Iron Gate 2 reservoirs as well as on a free flowing section in Hungary. Free flowing sections are influenced by medium erosion in Germany (downstream of Donauwörth, Vohburg, Straubing), in Austria (downstream of Melk, Freudenau) and in Hungary, Croatia and Serbia. In Austria, medium erosion also occurs downstream of Ottensheim-Wilhering and Abwinden-Asten. High sedimentation is upstream of Aschach, Gabcikovo and Iron Gate 1 reservoirs. Medium and low sedimentation is present in impounded sections of almost all dams along the Danube. Dynamic balance or no significant change is downstream of Wallsee-Mitterkirchen in Austria, in the old Danube channel downstream of Čunovo dam, and in section where the slope of the Danube is decreasing (boundary between Upper and Middle Danube) – downstream of Klizska Nema/Gyonyu towards Szob (SK-HU section). Another reach of dynamic balance/no significant change is downstream of Budapest and between Iron Gate 1 and Iron Gate 2 reservoirs. Lack of historical data did not allow to produce such output along the whole Danube for periods I. and II.

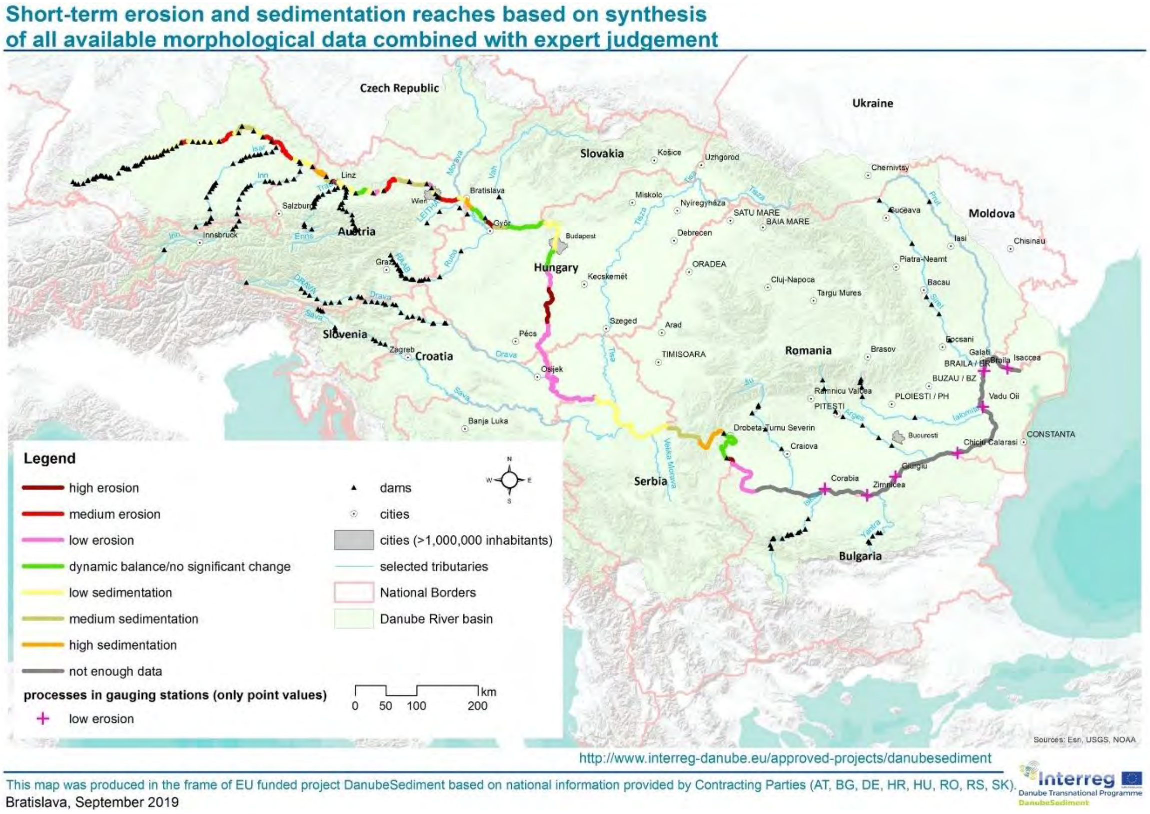


Figure 5.1.135 Map of the main trends of the river processes (erosion/sedimentation) prevailing in the Danube in period III.

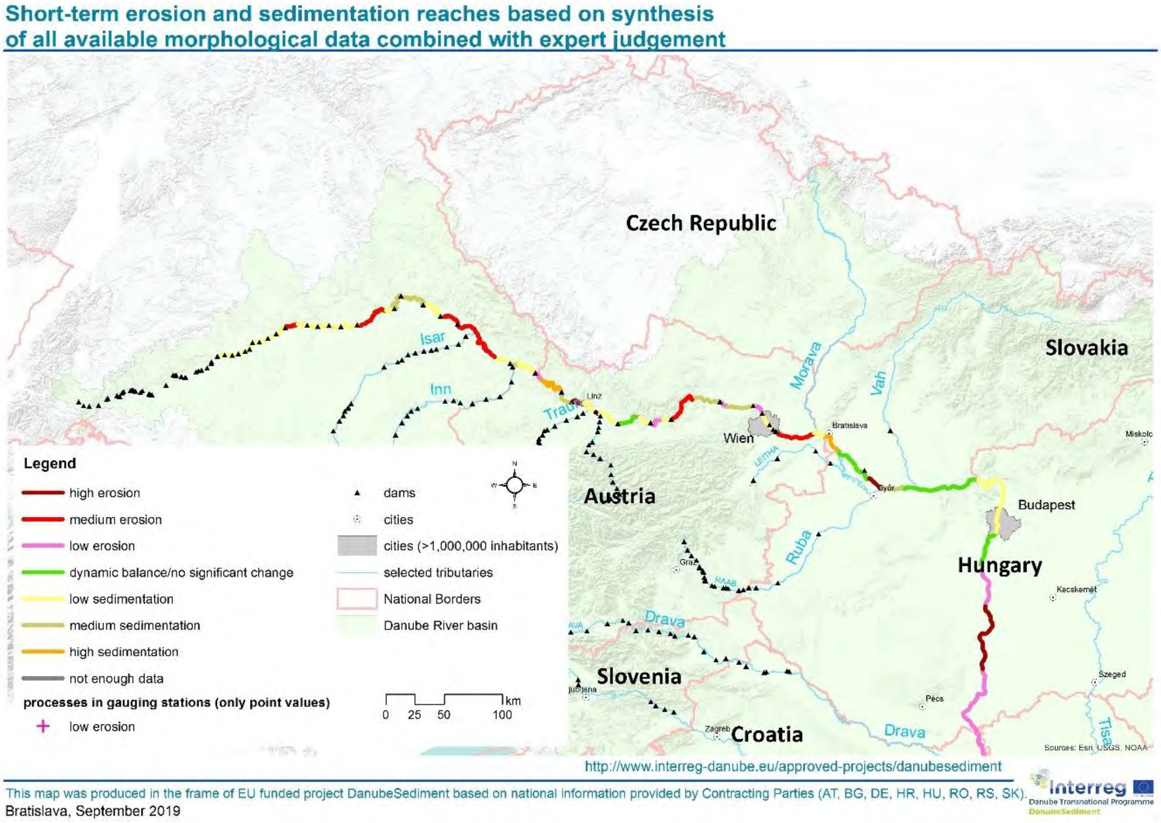


Figure 5.1.136 Map of the main trends of the river processes (erosion/sedimentation) prevailing in the Upper Danube in period III.

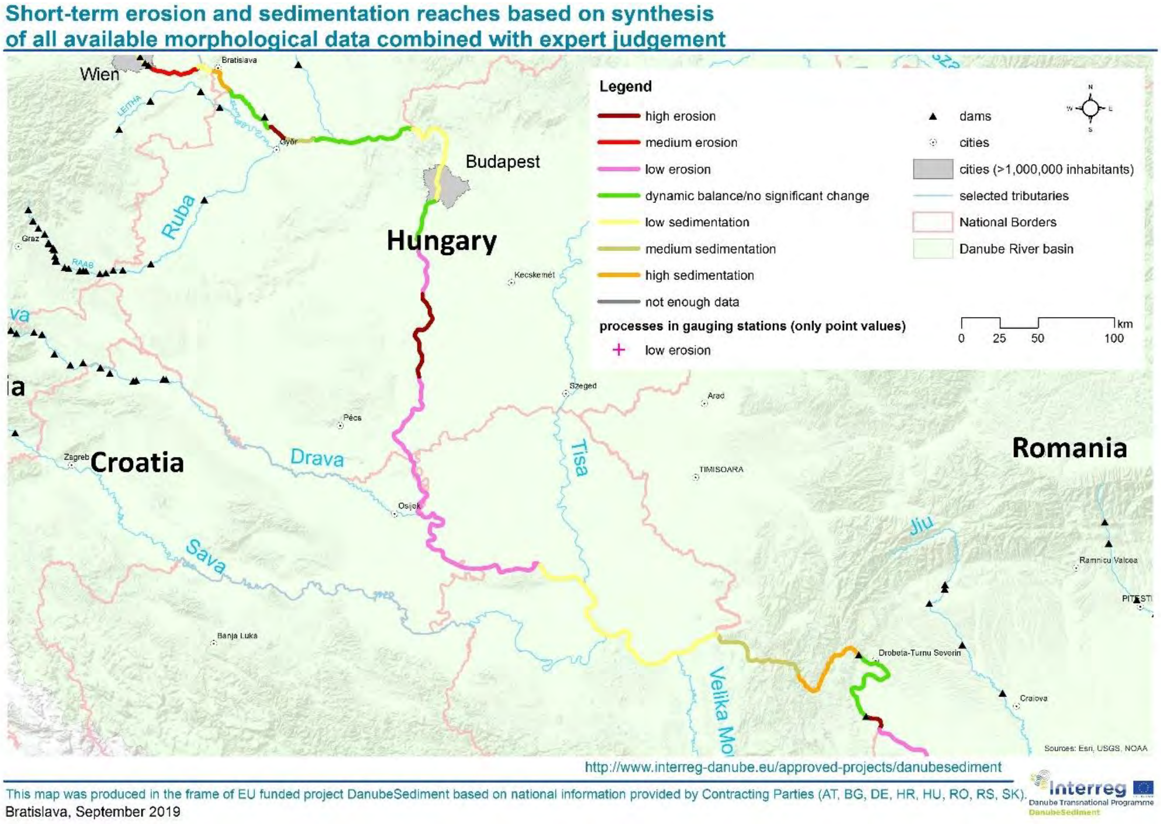


Figure 5.1.137 Map of the main trends of the river processes (erosion/sedimentation) prevailing in the Middle Danube in period III.

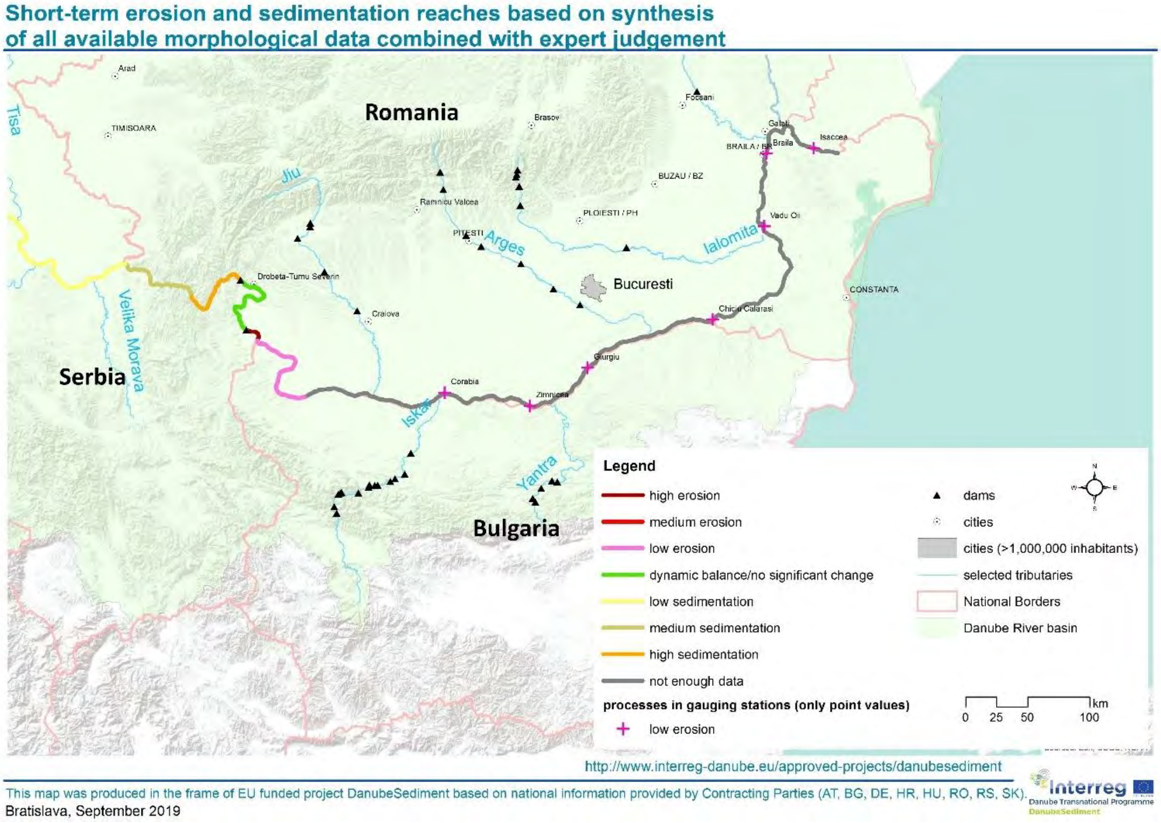


Figure 5.1.138 Map of the main trends of the river processes (erosion/sedimentation) prevailing in the Lower Danube in period III.

5.2 Long term changes in the longitudinal profile as a response to disrupted sediment continuity and other pressures

Background: The longitudinal profile illustrating the relationship between elevation and distance shows a steep gradient near the river's source and a gentle gradient as the river approaches its mouth. The ideal smooth, descending curve shown in Figure 5.2.1 is often affected by irregularities induced by the natural conditions and/or anthropogenic activities. The gradient determines the river's flow energy and sediment transport capacity, and the corresponding river types within the given geomorphological conditions. The river's response to human activates often results in gradual changes in the longitudinal profile. Thus, the longitudinal profile and its main characteristics (slope and shape) can be used as an indicator of morphological changes in alluvial streams.

The most frequent causes of natural irregularities in the longitudinal profile are the geomorphological and structural conditions and the sediment supply (from the tributaries). The river's rock bottom resistant to fluvial erosion forms a *natural local base level,* which is the lower limit for erosion. Thus, the rock bottom controls the development of the long profile. Barriers built across the river channel (dams, weirs, barrages, hydropower plants) form new *artificial local base levels* in the river stretches upstream and downstream of the structure. The changes in the longitudinal profile induced by a dam (new local base level) are shown in the scheme in Figure 5.2.1b. The natural and artificial local base levels represent limitations for the development of the river's longitudinal profile and thus they need to be considered in a morphological analysis.

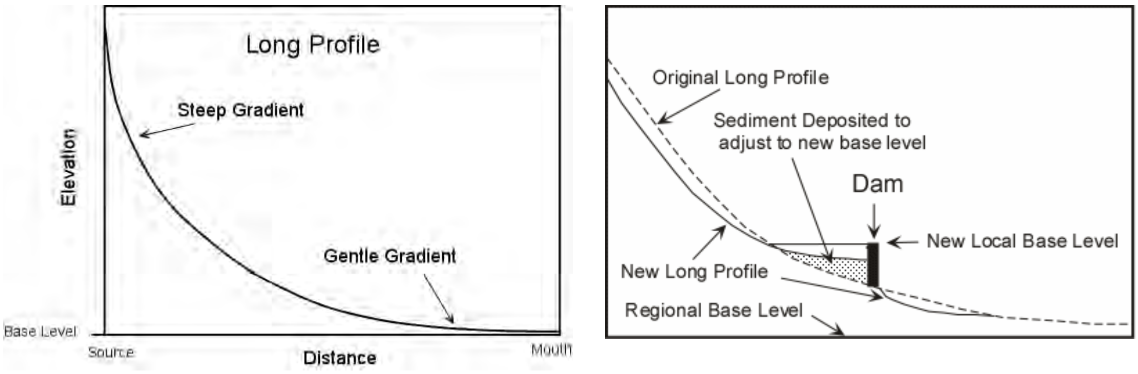


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Figure 5.2.1 Longitudinal profile of a river in ideal shape (a) and in modified shape with a new local base level created by a dam (b), including deformations upstream/downstream of the dam

In general, where the base level is lowered, the river bed is degraded and accelerated erosion is underway and, where the base level is raised, sediments are deposited in the river bed and the river readjusts its longitudinal profile to its new base level (Figure 5.2.1b). Therefore, barriers that create new base levels in the river channel considerably contribute to the reshaping of the longitudinal profile in the long term.

In addition to barriers, other engineering activities may also cause significant changes in a river’s longitudinal profile, particularly river channel straightening (the cut-off of meanders, isolation of side branches), which causes accelerated river-bed erosion and a rise in the river bed slope. Excessive river-bed dredging (usually for commercial purposes) is another serious intervention into the sediment balance, which often results in major river-bed degradation with a possible impact on the river-bed slope – mainly where dredging is concentrated within the short river stretch over a longer period.

Since the ‘20s of the 20th century, the gradual construction of hydropower plants on the Danube has principally changed the flow and sedimentary conditions, and stabilised the main shape and elevation of the longitudinal profile along the river stretches concerned. The combined effects of river regulation, reduced sediment supply from the tributaries (due to damming) and dredging have contributed to the local changes in the river-bed slope. As the longitudinal profile (shape and slope) may reflect the effects of several engineering activities, a temporal analysis of its changes can be used as an indicator of morphological changes in the river bed.

The main aims of the activities described in ‘*Long-term changes in the longitudinal profile caused by disrupted sediment continuity and other pressures’* were as follows:

- to compile a longitudinal profile for the Danube (rkm 2,500 to rkm 80), using real data (thalweg/mean) from the three periods under review (Periods I, II and III);
- to evaluate the river-bed slopes for the corresponding stretches of the Danube’s longitudinal profile – present state (Period III);
- to identify the main trends in river-bed changes (in stretches exposed to erosion/ sedimentation) on the basis of changes in the longitudinal profile (thalweg) for the long-term and mid-term periods;
- to identify the changes in the river-bed slope on the basis of long-term changes in the longitudinal profile (Periods I and III) along the national river sections.

The evaluation of river stretches exposed to erosion/sedimentation, based on a comparison of the river’s longitudinal profiles from different periods, identifies the basic trends of river-bed aggradation or degradation over a longer period, rather than a quantitative assessment of river-bed changes in stretches exposed to erosion/sedimentation, based on an analysis of bathymetric data (Chapter 5.1).

Limitations are given by the data used, which mostly represent the thalweg (the deepest points in the cross sections). Thus, the river-bed changes in the thalweg reflect the variations in the bed elevation within the deepest parts of the navigational channel. Data on the mean river-bed elevation (mean depth) allow a better interpretation of the river processes, however, these data are not available in most countries. While river-bed degradation is reflected quite well in the longitudinal profile (thalweg), the areas of sedimentation within impoundments (upstream of dams) are not shown properly as sediments are deposited along the sides of the navigational channel.

Nevertheless, the analysis of long-term and mid-term changes in the longitudinal profile caused by disrupted sediment continuity and other hydromorphological pressures (e.g. dredging, river training) provided valuable results, which has enhanced our knowledge about the morphological evolution of the river bed and about its modification, which are, in many aspects, unique to the Danube.

Data harmonisation – longitudinal profiles (thalweg)

The longitudinal profiles provided by the project partners were from different years within the periods under review (periods I, II and III) and the density of data points within the profiles varied. Moreover, the Danubian countries use various vertical systems, so it was necessary to harmonise the datasets covering the deepest points of the river bed (thalweg) into a common vertical system.

As already described in the Report *'Data analyses for the sediment balance and long-term morphological development of the Danube',* the European Vertical Reference Frame 2007 (EVRF2007) was used to harmonise the elevation data collected. Transformation parameters (see Table 5.2.1 and Chapter 4.1 *'Data collection'*) were used for the datasets received from the countries involved in the DanubeSediment project. Table 5.2.2 lists the time scales of these datasets.

Table 5.2.1 Reference tide gauges in the partner countries and the parameters used to transform the national heights to EVRF2007 (in cm)

Country	Vertical datum	Kind of height	Transformation parameter (cm)
Germany	Amsterdam	normal (Molodenski)	+1
Austria	Triest Adria (1,875)	normal orthometric	-34
Slovakia	Kronstadt Baltic sea	normal (Molodenski)	+14
Hungary	Kronstadt Baltic sea	normal (Molodenski)	+16
Croatia	Triest Adria	normal orthometric	-31
Slovenia	Triest Adria	normal orthometric	-39
Serbia	Triest Adria	normal orthometric	-35*
Bulgaria	Kronstadt Baltic sea	normal (Molodenski)	+23
Romania	Constanta Black Sea**	normal (Molodenski)	+6

* *No data available, so the average value for Croatia–Slovenia is used.*
** *Historical data from Romania refer to the Sulina gauge (Black sea)*

For the graphical illustration of the longitudinal profiles, all the data received were used (with the original point density). For calculations of river-bed changes from the longitudinal profiles and their graphical interpretation, the data had to be harmonised for stretches of the same distance (1 km-long stretches were used). When the distances between thalweg points were equal to or shorter than 1 km (e.g. 100 m, 200 m, 300 m) within the datasets, only the values for the beginning and end of the 1 km-long stretches were used. When the distances between thalweg points were longer than 1 km, the missing values for one kilometre were interpolated using the closest upstream and downstream values.

Some attempts were made to acquire and use data for the longitudinal profile of the mean river-bed elevation (mean depth), but such data are available only in few countries and they cover different stretches and periods. These data are not homogenous in time and space. Therefore, only thalweg values were used for compiling longitudinal profiles along the river bed of the Danube for the three periods considered in this study.

Table 5.2.2 Datasets used for evaluating the longitudinal profiles of the Danube

Country	Years covered by the longitudinal profiles		
	Period I	Period II	Period III
Germany	1927, 1943	1990	2010
Austria	1929	1970, 1971, 1973, 1976, 1980, 1981, 1983, 1984, 1985	2013, 2014, 2015, 2016, **2017**
Slovakia	**1910**, (1951)	1971	2013
Hungary	1959	no data available	2003, 2016
Croatia	no data available	no data available	2011, 2016
Serbia	1927	1986	2013
Bulgaria	no data available	no data available	no data available
Romania	1962	1987 (incomplete)	2008, **2017**

Data inconsistency and data gaps, differences in quantity and quality. An analysis of data quality showed that some of the data provided by the project partners are not reliable enough, owing to various reasons. For instance, an insufficient number of thalweg points/km (too long distances between cross sections), uncertainties in the elevation systems used (mainly in the case of historical data from Period I, i.e. before 1970), and other uncertainties (in data acquisition and processing) were found in the data obtained in recent years. These data had to be excluded from the data analysis. Therefore, several empty parts can be seen in all the long profiles and all three periods.

Longitudinal profiles of the Danube (along the river bed) for periods I, II and III

The longitudinal profiles compiled for the full length of the Danube are illustrated in figures 5.2.2, 5.5.4, and 5.2.5. The points of the profiles represent the river-bed elevation in the thalweg along the Danube from rkm 2,582 to rkm 100 within three periods (I, II, III), covering more than a hundred years (1910–2017, see Table 5.2.1). This relatively long period witnessed the gradual construction of hydropower plants on the Upper Danube and the channel regulation for low flows (for navigational purposes). Later, the construction of the Iron Gate I and II dams (1971, 1985), the finalisation of river training works for low flows (LNWL) and the construction of the last two hydropower plants on the Danube, i.e. Gabčíkovo (1992) built on a bypass canal and Freudenau downstream of Vienna, completed the main pressures affecting the Danube channel morphology.

A longitudinal profile of the Danube, showing the present state of the river bed (Period III) and indicating the free-flowing sections and the selected left and right-side tributaries, is illustrated in Figure 5.2.2. This longitudinal profile has been compiled from thalweg data between rkm 2,582 and rkm 300 – DE (2010), AT (2013, 2014, 2015, 2016, 2017), SK (2013), HU (2003, 2016), HR (2011, 2013), RS (2013) and RO (2008, 2017). The river bed within the stretch between rkm 380 and rkm 100 of the Lower Danube is covered by individual points, which represent the thalweg values from the cross sections measured (the distances between them are too long).

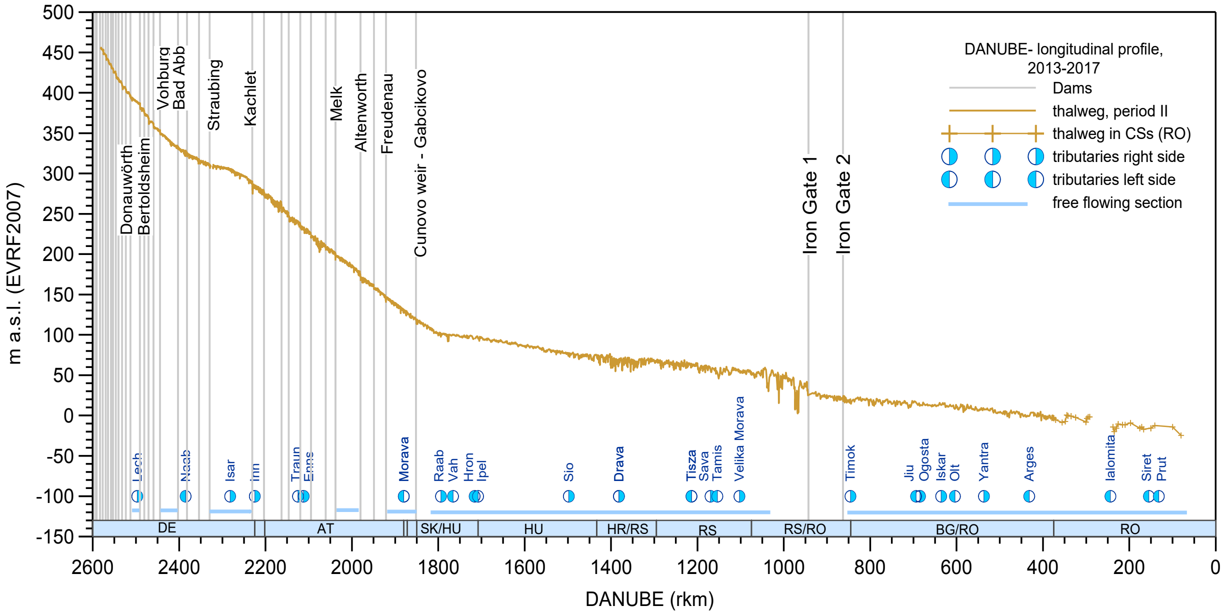


Figure 5.2.2 Longitudinal profile of the Danube (along the river bed), showing the free-flowing sections and the selected left and right-side tributaries (Period III, present state)

The irregular shape of the longitudinal profile of the river bed in the upper part of the Danube between rkm 2,330 and rkm 2,230 (a free-flowing section under the present conditions) reflects the geomorphological and geological conditions. The large amount of coarse sediments transported into the Danube from its Alpine tributaries (Issar and Inn in particular) in the past, could also contribute to the formation of the convex shaped long profile in this river section. Except for the natural local base levels (rock river bed resistant to erosion) spread along the Danube (the impact of the Alps on the Upper Danube and the Carpathians on the Middle Danube), the new base levels (caused by hydropower dams) also fixed the longitudinal profile and thus changes may occur mostly locally, in the free flowing sections. A more detailed analysis of the development of the Danube's longitudinal profile made by the project partners are included in Chapter 5.1 (*Spatial and temporal river-bed changes in the national sections of the Danube*).

The values of the river bed slope for particular river stretches were estimated using thalweg data from Period III (present state) for the whole Danube. The river-bed slope was estimated for longer stretches within which the local slope changes were omitted. These local changes are, however, identified and described in the next part of this report.

For the identification of long-term changes in the river-bed slope, local values from Period I were also used in the estimation. The values of the river-bed slope (from Period III) are summarised in Table 5.2.3 and illustrated in Figure 5.2.3. As thalweg data covered a longer period (from 2003 to 2017), smaller deviations may occur in the slope values along the national river sections, especially when they are compared with the long profiles compiled from mean bed data, which are more representative but are rarely available.

The values of the river-bed slope along the Upper Danube vary from 0.86‰ in the section between rkm 2,581 and rkm 2,510 (DE) to 0.34‰ in the section between rkm 1,880 and rkm 1,790 (SK-HU). Within the Middle Danube, the river-bed slope varies from 0.08‰ between rkm 1,790 and rkm 1,560 to 0.19‰ upstream of the Iron Gate 1 dam (rkm 1,050 – rkm 943). The slope values along the Lower Danube varies between 0.06‰ and 0.04‰.

Table 5.2.3 Values of the river-bed slope along the longitudinal profile of the Danube compiled for Period III, using thalweg values

country	**DANUBE (rkm)**		**Slope**	
	from	to	Absolute value	‰
UPPER DANUBE DE, AT, SK, HU	2,581	2,510	0.00086	**0.86**
	2,510	2,490	0.00043	**0.43**
	2,490	2,410	0.00064	**0.64**
	2,410	2,320	0.00030	**0.30**
	2,320	2,230	0.00025	**0.25**
	2,230	2,163	0.00041	**0.41**
	2,163	2,038	0.00050	**0.50**
	2,038	1,980	0.00041	**0.41**
	1,980	1,920	0.00045	**0.45**
	1,920	1,880	0.00041	**0.41**
	1,880	1,790	0.00034	**0.34**
MIDDLE DANUBE SK, HU, HR, RS RS, RO	1,790	1,710	0.00007	**0.07**
	1,710	1,560	0.00008	**0.08**
	1,560	1,450	0.00006	**0.06**
	1,400	1,200	0.00005	**0.04**
	1,200	1,050	0.00005	**0.05**
	1,050	943	0.00019	**0.28**
	943	863	0.00006	**0.08**
LOWER DANUBE BG, RO	863	516	0.00005	**0.05**
	516	375	0.00006	**0.06**
	375	100	0.00004	**0.05**

Certain specific changes in the river-bed slopes, occurring along the national sections of the Danube, were identified using data from the longitudinal profiles for periods I and II.

Minimum water level for navigation (LNWL): *low-flow water level* is one of the best indicators of river-bed changes as its decrease or increase over time very well corresponds to the degree of river-bed degradation or aggradation. The Danube Commission requires that the minimum water level for navigation (LNWL) be estimated for the free-flowing stretches of the Danube. LNWL, which means *low-flow water level* in this study, is usually calculated by means of 1D/2D hydrodynamic numerical models using bathymetric data on the river channel and measurements of low-flow water levels. The LNWL needs to be updated regularly, every 5-10 years and/or after major floods, owing to morphological changes occurring in the river bed. The water levels in the impounded river stretches (DE, AT) are given in the operating manuals of hydropower plants.

The low-flow water level (LNWL) estimated for the whole Danube is shown in Figure 5.2.3. The dashed lines indicate the water level in the impounded stretch upstream of the Iron Gate 1 dam and that along the Lower Danube, where the low-flow water levels were estimated only at the gauging stations (RO). The low-flow water level has not been estimated for the Slovak-Hungarian section of the Danube (Old Danube, from rkm 1851.75 to rkm 1,810) since the river is dammed and the greater part of daily discharges are diverted into the inlet canal of the Gabčíkovo hydropower plant. Therefore, an empty space can be seen in Figure 5.2.3 along this river section.

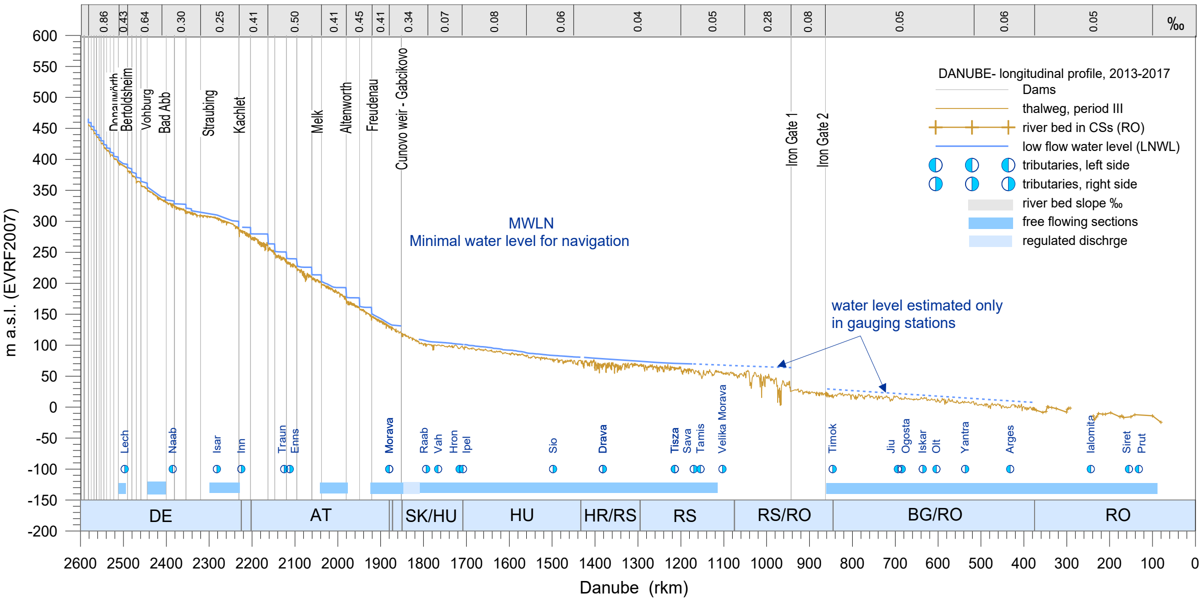


Figure 5.2.3 Longitudinal profile of the Danube (along the river bed), showing the free-flowing stretches and the corresponding river-bed slopes, and the left and right-side tributaries (Period III, present state)

Period II: The longitudinal profile for Period II shown in Figure 5.2.4 was compiled from thalweg data, which cover several years between 1970 and 1990 (see Table 5.2.2). Period II witnessed the gradual construction and operation of a chain of hydropower plants on the

Upper Danube. That period also saw the construction and putting into operation of the Iron Gate I and II dams, which have caused substantial changes in the flow and sediment regimes of the Middle and Lower Danube.

As it can be seen in Figure 5.2.4, the data sets for Period II are more incomplete than those for Period III. There are two shorter stretches with missing data in the Upper Danube section (DE) and an extended data gap in the Middle Danube section between rkm 1,709 and rkm 1,433 (HU). The values of river-bed elevation (thalweg) from Romanian gauging stations are available only for the Lower Danube downstream of the Iron Gate II dam (RO, BG), hence only these values are shown in Figure 5.2.4. The absence and poor data quality of data (long distances between the thalweg values) limited the analysis of mid-term river-bed changes to stretches for which data are available.

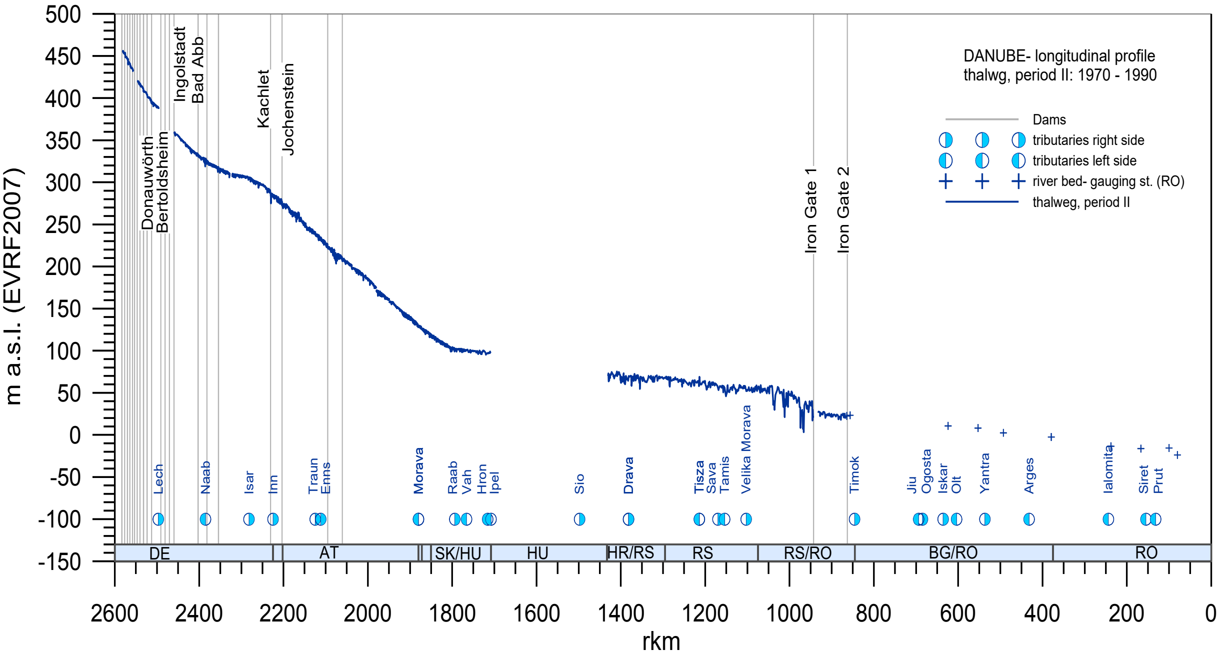


Figure 5.2.4 Longitudinal profile of the Danube (thalweg) for Period II (1970-1990), showing the hydropower plants already in operation and selected left/right-side tributaries

Period I: The longitudinal profile along the river bed of the Danube compiled for Period I (using data from: Germany 1927, 1943, Austria 1929, Slovakia 1910, Hungary 1959, Serbia 1927 and Romania 1962) is shown in Figure 5.2.4. Although the data used cover a fairly long time period (from 1910 to 1962), the longitudinal profile shows the situation when only one hydropower plant was in operation in the Upper Danube section (Kachlet, rkm 2,230.51). River channel regulation for mean water was already completed on the Upper and Middle Danube at that time, but low-water river regulation (groynes, deflective structures, side arms closure) continued, as well as sediment dredging in excessive amounts for commercial and other purposes, causing major changes in the river bed. Therefore, the longitudinal profile of the Danube (along the thalweg) for Period I was considered a *'reference state'* in this study for the evaluation of the longitudinal profile's development over time.

