Danube Transnational Programme

DanubeSediment

Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube

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Project Introduction

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

Data Analyses for the Sediment Balance and Long-term Morphological Development of the Danube

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Website: www.interreg-danube.eu/danubesediment

Table of Contents

1 Introduction

This report presents the main results of ***"Data collection & analysis for sediment balance assessment"*** (Activity 4.1.), which contributes to the overall assessment of the Danube Sediment Balance in the DanubeSediment project. The main tasks were to collect, sort and analyse data required for the quantification of downstream sediment fluxes and for the identification of sediment surpluses (sources) and deficits (sinks). They provide key data and information, supported by the results of basic analyses, necessary for the establishment of a sediment budget for the Danube and its selected tributaries, as well as for the assessment of spatial and temporal variations in the river channel's morphology. These results will contribute to the follow-up reports *"Assessment of the sediment balance of the Danube and its major selected tributaries"* and the *"Long-term morphological development of the Danube River in relation to the sediment balance"*.

We calculate the sediment balance by applying the sediment budget equation (Figure 1.1). This includes the following: ***a) inputs*** – sediment transport from upstream stretches, sediment transport from tributaries, sediments from river banks erosion, and sediments fed artificially into the river, and ***b) outputs and storage*** – sediment transport to downstream stretches, removal of riverbed sediments by dredging activities, sediments in the floodplains and/or groyne fields and abrasion of riverbed material.

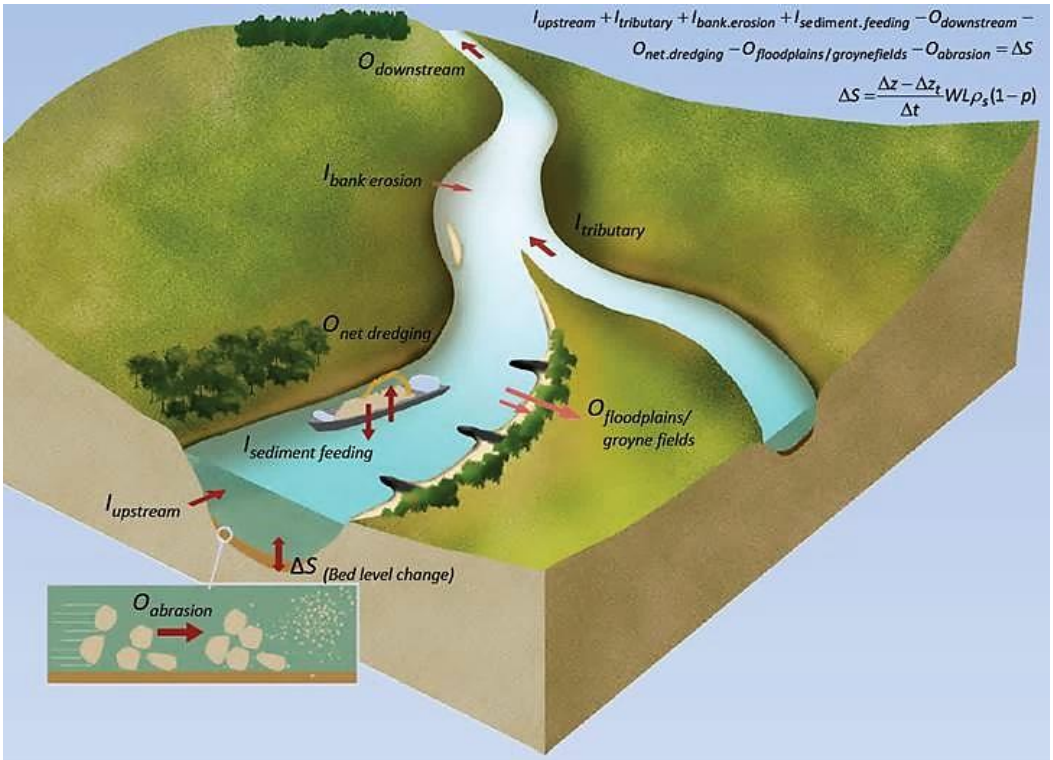

Figure 1.1: Scheme of sediment balance components (Frings et al. 2013)

Besides suspended load and bedload, which were provided by previous work in the Danube Sediment project (see report "Sediment Monitoring in the Danube River"), all the other components of the budget, e.g. riverbed changes, sediment dredging and feeding, need to be quantified. In addition, further data on the river's longitudinal profile and on bed sediments are needed to assess the spatial and temporal variations in the morphology of the Danube channel.

The present report is structured as follows: Chapter 2 focuses on the delineation of spatial and temporal scales for sediment budget and morphological analyses. Chapter 3 consists of two parts: the first part contains information about data availability – included in a meta-database based on preliminary investigation (Annex 1) and data that were actually collected and provided for the project (Annex 2). The legal framework for the supply of data (by countries) is also included in this part. The next important part, focused on the monitoring methods applied (measurements, observations, assessment, etc. – bathymetry, dredging, bed material sampling, low-flow water level), was compiled from information supplied by the project partners. On the basis of these data, homogenous data sets were selected and recommendations formulated for improving the methods of morphological monitoring for the future. The last part of the report includes the results of basic data analyses, including their graphical interpretation (published in Annex 3).

2 Delineation of spatial and temporal scales for sediment budget and morphological analyses

The quantification of downstream sediment fluxes and the assessment of surpluses and deficits in specific river stretches require that the fluvial processes (erosion and deposition), which are highly variable in both time and space, are identified.

A river is a morphodynamic system (Figure 2.1) in which the interaction between the water flow and sediment transport tends to cause morphological changes. Higher or lower amounts of sediments transported into a river stretch, compared with the amounts transported out of that stretch, may give rise to aggradation/degradation. The morphological changes will in turn affect the flow conditions and sediment transport.

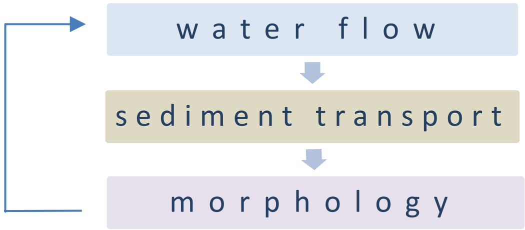

Figure 2.1: Scheme of a morphodynamic river system

Therefore, spatial and temporal scales were set up to compile homogenous data sets for an analysis of the Danube channel evolution and for sediment budget calculation.

2.1 Delineation of the spatial scales

The project covers the Danube River from river kilometre (rkm) 2,500 in Germany to the Danube Delta. The delineation of large scale units on the Danube takes into account the river channel's morphological characteristics and follows its traditional division into the Upper, Middle and Lower Danube sections (Figure 2.2).

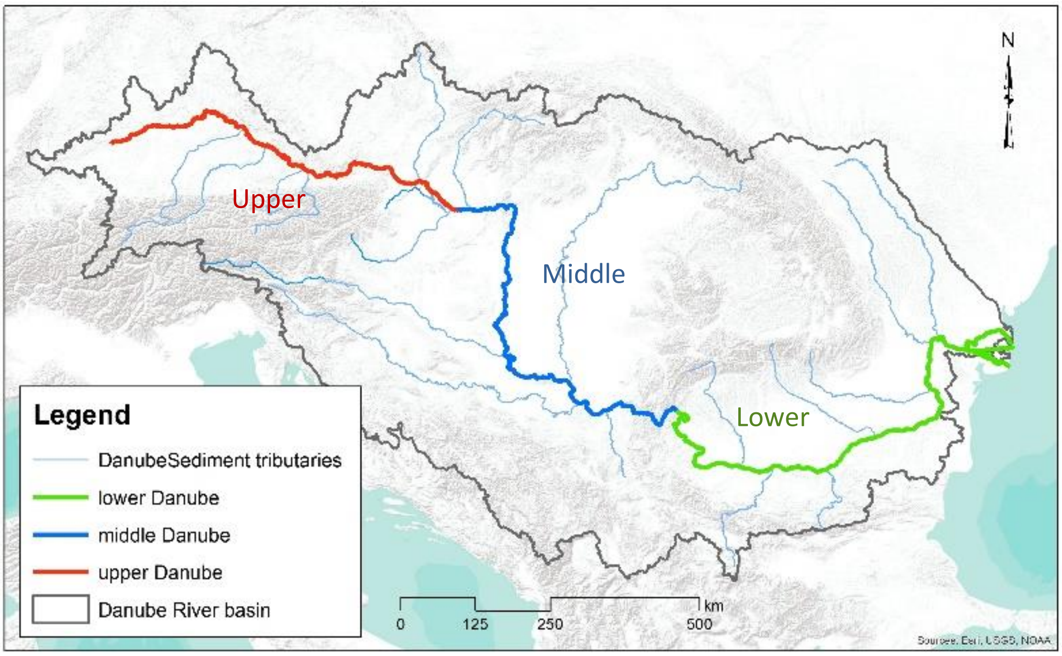

Figure 2.2: The three sections of the Danube River considered for analysis

Similarly, the delineation of alluvial rivers (upper, middle and lower sections) usually reflects the morphological characteristics of the river channel, in particular the natural evolution of the longitudinal profile (slope changes) and the corresponding river pattern (river type). Therefore, the lower boundary of the Upper Danube is situated at Gönyű (rkm 1,790, Figure 2.3) where the slope of the riverbed changes, as well as the river type.

The ICPDR assumes (ICPDR, 2015) that the lower boundary of the Upper Danube is at the river's confluence with the Morava River – at rkm 1,880 (Figure 2.3), i.e. 90 km upstream of Gönyű even though the clear criteria for this delineation are unknown.

Figure 2.3: Map showing the original and proposed boundaries between the Upper and Middle Danube

A short overview of the main principles of the evolution of an alluvial river's longitudinal profile is presented below for a better understanding of the reasons why the lower edge of the Upper Danube is situated not at Morava river confluence (rkm 1880) but at Gönyű (rkm 1,790).

Basic morphological outlines: The longitudinal profile (Figure 2.4) shows how the gradient of a river channel changes between its source and mouth (e.g. the sea). The longitudinal profile shows the height of the riverbed**,** above the base level, along the entire length of the river. The base level is the lowest point that a riverbed can erode to. The base level of a river is usually sea level**,** or the water level in the lake the river flows into. The erosion base is the hard (rocky) riverbed that controls the evolution (shape) of the longitudinal profile**.**

The amounts of erosion and deposition over the entire length of a river are balanced (total erosion equals total deposition). However, the rates of erosion and deposition vary along the course of the river. This may lead to the formation of various landforms such as waterfalls and lakes (where erosion is greater than deposition), producing an uneven longitudinal profile. Because the rate of erosion equals the rate of deposition over time, the river's longitudinal profile changes from an uneven curve to a smooth curve, which is known as a graded profile.

Figure 2.4 illustrates the division of a river into three sections – the upper (close to the source), middle (transitional) and lower section (near the mouth). Typical processes – responses within sediment system linked to Figure 2.4 can be described as follows:

- Upland – upper valley: vertical erosion of the riverbed prevails, bank abrasion, local areas of channel aggrade, narrow or very constrained floodplain (confined upland river reaches)
- Transfer – middle transitional reach: lateral erosion (bank erosion) prevails and vertical erosion of the riverbed decreases; bars accrete, floodplain is developed
- Lowland – lower reach: processes of deposition higher than erosion, bank erosion/ sedimentation followed by collapse; creation of channel forms - bars and islands; fine sediments transported to the sea

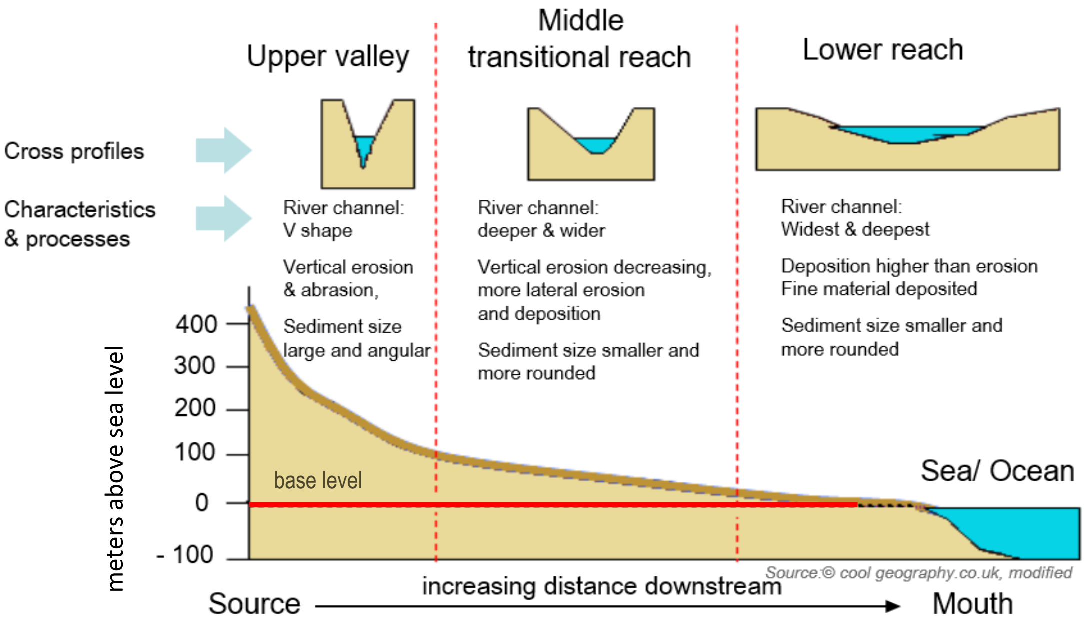

Figure 2.4: Diagram of the typical sections of an alluvial river's longitudinal profile and the corresponding channel shapes

A river's flow velocity and discharge are affected by its channel characteristics. As you move downstream from the river's source to its mouth, you can observe an increase in discharge, while flow velocity, riverbed slope and bed sediment size decreases. Discharge increases owing to the river's tributaries (smaller rivers/streams) joining the main channel and further inputs from surface runoff as you go downstream. The river's flow velocity is directly influenced by its gradient, discharge, and channel characteristics.

The diagram (Figure 2.4) also shows the typical cross-sections and changes in the different sections of a river's longitudinal profile. Vertical erosion creates narrow valley floors and steep v-shaped valleys in the upper section. Lateral erosion prevailing in the middle section creates wider valleys. Floodplains are formed on the valley floor through deposition. Wide valleys with gently sloping sides and wide floodplains caused by continued deposition are typical for a river's lower section.

Fluvial erosion and deposition processes create various river patterns depending on the specific geomorphological and flow conditions. A scheme of river course evolution between the river's source and delta can be seen in Figure 2.5.

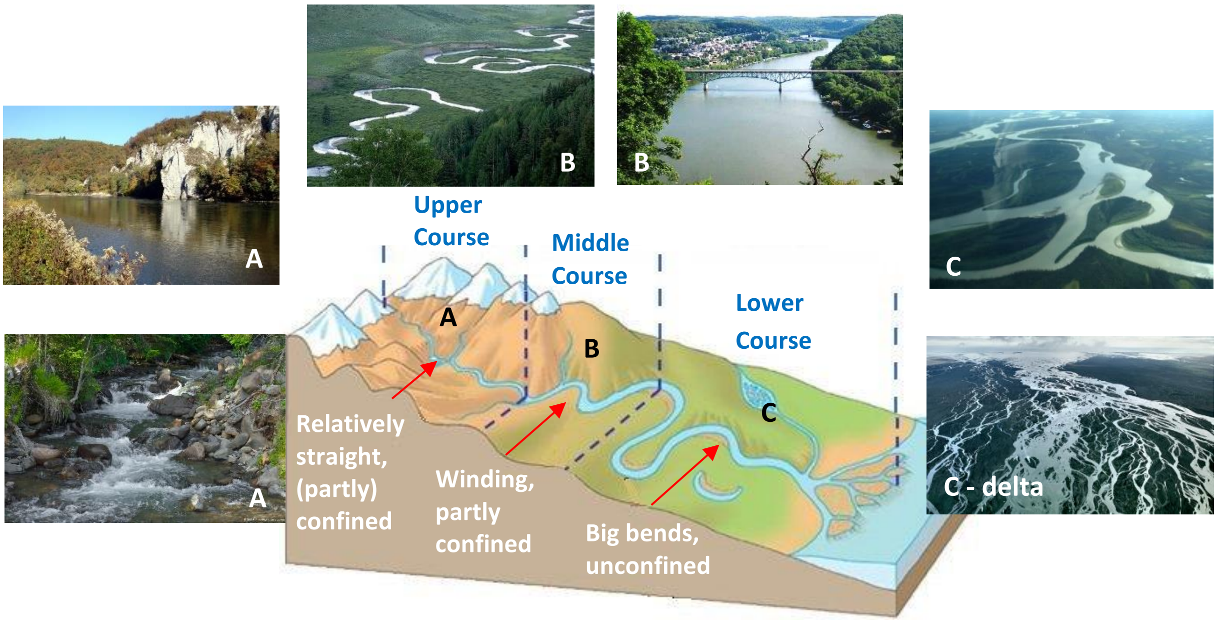

Figure 2.5: Schematic evolution of a river from source to delta and examples from various rivers (Illustration: Oxford University Press, modified)

The river channel in the **upper course** is mostly straight or slightly sinuous. It is often combined with braiding (the channel is divided into multiple channels separated by unstable islands/gravel bars – located closer to the river source as a rule – steep gradient) and/or with anastomosing stretches (the main channel and side arms are divided by more stable vegetated islands – mostly located closer to the lower edge of an upper course – moderate gradient). Both river types usually occur because of a drop in the riverbed slope, followed by increased deposits of transported sediments. A straight or slightly sinuous river channel in the upper course is often created under confined or partly confined conditions with no or spatially restrained floodplains.

