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SEDDON II

# T3.1.2 Problem Analysis - EN

## Report

SEDDON II (AT HU10)

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BOKU – Wasserbaulabor Errichtungs- und Betriebs-Gesellschaft m.b.H.
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SEDDON II

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# SEDDON II (AT HU10)
# Sedimentforschung und –management an der Donau II
# A Duna hordalékvizsgálata II

# Report

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## Abstract

This problem analysis report has been prepared as a part of the Sediment Research and -management at the Danube River II (SEDDON II) project within the ERDF funded Cross-border Cooperation Programme, Austria-Hungary 2014-2020.

The Danube River and its surrounding landscape nowadays lies in the field of various interest such as flood protection, hydropower, navigation and ecology. Due to this fact the formerly untamed and wild river system since the end of the 19th century faced a wide range of anthropogenic alterations leading to manifold hydromorphological issues. As one of the tasks in Work Package 3 (River Engineering) an analysis towards current sediment related problems in the two project reaches was carried out based on a list of relevant problems aiming to improve the hydromorphological condition of the Danube River.

This report attempts to analyse similarities and differences of both river reaches as well as underlying processes leading to these problems. Furthermore, the report contributes to the development and optimisation of river engineering measures that can handle the multiple problems the different stakeholders face and compensate the negative impacts of human pressures along river systems.

# Contents

# 1 Introduction

A detailed understanding of sediment related problems is essential for a successful and sustainable management of large rivers. The Upper Danube in Austria and Middle Danube in Hungary face several sediment related problems, which impact, among others, ecology, flood risk management, navigation and hydropower. Output T3.1.1 lists these problems affecting the SEDDON II study reach and builds the base for Output T3.1.2 (Report on the analysis of sediment related problems along the study reach of the Danube in Austria and Hungary).

# 2 Sediment related processes

In the following chapter a description of sediment related processes and related problems with a focus on the Austrian and Hungarian Danube reaches is provided.

## 2.1 Morphological characteristics and physical processes in alluvial rivers

The idealized watershed can be divided into three zones: that of erosion or sediment production (steep, rapidly eroding headwaters), transport (through which sediment is moved more or less without net gain or loss), and deposition (Schumm, 1977). In the river channel the erosional products from the headwaters are transported downstream in form of bedload or suspended sediment to the ultimate depositional sites at the sea (Kondolf, 1997).

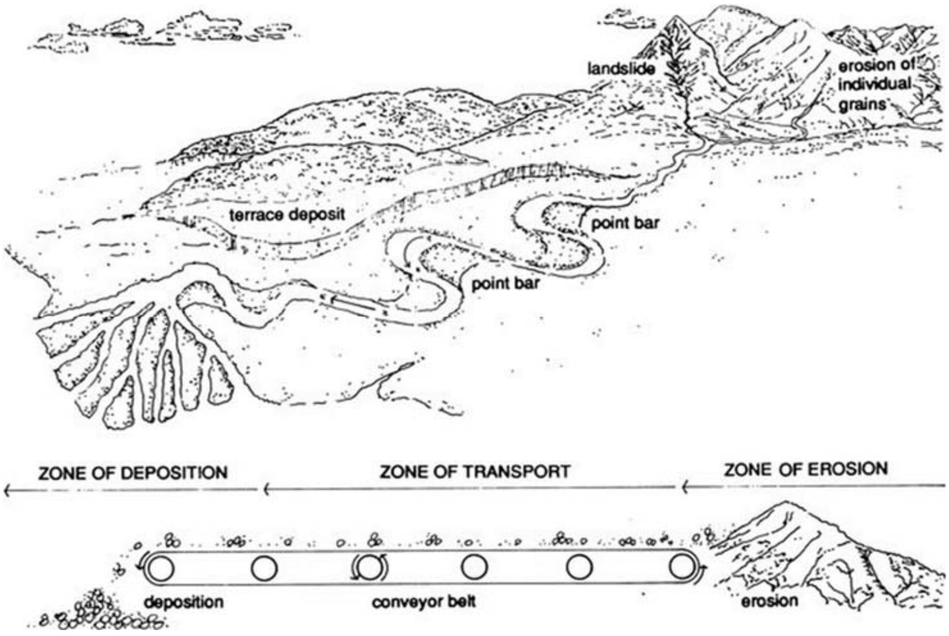


Figure 1 Diagram of zones of sediment production, transport and deposition illustrating the conveyor belt analogy for the zone of transport (Kondolf, 1994).

The river processes taking place within the river system produce typical morphological characteristics for the river channel in its upper, middle and lower sections. In the upper valley with a high gradient, vertical erosion dominates and a narrow, relatively shallow V-shaped channel cuts into the ground. Large amounts of coarse sediments produced by erosion in the catchment of the upper valley and in the channel itself, are transported downstream. In the middle section, vertical erosion decreases and the river channel is wider and deeper with a moderate gradient. Here, lateral erosion and deposition in the river channel prevails. In the transitional section, the sedimentary conditions are more balanced, 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. Both the composition and arrangement of bed sediments vary systematically along the river in the downstream direction (downstream fining). Coarse sediments transported form the upper river valley become progressively finer in the downstream direction due to abrasion and selective transport (Frings, 2004).

In natural rivers, that are in an equilibrium state of sediment budget, the river morphology is dependent on various sediment characteristics, such as grain size and sediment supply (Figure 2a). An increasing sediment supply leads, together with an adequate width, slope and grain size, e.g. to braided channels. In rivers with excessive sediment load (gravel or sand), where the dominant process is aggradation, usually channel bars develop. Various forms of channel bars exist that are typical for certain river types, e.g. braided and anabranching rivers. Point bars formed on the inner sides of channel bends are typical for meandering or sinuous rivers. An interruption of sediment continuity causes a transformation from a braided to a single thread river that erodes. Lack of sediment supply is followed by self-acting river narrowing and straightening and leads to a lack of aggregational features, thus limiting lateral erosion and morphodynamics.

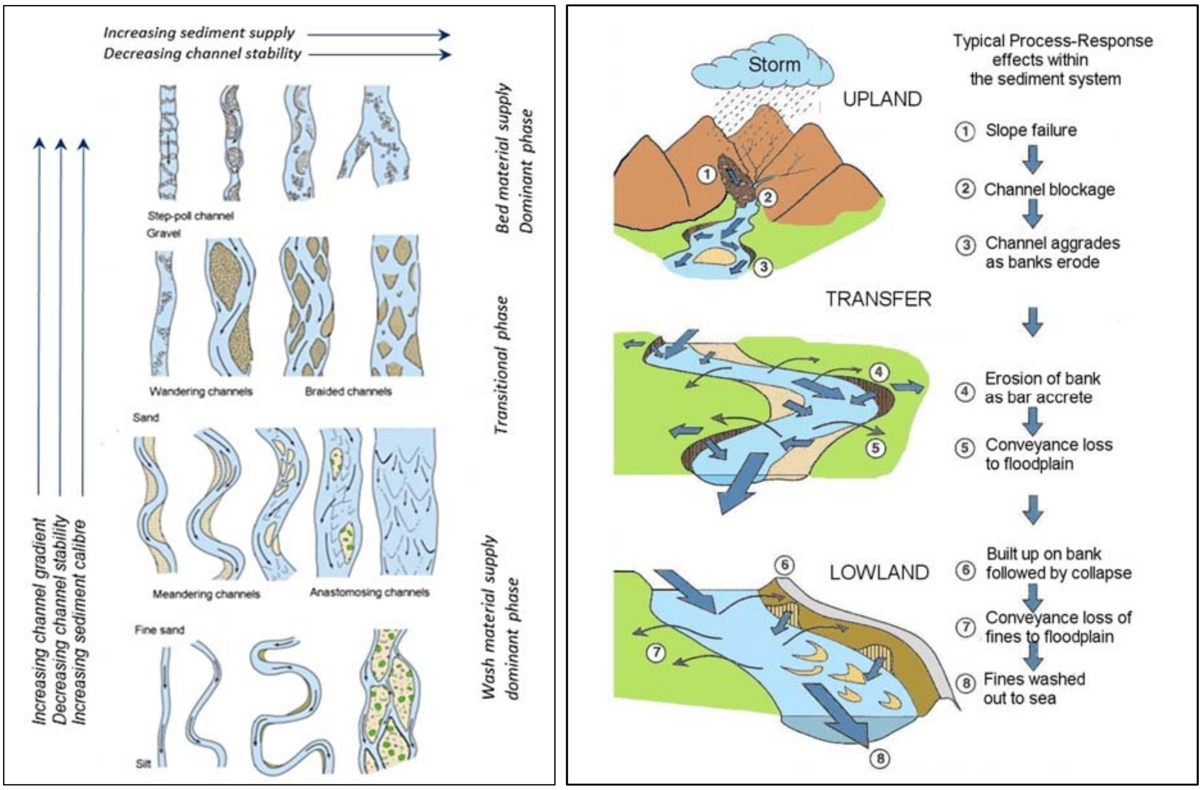


Figure 2 a) Dependency of the river morphology on sediment characteristics, including sediment supply (Church, 2006); b) Typical process-response effects within a fluvial sediment system (Sear and Newson, 1993)

Typical process-response effects that occur within a sediment system are illustrated in Figure 2b. A large sediment input caused by slope failure (1) from the upland section may cause channel blockage (2). Further downstream the channel aggrades and the banks erode causing channel widening (3). In the middle section, bars accrete leading to erosion of the banks (4) and the of loss of fine sediments by conveyance to the floodplains (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). Furthermore, fine sediments are lost back to the floodplain (7) and washed out to the sea (8).

## 2.2 The flow and sediment regime

The interaction respectively the feedback between flow and sediment dynamics within a geomorphic setting, leads to the development of different types of rivers, with characteristic planforms, cross-sectional shapes, gradients, sediment compositions, channel roughness or sediment transport characteristic, to name just a few.

Lane (1955) proposed a generalised relationship, which is illustrated in Figure 3 and shows the flow and sediment interactions that dictate the degradational and aggradational balance of a river. The relationship $Q_s d_{50} \alpha Q_w S$ indicates proportionality between the sediment load ($Q_s$), discharge ($Q_w$), sediment size ($d_{50}$) and the river-bed slope (S).

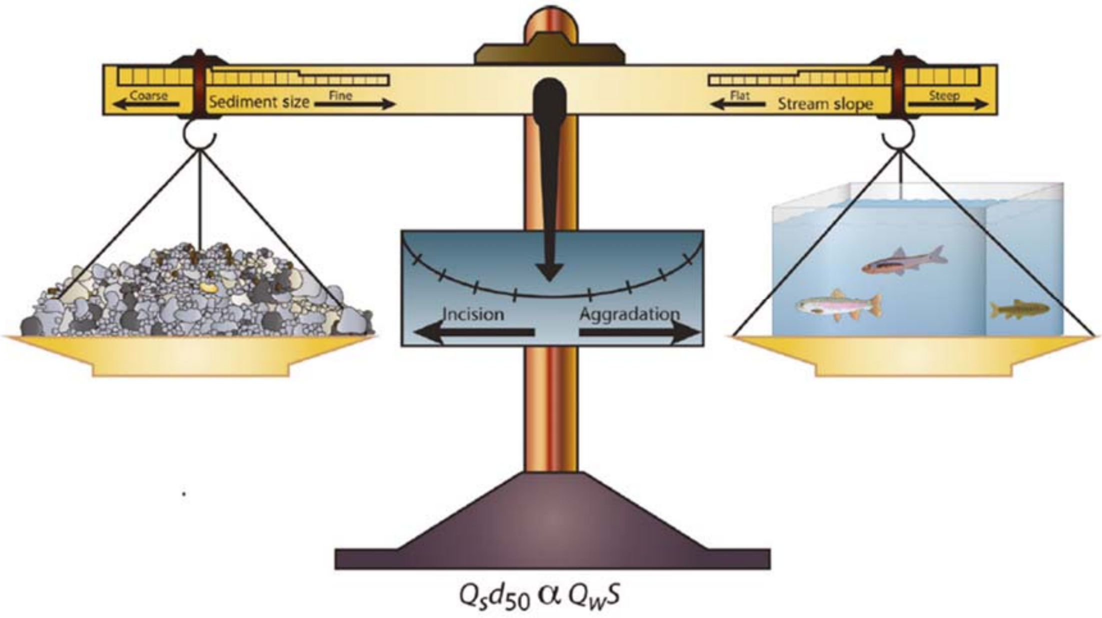


Figure 3: Relationship between the basic variables that determine the physical processes in rivers (Pollock et al., 2014 adopted from Lane, 1955)

If the scales shown in Figure 3 are subject to changes, any given river reach adjusts to a new state and over time, these adjustments lead to changes of the morphological characteristics of the river and its gradient, of the composition of riverbed and banks and the volume and size of the transported sediments.

The most important controls that determine the stability of a river channel over a certain period (years, decades) are the flow available to transport sediments and the sediment supply. Therefore, if the supply of water and / or sediments change, the river channel morphology usually is subject to considerable changes. The degree of these changes depends on the alteration of the supply (amount and size) from source areas like tributaries, hillslopes, upstream parts of the river itself. In his concept of river metamorphosis, Schumm (1977) described the potential impacts on short-term channel stability due to changes in the flow and sediment regime. The impacts on the channel morphology due to changes in the flow and / or sediment regime are summarised in Table 1.

Table 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 |
|---|---|---|---|
| $Q_s$ + $Q_w$ = | Aggradation, channel instability,<br>wider and shallower channel | $Q_s$ + $Q_w$ - | aggradation |
| $Q_s$ - $Q_w$ = | Incision, channel instability, narrower and deeper channel | $Q_s$ + $Q_w$ + | Processes increased in intensity |
| $Q_s$ = $Q_w$ + | Incision, channel instability, wider and deeper channel | $Q_s$ - $Q_w$ - | Processes decreased in intensity |
| $Q_s$ = $Q_w$ - | Aggradation, channel instability,<br>Narrower and shallower channel | $Q_s$ - $Q_w$ + | Incision, channel instability, deeper, wider? channel |

*$Q_s$ sediment discharge; $Q_w$ water discharge; + increase; - decrease; = remains constant;*
*? uncertain response.*

The interactions between the water flow and sediment transport (bedload and suspended sediments) within the boundary conditions of a river channel produce the characteristics of channel morphology in unconfined alluvial rivers. The balance between water and sediment inputs controls the channel aggradation or degradation tendencies. Both inputs values, i.e. water and sediment, are highly variable in time.

The sediment budget compares the input and output of sediments in a river reach, the exchanges of the mobile sediment with the ones stored in the riverbed, bank, bars and the floodplain. It also includes budget terms like dredging, feeding of sediment and input by tributaries. The budget provides an organizing framework for the different components of the sediment regime (Wohl et al., 2015) and helps to determine if it is balanced or disbalanced (net surplus or net deficit).