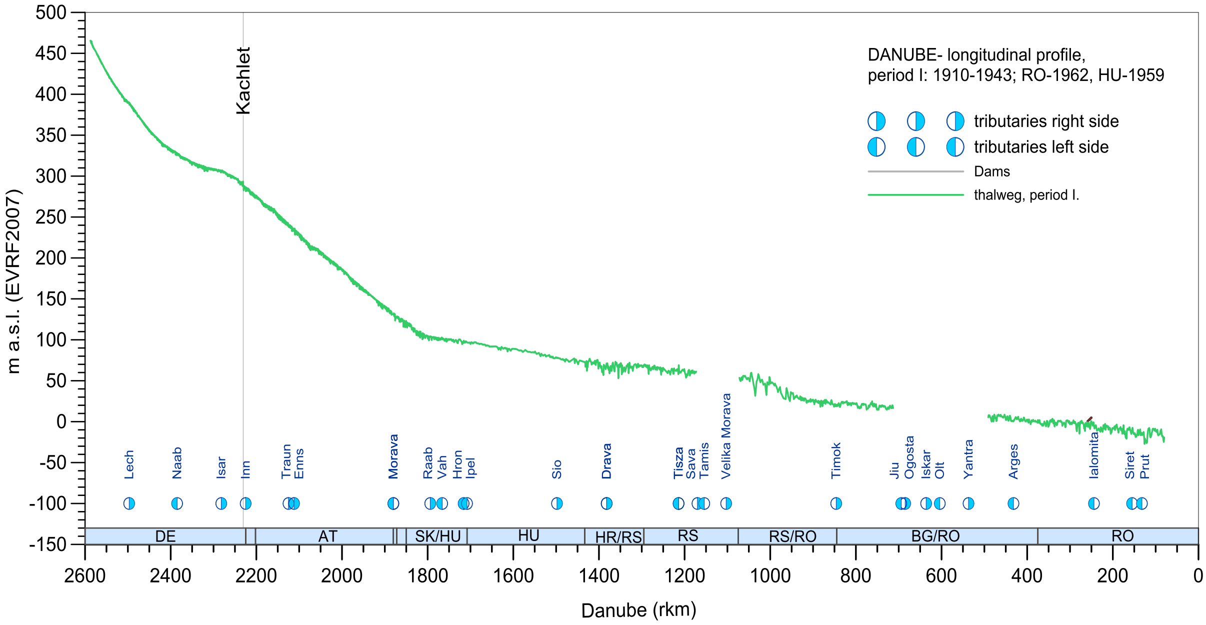


Figure 5.2.5 Longitudinal profile of the Danube (thalweg) for Period I (1910-1962), showing the Kachlet hydropower plant (rkm 2,230.51; built in 1927) and the tributaries

Owing to data availability, the long profiles are compiled from thalweg data only, so the analysis of river-bed changes indicates the main trends, rather than the results of a quantitative assessment.

All longitudinal profiles (along the thalweg with an average density of 2 km) for periods I, II and III are available in Annex 3 of Report "*Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube*".

Long-term and mid-term changes in the longitudinal profiles

THE ENTIRE DANUBE RIVER – in general

The longitudinal profile of the Danube for the first period was used for an analysis of the long-term (periods I–III) changes in the river bed (in the thalweg), generally along the entire Danube, as well as for its Upper, Middle and Lower sections. These changes show how the river bed responded to channel regulation (in the final phase) and to sediment continuity disruption caused by the gradual construction and operation of hydropower plants. Some specific local changes in the river-bed slope along the national river sections were identified and evaluated by comparing the present (Period III) and reference states (Period I).

A comparison of the Danube's longitudinal profiles along the river bed, representing the *'reference state'* and the present state is shown in Figure 5.2.6. The free-flowing stretches and selected tributaries are also depicted in this Figure. The calculated differences between the two longitudinal profiles illustrated in Figure 5.2.7 indicate the main trends in the long-term development of the river bed showing the stretches with prevailing erosion or sedimentation.

Figure 5.2.7 clearly indicates that, in long term, river-bed degradation (-3 m on average) prevails along the entire Danube.

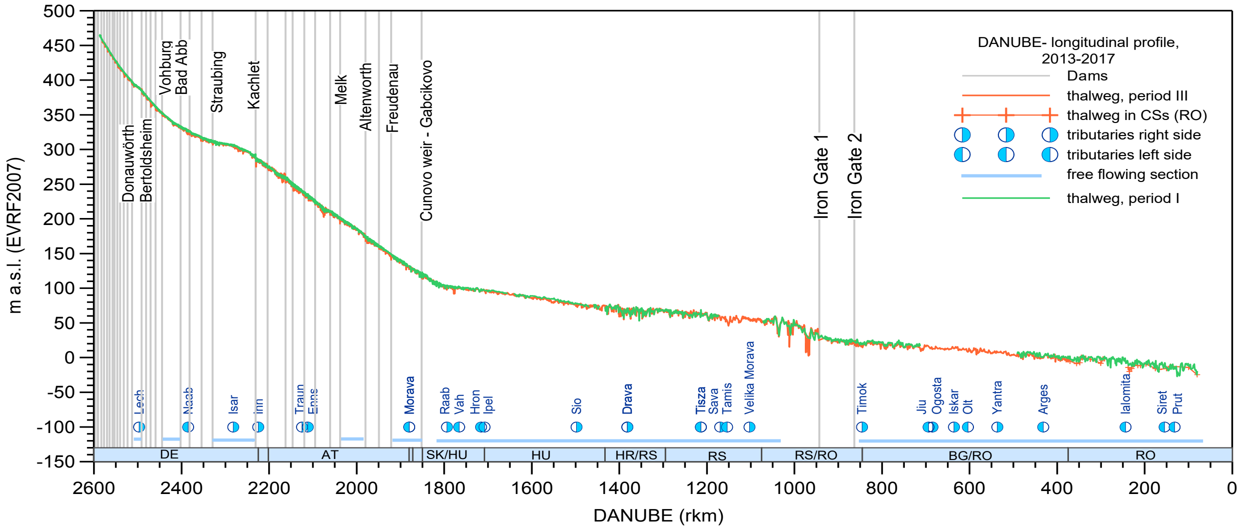


Figure 5.2.6 Comparison of the longitudinal profiles of the Danube (thalweg), for the *'reference state'* (Period I) and the present state (Period III)

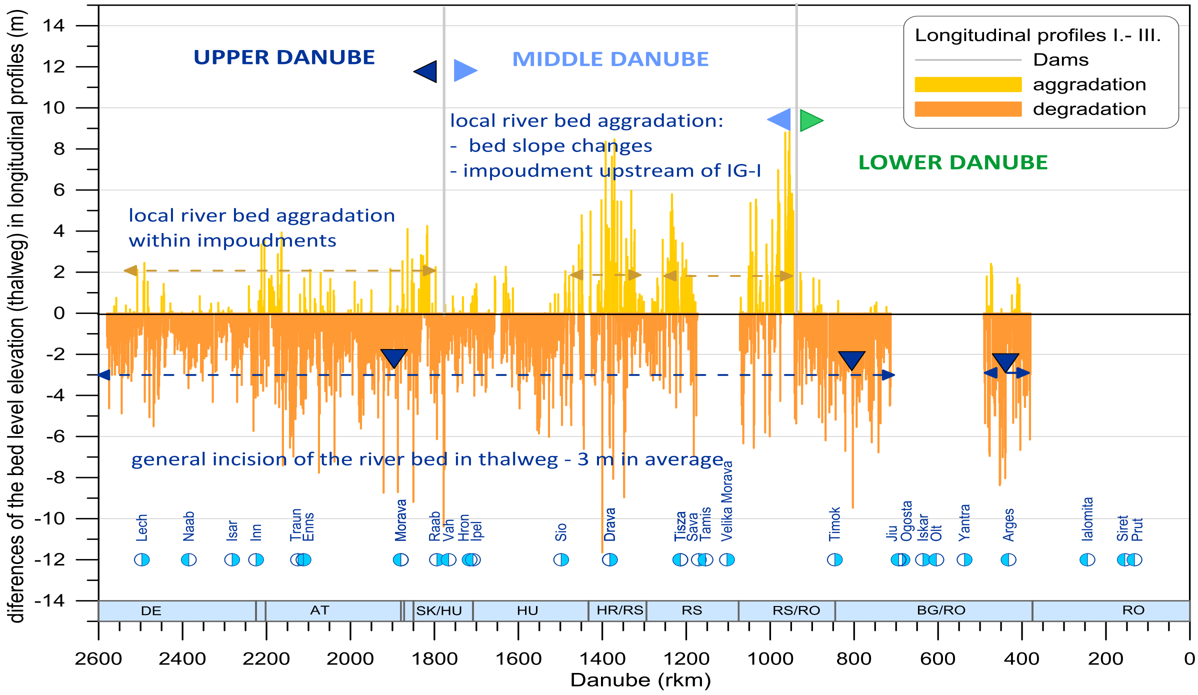


Figure 5.2.7 Differences in river-bed elevation (thalweg) in the longitudinal profiles of the Danube (periods I–III)

The river-bed degradation process was induced by the final phase of river channel regulation for low water levels (groyne fields, closure of side arms), by excessive commercial dredging, and by the gradual construction of hydropower plants. There was intense sediment deposition in impounded river stretches, reservoirs (Gabčíkovo and Iron Gate I), and in areas of major changes of the river-bed slope (in the transitional stretch between the Upper Danube and the Middle Danube at around rkm 1,790 and in the Middle Danube stretch upstream of Novi Sad). Mid-term changes in the river bed shown in Figure 5.2.8 (periods II–III) indicate that the erosion and deposition processes continued, though with lower intensity.

This period (the last ~ 50 years) represents the situation when the last hydropower plants were already in operation, creating new base levels. Thus, the position of the long profile was principally fixed and morphological changes in the longitudinal profile could occur only in the free-flowing or impounded river stretches between the hydropower plants. Disrupted sediment continuity caused local changes in the river-bed slope in areas exposed to erosion or sedimentation. The impact of river-bed aggradation/degradation on the river-bed slope is described in more detail in the chapters on the Upper, Middle and Lower Danube.

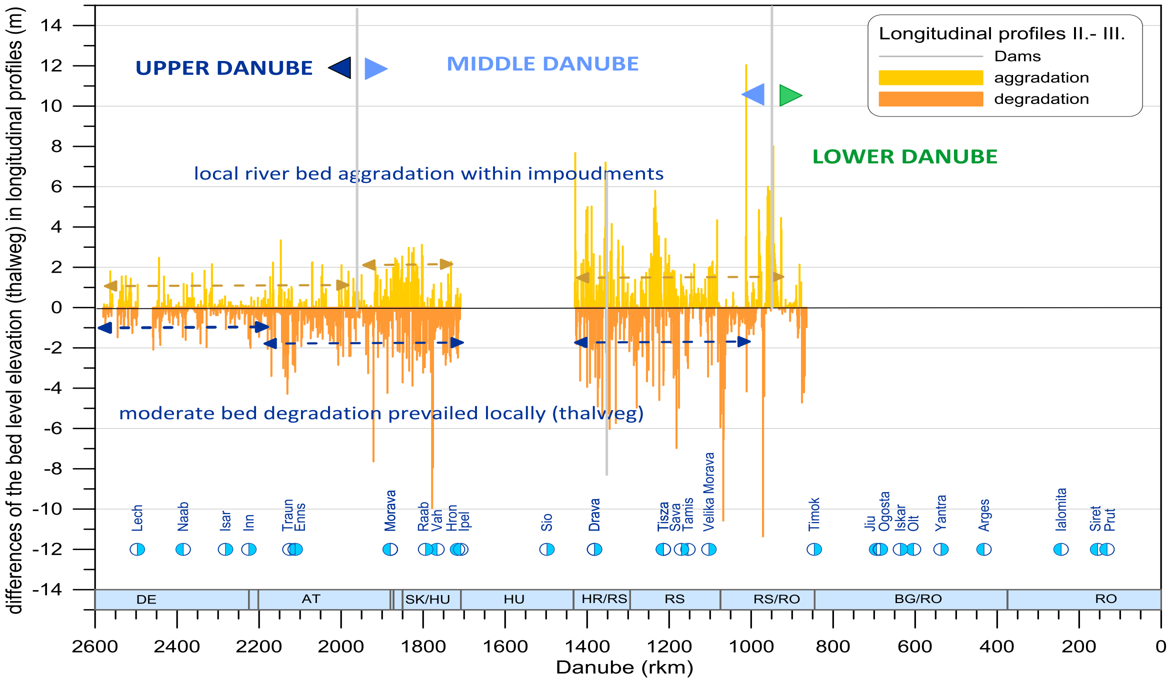


Figure 5.2.8 Differences in river-bed elevation (thalweg) in the longitudinal profiles of the Danube (periods I-III)

UPPER DANUBE

General information: The river in its upper section has a steep gradient, a narrow channel and usually flows through a V-shaped valley. The river bed consists of coarse sediments – boulders, rocks and gravel. When a river runs over alternating layers of hard and soft sediments, the prevailing vertical erosion process produces typical features, such as interlocking spurs, rapids, gorges and waterfalls. More resistant bottom rocks in vertical sequence create natural base levels, which control the thickness of erodible layers and the development of the river's longitudinal profile (including its shape) under natural conditions. Barriers built across the river channel (weirs, dams, barrages) have a similar impact on the river's long profile as they create new artificial local base levels.

The Danube River, which has its source in the Black Forest (Germany) at rkm 2,850, flows through a short narrow valley into a wide floodplain near Wolterdingen. Further downstream, the Upper Danube alternately flows in break-through stretches (narrow incised valleys – in a confined channel) and across relatively wide floodplains (in an unconfined channel – meandering, sinuous, anabranching channel).

The Upper Danube flows across Germany, Austria, Slovakia and Hungary. As the river section under investigation begins approximately 200 km downstream of the Danube's source, the beginning of the longitudinal profile of the Upper Danube is located near the city of Ulm (rkm 2,588), which is on the border between the federal states of Baden-Württemberg and Bavaria. Based on a morphological analysis, the end of the Upper Danube has been newly fixed (see Report 4.1, Chapter 2.1, figures 2.3 and 2.6) near the villages of Gönyű (HU) and Kližská Nemá (SK) at rkm 1,790.

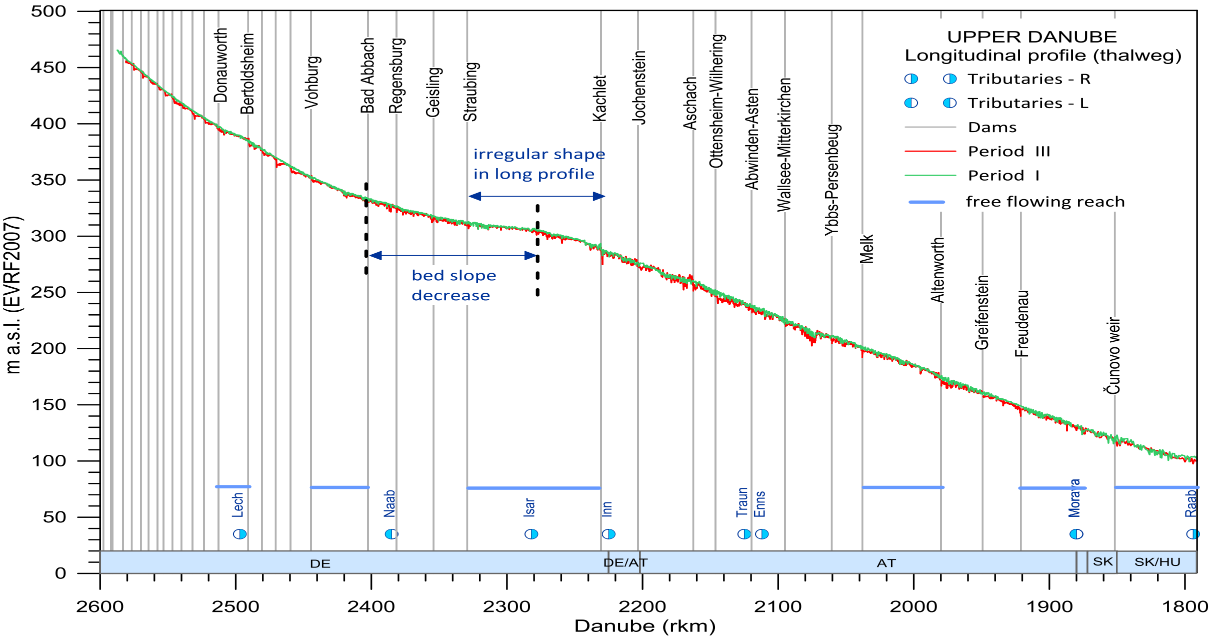


Figure 5.2.9 Comparison of the longitudinal profiles (thalweg) of the Upper Danube for Period I (1929/1943) and Period III (2010)

One of the two irregularities in the Danube's long profile is in its upper section between Straubing and Passau (Figure 5.2.9); the other can be seen in the Iron Gate gorge where a major change in the river-bed slope creates a *kickpoint*. The steep gradient of the Danube (~ 0.86‰) between Ulm and Donauworth (rkm 2,588 – rkm 2,510) changes into a moderate gradient (~ 0.53‰), which gradually decreases down to 0.35‰ – 0.11‰ between Bad Abbach (~ rkm 2,400) and Degandorf (rkm 2,280). This low-gradient river stretch is bounded by high-gradient river stretches. The geological conditions and large amounts of coarse sediments transported from the Alpine tributaries (particularly from the Isar River – rkm 2,282) contributed to formation of an untypical concave-shaped longitudinal profile. The irregularly shaped part of the long profile is between Straubing and Passau (rkm 2,330 – rkm 2,230), where the lower slope is changing back to a steep slope. The changes in the river-bed slope are also reflected in the different channel pattern (reference conditions). A more variable channel pattern can be seen in the river stretch with a low-gradient channel running across a wide floodplain (meandering, local braiding and anabranching channel pattern), in contrast with a high-gradient, break-through stretch with an incised straight/sinuous channel. This irregularly shaped longitudinal profile has remained unchanged since 1927 as it can be seen in Figure 5.2.9.

The longitudinal profile of the Danube in Austria (1929) is fairly uniform without continuous slope reduction (Figure 5.2.9, Table 5.2.3). This is due to the geomorphological conditions, which are described in more detail in Chapter 5.1 (Austrian Danube, BOKU). From the geomorphological point of view, the Danube in Austria is characterised by the alternation of break-through sections with a straight/sinuous river channel and sections in wider floodplains with an anabranching channel. However, the differences in channel pattern are not reflected in the river-bed slope changes owing to the geomorphological conditions. The Danube’s gradient decreases slightly, from 0.41‰ to 0.34‰ in the Slovak and Slovak-Hungarian river sections.

A comparison of the long profiles compiled for periods I and III (Figure 5.2.9) indicates that the overall shape of the Upper Danube’s longitudinal profile remained broadly unchanged. Apart from the geomorphological conditions, the construction of a chain of hydropower plants, which created new local base levels on the Upper Danube, contributed to the long-term ‘stability’ of the river’s long profile (1910 – 2017). The river-bed slope has changed locally in the river stretches between the HPPs, as well as in the free-flowing stretches downstream of the HPPs (e.g. Gabčíkovo). These local changes in the river-bed slope led to the fragmentation of the long profile in a smaller scale, producing a ‘*stepped-shaped*’ long profile in the Upper Danube section (see figures 5.2.12 – 5.2.15).

A comparison of the long profiles (periods I and III) illustrated in Figure 5.2.10 indicates the main trends in the erosion/sedimentation processes. The results, which represent the river-bed changes in the thalweg, clearly indicate the processes of river-bed degradation that prevail along the entire Upper Danube in the long term. The average river-bed degradation in the Danube channel reached -2 m in Germany and -3 m in Austria, Slovakia and Hungary. The local areas of aggradation shown in Figure 5.2.10 only partially reflected the ongoing sedimentation processes in impounded river stretches. Thalweg data represent the deepest points in the river channel, but sediment deposits within impoundments are located along the sides of the navigational channel, so thalweg data cannot document the sedimentation processes properly.

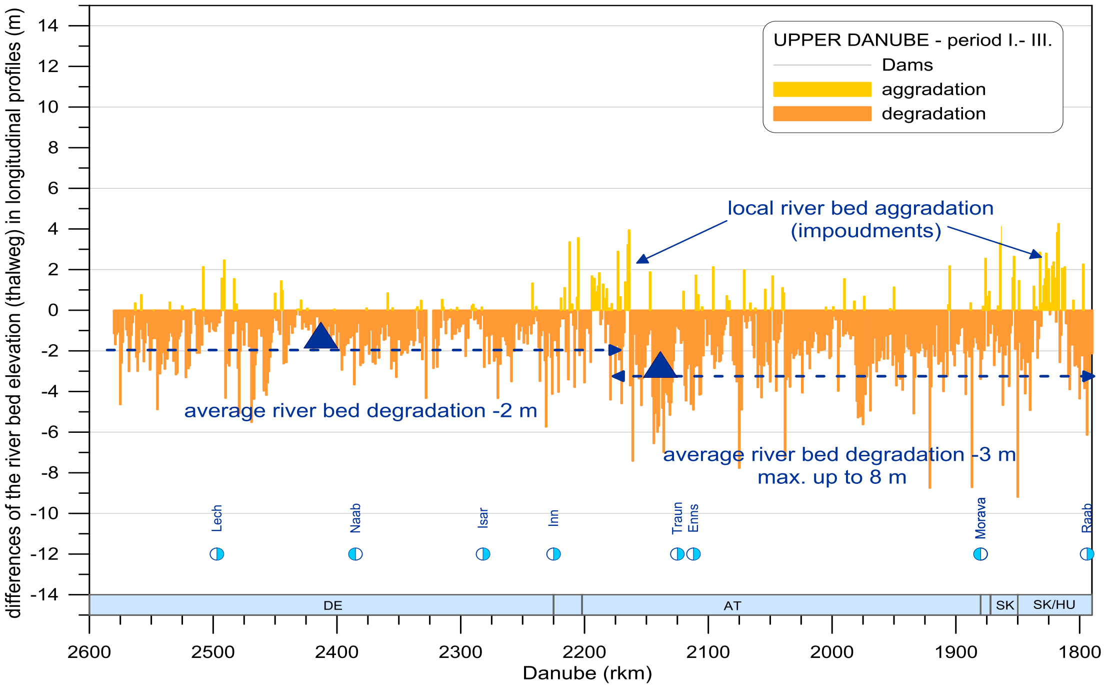


Figure 5.2.10 Differences in river bed elevation (thalweg) in the longitudinal profiles of the Upper Danube (periods I–III)

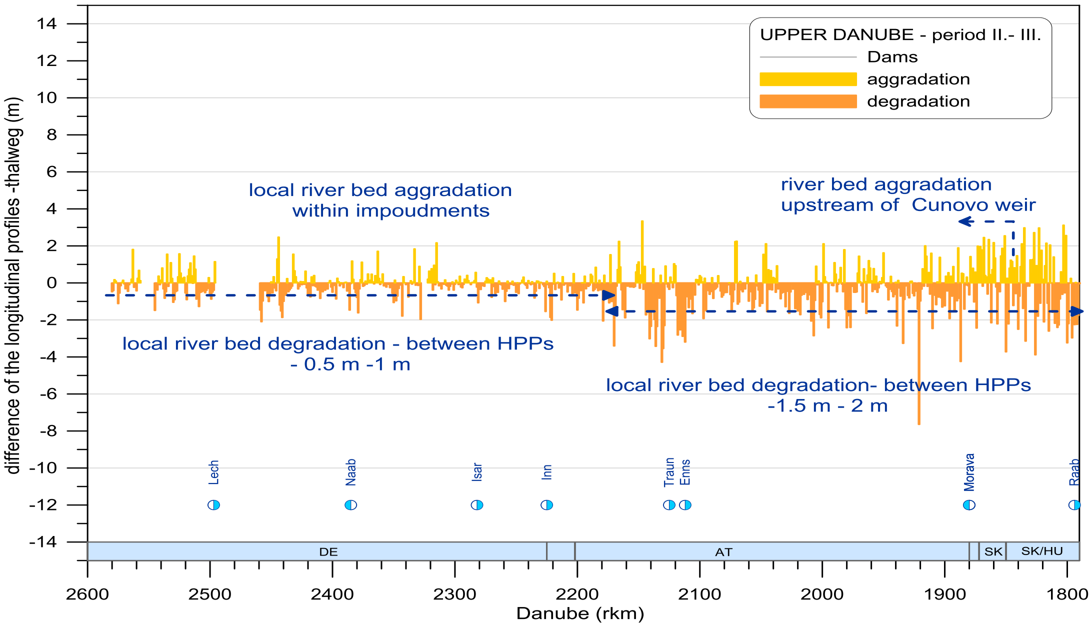


Figure 5.2.11 Differences in river bed elevation (thalweg) in the longitudinal profiles of the Upper Danube (periods II–III)

Mid-term changes in the Upper Danube’s longitudinal profile are shown in Figure 5.2.11. The erosion and sedimentation processes are similar but weaker than those causing long-term changes (Figure 5.2.10). Average river-bed degradation along the Danube reached less than -0.5 m in Germany and -1.5 m in Austria, Slovakia and Hungary. River-bed aggradation is more evident within impoundments, particularly in the stretch upstream of the Čunovo weir (Gabčíkovo HPP).

An analysis of the morphological development of the Upper Danube as reflected in its long profile indicates that the river-bed degradation processes were more intensive during the first and second periods (1910–1990). The moderate river-bed erosion continued in the next period (1990–2017) and sediment deposition within impoundments was more evident.

Local changes in the longitudinal profiles

A comparison of the Upper Danube's long profiles compiled for periods I and III illustrates the local changes in the river-bed slope along the national river sections (see figures 5.2.12 – 5.2.16). A slope reduction has been caused by river-bed degradation downstream of hydropower plants owing to a lack of sediments, and/or by tail impoundment dredging upstream of HPPs for maintaining optimal hydropower production. The range of changes is variable and depends on the specific morphological conditions and technical parameters of each HPP. More details can be found in Chapter 5.1 (5.1.1 Germany).

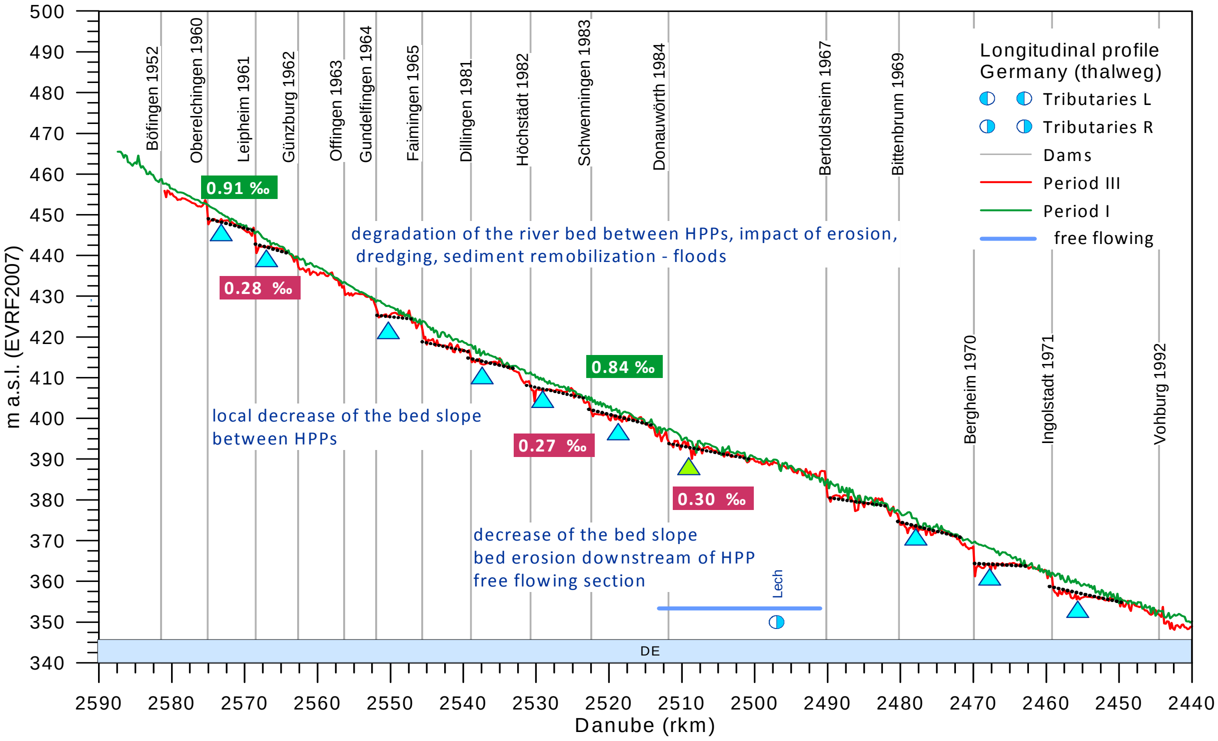


Figure 5.2.12 Comparison of the longitudinal profiles (thalweg) of the Upper Danube in Germany for periods I–III (rkm 2,588–2,450), showing the slope changes in impounded and free-flowing stretches

River-bed slope changes in particular stretches between hydropower plants and in free-flowing stretches of the German Danube are shown in figures 5.2.12 and 5.2.13. A comparison of thalweg data from periods I and III indicates that major differences in slope were identified in the upper stretch between rkm 2,588 and rkm 2,440 (Figure 5.2.12), where the river has a steep gradient. Slope change extension is variable, but in some cases (shorter distances between HPPs) the entire stretch between HPPs is affected.

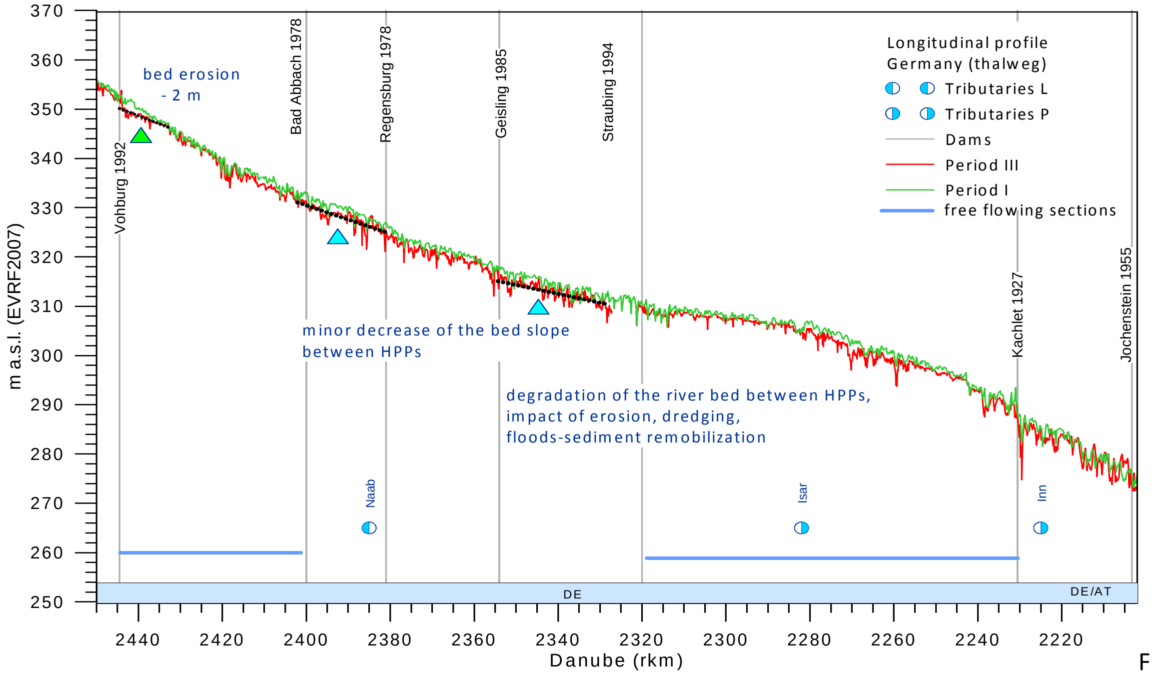


Figure 5.2.13 Comparison of the longitudinal profiles (thalweg) of the Upper Danube in Germany for periods I–III (rkm 2,450–2,220), showing the slope changes in impounded and free-flowing stretches

The current river-bed slope is very low compared with the original conditions (1927/1943). In some cases, the river bed is almost horizontal, e.g. between Gundelfingen and Faimingen (rkm 2,551.95 – 2,545.63) or Breghaim and Ingolstat (rkm 2,469.9 – 2,459.19). The most intense river-bed deepening occurs in areas just downstream of HPPs, where the largest differences are recorded in the thalweg (up to -5 m). These river-bed changes, caused mostly by maintenance dredging, have produced a *’stepped shaped’* longitudinal profile, which can also be seen in the Austrian section of the Danube (see figures 5.2.15 and 5.2.16). The differences in the thalweg slope range from 0.54 ‰ to 0.68 ‰ in the German section of the Danube upstream of Vohburg (rkm 2,445). The bed slope changes are smaller in the river stretch downstream of Vohburg (Figure 5.2.13), which includes two of the three free-flowing stretches of the Danube in Germany.

The river-bed slope decreases to a lesser extent in the free-flowing stretches, because the river bed is affected by erosion only (dredging works have been discontinued – at least in areas downstream of HPPs). However, river-bed degradation in the thalweg reaches a maximum of 2 – 2.5 m, which reduces the downstream distances in free-flowing stretches.

Similar river-bed slope decreases between HPPs can be observed in the Austrian section of the Danube (see figures 5.2.14 and 5.2.15). Slope differences in the thalweg range from 0.12‰ to 0.20‰ in impounded river stretches, and from 0.07‰ to 0.13‰ in free-flowing stretches. River-bed deepening in the thalweg reaches a maximum of 6 – 8 m in impounded river stretches. In this case, river-bed incision is caused mostly by dredging. Bed erosion downstream of the free-flowing sections reaches a maximum of 2.5 – 3 m in the thalweg.

More details about the morphological development of the Danube in Austria can be found in Chapter 5.1 (5.1.2 Austria).

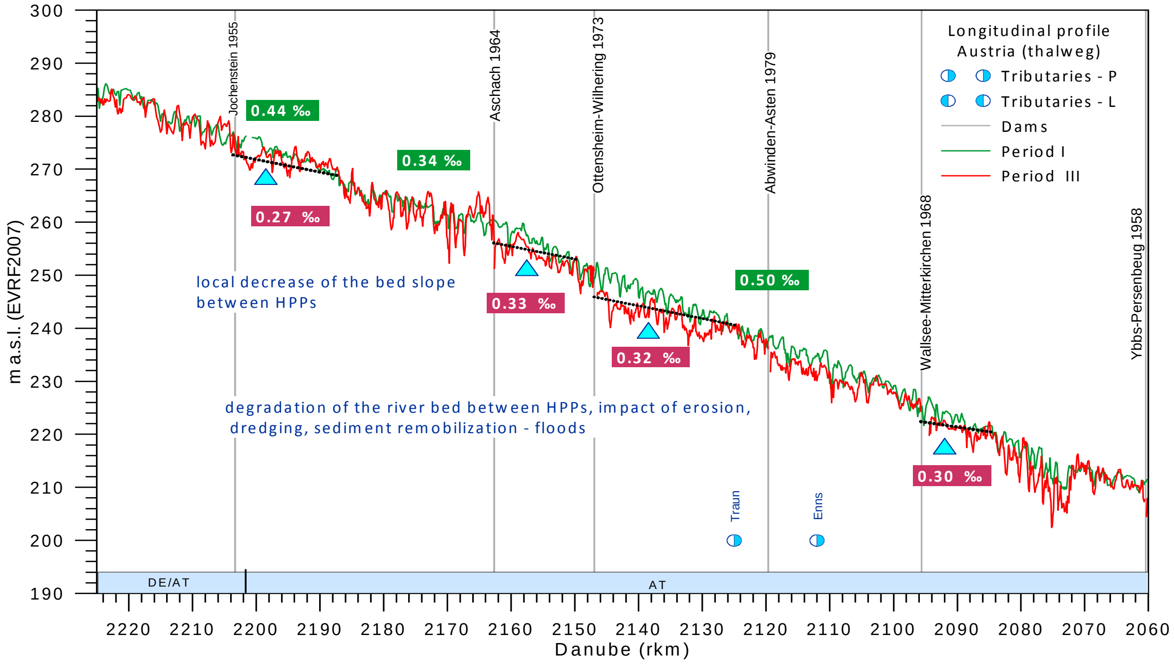


Figure 5.2.14 Comparison of the longitudinal profiles (thalweg) of the Upper Danube in Austria for periods I–III (rkm 2,200–2,060), showing the slope changes in impounded river stretches

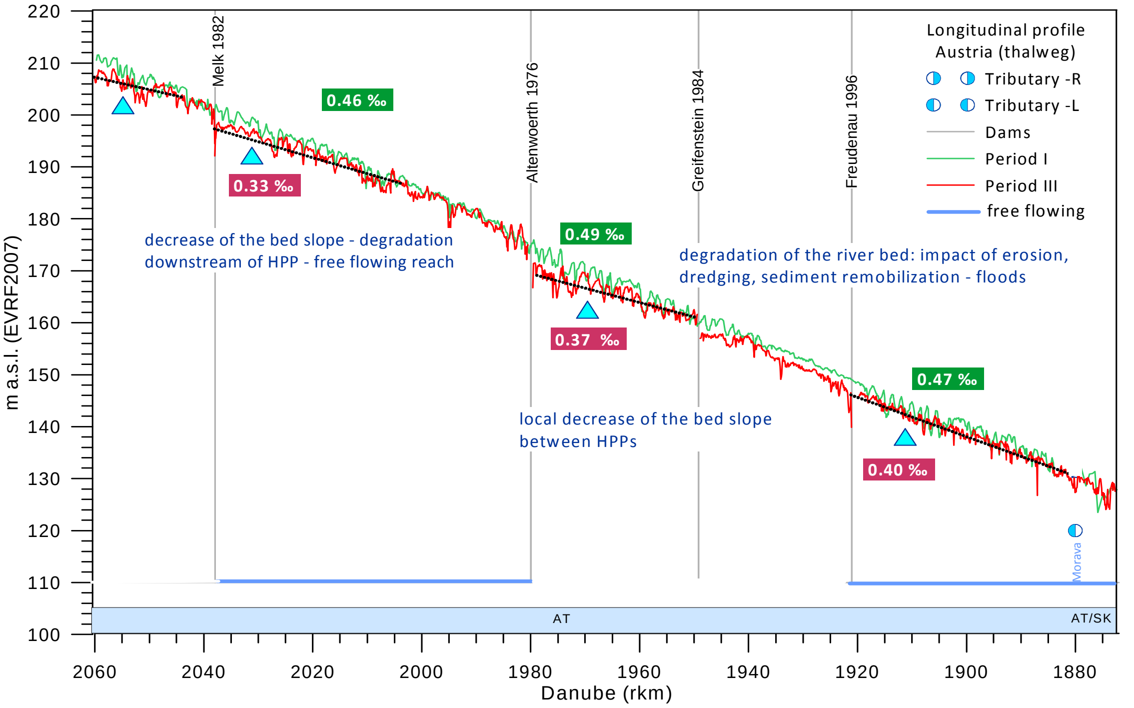


Figure 5.2.15 Comparison of the longitudinal profiles (thalweg) of the Upper Danube in Austria for periods I–III (rkm 2,060–1,880), showing the slope changes in impounded and free-flowing stretches

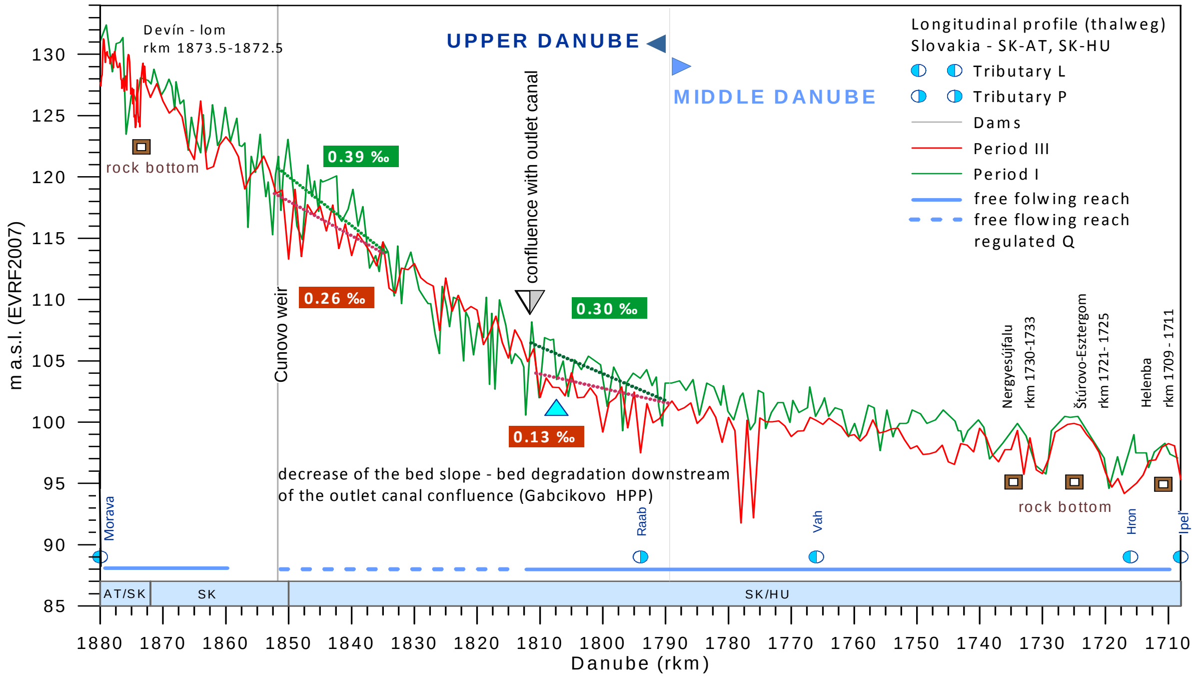


Figure 5.2.16 Comparison of the longitudinal profiles (thalweg) of the Upper Danube in Slovakia (stretches SK-AT, SK, SK-HU) between rkm 1,880 and rkm 1,710, periods I–III

There is a slightly different situation in the Slovak–Hungarian river stretch downstream of the Gabčíkovo hydropower plant, because this HPP is located on a by-pass canal. However, the impact of sediment continuity disruption on river-bed changes (slope and elevation) is similar. River-bed degradation downstream of the confluence of the outlet canal and the Old Danube (rkm 1,810) reaches -5 metres on average, but the maximum changes in the thalweg reached -10 m as it can be seen in Figure 5.2.17 (more details in Chapter 5.1/5.1.3 Slovakia).