The erosion and deposition processes form larger river bends and/or meanders in partly confined and/or unconfined stretches of the middle and lower river courses. Alternating areas of deep water (pools) and areas of shallow water (riffles) are formed along the sinuous or meandering stretches of gravel bed rivers in the **middle course**. Sediments eroded during floods are deposited across wider floodplains, the coarser sediments are deposited close to the river channel, or they build up on the river banks and form natural levees.

In its **lower course,** a river has a lower gradient but sufficient energy and erosive power (bank erosion prevails) to form meandering, sinuous or, more frequently, anabranching channel patterns (the main channel and side arms divided by more stable vegetated islands) within wider floodplains. When the river reaches the ocean (or another river), the slowly flowing water absorbs its energy, and thus transported sediments are deposited (alluvium) and the river channel is split into numerous distributaries forming a river **delta.**

On the basis of knowledge of the natural evolution of an alluvial river's longitudinal profile (Figure 2.4) and of the river pattern (Figure 2.5) and the corresponding morphological characteristics of the Danube (Figure 2.6 - 2.9), the lower edge of the Upper Danube has been shifted to its former locality at Gönyű (rkm 1,790, Figure 2.3). The steep gradient of the riverbed changes here significantly, from 0.35 ‰ to 0.05 ‰ (Figure 2.6) and the anabranching river pattern changes into transitional wandering downstream of the gradient change (Figure 2.9). As a result, the spatial boundaries are defined as follows: Upper Danube: rkm 2,600–1,790, Middle Danube: rkm 1,790–943 and Lower Danube rkm 943–0.

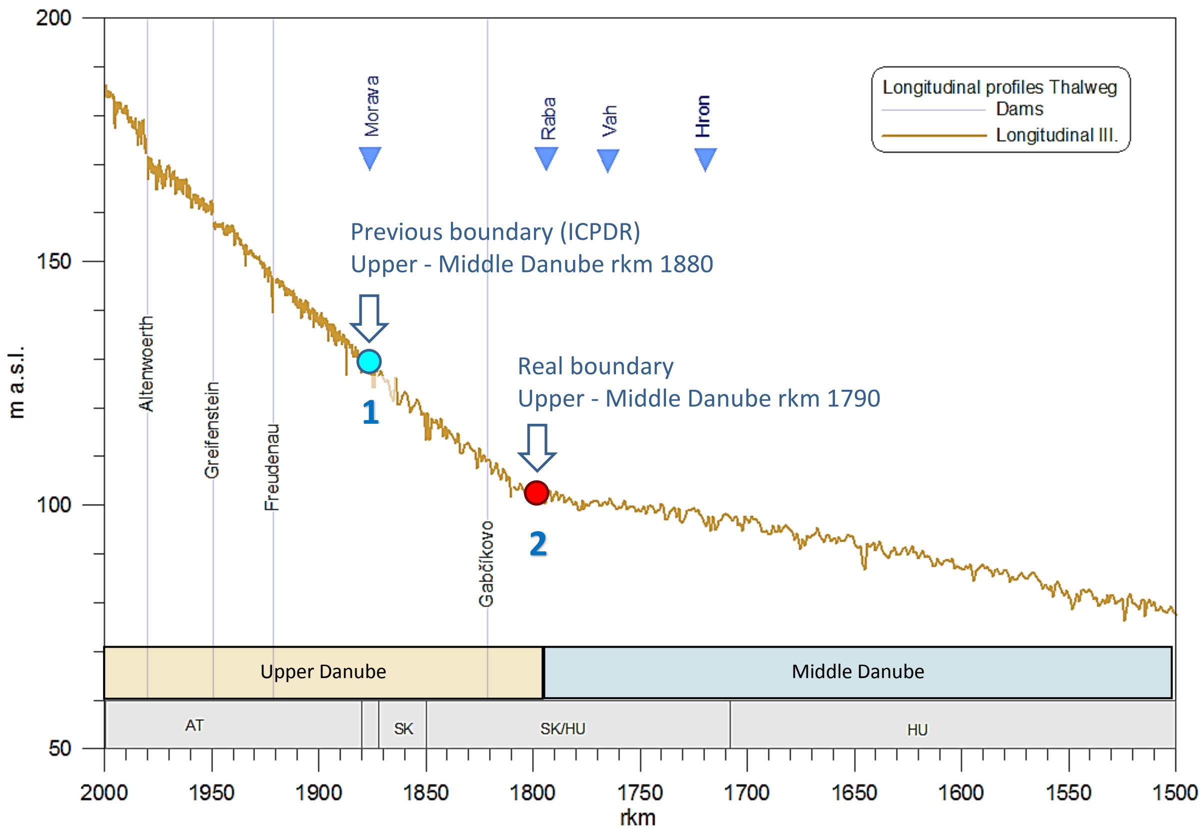

Figure 2.6: The longitudinal profile of the Danube River between rkm 2,600 and rkm 80 and the boundaries between Upper and Middle Danube

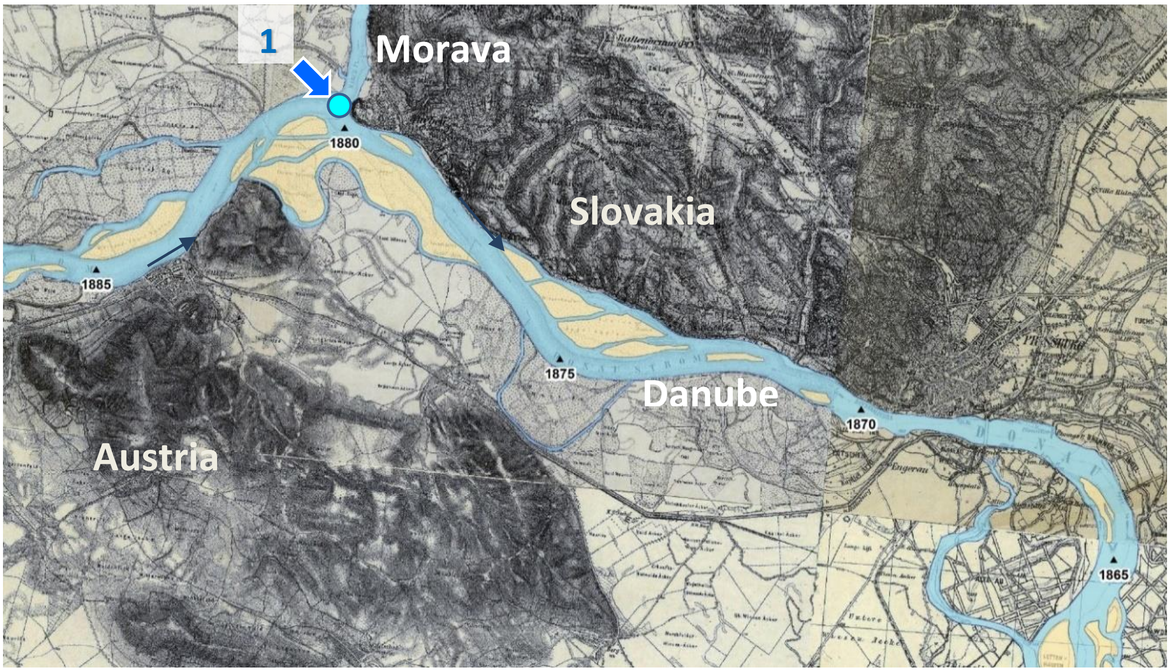

Figure 2.7: Anabranching stretch of the Danube River between Hainburg and Bratislava (3rd Military Mapping)

Figure 2.8: Anabranching stretch of the Danube River, Vienna – Devin (2nd Military Mapping)

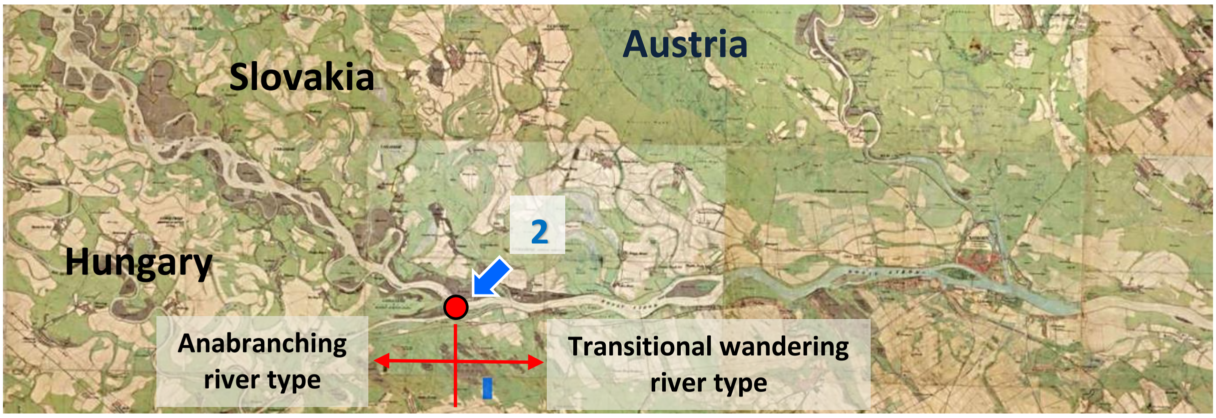

Figure 2.9: Historical map of the Danube River section between Gönyű and Komárno (2nd Military Mapping)

2.2 Temporal scales – historical and present

The temporal variations in the Danube channel's morphology were examined within three periods marked by the successive construction and operation of hydropower plants (HPPs). After the first HPP was built in 1927 (Kachlet, Germany), a series of HPPs (Table 2.2) were built between the 50ties and 80ties, with the last four HPPs built along the Upper Danube (two in Germany, one in Austria, one in Slovakia). Therefore, three periods were determined as follows: 1920–1970, 1971–1990 and 1991–2017 (Table 2.1). Period I covers the years when the first HPPs were built on the Danube in Germany and Austria. This period is connected with the initial impact of barriers hindering the transport of sediments and the morphological evolution of the riverbed along the Upper Danube, while the Middle and Lower Danube have remained free-flowing.

Table 2.1: Temporal scales – periods defined for DanubeSediment project purposes

Time scale	Periods	Years	Number of HPPs/national river stretch
Long-term	Period I	1920 - 1970	14 (DE, AT)
Mid-term	Period II	1971 - 1990	15 (DE, AT, RS +RO: IG I, II)
Short-term	Period III	1991 - 2017	4 (DE, AT, SK–HU: Gabčíkovo)

Table 2.2: List of hydropower plants on the Danube and the year of construction/operation

Country	Dam / weir / HPP	Danube river km	Distance to the downstream dam/ weir/HPP rkm	Operating since	Storage level m.a.s.l.
Germany	Ulm, Böfinger Halde	2,581.5	6.442	1952	465.7
Germany	Oberelchingen	2,575.058	6.598	1960	459.09
Germany	Leipheim	2,568.46	5.76	1961	452.62
Germany	Günzburg	2,562.7	6.33	1962	446.11
Germany	Offingen	2,556.37	4.42	1963	439.62
Germany	Gundelfingen	2,551.95	6.32	1964	434.62
Germany	Faimingen	2,545.63	6.68	1965	429.61
Germany	Dillingen	2,538.95	8.15	1981	423
Germany	Höchstädt	2,530.8	8.375	1982	417.45
Germany	Schwenningen	2,522.425	10.59	1983	410
Germany	Donauwörth	2,511.835	21.665	1984	403.7
Germany	Bertoldsheim	2,490.17	9.97	1967	391.5
Germany	Bittenbrunn	2,480.2	10.3	1969	384.5
Germany	Bergheim	2,469.9	10.71	1970	377
Germany	Ingolstadt	2,459.19	14.69	1971	369.5
Germany	Vohburg	2,444.5	44.5	1992	361.5
Germany	Bad Abbach	2,400	19	1978	338.2
Germany	Regensburg	2,381	27	1978	332.5

Country	Dam / weir / HPP	Danube river km	Distance to the downstream dam/ weir/HPP rkm	Operating since	Storage level m.a.s.l.
Germany	Geisling	2,354	34	1985	327.3
Germany	Straubing	2,320	33.85	1994	320
Germany	Kachlet	2,230.51	27.21	1927	299.8
Germany/AT[1]	Jochenstein	2,203.33	40.66	1955	290.3
Austria [1]	Aschach	2,162.67	15.76	1964	280
Austria[1]	Ottensheim-Wilhering	2,146.91 / 2,146.73	27.1	1973	264.2
Austria[1]	Abwinden-Asten	2,119.63 / 2,119.45	23.83	1979	251
Austria[1]	Wallsee-Mitterkirchen	2,095.62 / 2,094.50	34.08	1968	240
Austria[1]	Ybbs-Persenbeug	2,060.42	22.46	1958	226.2
Austria[1]	Melk	2,037.96 / 2,038.16	57.76	1982	214
Austria[1]	Altenwörth	1,980.40 / 1,979.83	30.6	1976	193.5
Austria[1]	Greifenstein	1,949.23 / 1,949,18	28.13	1984	177
Austria[1]	Freudenau	1,921.05	69.3	1997	161.35
Slovakia	Gabčíkovo–Čunovo	1,851.75	908.75	1992	131.1
Serbia/Romania	Iron Gate 1	943	80.2	1972	69.5
Serbia/Romania	Iron Gate 2	862.8	862.8	1985	

[1] viadonau (2012)

The second period (period II) saw the building of further HPPs on the Upper Danube, as well as the construction of Iron Gate I on the Middle Danube and Iron Gate II on the Lower Danube. These dams form significant barriers to sediment transport along the Upper, Middle and Lower Danube. The third period (Period III) saw the full operation of a cascade of HPPs on the Upper Danube, Iron Gate I and II on the Middle and the Lower Danube, and operation of the last four HPPs on the Upper Danube, including the Gabčíkovo HPP.

3 Morphological data collected for sediment balance and morphological analyses

As part of Activity 4.1, sediment-related and morphological data were collected, sorted and analysed. An overview of the preliminary investigation of existing data in countries prepared by the project partners is presented in Annex 1 including the template questionnaire for collecting metadata. A template for data submission (see Annex 2), was developed on the basis of metadata. It covers the main data groups: bathymetric data - assessment of riverbed changes; longitudinal profiles; riverbed sediments - grain size distribution curves; dredging, feeding and disposal; and low-flow navigable water levels. The metadata table listing all data provided by partners for the project is available in Annex 2. The results of basic analyses and data collected by project partners are presented in Annex 3.

The results of data collection and sorting, and of their basic analysis, showed significant spatial and temporal data gaps, as well as big differences in data quality, which resulted from the different methodologies used for field measurements (method, frequency, technical devices) and/or data processing along the national stretches of the Danube River. These findings have necessitated the formulation of recommendations for future data collection and data processing (data recording and storing, measurements, data evaluation, etc.), in view of the need for spatially and temporally homogenous data on the entire Danube and for the compilation of all components used in the sediment balance equation in the same quantity and quality. This brief manual is included in the report *"Long term-morphological development of the Danube in relation to the sediment balance"* prepared within Activity 4.3. The next sub-chapters of this report (3.1–3.4) provide an overview of the past and present methods used along the national stretches of the Danube River (prepared by the project partners) for data collection, measurements and assessment.

3.1 Riverbed topography

GERMANY: In Bavaria, regulated rivers are measured, if necessary, every year. The German section of the Danube River is measured along its full length. However, the frequency of measurement is not strictly set. In general, it depends on the river's importance in terms of its flow dynamics and the risk of flooding. The interval between two measurements should not be longer than eight years for rivers that transport sediment. One-year intervals are recommended for regulated rivers such as the Danube. Owing to the length of the Danube, it is not guaranteed that the river will be measured along its full length within a year. The locations of cross-sections are fixed (minor deviations are possible). The cross-sections are vertical to the river's longitudinal axis. Signs on the riverbank show the corresponding river kilometre (rkm) and there are fixed points in the cross sections, which ensure that the measurements are always repeated at the same locations. The cross-sections cover the entire riverbed, the river banks, and part of the surrounding areas.

Several approaches to riverbed surveying are applied: levelling (still used for small rivers), tachymetry, echo sounding and tachymetry, echo sounding and GPS. The distance between the measurement points depends on the relief. Generally, cross-sections are measured every 200 m. Furthermore, there are river stretches where the distance between cross-sections is 100 m or even 50 m.

Responsibility for riverbed observation is divided between the water management authorities of Baden-Württemberg and Bavaria, which covers the river stretch upstream of Kelheim (where navigation begins), and the Federal Waterways and Shipping Administration (WSV) that is responsible for the navigable stretch downstream of Kelheim. Primary data are not available to the public. However, the data collected and processed by the German partners LFU and TUM are available for the project.

AUSTRIA: For the purpose of riverbed topography surveying, the Austrian section of the Danube is divided into twelve river reaches: ten impounded reaches upstream of the ten hydropower plants and two free-flowing reaches. The free-flowing reach East of Vienna is subdivided into three parts. These river reaches are measured individually, i.e. the entire Austrian section of the Danube River is not necessarily measured within the same year.

Table 3.1 shows an overview of the river reaches and the most frequently measured data used in the project. The three parts of the free-flowing reach East of Vienna have been merged into one river reach.

Table 3.1: Overview of the Austrian stretch of the Danube, including its most frequently measured reaches and the number of cross-sections (every 50 to 100 m). I: Impounded; F: Free-flowing.