- Sediment balance: the sediment input in a river reach over a certain time period equals the output
- Sediment deficit: more sediments are transported out of a river reach than are supplied from upstream
- Sediment surplus: sediment input from upstream is exceeding the transport capacity

Changes in the sediment regime can have relatively rapid effects on channel morphology especially during floods and as a consequence also on associated ecosystems and human usages. Ecological processes usually respond faster than morphological processes, and thus short-term improvements of the ecosystem might not be an indicator for the mid to long term success of e.g. river restoration or changes of sediment management plans. Sediment budget assessments are very important to diagnose river geomorphic status and assess potential success of restoration actions (Habersack et al., 2019a), to plan sediment management strategies and to predict changes resulting from a changed sediment management or to evaluate future impacts.

## 2.3 Sediment related processes leading to problems

It is clear that there is a causal chain from sediment transport to river morphology and thus it is clear that a balanced sediment budget is a prerequisite for river morphodynamics and a functioning river system. Furthermore, there is no doubt that a disbalanced sediment regime and disturbed morphodynamics can have extensive consequences and negative impacts on a variety of parameters such as groundwater level, habitats, bank stability, fairway depth, etc. For example, morphodynamics and habitat dynamics are a prerequisite for a good habitat quality and thus directly influences the ecological status. Thus, the link between sediments and aquatic species is given by providing habitats, spawning places etc. Besides the risk of not achieving the good ecological status, an imbalanced sediment regime also puts other sectors such as navigation, flood protection and water supply at risk. Figure 4 and Figure 5 provide some examples on how sediment surplus and deficit as well as related processes can lead to problems and increase the risks in different sectors.

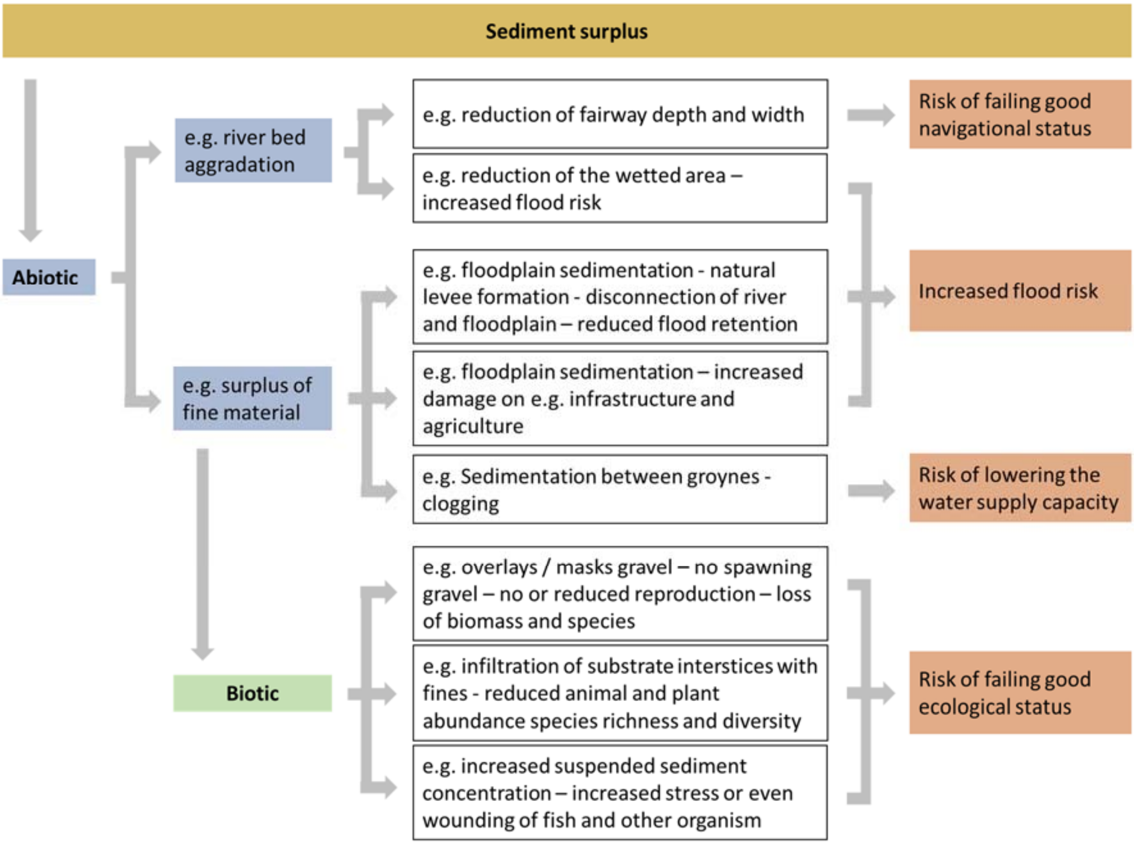


Figure 4 Examples of problems and risks related to sediment surplus

Thus, a balanced sediment regime where a dynamic equilibrium between sedimentation and erosion exists is of utmost importance. Type-specific natural bed forms and bed material should be provided. A balanced sediment regime as well as improved morphodynamics are beneficial to type-specific aquatic communities and water dependent terrestrial ecosystems (Habersack et al., 2019b). Furthermore, a balanced sediment regime is important to reduce flood risk, to achieve a good navigational status or to ensure (drinking) water supply.

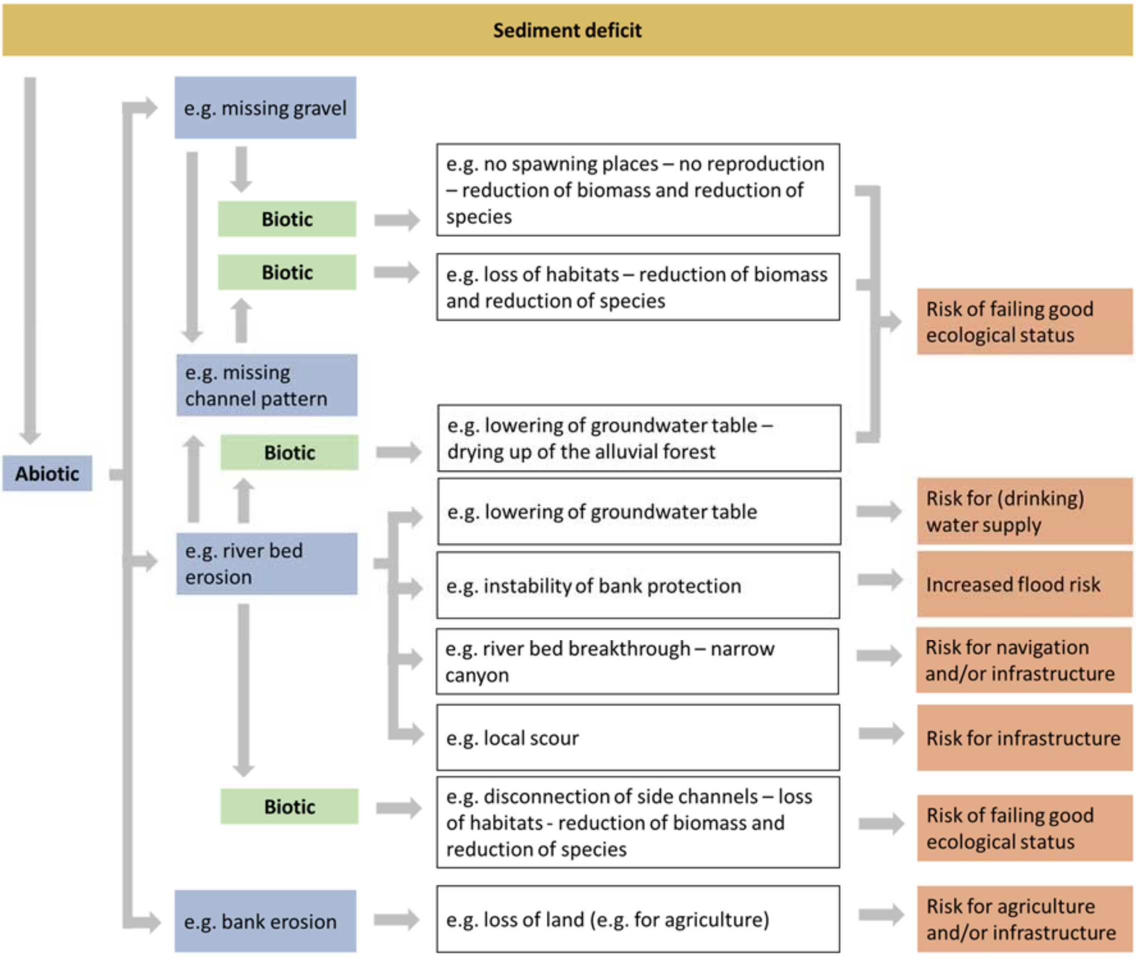


Figure 5 Examples of problems and risks related to sediment deficit

# 3 Description of the project reaches in AT & HU

In the following, a description of the Austrian and Hungarian Danube reaches with a focus on sedimentological and hydromorphological differences and similarities is provided.

## 3.1 Hydromorphological and sedimentological characterisation

Historically, the main river type “multi-thread anabranching” covered most of the Austrian and Hungarian reaches (Figure 6). In Austria the Danube was classified as high energy and this river type was only interrupted by short sections with the river type “confined single-thread – straight/sinuous”. In the Slovakian – Hungarian boarder section also the multi-thread anabranching (high energy)” river type was present followed by a short transitional wandering section. In the following Hungarian part of the Danube the low energy type was dominant, only interrupted by a short river section of “confined single-thread – straight/sinuous” river type. In the lower part of the Hungarian Danube, the river type “single-thread meandering” was present.

Figure 6 Danube River morphological type (reference state) (DanubeSediment, 2019a)

Nowadays, larger sections of the former complex river morphology with multi-thread anabranching and meandering river types have been changed to a single thread sinuous river type in the Austrian and Hungarian Danube. The river is now divided into the two clearly distinguishable units: river and floodplain, whereas the floodplains were drastically reduced in both countries. Consequently, various forms of riverbed degradation occur and naturally-formed sediment bars, islands, side channels and oxbow lakes have been drastically reduced or vanished in the free-flowing sections.

At Gönyű (rkm 1,790) lays the naturally formed boundary between the Upper and the Middle Danube. Here, the gradient of the riverbed changes significantly from 0.35 ‰ to 0.05 ‰ (Figure 7). This means that also the free surface slope decreases and so do consequently the kinetic energy and sediment transporting forces, resulting in considerable sediment deposits at places. Historically, here the anabranching river pattern changed into transitional wandering downstream of the gradient change (Figure 6).

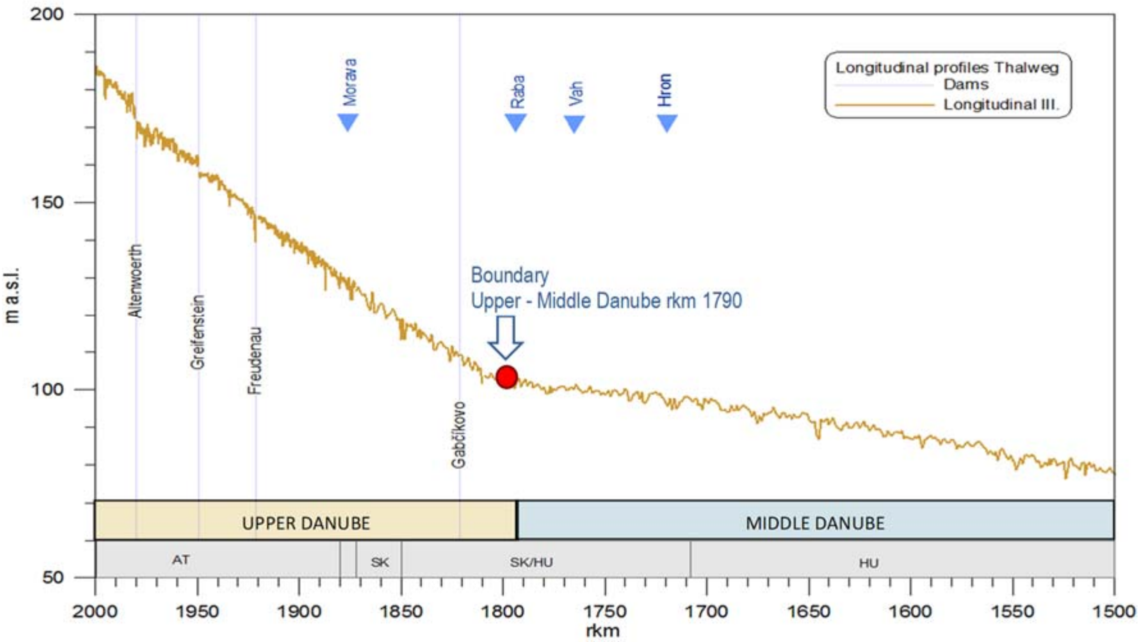


Figure 7 The longitudinal profile of the Danube River between rkm 2,000 and rkm 1,500 and the boundaries between Upper and Middle Danube (DanubeSediment, 2019a).

The change in the river bed slope is followed by a gradual change in the river bed composition. The Austrian Danube East of Vienna is gravel dominated, with a sediment diameter $d_{50}$ of 21 - 23 mm. In Hungary, the Danube River changes from a gravel bed to a sand bed river with the major change taking place within the transitional zone approximately between rkm 1,660 and rkm 1,420. The $d_{50}$ grain size along the gravel bed section of the Middle Danube varies between around 4 mm and 30 mm, along the transition zone $d_{50}$

varies within a wider range from 0.3 mm to 12 mm and along the sand bed section the $d_{50}$ varies between 0.18 mm and 0.6 mm (DanubeSediment, 2019a).