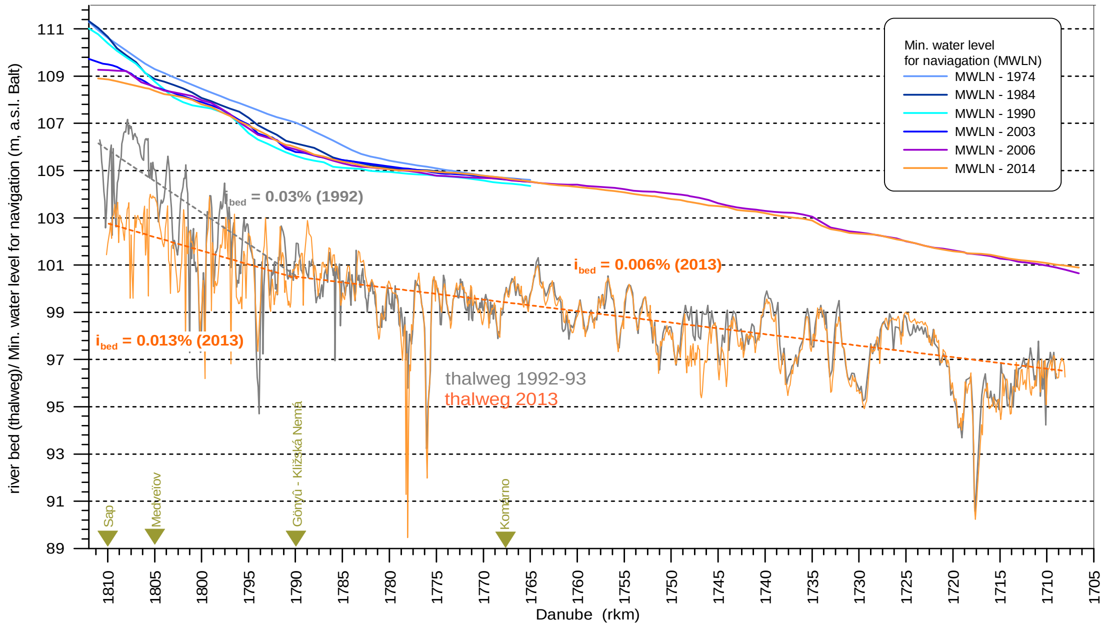


Figure 5.2.17 Changes in the minimum water level for navigation (LNWL) and in the river-bed slope along the Slovak-Hungarian Danube downstream of the Gabčíkovo HPP (rkm 1810 – 1710) over Period III

The erosion processes have affected the river bed along the free-flowing section between rkm 1,810 and rkm 1,790. The bed slope has changed from 0.30‰ (1992) to 0.13‰ (2013) in this river stretch. The modified bed slope converges to the low bed gradient of the Middle Danube downstream of Kližská Nemá – Gönyű (rkm 1,790), causing problems for navigation. Sediment continuity disruption has a similar effect on the river-bed slope in the area downstream of the Čunovo weir (Figure 5.2.16).

Intense river-bed degradation caused a significant decrease (up to 2 m) in the minimum water level for navigation (LNWL) over the period from 1990 to 2014 (see Figure 5.2.17).

MIDDLE DANUBE

General information: The middle section of the Danube has a wider channel and the sides of the valley have a gentler slope. The velocity is slower than in the upper section, because the river-bed gradient is lower. However, the channel is wider and deeper as the volume of water is increased by inflows from the tributaries. The middle section of the river has higher flow dynamics and discharges than the upper section. The gradient is gentler and lateral erosion results in channel widening. Meanders and side arms are typical landforms in this section of the river.

The Middle Danube begins in the Slovak-Hungarian section (at rkm 1,790) near the villages of Kližská Nemá and Gönyű, and ends at the Iron Gate 1 dam (rkm 943). It flows across Slovakia, Hungary, Croatia, Serbia and Romania. The longitudinal profiles (along the thalweg) of the Middle Danube for periods I and III are shown in Figure 5.2.18.

The free-flowing stretch of the Middle Danube is located between Gönyű (rkm 1,720) and Novi Sad (rkm 1,250). The next river stretch is affected by a slight impoundment between rkm 1,250 and rkm 1,050. Downstream of rkm 1,050, a strong impoundment from the Iron Gate 1 dam (reservoir) influences the river processes.

The river-bed slope is fairly uniform between rkm 1,790 and rkm 1,450, with an average value of ~ 0.07‰. Further downstream at around rkm 1,400, the river-bed slope decreases to 0.04‰, causing sediment deposition both upstream and downstream. This was one of the reasons for the commencement of extensive dredging, which has been reduced during the last decades.

Over the last centuries, the rock bottom of the Iron Gate gorge (rkm 1,050 – rkm 943), resistant to fluvial erosion, has formed a natural local base level (later – artificial base level after the Iron Gate I dam was built) and a kickpoint joint with a sharp change in the river-bed slope. The slope has changed from 0.05‰ upstream of the gorge to 0.28‰ within the gorge. The rock bottom of the Iron Gate gorge maintains the shape of the longitudinal profile of the Middle Danube.

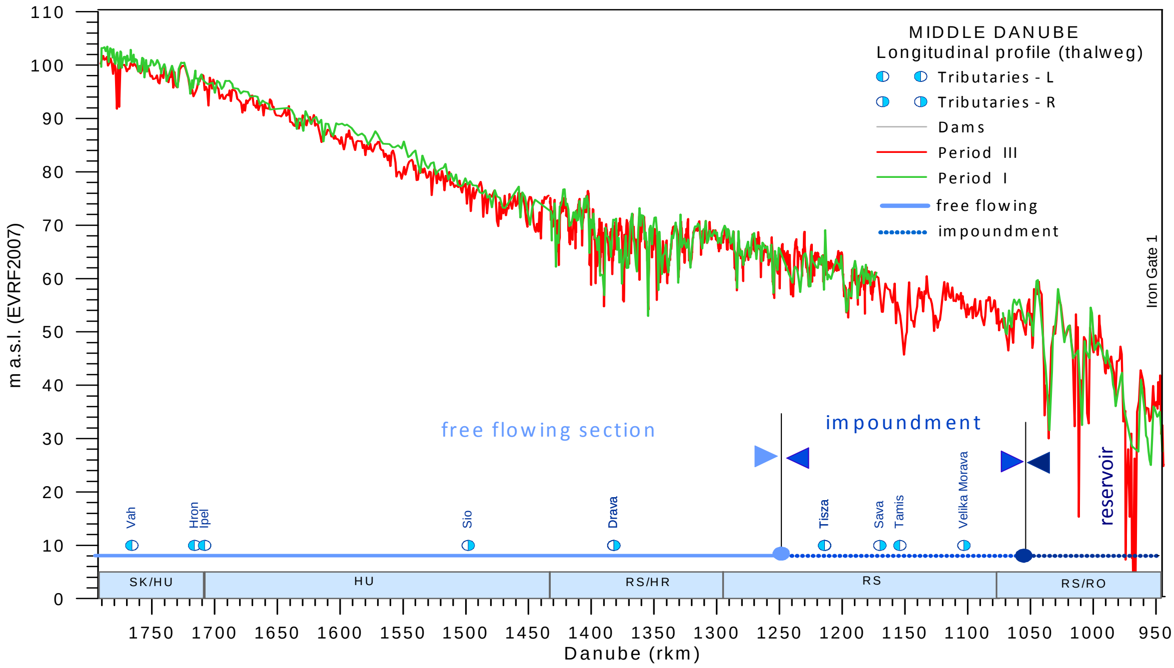


Figure 5.2.18 Longitudinal profiles of the Middle Danube along the thalweg (periods I and III)

The trends in the long-term and mid-term development of the Danube's river bed within its middle section were evaluated on the basis of a comparison of the river's long profiles from periods I, II and III (see figures 5.2.9 and 5.2.20).

As Figure 5.2.19 shows, river-bed degradation prevails in the upper part of the Middle Danube between rkm 1,790 and rkm 1,450, where the depth of thalweg incision varies from -2 m to -3 m on average and reaches a maximum of -6 m (locally -10 m). Sedimentation areas are very rare and are scattered along this river stretch. However, sediment deposition can be observed downstream of rkm 1,450. Sedimentation processes are caused by various factors.

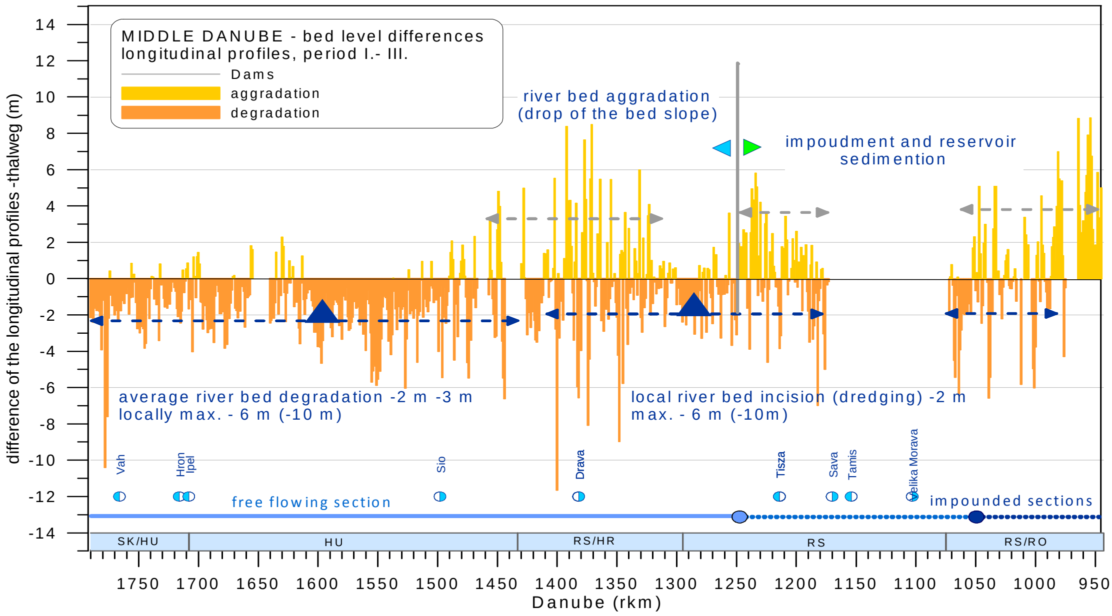


Figure 5.2.19 Differences in the longitudinal profiles (thalweg) of the Middle Danube (periods I and III)

One of them is the aforementioned natural change in the bed slope (from 0.07‰ to 0.04‰). Thus, river-bed aggradation between rkm 1,450 and Novi Sad (rkm 1,250) prevails in the long term, though degradation also occurs in this river stretch (thalweg -2m on average). This river-bed incision, caused probably by extensive dredging, was also supported by a sediment deficit (from the upstream stretch and from tributaries). Sedimentation in the neighbouring river stretch (rkm 1,250 – rkm 943) was caused by sediment continuity disruption at the Iron Gate I dam. Moderate sedimentation was observed in the river stretch between Novi Sad (rkm 1,250) and Moldova Veche (rkm 1,050).

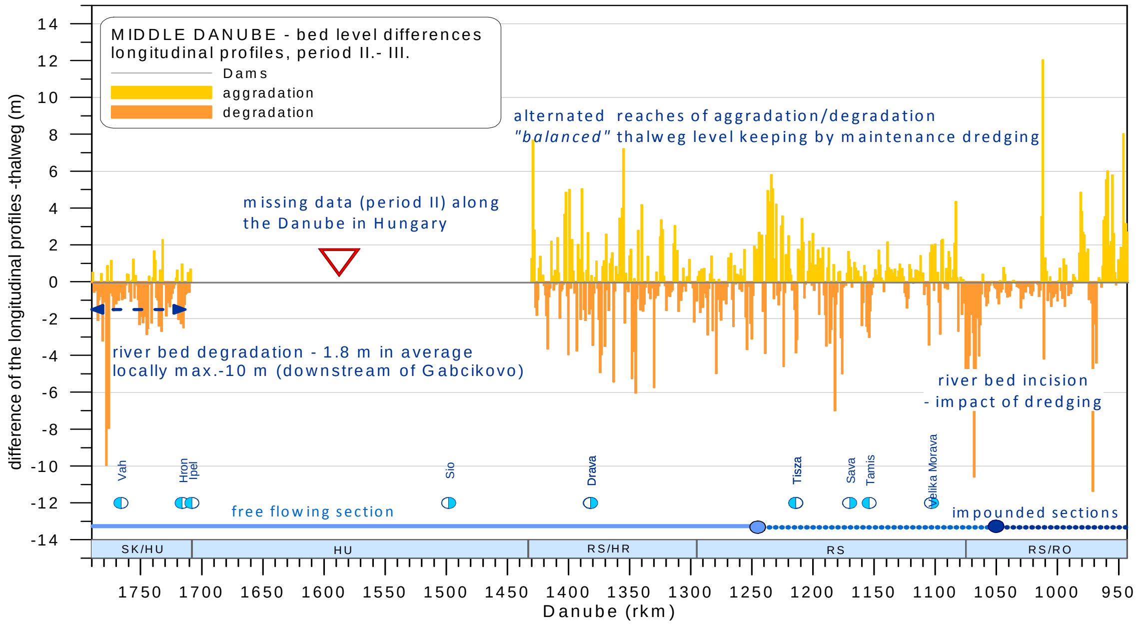


Figure 5.2.20 Differences in the longitudinal profiles (thalweg) of the Middle Danube (periods II and III)

The mid-term changes in the river bed (thalweg) shown in Figure 5.2.20 could be evaluated only in a short river stretch between rkm 170 and rkm 1,708, and then in the Serbian and Romanian river sections downstream of rkm 1,430. The section in Hungary (rkm 1,708 – rkm 1,430) could not be evaluated owing to missing data from Period II. The results illustrated in Figure 5.2.20 show similar trends in the spatial distribution of erosion and sedimentation processes and in their intensity. River-bed degradation processes are induced by sediment deficits and dredging activities. Aggradation is caused by a decrease in the river-bed slope and by the impoundment from the Iron Gate I dam.

The sediment budget and flow conditions, which determine the channel form, including the longitudinal profile of the Middle Danube along the river bed, is affected by:

- the disrupted sediment continuity at the lower end of the Middle Danube (Iron Gate I);
- the deficit in sediment transport from upstream (HPPs on the Upper Danube) and from the tributaries (damming);
- extensive sediment dredging from the river bed;
- river training works (channel regulation for low flows).

The changes in the river-bed slope of the Middle Danube are less evident than those observed in the Upper Danube as the bed slope is considerably lower. The river within a 540 km-long free-flowing section (rkm 1790 – rkm 1250) was affected mainly by bed sediment dredging and river training works. The deficit in sediment transport from upstream (Upper Danube) and from the tributaries also contributed to river-bed degradation. A comparison of the longitudinal profiles form periods I (1959) and III (2016) along the Danube in Hungary (Figure 5.2.21) indicates to what extent the bed level and bed slope have changed. In the long term, river-bed degradation prevails along the 220 km-long section of the Danube in Hungary (from rkm 1,700 to rkm 1,480). This bed incision was caused mostly by extensive dredging – the amounts of extracted sediments highly exceeded the local transport capacity of the Danube, and were concentrated in relatively short river stretches (more details are available in Chapter 5.1/5.1.4 Hungary). The concentrated dredging have induced river-bed degradation both upstream and downstream, varying from 1 m to 6 m.

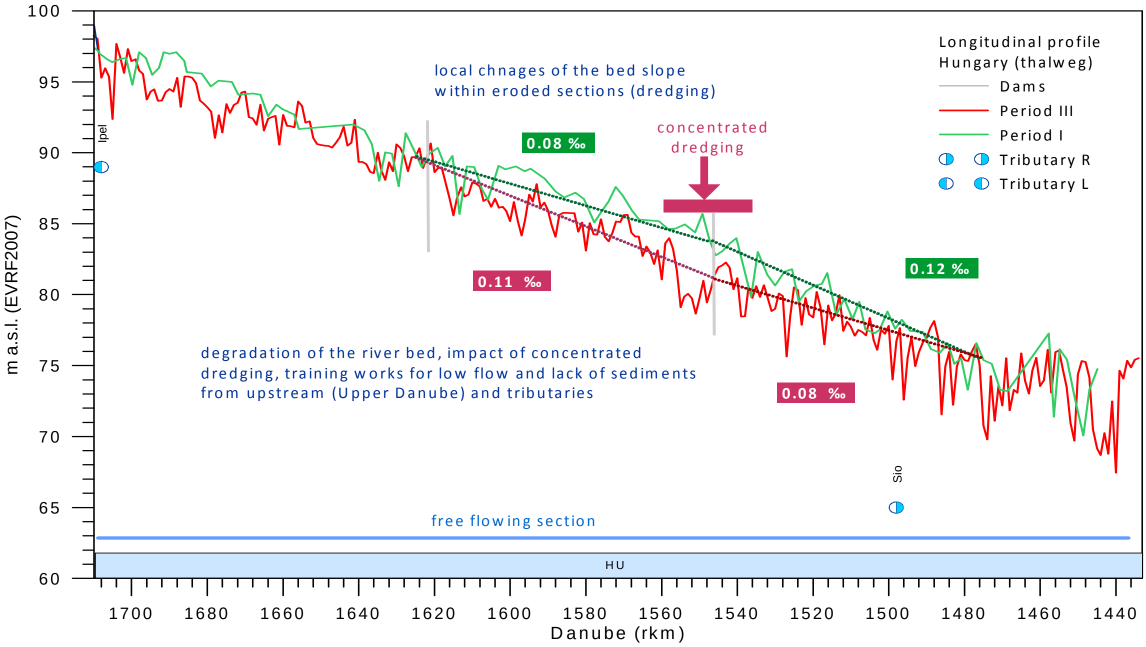


Figure 5.2.21 Comparison of the longitudinal profiles (thalweg) of the Middle Danube in Hungary between rkm 1,710 and rkm 1,430 (periods I – III)

The river-bed erosion processes caused local changes in the slope of the river bed, i.e. increases or decreases as it can be seen in Figure 5.2.21. Further downstream, where the erosion and deposition processes are more balanced, only minor river-bed changes were observed.

The longitudinal profiles shown in Figure 5.2.22, illustrating the long-term development of the river bed along the lower part of the Middle Danube (HR, RS, RO), indicate that only minor changes have occurred in the river bed. The alternating erosion and sedimentation processes have made the free-flowing river stretches more balanced than could be expected, but this equilibrium is merely apparent. The river bed around rkm 1,400 is naturally influenced by sedimentation in response to a decrease in the bed slope as it is mentioned above.

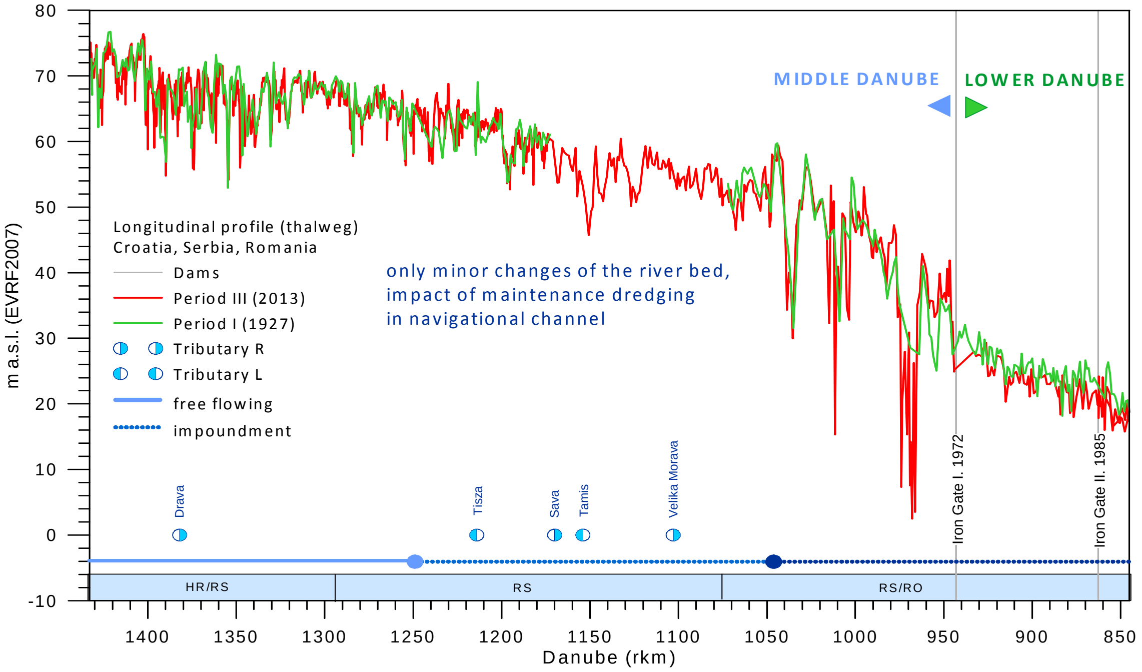


Figure 5.2.22 Comparison of the longitudinal profiles (thalweg) of the Middle Danube in Serbia, Croatia and Romania, from rkm 1,710 to rkm 1,430 (periods I – III)

The river stretch downstream (rkm 1,250 – rkm 1,050) is also affected by sedimentation, which is induced here by lower impoundment from the Iron Gate I dam. Therefore, the river-bed level in both river stretches exposed to sedimentation (rkm 1,430 – rkm 1,050) was maintained by permanent dredging performed to preserve the river's primary functions (navigation, flood protection). The prevailing sedimentation processes cannot be properly documented by thalweg data as thalweg represents the deepest points in the navigational channel and sedimentation takes place along the sides of the navigational channel.

As the river bed is maintained in a balanced state by dredging, no bed slope changes occurred in this section of the Middle Danube. More details about the morphological development of the Danube in Serbia can be found in Chapter 5.1 (5.1.6 – Serbia).

LOWER DANUBE

General information: The lower course of the river has a very gentle slope (close to zero). The river channel is wider and deeper than in the sections upstream, because the volume of water flowing in the river is greater, too. The increased discharge can be attributed to the supply of water from the tributaries. The river channel is deep and wide and the land beside the river is predominantly flat. The energy of the river is lower and sedimentation processes prevail under natural conditions. Before entering the sea, the Danube splits into several smaller rivers to form a delta, where the sedimentation processes are more dominant than erosive power of the sea.

The Lower Danube begins downstream of the Iron Gate II dam, at ~ rkm 862, and flows across Serbia, Bulgaria and Romania. The Danube Delta was not included the morphological analysis, so the lower section ends at rkm 80 (the beginning of the Delta).

The morphological development of the Lower Danube is affected by a deficit in sediment transport caused by the trapping effect of the Iron Gate reservoir. As the Danube channel has not been regulated systematically (only locally), the river may move laterally in response to river-bank erosion.

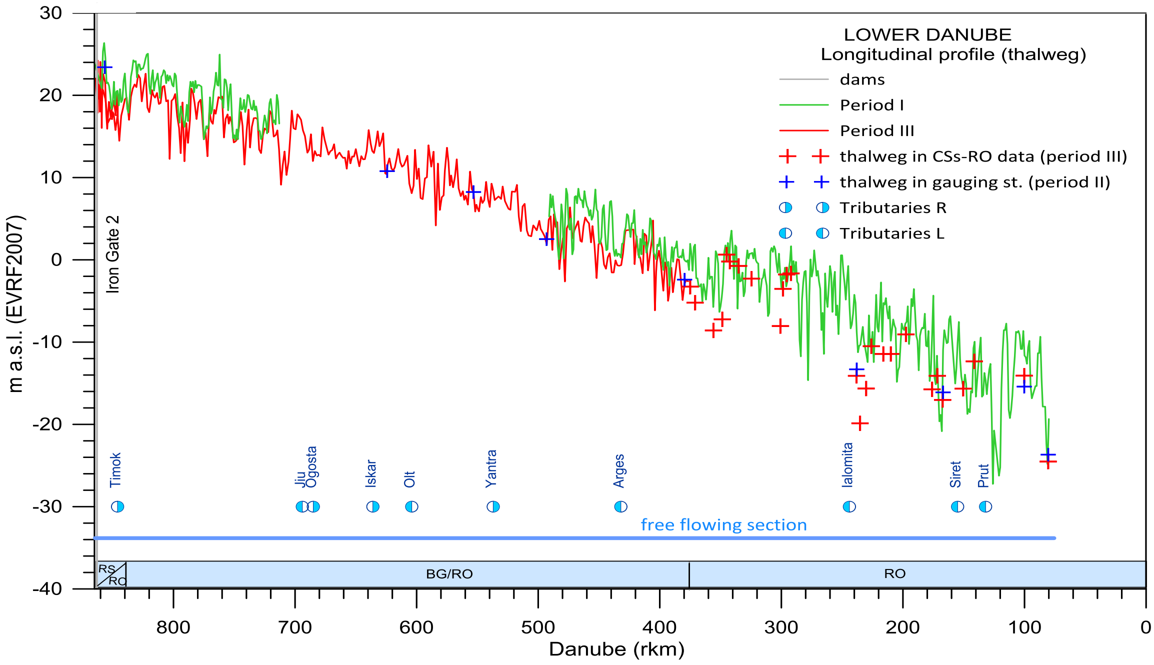


Figure 5.2.23 Longitudinal profiles of the Lower Danube (thalweg) and river-bed elevations from cross sections and from gauging station profiles (periods II,II, III)

The natural character of anabranching – a low-energy river channel has been preserved in numerous stretches of the Lower Danube. The disrupted sediment continuity and the resulting sediment deficit is considered to be the main pressure on the river. Moreover, river-bank erosion, which may have a major impact on the morphological development of the river channel, has not yet been observed. Hence, it is difficult or even impossible to identify the lateral and vertical processes. The longitudinal profiles of the Lower Danube for periods I, II and III are shown in Figure 5.2.23.

The data available and their quantity and quality did not allow a more detailed analysis of the river processes (for more details see Chapter 5.1/5.1.7 Romania). No data set covers the full length of the Lower Danube and, besides that, the data are from various sources. An analysis of the long-term development of the river's longitudinal profile is based on bathymetric data from 1962 (Period I), 2008 and 2017 (Period III), and on incomplete data from gauging stations.

A comparison of longitudinal profiles from periods I and III compiled for river stretches for which data are available shows a systematic decrease in the current river bed compared with the period (1962) before the Iron Gate dam was built (figures 5.2.23 and 5.2.24). River bed degradation has no major impact on the bed slope, which is fairly uniform along the delineated stretch of the Lower Danube (0.05‰ – 0.06‰ on average). Some local changes in the river-bed slope may occur in the area of extensive dredging (~ rkm 300 – rkm 100, see Chapter 5.1/5.1.7, Romania) as the data from cross sections and gauging stations indicate in Figure 5.2.23. However, this assumption cannot be proved owing to a lack of reliable bathymetric data (from CSs with a distance of less than 500 m between them).

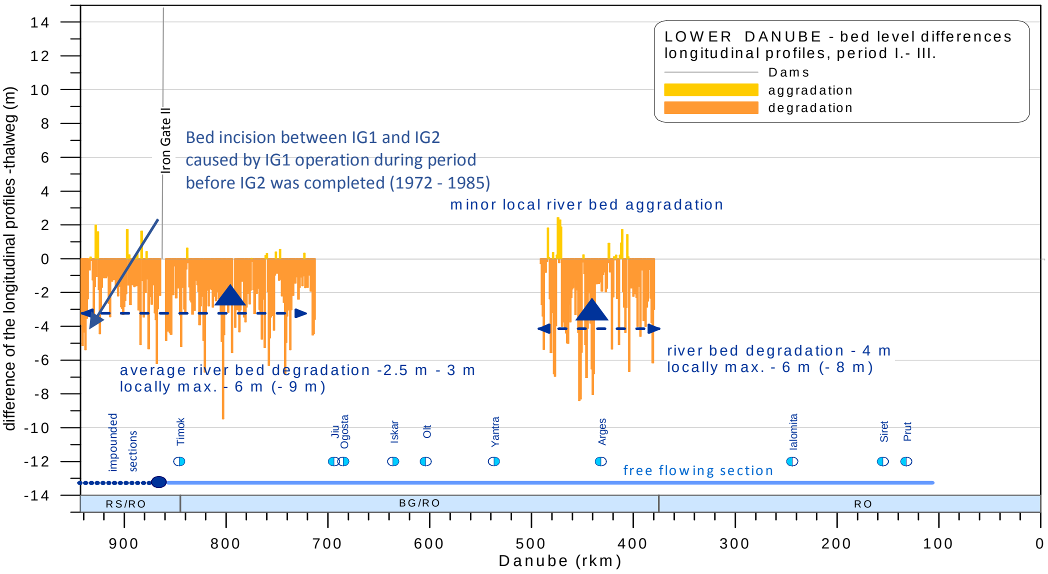


Figure 5.2.24 Differences in the longitudinal profiles (thalweg) of the Lower Danube (periods II – III)

River-bed degradation in the thalweg between the Iron Gate I and Iron Gate II dams (Figure 5.2.24) was caused by sediment continuity disruption at Iron Gate I during the period when Iron Gate II was built (1972–1985, 13 years). The maximum values of river bed incision were measured downstream of the Iron Gates between rkm 863 and rkm 700 where the thalweg decreased by -2.5 /-3.0 m on average (the maximum decrease was -6 m to - 9 m). The river-bed changes downstream between rkm 700 and rkm 490 (Figure 5.2.24) could not be evaluated, owing to the unavailability of data from that river stretch. However, based on the processes prevailing upstream and downstream of this stretch, we can assume that river-bed degradation is a long-term trend here. Even stronger river-bed degradation can be observed in the area between rkm 490 and rkm 390 (Figure 5.2.24) where the river bed has decreased to -4 m on average, with a local maximum of -8 m. It is obvious that the most intensive erosion processes prevailed in the river bed during the first decade after the Iron Gate I and II dams were put into operation.

A more thorough analysis of the present state of the Lower Danube's longitudinal profile, including an analysis of its response to the main hydromorphological pressures, will only be possible when complete bathymetric data are available. River-bank erosion as a process that has a major impact of the development of the river bed needs to be considered, too.

SUMMARY

This chapter provides new information about the long-term and mid-term development of the Danube's longitudinal profile along the river bed (thalweg) in response to sediment continuity disruption, low-flow river regulation and dredging.

The main results of this chapter can be summarized as follows:

- the data sets obtained from the project partners are not homogenous spatially and temporally, so the development of the river's longitudinal profile indicates the main trends, rather than enabling a quantitative assessment;
- the thalweg data were harmonised into a common vertical system, because the systems used by the Danubian countries are different;
- the longitudinal profiles of the Danube were compiled from thalweg data for three periods (I,II,III) defined for this project;
- the values of the river-bed slope of the Danube's longitudinal profile (present state) were evaluated and illustrated graphically with the corresponding low-flow water levels (LNWL);
- the hydropower plants built on the Danube have created new local base levels, which fix the overall position and shape of the longitudinal profile (thalweg) and reshape it in certain stretches, especially in the river's upper section *('stepped shape');*
- the disruption of sediment continuity by hydropower plants and river-bed dredging has a dominant effect on local bed slope changes; the river-bed slopes have lowered within impoundments between HPPs (along the Upper Danube) as a consequence of maintenance dredging (deposit removal, river-bed flattening); the river-bed slope also decreased in the free-flowing stretches downstream of HPPs, but the main reason is sediment deficit;
- the long-term development of the river bed, which covers almost 100 years (from 1920 to 2017) indicates that the degradation processes prevail and cause major river-bed degradation, which is evident along the entire Danube (3 m on average, with local values ranging from 6 m to a maximum of 10 m); the areas of sediment deposition are concentrated in localities where the river-bed slope changes naturally and within the impounded river stretches (upstream of HPPs on the Upper Danube) and reservoirs (Gabčíkovo, Iron Gate I and II);
- the mid-term development of the river bed, which covers a period of almost 50 years (from 1971 to 2017) indicates that the river-bed degradation processes continue, though with lower intensity and the areas of sediment deposition within impoundments are being promoted;
- the local changes in the river-bed slope are also connected with the areas of excessive bed sediment dredging where local bed slope increases/decreases occur (e.g. in Hungary).

5.3 Spatial and temporal variations in the grain size of river bed sediments

A study of the composition of river bed sediments usually focuses on gravel bed rivers, where the effects of morphological changes (changes in the flow and sedimentary conditions) are reflected in several processes, e.g. clogging, bed sediment sorting, armouring. Thus, the links between the morphological changes and variations in the size of river bed sediments can be better identified. Therefore, the primary focus of this study was on gravel bed sections of the Danube (Upper Danube and part of the Middle Danube), though the Danube River has been examined along its full length.

The spatial and temporal variability of river bed sediments along the Danube from rkm 2,600 to the Danube Delta was evaluated using data on the median particle size D_{50} (surface layer – bed sediments mostly form the central part of the river channel) provided by the project partners for three periods (I – 1920-1970, II – 1971-1990, III – 1991-2017). These data also include the values of D_{50} taken from grain size distribution curves provided by project partners and also those compiled within JDS3 (ICPDR, 2013). The characteristic grain sizes of river bed sediments (i.e. D_5, D_{16}, D_{25}, D_{50}, D_{65}, D_{75}, D_{84}, and D_{90}) estimated from grain size distribution curves are used for an analysis of the variability of river bed sediments along the Danube River reaches where data from at least two periods were available.

Table 5.3.1 Size gradation for sediments in the range from sand to boulder

Size class		Sediment size (mm)		
CLAY	clay	-	to	‹ 0.0002
SILT	very fine silt	0.0002	to	0.004
	fine silt	0.004	to	0.008
	medium silt	0.008	to	0.016
	coarse silt	0.016	to	0.031
	very coarse silt	0.031	to	0.063
SAND	very fine sand	0.063	to	0.125
	fine sand	0.125	to	0.25
	medium sand	0.25	to	0.5
	coarse sand	0.5	to	1
	very coarse sand	1	to	2
GRAVEL	very fine gravel	2	to	4
	fine gravel	4	to	8
	medium gravel	8	to	16
	coarse gravel	16	to	32
	very coarse gravel	32	to	64
COOBLE	small cobble	64	to	128
	large cobble	128	to	256
BOULDER	boulder		› 256	

The classification scheme included in Table 5.3.1 was used to identify the class and type of river bed sediments (from clay to boulder).

The composition of the Danube river bed varies from coarse gravel to fine sand (Figure 5.3.1, Table 5.3.1) and, in the tributaries, from coarse gravel (Inn, Isar, Inn, Hron) to fine gravel (Morava, Drava, Velika Morava, Timok), sand and silt (Mosoni Duna, Váh, Ipel, Tisza, Sava, Siret, Prut, Jantra, Iskar).

Data on the grain size of the river bed material were collected to identify the changes that occurred in the composition of sediments during the periods under review. The characteristic grain sizes were estimated from the relevant grain size distribution curves and evaluated in the context of the river channel's morphological development (Figures 5.3.1, 5.3.2). These data were used to evaluate the short-term and long-term changes in the composition of bed sediments and to identify the possible causes of these changes (impact of the main pressures).

Table 5.3.2 Localities of the free-flowing sections of the Danube

Country	Free-flowing sections		from rkm	to rkm
	from HPP	to HPP/site		
DE	Donauwörth	Bertoldsheim	2,511.0	2,490.17
	Vohburg	Bad Abb	2,444.1	2,411.5
	Straubing	Kachlet (Vilshofen)	2,320.0	2,230.51 (2,246.3)
AT	Melk	Altenworth	2,037.96 (2,038.16)	1,980.40 (1,979.83)
	Freudenau	Ćunovo weir - Gabcikovo	1,921.05	1,851.75
SK-HU/HU, HR, RS, RO	Čunovo weir - Gabčíkovo	Iron Gate 1	1,851.75	943.00
RS, BG, RO	Iron Gate 2	Danube Delta	862.80	0.00

The main pressures that have induced changes in the natural variability of bed sediments in the Danube are as follows:

- Hydropower plants built in the Danube channel, which restrain sediment continuity in the river bed by causing aggradation upstream (sedimentation, clogging) and degradation downstream (bed sediment sorting, bed armouring);
- Hydropower plants on the Danube's tributaries, which reduce the transport of sediments into the main channel of the Danube;
- River bed dredging in the Danube channel – excessive commercial dredging performed in the past, causing intense river bed degradation in numerous places (i.e. uncovered subsurface layers).

The cascade of HPPs on the German and Austrian Danube has completely stopped the natural movement of river bed sediments (bedload). Only local and very limited bedload movement is allowed along shorter reaches of the free-flowing sections (Table 5.3.1). In fact, bedload transport along these reaches allows only a local redistribution of bed sediments between two hydropower plants. The largest hydropower plants on the Danube, i.e. Gabčíkovo and Iron Gate 1 and 2, have affected the composition of the river bed along their impoundments in particular. The composition of bed sediments along the river's free-flowing sections downstream of the hydropower plants indicate changes caused by sediment deficit and bed erosion downstream of the HPPs, as well as by excessive dredging performed in the past (Period II).