Name	River reach	Most frequently measured: end of reach	start of reach	length of reach	Average measured width	Number of CSs (100 m)	Number CSs (50 m)
		rkm	rkm	km	m	number	number
01 Jochenstein	**I**	2,223.20	2,203.40	19.8	247	199	397
02 Aschach	**I**	2,203.20	2,162.70	40.5	249	406	809
03 Ottensheim-Wilhering	**I**	2,162.60	2,147.00	15.6	292	157	310
04 Abwinden-Asten	**I**	2,146.60	2,119.70	26.9	251	270	538
05 Wallsee-Mitterkirchen	**I**	2,119.30	2,095.70	23.6	275	237	474

Name	River reach	Most frequently measured: end of reach	start of reach	length of reach	Average measured width	Number of CSs (100 m)	Number CSs (50 m)
		rkm	rkm	km	m	number	number
06 Ybbs-Persenbeug	**I**	2,094.40	2,060.50	33.9	249	340	-
07 Melk	**I**	2,060.30	2,038.00	22.3	320	224	-
08 Wachau	**F**	2,038.05	2,010.00	28.1	269	281	562
09 Altenwörth	**I**	2,015.20	1,980.50	34.7	323	348	-
10 Greifenstein	**I**	1,979.70	1,949.40	30.3	322	304	-
11 Freudenau	**I**	1,949.00	1,921.10	27.9	264	280	-
12 East of Vienna	**F**	1,921.00	1,872.70	48.3	257	473	967

Surveys of the Austrian Danube are carried out by the competent waterway company, namely viadonau – Österreichische Wasserstraßen-Gesellschaft mbH, and by the hydro-power plant operator, namely VERBUND Hydro Power GmbH (VHP). Measurements are made along the entire Austrian section of the Danube River, including its common part with Germany (rkm 2,223.20–2,201.77) and Slovakia (rkm 1,880.10–1,872.70).

Additional project-related measurements are carried out for river engineering projects, erosion control around bridge piers, dredging control and wreck detection projects, or in harbours and their entrances.

Prior to 2002, the impounded reaches were measured on an annual basis. Currently, the interval between VHP measurements depends on the HPP and ranges from two years (Aschach HPP) to four years (in other impounded reaches), plus additional measurements are made after larger floods (above HW10 – with a return interval of 10 years). Viadonau performs measurements in the river's impounded reaches every second or third year. Overall, the impounded river reaches are measured every year or every second year (BMLFUW, 2015).

The two free-flowing river reaches (at Wachau and East of Vienna) are currently measured on a semi-annual basis (in spring and autumn) by viadonau. They were previously measured on an annual or bi-annual basis. The locations that are critical for navigation in these reaches of the Danube are measured several times a year by viadonau. VHP also performs measurements in the free-flowing river reach East of Vienna but not in the Wachau.

Until around 1980 (viadonau) and until the beginning of the 1990ies (VHP), such measurements were made as 16-point surveys, using position fixing and echo sounding. In these surveys, always the same 16 equidistant points per cross section were recorded (see Figure 3.1 – left picture and Figure 3.2 – left picture). The surveys were carried out by means of a single-beam echo sounder (e.g. viadonau used a SB Kongsberg EA 400 sonar).

Figure 3.1: Left picture: Bathymetry measurement in the past, using a “Doppelbild Tachygraph” (Embacher, 1969); right picture: viadonau’s multi-beam bathymetry vessel during (photo: Philipp Gmeiner /BOKU)

However, viadonau has recently switched from single-beam to multi-beam echo sounding (Figure 3.1– right picture; an Alpha vessel with a MB Kongsberg EM 3002D dual-head multi-beam echo sounder), so it now uses multi-beam echo sounders in measuring the Austrian Danube along its full length. The position of echo sounding is determined mostly with a GPS.

Cross-sections are measured at least every 100 m in geodetically fixed profiles, ensuring that the cross-sections measured are coherent. The locations of cross-sections are also indicated by markers along the river banks. The real distance between cross-sections may not be exactly 100 m, but slightly more or less (by a few meters), depending on the centre-line and sinuosity of the Danube River. Since 2000, measurements have been made by viadonau every 50 m (Figure 3.2 – right picture) and, since 2007, two river reaches of the yearly work programme were measured by means of multi-beam echo sounders. However, viadonau has recently switched completely from single-beam to multi-beam echo sounding, measuring now the entire Austrian section of the Danube with multi-beam echo sounders.

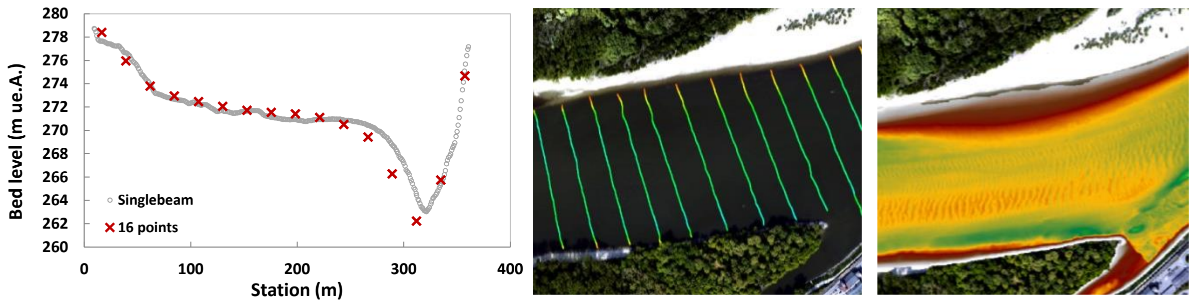

Figure 3.2: Left picture: Example of a 16-point survey (red crosses) versus single-beam echo sounding (grey circles) – time between surveys: approx. 1.5 years; Middle picture: Example of single-beam echo sounding with cross-sections every 50 m; Right picture: Multibeam. (Data sources: VHP and viadonau).

VHP and viadonau are responsible for the performance of riverbed measurements, and for the examination and storage of the data recorded, which are not publicly available.

Charts (in pdf-format) of the critical spots for navigation, indicating the current water depths in relation to the lowest navigable water level (defined by the Danube Commission) are available online at http://www.doris.bmvit.gv.at/fahrwasserinformation/seichtstellen/.

SLOVAKIA: The bed topography of the main river channel is regularly surveyed along the Slovak section of the Danube, as well as along the common Slovak-Austrian and Slovak-Hungarian stretches (rkm 1,880–1,708). In recent years (since 2003), cross-section measurements have been made on an annual basis, whereas earlier (before 2003) riverbed surveying took place at irregular intervals – mostly after higher discharges. Such measurements were carried out by the Slovak Water Management Enterprise (Slovenský vodohospodársky podnik – SVP), i.e. the authority responsible for river maintenance with a view to preserving the conditions for international navigation and for flood protection along the Danube River. In the border stretches, measurements are made and harmonised in cooperation with partners from Austria (viadonau) and Hungary (Éduvizig). Before the Gabčíkovo hydropower plant [HPP] was put into operation (1992), riverbed surveying was performed irregularly, mainly in river stretches showing significant morphological changes (fords, erosion or deposition). Therefore, the historical data are inconsistent in both time and space, and they differ according to the measurement methodology applied. Since 1992, the river stretch downstream of the old Danube confluence with the tailrace canal has been examined more frequently (after severe floods) and, since 2005, as frequently as once a year. Riverbed bathymetry within the impoundment upstream of the Gabčíkovo HPP is measured on a yearly basis, but only in the navigational channel. Complete reservoir bathymetry is surveyed by SVP only occasionally.

Some specific bathymetry measurements were made in shorter river stretches within several research projects focused mostly on sediment transport and flood protection. The riverbed of the Danube started to be monitored in 2008, in the Slovak–Austrian stretch (between rkm 1,880 and rkm 1,872). In 2013, this monitoring was extended downstream to cover the river stretch up to the Gabčíkovo HPP (about rkm 1,820).

Figure 3.3: Left: Bathymetry measurement performed by VÚVH using EchoLog during a surveying campaign in the past, photo: VÚVH; Right: using an multi-beam vessel – present; photo: SWME

In the past, series of cross-sections were measured every 100 to 250 m, using an EchoLog device. The values measured were evaluated in the form of depth isolines (in paper form). Subsequently, digital cross-sections were obtained from the depth isolines. Later a single-beam echo sounder (ADCP), combined with a GPS device, was used for riverbed surveying. At the present time, a multi-beam echo sounder is applied. Data from such measurements are recorded in digital form in both cases.

Cross-section measurements usually cover only part of the river channel, i.e. below the low-flow water level. The river banks are geodetically measured less frequently, because the river banks are stabilised (bank protection) almost along the entire national river stretch. LiDAR data are also used to compile or update the river channel's topography (the river banks and terrain above the water level). The data are collected and owned by the Slovak Water Management Enterprise (SVP) and are not publicly available (only for purchase).

HUNGARY: Bathymetric measurements are made with varying frequency in the Hungarian section of the Danube by three regional water directorates. The North-Transdanubian Water Directorate (ÉDUVIZIG) is responsible for the performance of riverbed measurements in the common Slovak–Hungarian river stretch (between rkm 1,811 and rkm 1,708), which are carried out annually in cooperation with the Slovak partners (as from 2005, HU measurements are made every second year, and SK measurements in the intervening years). Before 2005, surveying campaigns were organised in 1996 and 2003. The methodology applied was single-beam echo sounding (Figure 3.4) every 100 m.

Figure 3.4: EcoTrac GPS receiver and a connected single beam echo sounder used for riverbed topography measurements in Hungary (Source: Debóra Varga-Lehofer)

Figure 3.5: Head of multibeam echo sounder (left), Multibeam survey vessel (right) used for riverbed topography measurements in Hungary (Source: Middle-Danube-Valley Water Directorate)

The Middle-Danube Valley Water Directorate (KDVVIZIG) arranges riverbed measurements in the Danube between rkm 1,708 and rkm 1,560 at irregular intervals. Data from riverbed bathymetry are available for this river section from 1996, 2004, 2007 and 2016. Until 2007, single-beam echo sounding had been used to measure cross-sections every 100 m. Since 2016, multi-beam echo sounding has been applied (Figure 3.5, Figure 3.6).

The Lower-Danube Valley Water Directorate (ADUVIZIG) arranges irregular riverbed measurements in the Danube between rkm 1,560 and rkm 1,433. Data from riverbed bathymetry are available from 1970, 1978, 1997, 2003, 2007 and 2013. In the past, single-beam echo sounding was used to measure cross-sections every 100 m. Currently, multi-beam echo sounding is applied.

Bathymetric data are owned by the corresponding Water Directorate. These data are not publicly available (only for purchase).

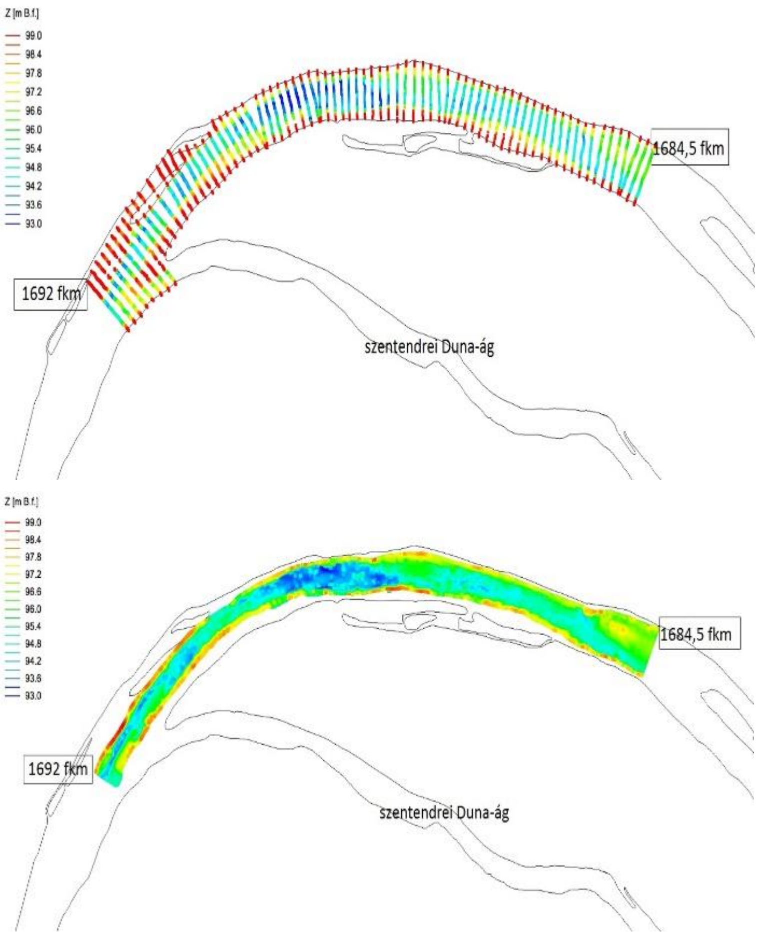

Fig 3.6: Tracks of single beam echo sounder survey (top) and a result map of multibeam echo sounding (bottom) (Source: Szilvia Ádány)

CROATIA: Cross-sections along the Danube and its tributaries, Drava and Sava, are surveyed occasionally at the hydrological stations (always in the same places), depending on the investor’s needs. At some of the hydrological stations, surveys are carried out every year (on the Sava and Drava). Such measurements are made along the whole national river section, but only in the cross-sections (no riverbed scanning is performed).

Until 2009, riverbed surveying in the cross-sections of hydrological stations was carried out using a classical method involving levelling and depth sounding. Later, a Total Station instrument designed for precise geodetic surveying was used in combination with an ADCP ultrasound device for river depth sounding. There was also a transitional period (a few years) during which levelling was used in combination with ADCP echo sounding.

At the national level, the Croatian Meteorological and Hydrological Service (DHMZ) is responsible for the performance of riverbed measurements, data evaluation and data storage. These data are publicly available, free of charge.

SERBIA: International inland waterways in the Republic of Serbia, Danube and Sava, and the interstate waterway of the Tisza River are surveyed on an annual basis by the Directorate for Inland Waterways (Plovput). Almost 1,000 km of the Danube, Sava, and Tisza rivers are covered by surveying campaigns, using the well-established methodology, the same for all three rivers.

A plan of regular annual surveys is prepared every year, so the object of surveying in the individual years may differ. As regards the Danube River, the river stretch from rkm 1,433+000 to rkm 1,170+000 is surveyed on a regular basis – once a year, with the exception of its critical parts, where hydrographic measurements are made several times a year (depending on the riverbed dynamics and the available fairway parameters). The downstream part, within the Iron Gate Reservoir, does not require surveying with such frequency, and is therefore surveyed once in several years (hydrographic measurements in this river stretch were made in 2018, from rkm 1,170+000 to rkm 1,038+000). This is compatible with the regular annual updating of the electronic navigational charts (in accordance with the Inland ECDIS 2.3 standard), which contain bathymetric data.

On the Sava River, surveys are done on an annual basis, too, but with the focus on river stretches critical for navigation. The Tisza River is surveyed, on an annual basis, along its full length through the Republic of Serbia, totalling 164 km.

Hydrographic surveys are carried out through the monitoring of cross-sections the locations of which are permanent and are marked by coastal markers on both sides of the river channel. Each marker has a prescribed geodetic position ensuring the provision of coherent data. Data on markers and survey results, reduced to the low-flow navigable water level, are stored in the internal database of the Directorate for Inland Waterways.

The measurement methods applied have varied since the establishment of a hydrographic surveying department within Plovput. First, starting from 1964, the *EchoLog* device was used to obtain the prime surveying data. In 1985, the *Polarfix* equipment was introduced at Plovput, i.e. a device enabling more accurate positioning. In 1995, Plovput started to apply a *Marimatech* “single-beam” sonar developed for quick and efficient hydrographic surveying, which was later upgraded and is currently used for regular hydrographic measurements. A “multi-beam” echo sounder started to be used in 2002. The continuing technological progress has provided a sound basis for multiannual changes in monitoring and data processing.

The locations of cross-sections are selected in a different manner compared with the first hydrographic surveys, depending on the surveying methodology applied. Currently, three types of cross-sections are used by Plovput. Originally, in 1962, cross-sections were surveyed every 1,000 m. At the beginning of 2000, additional cross-sections were surveyed for the Sava River, with shorter distances between them (50 m in critical sections). A similar principle was used on the Danube River in 2007 with cross-sections every 200 m, but later, in 2012, denser cross-sections (every 50 m) were introduced for the purpose of monitoring the critical river sections for navigation more precisely. On the Tisza River, cross-sections every 200 m started to be surveyed in 2016. In the area of the Iron Gate reservoir, a different surveying methodology is applied, since cross-sections in that area are used for sediment balance monitoring, and are surveyed every fourth year.

One of the ways of presenting the surveyed data is through electronic navigational charts and paper charts, in the form of contour lines, which are updated on an annual basis. These charts can be downloaded free of charge from Plovput's official website: http://www.plovput.rs.

ROMANIA: Regular riverbed measurements are made within the national monitoring network, but only in cross-sections at the hydrometric gauging stations (3 to 5 series of riverbed measurements per year) to determine the variability of the Danube riverbed in these cross sections. The number of annual measurements is higher when more flood events occur during the year. The locations of cross-sections are fixed. Measurements are also performed in other sections of the Danube River in connection with project contracts concluded subsequent to 2015. In addition to the locations of hydrometric gauging stations, other locations are also selected for riverbed surveying in view of the distance from the confluences of tributaries and/or islands. Once a location is in selection, a cross section is surveyed at the same location (though less frequently).

Until 1975, the topography of the submerged part of cross-sections had been measured by bottom probing. After 1975, *Acoustic Probes* were used, specifically PEL3 and PEL4 (Soviet products). Since 2009/2010, the cross-sections at hydrometric stations were measured sporadically by means of an ADCP ultrasound device, which was used more frequently after 2015. Using ADCP echo sounding, each cross section is measured a few times (4 to 6), then the average topographic cross section is determined. For each cross section, the distance from the first surveyed point to the river bank is computed using a telemeter or GPS, because the River Surveyor cannot measure the entire cross section. The river banks and the terrain above the water level are measured using a GPS and a Total Station instrument; the inflection of the ground is measured, too. The distances between cross-sections vary, depending on the distances between the hydrometric gauging stations (e.g. 20 to 40 km). Within the framework of certain projects, surveying campaigns were organised to obtain riverbed topography in different river stretches, specifically near the confluence of the Danube with its main tributaries and/or close to the place of its bifurcation into branches.