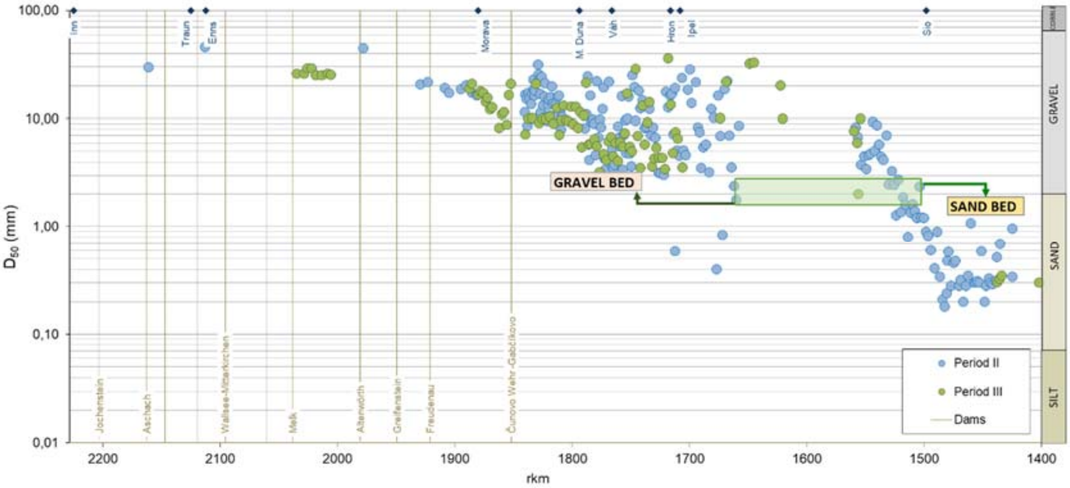


Figure 8 Variation of the median size of the bed sediments $D_{50}$ (surface layer) over three periods (II: 1971-1990; III: 1991-2016) along the Austrian – Hungarian Danube River (modified after DanubeSediment, 2019a)

## 3.2 River engineering

The Danube River has been modified to reduce the flood risk, to improve the conditions for inland navigation, with the construction of hydropower plants (Habersack et al., 2016) and to get new land for urban and agricultural development (Hein et al, 2016). With the beginning of the 19th century, systematic training works for flood protection and inland navigation started in large parts of the Danube River. As a consequence, the morphology of the river was severely altered as shown in Figure 9, for the reach East of Vienna (Second military survey) and near Gönyü (Third military survey).

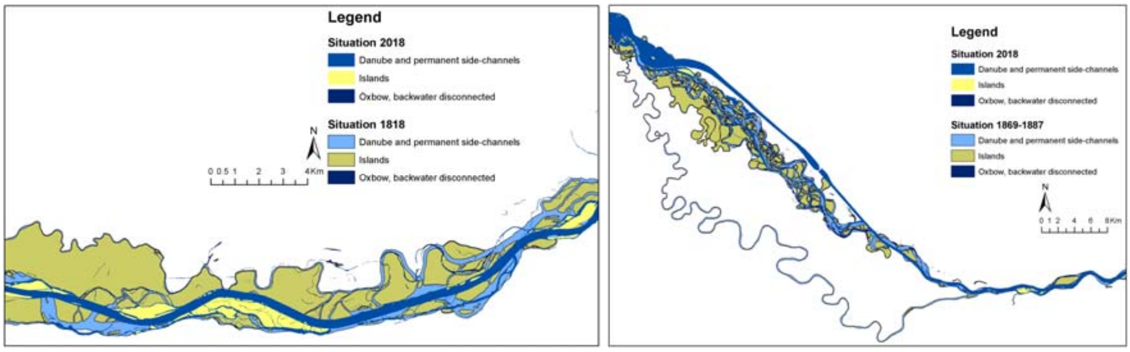


Figure 9 Comparison of the historic and current planform of the Danube River in selected reaches: left: East of Vienna – AT, right: near Gönyü – SK/HU, (modified after DanubeSediment 2019a)

Before 1850, only local measures for flood protection and navigation were implemented at the Austrian Danube without greater influence on the river's morphology. In the following decades the river regulations were extended from local measures onto a supra-local scale. Between approximately 1850 and 1950, the systematic mean and low water regulation for flood protection and inland navigation were realised, causing major changes in the river's morphology and sediment regime. Here, the mean water regulation caused the most significant changes, resulting in the Danube's confinement to a single channel with stabilised banks.

Concerning flood protection, the Danube River was regulated so that the riparian area is protected against floods with recurrence intervals of up to 1 in 100 years (Danube FloodRisk, 2013). The reduction and degradation of the floodplain system, decreased their capacity for water retention and thus changed the frequency and duration of floods (Habersack et al, 2016). Large inundation areas have been impacted by river regulation or flood protection measures. For instance, in Hungary an area of no less than 3.7 million hectares has been dyked (ICPDR, 2020).

Especially in the Upper and the Middle Danube, which also includes DE and the SK and SK-HU border reach, the width of the Danube River and its floodplains was drastically reduced. In the Austrian Danube, the total width was decreased on average by 42% (the active width by 24%) in the Slovak-Hungarian border section by 48% (the active width by 39%) and in the Hungarian Danube by 40% (the active width by 23%). The construction of river training structures such as guiding walls and groynes additionally decreased the width at lower water levels (Figure 10).

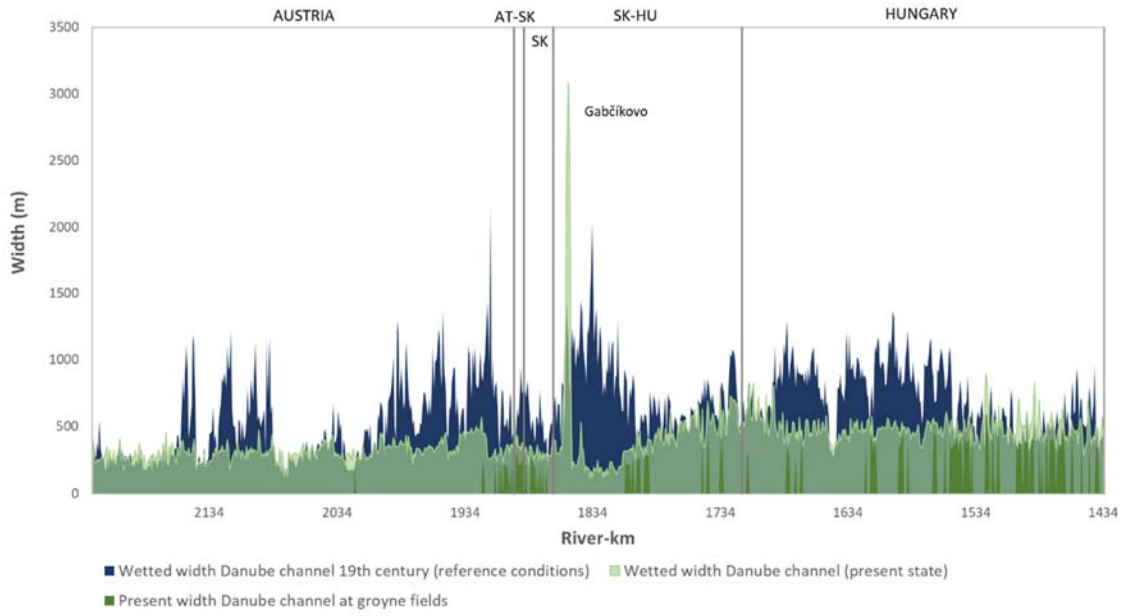


Figure 10 Change of the channel width of the Austrian and Hungarian Danube River: 19th century and current situation (modified after DanubeSediment, 2019a).

## 3.3 Navigation

Navigation is of high importance for the Danube River and has been has regulated by an international commission since 1856 and since 1948 by the Danube Commission. The Convention Regarding the Regime of Navigation on the Danube (“Belgrade Convention”) ensures free navigation on the Danube for all commercial vessels sailing under the flags of all nations (viadonau, 2019). Starting from Sulina and ending in Kelheim at the end of the Danube as a German federal waterway, 2415 rkm or about 85% of the Danube River are available for international waterway freight transport (viadonau, 2019).

The total freight transport on the entire Danube amounts to approx. 79.5 million tons yearly, related to the Danube – Black Sea Canal. These figures include transit traffic and bulk cargo, but there is no separate estimation for these categories. Austria, besides Romania and Serbia, is among the countries with the highest tonnage transported on the Danube (ICPDR, 2015). In a long-time average, around 10 million tons of goods are transported on the Austrian Danube each year. Around a third of these goods are ores and scrap metals, while petroleum products, agricultural products and forestry products each account for around one eighth of the transported goods (viadonau, 2019). In Hungary, agricultural products have the highest share in transport via inland navigation followed by ore and pig iron for iron and steel industry as well as iron and steel products (Scholten and Rothstein, 2016).

In the Danube region several factors limit inland navigation, e.g. the size and curve radii of the fairway and the height of bridges limit waterway transport on the Upper Danube. Other factors are the so called 'bottlenecks areas' with difficult shipping conditions. While low water levels have an impact on inland navigation along the whole river, it is most severe at the bottlenecks. At these bottlenecks the water is especially low then (e.g. due to massive rock formations in the river beds). Several bottlenecks can be found in Austria as well as in Hungary, where the minimum fairway depth of 2,5 m, which is required for the good navigational status (Muilerman et al., 2018), is not met at low water conditions (Scholten and Rothstein, 2016).

## 3.4 Hydropower

The river's natural gradient makes the Upper Danube well-suited for the construction of hydropower plants (Bachmann, 2010). Along the Austrian section of the Danube a chain of hydropower plants (HPPs) exists, consisting of ten HPPs (including the HPP Jochenstein at the DE-AT border) (Figure 11). Of these ten HPPs, nine were put into operation between 1955 (HPP Jochenstein) and 1984 (HPP Greifenstein), and the HPP Freudenau was completed in November 1997. The length of the impoundments varies from 16 to 41 km (VHP, 2013). Around 78% of the Danube in Austria are affected by impoundments, while only 22% or 77 km are free-flowing sections (NEWADA duo, 2014). In Austria, around 34% of the yearly generated electricity comes from hydropower plants located along the Danube River (Wagner et al., 2015).

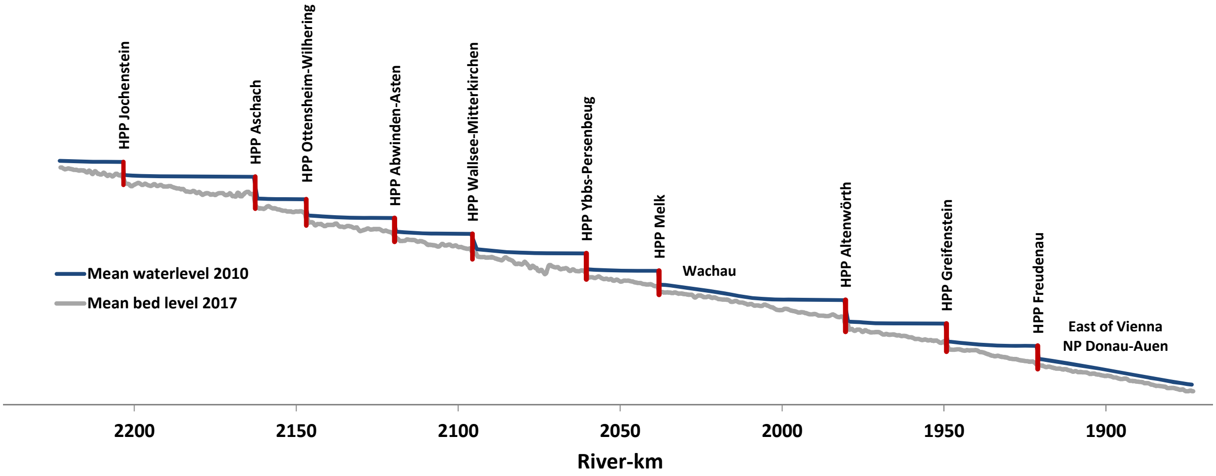


Figure 11 The Danube River in Austria: Locations of the hydropower plants and the free-flowing sections Wachau and East of Vienna (bed levels: VHP and viadonau; water levels and locations of the hydropower plants: viadonau (2012)).

At the lower end of the Upper Danube the HPP Gabčíkovo was constructed in Slovakia and put into operation in the year 1992. The HPP Gabčíkovo was built on a by-pass canal leaving only a reduced, mostly uniform discharge of about 400–600 m$^3$/s in the Old Danube Channel. Hence, the Danube River was modified substantially and the flow conditions as well as the sediment balance were greatly altered. The area of the Čunovo reservoir is 40 km², exclusively on the Slovak side. The impounded area has a length of more than 120 km, where the 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. The disruption of sediment continuity by the system of weirs at Čunovo and the HPP at Gabčíkovo has caused sediment deficits in the downstream sections.

## 3.5 Other relevant factors

### 3.5.1 Dredging

In the past, commercial dredging was often performed to gain raw material for the construction industry (buildings, roads, infrastructure, etc.) (Habersack et al., 2019c). The dredging volume between 1971 and 2016 in the Danube between Austrian und Hungary (incl. Slovakian border sections) totals to an amount of approximately 110 Mio. m$^3$, where the greater part was dredged in the first half of this period (Figure 12). A considerable portion of these sediments were used for commercial purposes. In some parts of Slovakia and Hungary, dredging amounts even exceeded the bedload supplied from upstream. The extracted sediments mainly consist of bedload material, which is already significantly influenced by continuity interruptions in the river (Habersack et al., 2019c). Nowadays, dredging is mainly done for flood protection and navigation and the perspective on dredging has begun to change. For example, between 1996 and 2005, 30 % of the excavated material from the Austrian Danube River was removed but since 2006, the entire amount of dredged sediments is reinserted in the main channel (Habersack et al., 2019c). In Austria and Hungary, commercial dredging (of gravel) is not performed/allowed anymore.

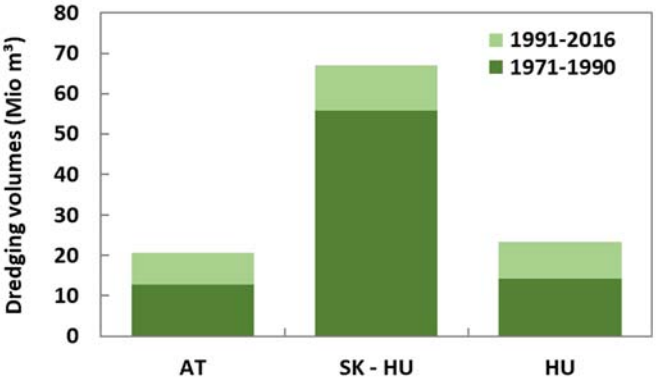


Figure 12 Dredging volumes divided by country for two different time periods

### 3.5.2 Water supply

In the Danube River basin, many waterworks along the Danube and its tributaries use bank-filtered water for domestic drinking water supply, industry and irrigation (Natchkov, 1997). In Austria, only a small portion of the water supply comes from bank-filtered Danube water, e.g. ca. 5% of Vienna's water is provided by groundwater including bank-filtered water from the Danube (Vienna Water, 2020). Some of the most important groundwater reservoirs in the east of Austria are located at the Danube east of Vienna: the Marchfeld on the left bank side, the area near Haslau and the area near Petronell, both on the right bank side. Here, the groundwater resources are mainly used for agricultural irrigation, for drinking water and as industrial water supply (Donauconsult, 2006). In Hungary on the contrary, a high percentage of 95% of the drinking water is supplied from groundwater (MTA, 2017). Riverbank-filtered water play an important role and is source of 40% of the drinking water supply and for the drinking water of almost all citizens of Budapest. The bank-filtered well system is especially located along the upper and middle sections of the Danube River, where gravel and sand characterize the riverbed.