5.3.1 Bed sediment composition along the Danube River

Between rkm 2,600 and 1,790, the river bed is composed of gravel. A few kilometres downstream of a major change in the bed slope (rkm 1,790, see Figures 5.3.1 and 5.3.2), the composition of river bed sediments is changing gradually from coarse gravel to fine gravel with larger volumes of coarse and fine sand. The major change from the gravel bed to sand bed river is taken place within transitional zone approximately between rkm 1,660 and rkm 1,420.

The gradual construction of hydropower plants over the three periods under review took into account the temporal variations in the size of bed sediments along the Danube.

The combined effect of disruption of the longitudinal continuity, reduced sediment supply from the tributaries and dredging activities (excessive amounts of commercial dredging – Period II) reflects changes in the composition of bed sediments (Figure 5.3.1).

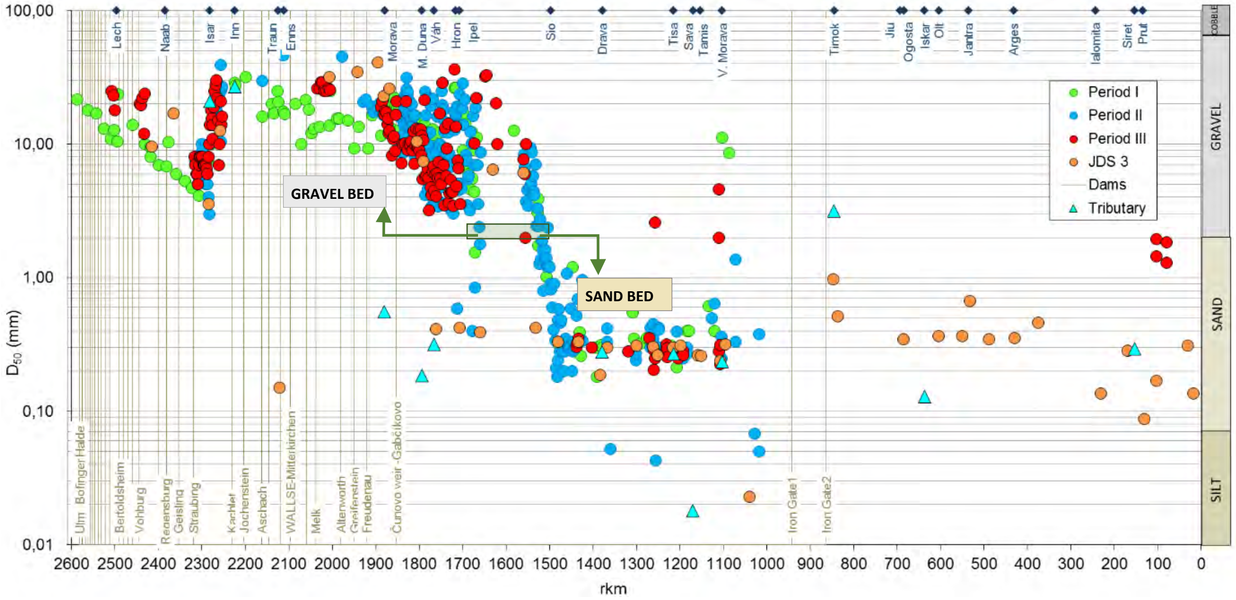


Figure 5.3.1 Variations in the median size of bed sediments D_{50} (surface layer) over three periods (I, II and III) along the full length of the Danube River

The variations in the median size of bed sediments D_{50} (surface layer) along the full length of the Danube over three periods (I, II and III), which are considered in this study, can be seen in Figure 5.3.1. This graph also shows the range of data (D_{50}), which were available for analysis of the river bed composition. The range of available data on the Lower Danube is available only for the third period (most of the D_{50} values are taken from JDS3 sampling – VÚVH) as it can be seen in Figure 5.3.1.

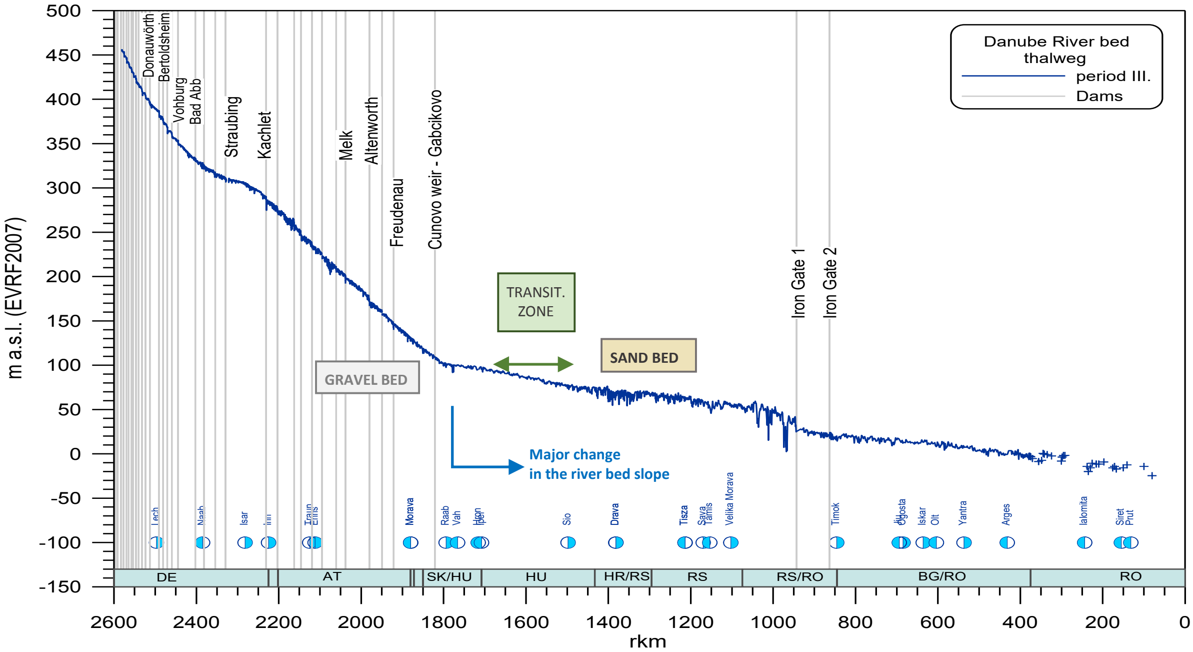


Figure 5.3.2 Longitudinal profile of the Danube river bed (Period III) in relation to stream classification

Therefore, only a basic analysis could be done for the Lower Danube with the main focus of attention being on the Upper Danube and the Middle Danube, i.e. the sections between rkm 2,600 and rkm 1,000 (Figure 5.3.3).

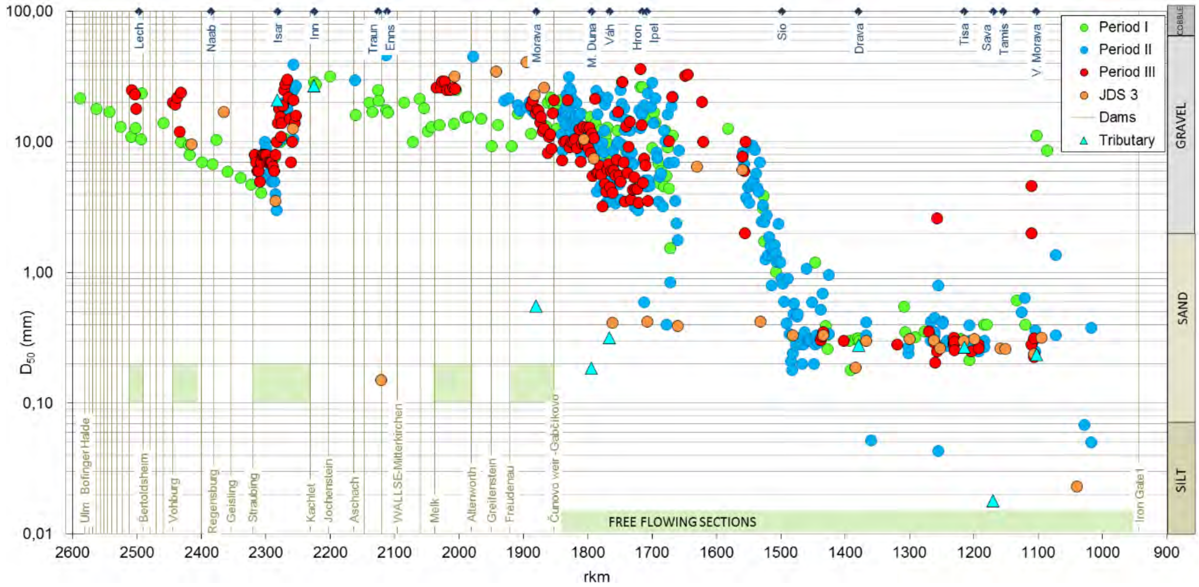


Figure 5.3.3 Variations in the median size of bed sediments D_{50} (surface layer) over three periods (I, II and III) along the Danube River between rkm 2,600 and rkm 1,000

Data from the first period cover almost the whole Upper and Middle Danube without significant data gaps (Figure 5.3.3), but data from the second and third periods (Figures 5.3.4

and 5.3.5) indicate rather big data gaps. This can be attributed to the hydropower plants built gradually over the second and third periods on the Upper Danube.

The composition of river bed sediments is an important piece of information needed for bedload transport modelling, estimating the coefficient of river bed roughness (needed for flow regime modelling) or for assessing the morphological changes occurring in of the river bed. This information is particularly important in the free-flowing sections of the Danube. River processes within a chain of impoundments are restrained to suspended load transport and sedimention. The only coarse sediments input from the tributaries had been also reduced due to their damming. The river bed of the navigational channel is regularly dredged to maintain the original conditions to provide navigation and flood protection. Therefore, bed sediment sampling within the third period is mostly concentrated in the free-flowing sections of the Upper Danube.

Changes in the composition of river bed sediments occur mostly along the free-flowing sections of the Upper Danube, where bed sediment coarsening can be seen in areas downstream of dams and bed sediment finning in impounded sections. These changes started during the second period (1970–1990) as a consequence of hydropower plant construction on the Upper Danube as shown in Figure 5.3.4. Only minor or no significant changes in the size of D_{50} grains occurred along the Middle Danube during these periods.

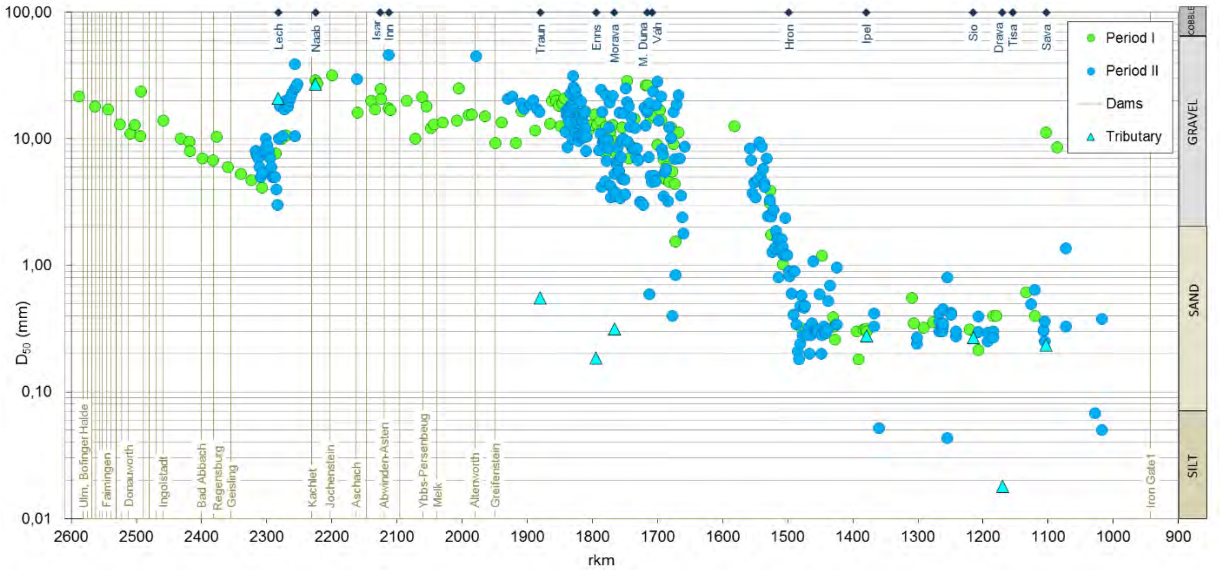


Figure 5.3.4 Comparison of bed sediments represented by the median size, D_{50} (surface layer) from periods I and II, along the Danube River between rkm 2,600 and rkm 1,000

An evaluation of long-term variations in the size of river bed sediments, D_{50} based on a comparison of data from the first and third periods (Figure 5.3.5), indicates a general trend consisting in bed sediment coarsening along the free-flowing river sections (downstream of dams but outside of impoundments from lower dams) within the chain of dams in the Upper Danube section up to Freudenau (AT, rkm 1,921.05).

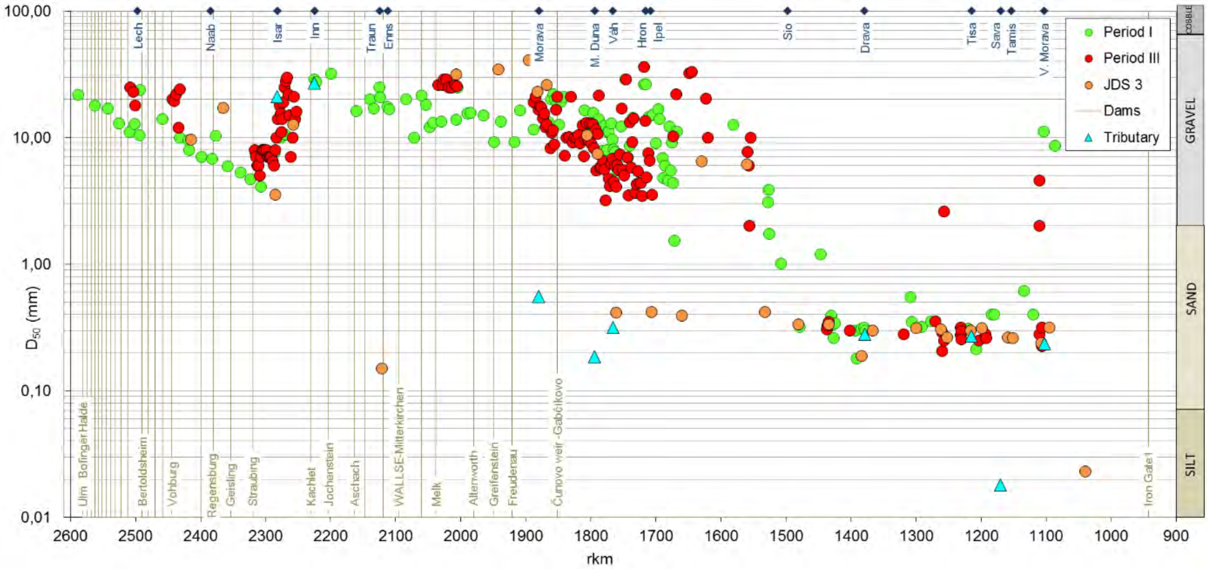


Figure 5.3.5 Overall changes in the bed sediments represented by the median size, D_{50} (surface layer) from periods I and III, along the Danube River between rkm 2,600 and rkm 1,000

Bed sediment coarsening downstream of dams indicate that there are conditions for the creation of bed armouring, but more detailed data are needed (composition of the subsurface layer) to verify and confirm these processes. The grain size changes in the Upper Danube's gravel bed reflects the actual degree of hydromorphological changes caused by sediment continuity disruption not only within the Danube channel but also within its tributaries. The dense network of hydropower plants in the Upper Danube Basin (Figure 5.3.6) has completely eliminated bedload transport along the Upper Danube and significantly reduced the supply of sediments from tributaries.

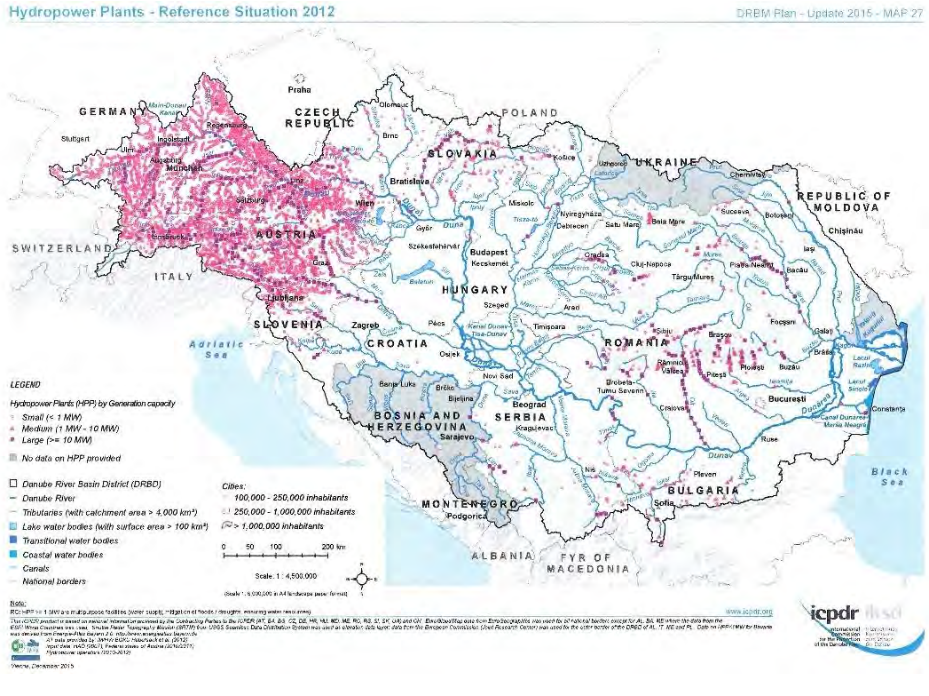


Figure 5.3.6 Localities of hydropower plants on the Danube – Reference Situation 2012 (DRBM Plan–Update 2015 – Map 27)

Apart from the disrupted sediment continuity and restrained sediment input from the river's tributaries, changes in the flow dynamics also had a negative impact on bedload transport along the Upper Danube, creating areas where deposition processes prevail. The intensity of deposition depends on the type (run-of-the-river power plants, power plants built on bypass canals such as Gabčíkovo) and technical parameters of the hydropower plants in operation and their location within the river basin (a more detail evaluation is available for the Upper, Middle and Lower Danube sections). In view of these criteria, the most intense river bed aggradation processes (bedload deposition at the end of the impounded area and suspended load deposition within the Čunovo reservoir) take place upstream of the Gabčíkovo HPP. This is also reflected in the composition of the river bed.

The opposite process to bed sediment coarsening is the fining of bed sediments, which can be observed in an area downstream of the Čunovo weir, as well as downstream of the confluence of the Old Danube and the outlet canal (Gabčíkovo). Bed sediment fining, occurring at the lower end of the Upper Danube between rkm 1,850 and rkm 1,790, and at the beginning of the Middle Danube (between rkm 1,790 and rkm 1,765 – at the mouth of the Váh River), is probably the result of extensive dredging (see Chapter 5.1) performed along this section of the Danube in the past. These changes in bed sediment size began in the second period when gravel was dredged in excessive amounts in this area for commercial purposes.

A similar but less intense process of bed sediment finning can be observed upstream of the transitional zone between rkm 1,765 and 1,660 where the river bed influenced in some parts by excessive commercial dredging is changing from fine gravel into coarse sand.

Generally, changes in the grain size of bed sediments are important in the case of gravel bed rivers, for they can indicate processes such as sediment sorting, downstream fining, bed armouring, clogging, etc. However, some changes – particularly in the content of finer/coarser grains in the river bed material, can also be estimated for sand bed rivers to identify the changes caused by the morphological evolution of the river bed (deposition of fine sediments in impounded sections). In this context, only very slight bed sediment fining can be observed along the lower part of the Middle Danube downstream of the transitional section (rkm 1,550 – 1,100). These minor changes are attributable, in particular, to impoundment from the Iron Gate 1 HPP (deposition), excessive dredging in the past (Period II, see Chapter 5.2), and to a decrease in sediment supply from the tributaries and upstream reaches of the Danube.

5.3.2 The Upper Danube

For the purposes of this study, the Upper Danube extends from rkm 2,600 to rkm 1,790 (the river source is at rkm 2,850). Bed sediments vary from fine to coarse gravel. Data on bed sediments represented by the grain size D_{50}, which cover this river section during all three periods, enable an analysis of the grain size changes for a longer period. Grain size distribution curves provided by the project partners (Germany, Austria and Slovakia) represent an important source of information for a more detailed analysis of the long-term changes in the composition of the Danube river bed. These data enable us to identify the impact of the main pressures such as the cascade of hydropower plants and sediment dredging, and the influence of the tributaries on the bed sediment size. However, a deeper analyses would require a higher quantity and quality of data (e.g. bed sediment sampling with targeted spacing, including surface and subsurface layers).

German data on the grain size of bed sediments for the first period were obtained in 1965. Of the total number of run-of-the-river power plants along the German Danube (22), 12 HPPs had already been built at that time (Figure 5.3.7). Austrian data on the D_{50} grain size for the same period were obtained during the period 1920–1937, when there was no hydropower plant in the Austrian section of the Danube. The same situation existed in the Slovak–Hungarian Danube section (SK-AT, SK, SK-HU). Sediment continuity along the Upper Danube was influenced mostly by the run-of-the-river power plants built on the German Danube during the first period.

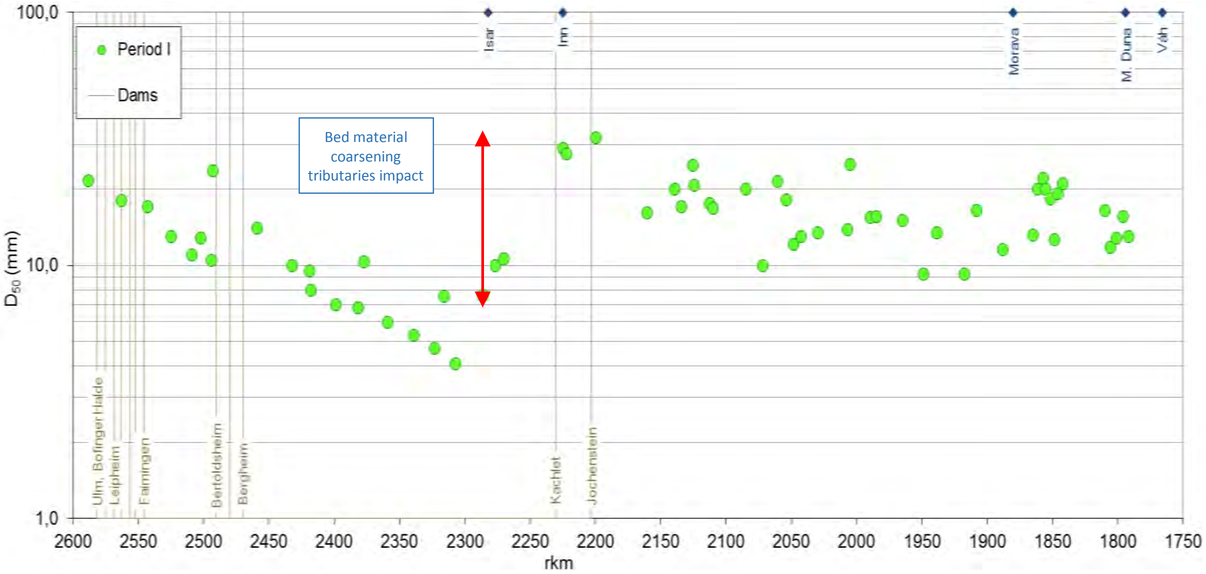
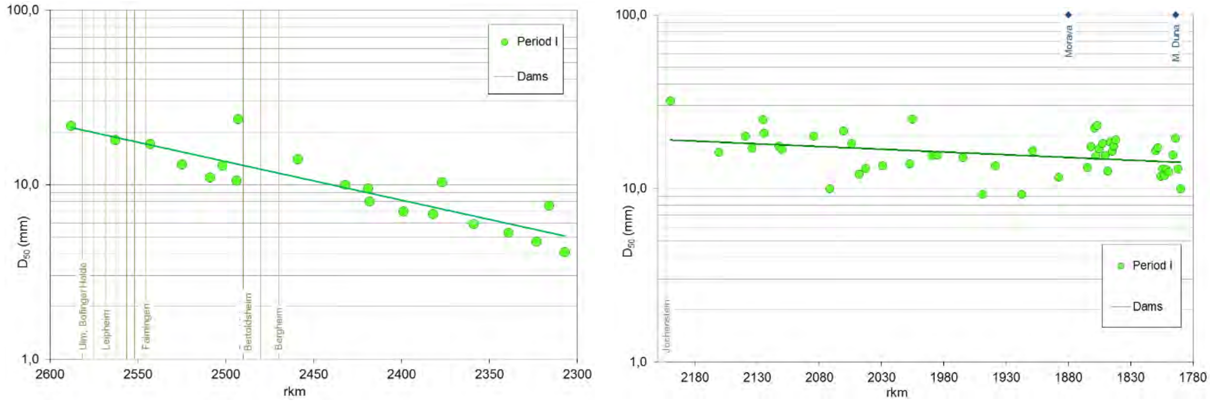


Figure 5.3.7 Variations in the median grain size of bed sediments D_{50} (surface layer) along the Upper Danube – Period I (German data, 1965; Austrian data, 1920-1937; Slovak data, 1967)

The size of bed material grains in the German Danube upstream of the Isar and Inn tributaries indicates natural bed sediment fining downstream, between rkm 2,600 and rkm 2,300 (Figure 5.3.7). The bed material varies from the coarse to fine gravel. Although sediment continuity has already been affected by twelve hydropower plants, their impact on the composition of bed sediments has not yet been demonstrated (Figure 5.3.8, a). There is only a very slight indication of bed sediment coarsening downstream of some HPPs (Figure 5.3.7). However, this may also be a sign of the bed material's natural variability. A natural increase in the grain size between rkm 2,320 and rkm 2,200 is caused by large amounts of coarse gravel transported from the Alpine tributaries – the Isar River (D_{50} ~ 10 mm) and, in particular, the Inn River (D_{50} ~ 30 mm).



a) German Danube between rkm 2,600 and rkm 2,300 b) Austrian, Slovak–Hungarian Danube between rkm 2,200 and rkm 1,790

Figure 5.3.8 Downstream fining of bed sediments – trend lines (power regression) for the German (1965), Austrian (1920-1937) and Slovak-Hungarian Danube sections (1965) –Period I

The variability of bed sediments along the Austrian, Slovak and Hungarian sections (rkm 2,200 – rkm 1,790) of the Upper Danube shows more natural conditions in relation to sediment continuity, because there is no barrier in this part of the Danube (Figure 5.3.8, b). However, bedload transport and coarse sediment supply from the river's tributaries has already been reduced by 12 hydropower plants built in the German section of the Danube. Bed sediments vary from very coarse gravel to medium gravel and there is an apparent trend of sediment fining downstream, along the whole river section (Figure 5.3.8, b).

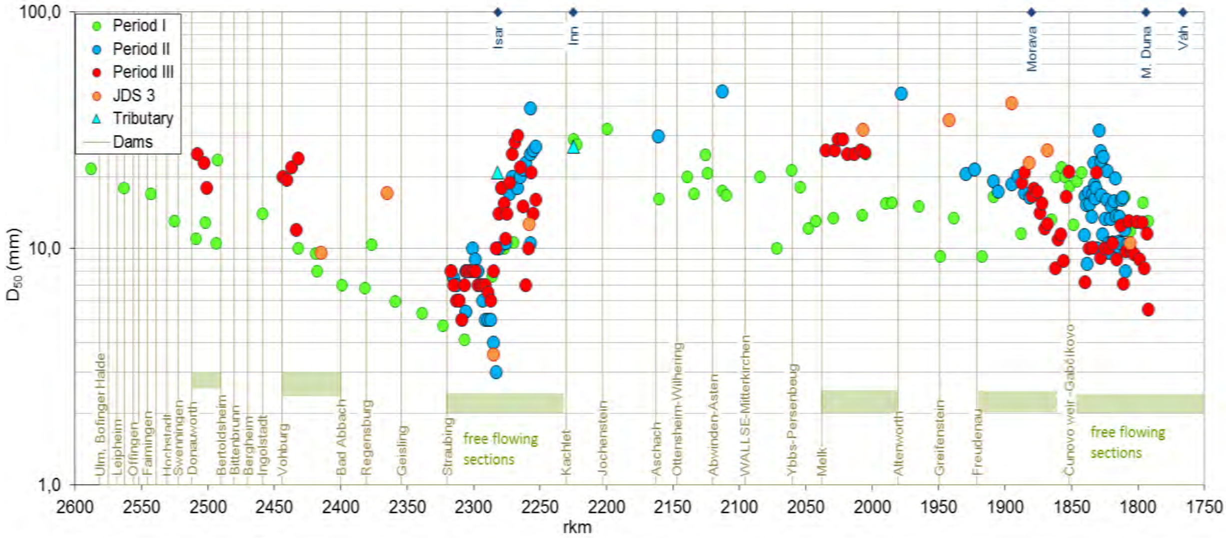


Figure 5.3.9 Variations in the median size D$_{50}$ of bed sediments (surface layer) over three periods (I, II and III) along the Upper Danube

Figure 5.3.9 shows a comparison of bed sediments according to the D$_{50}$ grain size from the three periods considered in this study. A cascade of run-of-the-river power plants in the German and Austrian Danube sections and the Gabčíkovo hydropower plant (Slovakia) built on a bypass canal have completely stopped the transport of bed sediments from the upper parts of the Danube to its middle and lower sections. As a consequence, the transport of bed sediments along the Upper Danube is limited to the six remaining free-flowing sections (Table 5.3.2, Figure 5.3.9). The other parts of the cascade of HPPs on the Upper Danube are influenced mostly by the deposition of finer sediments. More distinct changes in the river bed composition are linked to river sections with intense sediment transport. Therefore, the focus of attention in evaluating the variability of bed sediments in the Upper Danube section was on the free-flowing sections. This was also supported by the availability of data for periods II and III.

photo JDS3 -VUVH

Figure 5.3.10 Bed material (sediment) samples from the Upper Danube, Period III.

Currently, the composition of bed sediments shows signs of disrupted sediment continuity (due to HPPs) and changes in flow dynamics (in impounded sections). The variability of bed sediments in the Upper Danube is illustrated in Figure 5.3.10.

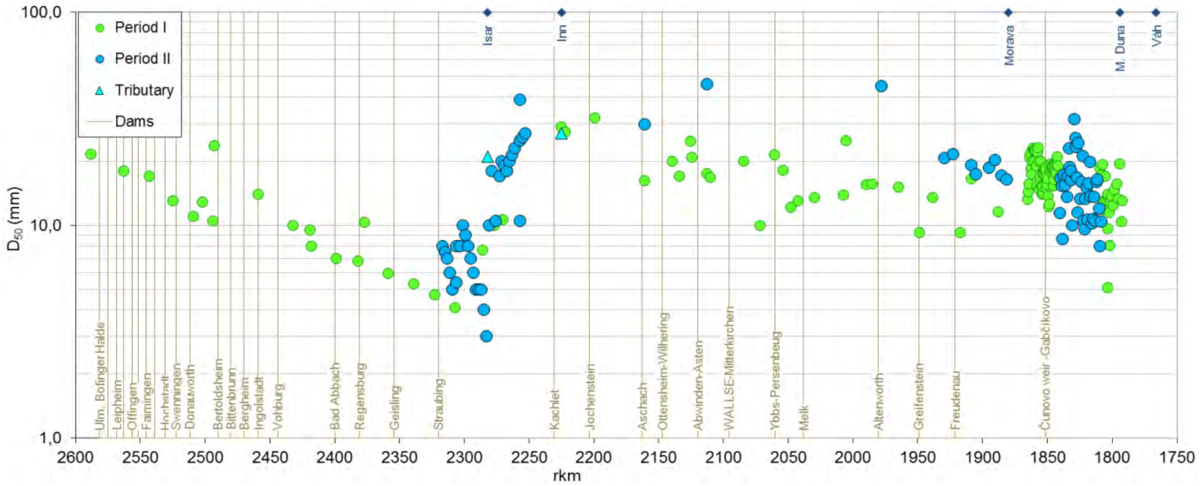


Figure 5.3.11 Comparison of bed sediments according to the median D_{50} grain size (surface layer) – Periods I and II, Upper Danube

A comparison of bed sediments from the first and second periods according to the D_{50} grain size indicates that no significant changes have occurred in river sections for which data are available from both periods (Figure 5.3.11). However, the data from the second period are rather limited (they cover only shorter sections, see Figure 5.3.11), so they do not provide a sound basis for a reliable evaluation.

The scope of data from for the third period is also limited, but the data cover all the free-flowing sections of the Upper Danube. On the basis of these data, it is possible to evaluate the long-term changes occurring in these river sections.

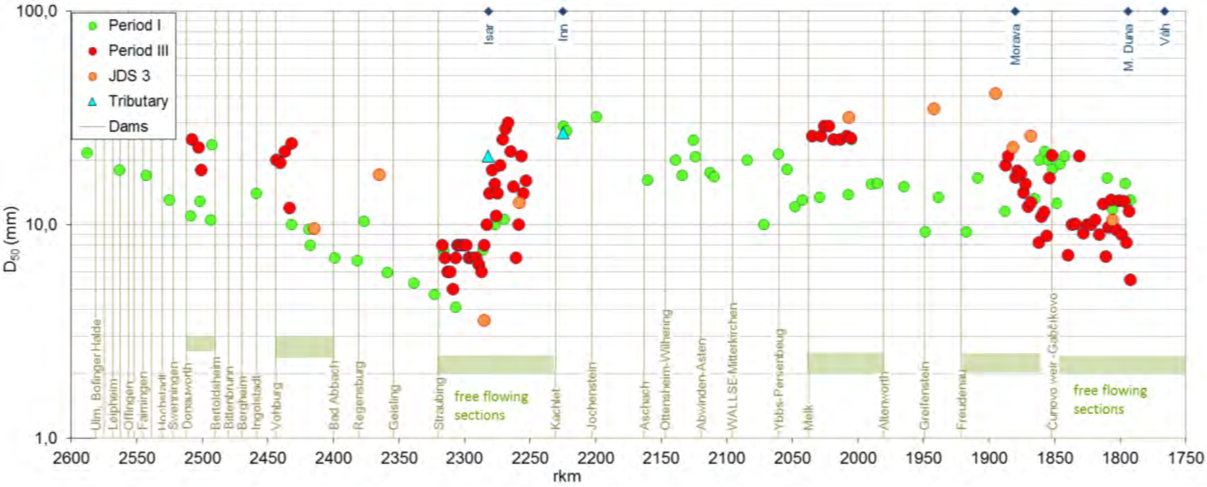
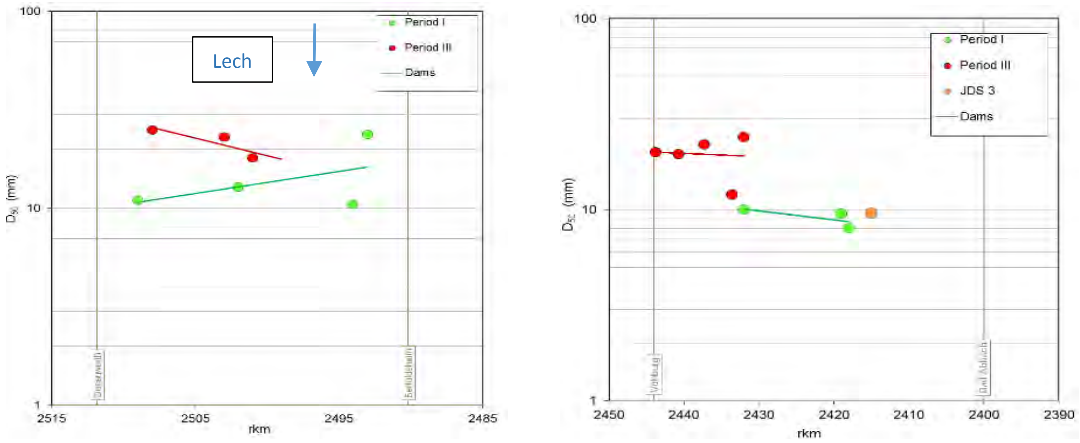


Figure 5.3.12 Overall changes in the median D_{50} grain size of bed sediments (surface layer) – Periods I and III, Upper Danube

Apart from the disrupted sediment continuity, changed flow dynamics and limited sediment supply from the tributaries (caused by cascades of hydropower plants, Figure 5.3.6), the river bed composition is affected by the prevailing sedimentation processes in impounded sections (except in short sections identified downstream of some hydropower plants in Austria, where the river bed is affected by erosion). The range of changes varies depending on the type and technical parameters of each hydropower plant. The most intensive deposition of fine sediments occurs within the reservoir upstream of the Gabčíkovo HPP (D_{50} ~ 0.021 mm), but less intense deposition process can also be observed within the cascade of run-of-the-river power plants (e.g. Abwinden, D_{50} ~ 0.16 mm; Figures 5.3.5 and 5.3.10).



a) Danube between Donouworth and Bertoldsheim (DE) b) Danube between Vohburg and Bad Abbach (DE)

Figure 5.3.13 Comparison of the trend lines (power regression) of bed sediments (the D_{50} grain size) for periods I and III in the free-flowing sections of the Upper Danube: a) rkm 2,511.85 –2,490.17; b) rkm 2,444.5 – 2,400)

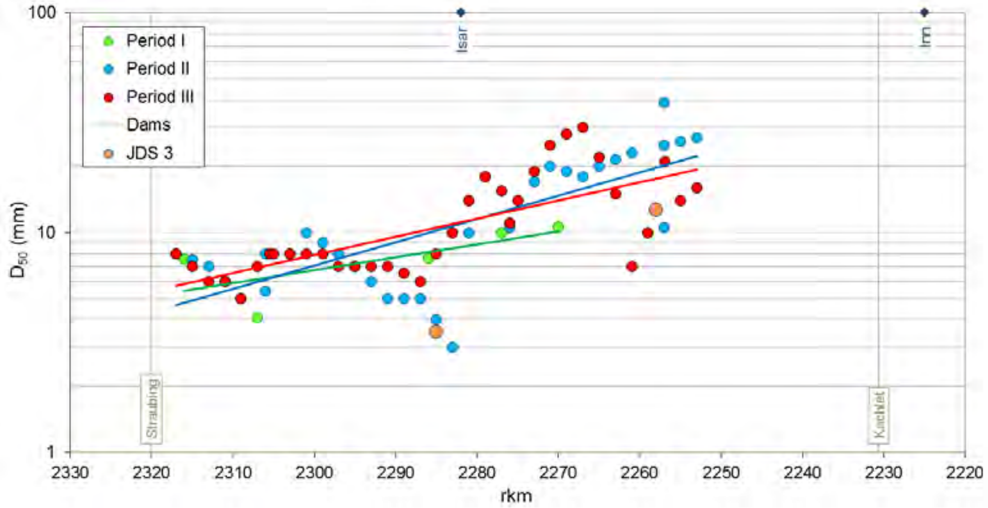


Figure 5.3.14 Comparison of the trend lines (power regression) of bed sediment (the D_{50} grain size) for periods I, II and III in the free-flowing section of the Upper Danube between Straubing and Kachlet (DE)

River bed erosion in some of the short sections downstream of hydropower plants within impoundments (identified by the Austrian partner) may also affect the composition of the river bed material (sediment sorting and armouring), but no data are available to validate and confirm these processes.