The owner of the data is the National Administration “Apele Romane” / National Institute of Hydrology and Water Management. The database is kept up to date through the national hydrometric network covering the Danube along its full length. The methodology of measurement and data processing, including verification and validation, is coordinated by NIHWM specialists. Data verification and validation are related to the results of field measurements in the following areas: compliance with the measurement procedure, continuity between the riverbed and river banks within the cross sections, the coordinates of the end points of cross sections, the trajectory of ADCP sounding, differences between consecutive cross sections, etc. The data are available only with the data owner’s approval.

In Romania, after 2006, several other institutes, such as the Danube Delta National Institute for Research and Development (INCDD), the Fluvial Administration *Dunarea de Jos*, (AFDJ) and GeoEcomar, etc., carried out bathymetric measurements in cross-sections along the Danube, using modern measuring instruments (ADCP, multi-beam echo sounder, etc.).

BULGARIA: The Executive Agency for Exploring and Maintaining the Danube River (EAEMDR) is a national public authority established within the Ministry of Transport, Information Technology and Communications (MTITC). It is also a secondary administrator of budgetary credits. Under Article 77 of the Act on Sea Waters, Inland Waterways and Ports in the Republic of Bulgaria, the Ministry of Transport, Information Technology and Communications shall, through EAEMDR, organise, manage and control the exploration and maintenance of the conditions for navigation along the inland waterways of Bulgaria in accordance with the applicable internal and international laws. The Agency’s headquarter is in the city of Ruse.

In the past, riverbed scanning took place in the individual cross sections. Currently, multi-beam echo sounding is used for riverbed scanning.

A plan is prepared every year for the conduct of regular annual surveys, so the sections surveyed in the individual years may differ. As regards the Danube River, its free-flowing stretches are surveyed on a regular basis, i.e. once per year, while its critical stretches are subject to hydrographic measurement several times a year. Monthly measurements are made where the situation is more critical. The maximum distance between cross-sections is 50 m with cm-level accuracy.

Equipment for hydrographic and hydrologic measurements:

- Hydrographic vessel Dunav 1 – built in 2017 with a draft of 1.19 m, equipped with a multi-beam echo sounder and a Side Lidar Scanner. The vessel has a small boat equipped with a single-beam sonar;
- Hydrographic vessel Pc 2070 – built in 2018 with a draft of 0.40 m, equipped with a multibeam sonar.

One of the ways of presenting surveying data is through electronic navigational charts and paper charts, in the form of contour lines, which are updated on an annual basis. These charts can be downloaded free of charge from the official website of EAEMDR at: http://appd-bg.org/ under *Navigation* and on the *FIS portal*.

The information published on the EAEMDR website is publicly available (free download). As regards the Danube's tributaries in Bulgaria, there is no information available about their bed topography. The tributaries are not navigable and their bed topography shows dynamic changes in certain stretches. Their cross-sections are measured regularly only at the hydrometric gauging stations (once per month). There are also sporadic cross-section measurements in other parts of the tributaries, made in connection with national and international projects aimed at flood protection in flood risk zones.

3.2 Riverbed sediments

GERMANY: Bed material samples from the Danube are taken only occasionally. There are several fixed sites, where sediment sampling takes place repeatedly about every 10 years. Samples are taken in selected river stretches only. The tributaries are also sampled only occasionally in selected stretches and for specific analyses/projects/constructions, etc. Some of the sampling sites are fixed, with sampling repeated occasionally, but there are also additional sites for one-off sampling (construction sites, etc.). Riverbed material sampling is done in one or in several verticals within a cross section, depending on the purpose of sampling. Samples are taken not only from the river channel, but also from gravel bars, islands, and from the sites of tributary confluences.

Sediment sampling normally takes place during a low-flow season. Samples from different layers (0–0.1 m and 0.1–0.3 m) are taken from a diving bell ship according to DIN 18123. Additionally, 1.5 m deep boreholes are drilled. The number of samples depends on the width of the river and on the variability of the given cross section. One-off sampling is ensured by dredging using an excavator. First, a picture of the sample is taken, then the sample is dried (at 105°C) and weighed. Finally, a sieving analysis is carried out according to DIN18123. In most of the cases, a complete grain-size distribution curve is compiled.

Riverbed material samples can be taken by several organisations. The samples are analysed by LfU/WWA/BAW/WSV, but when necessary an external geotechnical company was also hired. The organisation or company that carried out the sampling procedure and the grain-size analysis owns the primary data. The results are not available to the public. The data processed by TUM are available for the DanubeSediment project.

AUSTRIA: Riverbed material sampling is not regularly performed. Since 2017, the composition (grain size distribution) of sediments dredged from fords have been analysed by viadonau. Overall, there have been only three sampling campaigns within the last few decades that span the longer parts of the Austrian Danube: the entire Austrian section in the 1930ies (HZB, 1937), the Vienna/East of Vienna stretch from rkm 1,940 to rkm 1,881 in 1987 (Zottl and Erber, 1987), and the Wachau stretch from rkm 2,035 to rkm 2,001 in 1999 (Schmautz and Strobl, 2000). Sediment sampling was also carried out for certain projects, but they covered a small area only. In the period from 2006 to 2016, regular sampling took place between rkm 1,884 and rkm 1,888 (Habersack et al., 2016). The criteria for selecting a sampling site usually depend on the related project.

Three verticals per cross section were chosen for sampling during the campaigns in the 80ies and 90ies, as well as for sampling in 2006–2016, between rkm 1,888 and rkm 1,884.

Samples in the 1930ies were taken from gravel bars during low flows near the water edge. In the 80ies and 90ies, samples were taken from the main river channel. In 2006–2016, samples were taken between rkm 1,888 and rkm 1,884, from the main stream of the Danube and from gravel bars and islands.

Methods: The bed material based on the publication from the HZB (1937) was taken from the subsurface (the surface material was removed before sampling). The three samples from 1979 published by Rainov et al. (1979) were taken at rkm 2161, 2113 and 1978. These samples were surface samples taken with a scrapping bucket (Figure 3.7).

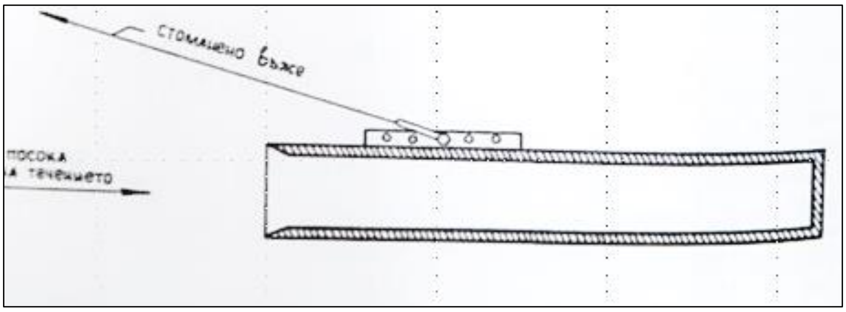

Figure 3.7: A sketch of the sampling equipment (scrapper) used by Rainov et al. (1979).

In 1987 (Zottl and Erber, 1987), bed material was taken from the main stream of the Danube between rkm 1,940 and rkm 1,881 by means of a closed grabber, which was positioned on a barge. The samples in this case were bulk samples, including surface and subsurface material.

In 1999 (Schmautz and Strobl, 2000), samples were again taken from the main stream of the Danube, roughly between rkm 2,035 and rkm 2,001. Details about the sampling equipment are not available; it is assumed that bulk samples were taken, including surface and subsurface material.

Samples from the river stretch between rkm 1,888 and rkm 1,884 (Habersack et al., 2016) were taken in the main stream of the Danube with a closed grabber mounted on an excavator (Figure 3.8). The samples were split on the ship to reduce the mass used for a sieve analysis to 200–400 kg per sample (Figure 3.8 – right picture).

Figure 3.8: Left picture: Grabbing a volumetric sample; right picture: Splitting the sample
(photos: Philipp Gmeiner / BOKU)

Figure 3.9: Volumetric samples from the Danube in Austria. Left picture: Surface; right picture: Subsurface (photos Philipp Gmeiner / BOKU)

Figure 3.9 shows the sediment in the grabber directly after the sample was taken. In the left picture of Figure 3.9, the surface of the gravel bed is depicted; in the right picture of Figure 3.9, the subsurface sediment is shown.

Other sampling methods used in this river stretch are freeze-core and freeze-panel sampling. For freeze coring, a steel pipe is driven into the riverbed and cooled down with liquid Nitrogen (N_2), to retrieve a 1 to 1.5 m long sample of the riverbed material (Figure 3.10, Figure 3.11 and Figure 3.12). The freeze core is afterwards subdivided into 10 cm layers or, in thicker slices, depending on the visible changes in the vertical grain-size composition.

Figure 3.10: Left picture: Steel pipe and panel of a combi-corer used for freeze-core sampling; Right picture: Freezing procedure with liquid Nitrogen (photos: Sebastian Pessenlehner / BOKU)

Figure 3.11: A freeze-core sample (photo: Philipp Gmeiner / BOKU)

Figure 3.12: Left picture: Freeze-panel sampling; Right picture: A freeze panel
(photos: Sebastian Pessenlehner / BOKU)

For the freeze-panel sampling (Figure 3.12), a circular metal plate is lowered onto the riverbed; the plate is previously cooled down with liquid Nitrogen (N_2) to obtain an undisturbed sample of the upper part of the sediment layer.

The freeze-panel is embedded in sand after sampling with the aim of preserving the grain structure of the sample during the thawing process. The grains are then removed as single layers and are dry sieved.

An effective method for taking samples from gravel bars and islands is either areal sampling or linear pebble counting (sampling pebbles along a tape).

In areal sampling, a 0.5 x 0.5 m frame is placed on the sediment surface, which is then spray painted (Figure 3.13 – left picture). Subsequently, the painted surface is manually removed and finally a subsurface sample is taken with a small shovel (Figure 3.13 – right picture). The samples are then dried and sieved in a laboratory.

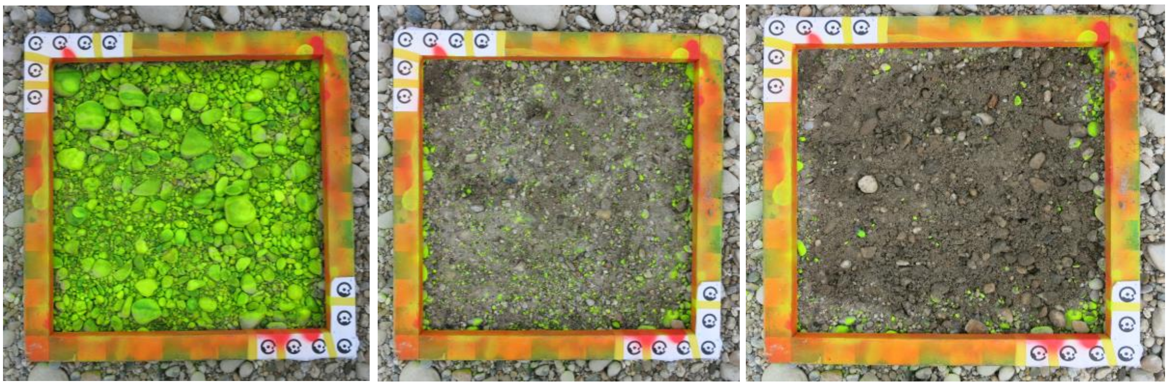

Figure 3.13: Areal sampling of a gravel bar; from left to right: spray painted surface – sample surface – sample subsurface (photos: Philipp Gmeiner / BOKU)

In linear pebble counting, all pebbles that intersect a tape, which is spanned across the sampling area, are sampled and their b-axis (intermediate axis) is measured. At least 150 pebbles are collected with at least 30 of them in the middle fractions of the sample. A grain size analysis is then performed using the calculation method by Fehr (1987).

The riverbed material referred to in the HZB publication (1937) was sieved down to a mesh size of 3 mm. It is not indicated in the publication whether square or round-hole sieves were used. The samples taken in 1987 (Zottl and Erber, 1987) between rkm 1,940 and rkm 1,881 were dry sieved down to a mesh size of 4 mm (assuming that square-hole sieves were used). The samples taken in 1999 (Schmautz and Strobl, 2000) between rkm 2,035 and rkm 2,001 were dry sieved down to a mesh size of 2 mm (assuming that square-hole sieves were used). The samples taken in 2006-2016 (Habersack et al., 2016) between rkm 1,888 and rkm 1,884 were dry sieved (according to ÖNORM B4412) down to a mesh size of 0.125 mm using square-hole sieves. The maximum sieve size used ranged from 125 to 200 mm, depending on the maximum grain size in the sample.

The data set from the 1930ies was not evaluated in the aforementioned publication, but the characteristic grain sizes have been determined and used in the DanubeSediment project. The characteristic grain sizes from the rest of the sampling campaigns have also been determined for use in various calculations and comparisons (past/present changes, before-after impact assessment, downstream fining – abrasion, sediment transport calculations, determination of the roughness coefficient for hydrodynamic numerical modelling, etc.).

There is no real responsibility for riverbed material sampling, as it is neither mandatory nor requested by any official body. The data owners are the entities that are financing the projects for which the samples have been taken. The data derived from the samples are usually evaluated by the project contractor that has taken the samples. These data are not publicly available.

SLOVAKIA: Riverbed material sampling in the Danube is usually done only occasionally within the scope of field investigations undertaken for research projects or tasks. The investigation of riverbed sediments has a long tradition at the Water Research Institute [VÚVH] (since 1951) in connection with the study of sediment transport and riverbed morphology in the Danube River (Szolgay, J. and Nather, B., 1954, Szolgay, J., 1961, Holubova, K. and Szolgay, J. 1999, Holubová, K., et al 2003, Holubová et al 2004, Holubová et al 2014). Therefore, data on the composition of Danube sediments, from the past and/or recent decades, are available on request at VÚVH. The data cover the entire Danube section passing through or touching the borders of Slovakia (from rkm 1,880 to rkm 1,710).

Figure 3.14: Volumetric sediment sampling and grain-size distribution analysis using a sieve shaker in the laboratory of VÚVH (photo: Holubová, Petrisko - VÚVH)

Besides volumetric sampling, which is used more frequently, surface sampling is also applied (Wollman's pebble count procedure using heel-to-toe walk or photographs). Volumetric samples are usually taken by means of a bottom sampler, i.e. a steel drag bucket sampler produced at VÚVH (Figure 3.14). Riverbed material samples are collected from a boat. The sampler is lowered to the river bottom and dragged along the riverbed to be filled with sediments. The minimum amount of a sample is about 20 to 40 kg, depending on the homogeneity of sediments in terms of size. The samples taken show the composition of a mixed surface layer. The samples are then transported to the Hydraulic Laboratory of VÚVH, where a photograph is taken of each sample before it is analysed by means of a sieve shaker (dried at 105ºC or wet samples, Figure 3.2). The grain-size distribution curves compiled, including the characteristic grain sizes D_{16}, D_{50}, D_{65}, D_{84}, D_{90} and other information (photos, locality, sketch, etc.) are collected and stored at VÚVH. Some historical data, mainly from the period 1950-1960, include only the characteristic grain sizes D_{50}, D_{65} and D_{84}. The data obtained by VÚVH are owned by the institute, so they may be used solely with its permission. Occasionally, riverbed material sampling is also done by private companies for various other purposes.

The place of sampling depends on the morphological conditions and the specific aims of the investigation. Usually one sample is taken every river kilometre (at the signs on the river banks) in the middle part of the river channel, plus two additional samples (from the left and right sides of the river) where necessary. For special investigations, more samples are collected in several verticals within each cross section selected. Under low-flow conditions, samples are taken from both the surface and subsurface layers of point or lateral gravel bars. Samples are also taken from the tributaries that have a measurable impact on the investigated river stretch.

HUNGARY: Riverbed material sampling along the Hungarian section of the Danube is performed irregularly, within the scope of surveying campaigns organised in connection with specific research projects. There is no standardised method for selecting a suitable site for sampling. Formerly, bed material samples were taken along cross sections, but currently only point samples are taken. Data on sediments in the tributaries are not available. The criteria for selecting a sampling site are related to the project for which the samples are taken.

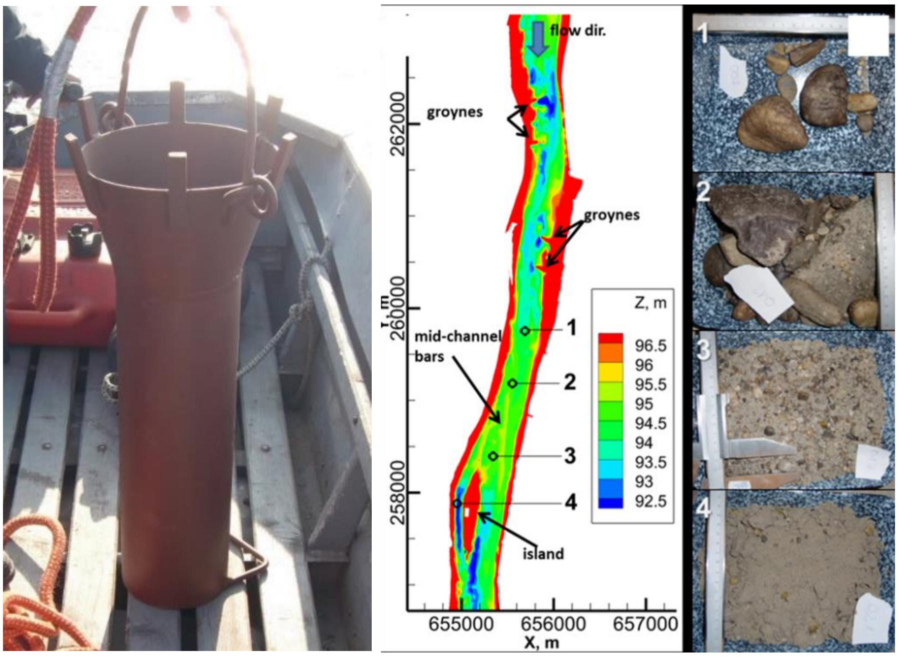

Figure 3.15: Left: Grab sampler (Source: Nikolett Tőkési) and an example of locations of bed material sampling and photos of related dried samples (right)

Disturbed bed material samples are collected using an in-house made steel pipe-dredge sampler (Figure 3.15). During the sampling process, the sampler is lowered to the riverbed, and pulled by a motorboat to grab a 1 to 10 kg sample of the bed material. The samples are dried at 105 °C for 24 hours and then analysed in a sieving machine. Finally, grain-size distribution (GSD) curves are compiled. The data derived from bed material samples are owned by the partners engaged in the project for which the samples have been taken, and are therefore not freely available.