# 4 Problems along the study reach of the Danube in Austria and Hungary

## 4.1 Upper Danube (Austria)

### 4.1.1 Problems related to river engineering

#### 4.1.1.1 Flood risk protection

The upper reaches of the Danube and large parts of the Middle Danube have been protected against floods by engineering measures, which have affected the hydromorphology of the river. For instance, classic flood protection measures such as dykes have led to a decoupling of the river from the floodplain and a cut-off of side arms resulting in reduced flood retention volumes (Figure 13). Other consequences were a reduction of river length and width leading to increased flow velocities and therefore increased bed shear stresses and river bed degradation (Habersack et al., 2015; Habersack et al., 2016).

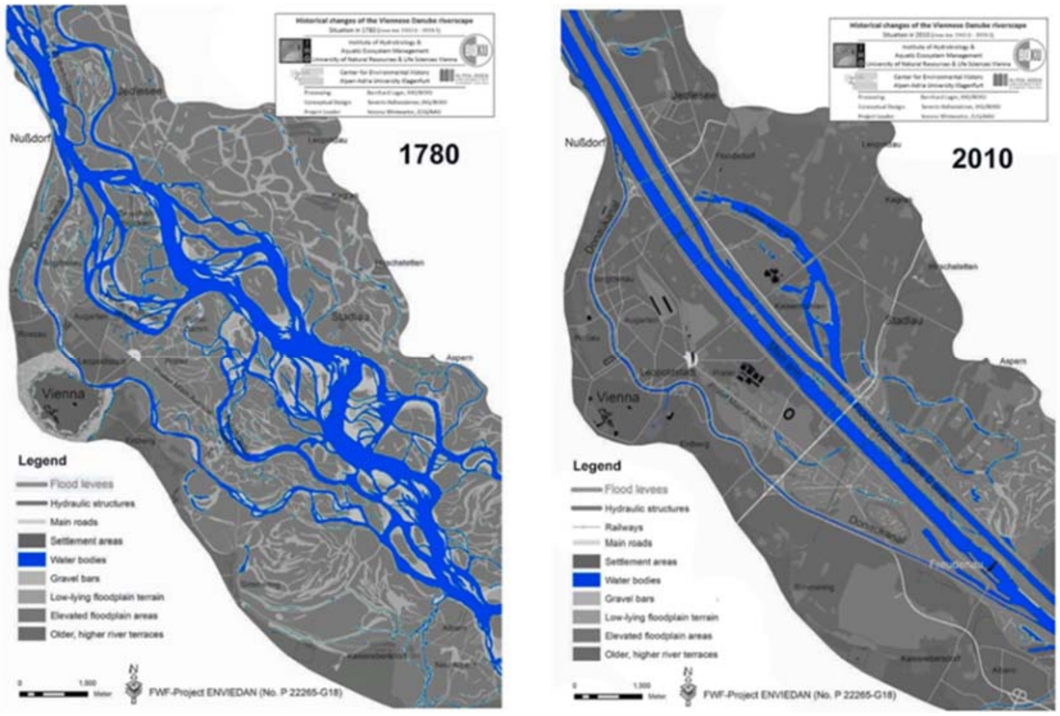


Figure 13 a) Planview of the Viennese Danube River in 1780 and b) after anthropogenic alterations in the current state (modified after Hohensinner & Schmidt, 2012)

#### 4.1.1.2 Instream channel alterations

River engineering measures like groynes and guiding walls serve to improve navigation conditions (e.g. to ensure sufficient water depth) and protect rivers banks from erosion, but also significantly affect the hydrodynamics and morphodynamics within a river reach. The construction of groynes and guiding walls leads to a relatively deep navigational channel and a fixed planform prohibiting lateral morphodynamics. This results in an increased erosion of the river bed in the main channel whereas the groyne fields face sediment aggradation (Habersack et al., 2016; Glas et al., 2018; Ten Brinke et al., 2004).

Figure 14 Orthogonal groyne at mean water level (as a consequence of river bed degradation) (Habersack et al., 2012)

### 4.1.1.3 River bed incision

Impounded reaches in the Upper Danube significantly affect the sediment continuum downstream. Due to engineering structures upstream such as torrent controls in the catchment and hydropower plants, almost no bed load is transported into the reach of the Danube east of Vienna. The resulting bed load deficit causes considerable river bed incision (Figure 15a). Despite an artificial bed load supply of 186000 $m^3/a$ in the years from 1996 to 2017 (recently increased to 235000 m3/a) an erosion of approximately 1 - 2 cm per year occurs according to different authors with a trend of slowdown due to a change of the sediment dredging management of the viadonau in the reach (Pessenlehner, 2016). This degradation also increases the risk of a riverbed breakthrough (e.g. Salzach River, Figure 15b), which might occur once the quaternary gravel layer is fully eroded and the Danube could incise into the underlying finer marine deposits resulting in the formation of a canyon (Habersack et al., 2016).

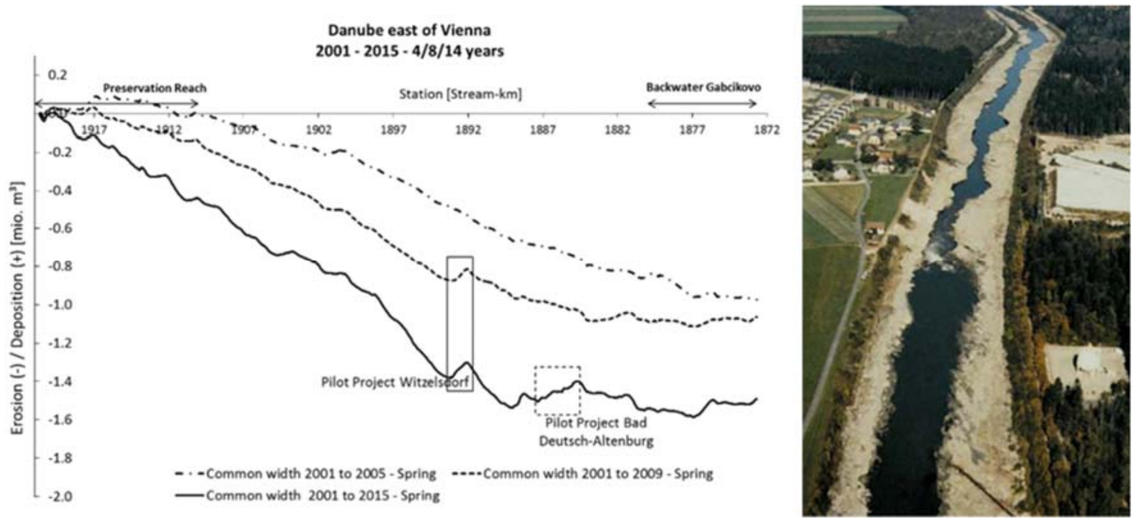


Figure 15 a) Accumulated bed volume change of the Danube River between hydropower plant Freudenau and the Slovak border (Stream-km 1920.6 to 1872.7) for the period 2001 to 2015 (Pessenlehner et al., 2017) b) riverbed breakthrough at the Salzach River, Austria (WRS, 2000)

#### 4.1.1.4 Prevented side erosion

Restricted lateral erosion due to river engineering measures (e.g. bank protection, river straightening, levee construction) inhibits the lateral sediment input into the Danube. Together with an enhanced sediment transport capacity caused by a reduced channel width due to river straightening and narrowing, increased channel slope and backward erosion following a river bed lowering for flood protection in the city of Bratislava the prevented lateral erosion contributes to river bed incision (Habersack et al., 2016).

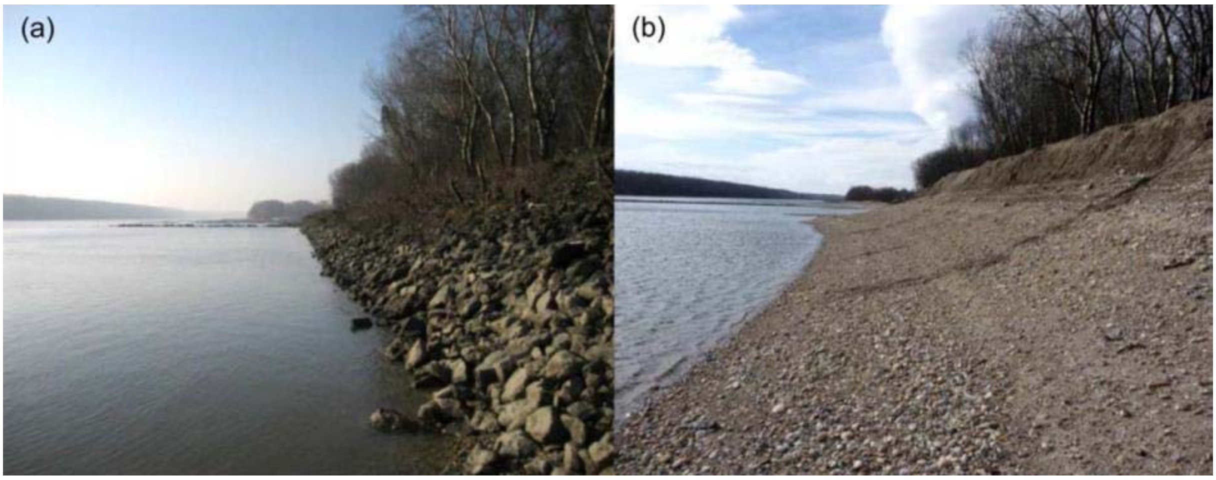


Figure 16 Example of the left bank of the Danube River at Witzelsdorf (viewing upstream) (a) before and (b) after the restoration project in 2009 (photos: viadonau)

#### 4.1.1.5 Decoupling of river and floodplain

The free-flowing section of the Danube east of Vienna is part of a national park, which faces increasing pressures and might be endangered on the long term. River regulation measures (e.g. fixed embankments, groyne structures) and the bedload deficit due to torrent controls in the catchment and hydropower plants upstream of the national park lead to degradation of the riverbed in the main channel and declining groundwater levels. At the same time aggradation of fine sediments in the floodplain area can be observed due to the fixed embankments and thus together with the incision of the main channel a riparian dewatering occurs. A lowering of the groundwater level leads to a decrease or loss of wetland habitats and corresponding flora and fauna and may have negative effects on drinking water supply with respect to quantity and quality, as well as problems for agricultural areas (Habersack et al., 2016; Pessenlehner et al., 2016).

#### 4.1.1.6 Disconnected side arms

Due to degradation, the main channel of the Danube and the floodplain are gradually disconnected. The frequency and duration of inflows into side-arms of the river are decreasing and in connection with siltation these side-arms are transformed into riparian forest or dry out (Klasz et al., 2013).

Figure 17 a) Location of the Johler Side Arm near Hainburg and b) the situation below mean water level before the side arm reconnection within the pilot project Bad Deutsch-Altenburg (photos courtesy of Nationalpark Donauauen & viadonau)

#### 2.1.1.8 Ecology

The Danube east of Vienna originally constituted an anabranched laterally active river-system with a main stem, several side branches and extensive riverine woodlands (Hohensinner et al., 2004). Current and past river regulation measures have caused strongly reduced fluvial dynamics and changes in habitat diversity. The size of water bodies, area of gravel bars, length of the shorelines and number of islands have decreased dramatically. In addition, several barriers were constructed along the Danube in recent years. All these factors have presented a significant challenge for many organisms. For instance, riverine fish rely on a broad range of habitats throughout their life cycle and the pressures of anthropogenic impacts have resulted in a reduction of species richness (Reckendorfer et al., 2005). The majority of riverine species in the Danube are on the red list of endangered species. Even though the free-flowing section downstream of Vienna is part of a national park, the construction of dams up- and downstream, the river regulation in the reach and partial disconnection of sidearms and floodplains have led to ecological deficits. For instance, the large diadromous sturgeons have disappeared in the upper sections of the Danube because their migration routes have been blocked by downstream barriers (Keckeis and Schiemer, 2002). Fish biomass as an indicator for a good ecological status stated in the EU Water Framework Directive, decreased heavily over the last years. From 248.4 kg/ha in 2007 biomass now is in risk to fall below the threshold value of 50kg/ha (Scheiblechner, 2018).

#### 2.1.1.9 Recreation

Various sediment related issues at the Danube east of Vienna are affecting the recreation or at least pose a potential risk towards it. The consequences of decreasing low water levels influence the navigability of this section (Habersack, 2007; Habersack et al., 2016) and therefore is critical for cruise tourism. Furthermore, the decoupling of river and floodplain reduces the accessibility for paddlers and together with other factors leads to decreasing fish biomass in the Danube east of Vienna (Scheiblechner, 2018) with negative effects for fishing activities.

#### 2.1.1.10 Water supply

In the Danube east of Vienna there are three groundwater bodies – the Marchfeld on the left bank side, the area near Haslau and the area near Petronell, both on the right bank side- which are among the most important groundwater reservoirs in the east of Austria. In many of these areas, groundwater resources are used intensively for agricultural irrigation (e.g. Marchfeld) as well as for drinking water (Wasserwerk Lobau, Stadtgemeinde Schwechat) and industrial water supply (OMV, Air Liquid, Borealis, Brauerei Schwechat). Because of this high economic importance (irrigation, drinking and industrial water) and the role played by the natural environment (water supply to plants, spiking of waters during periods of drought), the quantity and quality of these aquifers is of enormous interest. (Donauconsult, 2006)

Sediment related issues such as river bed incision and declining water levels as well as the disconnection and siltation of side-arms have an observed and significant impact on the adjacent groundwater bodies and their groundwater level elevation. (Donauconsult, 2006)

### 4.1.2 Problems related to navigation

There is a strong economic interest to increase navigation on the Danube. However, a balance needs to be found between the needs for navigation of 2,5 m minimum depth and 120 m width at low flow condition (Figure 18), the hydro- and morphodynamics of the river and the ecological situation.