A comparison of bed sediments according to the D_{50} grain size for periods I and III in two free-flowing sections of the German Danube (Figure 5.3.13) indicates bed sediment coarsening in Period III in the areas downstream of the Donouworth and Vohburg hydropower plants (Figure 5.3.13, a and b). Although limited data are available for both free-flowing sections, the regression lines indicate trends of bed sediments coarsening, which can also be observed in other free-flowing sections of the German and Austrian Danube (Figure 5.3.14). Such changes in the composition of bed sediments downstream of dams are caused by a lack of coarse sediments, higher flow energy and bedload transport capacity immediately downstream of the dams, which induced river bed erosion and sediment sorting. The regression line (Figure 5.3.13, a – Period I) shows a downstream trend towards bed sediment coarsening in a free-flowing section, owing probably to the higher supply of coarse gravel from the Lech tributary. Both trend lines for Period III indicate downstream sediment fining, which is influenced artificially in this case. Impoundment accompanied by a decrease in the flow velocity (from the lower dam) leads to the sedimentation of finer particles in the river bed.

Data on D_{50} for the third free-flowing section (Figure 5.3.14) in the German section of the Danube cover all three periods. While data from the first period reflect a natural coarsening of bed sediments influenced by intense sediment transport from the Isar tributary, the grain size of bed sediments increased further during the second and third periods as a result of sediment continuity disruption followed by river bed degradation downstream of dams. Thus, finer sediment particles were washed out from the surface layer and transported further downstream. This led to coarsening and sorthing of the bed sediments.

In general, river bed erosion downstream of hydropower dams in connection with changes in the bed material composition (coarsening, armouring) can be observed in almost all free-flowing sections of the Danube in Germany and Austria and partly in some of the impounded sections within the cascade of HPPs. Bed sediment coarsening of this type can also be seen in the Austrian section of the Danube between the Melk and Altenworth HPPs (Figure 5.3.15).

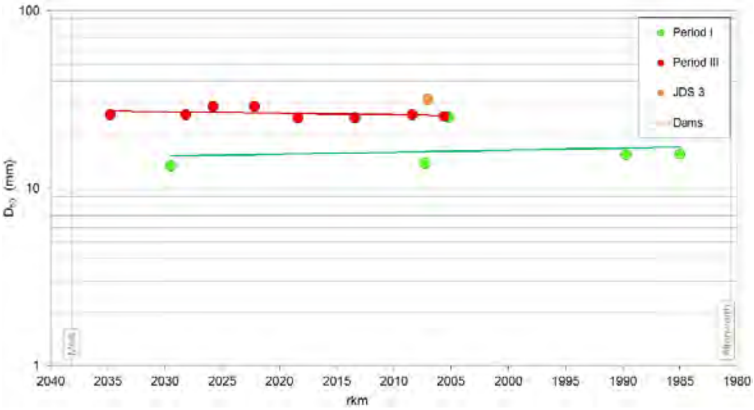


Figure 5.3.15 Comparison of the trend lines (power regression) of bed sediments (the D_{50} grain size) for periods I and II in the free-flowing section of the Upper Danube between Melk and Altenworth (AU)

In fact, a free-flowing section between two dams consists of three sub-sections with different processes that may cause changes in the river bed composition:

- River bed erosion downstream of the upper dam: bed sediment coarsening, sediment sorting, bed armouring (the surface layer of the river bed is coarsened relative to the subsurface);
- Deposition of coarse sediments (gravel, sand): sediments transported from eroded areas are deposited immediately downstream of the eroded area (gravel deposits are usually dredged as they can negatively influence navigation and/or flood protection);
- Deposition of fine sediments (sand, silt): fine sediments are deposited in areas affected by impoundment from the lover dam.

The total length of the three sub-sections depends on the type and technical parameters of the two HPPs between which the free-flowing section is located, and on the operating regimes of these HPPs.

Data on D_{50} grains for the first and second periods do not indicate any visible changes in the composition of the bed material in the free-flowing section between Vienna (rkm 1,920) and Bratislava (rkm 1,868) (see Figure 5.3.16). During the first year of operation of the Freudenau HPP, the river bed downstream of the dam was influenced by the same coarsening process as that identified in other free-flowing sections upstream of Vienna. However, insufficient data are available to prove this assumption (Figure 5.3.16). In recent years, the composition of the river bed material has been influenced by several restoration measures taken to reduce the erosion rate of the river bed downstream of Freudenau. Artificial sediment supply (bedload feeding – sorted grains of gravel for river bed stabilisation) and bank protection removal with the aim of reducing the capacity of bedload transport have affected the composition of bed sediments to some extent. But the data used in this project provide no evidence in support of these processes.

A comparison of regression lines for the first and third periods for the river section between the Morava River's mouth and the Čunovo weir (Gabčíkvo, 1992) clearly indicates a trend towards bed sediment fining as a result of sediment deposition within the area affected by impoundment from the Čunovo weir (Figure 5.3.16).

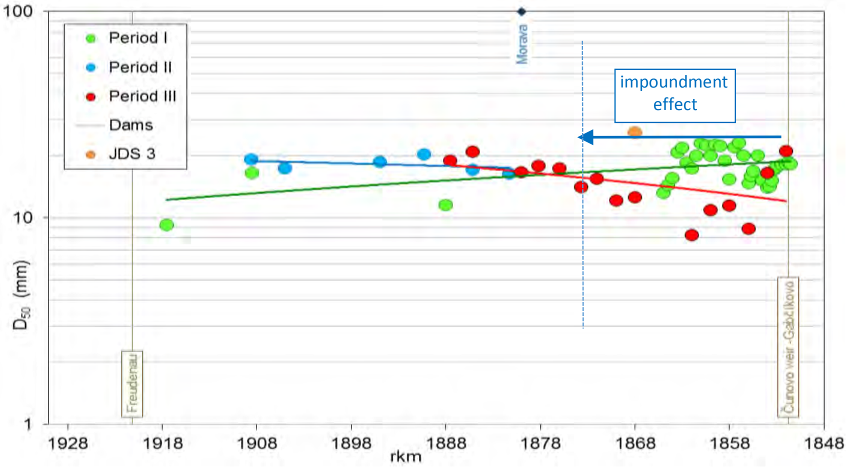


Figure 5.3.16 Comparison of the trend lines (power regression) of bed sediments (the D_{50} grain size) for periods I and II in the free-flowing section of the Upper Danube between Freudenau (Austria) and Čunovo (Gabčíkovo, Slovakia)

The last free-flowing section of the Upper Danube is located between the Čunovo weir (rkm 1,851.75) and the lower edge of the Upper Danube (rkm 1,790), where the river's morphological character changes. This section is greatly affected by the operation of the Gabčíkovo HPP, which is situated on a bypass canal.

In the past, intense sediment dredging and the closure of side arms, both performed mostly during the second period, led to severe river bed degradation in this locality. Since the 90ies of the last century, the operation of Gabčíkovo HPP has been strongly influencing the flow conditions, sediment regime, and the channel morphology of the Danube in this section.

The sediment transport processes are affected by the disrupted sediment continuity caused by the Čunovo weir and by regulated discharges (mostly a constant discharge of 400 m^3/s to 600 m^3/s) released into the original channel of the Danube River – now the Old Danube. The actual flow conditions considerately limited the sediment transport, mostly to suspended load. Bedload transport occurs only occasionally during floods ($Q_{BA} > 7,000$ m^3/s) when higher discharges are released into the Old Danube ($Q_{OD} > 3,500$ m^3/s).

The lower part of this free-flowing section between the confluence of the outlet canal (rkm 1,810) and the end of the Upper Danube (rkm 1,790) was also affected by river bed degradation caused by the closure of side arms and by intensive dredging in the past. These negative impacts were increased by the construction and operation of the Gabčíkovo HPP.

The combined effects of human activities performed in the Danube channel during all three periods were reflected in the morphological changes shaping the present state of the river channel. These changes were also mirrored in the composition of river bed sediments along this free-flowing section of the Upper Danube (rkm 1,851.75 – rkm 1,790).

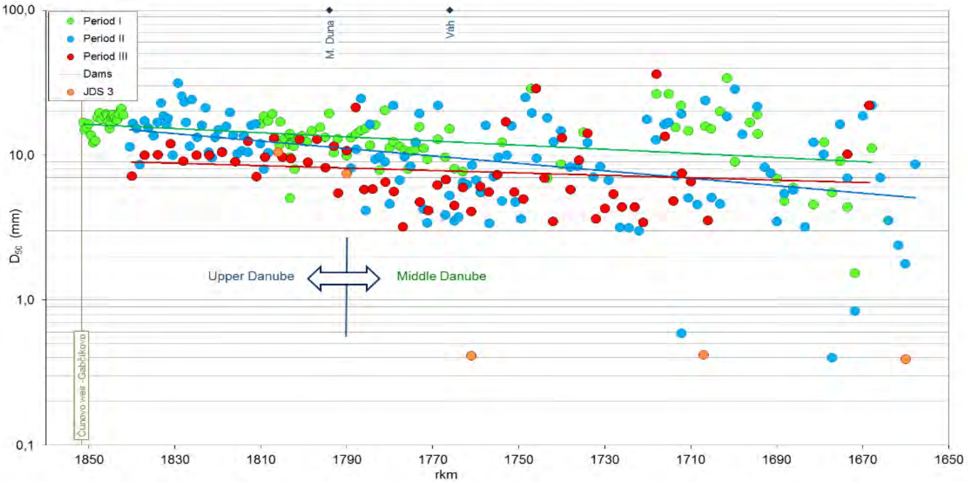


Figure 5.3.17 Comparison of the trend lines (power regression) of bed sediments (the D_{50} grain size) for all three periods in the last free-flowing section of the Upper Danube – downstream of the Čunovo weir (Gabčíkovo), including the gravel bed section of the Middle Danube

A comparison of bed sediments according to the D_{50} grain size indicates a decrease in the size of bed sediments (fining), as well as smaller size variations (Figure 5.3.17). These changes occurred in the Old Danube during the third period – after the Gabčíkovo HPP had been put into operation – as a response to the specific flow conditions and the altered sediment transport regime. Smaller changes in the grain size of bed sediments can also be observed in the section downstream of the outlet canal's confluence with the Danube up to the end of the Upper Danube. An even larger decrease in the grain size of bed sediments occurred at the beginning of the Middle Danube (Figure 5.3.17).

The changes in the composition of bed sediments along the Upper Danube indicated by variations in the D_{50} grain size were concentrated mostly in the free-flowing sections of the Upper Danube. These changes are reflected in the following areas:

- areas downstream of the hydropower plants – river bed coarsening, higher sediment sorting due to a bedload deficit and higher transport capacity (river bed erosion);
- areas upstream of the hydropower plants – bed sediment fining caused by the deposition of finer sediments transported within the cascade of HPPs (river bed aggradation). The sedimentation rate is variable, depending on the type and technical parameters of each HPP, the specific flow conditions, sediment supply from the tributaries (mostly suspended load for the time being).

The trends indicated by the changes described above are supported by the results of an analysis of grain size distribution curves (surface layer), which provide more detailed information on the variations in the grain size of bed sediments (perceptual content of the individual fractions within a sample).

Note: Some incomplete curves were excluded and some curves with a missing lower part were taken into account in the analysis.

Period I (Figure 5.3.18) – From the river section between rkm 2,563 and rkm 2,307 (Germany), bed sediment samples were taken in 1965, when a certain number of hydropower plants had already been built in the German section of the Danube.

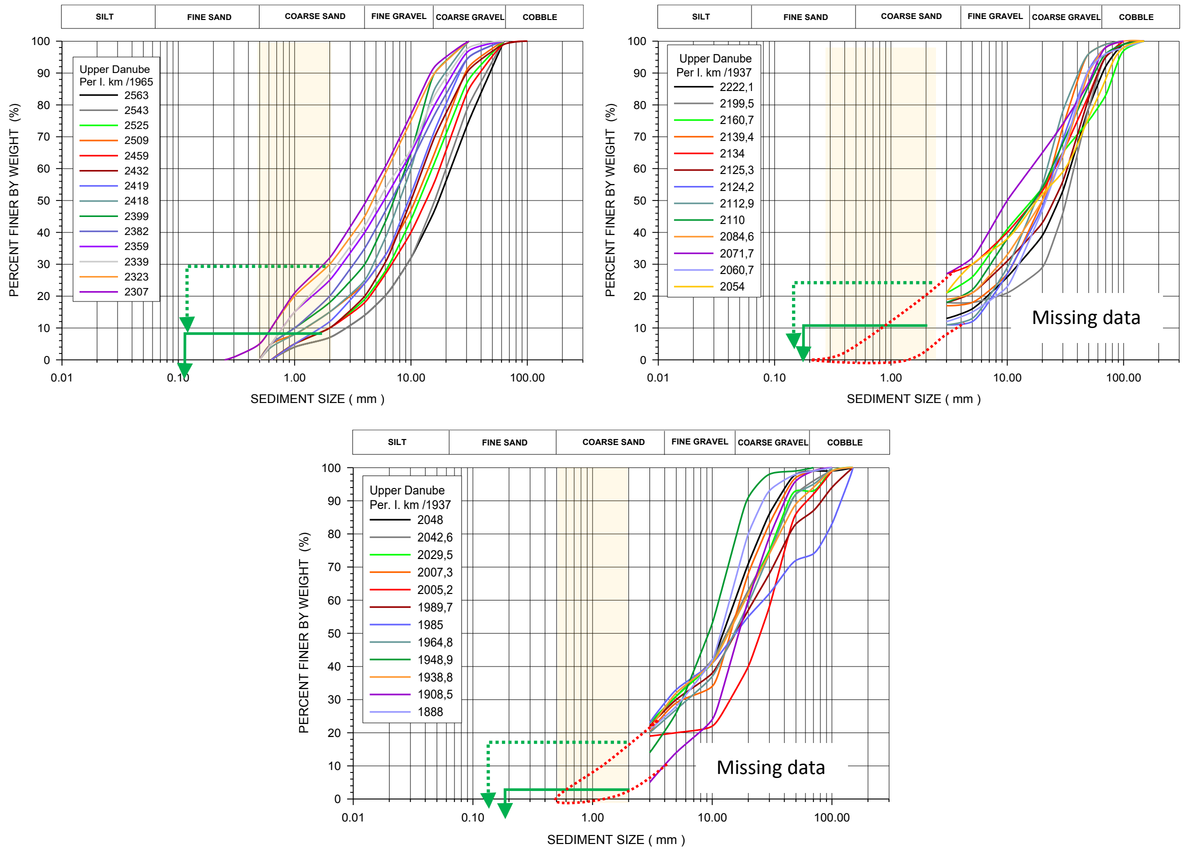


Figure 5.3.18 Grain size distribution curves of the surface layers of bed sediments – samples taken from the Danube channel in the Upper Danube (Germany/1965, Austria/1937), Period I

The shape of the grain size distribution curves from that period is rather uniform, the composition of bed sediments is homogenous, the river bed consists mostly of fine to medium-grained gravel (D_{50} ~ 4 mm to 17 mm) and the content of finer sediments (sand) ranges from 7% to 30%. Samples from the next river section between rkm 2,230 and rkm 1,880 (Austria) were taken in 1937, when there was no hydro-power plant in operation the Austrian section of the Danube. In general, bed sediments in the Austrian Danube are coarser (D_{50} ~ 10 mm to 30 mm) than in the German Danube, owing to sediment transport from the Alpine tributaries (Isar, Inn and Traun). The content of coarse sand ranges from roughly 4% to

20% (based on an expert opinion – due to a lack of data). The values of D_{50}, D_{16} and D_{90} vary within a relatively narrow range along the whole Upper Danube.

Period II (Figure 5.3.19) – From the river section between 2,300 and rkm 2,250 (Germany), bed sediment samples were taken in 1988. Samples from the next river section between rkm 2,161 and rkm 1,881 (Austria) were taken in 1979 and 1987. The majority of hydropower plants in the Upper Danube section were built in this period.

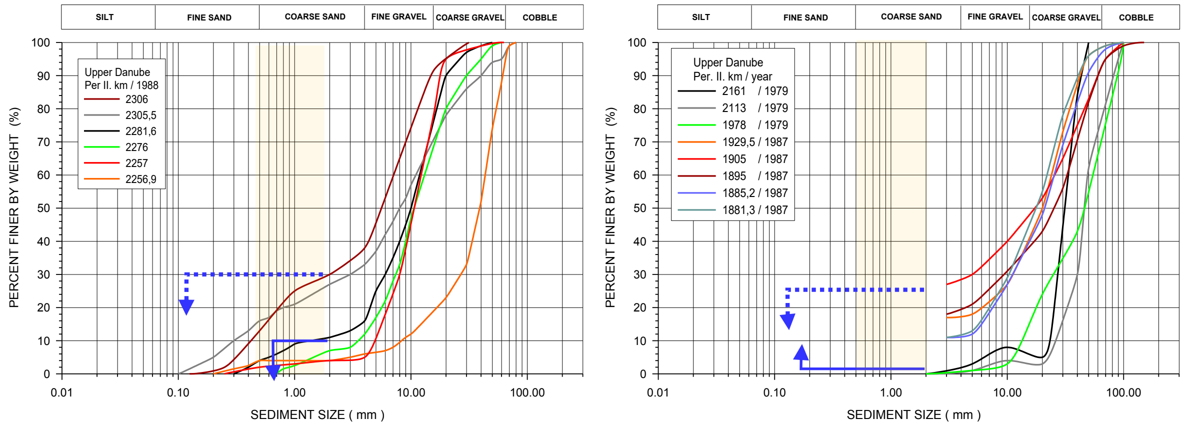


Figure 5.3.19 Grain size distribution curves of the surface layer of bed sediments – samples taken from the Danube channel in the Upper Danube (Germany, Austria), Period II

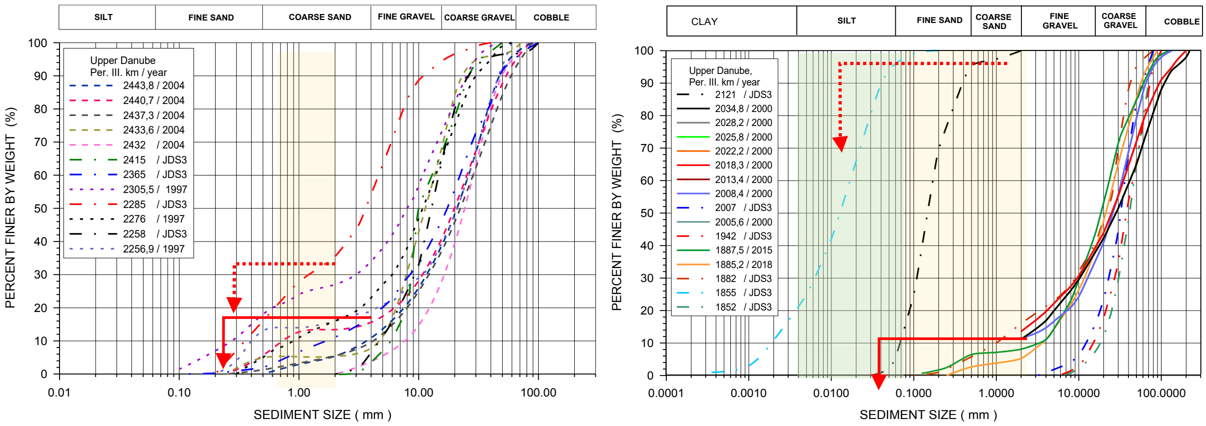


Figure 5.3.20 Grain size distribution curves of the surface layers of bed sediments – samples taken from the Danube channel in the Upper Danube (DE, AT, SK, HU), Period III

Their initial effect on the composition of bed sediments, documented by bigger differences in the shape of grain size distribution curves, can be seen in Figure 5.3.19. Some of the curves indicate a higher content of finer sediments, while others show a higher content of coarse sediments with very low or no content of sand fractions. Bed sediments vary within a wider range of size classes, from fine to very coarse gravel (D_{50} ~ 5.5 mm to 36 mm).

Period III (Figure 5.3.20) – Within the river section between rkm 2,450 and rkm 2,250 (Figure 5.3.20), bed sediment samples were taken in 1997 and 2004. The situation in the next river section between rkm 2,035 and rkm 1,852 (Austria, Slovakia) is documented by grain size distribution curves from 2000, 2013 and 2015 (Figure 5.3.20). The composition of bed sediments is comparable with the second period, but the changes are more visible, compared with data from the first period. Some of the grain size distribution curves indicate a trend towards to coarser sediment fractions (river bed erosion) and some of them indicate a higher content of very fine sediments (sand, silt deposited in impounded sections).

An analysis of the grain size distribution curves has revealed important changes in the original bed sediment composition, which started in the first period as a consequence of hydropower dam construction. This effect became more evident during the second period (1970-1990) in the presence of a chain of HPPs built along the Upper Danube. The main causes of these changes in the Upper Danube section are as follows:

- *sediment continuity disruption* – gradual emergence of deposition areas upstream and of erosion areas downstream of HPPs during the period from the start of hydropower plant construction (Period I) to the full operation of a cascade of HPPs (Period III);
- *flow variability – changes in flow dynamics and/or in discharges* – the areas affected by a flow velocity decrease (due to impoundments upstream of HPPs) and/or by the discharge conditions – in particularly by water abstraction, e.g. regulated discharges in the Old Danube downstream of the Čunovo weir;
- *decreasing sediment supply from the tributaries* – the impact of the cascade of HPPs on the major tributaries (Isar and Inn), which has considerably restrained the transport of coarser sediments to the Danube channel;
- *extensive dredging of river bed sediments* – mostly free-flowing sections are effected (removal of the coarser surface layer by extensive dredging performed in Period II).

The combined effect of all these factors has caused unnatural variations in the grain size of bed sediments, which has been supported by the operation of the cascade of HPPs on the Upper Danube in the recent decades (Period III, 1990 - 2017).

These findings are complementary to the spatial and temporal variations in the D_{50} grain size along the Upper Danube. As a consequence, sites of bed sediment coarsening downstream of hydropower plants and sites of bed sediment fining upstream of hydropower plants are more evident in free-flowing sections of the Upper Danube. However, such changes have also been identified in some sites within impounded sections between dams (Austrian Danube).

Sedimentation within impoundments from the cascade of run-of-the-river power plants in the Austrian and German sections of the Danube is considerably lower than in the large Hrušov reservoir created upstream of the by-pass hydropower plant at Gabčíkovo. This reservoir has affected the flow and sedimentary conditions causing intensive deposition of fine sediments. The range of sedimentation documented by photos taken during the inlet canal's reconstruction (10/2013) can be seen in Figure 5.3.21.

Finer sediments (sand, silt and clay) are concentrated in deposits outside of the navigation channel (Figure 5.3.22). Coarser sediments (bedload) are deposited in the Danube channel upstream of the reservoir (between rkm 1,863 and rkm 1,873). The river bed had to be dredged to maintain the required conditions for navigation along this river section

Photo © Miloš Podoba

Figure 5.3.21 The Hrušov reservoir (upstream of the Čunovo weir, Gabčíkovo HPP) during water level lowering due to reconstruction of the inlet canal (2013)

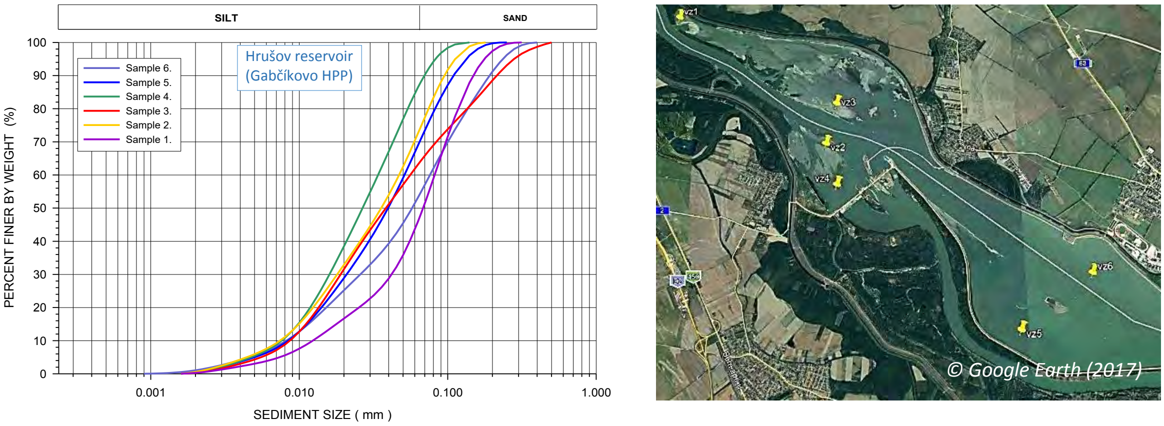


Figure 5.3.22 Grain size distribution curves of bed sediments; samples taken from deposits in the Hrušov Reservoir – aerial image (upstream of the Čunovo weir, Gabčíkovo HPP)

Role of the Upper Danube's tributaries

Eight Danube tributaries are considered in this project: Lech, Naab, Isar, Inn (DE); Traun, Enns. (AT); Morava (SK-AT); Rába (HU). The river bed of the Alpine tributaries – Lech, Isar, Inn, Traun and Enns is composed of coarse gravel. Grain size distribution curves for some of these tributaries are shown in Figure 5.3.23. These Alpine rivers transported large amounts of coarse sediments into the Danube in the past. However, the construction of a series of hydropower dams gradually decreased the supply of sediments from tributaries during the second and third periods (Figure 5.3.6). Currently, sediment transport in the tributaries of the German and Austrian Danube is dominated by fine sediments (suspended load), which are deposited mostly in the area of their mouth, thus sediment supply into the Danube has decreased to a great extent. Tributaries can contribute to the suspended sediment regime of the Danube, but their influence on the river bed composition is minimal.

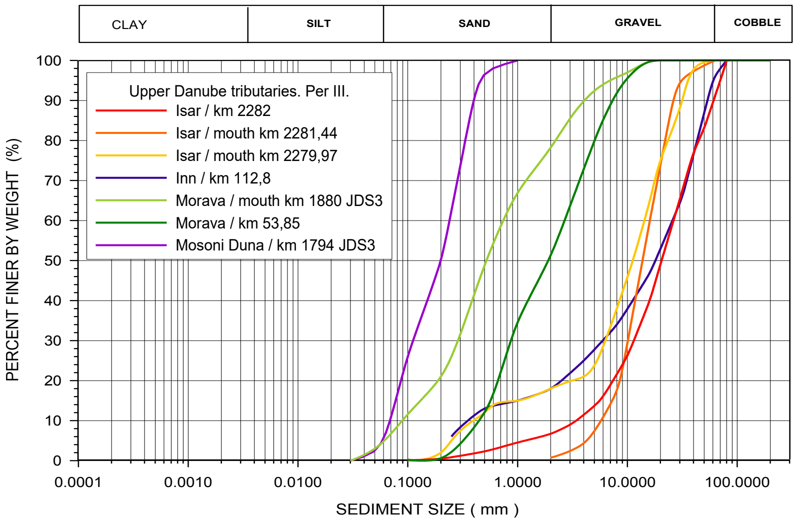


Figure 5.3.23 Grain size distribution curves of the surface layers of bed sediments from samples taken from the Upper Danube’s tributaries (DE, AT, SK, HU),Period III

The river bed of the tributaries in the lower part of the Upper Danube (Morava, Rába, Mosoni Duna) consists of finer sediments, i.e. fine gravel and sand (Figure 5.3.23). The first barrier on the Morava River is about 80 km upstream of its mouth, thus certain volumes of bed sediments may be transported into the Danube. The Morava is a lowland gravel bed river, slowly flowing with a lower bedload transport capacity and a comparable bed sediment size (fine gravel). Therefore, sediments transported into the Danube have no effect on changes in the composition of the bed material. Even smaller amounts of fine sediments are transported from the right-side tributaries (Mosoni Duna and Rába) located close to the lower edge of the Upper Danube. The impact of both tributaries on the composition of the Danube’s river bed is negligible.

Detailed data on the bed material of the Isar and Inn rivers (TUM) provide interesting information on the composition of the surface and subsurface layers on the basis of sediment samples taken from the river mouth and also from a section about a hundred kilometres upstream. Data on the Isar and Inn rivers provided by TUM were obtained from a measurement campaign conducted at the Issar River’s mouth (where a sediment island has been formed) and from the Inn River between rkm 100 and rkm 127 (Period III, 2010, 2014, 2015).

Increased river bed coarsening in the Upper Danube is caused by sediment supply from the next Alpine tributary – the Inn River. Although bedload transport from both tributaries has decreased dramatically over the last few decades (owing to a cascade of HPPs built on both tributaries, see Figure 5.3.24), detailed data on the composition of bed sediments provide valuable information about the variability of the grain size of bed sediments.

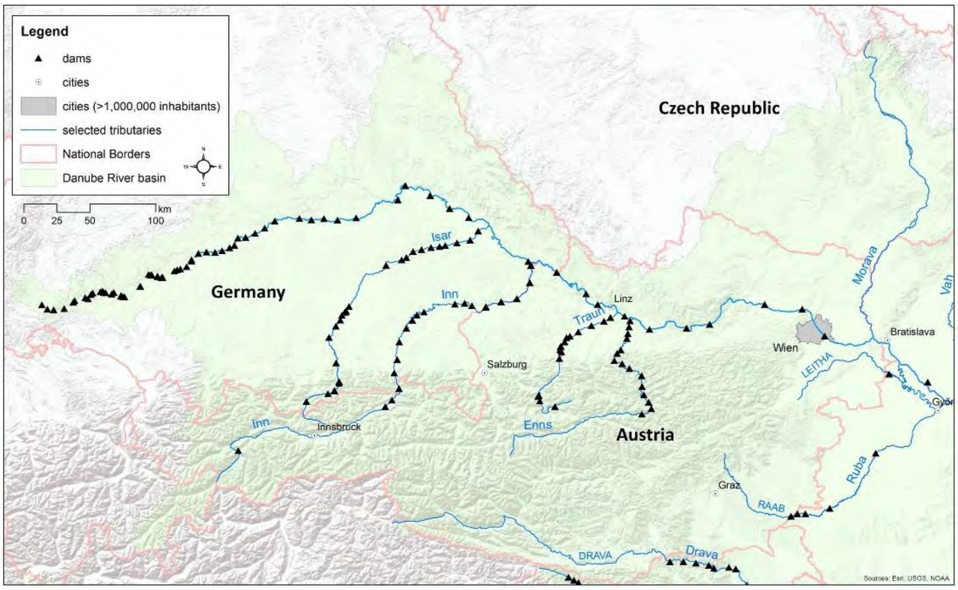


Figure 5.3.24 Localities of the hydropower plants along the Danube and its tributaries

ISAR (Germany) – The Isar River (coarse gravel bed) is one of the Alpine tributaries, which significantly contributed to the natural coarsening of the Upper Danube's river bed in the past (before its damming). As it is shown in figures 5.3.7, 5.3.11 and 5.3.12, the original grain size of the bed material (D_{50}) upstream of the Isar River's mouth was around 4 mm to 5 mm (Period I), but the grain size downstream of its mouth ranged from 30 mm to 40 mm (Figure 5.3.11).

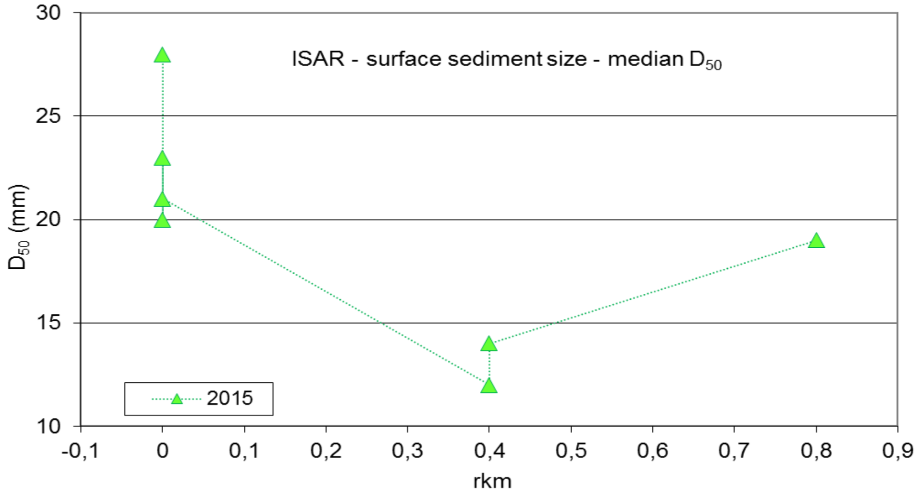


Figure 5.3.25 Bed sediment size represented by the median D_{50} grains (surface layer) at the Issar River's mouth – right-side tributary of the Upper Danube, Germany

The graph in Figure 5.3.25 shows the variations in the median D_{50} grain size of the bed material at the mouth of the Isar River. The D_{50} values range from 13 to 28 mm (the average is 20 mm), which corresponds to the grain size of the bed material downstream of the Isar River's mouth.

Bed sediment sampling, which took place in the Isar channel upstream of the river mouth (between rkm 0 and rkm 0.8), has revealed coarser gravel (Figure 5.3.25) compared to the bed material deposited in the gravel bar (Figure 5.3.27), which has been formed at the Issar River's mouth and spreading into the Danube channel (Figure 5.3.26).

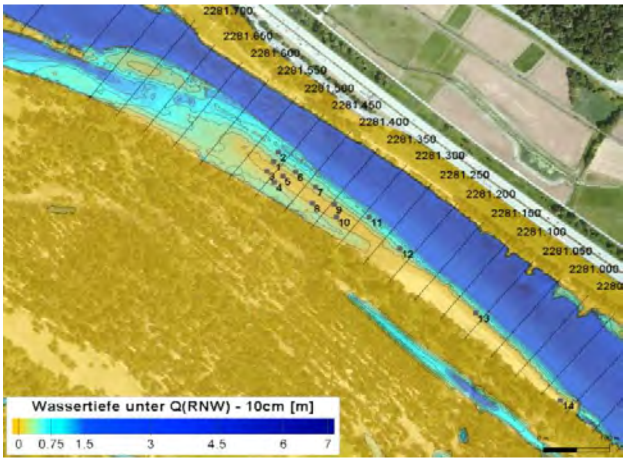


Figure 5.3.26 Sampling sites along a gravel bar at the Issar River's mouth, Upper Danube, Germany (2015)

The gravel bar consists of finer sediments that are transported from a short section downstream of the first barrier built on the Isar River. A mixture of finer sediments with similar properties (D_{50} ~10 mm, Figure 5.3.27) are deposited at the river mouth forming a gravel bar without any distinctive vertical sorting. Therefore, the differences in grain size between the surface and sub-surface sediments are very small along the whole gravel bar.

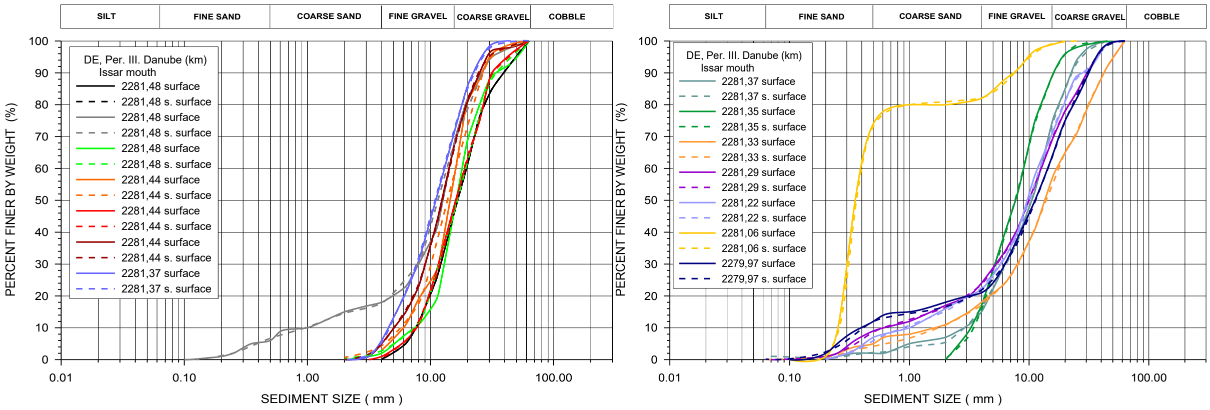
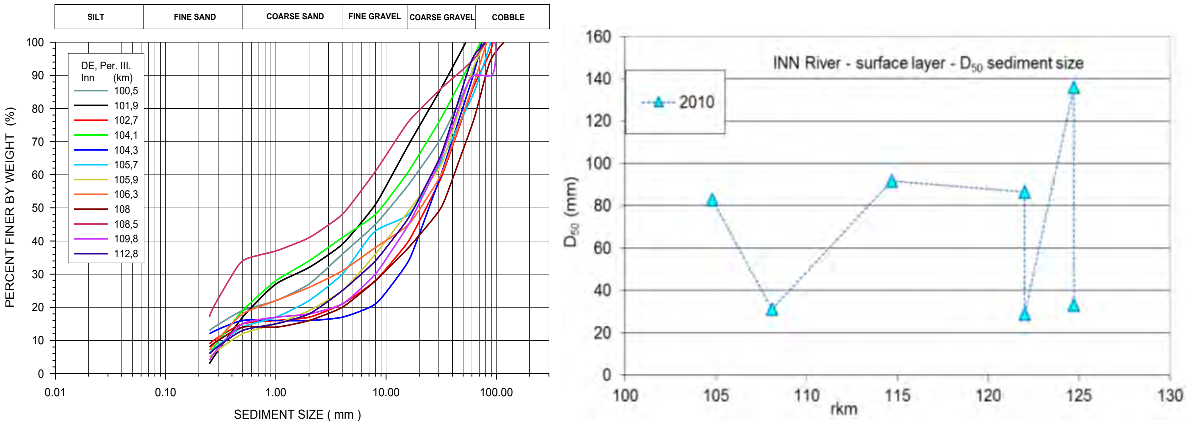


Figure 5.3.27 Grain size distribution curves of the surface and subsurface (s. surface in the graph) layers of bed sediment samples taken from the gravel bar located at Isar River's mouth (2015)

While the Isar River contributed to the coarsening of the Danube's river bed in the past, its river bed coarsening effect has disappeared almost completely owing to the disruption of longitudinal sediment continuity (damming, Figure 5.3.24). Therefore, only smaller amounts of gravel are now transported into the Danube channel, exerting only a modest local effect on the river bed composition.

INN River (Germany) is the largest tributary of the Upper Danube. It contributed significantly to the natural coarsening of the Danube's river bed in the past (before its damming). The basic properties of bed sediments are documented by grain size distribution curves (Figure 5.3.28, a), compiled for a 100 km long section upstream of the river mouth (between rkm 100 and rkm 125), and by the values of D_{50} determined for the same locality but at different times (Figure 5.3.28, b). Although river bed sampling took place within the same section, the differences in the characteristic values of D_{50} are rather large. The grain size distribution curves show values of D_{50} ranging from 5 mm to 40 mm, what indicates that the river bed composition varies from fine gravel to very coarse gravel. Data from 2010 show D_{50} values ranging from 25 mm to 130 mm, what indicates variations in the bed sediments from coarse gravel to coarse cobble. These differences also document the impact of a damming, which is reflected in the higher horizontal and vertical sorting of bed sediments in the Inn River.



a) Grain size distribution curves – surface layer (2014) b) Values of the median D_{50} grain size in the surface layers (2010)

Figure 5.3.28 Grain size distribution curves (a) and values of D_{50} (b) along a section of the Inn River (rkm 100 –125), Germany

Inn (rkm 108), a photo of the surface layer (LfU) Inn (rkm 108), a photo of the sub-surface layer (LfU)

Inn (rkm 120.2), a photo from the surface layer (LfU) Inn (rkm 120.2), a photo of the sub-surface layer (LfU)

Figure 5.3.29 Photos of samples taken from the surface and sub-surface layers of bed sediments in the Isar River – a left-side tributary of the Upper Danube, Germany (2014)

The photos in Figure 5.3.29 show bed material samples taken from the Inn River (between rkm 100 and rkm 125), including the surface and sub-surface layers. Compared with the Isar River, higher vertical sorting can be seen along the section of the Inn under investigation. The sorting process may affect the development of river bed armouring in shorter river sections (Figure 5.3.29). This situation also indicates that river bed coarsening in the Danube is currently induced (compared with Period I) by the river processes prevailing in the Danube channel. The impact of the Inn River diminished considerably during the periods II and III.