CROATIA: Riverbed sediment sampling is performed only in the tributaries of the Danube: the Drava and Sava rivers. The sampling sites are always the same, because samples are taken solely at the existing hydrometric stations. Riverbed material sampling is done in cross sections, in several verticals (3 or 5). The bed material samples are taken from the river channel, as well as from the gravel/sand bars.

Riverbed samples are collected using a grab sampler, which is lowered down a rope to the river bottom to grab samples from the sediment deposits. The methods used for grain-size analyses are sieving and hydrometer tests. Complete grain-size distribution curves are compiled, not only for the D_{50} values.

The sampling of riverbed sediments is ensured by DHMZ, whereas laboratory analyses and the compilation of grain size distribution curves take place at the Faculty of Geotechnical Engineering in Varaždin. The data derived from the samples are not publicly available, but may be obtained on request, free of charge.

SERBIA: Riverbed material sampling along the Serbian section of the Danube, as well as along its main tributaries, is performed irregularly, within the scope of navigation, hydropower or infrastructure projects. The Jaroslav Cerni Institute has been engaged in sediment sampling in the Danube and its tributaries since the 1960ies. The first sampling campaign took place in the early 60ties, but it covered only the river’s critical stretches for navigation between Belgrade and the Hungarian border. Extensive measurement campaigns on the Danube and its tributaries were organised in 1964/65 and 1966/67 during the preparation of the Iron Gate HPP project. Bottom sediment sampling was also included in the monitoring programme established for Iron Gate I and II (1974-2017); samples were taken mostly in the sediment monitoring sites.

Bed material samples are always taken during cross-sectional flow and sediment measurements, in all verticals across the river channel. Sampling from sediment bars only is never performed. Samples are taken using a mechanical grab sampler (sample mass: 5 kg) and then transported to the JCI Laboratory for processing. Processing includes a sieve analysis for larger particles (gravel and sand) and fall velocity measurement for very fine particles (fine sand and silt, diameter < 0.062 mm). Subsequently, grain size distribution curves are compiled and the characteristic diameters are determined, including D_{50}.

There is no institution responsible for riverbed material sampling. Data on the composition of sediments are not publicly available.

ROMANIA: Alluvium samples from the Danube are taken sporadically, usually at hydrometric gauging stations, within the framework of surveying campaigns. Since 2014, an analysis of the composition of riverbed sediments has also been considered a mandatory part of monitoring (observation/measurement) taking place at selected hydrometric gauging stations. Within the scope of specific projects, riverbed material sampling has been performed on several occasions since 2015, in cross-sections along the Danube River.

Figure 3.16: Grab sampler designed for bed material sampling (photo: Mravcova, VÚVH)

Samples are taken in several verticals within a cross section, together with bedload/suspended load samples. The number of verticals depends on the river width (the distance between the verticals is about 50 to 100 m). Bed material sampling is performed by means of a grab sampler, i.e. a small excavator (Figure 3.16). The opening and closing of the bucket cups are controlled by a cable. The places of the verticals are determined with a GPS device, enabling the sampling sites to be located precisely. The monitoring programme focusing on the composition of riverbed sediments does not cover the tributaries of the Danube. The samples taken from the riverbed material represent a surface layer with a thickness of about 10–15 cm.

Bed material and suspended load samples are often taken after severe floods. More than four samples are taken per year. Technical data and information, documenting the sampling procedure (date, locality, verticals,) are recorded during the field campaign.

Grain size distribution is analysed in laboratories using the standard sieving method to determine the granulometric composition of the bed sediments. At first, sediment samples in porcelain bowels are dried in an oven at 105ºC for four hours. The samples are then sieved through a set of sieves with mesh diameters ranging from 50 mm to 0.063 mm (Figure 3.17) and the sediment fractions are weighted. Larger sediment particles are measured and weighted separately, and then included in the total amount of each sample. Data processing following by a grain-size analysis, including the compilation of grain-size distribution curves, is carried out at the hydrological stations where the samples were taken.

Figure 3.17: Analysis of sediment samples from the Romanian section of the Danube

The data obtained are owned by NARW and NIHWM (the institutes responsible for sampling and methodology development, including data verification and validation). The verification and validation of data are related to the results of field measurements, i.e. compliance with the sampling and laboratory procedures, compilation of granulometric curves, causes of differences in granulometry between the field campaigns, etc. The data are available upon request only, with the owner's approval.

BULGARIA: Riverbed material sampling along the Bulgarian section of the Danube, as well as along its main tributaries, is performed rather irregularly. There is no national institution in charge of bed material sampling.

As from 2019, EAEMDR uses a Van Veen 1,000 cm^3 bottom sampler (grab sampler) to take sediment samples from the Danube. A sampler enabling more detailed sediment sampling will be purchased, too. Samples are taken regularly from the same locations in the river's critical stretches, in several verticals within the cross-sections selected, and periodically along the full length of the Bulgarian Danube. Sampling by EAEMDR is always done as part of a specific project. Data about the composition of bed sediments are not publicly available.

The National Institute of Meteorology and Hydrology is a research institute responsible, inter alia, for the study of river sediments. The regular measurements made in Bulgarian rivers focus solely on suspended sediments. They are measured at the hydrometric stations and the samples are analysed at the aforementioned institute, which, however, has only sporadic information about bed sediments where sediment samples are collected within the scope of other projects. The results are only indicative owing to the strong dynamics of the sedimentation process, but they give a realistic picture of the composition of sediments in certain river stretches. For example, the results for the estuary parts of the Yantra and Iskar rivers are shown below (Figure 3.18). They are depicted as grain-size distribution curves compiled for bed sediments from both rivers.

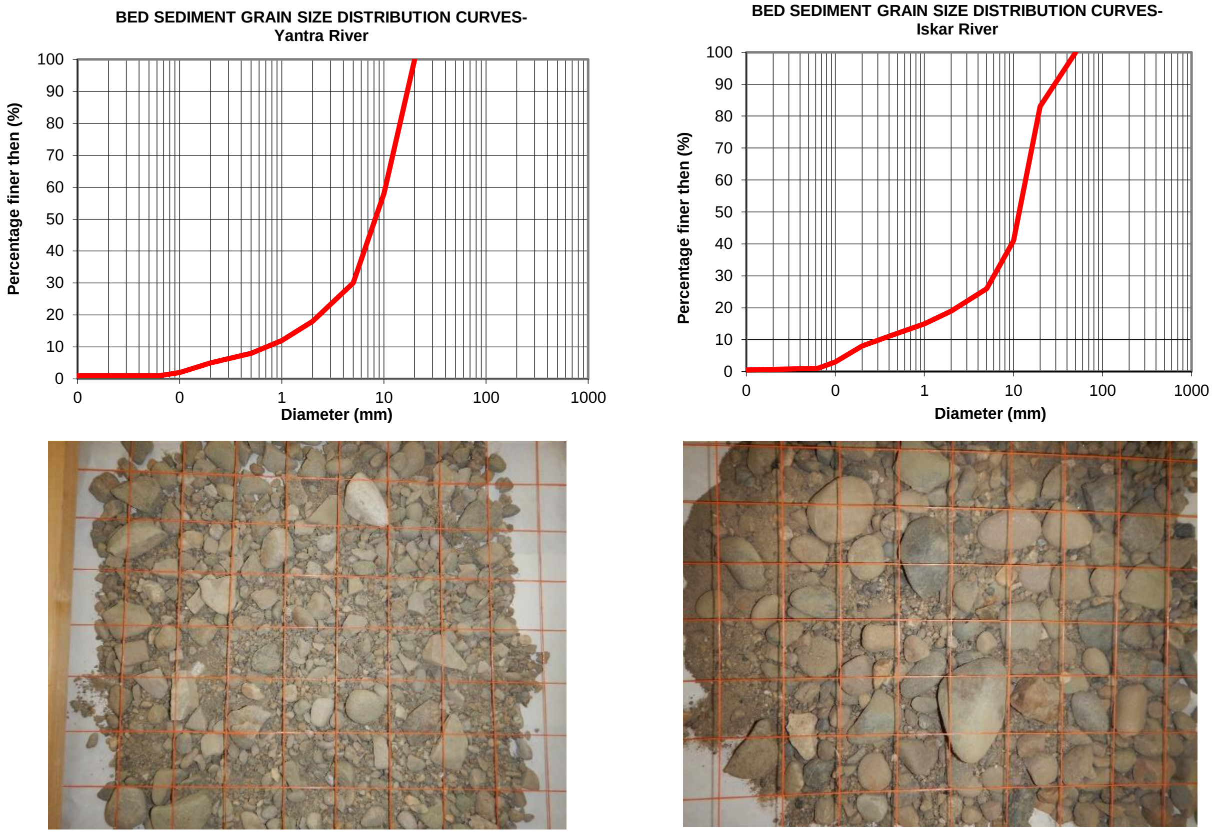

Figure 3.18: Example of grain-size distribution curves and bed material samples from Bulgarian tributaries

There is no information about bedload transport into the main stream of the Danube from its Bulgarian section. That is a task for the future.

3.3 Dredging, feeding and disposal

GERMANY: In the past, riverbed material used to be dredged mostly for commercial purposes, i.e. for construction works on riverbanks, navigation, road construction, dam construction, etc. Currently, the main purpose of dredging is to empty the reservoirs of hydropower plants for navigational purposes or to reconnect old river branches. Riverbed dredging is usually performed at selected river kilometres (often in front of dams). A comparison of the past and present dredging practices shows that commercial dredging is no longer performed. The volumes of riverbed sediments dredged/fed/disposed are recorded in time and space (m^3 or t/year/km).

Wasserwirtschaftsämter WWA (regional water authorities, which are part of the Ministry) are responsible for performing and monitoring the dredging/feeding/disposal of bed sediments, including the yearly collection of data concerning the dredging / feeding activities performed by themselves or by other entities. Primary data are not available to the general public. Data processed by TUM are available for the DanubeSediment project.

AUSTRIA: The legal aspects of dredging in Austria (NEWADA duo, 2014b): “*In Austria, official notifications or licences are needed for dredging works related to fairway maintenance as referred to in the environmental law (water rights, including an impact evaluation with regard to Natura 2000 areas), the navigation law, and the national park law (for a free-flowing river stretch east of Vienna, crossing the Danube Floodplains National Park). In principle, these notifications are to be requested from the competent legal authorities for every single dredging measure in the river. An effectual notification always includes certain regulatory requirements as to how the dredging works in question are to be performed (e.g. specifying the months in which no dredging is allowed, because of disturbance of the fauna and flora, specific water levels above/below which dredging is forbidden, or restrictions on the amount of dredged material to be dumped in the river at once). In some cases, permanent notifications are issued by the authorities, which may cover dredging interventions over the period of several years, based on specific regulatory requirements for the approved dredging works.*

The Austrian authorities responsible for issues of environmental law also check compliance with the provisions of the EU legal acquis, especially the Water Framework Directive (WFD).”

In the past, dredging was performed for navigation, flood protection, river regulation, road construction, commercial purposes, and for the construction of hydropower plants. At the present time, dredging is undertaken mainly for navigation, flood protection and river restoration projects. Furthermore, infrequent dredging is done at the mouths of smaller tributaries in the river's impounded reaches, as well as in harbours and harbour entrances. According to the level of dredging activity, the Danube in Austria can be divided into two free-flowing reaches and ten impounded reaches.

The critical locations for navigation in the two free-flowing reaches of the Austrian Danube are listed in Table 3.2 and Table 3.3 and in Figure 3.19 and Figure 3.20. Such locations are defined in the catalogue of critical locations below.

Table 3.2: Catalogue of critical locations in the free-flowing reach of the Austrian Danube in the Wachau valley (from rkm 2,038.00 to rkm 1,998.00) (Source: NEWADA duo, 2014a)

No.	from rkm	to rkm	Name	Type	ECDIS
01	2,030.80	2.029.80	Aggsteiner Wände	Ford	No
02	2,028.20	2,027.50	Aggsbach Markt	Lateral accumulation left	No
03	2,026.30	2,025.30	Aggsbach	Ford	No
04	2,025.30	2,024.20	Aggstein	Ford	No
05	**2,022.50**	**2,022.00**	**Schwallenbach**	**Ford**	**Yes**
06	**2,020.50**	**2,019.40**	**Hinterhaus**	**Ford**	**Yes**
07	**2,019.00**	**2,018.50**	**Hofarnsdorf**	**Ford**	**Yes**
08	**2,018.20**	**2,017.20**	**Bacharnsdorf**	**Ford**	**Yes**
09	2,016.70	2,016.00	Wösendorf	Lateral accumulation left	No
10	**2,014.60**	**2,013.50**	**Weißenkirchen**	**Ford**	**Yes**
11	**2,010.20**	**2,008.90**	**Dürnstein**	**Lateral accumulation right**	**Yes**
12	2,005.90	2,005.20	Rothenhof	Ford	No

Table 3.3: Catalogue of critical locations in the free-flowing reach of the Austrian Danube east of Vienna (from rkm 1,921.00 to rkm 1,872.70) (Source: NEWADA duo, 2014a)

No.	from rkm	to rkm	Name	Type	ECDIS
01	1,918.40	1,918.10	Albern	Lateral accumulation left	No
02	1,917.50	1,916.30	Lobau	Ford	No
03	1,912.20	1,911.90	Buchenau	Lateral accumulation right	No
04	1,911.60	1,910.90	Buchenau	Lateral accumulation left	No
05	**1,910.40**	**1,909.80**	**Kuhstand**	**Lateral accumulation left**	**Yes**
06	1,908.50	1,907.70	Fischamend	Lateral accumulation left	No
07	1,907.20	1,906.50	Pfarrgraben	Lateral accumulation right	No
08	**1,902.70**	**1,902.10**	**Orth**	**Lateral accumulation left**	**Yes**
09	**1,901.60**	**1,901.10**	**Orth**	**Lateral accumulation right**	**Yes**
10	**1,898.80**	**1,898.00**	**Regelsbrunn**	**Ford**	**Yes**
11	**1,896.50**	**1,895.50**	**Rote Werd**	**Ford**	**Yes**
12	**1,893.20**	**1,891.90**	**Petronell-Witzelsdorf**	**Ford**	**Yes**
13	1,891.20	1,890.10	Rübenhaufen	Lateral accumulation right	No
14	1,890.00	1,888.80	Schwalbeninsel	Lateral accumulation left	No
15	**1,888.40**	**1,887.60**	**Treuschütt**	**Ford**	**Yes**
16	1,887.50	1,886.70	Bad Deutsch-Altenburg	Ford	No

No.	from rkm	to rkm	Name	Type	ECDIS
17	1,886.10	1,885.00	Schanzl	Lateral accumulation right	No
18	**1,884.70**	**1,883.50**	**Hainburg**	**Lateral accumulation left**	**Yes**
19	**1,883.50**	**1,882.40**	**Röthelstein**	**Lateral accumulation left**	**Yes**
20	**1,881.80**	**1,881.00**	**Röthelstein**	**Lateral accumulation right**	**Yes**
21	**1,879.80**	**1,879.10**	**Wendeplatz Theben**	**Ford**	**Yes**
22	1,878.50	1,877.40	Theben	Lateral accumulation left	No
23	**1,875.70**	**1,875.10**	**Käsmacher**	**Ford**	**Yes**
24	**1,873.50**	**1,872.70**	**Grenze**	**Ford**	**Yes**

Catalogue of critical locations in the two free-flowing reaches (NEWADA duo, 2014a): *"viadonau has defined a catalogue of critical locations for the two free-flowing reaches of the Danube waterway in Austria, distinguishing between locations with fords ('Furten') and those with lateral sedimentation ('Haufenränder'). Critical locations with highly dynamic morphological processes are characterised as being of top priority for maintenance measures, with fords given the highest priority, as at such locations shallow areas usually cover the entire width of the fairway, whereas at locations showing lateral sediment accumulation only a part of the fairway is affected by shallow areas. Sedimentation in fords is usually a bigger problem for navigation (reduced fairway depths) than it is in areas with lateral sedimentation, as a deeper part of the fairway can still be used for navigation there. In total and for both free-flowing reaches of the Austrian Danube, 36 critical locations are currently included in the catalogue of critical locations, of which 19 have a high priority. The medium length of a critical location amounts to approx. 860 m, with a variation ranging from 300 m to 1,300 m."*

Not all the critical locations listed in Table 3.2 and Table 3.3 are dredged regularly. Some of them are dredged rather infrequently, depending on the prevailing morphological conditions. Most of the frequently dredged locations are situated in the river reach East of Vienna. In the Wachau valley, only a shallow part near Weißenkirchen is dredged more frequently.

In three of the critical locations in the free-flowing reach East of Vienna (Table 3.3), the engineering structures were optimised to reduce the amount of dredging and to guarantee stable conditions for navigation. The optimisation of structural engineering works in shallow stretches of the Danube was finalised as follows: in the Petronell–Witzelsdorf stretch in October 2015, in the Bad Deutsch–Altenburg stretch in January 2017, and in the stretch at Treuschütt at the end of 2018. In the shallow stretch at Rote Werd, a gravel island was built to reduce locally the amount of sedimentation and dredging in the navigational fairway.