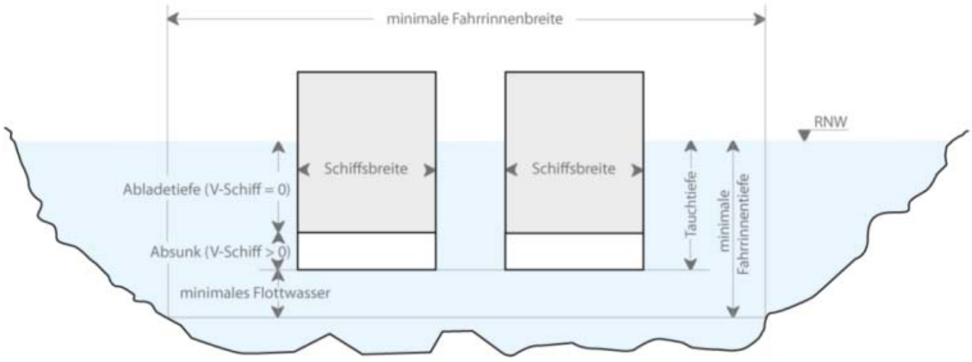


Figure 18 Navigation requirements at the Austrian Danube River (Donaukommission, 2011)

#### 4.1.2.1 Hydro- and Morphodynamics

River canalisation and river training works for navigation (described in 4.1.1.1 and 4.1.1.2) have led to increased bed slopes and shear stresses and therefore increased erosion and sediment transport rates, which subsequently resulted in river bed incision. Furthermore, the maintenance of the navigation channel to meet the minimum requirements during low flow periods results in dredging activities in areas of fords (Habersack et al., 2016). Until 2005 only 50 % of the excavated volumes were returned in the main channel, 20 % were returned in groyne fields and 30 % were totally withdrawn from the system. After 2005 the entire dredged gravel was returned in the main channel. Since 2009 the gravel is transported upstream before it is returned in the river and since 2015 the shipping distances were increased to ~10 km as part of a new sediment management strategy to tackle river bed incision at the Danube East of Vienna.

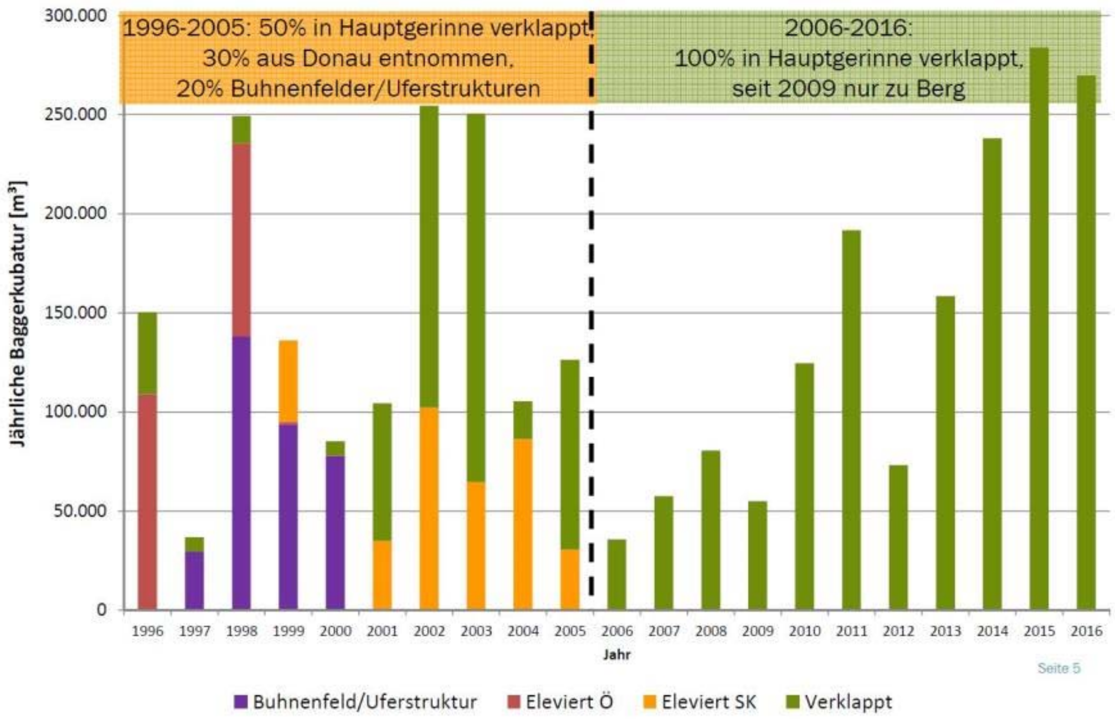


Figure 19 Maintenance dredging works at the Danube River east of Vienna 1996-2016 – annual volumes & purpose (Simoner & Berger, 2016)

### 4.1.2.2 Restrictions for navigation in low flow periods

There are several reaches of the Danube in which hydrological and hydromorphological characteristics lead to restrictions for navigation. Especially in areas with sedimentation extending over the entire width of the channel present significant bottlenecks for navigation. Particularly during low flow periods, the minimum water depth of 2,5 m is not always met. To maintain the river corridor and enable continuous navigation subsequent maintenance (e.g. dredging) is needed (Habersack, 2007; Habersack et al., 2016).

### 4.1.2.3 Ecology

Increased navigation on the Danube also has a negative impact on ecology. Wave splash, water drawdown (risk of stranding) and energy impact due to high frequency of waves represent direct negative impacts for juvenile fish habitats near the shore line. Furthermore, sediment turbulences, shear stress and pollution caused by ship traffic negatively affect the riverine biota and can lead to habitat loss (Kucera-Hirzinger et al., 2009, Liedermann et al., 2014, Schludermann et al., 2014).

Figure 20 a) Ship in the area of the Nationalpark Donauauen (photo: IWA/BOKU) and b) a scheme of the habitat loss related to water drawdown respectively waves due to inland navigation (Schludermann et al., 2014)

### 4.1.3 Problems related to hydropower

#### 4.1.3.1 Sedimentation in reservoirs or impoundments

Engineering structures like hydropower plants interrupt the sediment continuum, especially of bedload, leading to a surplus of sediment upstream and a sediment deficit downstream of the impoundments. The sediment trapping efficiencies of existing hydropower plants along the Danube River vary depending on the reservoir size, shape, and depth, as well as basin vegetation. While reservoirs or impoundments tend to silt up over time, during extreme floods large amounts of sediment are remobilised from the reservoirs or impoundments. This is in strong contrast to the past, when sediment transport occurred more evenly throughout the year (Habersack et al., 2016). On the other hand, sedimentation in reservoirs / impoundments can lead to an increase of floodrisk (Habersack et al., 2013).

Figure 21 Hydropower plant Aschach at the Danube River (photo: Verbund AG)

#### 4.1.3.2 Reservoir flushing

The loss of storage capacity in hydropower plants (see 4.1.3.1) sometimes necessitates the flushing of reservoirs. However, these measures can have drastic consequences for ecology. For instance, a sudden increase in sediment load can lead to a clogging of hyporheic interstices, which in turn leads to reduced oxygen availability in benthic zones. Flushing of reservoirs can also lead to increased stress or even wounding of fish and other organisms, as well as to the loss or change of habitats (Jungwirth et al., 2003; Habersack et al., 2013; Habersack et al., 2016). On the other side, sediments are needed downstream for spawning places and habitat dynamics etc. Thereby both – sediment concentration and duration – are determining the impact of flushing on the ecosystem.

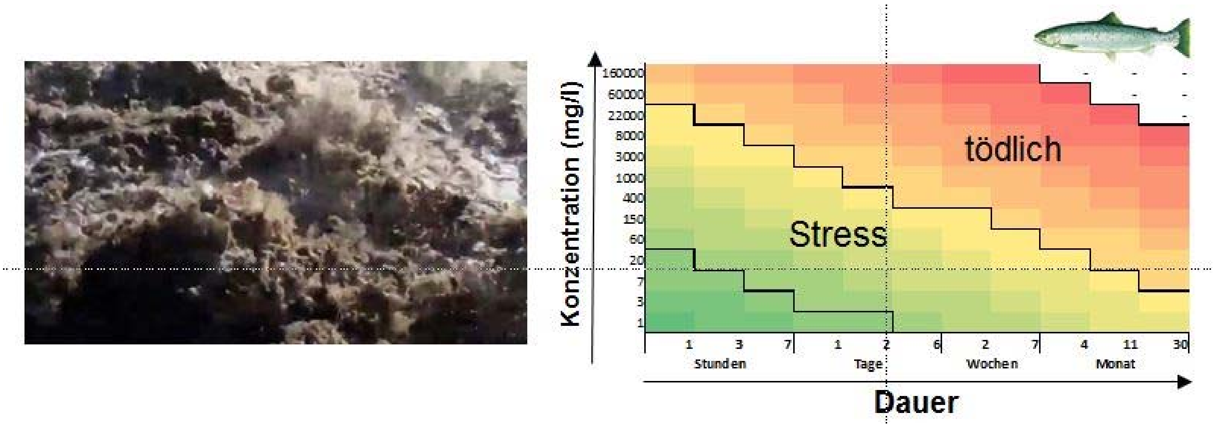


Figure 22 a) Reservoir flushing of the Mur river (photo: YouTube) and b) stress indicator of fine sendiments on fish depending on duration and concentration (figure modified after Newcombe & Jensen, 1996)

In case of flushing or major flood events, fine sediments can be remobilised from reservoirs or impoundments. Such an event can lead to major problems for the river ecosystem, e.g. it may congest the respiratory system of fauna, clog spawning places, bury plants and increase the oxygen demand, as well as adding sediment to the floodplains (Figure 23). The sedimentation in the floodplain and settlements can significantly increase damages and thus floodrisk.

Figure 23 Floodplain sedimentation (photo: Verbund AG)

#### 4.1.3.3 Interruption of sediment continuum

Today, only five free flowing sections remain throughout the Danube, two of them in Austria (Figure 24). As a consequence of several impounded reaches, the river is affected by severe hydrological and hydraulic changes. Changes in the sediment balance become increasingly noticeable including an interrupted bed load continuum, a deposition of suspended sediment in impounded reaches and a sediment deficit in the free-flowing sections (Habersack et al., 2016).

Figure 24: The Danube River in Austria: Locations of the hydropower plants (red) and the free-flowing sections (green) (bed levels: VHP and viadonau; water levels and locations of the hydropower plants: viadonau (2012)).

## 4.2 Middle Danube (Hungary)

### 4.2.1 Problems related to river engineering

#### 4.2.1.1 Flood risk protection

Similar to the situation in Austria, significant measures were implemented along the Hungarian Danube section to mitigate flood risk from the 19th century. For this purpose, dykes were constructed along the river and the river banks were stabilized, decreasing both the width and length of the active channel (Figure 25). The main impact of these sort of engineering measures is the increasing flow velocity in the main channel and consequently, the increasing bed shear stress results in river bed incision. Besides the geometry of the main channel, the land use in the floodplain also changed. Until the mid of the 20th century the floodplain and the islands were mostly utilized for grazing. However, actually floodplains can be characterized with dense forest, which steers higher discharge into the main channel during floods. In contrast with the deepening of the main channel and the related lowering of the low water levels, the flood water levels increase (EDUVIZIG, 2014).

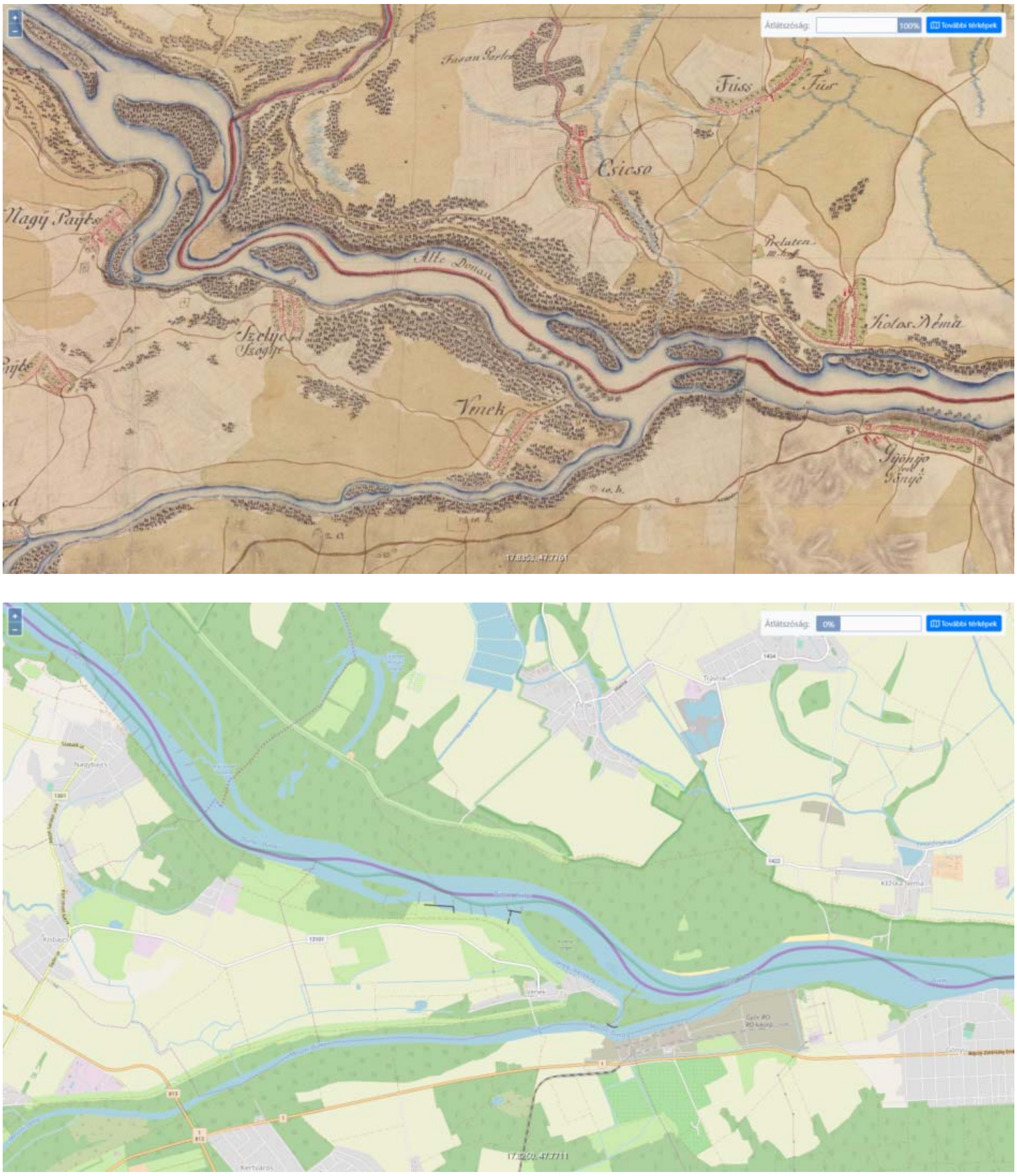


Figure 25 a) Planview of the Hungarian Danube River in 1782-1785 (First Military Mapping) and b) after anthropogenic alterations in the current state (2018)

#### 4.2.1.2 Instream channel alterations

Conventional river engineering structures, such as groynes and training walls were constructed in the river to narrow the main channel in order to ensure the adequate navigational depth (Figure 26 and Figure 27). Besides the construction of structures, navigational bottlenecks are continuously dredged. Furthermore, extreme volumes of gravel were dredged along the Upper-Hungarian Danube reach between 1970-1991 for house construction purposes. The extracted volume during the 21 years reached 64 M m$^3$ between the river sections rkm 1810-1702.