Summary: Overall, it can be stated that sediment continuity disruption has affected the composition of the river bed material not only in the Upper Danube but also in its tributaries. While the Alpine tributaries (i.e. the Isar and Inn rivers) transported a large amount of coarse sediments (coarse gravel and cobble) into the Danube and thus contributed significantly to the natural coarsening of its river bed in the past, their river bed coarsening effect has disappeared almost completely since the tributaries were dammed. Consequently, the actual changes in the composition of bed sediments in the Danube are caused by the river processes prevailing in the Danube channel, determined primarily by the disrupted sediment continuity.

5.3.3 The Middle Danube

The Middle Danube begins at rkm 1,790.0 in the Slovak–Hungarian section and ends at rkm 943.0 where the Iron Gate 1 HPP is located. The upper edge of the Middle Danube linked to a major change in the river bed slope (from 0.37% to 0.06%) is followed by a gradual change in the river bed composition. The gravel bed changes from coarse gravel into fine gravel within ***Zone 1*** located between rkm 1,660 and rkm 1,520, and from coarse sand into fine sand within ***Zone 2*** located between rkm 1,520 and rkm 1,420 (Figure 5.3.30).

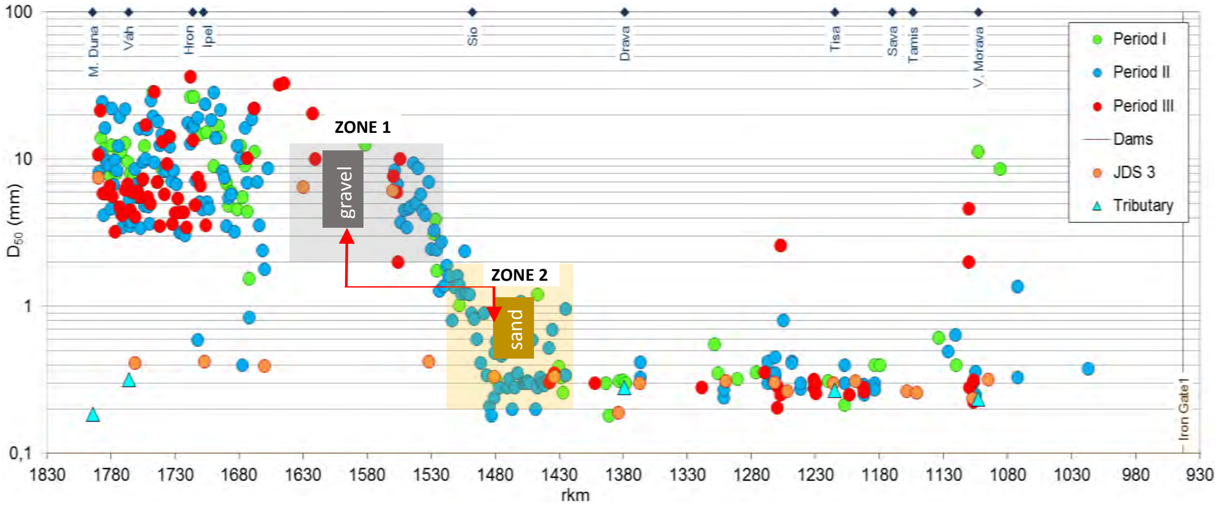


Figure 5.3.30 Variations in the median D_{50} grain size of bed sediments over three periods along the Middle Danube, including the delineation of transition zones: Zone 1– change from medium gravel to very fine gravel, and Zone 2 – very fine grave to medium sand

During the first period, the flow and sedimentary conditions in the Middle Danube were affected by river regulation and sediment dredging, but no hydropower plants were built within this river section. Thus, data on the river bed composition (D_{50}), which cover the section between rkm 1,790 and rkm 1,100, represent only slightly modified conditions.

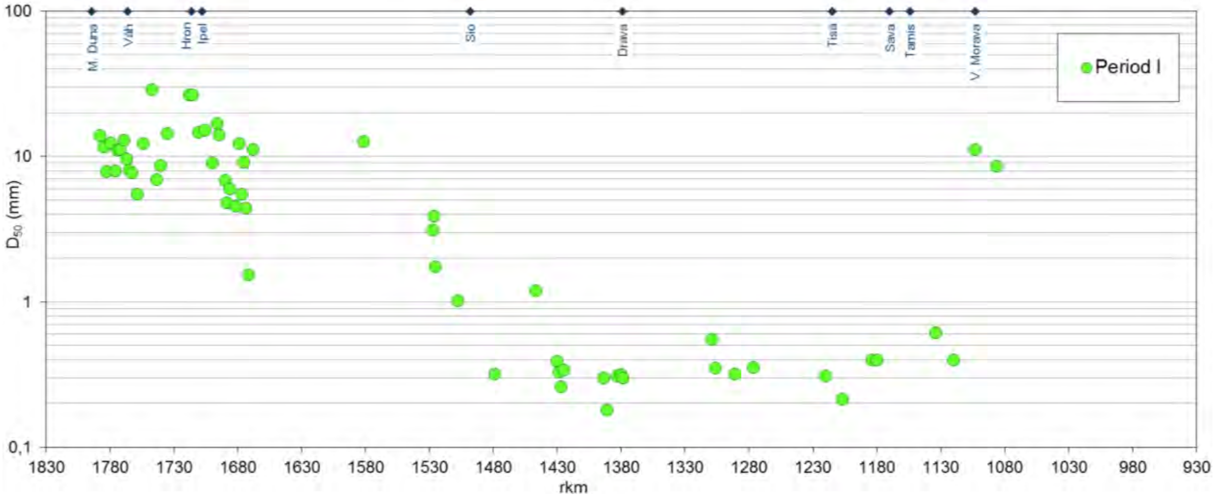


Figure 5.3.31 Variations in the median D_{50} grain size of bed sediments (surface layer) for the first period along the Middle Danube

Sediment transport along the Middle Danube over the first period was indirectly affected by the disruption of sediment continuity. The trapping effect of HPPs already built on the Upper Danube induced a decrease in the transport of sediments from the upper parts of the Danube into its middle section. Data from the first period show natural variations in the river bed material along the gravel bed section, the transition zone, and along the sand bed section (Figure 5.3.31) with an indication of the local effect of tributaries (coarsening – Hron, Velika Morava or fining – Váh, Ipel). The data also show signs of natural downstream finning along the river's gravel bed section and transition zone.

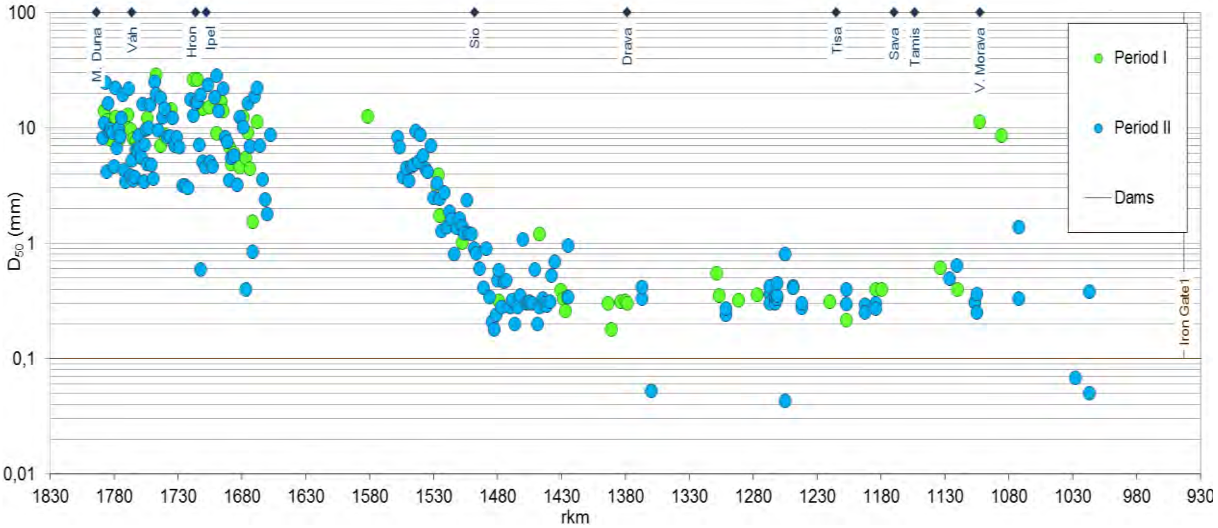


Figure 5.3.32 Comparison of bed sediments according to the median D_{50} grain size for periods I and II along the Middle Danube

The D_{50} grain size along the gravel bed section varies between ~4 mm and 30 mm; along the transition zone, D_{50} varies within in wider range (0.3 mm to 12 mm), and along the sand bed section, D_{50} varies between 0.18 mm and 0.6 mm and locally between 8 mm and 10 mm (due to gravel transport from the Velika Morava River).

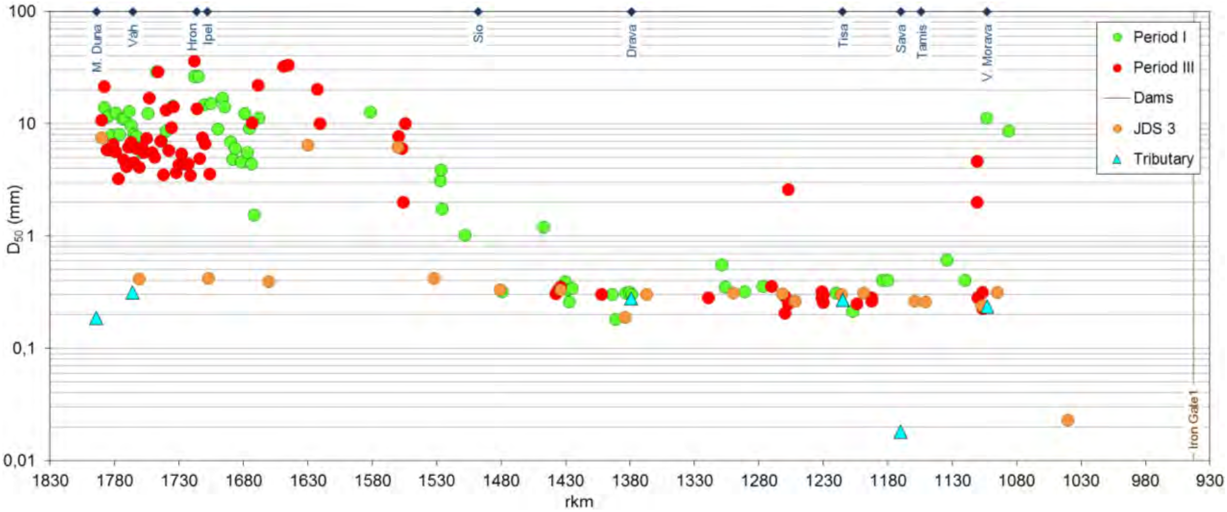


Figure 5.3.33 Overall changes in the median D_{50} grain size of bed sediments in periods I and II along the Middle Danube

In the second period, sediment continuity in the Middle Danube was already influenced by the operation of Iron Gate 1. A comparison of bed sediments according to the median D_{50} grain size for Period I and Period II indicates smaller changes (Figure 5.3.32). During the first period, tendencies towards bed sediment fining can be observed along both the gravel bed section and the transitional zone. The local effects of tributaries (coarsening and fining) and the impact of impoundment from the Iron Gate 1 HPP (sedimentation of finer fractions) on the river bed composition can also be observed during that period.

More systematic river bed fining processes occurred along the gravel section and transition zone of the Middle Danube in the third period (Figure 5.3.33). During this period, sediment continuity was seriously affected not only by Iron Gate 1 but also by the operation of the Gabčíkovo HPP, which is located close to the beginning of the Middle Danube.

The combined effect of the cascade of HPPs on the Upper Danube, including the trapping effect of the Gabčíkovo HPP, caused a decrease in the transport of coarse sediments from the Upper Danube into the Middle Danube. The impoundment from the Iron Gate 1 dam gave rise to intensive sedimentation: bedload sedimentation in the upper section (coarse sand and/or fine gravel locally) and fine sediment deposition in the lower section (Iron Gate gorge). These processes influenced the composition of the bed material in the Middle Danube during the third period. Apart from the disruption of sediment continuity, the composition of the river bed was also affected by intensive dredging, performed mostly in the second period.

Bed material samples from the Middle Danube can be seen in the photos above (Figure 5.3.34). Most of the samples were taken during a field campaign conducted within the scope of JDS3 (IDCPR, 2013). They show how the river bed material changes along this section of the Danube. The bed material varies from gravel, through coarse and fine sand, to silt (due to impoundment from the Iron Gate 1 dam).

Photo VUVH/JDS3 (ICPDR)

Figure 5.3.34 River bed material samples taken from the Middle Danube (Period III)

Trend lines (power regression) were used to illustrate the distinctions in the river bed composition along the Middle Danube, which occurred during the three periods under review. As the river bed composition in the gravel section of the Middle Danube needs to be considered in view of the neighbouring part of the Upper Danube, the D_{50} data cover the upstream section up to the last continuity barrier, i.e. the Čunovo weir on the Upper Danube (Figure 5.3.17). For the same reason, Figure 5.3.17 is already displayed in Chapter 5.5.2 as part of a bed sediment analysis on the lower edge of the Upper Danube.

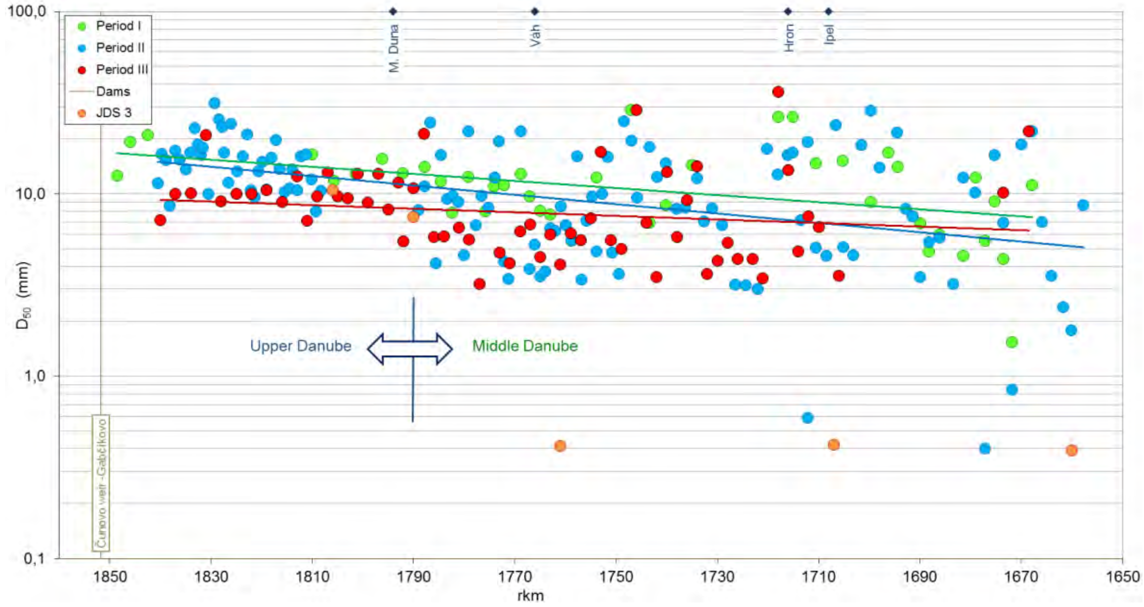


Figure 5.3.17 Comparison of the trend lines (power regression) of the bed sediment size (D_{50}) for three periods in a gravel bed section of the Middle Danube, including the neighbouring free-flowing section of the Upper Danube

The trend lines developed for three periods (Figure 5.3.17) reflect a tendency towards bed sediment fining, which started in the second period and continued in the third (last) period. The D_{50} grain size of bed sediments in Period III showed lower variability and was fairly uniform (Figure 5.3.17) along a longer part of the gravel bed section (from rkm 1,790 to rkm 1,730), which had been dredged intensively in the past (Period II). Although the volume of sediments dredged has decreased over the last decades, river bed dredging is still performed for the maintenance of stable conditions for navigation. For gravel mining, the surface layer of coarser sediments is removed and the finer sediments in the sub-surface layers are uncovered. Owing to permanent dredging, the surface layer of coarser sediments cannot be restored.

The river bed along the transition zone of the Middle Danube consist of medium gravel in the upper part, coarse sand in the middle part and medium sand in the lower part of the section. Data (D_{50}) on the transition zone cover mostly the second period, only a few values are available to document the first and third periods. Therefore, a trend line has been developed only for the second period, but data from periods I and III are also displayed in Figure 5.3.35.

The trend line indicates gradual downstream fining across the transition zones with a lower scatter (Figure 5.3.35), which reflects a low degree of modification. A comparison of the D_{50} vales that cover all three periods indicates no major changes, and the data available, especially those for Period III, are too limited to enable us to formulate final conclusions for this section of the Middle Danube.

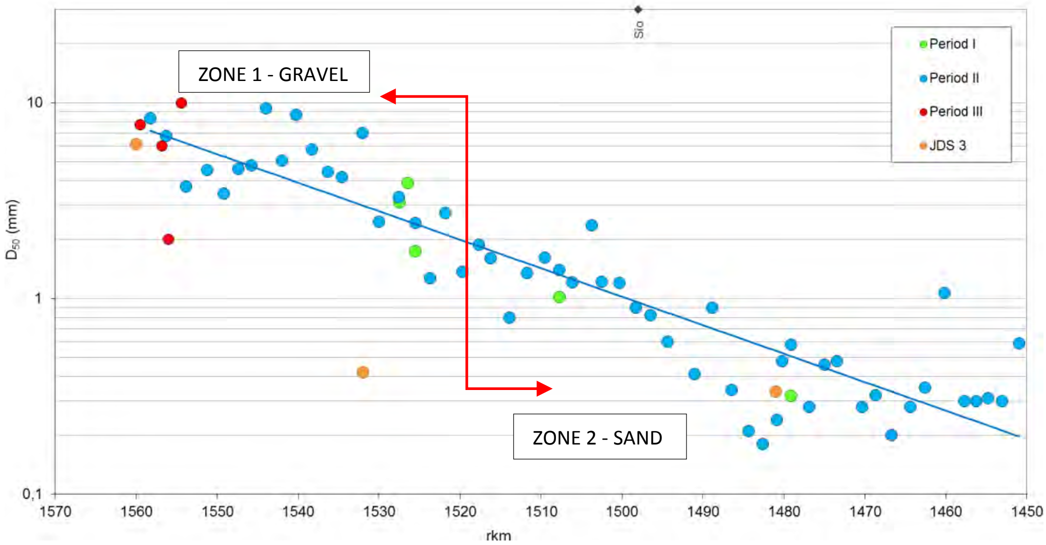


Figure 5.3.35 Trend line (power regression) of the bed sediment size (D_{50}) for Period II with background data for periods I and II, and the transition zone of the Middle Danube

The third section of the Middle Danube, located downstream of the transition zone, stretches from the beginning of the Iron Gate gorge and its lower part is influenced by impoundment (Figure 5.3.36). The river bed is composed mostly of medium sand with bed coarsening at the mouths of certain tributaries (e.g. Velika Morava). This lower section of the Middle Danube is split into two parts, which differ in the sedimentary and flow conditions. While the first part (from rkm 1,450 to rkm 1,250) is not directly affected by sediment continuity disruption, the second part downstream of Novi Sad is influenced by impoundment from the Iron Gate 1 dam.

The different sedimentary and flow conditions are also reflected in the variations occurring in the grain size of bed sediments in both parts of the river section under review (Figure 5.3.36).

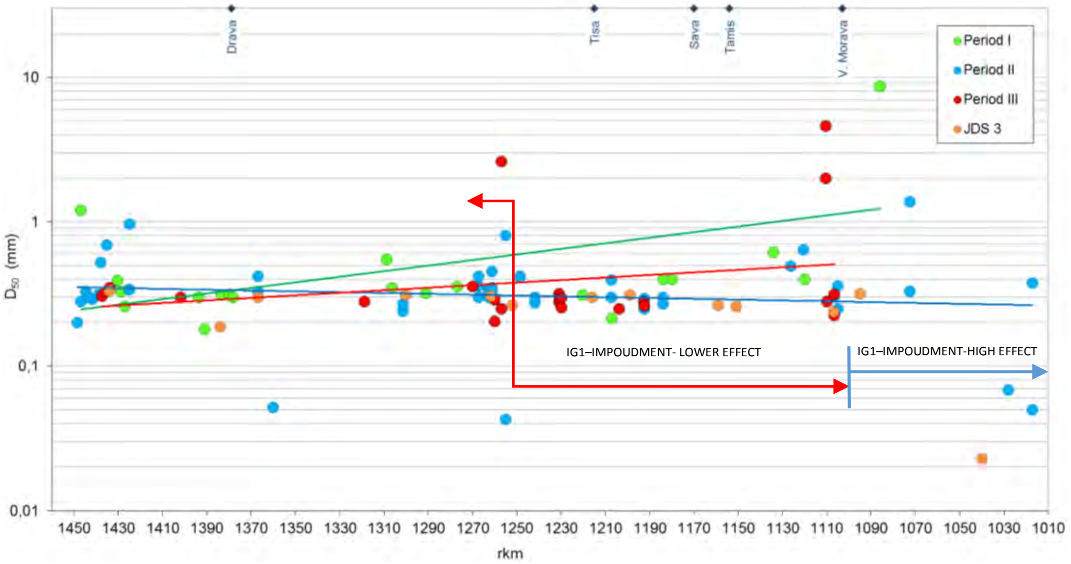


Figure 5.3.36 Comparison of the trend lines (power regression) of the bed sediment size (D_{50}) for three periods along a free-flowing sand bed section of the Middle Danube (between rkm 1,450 and 1,010)

The trend line for the first period indicates downstream coarsening (Figure 5.3.36), which is not in line with Sternberg's abrasion law. Sternberg derived an empirical formula for determining the abrasion coefficient of natural rivers – the grain size decreases with the increasing distance. However, this is valid mostly for natural rivers. A deviation from the Sternberg law may have natural or human-induced reasons. In our case, river bed coarsening in the past was caused by coarse sediments transported from gravel bed tributaries, particularly from Velika Morava. This process has been reduced by the damming of the river's tributaries. A comparison of the trend lines for all periods does not indicate changes in the river bed composition upstream of impoundments (Figure 5.3.36), but sediment fining along an impounded section is evident, especially at the lower end (rkm 1,050 – 1,030), close to the gorge. These changes are induced by a flow velocity decrease followed by the deposition of fine sediments.

Grain size distribution curves of bed sediments for the Middle Danube show high variability, which corresponds to the transition of the river bed material from coarse gravel to fine sand (Figure 5.3.37).

The content of finer fractions increases with the downstream distance. The shape and steepness of the curves considerably differ from those compiled for the Upper Danube. There are some very steep curves, compiled mostly for uniform grains (gravel/sand), as well as very flat curves, which represent a wider range of sediments: gravel, sand and even silt. Grain size distribution curves with higher variations are typical for transition zones (Figure 5.3.37, a, b), while sediment curves for sand belt sections are steep and reflect the content of uniform sand grains (Figure 5.3.37, c).

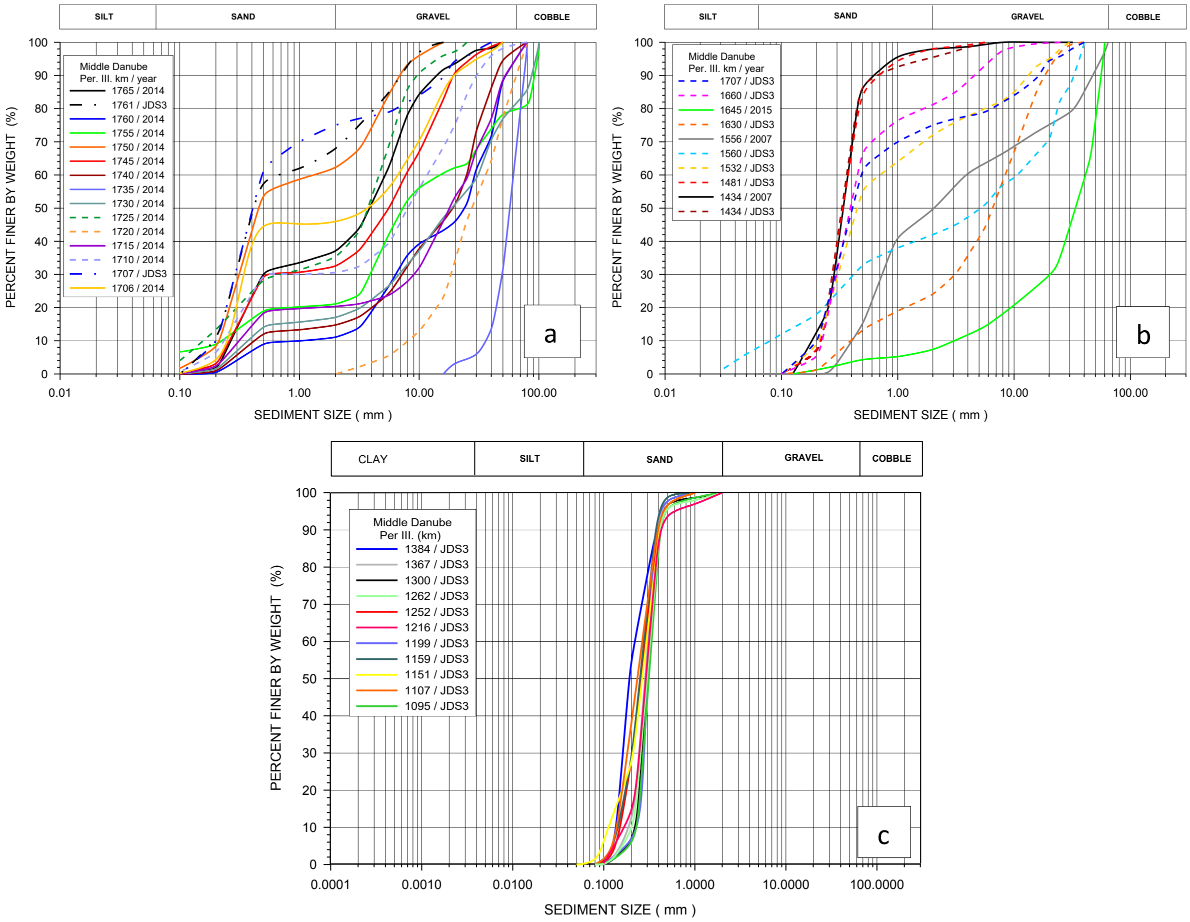


Figure 5.3.37 Grain size distribution curves of bed sediments – samples taken from the river channel of the Middle Danube (SK, HU, HR, RS, RO), Period III; a, b – gravel bed section and transition zone; c – sand bed section

The role of tributaries on the Middle Danube

Sediment balance, as well as the composition of the river bed, was greatly affected in the past by sediment transport from the river's tributaries. The construction and operation of numerous hydropower dams on the tributaries considerably reduced the sediment input during the second and third periods. Although these barriers have modified the conditions for bedload transport, there are still longer free-flowing sections downstream of hydropower dams, allowing partially reduced bedload transport in some of the tributaries (Figure 5.3.38).

Basic information on potential sediment input into the Danube from its tributaries in view of the dams built on the tributaries is summarised in Table 5.3.3. The estimation of potential sediment input from tributaries is based on expert opinions and practical experiences, combined with information provided by the project partners.

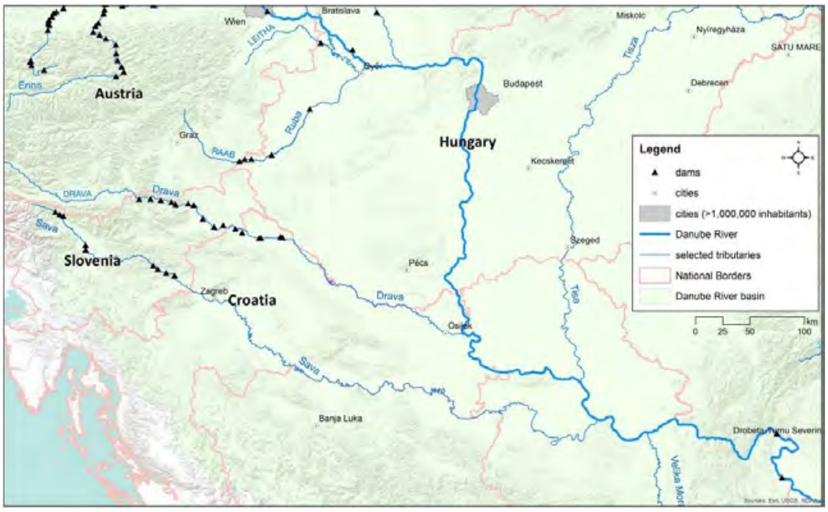


Figure 5.3.38 Localities of hydropower dams on the Middle Danube and its tributaries

Tributaries in the upper part of the Middle Danube, i.e. Váh, Hron and Ipel (see Figure 5.3.39 and Figure 5.3.40) affected the composition of the river bed in the past. The Hron River transported larger amounts of coarse gravel into the Danube causing river bed coarsening (along a few rkm- long section downstream), while sediments transported from the Váh and Ipel rivers (sand/silt) have enriched the Danube with fine sediments (Figure 5.3.31). The damming of these tributaries (Table 5.3.3) has greatly reduced the transport of sediments into the Danube over the last few decades and thus their current effect on the river bed is minimal.

Table 5.3.3 Basic characteristics of selected tributaries of the Middle Danube and the possible sediment input into the Danube channel in relation to dams built on the tributaries

No.	Tributary/mouth in country	River bed material/ at the mouth	Danube (rkm)	River side (R/L)	Q_a (m^3/s)	Length (km)	River basin area (km^2)	Possible sediment input (SR, MR, HR*) into the Danube / brief description
1	Váh – SK	sand	1766	L	152	406	10,640	**HR –**chain of hydropower plants, the first HPP ~ 65 km upstream of the mouth
2	Hron – SK	gravel	1716	L	54	298	5,453	**MR –**several small hydropower plants, first HPP ~ 30 km upstream of the river mouth
3	Ipel - SK	fine sand/silt	1708	L	21	232.5	5,151	**MR –** several barrages, the first barrage ~ 18 km upstream of the mouth
4	Drava - HR	gravel/sand on the mouth	1382	R	670	710	40,000	**MR –** 22 hydropower plants, the first HPP ~ 200 km upstream of the mouth
5	Tisza - RS	fine sand, silt	1214	L	792	966	157,186	**MR –** dam (RS) ~ 63 km upstream of the river mouth
6	Sava – RS	fine sand, silt	1170	R	1,609	990	97,713.2	**SR** – several HPPs + reservoirs on tributaries; the first HPP in Slovenia ~ 435 km upstream of the mouth
7	Tamis – RO	fine gravel, sand	1154	L	47	359	10,280	**SR** – reservoir in the RO section ~ 200 km upstream of the mouth
8	Velika Morava - RS	gravel	1103	R	255	185	38,207	**SR** – no dams on the main river; several dams on the tributaries
9	Nera/ RO,RS	gravel	1075	L		124	1,240	**SR –** no dams

**Sediment input (bedload): HR – highly reduced, MR – moderately reduced, SR – slightly reduced.*

The tributaries Drava (HR), Tisza (RS), Sava (RS), Tamis (RS), Velika Morava (RS) and Nera (RS) are located in the lower section of the Middle Danube, where the river bed is composed mostly of sand. Bed material in these tributaries varies within a wider range: from coarse gravel to sand, silt and clay (Figure 5.3.39, 5.3.40). The sediment balance of the Middle Danube had been influenced by the river's tributaries mostly in the period before a number of hydropower dams were built on the tributaries. To some extent, bed sediments can still be transported from the longer free-flowing sections of these tributaries (Table 5.3.3, Figure 5.3.38).

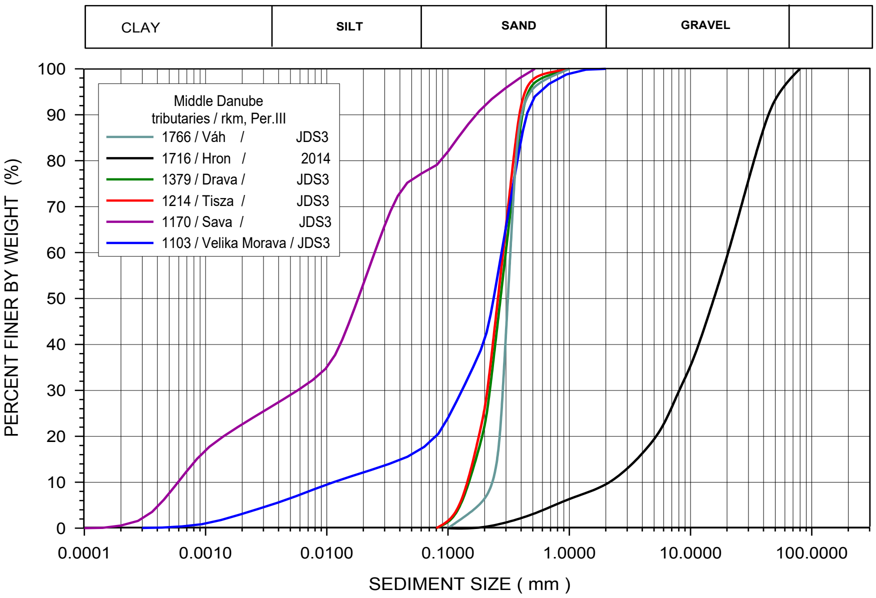


Figure 5.3.39 Grain size distribution curves of bed sediments forming the surface layer – samples taken from the tributaries of the Middle Danube (SK, HU, HR, RS,RO), Period III

Figure 5.3.40 Bed sediment samples taken from the tributaries of the Middle Danube : Váh (SK), Hron (SK), Ipel (SK) and Drava (HR), Period III

Gravel bed tributaries transporting coarse gravel into the Middle Danube (especially Velika Morava and Nera) considerably affected the composition of the Danube’s river bed in certain sections. Downstream of these tributaries, the sand bed of the Danube also contains larger amounts of gravel. This can be observed in shorter sections of the Middle Danube (a similar situation can also be seen in the Lower Danube).

5.3.4 The Lower Danube

The variability of river bed sediments was investigated in the Lower Danube section between the Iron Gate 2 dam (rkm 862) and the Danube Delta (rkm 20). Data on the bed composition (D_{50}) are available only for the third period (Figure 5.3.41). Most of the data were obtained during a field campaign conducted within the scope of JDS3 (ICPDR/2013); only a few data were provided by the project partners (RO, BG). The temporal variations occurring in the bed sediments could not be analysed owing to data gaps (in periods I and II). Therefore, only a basic evaluation of the river bed composition and its variations along the Lower Danube (in view of the effects of tributaries) could be made for the current situation (Period III).

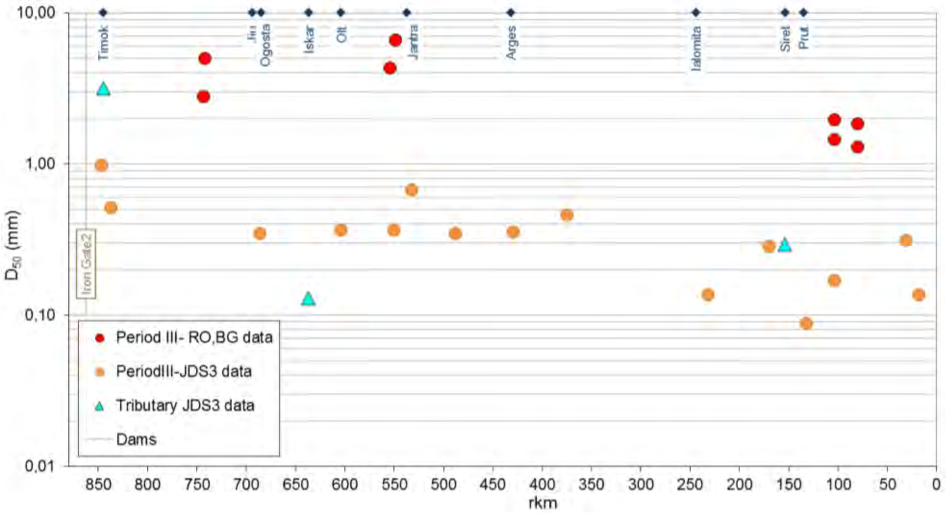


Figure 5.3.41 Variations in the grain size of bed sediments (D_{50}) for Period III along the Lower Danube section between Iron Gate 2 and the Danube Delta (rkm 862.8 – rkm 100)

Figure 5.3.42 Samples of bed sediments taken from the Lower Danube (Period III.)

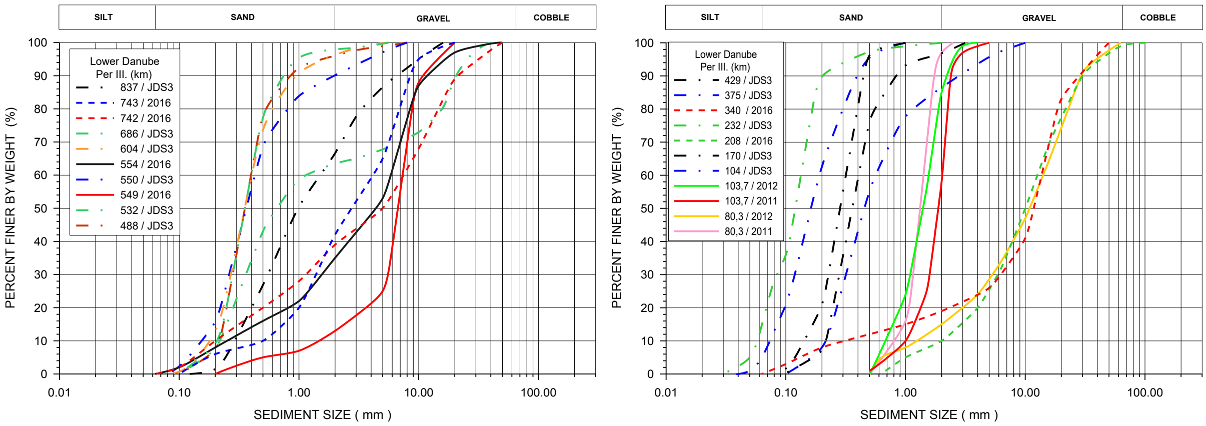


Figure 5.3.43 Grain size distribution curves of bed sediments – samples taken from the Lower Danube (JDS3, RO, BG), Period III

The river bed of the Lower Danube is composed mostly of sand (D_{50} ~1 mm to 0.09 mm). Natural river bed coarsening can be observed in shorter sections downstream of the mouth of gravel bed tributaries, e.g. Timok, Jantra and Iskar (Figures 5.3.42 and 5.3.46), which used to transport coarse sediments into the Danube in the past. By now, bedload transport in the tributaries has been reduced by damming (Figure 5.3.45). River bed coarsening (see the sample taken downstream of Jantra in Figure 5.3.42) has only a local effect on the sand river bed, which prevails along the whole Lower Danube.