In the past, riverbed material was mostly excavated, whereas the current practice is to refeed the dredged material into the main stream, and/or to build gravel islands and bars in near-shore areas of the main stream. The aim is to keep the sediment within the river system.

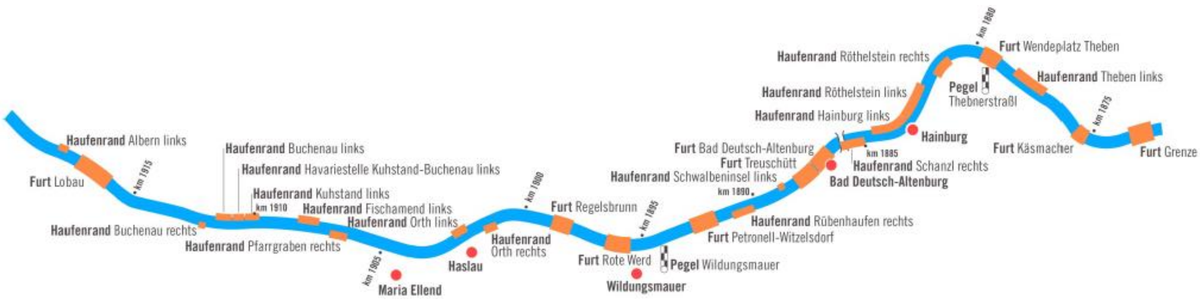

Figure 3.19: Critical locations East of Vienna (Source: NEWADA duo, 2014a)

The general practice today is as stated in the NEWADA duo project (2014b): *"In Austria, it is seen as a violation of the provisions of the WFD to withdraw gravel from the Danube, as this would deteriorate the stipulated 'good ecological status' of the river. On the other hand, it is not forbidden to remove fine sediments from the river, as these are not seen as being ecologically valuable."*

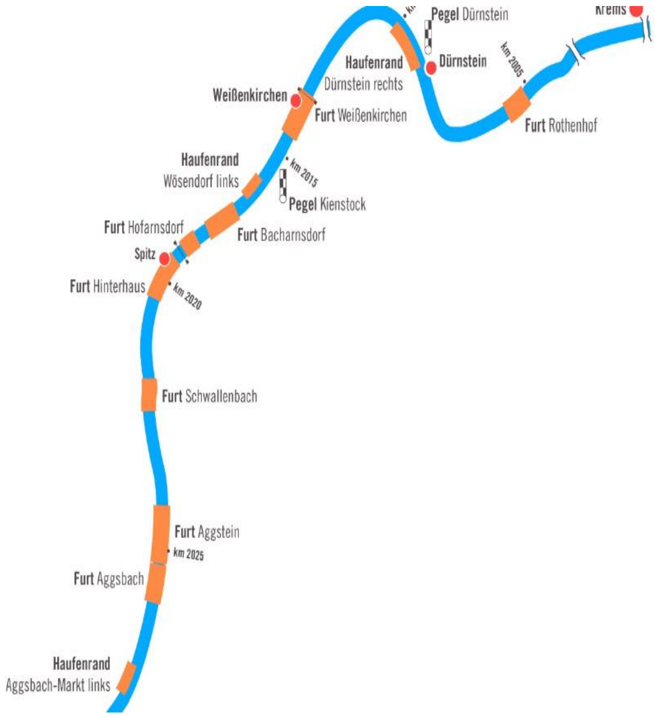

Figure 3.20: Critical locations at Wachau (Source: NEWADA duo, 2014a)

In selecting a suitable disposal site, viadonau sticks to the following principles: "*The choice of a specific disposal site has both an economic (costs related to the transport distance between the dredging site and the disposal area) and an ecological aspect (where is the best place to dispose of the dredged material in terms of the environmental consequences). In the free-*

flowing reach between Melk and Krems (Wachau valley), the excavated material (gravel) is used to create new gravel islands in the river channel (combination of ecological and river regulation effects)" (NEWADA duo, 2014b).

The dredging sites and the volume of dredged sediments have changed in Austria over the years, owing mainly to the implementation or finalisation of low and mean-water river regulation measures and to the construction of 10 hydropower plants (HPPs) between 1955 and 1997. During the river regulation works, sediments were dredged in considerable amounts for both construction and maintenance purposes (Tschochner, 1957; Geitner, 1969; Geitner, 1978). Overall, not all the dredged material was excavated, part of it was kept in the main stream of the Danube and another part was used for river regulation works. During these years, not only gravel was dredged but also large amounts of rocks, which were blasted into smaller pieces and then removed. When the HPP construction began, the maintenance and regulation activities shifted more into the free-flowing reaches of the river. Currently, there are also dredging activities in the backwater areas of the HPPs (e.g. flood protection for the cities of Linz and Krems or near the "Schlögener Schlinge" in the impoundment of the HPP Aschach).

Dredged material management for fairway maintenance has undergone several stages over the last 20 years East of Vienna. According to Simoner (2018), between 1996 and 2005, approx. 50% of the dredged material was fed back into the main stream, 30% was excavated, 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 then, from 2009, upstream of the dredging site. Finally, from 2015 on, the upstream transfer distance increased considerably, to an average of 11 km (Simoner, 2018). According to BMNT (2018), the official regulations stipulated for the river reach East of Vienna, until recently, that at least 50% of the dredged material had to be kept within the main stream and the rest was allowed to be used for ecological/river restoration measures, e.g. for building gravel islands and bars in the main stream of the Danube. This amount has recently been changed so that now at least 80% of the dredged material is to be kept within the main stream to be available for transport (BMNT, 2018). Furthermore, the disposal site has been moved upstream of the dredging site, which is currently the practice of viadonau (since 2009), with a longer upstream transport distance since 2015. The remainder of the dredged sediment (max. 20%) can still be used for the construction of in-stream structures, such as gravel bars and island.

Since the beginning of the 21st century, the riverbed material dredged at Wachau has been used for the construction of gravel bars and islands in near-shore areas of the Danube's main stream. Since 1998, the gravel transported from the free-flowing reach at Wachau into the backwater area of the Altenwörth HPP has been dredged and transported downstream of the Freudenau HPP for use as material for gravel nourishment (feeding) (VHP, 2013).

In impounded reaches, the dredged sediment was used, for example, in the impoundments at Aschach, Ottensheim-Wilhering and Abwinden-Asten to build habitats (gravel structures and islands) in the 1980ies and 1990ies. More recent activities of the VHP are the construction of in-stream structures in the impoundments at Aschach and Melk.

Gravel nourishment (feeding) takes place only downstream of the Freudenau HPP, with the aim of mitigating the impact of the Freudenau HPP on the gravel supply from the upstream reach of the river. Responsibility for feeding lies with VHP, the hydropower plant operator. The maintenance reach downstream of the Freudenau HPP extends from rkm 1,921 to rkm 1,910. The target was to keep the mean riverbed level in this reach at the level of 1995 (when the last riverbed survey was carried out before the Freudenau HPP was partially filled). Recently, a new reference bed level respectively maintenance bed level was defined by the legal authorities. The amount of gravel nourishment (feeding) downstream of the Freudenau HPP in the maintenance reach from rkm 1,921 to rkm 1,910 was approx. 186,000 m³/a in the years from 1996 to 2017. This amount has recently been increased to 235,000 m³/a (BMNT, 2018).

In the past, the records of dredging works contained mainly the location of the dredging site (rkm), the purpose of dredging, and the amount, purpose and type of the material dredged (fine sediment, gravel or rock). Nowadays, the entity performing the dredging works is usually noted in the daily records (external contractors in case of the viadonau and to some extent in the case of the VHP). In the current records of viadonau, for example, the location (rkm), time of dredging (year), amount (m3) and type of the material dredged (fine sediment or gravel) are recorded. In the records of VHP, sediment feeding is recorded in both time and space (rkm, year and m³).

VHP and viadonau are responsible for performing and monitoring the dredging/feeding/ disposal of sediments. These data are not available to the public.

SLOVAKIA: In the past, riverbed material dredging in the Danube was performed for both commercial and maintenance purposes (mainly to maintain the conditions for navigation and to improve flood protection). In the 60ties and 70tis, excessively large volumes of river sediments were dredged for commercial purposes downstream of Bratislava in particular. This led to significant riverbed degradation (between rkm 1,860 and rkm 1863), followed by extensive downstream and upstream propagation. Since the 90ties, commercial dredging in the Danube has been limited to dredging for navigation and flood protection purposes.

Riverbed dredging is performed by the River Authority (SVP), the national authority in charge of river maintenance. The technical aspects of dredging (volumes, locations, etc.) along the international river sections (Slovak–Austrian and Slovak–Hungarian) must be negotiated within the Border Commissions. SVP collects the relevant data and information (records of the amounts of sediments dredged and the corresponding locations); these data are available on request and can be used with permission only. The long-term records indicate a decreasing tendency in the volumes of sediments dredged along both international river sections. The ongoing dredging activities are concentrated in two localities: between rkm 1,868 and rkm 1,860 (the end of impoundment upstream of the Gabčíkovo HPP) and at rkm 1,790 (significant change in the riverbed slope downstream of Gönyű). Bed material removal is performed to maintain the necessary conditions for navigation and flood protection.

HUNGARY: There are irregular dredging activities taking place along the Hungarian section of the Danube. The main aims of dredging are to maintain the waterway and to revitalise the river's side branches. Formerly, mainly before 1990, a significant amount of gravel was excavated from the Upper-Hungarian Danube stretch to obtain building material (for commercial purposes). No sediment feeding and disposal is performed in the Hungarian section of the Danube. A large part of the sediments dredged is recorded by the responsible water directorates. The information available is, however, limited (recorded in time and space: m^3 (t/year/rkm). The data are owned by the water directorates. Information about riverbed dredging is available at the competent water directorate, but not free of charge.

CROATIA: There was no sediment dredging from the Drava River, nor from the flood retention area, after a highway was built (1993–2003) in an area falling within the competence of the Water Management Department (WMD) for the Mura and Upper Drava. Before the highway construction began, the concession holder performed dredging activity and this was recorded in the records of sediment dredging. The material for the highway was excavated from the old Drava riverbed along the Čakovec and Varaždin hydropower plants (HPPs). Calculations were made for each change recorded in the riverbed and the material dredged was weighed before transport. In addition, stone thresholds were built for maintaining the low-flow water level.

In the past, dredging activity was also performed with the aim of ensuring flood protection or reducing the negative impacts of HPPs (cross section reduction for a higher water level). Such dredging was performed only in locations where the river's flood defence structures were negatively affected and in old riverbeds at the Varaždin and Čakovec HPPs. In the Drava River, there has been no sediment dredging since 2003 in the stretch between rkm 176.4 and rkm 322.8 (maintained by WMD for the Mura and Upper Drava).

The organisation responsible for performing and monitoring the dredging/feeding/disposal of sediments in the Danube River is Hrvatske vode, Water Management Department (WMD) for the Danube and Lower Drava. The data are not publicly available, but can be obtained on request.

SERBIA: Sediment dredging from the Danube (and from its tributaries) used to be a commercial activity in the past. The dredging sites were selected in view of the physical characteristics of the sediments and of the local demand (for material for building dikes, filling up the ground for new construction sites, etc.). Commercial dredging was gradually restricted to areas where dredging is a flood protection measure, and is limited to a certain yearly volume.

According to the intensity of sediment dredging, four river stretches can be distinguished along the Serbian section of the Danube River:

- The upstream river stretch (rkm 1,433–1,170), with waterway maintenance being a top priority and sediment dredging concentrated in the main river channel;
- The shallow stretch of the Iron Gate 1 reservoir upstream of Velika Morava (rkm 1,170–1,106), with sand dredging in small quantities. By contrast, gravel dredging between Velika Morava and the upstream end of the Iron Gate gorge (rkm 1,106–1,040) is of special interest, since it partially reduces the unfavourable effects of sediment deposition in the reservoir;
- The deep stretch of the Iron Gate reservoir (rkm 1,040–943), where excavation is limited both economically and technically. The deposits are composed of fine sand and silt, while the water is very deep throughout the year. Excavation is not really feasible, owing to the limitations of the dredging technology applied and the lack of space for sediment dumping;
- The river stretch downstream of the Iron Gate 1 dam, with sediment dredging in very small quantities.

Under the new Water Law, a sediment dredging plan has been adopted for the Danube (2017–2019, 2019-2021 is in preparation). In this plan, the volume of sediments dredged is limited to a renewable quantity, except in the shallow stretch of the Iron Gate 1 reservoir (where dredging represents a measure to cope with reservoir sedimentation). Strict procedure including the precise record of sediment extraction dynamics, location and quantities is set in the Plan. The data owner is the Ministry responsible for water management, but in the past it held only data on approved quantities. Data on the actually dredged quantities (including the dredging sites) are scarce. The data were not available to the general public.

ROMANIA: Riverbed sediments from the Danube are dredged for various purposes, the most important being fairway maintenance (navigation), sale as building material for construction works, and mineral extraction (from gravel and sand). The dredging sites are selected according to the actual requirement to maintain navigation along the Danube waterway. Sediments excavated from the Danube are deposited within the river channel along the banks, near the dredging sites (sediment replacement), or outside of the river channel, near a gravel or sand deposit.

The data about volumes and locations of dredged sediments are not well known, because dredging is carried out by several institutions coordinated by the Fluvial Administration of the Lower Danube in Galati and the National Administration “Apele Romane” and there is no unique database about it. The historical records are available at Danube Commission. The data are owned by two institutions, i.e. the Fluvial Administration of the Lower Danube and the National Administration “Apele Romane”. Data from these institutions can be obtained solely with their approval. Dredging data for the purposes of the DanubeSediment project are provided from the Danube Commission’s records for the period 1920-2004 and from the other two institutions for the period 2010-2016.

BULGARIA: Since the beginning of 2017, dredging activity in the Danube River with the aim of sediment deposition has been restricted owing to changes in the relevant legislation. For the DanubeSediment project, dredging data have been provided by EAEMDR. In 2018, EAEMDR commenced extensive dredging works to create more favourable conditions for navigation:

- According to an agreement between MTITC and EAEMDR, a common public procurement procedure was conducted in 2017, as a result of which a contract for the performance of maintenance dredging activities was signed in February 2018;
- Contracting authorities: MTITC and EAEMDR; external contractor – Cosmos Shipping Ltd.;
- Contract value: about EUR 4 million.

The contract period is: up to 36 months or until the financial resources (contract value) are exhausted, which of the two circumstances occurs earlier, the contract is concluded with delayed execution (as per Art. 114 of the Public Procurement Law) – dredging is allowed where necessary, if the resources are available. The contractor starts performing dredging works within ten days of receipt of a written notice from EAEMDR, defining the location of the dredging site and setting a deadline for completion of the dredging works.

The written notice includes the following attachments: a dredging project prepared by EAEMDR, containing explanatory notes, a dredging plan, and a scheme for sediment disposal.

The explanatory notes contain the following information:

- Detailed information about the hydrographic measurements made by EAEMDR before the beginning of dredging (the methods and equipment used, and the meteorological conditions during the measurement period).
- A dredging plan with information about the dredging site, including a drawing showing the width and depth of the designed fairway and information on sediment disposal.
- The volume of sediments to be excavated, as calculated from the difference between the measured depths below low-flow navigable water level (LNWL) and the required depth below LNWL – 300 cm.
- Final hydrographic measurements and executive drawings for quantity identification and assessment of the dredging works (by EAEMDR), no later than ten days after the completion of dredging.
- The time of payment – payment is due on acceptance of the actual dredging works, duly certified with a delivery and acceptance protocol with an attachment including the hydrographic schemes, executive drawings, and a report on the quantity and quality of the dredging works carried out.

Sediments were excavated in the following quantities: 133,292 m³ between rkm 564.600 and rkm 565.300, 22,347 m³ between rkm 564.300 and rkm 564.500; 101,011 m³ between rkm 545.000 and rkm 547.800.

Since the Bulgarian tributaries are not navigable, sediment dredging is not linked to shipping, and is performed solely for commercial purposes and/or for the maintenance of hydrological connectivity in relation to flood protection. Such dredging is performed in most of the Danube's tributaries in Bulgaria, including the biggest ones – Iskar and Yantra.

Data on the volumes of dredged sediments and the dredging sites along the Bulgarian section of the Danube are collected by the Danube Basin Directorate, and are to be approved at national level. Data on the performance of dredging works are not publicly available. The table below contains data about settlements where dredging activities were performed in the past and are still performed, including the volumes of sediments allowed to be dredged from the two biggest tributaries – Iskar and Yantra (from the main stream only). The total volume is approximate, because the data are incomplete. The data presented below have been obtained from the Danube Basin Directorate in Pleven.