Figure 26 River engineering structures at low level around rkm 1799 (aerial photo taken in 2011)

Figure 27 River engineering structures along the Hungarian study section, rkm 1800-1790 (source: eduvizig.hu)

#### 4.2.1.3 River bed incision

Significant deepening of the main channel took place in the last decades along the Upper-Hungarian Danube reach. The most dynamic part of the river is located between Sap and Gönyű, between rkm 1811-1793. The permanent bed erosion is the combined influence of different human interventions. As mentioned above, first, conventional river regulation measures took place for flood risk mitigation with the construction of a dyke system along the river as well as the stabilization of the river banks were implemented. Second, groyne fields together with training walls were built in the main channel to ensure the flow depth for ships. Third, due to the intensive house constructions between 1970-1991, several million m$^3$ of gravel was extracted from the river bed. And finally, the impounded reaches in the Upper Danube and mainly the hydropower plant at Bős (SK) significantly affect the sediment continuum downstream. Due to sediment trapping effect of the hydropower plant, almost no bed load is transported into the reach of the Hungarian section. As a consequence of the indicated anthropogenic measures considerable river bed incision could be observed in the last decades. The bed incision can be well captured looking at the temporal variation of the low navigation water levels (Figure 28). Furthermore, the temporal variation of mean bed levels (calculated within the navigational channel) of two characteristic sections is plotted in Figure 29. Section 1797.318 is a typical ford section, whereas rkm 1795.149 is a deeper, typical river bend section. For the former a significant decrease between 1957-2007 can be seen and a rather dynamic equilibrium in the last decade, whereas the deeper section is continuously lowering via time with some short-term variations due to the influence of wet and dry years.

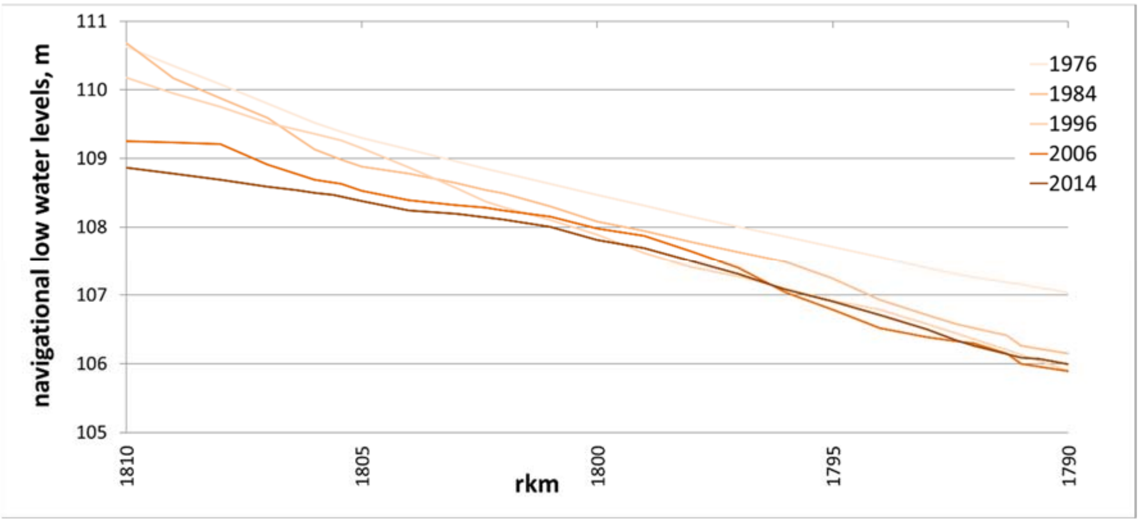


Figure 28 Navigational low water levels between rkm 1810-1790, Hungary

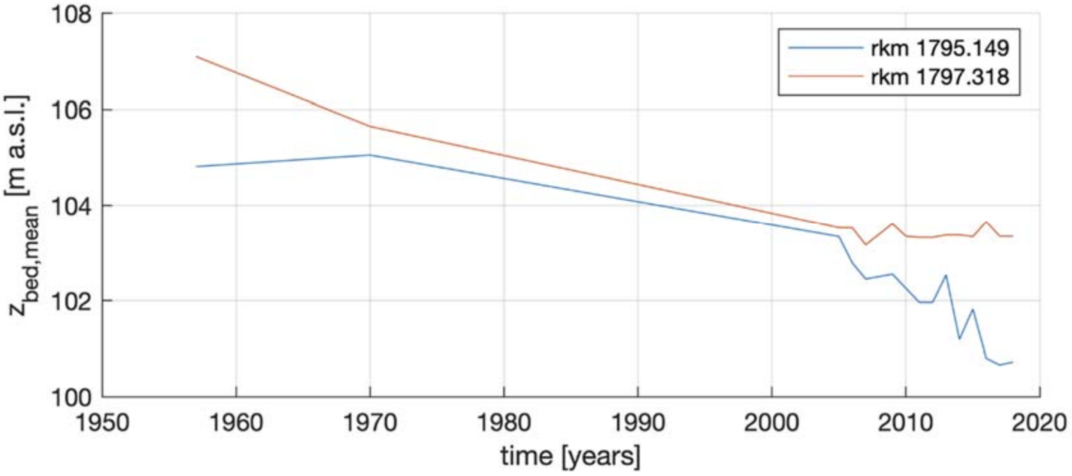


Figure 29 Mean bed elevation changes (within the navigational channel) at two characteristic sections of the upper-Hungarian Danube

#### 4.2.1.4 Prevented side erosion

The river banks along the major section of the Upper-Hungarian Danube is protected by ripraps, which prevents natural lateral erosion of the river bed. These structures also enhance bed erosion processes in the main channel. See an example of the bank protection together with a typical cross-section of the structure in Figure 30.

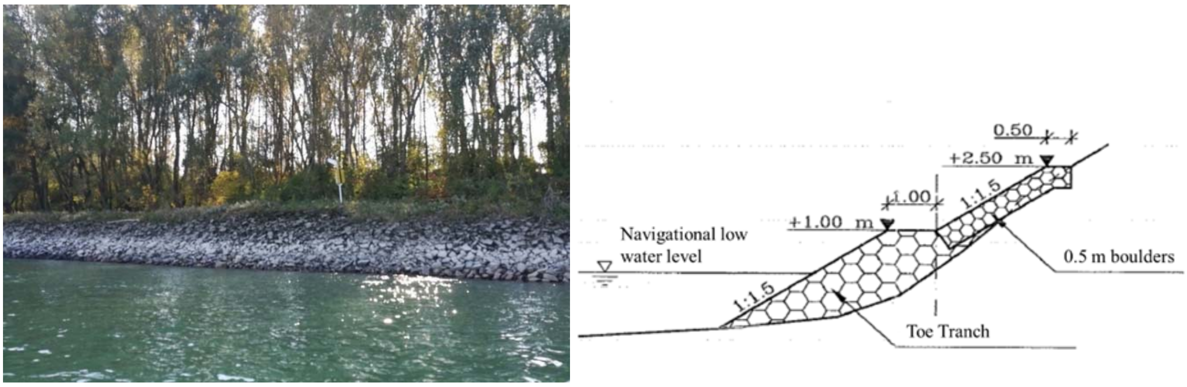


Figure 30 a) Example of the right bank protection of the Danube River at Vámosszabadi (source: ÉDUVIZIG) b) cross section of rivebank protection (HU-SK River regulation plan 1996)

On the other hand, natural high banks, that are not stabilized with ripraps, are exposed more and more to bank failure (Figure 31). The incision of the river bed strongly increases the chances of such a disaster.

Figure 31 Natural river bank at Gönyű (source: www.gonyu.network.hu)

### 4.2.1.5 Decoupling of river and floodplain

Due to the increasing vegetation along the floodplains, the flood conveyance capacity of these zones are continuously decreasing, moreover, sedimentation processes during floods result in increasing floodplain elevation. Decreasing flow discharge in the floodplains yields higher flood discharges transported in the main channel, further increasing the bed erosion, especially during high water. On long-term, high water levels increase, low water levels decrease (Figure 32), and the latter consequently lowers the connecting ground water levels, too.

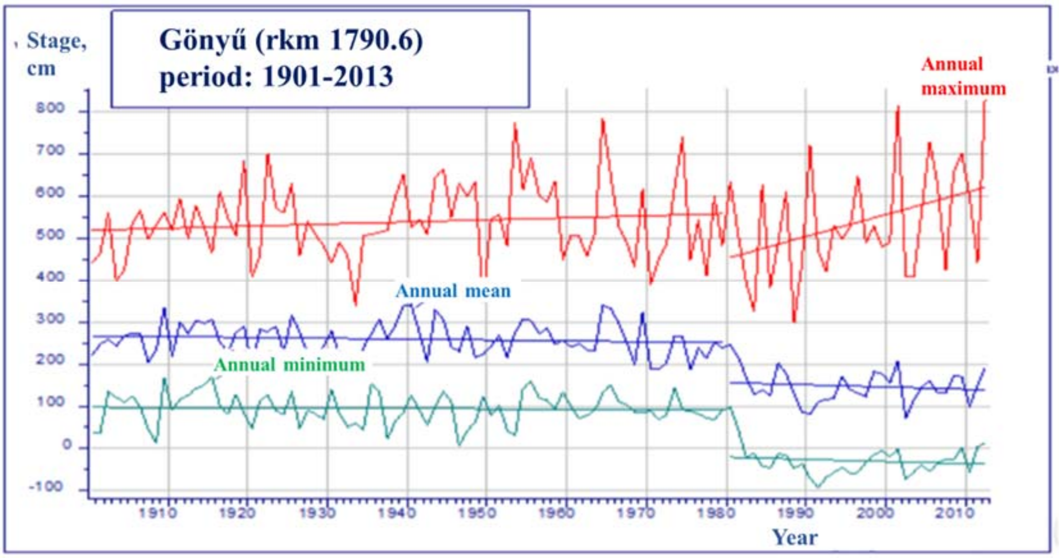


Figure 32 Temporal variation of water level time series at Gönyű, Hungary

### 4.2.1.6 Disconnected side arms

Similar to the issues related to the floodplain, the river bed incision in the main channel negatively affects the connection to side arms. Moreover, conventional river regulation measures applied the artificial cut-off and even upfilling of the side arms. Duration of direct connections between the main channel and the side arms is decreasing, as well as the volume of water in the side arms. This problem is even more enhanced with the continuous upfilling of the culverts at the inlet sections of the side arms, which should ensure the water supply towards the side arm.

Figure 33 Side arm sedimentation near Vének at rkm 1798 rkm (source: ÉDUVIZIG, 2018)

### 2.1.1.8 Ecology

The entire Hungarian Danube reach is a Natura2000 site (see the location of protected areas along the upper-Hungarian Danube in Figure 34), which enhances the ecology related impacts of the deteriorating sediment transport processes. The permanent river bed incision results in the development of vegetation on formerly shallow gravel fords in the main channel, which yields the disappearing of important habitats and spawning places. In fact, according to the Water Framework Directive the main stretch of the Hungarian Danube is declared as “Heavily modified water bodies – Final Designation”. The only two exceptions are located directly upstream of Budapest; these are designated as “Natural water bodies”. Figure 35 displays the ecological status and ecological potential of the Hungarian Danube – according to the Danube River Basin Management Plan/Update 2015 – against the background of the critical navigation locations in Hungary.

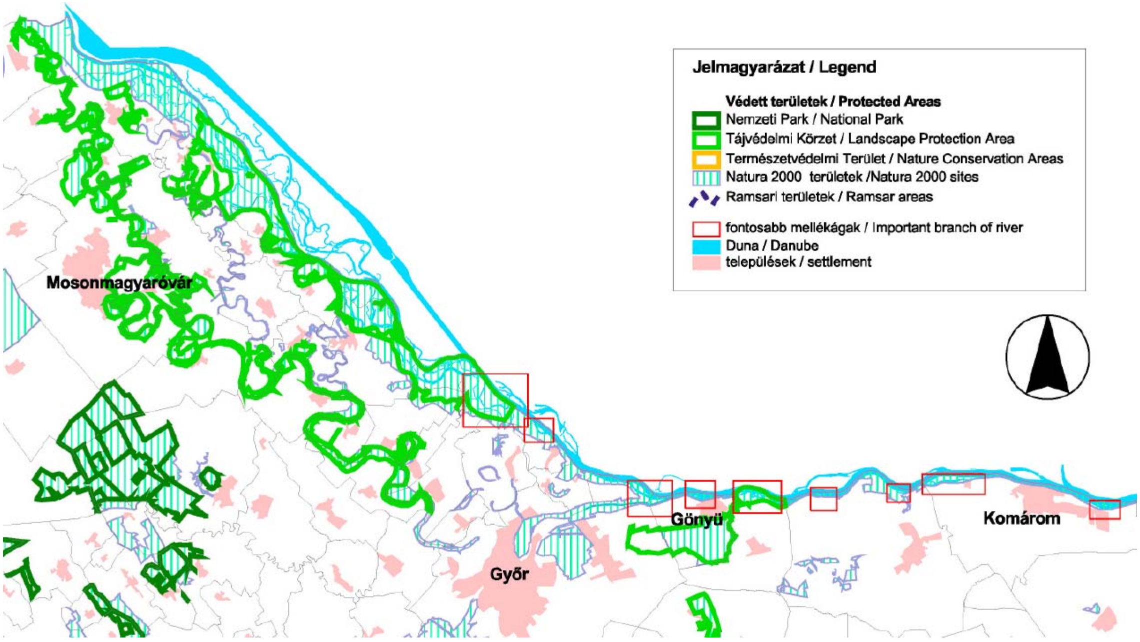
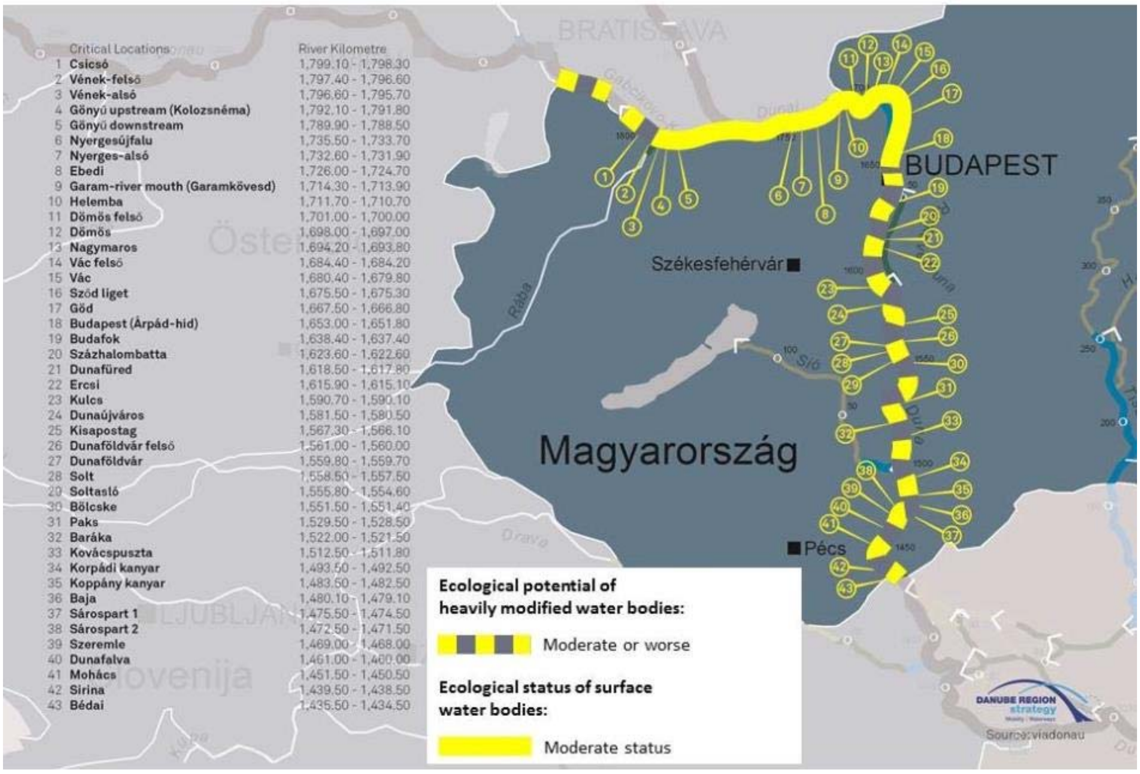