The data provided by the project partners on the composition of bed material samples taken from the Danube at the mouths of gravel bed tributaries are not used for compiling a regression line. These data document the local impact of natural river bed coarsening at the mouths of gravel bed tributaries. They do not represent a typical bed material sample from the Lower Danube. Therefore, homogeneous data obtained by the same sampling and assessment method during the JDS3 campaign (2013, ICPDR) are used in the next considerations (see figures 5.3.41 and 5.3.43).

The trend line of the bed sediments grain size (D_{50}) indicates natural downstream fining (Figure 5.3.44). The Iron Gate 1 and 2 hydropower dams are the main pressures that affect the Lower Danube. However, the effect of downstream coarsening, which can be observed downstream of hydropower dams on gravel bed rivers (parts of the Upper Danube), cannot be identified in the Lower Danube, for its bed is composed mostly of coarse and find sand.

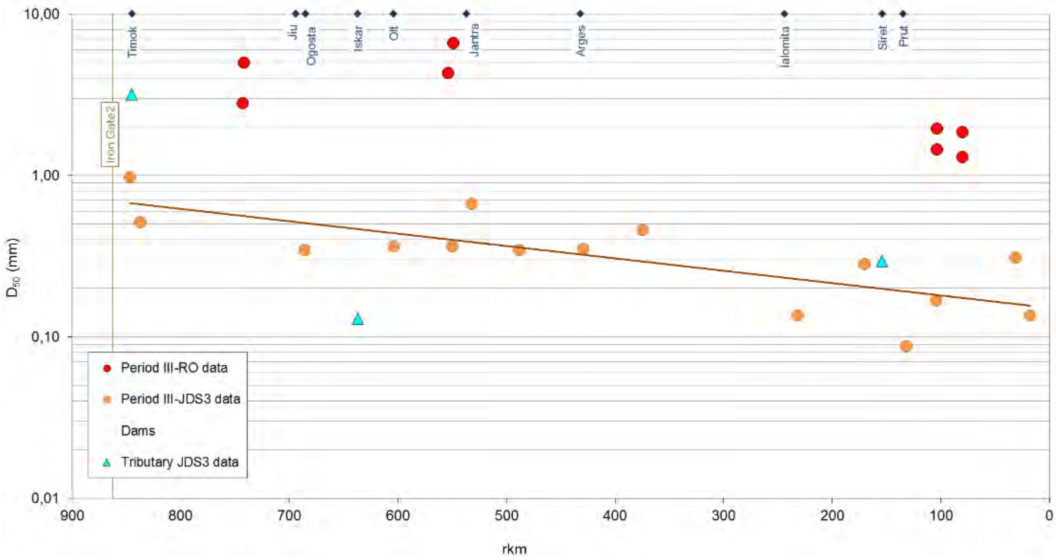


Figure 5.3.44 Trend line (power regression) of the bed sediment grain size (D_{50}) from for Period III in a free-flowing section downstream of the Iron Gate 2 dam – Lower Danube

The gradual river bed fining along the Lower Danube indicates the presence of more natural conditions compared with those seen in the Upper and Middle Danube. The impact of Iron Gate 1 and 2 on variations in bed sediments could only be verified on the basis of historical data or by a new investigation of river bed sediments, which could be carried out in the next period (10 years).

The role of tributaries – Lower Danube

The impact of some tributaries on the variability of bed sediments in the Lower Danube is apparent and is concentrated in areas at the mouths of the river's tributaries and in shorter sections downstream.

Figure 5.3.45 Hydropower dams on the Middle Danube and on its tributaries

Although this effect is only local, it is clearly manifested owing to big differences in the size of gravel from the tributaries (figures 5.3.46 and 5.3.42) and sand, which is the original bed material in the Lower Danube. An overview of the tributaries, which may contribute to the content of gravel in the bed sediments, is provided in Table 5.3.4. This table also includes an assessment of the possible sediment input into the Danube in view of the dams built on the tributaries (based on expert opinions and the partner´s practical experiences).

Table 5.3.4 Basic characteristics of selected tributaries of the Lower Danube and the possible sediment input into the Danube in relation to the dams built on the tributaries

No	Tributary/ country	Danube (rkm)	Bed material/ river mouth	River side L/	Q_a River mouth (m^3/s)	Length (km)	River basin area (km^2)	Possible sediment input (SR, MR, HR*) into the Danube / brief description
1	Timok/BG	846	gravel	R	31	202	4,626	**SR** – no dams (?)
2	Jiu/RO	694	gravel	L	95	339	10,080	**HR –** 4 dams**,** first dam ~20 km upstream
3	Ogosta/BG	685	sand	R	18	147,4	3,157	**HR –** dam ~14 km upstream of the mouth
4	Iskar/BG	636	gravel	R	55	368	8,617	**HR** – cascade of HPPs, first ~20 km upstream
5	Olt/RO	604	gravel	L	174	615	20,050	**HR** – first dam ~18 km upstream of the mouth
6	Yantra/BG	537	gravel	R	47	285	7862	**HR** – number HPPs, first dam ~13 km upstream
7	Arges/RO	432	sand/gravel	L	71	350	12,550	**HR** – number HPPs, first dam ~14 km upstream
8	Ialomita/RO	244	sand	L	45	417	10,350	**HR** –number of HPPs, first ~ 30 km upstream
9	Siret/RO	155	sand	L	250	647	44,811	**HR** –number of HPPs, first dam ~15 km upstream
10	Prut/RO	132	sand/silt	L	110	953	27,500	**MR** – dam ~300 km upstream of the mouth

**Sediment input (bedload): HR – highly reduced, MR – moderately reduced, SR – slightly reduced.*

Natural river bed coarsening is caused by fractions of coarse grains (gravel) are transported into the Lower Danube the bed of which is composed of sand (see Figure 5.3.42, downstream of Jantra). The consequences of river bed coarsening from the past (before the tributaries were dammed) have remained in the Lower Danube. By now, the sediment input – bedload transport from the tributaries has stopped almost completely owing to the barriers (hydropower plants, dams, weirs) built on the Danube's tributaries during the second and third periods (Figure 5.3.45)

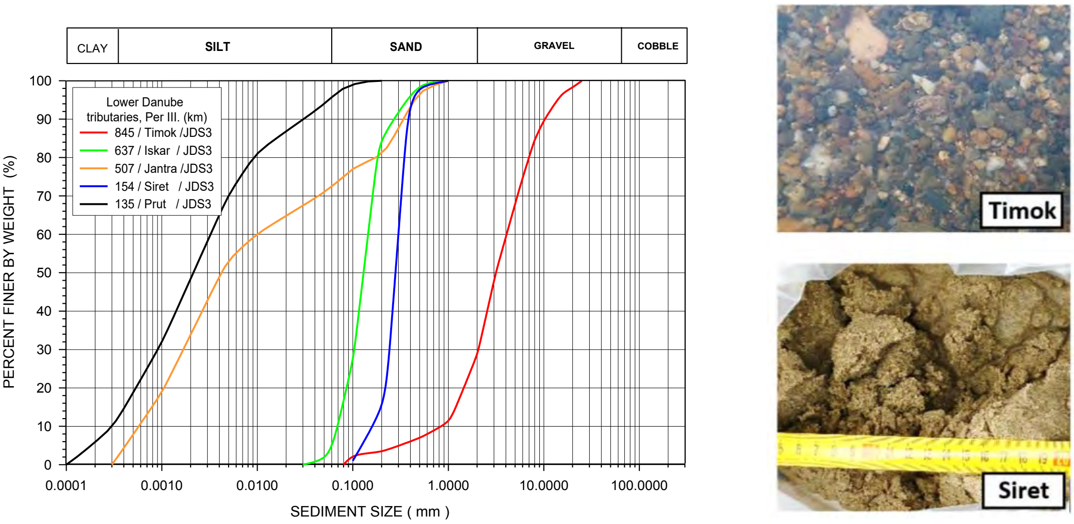


Figure 5.3.46 Grain size distribution curves of the bed sediments – samples taken from the tributaries – Lower Danube (RS, BG, RO), Period III

Natural river bed coarsening is caused by fractions of coarse grains (gravel) are transported into the Lower Danube the bed of which is composed of sand (see Figure 5.3.42, downstream of Jantra). The consequences of river bed coarsening from the past (before the tributaries were dammed) have remained in the Lower Danube. By now, the sediment input – bedload transport from the tributaries has stopped almost completely owing to the barriers (hydropower plants, dams, weirs) built on the Danube's tributaries during the second and third periods (Figure 5.3.45).

5.3.5 Additional parameters of the Danube sediments indicative to the river processes

River bed material samples have been taken in order to obtain information on grain size distribution in the river bed. According to Bunte and Abt (2001), the main purposes for obtaining such information can be grouped into three major areas:

- river bed monitoring for detecting watershed effects, analysis of stream habitats, and the evaluation of mitigation /restoration efforts;
- computation of flow hydraulics, bedload transport rates, transport capacity, and of the flow competence to analyse and predict river behaviour;
- advancement in the understanding of river processes.

Grain size distribution curves provided by the project partners for the Danube are based on data obtained during occasional river bed monitoring campaigns and during field campaigns conducted within the scope of JDS3 (2013, ICPDR). These data provide more detailed information on the composition and variability of bed sediments despite their spatial and temporal inhomogeneity.

A basic analysis of the grain size distribution curves of bed sediments in the Danube is already included in chapters 5.3.2, 5.3.3 and 5.3.4. The characteristic grain sizes of river bed sediments (from D_5 to D_{95}) are estimated for the whole Danube River. The statistical parameters of grain size distribution curves provide a deeper view of the content of coarse/fine sediment fractions in the bed material samples and contribute to the knowledge of river processes (erosion/ sedimentation). Such analysis is usually carried out for gravel/cobble bed rivers, where statistical parameters like mean/median, sorting, skewness and kurtosis can reflect the prevailing processes. However, a statistical analysis requires adequate data quality and quantity.

The bed material particle size can be quantified through an analysis of the frequency distribution of particle sizes contained within a bed material sample. In order to obtain reliable results, the bed material samples need to be representative enough for the river sections under review. The sampling approach to gravel/cobble bed rivers differs markedly from that to sand bed rivers and generally depends on study objectives. Sampling in a sand bed river is a relatively straightforward task as samples taken from several locations distributed systematically over the river bed provide sufficient information, while sampling in a gravel/cobble bed river is rather complicated. In view of the spatial variability of the bed material, sampling localities need to be determined within an appropriate channel length (5–7 channel widths or a downstream sequence of riffles/pools), width (left/right side, central part) and depth (for specific tasks also the composition of the subsurface layer – usually for sediment transport calculations).

Most of the data provided by the project partners represent results from occasional sampling obtained by various methods within different periods and only from a few sites. No specific emphasis is laid on locality representativeness (the distances between samples often exceeded tens or hundreds of kilometres). Many of the bed sediment curves are incomplete, either in their lower parts (fine fractions, sand and silt are missing, see figures 5.3.18 and 5.3.19) or more than half of the curves are missing (these data have been excluded from further analyses). Although the data available do not represent a sufficient quantity and quality for a comprehensive statistical analysis, some parameters are estimated (mean/ median, sorting, skewness) to document data gaps and options for future improvement.

The characteristic sizes of riverbed sediments (D_5 D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, D_{95}) are estimated for whole Danube River, for Period III (Figure 5.3.47). The distribution of these characteristic values along the Danube show not only the bed material prevailing along certain river sections, but also indicate the content of coarse or fine sediments (Figure 5.3.47).

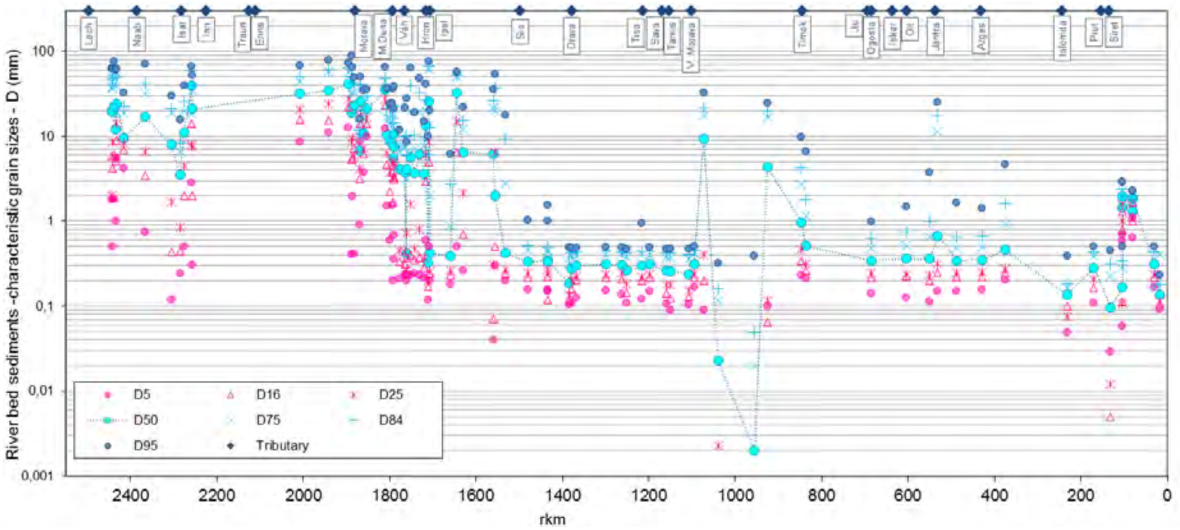


Figure 5.3.47 Characteristic grain sizes of riverbed sediments (D_5 D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, D_{95}) along the whole Danube River (Period III)

Particle size distribution for a gravel or cobble bed river can be commonly characterised by the following distribution parameters:

- *Median* – corresponds to 50 percentile on a cumulative curve, where half of the particles by weight are larger and half are smaller than the median, it can be measured in mm or ϕ;
- *Mean* – characterizes the central part of the distribution;
- *Sorting* – standard deviation or width of the distribution, i.e. the range of particle sizes within which the present percentage of all data is contained;
- *Skewness* – which is a measure of deviation from the symmetry of a distribution;
- *Kurtosis* – which is the flatness or peakedness of the distribution.

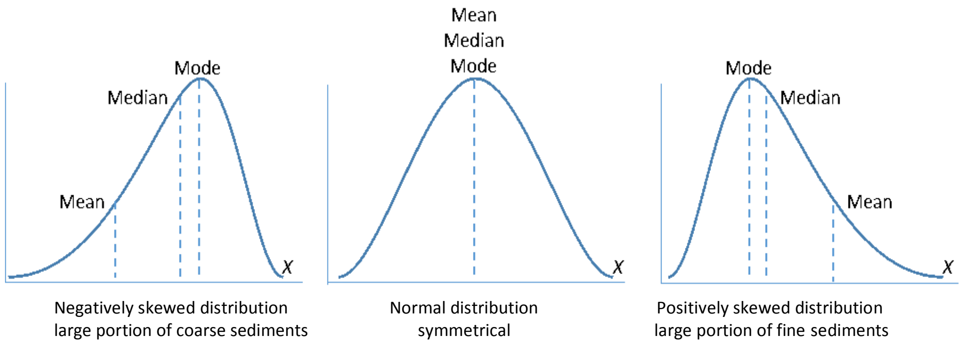


Figure 5.3.48 Graphical interpretation of statistical parameters: mode, median and mean in different types of distribution curves

The parameters median, mean and skewness represent the degree of symmetry in different types of distribution curves (Figure 5.3.48). The literature offers several possibilities for the estimation of distribution parameters (Bunte and Abt, 2001). These parameters can be computed using percentiles (a graphic approach) or the percentage frequency of distribution (a frequency approach). Both methods can be applied to particle sizes in mm (a geometric approach) or to particle size in ϕ-units (an arithmetic approach). Trusk´s mixed approach (1932) was used for computing the distribution parameters (mean, sorting, skewness) in this study.

In regard to data quality and availability, only data covering the gravel bed section of the Danube between rkm 2,580 and rkm 1,800 (a major part of the Upper Danube) can be used for statistical analysis. The median and mean values are compared for the whole Danube and Period III.

Median: corresponds to 50 percentile on cumulative curves (D_{50}), its value is estimated from grain size distribution curves;

Mean M_z: represents the average grain size of riverbed sediments, its value is calculated using the following equation (5.3.1).

$$M_z = \frac{D25 + D75}{2} \qquad (5.3.1)$$

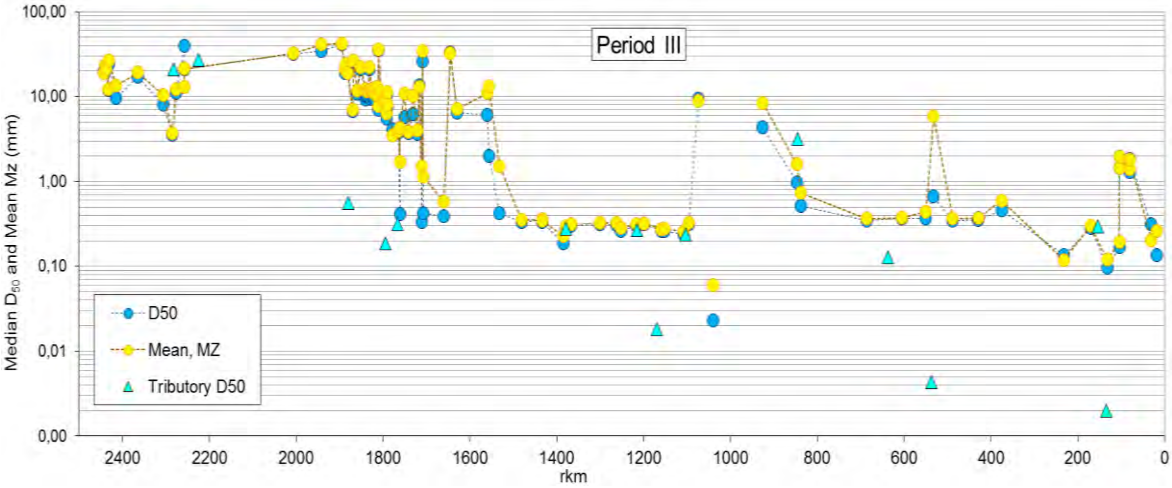


Figure 5.3.49 Variations in the median D_{50} and mean M_z values along the whole Danube River (Period III)

A comparison of the mean (M_z) and median (D_{50}) values shown in Figure 5.3.49 indicates that there is a portion of fine (positively skewed distribution) or coarse sediments (negatively skewed distribution) in the samples of river bed sediments along the whole Danube within the third period. The mean and median values are almost identical or are very close to each other in many sites on the Middle and Lower Danube. It means that the distribution curves are symmetrical (normal distribution) and the bed material contains proportional amounts of finer and coarse sediments. Smaller deviations from normal distribution occur in areas of local bed material coarsening/finning caused by the tributaries (negatively/positively skewed) and bed sediments fining within impoundments from the Iron Gate 1 dam (positively skewed – larger portions of fine sediments). However, the river processes can be identified only in the case of better data. With regard to data availability, these results are only indicative. The main purpose of this comparison (Figure 5.3.49) is to document the information and knowledge obtained where data of higher quality are available.

The mean and median values were calculated for two periods (I, III) in a section of the Upper Danube (between rkm 2,600 and rkm 1,800). As a paradox, the data obtained for the first period are more detailed and they cover a larger part of the Danube section under investigation (Figure 5.3.50) then the data on the current state – Period III (Figure 5.3.51).

A comparison of the mean and median values calculated for the first period (Figure 5.3.50) show more natural variations in the bed material size (compared with Period III – Figure 5.3.51), as well as variable portions of coarse and fine sediments (left/right skewed distribution) in the river bed. Sites where both values are identical represent areas where the portions of coarse and fine sediments are balanced (normal distribution).

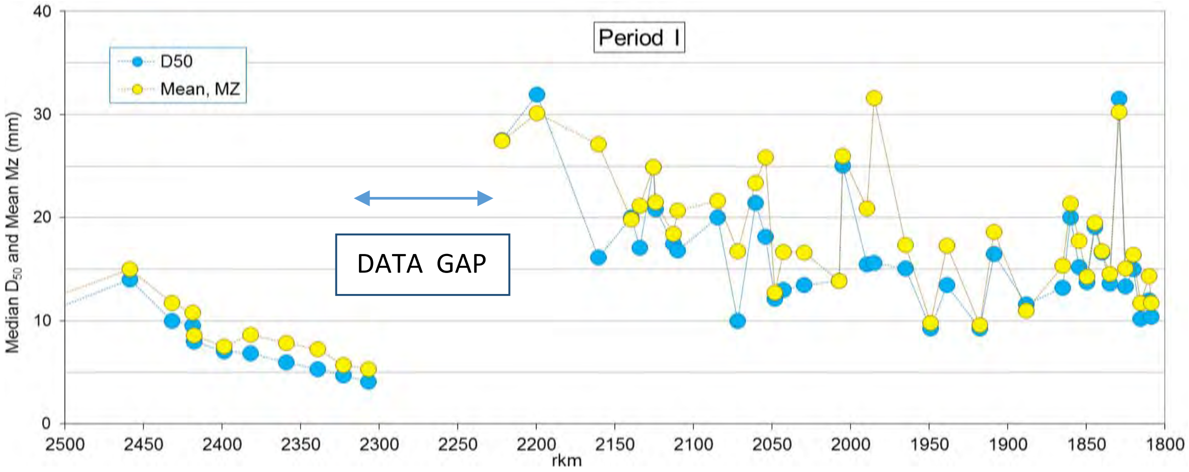


Figure 5.3.50 Variations in the median D_{50} and mean M_z values – Upper Danube (Period I)

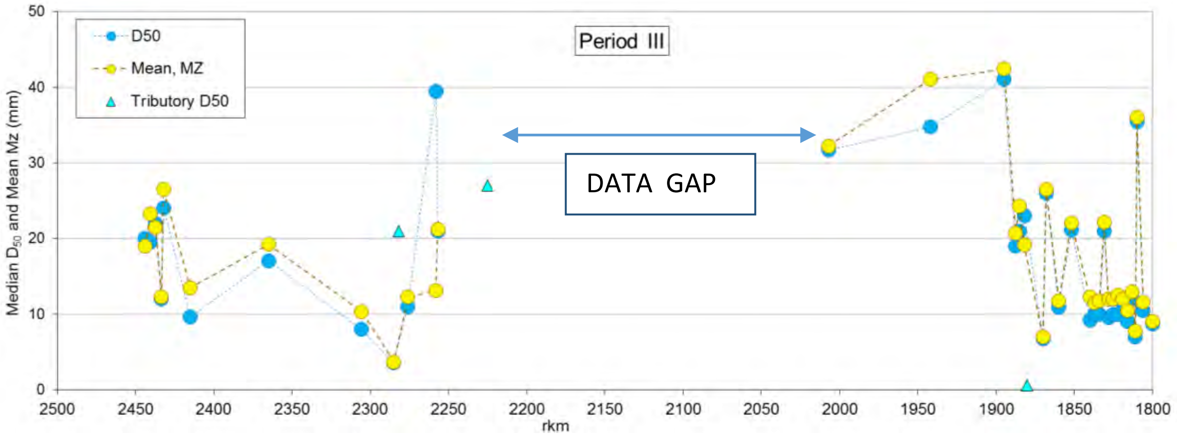


Figure 5.3.51 Variations in the median D_{50} and mean Mz values – Upper Danube (Period III)

Major changes in the mean and median values estimated for Period III (Figure 5.3.51) indicate river bed coarsening in certain localities. Comparisons of these values within two periods indicate basic trends, but the range of data, including data gaps, does not allow us to draw reliable conclusions from the variations occurring in the river processes. In view of the present state of the Upper Danube, river bed monitoring in the future should focus on the free-flowing gravel bed sections of Danube.

Bed material sorting σ (including graphic standard deviation): is the measure of particle size sorting or of particle size variations. Quantitatively, bed material sorting specifies the range of particle size variations. The terms defining the sorting of sediments are included in Table 5.3.5, with a graphical illustration of interoperations in Figure 5.3.52.

Sediments in gravel bed rivers are naturally sorted, laterally and longitudinally. Depending on the flow and sedimentary conditions, riffle/poll sequences are developed and variable habitats are created in the river channel. Sorting in a gravel bed river also gives rise to the creation of a natural coarser layer on the bed surface. However, natural sorting has been affected by river training, flow regulation and sediment continuity disruption. The modified flow and sedimentary conditions have led to the creation of bed armouring in the areas downstream of dams.

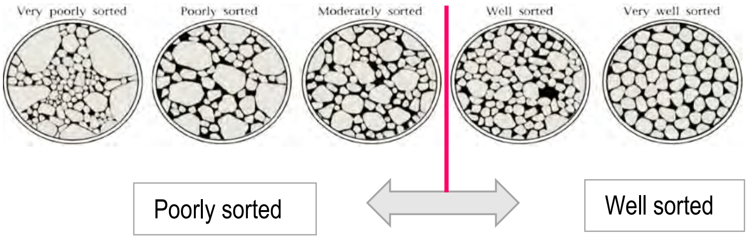


Figure 5.3.52 Samples of river bed sediments with different degrees of sorting

Table 5.3.4 Classification of the degree of sorting (Folk & Ward, 1957)

Sorting coefficient	Characterisation
> 4	extremely poor
2 – 4	very poor
1 – 2	poor
0.71 – 1	moderate
0.50 – 0.71	moderately well
0.35 – 0.50	well
< 0.35	very well

Armouring as a segregation phenomenon, occurs when the bed surface of a gravel-bed river is coarsened in relation to the sub-surface. The degree of armouring can be expressed by the armour ratio:

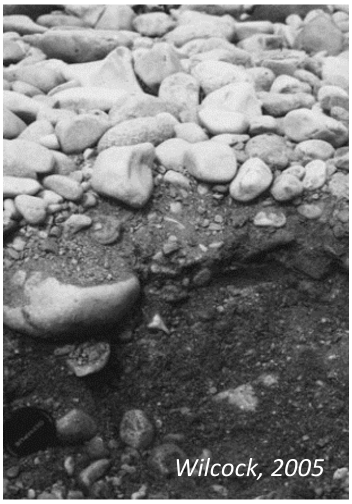
$$Armour\ ratio = \frac{\mathrm{D50,\ surface}}{\mathrm{D50,\ subsurface}} \qquad (5.3.2)$$

Where D_{50} surface > D_{50} subsurface, river bed armouring is taking place.

Gravel-river beds typically have an ‘armoured’ layer of coarse grains on the surface, which protects the finer particles underneath from erosion (Behrooz Ferdowsi et al, 2017)

Armouring process (Curran & Tan, 2010): the water flow exerts shear stresses weaker than required to move large particles but strong enough to move the fine particles. The flow entrains the fine particles, winnowing them from the bed surface forming a coarse surface layer without fine grains. The coarse layer increases its resistance to entrainment, while gravel bed armouring influences in-stream hydraulics and habitats. Dams that are very distinct, both spatially and temporally, exacerbate armouring in gravel bed streams.

The armour layer clast size distribution is generally coarser than its substratum such that the armour ratio (armour median/sub-armour median) lies generally within the range of 1.5 to 2, but its ranges not untypically up to the value of 6 (Andrews and Parker, 1987; Sutherland, 1987).



Armour layer- gravel bed river

Knowledge of the development of an armour layer is important in particular for a quantitative investigation of sediment transport and for a morphological analysis of the river channel. River bed armouring can be identified using equation shown above (5.3.2), but data on the composition of the subsurface layer (D_{50sub}) are available only for the Upper Danube. Therefore, sections with river bed armouring cannot be identified in this study. In this context, the values of bed sediment sorting (σ) indicate a potential for armouring development. The lower the sorting coefficient (σ < 0.5), the higher the probability of armouring.

Sediment sorting coefficients (σ) are calculated using the following equation:

$$\sigma = \sqrt{\frac{D84}{D16}} \tag{5.3.3}$$

The values of sediment sorting coefficients (σ) for a delineated section of the Upper Danube and data from the first and third periods are shown in Figure 5.3.53. The sorting coefficients (σ) cover three areas, ranging from ‘extremely poor’ to ‘poor’ sorting. The variations in particle size distribution within the third period represent more natural conditions, particularly along the Austrian Danube (based on data from 1937). Most values are displayed as ‘extremely poorly sorted’ – which is reflected in the high grain size variability. The values, along the German (data from 1965) and Slovak–Hungarian (data from 1967) sections of the Danube document the period when the flow and sedimentary conditions had already been modified (HPPs, dredging). This is reflected in the lower grain size variability, as well as in the decreased sediment sorting coefficients, which are displayed as ‘very poorly sorted’ and ‘poorly sorted’.

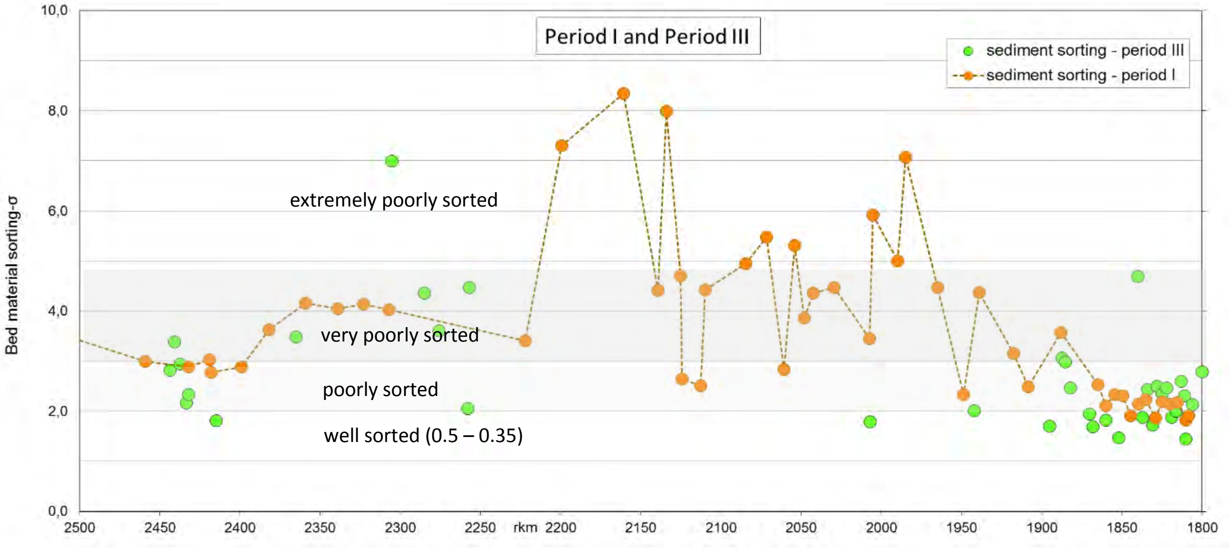


Figure 5.3.53 Comparison of bed sediment sorting (σ) within a delineated section of the Upper Danube – Periods I and III

The comparison of sorting values obtained for two periods (Figure 5.3.53) is restrained by the scope of data available for the present period, hence the results can only indicate the basic trends. In this case, a minor decrease in the sorting values, from 'extremely poorly sorted' to 'poorly sorted' indicate the actual modification of the Danube River.

Two further statistical parameters, i.e. *bed material skewness* sk_1 (measures the degree to which a cumulative curve approaches symmetry) and *bed material kurtosis* k_g (measures the 'peakedness' in distribution curves), are not taken into account in the evaluation. Both parameters are too specific, usually calculated and analysed with the scope of a very detailed investigation of a gravel/cobble river bed, which is beyond the main objectives of this study. The scope of data and their quality is also limiting factor.

5.3.6 Conclusions and recommendations

The morphology of an alluvial river channel is the consequence of sediment transport and of the erosion and sedimentation processes taking place in the river. The morphological process is determined mainly by the calibre and quantity of sediments transported into the river channel, though it is modulated by the channel scale (Church, 2006). Therefore, sediment calibre is one of the key morphological characteristics of a river channel. The composition of bed sediments and their spatial variability belong to the key parameters in any quantitative estimation of sediment transport. The main hydromorphological pressures affect the spatial and temporal variations of the sediment budget, including the bed sediment size. Therefore, the variability in the bed sediment size over space and time is one of the important indicators that can be used to identify the causes of hydromorphological pressures and their effects on morphological changes.

This chapter provides important information on the spatial and temporal variations observed in river bed sediments along the Danube (between rkm 2600 and rkm 100) and its main tributaries. Analyses of bed sediments are based on temporal variations of the median grain size (D_{50}) and on the grain size distribution curves, which provide a more detailed view of the composition of the bed surface layer. Although the data are not homogeneous (owing to the use of different sampling methods, time, sampling sites, and incomplete data), a large number of data covering all three periods provide a sound basis for an analysis of the current composition of bed sediments and its variability over time. The impact of disrupted sediment continuity (the main hydromorphological pressure on the Danube) on the composition of bed sediments can be observed in certain sections of the Danube. Generally, it can be stated that dams/HPPs built on the Danube have caused bed sediment fining within impounded sections upstream of the dams (sedimentation) and bed sediment coarsening downstream of the dams (owing to erosion and potential armouring) along gravel bed sections of the Danube. Extensive dredging have caused bed sediment fining (removed the naturally coarser surface layers) along the gravel bed section of the Middle Danube. River bed sediments in the Lower Danube do not indicate any significant changes.

With regard to the quantity and quality of the data available, the results of a statistical analysis point to the type of knowledge that could potentially be obtained if higher-quality data were available. For grain size distribution curves, the basic statistical parameters are estimated and compared within three periods (*median*, *mean, sorting*). The characteristic grain sizes of river bed sediments D_5 D_{16}, D_{25}, D_{50}, D_{75}, D_{84}, D_{95} in the Danube channel (Period III) are estimated for the whole Danube and the variability of the median grain size (D_{50}) for three periods are graphically illustrated as GIS layers (see figures 5.3.54, 5.3.55 and 5.3.56).

An in-depth analysis of the spatial variations of bed sediments in relation to the main pressures and modified flow and sedimentary conditions has revealed higher-quality data on the surface and subsurface layers of the river bed.

The main results can be summarised as follows:

- **The river bed of the Danube** is composed of gravel and sand. The bed material in the Upper Danube (between rkm 2,600 and rkm 1,790) consist of coarse and fine gravel. The Middle Danube includes a transitional zone, the gravel bed of which changes into a sand bed (gravel bed section: from rkm 1,790 to rkm 1,520, sand bed section: downstream from rkm 1,520). Bed sediments in the Lower Danube (from Iron Gate 2 at rkm 862.8 to rkm 100) consist of coarse and fine sand, and clay in the Danube delta.

- **Changes in the composition of the bed material:** except of natural downstream fining, a variability of the bed sediments on gravel bed section between rkm 2,600 and rkm 1,520 is affected particularly by disruption of sediment continuity and bed dredging, which are the main hydro-morphological pressures that have caused local bed material changes in the Danube. Excessive dredging induced bed sediment finning downstream of the

Gabcikovo HPP. Fine sediments are deposited within impounded areas (sedimentation) upstream of HPPs and coarsening occurs at several localities downstream of HPPs on free flowing sections. The lower section of the Middle Danube is affected by sedimentation and bed material fining in the area of the Iron Gate reservoir. In view of the morphological character of the Lower Danube and the possible impacts of the main hydromorphological pressures, the sand river bed do not indicate any significant changes, though certain data from the past are missing.

- **Impact of tributaries in the past (Period I):** the tributaries of the Danube contributed substantially to the river's sediment budget and affected the composition of the bed sediments in varying degrees. River bed coarsening was observed in the Upper Danube (it was caused by the river's Alpine tributaries, i.e. Isar and Inn), in the Middle Danube (caused by gravel bed tributaries, i.e. Hron and Velika Morava), and in the Lower Danube (caused by the Timok and Jantra tributaries). River bed fining occurred mostly in the Middle and Lower Danube sections (it was caused by the tributaries Váh, Ipel, Tisza, Sava, Siret and Prut). While the impact of the Alpine tributaries on river bed coarsening was fundamental, the impact of others tributaries was mostly local, inducing river bed coarsening or fining in the shorter sections. **At the present time (Period III):** the impact of the Danube's tributaries on the grain size of bed sediments has been reduced considerably during the second and third periods by dams built across the tributaries. Currently, only reduced amounts of finer sediments are transported into the Danube. The river processes prevailing in the Danube channel and reflecting of effects of disrupted sediment continuity are driven mostly by the actual changes occurring in the composition of bed sediments.

FINDINGS IN THE UPPER DANUBE

Period I (12 HPPs already built on the German Danube, but no HPP on the Austrian and Slovak–Hungarian Danube): the median grain size (D_{50}) of bed sediments varied from ~4 mm to 30 mm; the Alpine tributaries (Isar and Inn) induced intense natural river bed coarsening in the Danube channel, with the median value (D_{50}) increasing from ~4 mm to 30 mm.

Period II (most of the HPPs already built): the median grain size (D_{50}) of bed sediments varied form ~3 mm to 45 mm.

Period III – present state: the median grain size (D_{50}) of bed sediments varies from ~3.5 mm to 40 mm; within impoundments upstream of run-of-the-river power plants: $D_{50} > 0.16$ mm; in the Hrušov Reservoir upstream of the Gabčíkovo HPP built on a bypass canal: $D_{50} > 0.03$ mm.

Impacts of disrupted sediment continuity in the Upper Danube: changes in free-flowing sections downstream of HPPs – river bed coarsening with a maximum difference in the D_{50} grain size (average value for eroded areas) from 10 mm to 22 mm, representing a 220% increase in the median grain size; changes within impoundments upstream of run-of-the-river power plants – a maximum decrease from 10 mm to 0,16 mm, and in the Hrušov Reservoir (Gabčíkovo HPP) from 20 mm to 0.04 mm.

FINDINGS IN THE MIDDLE DANUBE

The river bed composition is changing from coarse gravel to fine sand according to the type of the river's bed material, the Middle Danube can be split into three sections: a gravel bed section between rkm 1,790 and rkm 1,660, a transitional section (gravel and sand) between rkm 1,660 and rkm 1,420, and a sand bed section between rkm 1,420 and rkm 943.

Period I: in the gravel bed section, the median values (D_{50}) varied from ~ 4 mm to 30 mm; in the transitional section within which the river bed material is changing from coarse gravel to fine sand (between rkm 1,660 and rkm 1,420), two zones can be distinguished: Zone 1 (between rkm 1,660 and rkm 1,520) within which medium gravel is changing into very fine gravel, with the median D_{50} values decreasing from ~16 mm to 2 mm, and Zone 2 (between rkm 1,520 and rkm 1,420) within which very fine gravel is changing into medium sand, with the median D_{50} values decreasing from ~2 mm to 0.3 mm; in the sand bed section (between rkm 1,420 and rkm 943), the median D_{50} values vary from ~ 0.18 mm to 0.60 mm, with local coarsening at the mouths of the tributaries (D_{50} can locally reach 8 – 10 mm).

Period II – river bed fining was first observed in the upper part of the gravel bed section of the Middle Danube (as a consequence of dredging) and also within an impounded part of the sand bed section (as a consequence of sedimentation) in which the median values (D_{50}) decreased in some locations to 0.04 mm.