Table 3.4: Riverbed sediment dredging in the Iskar and Yantra rivers

№	Place of dredging		Aim of dredging	Scheme and parameters				Permitted volume m^3/year
	River	Settlement		Length m	Width m	Depth m	Total volume m^3	
1	Iskar	Eliseina	BSD*	118.5	21.75	1.5	1,5000	6,000
2	Iskar	Brusen	BSD	175.4	32	1.5	7,313.78	6,250
3	Iskar	Slavoviza	BSD	n.a.	n.a.	0.42	n.a.	1,300
4	Yantra	Krushina	BSD	800	61	0,76	21,773	5,000
5	Yantra	Petko Karavelovo	BSD	500	69,4	1,47	33123,84	5,000
6	Yantra	Draganovo, Dolna Oryahoviza	BSD	850	51	1,8	18,457	5,000
7	Yantra	Kuzina	BSD	390	59,35	1,09	18,205	5,000
8	Yantra	Gorski Dolen Trumbesh	BSD	220	40.33	1.54	3,710.848	5,000
9	Yantra	Petko Karavelovo	BSD	500	34.5	1.13	10,000.99	5,000
10	Yantra	Petko Karavelovo Radanovo	BSD	700	62.68	0.96	32,315	5,000
11	Yantra	Vurbiza;Gorski Dolen Trumbesh	BSD	300	40.24	2.4	4,278	2,200
12	Yantra	Gorna Oryahoviza, Pravda	BSD	465	66	1.11	14,626	5,000
13	Yantra	Draganovo	BSD	548	47.7	1.26	7,481	5,000
14	Yantra	Pisarevo, Kozaravez	BSD	205	73	1.15	9424	5,000
15	Yantra	Pisarevo, Kozaravez	BSD	305	72.9	0.97	13,903	n.a.
16	Yantra	Pisarevo, Kozaravez	BSD	375	64.52	0.83	8,493	n.a.
17	Yantra	Pisarevo, Kozaravez	BSD	205	73	1.15	9,424	5,000
18	Yantra	Pisarevo, Kozaravez	BSD	305	72.9	0.97	13,903	n.a.
19	Yantra	Pisarevo, Kozaravez	BSD	375	64.52	0.83	8,493	n.a.
20	Yantra	Pisarevo, Kozaravez	BSD	205	73	1.15	4,135	n.a.
21	Yantra	Polski Trumbesh; Karanzi	BSD	540	71.76	1.2	27,115	5,000
22	Yantra	Vurbiza	BSD	78	40	0.96	1,758	5,000
23	Yantra	Vurbiza	BSD	189	38.35	0.53	4,566	n.a.
24	Yantra	Vurbiza	BSD	176	25	0.7	3,044	n.a.
25	Yantra	Petko Karavelovo	BSD	455	73.7	1.01	14,930	5,000
26	Yantra	Petko Karavelovo	BSD	315	60.15	0.85	7,730	5,000
27	Yantra	Petko Karavelovo	BSD	565	111.4	0.79	24,170	5,000
28	Yantra	Vurbiza	BSD	195.6	38	1.12	17,556	5,000
29	Yantra	Vurbiza	BSD	288	41	1.08	n.a.	n.a.
30	Yantra	Gorna Oryahoviza, Pravda	BSD	630	35.8	0.82	9.34	5,000
31	Yantra	Lyaskovez	BSD	440	61.09	2.05	24,952	5,000
32	Yantra	Purvomaizi	BSD	970	98.36	1.81	42,793	5,000
33	Yantra	Purvomaizi	BSD	165	60	0.65	2,520	2,500
34	Yantra	Lyaskovez	BSD	440	61.09	2.05	24,952	5,000
35	Yantra	Gorna Oryahoviza, Pravda	BSD	465	66	1.11	14,626	5,000

№	Place of dredging		Aim of dredging	Scheme and parameters				Permitted volume m^3/year
	River	Settlement		Length m	Width m	Depth m	Total volume m^3	
36	Yantra	Vurbiza, Gorski Dolen Trumbesh	BSD	300	40.24	2.4	4,278	2,200
37	Yantra	Purvomaizi	BSD	164	60	0.31	1,324.13	1,300
38	Yantra	Draganovo	BSD	450	51.77	0.89	5,202.40	5,000
39	Yantra	Draganovo	BSD	872	66	0.8	12,942	12,900
40	Yantra	Draganovo	BSD	872	66	0.8	12,942	12,900
41	Yantra	Vurbiza	BSD	195.6	38	1.12	17,556	5,000
42	Yantra	Vurbiza	BSD	288	41	1.08	n.a.	n.a.
43	Yantra	Велико Търново	SRBC**	n.a.	n.a.	n.a.	n.a.	n.a.

**BSD - bed sediment dredging, **SRBC* - support of riverbed conductivity

3.4 Low navigable water levels

GERMANY: Low-flow water levels for navigation have not been set for the German section of the Danube, because dams ensure the water level for main parts of the river. However, the highest water levels for navigation are recorded in Germany (Table 3.5).

Table 3.5: Waters levels for navigation in the German section of the Danube

Gauging station	Water level cm	River reach
Oberndorf	480 (331.32 m.a.s.l.)	Kelheim - Schleuse Regensburg
Regensburg-Schwabelweis	520 (324.783 m.a.s.l.)	Schleuse Regensburg - Schleuse Geisling
Pfatter	600	Geisling - Straubing
Pfelling	620	Straubing - Deggendorf
Hofkirchen	480	Deggendorf - Schalding
Passau-Donau	780	Schalding - Jochenstein

AUSTRIA: Data from older data sets (as listed in KWD: Kennzeichnende Wasserstände Donau) are available for the whole national river section between rkm 2,226.72 and rkm 1,868.75, and data from the most recent data sets are available for the river stretch between rkm 2,223.05 and rkm 1,873.00. The data are available for every river kilometre, plus for the most important gauging stations, as well as for the up- and downstream locations of hydropower plants (Table 3.6).

Table 3.6: Example of the KWD2010: Water levels at every river kilometre and at the most important gauging stations along the Austrian Danube. RNW – low-flow navigable water level, MW – mean water level, HSW – highest navigable water level, HW30 and HW100 – water levels during floods with a 30 and 100-year return period. (Source: viadonau, 2012)

Rkm	Gauging station	RNW 2010	MW 2010	HSW 2010	HW 30	HW 100
		'0' Adriatic m.a.s.l.				
2,223.05	Achleiten	290.62	291.21	293.14	296.35	297.18
2,223		290.62	291.21	293.14	296.32	297.16
2,222		290.57	291.09	292.87	296.15	297.05
2,221		290.53	290.97	292.52	295.72	296.66
2,220		290.50	290.89	292.33	295.34	296.29
2,219		290.48	290.81	292.10	295.08	296.06
2,218		290.47	290.77	291.94	294.63	295.58
2,217		290.45	290.71	291.75	294.29	295.24
2,216		290.44	290.65	291.51	293.82	294.78
2,215		290.42	290.58	291.16	293.11	294.12
2,214.51	Erlau WP	290.42	290.57	291.14	292.77	293.78
2,214		290.41	290.55	291.11	292.56	293.59
2,213		290.40	290.50	290.93	291.85	292.85
2,212.81	Pyrawang	290.40	290.50	290.91	291.78	292.80
2,212		290.39	290.48	290.83	291.57	292.67
2,211		290.38	290.46	290.78	291.18	292.28
2,210		290.37	290.44	290.69	290.74	291.86
2,209		290.37	290.42	290.64	290.44	291.63
2,208.97	Obernzell	290.37	290.42	290.64	290.43	291.61

For the first KWD published in 1940, no definition was provided for the characteristic water levels. For the next two KWDs (1949 and 1956), the low-flow navigable water level was determined on the basis of a 56-year period and a discharge that was exceeded on 340 days a year. For a year having 365.25 days, the annual exceedance probability is about 93%. The discharges for the lowest and highest navigable water levels in the previous publications were calculated according to the guidelines of the Danube Commission. They are based on a 40-year period for KWDs 1970, 1976 and 1985, and on a 30-year period for KWD 1996 and KWD 2010. The annual exceedance probabilities of discharges corresponding to the characteristic water levels (94% for the low-flow navigable water level and 1% for the highest navigable water level) are based on the Danube Commission's guidelines. The purpose of the low and highest navigable water levels (LNWL and HNWL) is to provide an overview of the unfavourable navigational conditions. In impounded river stretches, the LNWL corresponds to the lower tolerance of the reservoir water level at the hydropower plant. As for the HNWL in impounded stretches, it is the highest possible water level that occurs at the highest navigable discharge, when the weir operation regulations are met (viadonau, 2012). A decisive factor concerning the HNWL in this case is the required vertical bridge clearance (the distance between the lowest part of the bottom edge of a bridge over the entire width of the fairway channel and the highest navigable water level).

Depending on the period, there are 65 to 105 gauging stations along the Austrian Danube, which are used as a baseline for determining the low-flow water level. These gauging stations are either recording stations or daily/infrequently monitored staff gauges.

According to the KWD 1976 (Bundesstrombauamt, 1978), a significant change compared with the KWD1970 occurred in the representation of LNWL 76 in the free-flowing river reaches. LNWL 76 was not assumed for longer distances, i.e. from gauging station to gauging station, using a uniform gradient, but the actual low-flow water level (LNWL) was used for each river kilometre or gauging station. The free-flowing river reaches at that time consisted of the downstream part of the Ybbs-Persenbeug HPP up to the beginning of the backwater area of the Altenwörth HPP and of the Danube stretch downstream of the Altenwörth HPP. Additional water levels in the KWD are the mean water levels (based on the arithmetic average of the mean annual discharge of a 30-year period) and the 30 and 100-year water levels (based on discharges with an exceedance probability of 1/30 and 1/100 of the annual flood).

In the KWD 2010 (viadonau, 2012), it is stated that water levels were calculated in accordance with to the valid standards and the latest state of the art. For this purpose, one-dimensional ydraulic models were calibrated and validated on the basis of measured values reflecting the current discharge conditions, taking into account the most recent bed elevation measurements.

The KWDs are planned to be updated according to the relevant requirements at intervals ranging from 6 to 14 years. Viadonau is responsible for the performance of calculations and modelling works, and owns the data obtained. The latest version of the KWD has been published as a report and is available to the general public.

SLOVAKIA: Low-flow water level is defined as the minimum water level for navigation (LNWL). The discharge corresponding to the minimum navigable water level varies and is determined on the basis of a statistical analysis of long-term hydrological series of daily average discharges measured at gauging stations as a discharge with an annual exceedance probability of 94%. The first longitudinal profile of minimum navigable water levels was compiled in 1957. This was updated in 1974, 1984, 1990, 2003, 2006 and 2014. In the past, this water level was calculated from measurements and data from gauging stations (Q,) and water gauges along both sides of the national and shared sections of the Danube River (Table 3.7 and Table 3.8).

Since the 1980ties, one-dimensional (1D) numerical models have been used to determine the minimum navigable water levels (VÚVH is responsible for modelling). These water levels are updated at regular intervals (five to ten years), depending on the morphological changes occurring in the riverbed and always after severe floods.

Table 3.7: Water gauges (d) and gauging stations (Q/d) and corresponding levels for LNWL and HNWL on the Austrian/Hungarian reaches of the Danube (Baltic, 2010 AT-Adriatic)

Country	Station name	Type*	Locality	'0' Baltic	LNWL - 2014		HNWL - 2014	
			rkm	m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.
AT**	Thebnerstrassl	GS	1,879.250	132.69	980	134,58	5130	139,24
	Wolfsthal	WG	1,874.840	129.64	1049	133,04	5340	137,70
	Berg	WG	1,873.500	129.18	1049	132,74	5340	137,01
HU	Rajka	GS	1,848.400	122.58	-	-	-	-
	Doborgaz	GS	1,839.500	110.00	-	-	-	-
	Dunaremete	GS	1,825.500	113.24	-	-	-	-
	Vámosszabadi	GS	1,805.600	108.40	1010	108,47	5040	113,71
	Nagybajcs	WG	1,801.000	107.40	1010	108	5040	112,97
	Gönyű	WG	1,790.610	106.04	1010	106,07	5052	111,22
	Komárom	GS	1,768.300	103.88	1060	104,71	5052	109,24
	Dunaalmási	GS	1751.8	103.12	1167	103,91	5383	108,03
	Lábatlan	WG	1,737.760	101.50	1167	103,05	5383	107,19
	Esztergom	GS	1,718.500	100.92	1168	101,51	5383	105,95
	Szob	WG	1,706.600	100.98	1168	100,90	5383	105,05
	Nagymaros	GS	1,694.600	99.43				

**GS: gauging station, WG: water gauge ***source: viadonau (2012)

Table 3.8: Water gauges (d) and gauging stations (Q/d) corresponding levels for LNWL and HNWL at the Slovak reach of the Danube

Country	Gauging station	Type	Locality	'0' Baltic	LNWL - 2014		HNWL - 2014	
			rkm	m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.
SK	Bratislava -Devín	GS	1,879.800	132.87	1049	134,75	5340	139,45
	Devín - Lom	WG	1,877.300	131.76	1049	133,70	5340	138,48
	Bratislava	GS	1,868.750	128.43	-	-	-	-
	Rusovce	WG	1,855.900	123.90	-	-	-	-
	Čunovo - weir	WG	1,851.600	129.92	-	-	-	-
	Hamuliakovo	WG	1,850.000	120.01	-	-	-	-
	Dobrohošť	WG	1,838.500	115.16	-	-	-	-
	Gabčíkovo	WG	1,819.000	110.82	-	-	-	-
	Sap	WG	1,809.970	108.09	1010	108,86	5040	114,36
	Medveďov	GS	1,806.400	107.38	1010	108,54	5040	113,82
	Kližská Nemá	WG	1,792.370	104.65	1010	106,34	5040	111,43
	Zlatná na Ostrove	WG	1,779.100	103.92	1010	105,02	5040	109,98
	Komárno-bridge	GS	1,767.800	103.40	1060	104,80	5052	109,21
	Iža	GS	1,763.960	103.64	1167	104,47	5383	108,95

Country	Gauging station	Type	Locality	'0' Baltic	LNWL - 2014		HNWL - 2014	
			rkm	m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.	Q m^3s^{-1}	Level m.a.s.l.
	Radvaň/Dunajom	WG	1,748.250	102.88	1167	103,69	5383	107,85
	Štúrovo	GS	1,718.600	100.94	1168	101,52	5383	105,96

**GS: gauging station **WG: water gauge*

The minimum water levels are estimated by VÚVH (using a 1D hydrodynamic model) as required by the River Authority (SVP), which is the data owner. The data are available to the public on the request. Except of LNWL also high (maximum) navigable water levels (HNWL) and flood water levels (Q_{20}, Q_{50}, Q_{100}) are estimated and regularly updated within periods ranging from five to ten years (or after high floods $Q>Q_{50}$). Since Gabcikovo was put into operation (1992) these water levels are not estimated within impounded river section (Bratislava GS) and along the Old Danube except of flood discharges.

HUNGARY: Low-flow navigable water level profiles are compiled by the responsible water directorates at irregular intervals. Before 2003, a statistical analysis was carried out in respect of the water levels and flow discharges in the relevant stretches of the Danube River. On the basis of that analysis, the low-flow water levels (at Q_{min} with an annual exceedance probability of about 94%) were estimated for the SK-HU river stretch (i.e. low flows in 2006 and 2014, and high flows suitable for navigation in 2014). Recently, 1D numerical model simulations have been performed to compile a low-flow water level profile. The navigable low-flow water level profiles were updated in 1966, 1976, 1990, 2006 and 2014 (Figure 3.21). The data are owned by and available at the competent regional water directorates.

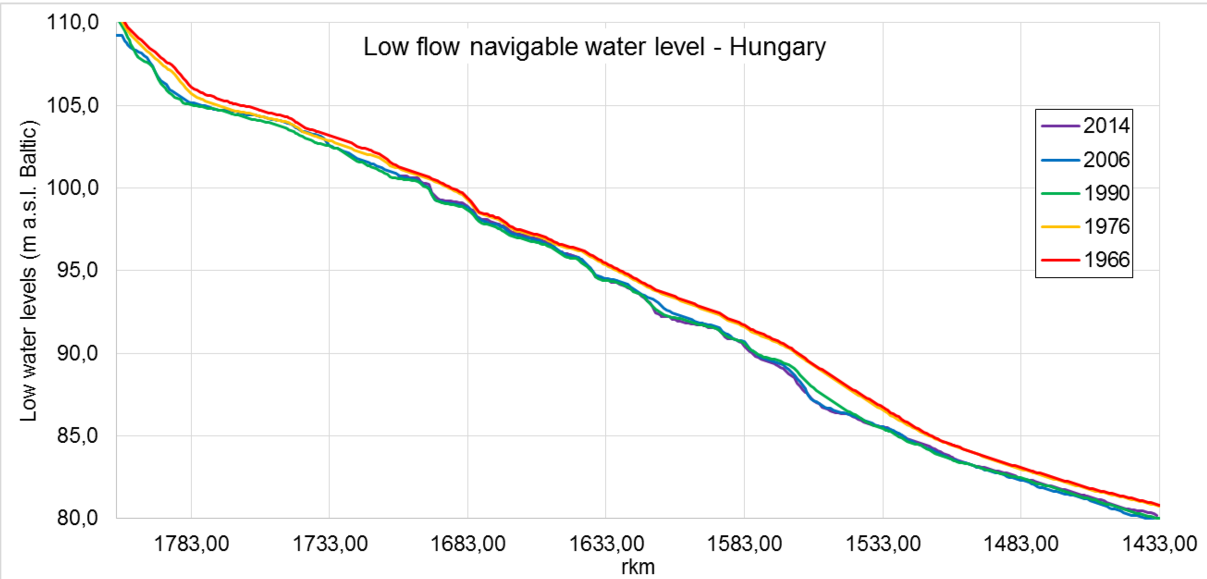

Figure 3.21: Low-flow navigable water levels along the Hungarian Danube reach

CROATIA: The low-flow navigable water level for the Danube has been defined by the Danube Commission. The relevant calculations were made for water levels at a discharge with an annual exceedance probability of 94%, measured at the existing gauging stations. In cooperation with the Serbian side, the water levels corresponding to such discharges were calculated every 200 m along the river's longitudinal profile.

For the Drava River, calculations were made for water levels at a discharge with an annual exceedance probability of 94% within the scope of the 'Preliminary Plan for Maintaining the Drava River as a Waterway of International Importance from rkm 0 to rkm 22' (Hidroing, 2003).

For the Sava River, calculations for water levels at a discharge with an annual exceedance probability of 94% were made during the preparation of related designs. The results are owned by the competent river authorities (Hrvatske vode, Agency for Inland Waterways).

The data are not available to the public, but can be obtained on request.

SERBIA: The low-flow navigable water levels (LNWL) for the Serbian section of the Danube River are calculated using the methodology recommended by the Danube Commission (DC) (Recommendations concerning the Minimum Requirements for Standard Fairway Parameters, Hydrotechnical and Other Improvements to the Danube River, DC 2012). The LNWLs are calculated for all navigable stretches of the Danube, on the basis of a discharge with an annual exceedance probability of 94% recorded over a period of 30 years, on days without ice. The updating period is ten years.