Figure 34 Protected areas along the upper-Hungarian Danube (source: ÖKO Zrt.)



| | Critical Locations | River Kilometre |
|---|---|---|
| 1 | **Csicsó** | 1,799.10 - 1,798.30 |
| 2 | **Vének-felső** | 1,797.40 - 1,796.60 |
| 3 | **Vének-alsó** | 1,796.60 - 1,795.70 |
| 4 | **Gönyű upstream (Kolozsnéma)** | 1,792.10 - 1,791.80 |
| 5 | **Gönyű downstream** | 1,789.90 - 1,788.50 |
| 6 | **Nyergesújfalu** | 1,735.50 - 1,733.70 |
| 7 | **Nyerges-alsó** | 1,732.60 - 1,731.90 |
| 8 | **Ebedi** | 1,726.00 - 1,724.70 |
| 9 | **Garam-river mouth (Garamkövesd)** | 1,714.30 - 1,713.90 |
| 10 | **Helemba** | 1,711.70 - 1,710.70 |
| 11 | **Dömös felső** | 1,701.00 - 1,700.00 |
| 12 | **Dömös** | 1,698.00 - 1,697.00 |
| 13 | **Nagymaros** | 1,694.20 - 1,693.80 |
| 14 | **Vác felső** | 1,684.40 - 1,684.20 |
| 15 | **Vác** | 1,680.40 - 1,679.80 |
| 16 | **Sződ liget** | 1,675.50 - 1,675.30 |
| 17 | **Göd** | 1,667.50 - 1,666.80 |
| 18 | **Budapest (Árpád-hid)** | 1,653.00 - 1,651.80 |
| 19 | **Budafok** | 1,638.40 - 1,637.40 |
| 20 | **Százhalombatta** | 1,623.60 - 1,622.60 |
| 21 | **Dunafüred** | 1,618.50 - 1,617.80 |
| 22 | **Ercsi** | 1,615.90 - 1,615.10 |
| 23 | **Kulcs** | 1,590.70 - 1,590.10 |
| 24 | **Dunaújváros** | 1,581.50 - 1,580.50 |
| 25 | **Kisapostag** | 1,567.30 - 1,566.10 |
| 26 | **Dunaföldvár felső** | 1,561.00 - 1,560.00 |
| 27 | **Dunaföldvár** | 1,559.80 - 1,559.70 |
| 28 | **Solt** | 1,558.50 - 1,557.50 |
| 29 | **Soltasló** | 1,555.80 - 1,554.60 |
| 30 | **Bölcske** | 1,551.50 - 1,551.40 |
| 31 | **Paks** | 1,529.50 - 1,528.50 |
| 32 | **Baráka** | 1,522.00 - 1,521.50 |
| 33 | **Kovácspuszta** | 1,512.50 - 1,511.80 |
| 34 | **Korpádi kanyar** | 1,493.50 - 1,492.50 |
| 35 | **Koppány kanyar** | 1,483.50 - 1,482.50 |
| 36 | **Baja** | 1,480.10 - 1,479.10 |
| 37 | **Sárospart 1** | 1,475.50 - 1,474.50 |
| 38 | **Sárospart 2** | 1,472.50 - 1,471.50 |
| 39 | **Szeremle** | 1,469.00 - 1,468.00 |
| 40 | **Dunafalva** | 1,461.00 - 1,460.00 |
| 41 | **Mohács** | 1,451.50 - 1,450.50 |
| 42 | **Sirina** | 1,439.50 - 1,438.50 |
| 43 | **Bédai** | 1,435.50 - 1,434.50 |

Figure 35 Ecological status and ecological potential of surface water bodies (Source: draft Hungarian NRBM Plan – Update 2015)

The ecological status of the two natural water bodies is moderate; the good ecological status is estimated to be achievable in 2027. The designation as heavily modified water body of main parts of the Danube is mainly attributed to bank revetment, which was supported by biological elements. The good ecological potential is estimated to be achieved as follows: in 2021 1 pc, in 2027 2 pc's and after 2027 2pc's. For the heavily modified water bodies measures are to be implemented in order to achieve good ecological potential.

A general issue of ecology is that due to the sedimentation along the floodplains and side arms, the affected areas are drying up the potential of habitats is continuously shrinking.

#### 2.1.1.9 Recreation

River bed incision in the Danube and the consequent decrease of low water levels influences the low water levels in the lower sections of the connecting tributaries, such as the Mosoni-Duna, located within the Hungarian study section. The critical lowering of the water levels limits the utilization of river banks, recreational activities, sports (Figure 36). Due to the nearby location of Győr, the most important city of northwest Hungary, which is situated at the bank of river Mosoni-Duna, a high number of citizens is affected.

Figure 36 Low water in river Mosoni-Duna at Győr (source: www.kisalfold.hu)

#### 2.1.1.10 Water supply

The majority (95%) of drinking water supply in Hungary is provided from ground water (MTA, 2017), out of which river bank filtered water sources are play an important role (40% of the total drinking water supply). The bank filtered well system is located along the Danube River, especially in the upper and middle sections, where gravel and sand characterize the river bed. The conventional river engineering works might have negative influence on the quantity of the water supply as well as its quality. Dredging of the river bed results in the decrease of the thickness of the water supply layer. On the other hand, sedimentation between groynes can result in clogging effects, and a consequent lowering of the water supply capacity.

### 4.2.2 Problems related to navigation

Due the road and rail transport overload there is a strong economic and public interest to increase navigation on the Danube. However, a balance needs to be found between the needs for navigation of 2.5 m minimum depth and 120 m width at low water condition, the hydro- and morphodynamics of the river and the ecological situation.

Based on the Danube Commission recommendation and EU AGN Agreement (European Agreement on Main Inland Waterways of International Importance), the parameters of the fairway are defined. The AGN establishes an international legal framework laying down a coordinated plan for the development and construction by Governments of a network of inland waterways and ports of international importance, based on agreed infrastructure and operational parameters, which they intend to undertake within the framework of their relevant development programmes. The Agreement underlines the importance of inland water transport which, in comparison with other modes of inland transport, presents economic and environmental advantages and may, therefore, contribute to reducing congestion, traffic accidents and negative environmental impacts in the pan-European transport system.

The Danube Commission is concerned with the maintenance and improvement of navigation conditions of the Danube River, from its source in Germany to its outlets in Romania and Ukraine, leading to the Black Sea. It was established in 1948 by seven countries bordering the river, replacing previous commissions that had also included representatives of non-riparian powers. Its predecessor commissions were among the first attempts at internationalizing the police powers of sovereign states for a common cause. They set *recommendation on minimum requirements for standard fairway parameters, hydrotechnical and other improvements on the Danube* (doc. CD/SES/77/11 entered into force on 1 January 2013)

### 4.2.2.1 Hydro- and Morphodynamics

In order to maintain the navigational channel, continuous dredging is performed in both countries along the shared HU-SK section of the Danube River. However, the amount of the dredged material is decreasing with time, due to the more and more strict environmental requirements (Figure 37). Dredging of the river bed can result in the extraction of the uppermost armoured layer, typical to this reach of the Danube. As a consequence, finer compositions will be exposed to the flow (Figure 38), which inherently causes a more dynamic nature of the river bed with locally increasing bedload transport. A similar phenomenon can take place when large barges with high draught reach the river bed at lower water periods, which also results in the break-up of the bed armour.

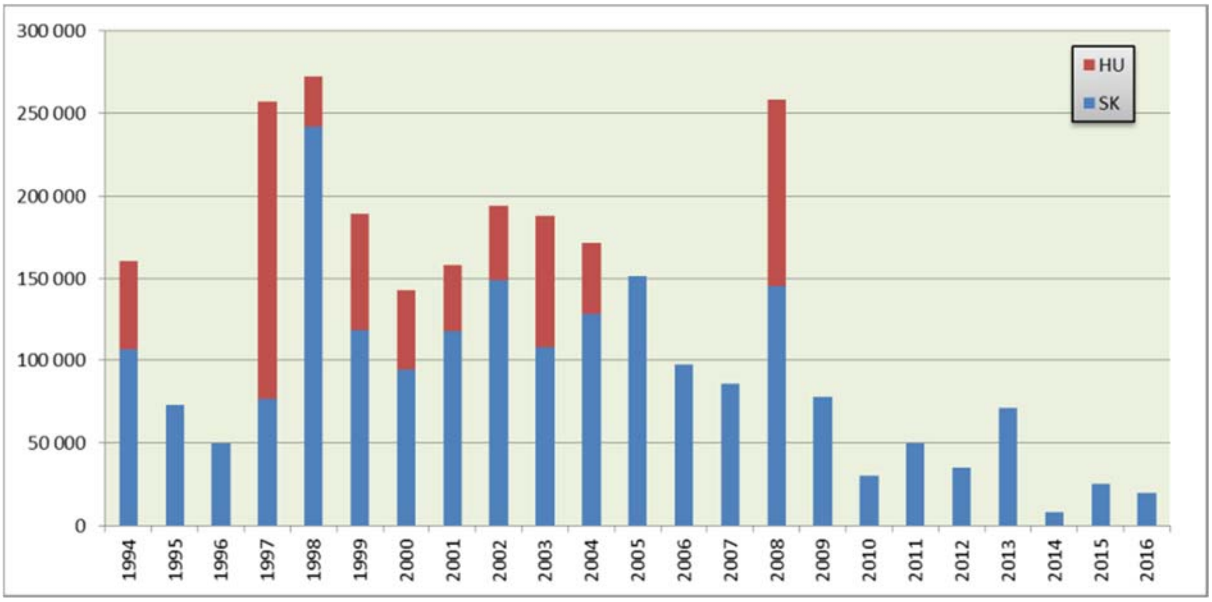


Figure 37 Maintenance dredging works (in m$^3$) at the HU-SK common section of the Danube River

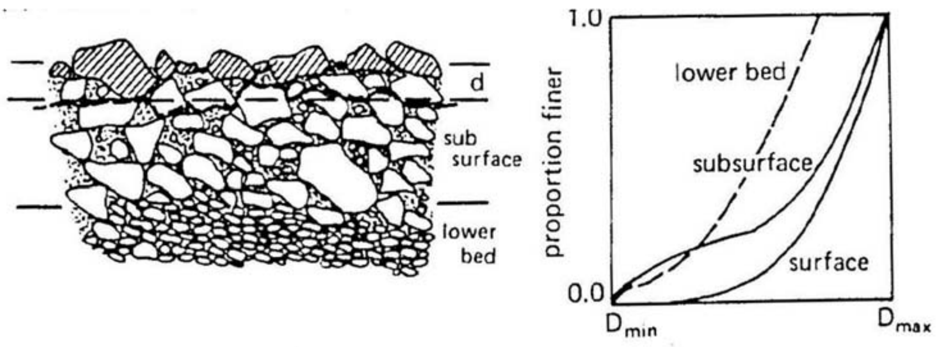


Figure 38 Typical grain composition of armoured river bed

### 4.2.2.2 Restrictions for navigation in low flow periods

There is a significant number of navigational bottlenecks and fords along the Hungarian study section, where restrictions are implemented during low water regime, since the required parameters of the navigational routes cannot be satisfied. Between rkm 1810-1790 there are 12 shorter reaches with navigational problems (see an example in Figure 39).