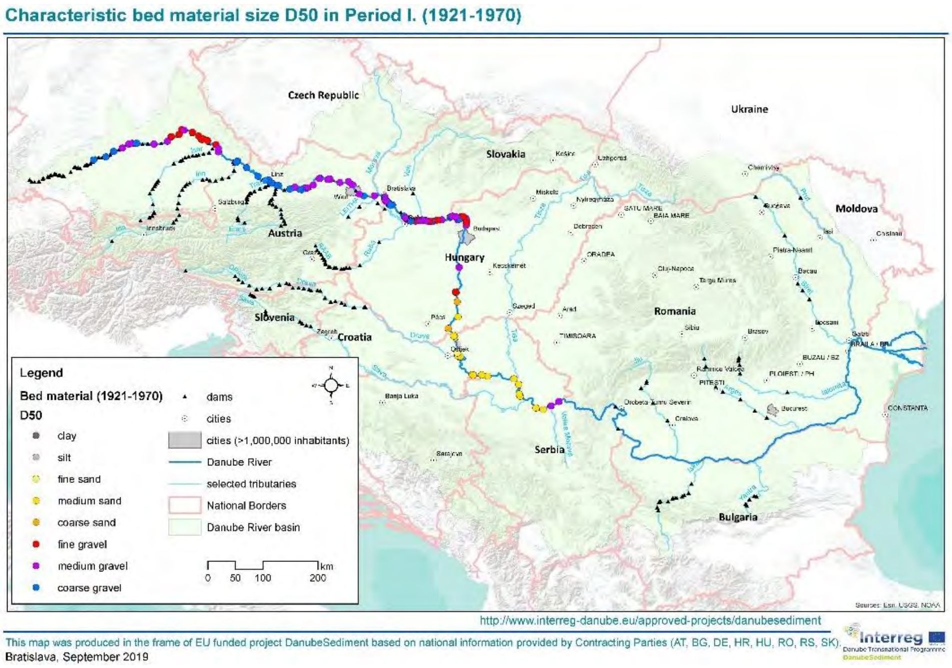
Period III – the impact of dredging on the upper part of the gravel bed section of the Middle Danube: higher sediment sorting, the D_{50} values have decreased to an average of 5 mm representing finer sediments, with local river bed coarsening (D_{50} ~40 mm) and fining (D_{50} ~ 0.40 mm) caused by the tributaries, i.e. Hron and Váh/Ipel respectively. In the transitional zones, there are some indications of bed sediment fining, but this cannot be proved owing to the lack data from Period III. In the sand bed section of the Middle Danube, there are natural variations in the grain size of bed sediments up to rkm 1,250; an impounded section downstream is affected by sediment fining, with the D_{50} values decreasing to 0.022 mm.

Middle Danube tributaries: the gravel bed tributaries of the Middle Danube (Hron, Velika Morava and Nera) contributed to river bed coarsening (D_{50}) in the river's gravel bed and sand bed sections in the past (Period I); this river bed coarsening effect has been eliminated almost completely by the building of dams across the tributaries; the sand bed tributaries affected the composition of the bed material in the Danube mainly in its gravel bed section where bed sediment fining can be observed.

FINDINGS IN THE LOWER DANUBE

The Lower Danube and its tributaries (Period III): the bed material of the Lower Danube consists of sand – coarse and fine sand (between rkm 862.8 and rkm 100); the median grain size (D_{50}) of bed sediments varies from ~1 mm to 0.09 mm; no unnatural effect on the bed material is observed along the Lower Danube; the river's gravel bed tributaries (Timok, Jantra, Iskar) gave rise to natural coarsening in the Lower Danube's sand-bed channel in areas at the mouths of the tributaries (local effect) however this effect is currently being reduced considerably by tributaries damming; the natural river bed fining taking place downstream indicate more natural conditions compared to those in the Upper and Middle Danube.

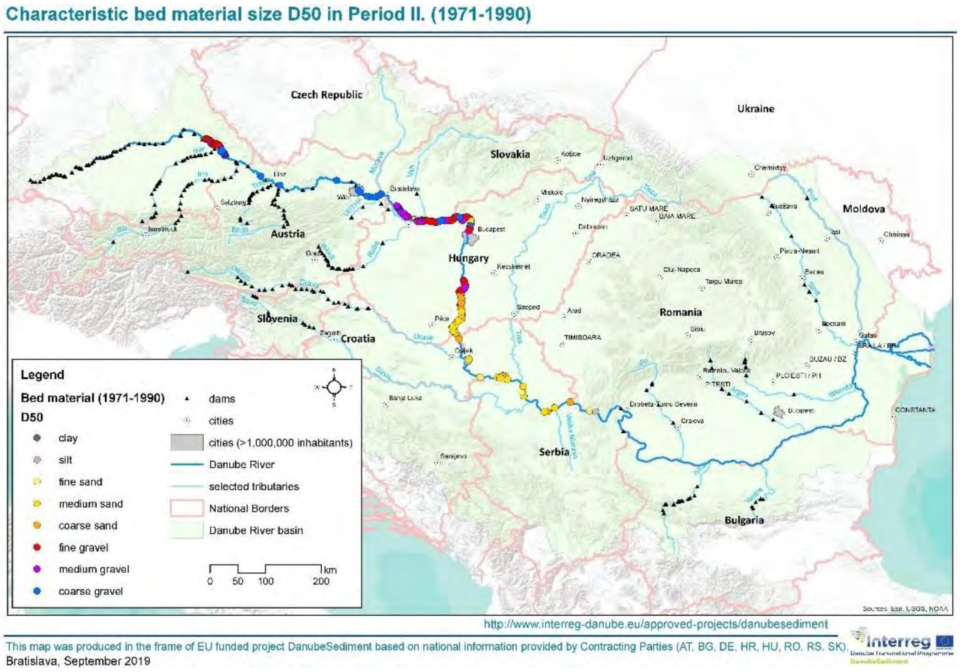
Spatial distribution of characteristic bed material size D_{50} for the three evaluated periods is shown on maps on Figure 5.3.54, 5.3.55 and 5.3.56.


Characteristic bed material size D50 in Period I. (1921-1970)

http://www.interreg-danube.eu/approved-projects/danubesediment

This map was produced in the frame of EU funded project DanubeSediment based on national information provided by Contracting Parties (AT, BG, DE, HR, HU, RO, RS, SK).
Bratislava, September 2019

Figure 5.3.54 Variations in the D_{50} grain size of bed sediments (median) along the Danube in Period I


Characteristic bed material size D50 in Period II. (1971-1990)

http://www.interreg-danube.eu/approved-projects/danubesediment

This map was produced in the frame of EU funded project DanubeSediment based on national information provided by Contracting Parties (AT, BG, DE, HR, HU, RO, RS, SK).
Bratislava, September 2019

Figure 5.3.55 Variations in the D_{50} grain size of bed sediments (median) along the Danube in Period II

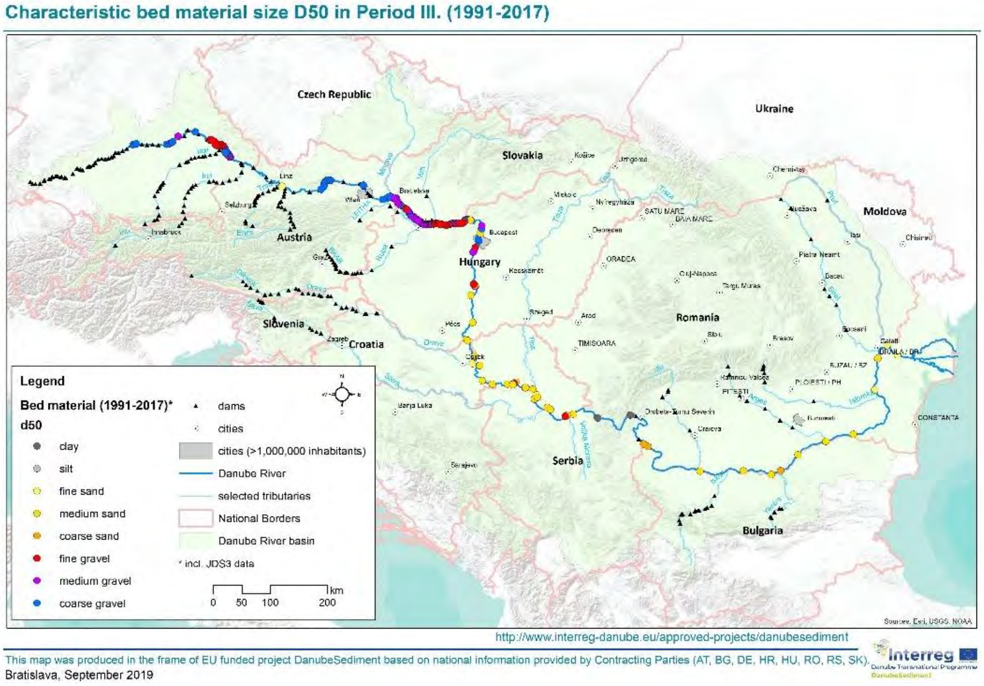


Figure 5.3.56 Variations in the D50 grain size of bed sediments (median) along the Danube in Period III

6. Recommendations for long- term morphological monitoring

Data on sediment transport (suspended load and bedload), channel morphology (bathymetry, bed sediment size) and dredging are necessary input data to evaluate the sediment balance equation. Quantification of sediment deficits and surpluses is as reliable as input data. Therefore, the data quality and availability directly determine if the sediment balance can be calculated. The results of this project showed different data quality and their availability across the countries (uncomplete data, data gaps). Present situation also highlighted the need to harmonize at least basic methods of hydromorphological measurements and observations including their frequency to ensure the required data quality and comparability that should be obtained within all Danube countries. The quality and comparability of hydromorphological monitoring has also become of high importance in the Water Framework Directive.

Data gaps as well as lower data quality did not allow to perform more comprehensive morphological analyses and calculation of sediment balance components on the Danube. The recommended sediment transport monitoring strategy has been proposed and summarized in the *"Handbook on Good Practices in Sediment Monitoring"* (WP3). The aim of this chapter is only to set the main rules for the key morphological measurements in order to harmonize procedures used in all Danube countries, but not to propose a detailed manual, as these type of measurements are mostly implemented by each country. Application of common procedures will allow to achieve higher data quality and comparability on the bed topography, composition of bed sediments as well as reliable information on volumes of the river bed dredging/ feeding along the whole Danube.

Channel topography

Channel and floodplain topography characterise the river system in terms of its main morphological parameters like width, depth and river bed slope (longitudinal profile). In combination with bed and bank sediments the river channel /floodplain also determine the river type, flow and sediment transport capacity. Changes of these morphological parameters and river processes are determined on the basis of topographic changes in channel bathymetry. Therefore regular monitoring of the channel topography is essential for any analyses on sediment transport and development of channel morphology.

- ***Channel bathymetry:*** measurements of the ***whole cross sections*** (CSs) of the river channel perpendicularly to water flow, covering the whole river width from the left to the right river bank including islands or other channel forms (if occurred); cross sections should be measured within predefined localities – geodetically fixed, particularly in the case of longer distances between cross sections (more than 100 m); bathymetric data have to be provided in coordinate system and altitude. In the case of *natural river banks which are exposed to bank erosion* (Lower Danube), CSs measurements should be adapted to these processes in order to be able to evaluate also bank erosion rate

- ***Floodplain topography*** (sedimentation): cross sections evaluated from LIDAR scanning of the floodplain or cross sections geodetically measured in recommended distance between them ~ 1,000 m

- ***Devices*** for bathymetric measurements: ADCP measurements within predefined cross sections or multibeam scanning in case that specific 3D devices are available

- ***Cross sections distances:*** the shorter distances between CSs, the more reliable channel topography, therefore following distances for the Danube are recommended: the Upper Danube: 50 m - max.200 m, the Middle Danube: 100 m - max.300 m and the Lower Danube 300 m - max. 500 m. In the case of longer distances between CSs (300 m – 500 m), special attention should be focused on preselection of appropriate localities of CSs, covering areas of significant channel planform changes (e.g. narrowing, widening, lager channel bars and islands, tributary confluence, etc.); in the reaches with bank erosion shorter distances are recommended (300 m)

- ***Measurements frequency:*** every three or max. five years and after bigger flood event occurs; measurements of channel bathymetry should be coordinated and harmonized along the whole Danube, this should include free flowing sections, impounded river sections and reservoirs (Gabcikovo, Iron Gate)

- **Evaluation of channel changes (sedimentation/erosion)** is based on the difference of the cross-sectional areas in the same locality but from two different periods (+sedimentation, - erosion) multiplied by the distance between the cross-sections. The result represents spatial changes of the river bed along the given river reach and period. Examples of several comparable methods for calculation of the river bed changes within the series of cross section are presented in the project report of the activity WP4.1 *" Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube"* (e.g. mean depth (DE), (AT), low flow water level (SK)).

Bed sediments

Sediment calibre and composition of the bed sediments can provide wide range of useful information for identification of morphological river type, physical processes prevailing in the river channel as well as type of anthropogenic pressures which induce changes of the river bed material. An experienced fluvial morphologist is able to identify the bed structure in a field survey, i.e. the cover layer (erosion, armour layer) or bed clogging (impounded areas affected by sedimentation of fine-grained sediments) which indicate the ongoing processes in the river channel. If this information cannot be obtained directly in the field, details about the flow processes can be obtained by analysing the grain size distribution curves.

Bed sediments that act as isolated grains are characterised by their physical properties (grain size and shape), which are highly variable – both laterally and longitudinally particularly in gravel bed rivers. Therefore, selection of the sampling sites is very important and it should be pre-selected according to satellite images taking into account the river's type and typical features (channel bars, islands), as well as its tributaries and major structures (dams, HHPs).

Grain-size distributions of bed material sediment in large alluvial rivers like the Danube are required for various scientific and management applications (evaluation of bed stability, sediment transport, designation of the sediment management plans, etc.). Therefore sediment sampling and analyses of the bed material are important part of the regular morphological monitoring. Recommendations for selection of sampling locality, sampling devices, and basic laboratory evaluation and sampling frequency are provided in this part in order to provide comparability of the results between the countries with required quality. As there are significant differences in physical processes and characteristics of gravel and sand bed rivers, also procedures are different in some aspects (e.g. number of samples, surface/subsurface layers, etc.). More detailed information on sampling methods, laboratory and statistical analyses can be find in literature (e.g. Bunte and Ant, 2001).

- ***Sampling sites:*** pre-selection of sampling sites should be done according to satellite images (obtained under low flow conditions) taking into account typical features like channel bars, islands and tributaries (upstream and downstream) as well as major structures – dams and HHPs (upstream and downstream). Natural longitudinal variability of the river bed – riffle/pool sections should be considered. The final selection of the site should be refined in a field survey. Sediment sampling sites should be representative, covering the key sites of the river stretch concerned (revised CEN standard EN 14614:2018).

- ***Sampling method and number of sampling sites:*** bed sediments sampling should be done during low flow conditions (summer, autumn); ***gravel bed river reaches****:* samples taken from the top or side benches or islands should include samples from surface and subsurface layers; samples taken from the river channel (using a boat) usually consist of mixed sediments of the surface layer. In the case when devices for freeze core sampling is available, the subsurface layer can be extracted as well. Three samples should be taken in cross sections every 1,000 m, in the left and right side and middle of the channel. Higher spatial density (200 m – 500 m) of sampling sites is recommended in areas of dams /hydropower plants and tributaries.

- ***Sand bed river reaches:*** only surface layer is sampled; with regard to relatively homogenous material of sand bed reaches, one sample should be taken in the middle of the channel every 1,000 m; three sampling sites and higher spatial density (200 m – 500 m) are recommended in area where the composition of the river bed is affected by coarser sediments transported into the Danube from tributaries and also in the upstream and downstream of dams /hydropower plants.

- ***Sampling devices: freeze core sampling*** enables to extract surface and subsurface sediments from gravel bed river reaches; surface and subsurface sampling can also be performed by ***volumetric sampling*** (manual digging) but only on side channel bars or islands; this method is also recommended for sampling of the river bed under water (from the boat). Volumetric samples can be excavated by digger (big ship is needed) or various types of bottom samplers (e.g. drag bucket type – from the boat) can be used.

- Bottom samplers are lowered to the river bottom and dragged along the bed to be filled with sediments. Minimum recommended amount for each sample is about 20 kg. Each sample (freeze core and volumetric samples) after extraction must be documented by a photograph using a scaled frame (usually 50cm x 50cm).

- ***Sampling frequency:*** should be harmonized with bathymetry measurements thus time interval should be every 5 years but also after big floods or/and in the case when significant changes can occur (e. g. implementation of measures)

- ***Laboratory evaluation:*** analyses of bed sediment samples should be performed by sieving in laboratory; the results are used to compile the grain size distribution curves. The characteristic grain sizes of river bed sediments (i.e. D_5, D_{16}, D_{25}, D_{50}, D_{65}, D_{75}, D_{84}, D_{90}) can be estimated from grain size distribution curves for specific purposes (bedload transport, assessment of the river bed stability, morphological and/or statistical analysis, etc.). More details on laboratory and statistical analyses can be found in literature (e.g. Bunte and Ant, 2001). In some countries only size D_{50} is evaluated but it needs to be stressed that complete laboratory analysis of bed material samples and compilation of full grain size distribution curves have to be performed for all sampling sites as it provides complex information on composition of the bed material. This enables comparability between countries and deeper insight into river processes and spatial/ temporal changes of bed material induced by human activities.

- ***The sample-collection strategy:*** with respect to project results a designation of the common strategy for sampling of the river Danube river bed ***(also bathymetric measurements could be included)*** is strongly recommended. This strategy should be designed to yield ***representative sites*** of bed sediments samples and ***proper laboratory*** evaluation. The basic sampling procedures proposed here are suitable for sampling most sites, and every effort should made to ***follow common approach*** to ensure consistency among countries. Some specific local conditions may require some adaptation, however, the conceptual approach should be maintained.

Dredging/feeding of bed sediments

Dredging of the bed sediments seriously impacts the morphology of the river bed. Excessive amounts of dredging can initiate significant processes of the river bed degradation with propagation upstream and downstream from the dredged sites. Therefore it is very important to document very carefully the volumes, sites and time of excavated material particularly in the case when bed material is completely removed from the river. Sediment feeding should be recorded in the same way.

- Identification of the dredging/feeding localities – from rkm to rkm or coordinates
- Amount of dredging and feeding (mass or volume) - documented by the River Authority
- Period of dredging/feeding localities (month/year)
- It is useful to document the impact of dredging/feeding by bathymetric measurements along the river section including upstream and downstream areas; this measurments should be done before and after each more excessive dredging.

7. Summary and conclusions

The final report on *WP4.3*: *Long-term Morphological Development of the Danube in Relation to the Sediment Balance,* presents important knowledge gained from quantitative data on the Danube channel's morphological evolution and variation within the given space (***the Upper, Middle and Lower Danube***, and the national river sections) and time scales (***historical:*** from the **19th century** – reference state – to 2017; ***long-term:*** from **Period I (1920-1970)** to 2017; ***mid-term:*** from **Period II (1971-1990)** to 2017; and ***short-term:*** over **Period III (1991-2017),** taking into account the main hydromorphological pressures (river regulation, hydropower dam construction, dredging). The Danube River's response to these pressures (changes in the river processes) was identified and its key morphological characteristics (longitudinal profile, channel topography, river-bed sediments) were assessed in quantitative terms in the context of sediment balance variation. The results obtained and the knowledge derived therefrom are summarised below.

7.1 Historical evolution of the Danube river pattern and its morphological classification

- Using historical maps depicting the reference conditions, a morphological classification (using the REFORM typology developed by Rinaldi et al., 2015) was made to identify the type of the river channel, its confinement and typical morphological characteristics such as length, width, sinuosity and the anabranching indexes.

- A comparison of the Danube channel in its reference state (prior to the main human interventions) with its present state shows that the river pattern has changed dramatically, especially in the Upper and Middle Danube sections. Besides the river-bed slope reflecting the changes in the river length and width, the sediment balance has been affected, too. Another essential impact on the sediment balance has been exerted by the construction and operation of hydropower plants, which have also caused major changes in the morphological characteristics of the Danube's regulated channel.

- An analysis has revealed that the Danube channel's morphological characteristics changed substantially in the period from the reference state to date. The wide and meandering river channel with many branches and side arms changed into a uniform single-thread channel, especially in its upper and middle sections. In its reference state, the Danube was a multithread anabranching river along a length of 1,685 kilometres. At present, there is only a 745 kilometre-long multithread anabranching (low energy) river reach in the Lower Danube section. The multithread anabranching (high energy) river type no longer exists.

- At present, the Danube River is ***shorter*** (by roughly 130 kilometres), as a result of river regulation such as channel straightening, damming and bypass-canal building. Extensive flood protection measures, mean water regulation and low-flow water level regulation have also led to ***narrowing*** of the river system. On average, the total width of the Upper Danube has decreased by 39% (the active width by 22%) and that of the Middle Danube by 12% (the active width by 1%). Groin fields in the river channel have reduced its active width for sediment transport by another almost 50%. Although the Lower Danube's width has changed only slightly (by an average of 4%), bank erosion is an ongoing process in numerous river stretches. The river bed slope has been affected by river channel narrowing, shortening and unification, caused by measures implemented for flood protection, navigation or hydropower generation.

7.2 Morphological development of the Danube in response to the main pressures

River channel morphology, as reflected in the size, cross-sectional shape, longitudinal profile and planform pattern of the river channel, stems from the processes of sediment erosion, transport and deposition within the constraints imposed by the geological conditions, the drainage basin's terrain and the main human pressures. Anthropogenic interventions into the Danube (flow and sediment transport regime), which caused river channel instability, resulted in changes in the main morphological characteristics of the river channel, i.e. the river-bed level (erosion/sedimentation), longitudinal profile and bed material type and size. The main spatial and temporal changes recorded in these morphological characteristics are summarised below.

7.2.1 Changes of the Danube's river bed along the national sections

As the flow and sedimentary conditions are rather complicated and specific along each national river section of the Danube (and basic data and information are available only at national level), this part of the report was prepared by the project partners in the agreed structure. This includes spatial and temporal variations in the river pattern (from the reference state to date) and in the longitudinal profile (in all three periods), but the main emphasis was on an analysis of the channel changes – river-bed changes (identification of stretches exposed to erosion and sedimentation). These spatial changes in the river channel, caused mostly by a sediment imbalance stemming from the construction and operation of hydropower plants, are markedly different in the Upper, Middle and Lower Danube.

Therefore, the detailed results are available in the sub-chapters (Chapter 5.1) focusing on the national river sections. The most relevant conclusions based on a national analysis are summarised for the Upper, Middle and Lower Danube sections as follows:

UPPER DANUBE (in the section from rkm 2,500 to rkm 1,790):

- **Main pressures on the sediment balance:** sediment continuity disruption by a chain of run-of-river power plants on the Danube and its tributaries; the Hrušov reservoir and the Gabčíkovo hydropower plant on a bypass canal; excessive dredging.
- **Impacts within the chain of run-of-river power plants:** bedload transport – virtually eliminated (in free-flowing reaches); reduced suspended load within impoundments of HPPs; sedimentation within impoundments of HPPs (in various degrees depending on size, operation manual, effect of flushing, etc.) within a chain of run-of-river power plants; erosion downstream of HPPs in free-flowing reaches (FFR) but also at the end of impoundments within the chain of HPPs (observed in Austria); coarsening of bed sediments downstream of HPPs; local changes of the longitudinal profile and bed slope as a consequence of disrupted sediment transport and dredging activities (reaches of erosion/sedimentation).
- **Impacts of the big reservoir upstream of the Gabčíkovo HPP:** intensive sedimentation in the Hrušov reservoir; major river-bed degradation downstream of HPP still continuing with lower intensity; bed sediment changes – fining downstream of the Gabčíkovo HPP as a result of extensive dredging; descending river bed slope downstream of the Gabčíkovo HPP induced by significant incision of the river bed.

MIDDLE DANUBE (in the section from rkm 1,790 to rkm 943):

- **Main pressures on the sediment balance:** sediment deficit from upstream (Gabčíkovo); dredging, Iron Gate 1.
- **Impacts:** bedload transport influenced by sediment deficit from upper parts of the Danube and considerably reduced sediment input (bedload and suspended load) from tributaries due to damming; sedimentation within the impoundment and reservoir of Iron Gate 1; river bed erosion – along the Hungarian Danube (dredging) and downstream of Iron Gate 2 (sediment deficit); major incision of longitudinal profile – in the past as a consequence of extensive dredging; local changes in the river bed slope (dredging).

LOWER DANUBE (in the section from rkm 943 to rkm 80):

- **Main pressures on the sediment balance:** Iron Gate 1 and 2; sediment deficit downstream of Iron Gate 2; river-bed dredging;
- **Impacts**: major sedimentation within impoundments – Iron Gate; sediment deficit – suspended load and bedload downstream of Iron Gate 2; reduced sediment supply from the tributaries (impact of damming); erosion – downstream of Iron Gate 2,

enhanced by dredging; longitudinal profile – river-bed incision in the past, the present processes need to be documented (bathymetry), local changes in the bed slope.

7.2.2 Development of the Danube's longitudinal profile

An analysis of the long-term and mid-term development of the Danube's longitudinal profile along the river bed (thalweg), influenced by sediment continuity disruption, low-flow river regulation and dredging, has provided the following results:

- the data sets obtained from the project partners were not homogenous spatially and temporally, so the development of the river's longitudinal profile indicates the main trends, rather than enabling a quantitative assessment;
- the longitudinal profiles of the Danube were compiled from thalweg data for all three periods (I,II,III) defined for the project under review;
- the river-bed slope values along the Danube's longitudinal profile (present state) were evaluated and illustrated graphically together with the corresponding low-flow water levels (LNWL);
- the hydropower plants built on the Danube have created new local base levels, which fix the overall position and shape of the longitudinal profile (thalweg) and reshape it in certain stretches, especially in the river's upper section *('stepped shape');*
- the disruption of sediment continuity by hydropower plants and river-bed dredging has a profound effect on local bed-slope changes; the river-bed slopes descend within impoundments between HPPs (along the Upper Danube) as a consequence of dredging for maintenance purposes (deposit removal, river-bed flattening) or of a sediment deficit in certain cases; the river-bed slope also descends in free-flowing stretches downstream of HPPs, but the main cause is sediment deficit;
- the long-term evolution of the river bed, which covers almost 100 years (from 1920 to 2017) indicates that the degradation process prevails and causes major river-bed degradation, which is evident along the entire Danube (3 m deep on average, with local values ranging from 6 m to a maximum of 10 m); the areas of sediment deposition are concentrated in localities where the river-bed slope changes naturally and within the impounded river stretches (upstream of HPPs on the Upper Danube) and reservoirs (Gabčíkovo, Iron Gate 1 and 2);
- the mid-term development of the river bed, which covers a period of almost 50 years (from 1971 to 2017) indicates that the river-bed degradation process continues, though with lower intensity and the areas of sediment deposition within impoundments are being promoted;

- the local river-bed slope changes in the areas of the river bed incision downstream of HPPs (chain of HPPs, Gabcikovo HPP) and in the areas of excessive bed sediment dredging where the local bed slope ascends/descends (e.g. in Hungary).

7.3 Spatial and temporal variations in the grain size of bed sediments

Important data on spatial and temporal variations in river-bed sediments along the Danube (between rkm 2,600 and rkm 100) and its main tributaries are summarised in Chapter 5.3. Bed sediment analyses were carried out on the basis of the temporal changes observed in the median grain size (D50) and in the grain size distribution curves, which give a more detailed insight into the composition of the bed surface layer. Although the data were not homogeneous (owing to the use of different sampling methods, time, sampling sites, and incomplete data), a large number of data covering all three periods provide a sound basis for an analysis of the current composition of bed sediments and their variability over time. The impact of disrupted sediment continuity (the main hydromorphological pressure) on the composition of bed sediments can be observed in certain stretches of the Danube.

The general knowledge about bed sediments can be summarised as follows:

- Disruption of sediment continuity by hydropower plants built on the Danube have induced changes in bed sediment size: fining within impoundments upstream of the dams (sedimentation) and bed sediment coarsening downstream of the dams (owing to erosion and potential armouring) in gravel-bed stretches of the Danube. Extensive dredging have caused bed sediment fining (removed the naturally coarser surface layers) in gravel-bed stretches of the Middle Danube. Bed sediments in the Lower Danube do not indicate any significant changes.

- The characteristic grain sizes of river-bed sediments D5, D16, D25, D50, D75, D84, D95 in the Danube channel (Period III) were estimated for the entire Danube. The variability of the median grain size (D50) for all three periods is illustrated spatially on maps in Annex 1.

- A statistical analysis (median, mean, sorting) of bed sediments in the Danube was carried out on the basis of grain size distribution curves provided for selected river stretches. With regard to the quantity and quality of the data available, the results of the statistical analysis made point to the type of knowledge that could potentially be obtained if higher-quality data were available.

- An in-depth analysis of the spatial variations in bed sediments in relation to the main pressures and the modified flow and sedimentary conditions would require higher-quality data on both the surface and subsurface layers of the river bed. However, such site-specific data are available only very rarely (in the Austrian Danube).

The results of analyses and the general knowledge gained can be summarised as follows:

- **The river bed of the Danube** is composed of gravel and sand. The bed material in the Upper Danube consists of coarse and fine gravel. The Middle Danube includes a transitional zone, the gravel bed of which changes into a sand bed (gravel bed: from rkm 1,790 to rkm 1,520, sand bed: from rkm 1,520 to Iron Gate 1). Bed sediments in the Lower Danube (from Iron Gate 2 at rkm 862.8 to rkm 100) consist of coarse and fine sand, and clay in the Danube delta.

- **Changes in the composition of the bed material:** except of natural downstream fining, a variability of the bed sediments on gravel bed section between rkm 2,600 and rkm 1,520 is affected particularly by disruption of sediment continuity and bed dredging, which are the main hydro-morphological pressures that have caused local bed material changes in the Danube. Excessive dredging induced bed sediment fining downstream of the Gabcikovo HPP. Fine sediments are deposited within impounded areas (sedimentation) upstream of HPPs and coarsening occurs at several localities downstream of HPPs on free flowing sections. The lower section of the Middle Danube is affected by sedimentation and bed material fining in the area of the Iron Gate reservoir. In view of the morphological character of the Lower Danube and the possible impacts of the main hydromorphological pressures, the sand river bed do not indicate any significant changes.

Impact of tributaries on sediment size of the Danube bed material:

In the past (Period I): the Danube's tributaries contributed substantially to the river's sediment budget and affected the composition of bed sediments in varying degrees. River-bed coarsening was observed in the Upper Danube (it was caused by the river's Alpine tributaries, i.e. Isar and Inn), in the Middle Danube (caused by gravel-bed tributaries, i.e. Hron and Velika Morava), and in the Lower Danube (caused by the Timok and Jantra tributaries). River-bed fining occurred mostly in the Middle and Lower Danube sections (it was caused by the tributaries Váh, Ipel, Tisza, Sava, Siret and Prut). While the impact of the Alpine tributaries on river-bed coarsening was fundamental, the impact of others tributaries was mostly local, inducing river-bed coarsening or fining in shorter stretches.

At the present time (Period II–III): the impact of the Danube's tributaries on the grain size of bed sediments has been reduced considerably by dams built across the tributaries. Currently, only reduced amounts of finer sediments are transported into the Danube. The river processes prevailing in the Danube channel and reflecting the effects of disrupted sediment continuity are driven mostly by the actual changes taking place in the composition of bed sediments.

- **Upper Danube:** ***Period I*** (with 12 HPPs already built on the German Danube, but no HPP in the river's Austrian and Slovak–Hungarian sections): the median size (D_{50}) of bed sediments varied from ~4 mm to 30 mm; the Alpine tributaries (Isar and Inn) caused intense natural river-bed coarsening in the Danube channel, with the median value (D_{50}) increasing from ~4 mm to 30 mm. ***Period II*** (with most of the HPPs already built): the median size (D_{50}) of bed sediments varied form ~3 mm to 45 mm. ***Period III*** – present state: the median size (D_{50}) varies from ~3.5 mm to 40 mm; within impoundments from run-of-the-river power plants: $D_{50} > 0.16$ mm; in the Hrušov Reservoir upstream of the Gabčíkovo HPP built on a bypass canal: $D_{50} > 0.03$ mm.

- **Impacts of disrupted sediment continuity in the Upper Danube**: changes in free-flowing stretches downstream of HPPs – river-bed coarsening with a maximum difference in the D_{50} grain size (average value for eroded areas) ranging from 10 mm to 22 mm, representing a 220 % increase in the median grain size; changes within impoundments upstream of run-of-the-river power plants – a maximum decrease from 10 mm to 0.16 mm, and in the Hrušov Reservoir (Gabčíkovo HPP) from 20 mm to 0.04 mm.
- **Middle Danube:** the river bed material changes from coarse gravel to fine sand (between rkm 1,790 and rkm 943). According to the type of the bed material, the Middle Danube section can be split into three subsections: a gravel-bed subsection between rkm 1,790 and rkm 1,660, a transitional subsection (gravel and sand) between rkm 1,660 and rkm 1,420, and a sand-bed subsection between rkm 1,420 and rkm 943. ***Period I:*** in the gravel-bed subsection, the median values (D_{50}) varied from ~ 4 mm to 30 mm; in the transitional subsection within which the river-bed material changed from coarse gravel to fine sand (between rkm 1,660 and rkm 1,420), two zones can be distinguished: Zone 1 (between rkm 1,660 and rkm 1,520) within which medium gravel changed into very fine gravel, with the median D_{50} values varying from ~16 mm to 2 mm, and Zone 2 (between rkm 1,520 and rkm 1,420) within which very fine gravel changed into medium sand, with the median D_{50} values varying from ~2 mm to 0.3 mm; in the sand-bed subsection (between rkm 1,420 and rkm 943), the median D_{50} values varied from ~ 0.18 mm to 0.60 mm, with local coarsening at the mouths of the tributaries (D_{50} reached 8–10 mm in certain locations). ***Period II*** – river-bed fining was first observed in the upper part of the gravel-bed subsection of the Middle Danube (as a consequence of dredging) and also within an impounded part of the sand-bed subsection (as a consequence of sediment deposition) in which the median values (D_{50}) decreased in some places to 0.04 mm. ***Period III*** – the impact of dredging on the upper part of the gravel-bed subsection of the Middle Danube: higher sediment sorting, the average D_{50} value is 5 mm representing finer sediments, with local river-bed coarsening (D_{50} ~40 mm) and fining (D_{50} ~ 0.40 mm) caused by the tributaries, i.e. Hron and Váh/Ipel respectively. In the transitional zones, there are some indications of bed-sediment fining, but this cannot be proved owing to the lack data from Period III. In the sand-bed subsection of the Middle Danube, there are natural variations in the grain size of bed sediments up to rkm 1,250; an impounded section downstream is affected by sediment fining, with the D_{50} values decreasing to 0.022 mm.

- **Middle Danube tributaries:** the gravel-bed tributaries of the Middle Danube (Hron, Velika Morava and Nera) contributed to river-bed coarsening (D_{50}) in the river's gravel- bed and sand-bed subsections in the past (Period I); this river-bed coarsening effect has been eliminated almost completely by the building of dams across the tributaries; the sand-bed tributaries affected the composition of the bed material in the Danube mainly in its gravel-bed subsection where bed sediment fining can be observed.

- **The Lower Danube and its tributaries (Period III)**: the bed material of the Lower Danube consists of sand – coarse and fine sand (between rkm 862.8 and rkm 100); the median grain size (D_{50}) of bed sediments varies from ~ 1 mm to 0.09 mm; no unnatural effect on the bed material is observed along the Lower Danube; the river's gravel-bed tributaries (Timok, Jantra, Iskar) gave rise to natural coarsening in the Lower Danube's sand-bed channel in areas at the mouths of the tributaries (local effect); this effect is currently being reduced considerably by the building of dams across the tributaries; the natural river-bed fining processes taking place downstream indicate more natural conditions compared to those in the Upper and Middle Danube. The spatial distribution of D_{50} values of bed sediments are illustrated in maps for all three periods (Annex 1).

The results obtained within the scope of this activity showed important changes in the river processes (sediment transport, erosion/sedimentation), which resulted in significant modification of morphological character of the Danube channel. In the first phase, these changes were induced by river training and resulted in considerable changes of the river pattern and reduction of lateral connectivity (from nearly natural conditions to regulated - narrowed and straightened river channel). During the second phase, construction of hydropower plants and other human interventions (e.g. extensive dredging) have had a dominant effect on further changes in sediment transport (unnatural redistribution of the river sediments - reaches of erosion and deposition reduced sediment input from tributaries) and morphological development of the Danube river bed, reflecting the specifics of the Upper, Middle and Lower Danube.

Quantitative morphological results were used for calculation of some components of the Danube sediment balance (WP4.2) and also for designation of sediment management to improve the water-management functions and to preserve ecological status of the Danube River (WP6). These results also contribute to a better understanding of the spatial and temporal variations in the physical processes taking place in the Danube channel.

Results of this activity based on large amount of collected data, for the first time provided a complex knowledge on lateral and longitudinal morphological development of the entire Danube in response to various types of engineering measures, which were successively implemented over the long period. In this respect, the results published in this activity are unique and provide an excellent basis for further detailed scientific analysis.

* * *

List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
AFDJ	Fluvial Administration Dunarea de Jos (Romania)
AT	Austria
BAW	Federal Waterways Engineering and Research Institute (Germany)
BG	Bulgaria
BME	Budapest University of Technology and Economics
BOKU	University of Natural Resources and Life Sciences (Austria)
DC	Danube Commission
DE	Germany
DHMZ	Hydrological and Meteorological Service (Croatia)
DTP	Danube Transnational Programme
EAEMDR	Executive Agency for Exploring and Maintaining the Danube River (Bulgaria)
ÉDUVIZIG	North-Transdanubian Water Directorate (Hungary)
EU	European Union
GPS	Global Positioning System
GSD	Grain-size distribution
HNWL	Highest navigable water level
HPP	Hydropower Plant
HR	Croatia
HU	Hungary
HZB	Hydrographisches Zentralbüro (Austria)
ICPDR	International Commission for the Protection of the Danube River
INCDD	Danube Delta National Institute for Research and Development (Romania)
INSPIRE	Infrastructure for Spatial Information in Europe
IWA	Institute of Hydraulic Engineering and River Research (Austria)
JCI	Jaroslav Černi Water Institute
JDS3	Joint Danube Survey 3
KWD	Kennzeichnende Wasserstände Donau
LfU	Bavarian Environment Agency (Germany)
LiDAR	Light Detection and Ranging
LNWL	Low navigable water level
MTITC	Ministry of Transport, Information Technology and Communications (Bulgaria)
MWL	Mean water level
NARW	National Administration ‘Apele Romane’
NIHWM	National Institute of Hydrology and Water Management (Romania)
Plovput	Directorate for Inland Waterways (Serbia)
RKM	River kilometer
RO	Romania
RS	Serbia
SK	Slovakia
SVP	Slovak Watermanagement Enterprise
TUM	Technical University Munich (Germany)
VHP	Verbund Hydro Power GmbH (Austria)
VUVH	Water Research Institute (Slovakia)

WFD	Water Framework Directive
WMD	Water Management Department (Croatia)
WP	Work Package
WSV	Federal Waterways and Shipping Administration (Germany)
WWA	Wasserwirtschaftsämter - Regional water authorities (Germany)

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