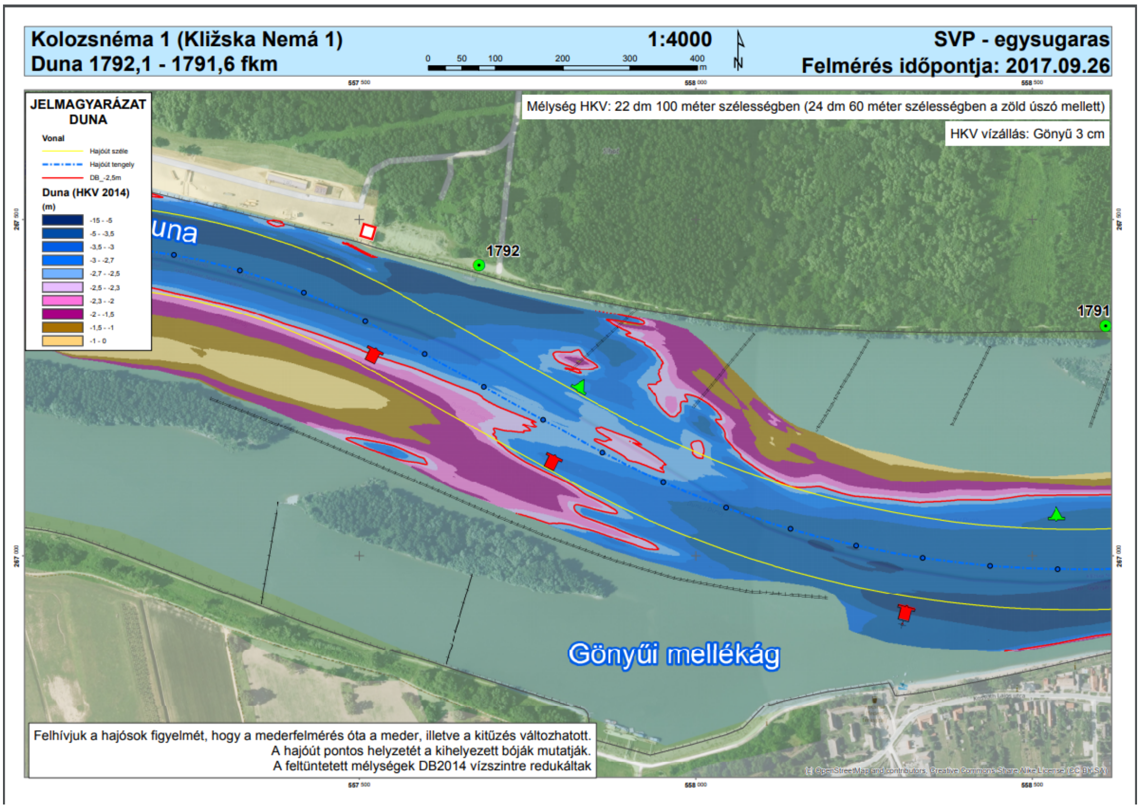


Figure 39 Ford at Gönyű (rkm 1791.7) source: www.eduvizig.hu

### 4.2.2.3 Ecology

The most important natural values of the Danube River, such as native endemic species, can be found in the shallow, gravel bed parts of the river, which can be characterized with high flow velocities. These places are generally navigational bottlenecks and therefore a typical point of conflict. As for the ships, direct contact with ship hulls and/or propellers may cause mechanical damages to aquatic animals (Bulté et al., 2010), while oil and fuel discharges have unfavourable effect on the water quality (Jackivicz and Kuzminski, 1973). Canals built for navigational purposes often remove biogeographical boundaries which can lead to the degradation of biodiversity. Navigation also affects many biotic and abiotic variables through the temporal alteration of the local hydraulic regime, i.e. generation of ship-induced waves and currents, especially at low water stages.

Figure 40 a) Ship in the area of the Helemba-island and b) gravel bar at rkm 1709 (photos by ÉDUVIZIG)

### 4.2.3 Problems related to hydropower

#### 4.2.3.1 Reservoir sedimentation

As shown in the previous point the Upper-Hungarian section of the Danube River is strongly exposed to the Slovakian upstream sections, where hydropower plants are located. The reservoir of the Gabčíkovo HPP, called Hrušov, is characterized with continuous sediment deposition (Figure 41). As shown in the DanubeSediment project (DanubeSediment, 2019), although complete bathymetric data to evaluate sedimentation rate in Hrušov reservoir is not available, the total volume of deposits ~20 M m$^3$ has been published by Water Management Enterprise (WME).

Figure 41 Sediment deposition zones upstream of Gabčíkovo dam (Google Earth).

### 4.2.3.2 Reservoir flushing

During high water regime and floods an increased flow discharge is let towards the Old Danube in Hungary by the Slovakian HPPs. This means increased fine sediment discharge as well, which is transported into the secondary branch system, Szigetköz, of the Danube. Due to the dense floodplain vegetation the sediment is deposited along the river banks, leading to higher floodplain elevations (Figure 42). Even though there is limited information available about these formations, it is clear that the increased sediment transport due to reservoir operation can alter the morphology of the river and can affect the flood conveyance capacity as well as the ecology of the river.

Figure 42 Floodplain sediment depositions during the 2013 flood in Hungary (photo:EDUVIZIG).

### 4.2.3.3 Interruption of sediment continuum

As mentioned in point 4.1.1.3 the Upper-Hungarian Danube reach is, even though that the entire Hungarian Danube is free-flowing, strongly affected by the upstream impounded reaches, primarily by the Slovakian hydropower plants (Figure 43). Changes in the sediment balance can be clearly captured both in the suspended sediment and bed load transport. The sediment load analysis for the entire Danube prepared within the DanubeSediment project (DanubeSediment, 2019b) indicated a suspended sediment trapping efficiency of the Gabčíkovo reservoir of 70% (see the red circle in Figure 44). Due to very limited bed load data, quantitative assessment of the bed load blocking influence of the hydropower plants could not be estimated, however, the increasing bed erosion processes in the free-flowing sections after the constructions clearly suggest this impact.

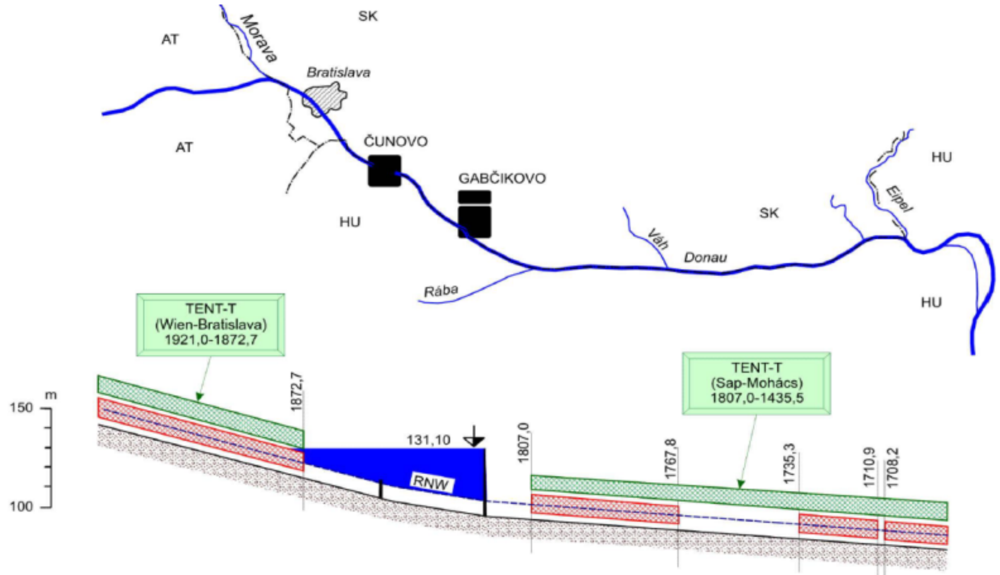


Figure 43 Nearest impounded section upstream of Hungary

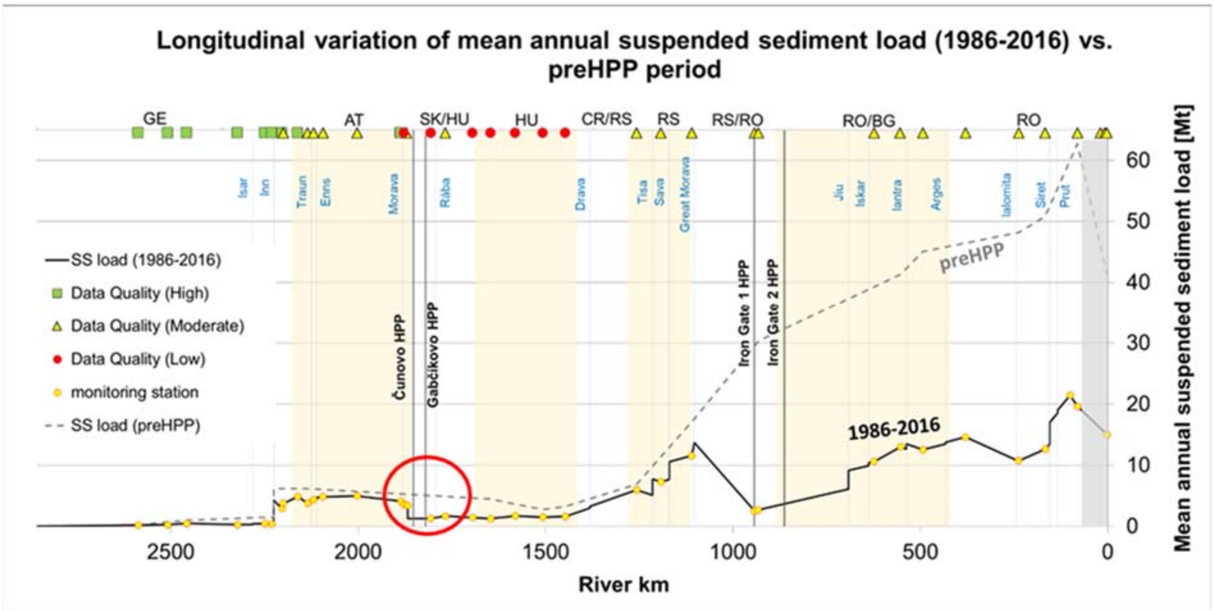


Figure 44 Longitudinal variation of long-term (1986-2016) mean annual suspended sediment load along the Danube River compared to the time period before the operation of hydropower plants (data source AT: viadonau and Verbund)

## 4.3 Common problems and differences of the project reaches in AT & HU

Within this report it was clearly shown that both project reaches face various problems related to river sediments. By describing the project reaches and outlining a common process understanding of sediment transport the boundary conditions for occurring problems were defined. As presented both river reaches are facing numerous anthropogenic influences related to river engineering, navigation and hydropower use leading to similar problems with a different range of impact. Differences are due to the determined differences of both reaches towards morphological characteristics e.g. in terms of slope and characteristic grain sizes on the one hand and use of the river e.g. in terms of drinking water supply, recreation or navigation. Table 2 compares the identified sediment related problems and their impact on the project reaches in AT & HU.

Table 2 Identified sediment related problems and their impact on the project reaches in AT & HU

| **impact in the reach (AT)** | | | **Idetified sediment related problems** | | **impact in the reach (HU)** | | |
|---|---|---|---|---|---|---|---|
| **minor** | **moderate** | **severe** | **Category** | **Problem** | **minor** | **moderate** | **severe** |
| | x | | **Problems related to river engineering** | Flood risk protection | | x | |
| | | x | | Instream channel alterations | | x | |
| | | x | | River bed incision | | | x |
| | x | | | Prevented side erosion | | x | |
| | x | | | Decoupling of river and floodplain | | x | |
| | x | | | Disconnected side arms | | | x |
| | x | | | Ecology | | x | |
| x | | | | Recreation | | x | |
| x | | | | Water supply | x | | |
| | x | | **Problems related to navigation** | Hydro- and Morphodynamics | | x | |
| | x | | | Restrictions for navigation in low flow periods | | | x |
| | | x | | Ecology | | x | |
| | x | | **Problems related to hydropower** | Reservoir sedimentation | x | | |
| | x | | | Reservoir flushing | x | | |
| | | x | | Interruption of sediment continuum | | | x |
| | | x | | Ecology | | x | |

Figure 45 depicts the identified sediment related problems and their impact on the project reaches in AT & HU in a spider chart. At the Austrian reach both for navigation and for hydro power use the impacts on ecology were determined more severe than in the Hungarian reach. Slight differences are also visible towards river engineering aspects e.g. at the Austrian reach a higher impact through instream channel alterations is given, whereas recreation and disconnection of side arms is a more severe problem at the Hungarian reach.

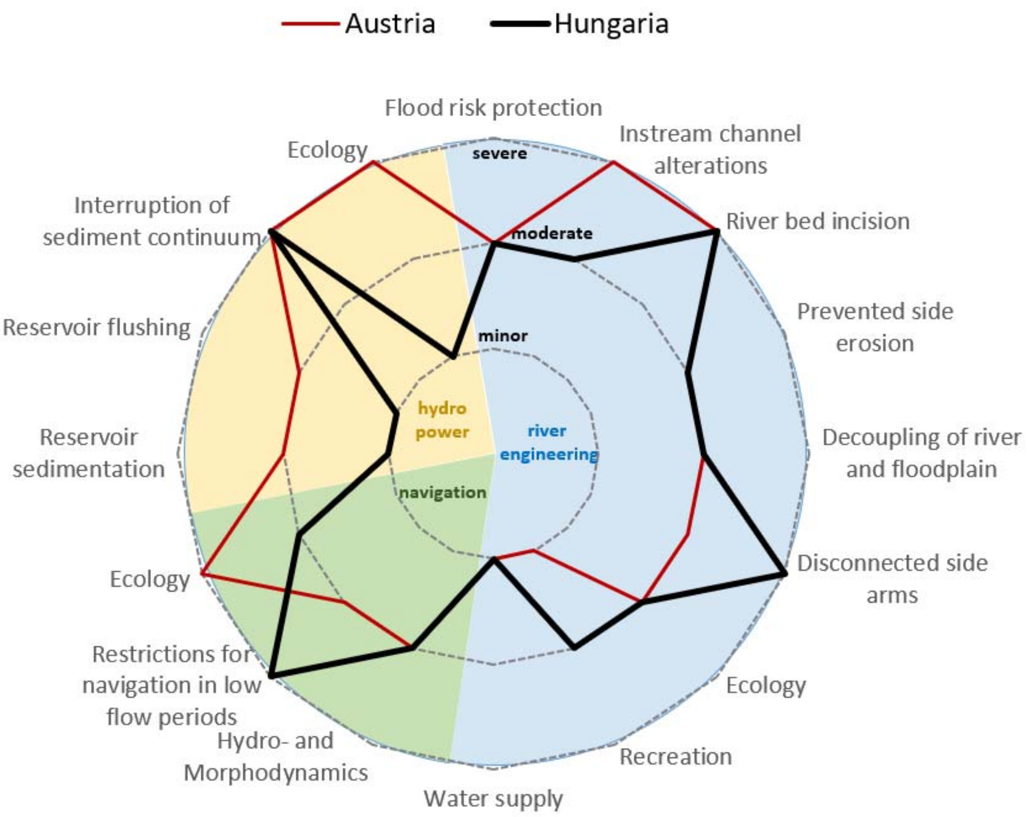


Figure 45 Spider chart of the identified sediment related problems and their impact on the project reaches in AT & HU

# 5 Summary

The analysed results and findings gathered in this report are an important data base towards a sustainable river engineering approach. Problems, their impacts as well as the underlying sediment related processes at the Seddon II study reaches at the Danube in Austria and Hungary were determined to gain important process understanding for future challenges in the field of river engineering. Based on the report it is aimed to improve and optimise engineering measures that can handle the multiple problems the different stakeholders face and compensate the negative impacts of human pressures along river systems.

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