In the past, the characteristic water levels were calculated for gauging stations where discharge measurements were made in the free-flowing river stretches (Bezdan and Bogojevo), and then interpolation was used, were it was possible.

The latest characteristic water level measurements were published in the document "Low-flow Navigable and Regulatory Water Levels, and High Navigable Water Levels at Important Gauging Stations in the Period 1981-2010, DC, 2015". The characteristic discharges were calculated using the existing DC methodology for the period 1981-2010, and those discharges were used as input data for a 1D hydraulic model of the free-flowing stretch of the Danube, from the HU-CRO-SRB border to Belgrade. Thus, the characteristic water levels have been defined for all profiles along which a hydrographic survey is to be performed. The data are not available to the public.

Publicly available data are the characteristic water levels measured in cross-sections at gauging stations, and published in the Navigational Bulletin of the Directorate for Inland Waterways (http://www.plovput.rs/navigational-bulletin).

For the Sava River, a different methodology is applied, owing to the unavailability of data on discharges. The calculations are made for water levels corresponding to a discharge with an annual exceedance probability of 94% over a period of 30 years, on days without ice, and then the data are interpolated between the gauging stations.

The characteristic water levels in cross-sections at gauging stations on the Sava River are available on the website of the Navigational Bulletin of the Directorate for Inland Waterways (http://www.plovput.rs/navigational-bulletin).

ROMANIA: The low-flow navigable water level for the Danube has been defined by the Danube Commission and the authority responsible for its maintenance in Romania is Administration of the Lower Danube in Galati. The minimum discharge, corresponding to the lowest navigable water level, is defined as a discharge (Q_{min}) with an annual exceedance probability of 94%. Its value is based on a statistical analysis of the long-term series of daily average discharges measured at gauging stations over a period of more than 40 years, excluding days with strong winter phenomena (ice floes, ice barriers). The minimum discharge for navigation is updated on an annual basis.

The low-flow navigable water levels provided for this project cover the three periods defined for the project (years 1941, 1971, 2010 - see Figure 3.22). The data are owned by the Administration of the Lower Danube in Galati and the National Administration "Apele Romane", and are available with their permission only.

The low-flow water levels in Romania were provided only for ten gauging stations on river km 795-103,8 but the water level does not correspond with riverbed morphology (longitudinal profile) - at many places only about 5 m water depth does not reflect reality.

The water level is therefore represented only by discrete point values (stations distant up to about 100 km) and the course of the low flow navigable water level (LNWL) along Romania is not depicted as a connected line in the graph (Figure 3.22).

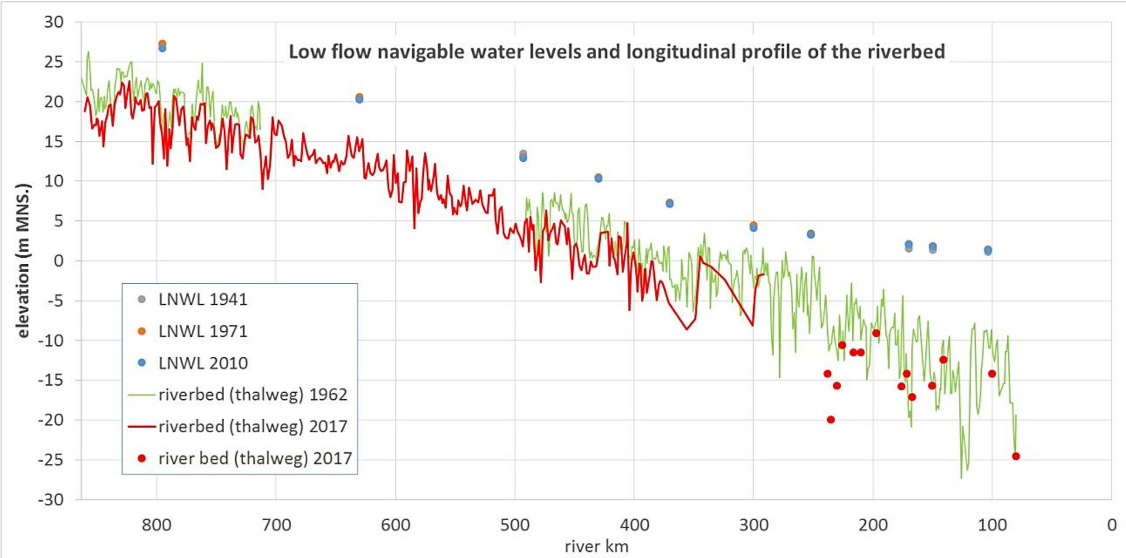

Figure 3.22: Low-flow navigable water levels along the Romanian Danube reach and comparison with riverbed development

BULGARIA: The values of low-flow navigable water levels (LNWL) for the Bulgarian section of the Danube are calculated using the methodology recommended by the Danube Commission (DC) ("Recommendations concerning the Minimum Requirements for Standard Fairway Parameters, Hydrotechnical and Other Improvements to the Danube River", DC 2012). They are calculated for the entire navigable river stretch at a discharge with an annual exceedance probability of 94%, for a period of 30 years, on days without ice. The updating period is 10 years.

Publicly available data are the characteristic water levels measured in cross-sections at the gauging stations, published in the Navigational Bulletin on the Agency's official website at http://appd-bg.org in the section Navigation and the related hydrological data and information published in the section Exploration.

The tributaries of the Bulgarian Danube are not navigable and therefore the low-flow water levels for shipping have not been investigated. The low flows in these tributaries are important only from the viewpoint of water consumption and ecology.

3.5 Hydromorphological reference conditions

Pristine reference conditions: pristine conditions represent a complete lack of human intervention and pressures. In European rivers, however, pristine conditions in the form of undisturbed hydrological and morphological processes and characteristics (water flow and sediment regimes, longitudinal and lateral connectivity, longitudinal profile and cross sections, geomorphological features and vegetation, and the character of the river channel, riverbed and river banks) are extremely rare. Since the flow of water and sediment transport in rivers are affected by human activities across all scales of spatial units, fully pristine conditions, if they occur, are likely to be confined to headwater streams (CEN, EN 14614:2018).

Therefore, **near-natural reference conditions** are used to determine to what extent the river channel has changed. Near-natural reference conditions are defined by the water flow and sediment regimes, longitudinal connectivity without major barriers or near-natural flow regulation measures within the upstream part of the river network, near-natural conditions and processes with a low level of human interference in the river stretches concerned, and by the relative freedom of the river channel and floodplain to adjust to the flow and sediment processes (final draft CEN, EN 14614:2018).

Historical maps have been collected by the project partners to document the reference conditions of the Danube River from the period before major human alterations were made, such as extensive flood protection measures (continuous flood dikes), mean water regulation (river channel rectification, closure of side channels) and low water level regulation (groyne fields). The georeferenced maps have been digitised and polygon features have been created for the river channel, side-arms and islands. The available historical maps cover the Danube River from Ulm in Germany (rkm 2,588) to the Danube Delta. For an analysis of the river channel's morphological development, historical maps from the end of 19th century/beginning of the 20th century were used (Table 3.9). For the German section of Danube, maps from the period around 1860 were used (Figure 3.24), but for certain river stretches, maps from 1806-1808 (Figure 3.23) had to be used, because the newer maps already showed signs of river regulation.

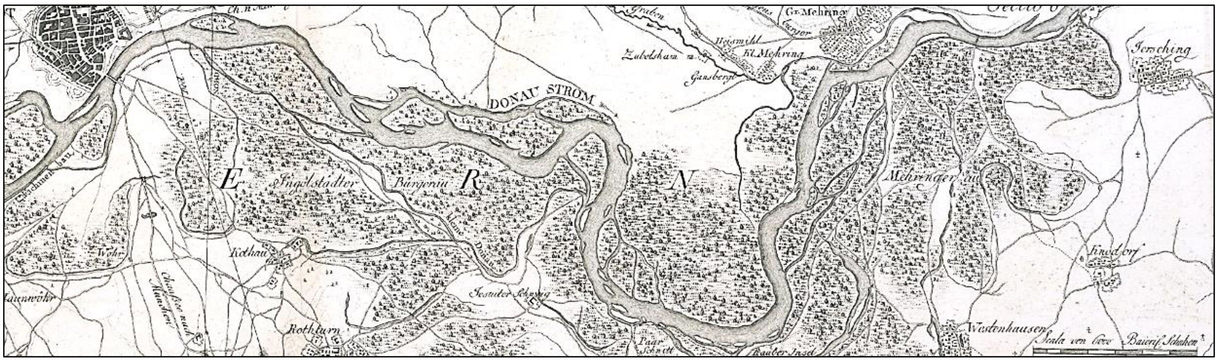

Figure 3.23: German historical map by Adrian von Riedl (1806-1808)

Figure 3.24: German historical map (from around 1860)

The section of the Danube in the former Austro-Hungarian Empire was covered by maps from the Third Military Survey (1869-1887). These maps were used for the Slovak, Hungarian, Croatian and Serbian sections (Figure 26). On the other hand, older maps from the Second Military Survey (1806-1818) had to be used for the Austrian section (example on Figure 3.25), because most of the river regulation measures already existed in the Third Military Survey maps, and thus the pristine conditions could not be assessed.

For the Romanian section of the Danube, maps of Planurile Directoare de Tragere (Drawing plans), were used (Figure 3.27). These maps were made on the basis of a topographic survey carried out at the beginning of 1910 by Romanian specialists at a scale of 1:20 000. As some shorter river stretches and the delta are not shown in these maps, maps from 1910 had to be combined with topographic maps from 1959.

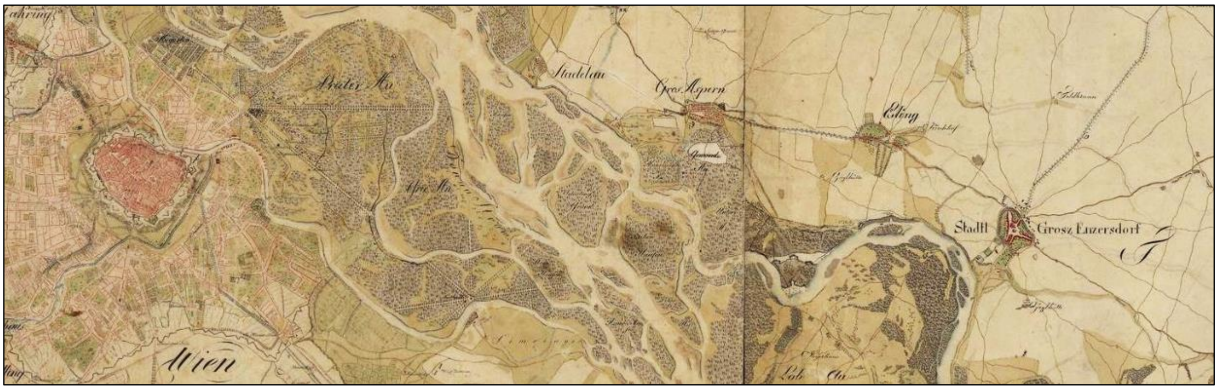

Figure 3.25: Second Military Survey /Franziszeische Landesaufnahme/ map of Austrian reach of the Danube (from 1809-1818)

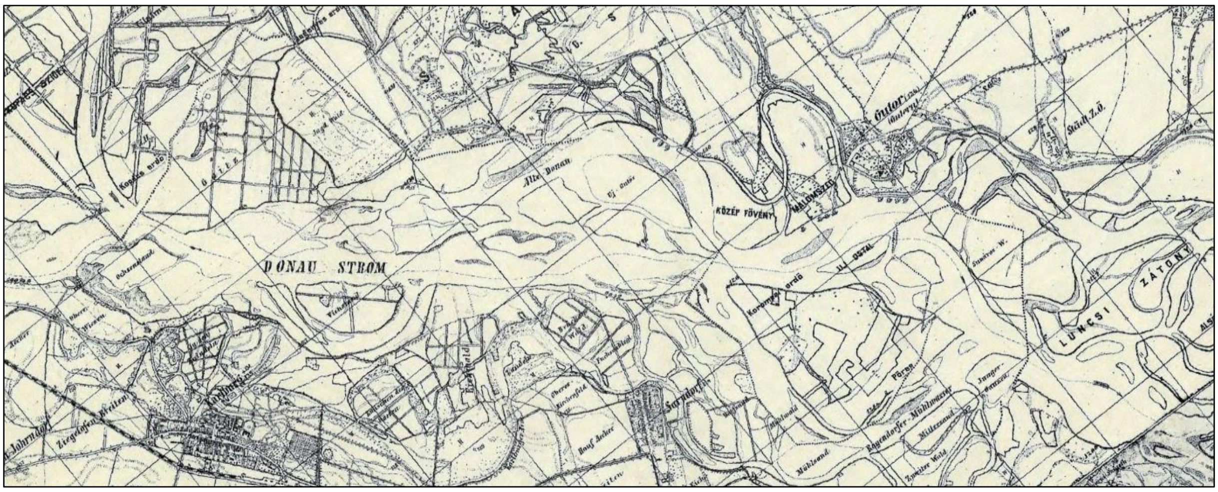

Figure 3.26: Third Military Survey map of the territory of present-day Slovakia, Hungary, Croatia and Serbia (1869–1887)

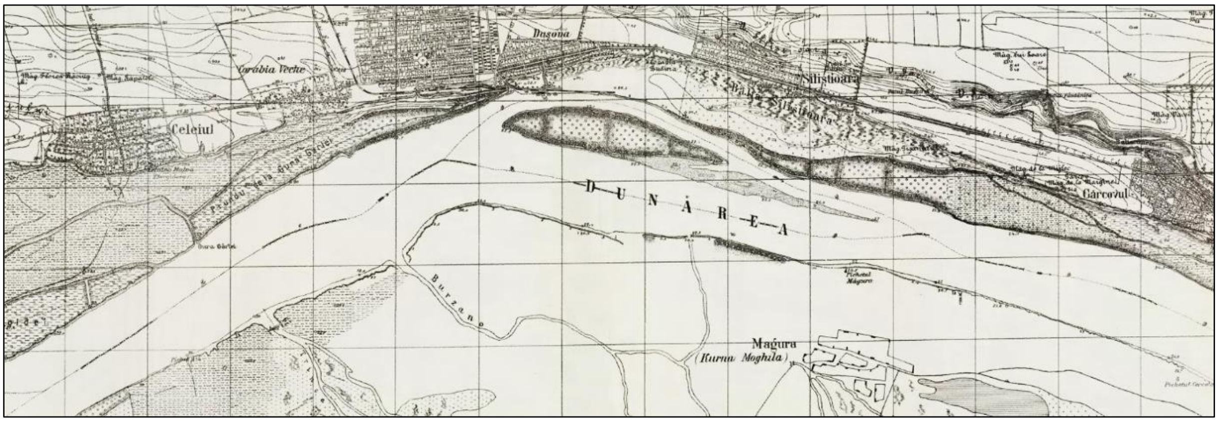

Figure 3.27: Romanian historical map of Planurile Directoare de Tragere (Drawing plans), showing the Danube in Romania and along the Romanian-Bulgarian border (from around 1910)

Table 3.9: Historical mapping of the Danube River Basin – data sources

Country	Map	Year of mapping	Scale	References
Germany	Adrian von Riedl	1806-1808	1:28.800	R. Finsterwalder in: 400 Jahre Mercator, 400 Jahre Atlas, 1995
Germany	Bayern Atlas	1860	1:25.000	https://geoportal.bayern.de/bayernatlas/?zoom=6&lang=de&topic=ba&bgLayer=historisch&E=700127.95&N=5425669.56&catalogNodes=11,122
Austria	Second Military Survey	1809-1818	1:28.800	Österreichisches Staatsarchiv (all rights reserved): 'Franziszeische Landesaufnahme'/ 'Zweite Landesaufnahme', purchased via https://mapire.eu/de/, usage of WMTS
Slovakia	Third Military Surve	1869-1887	1:25.000	Biszak, S., Timár, G., Molnár, G., Jankó, A. (2007). Third Military Survey, 1869-1887. Digitised maps of the Habsburg Empire, 1: 25,000. DVD-ROM, Arcanum Adatbázis Kft., Budapest
Hungary	Third Military Survey	1869-1887	1:25.000	Biszak, S., Timár, G., Molnár, G., Jankó, A. (2007). Third Military Survey 1869-1887. Digitised maps of the Habsburg Empire, 1: 25,000. DVD-ROM, Arcanum Adatbázis Kft., Budapest
Croatia	Third Military Survey	1869-1887	1:25.000	Biszak, S., Timár, G., Molnár, G., Jankó, A. (2007). Third Military Survey 1869-1887. Digitised maps of the Habsburg Empire, 1: 25,000. DVD-ROM, Arcanum Adatbázis Kft., Budapest
Serbia	Third Military Survey	1869-1887	1:25.000	Biszak, S., Timár, G., Molnár, G., Jankó, A. (2007). Third Military Survey 1869-1887. Digitised maps of the Habsburg Empire, 1 : 25,000. DVD-ROM, Arcanum Adatbázis Kft., Budapest
Romania	Drawing plans (Planurile Directoare de Tragere)	1910	1:20.000	www.geo-spatial.org http://www.geo-spatial.org/harti/ 7 sheets of a map in Lambert projection, 1:20 000, bought by the National Institute of Hydrology and Water Management at the Romanian Ministry of National Defence through Military Unit No. 02583 in Bucharest (Contract No. A-6894/10.11.2017).
Bulgaria	Drawing plans (Planurile Directoare de Tragere)	1910	1:20.000	www.geo-spatial.org http://www.geo-spatial.org/harti/ 7 sheets of a map in Lambert projection, 1:20 000, bought by the National Institute of Hydrology and Water Management at the Romanian Ministry of National Defence through Military Unit no. 02583 in Bucharest (Contract No. A-6894/10.11.2017).

3.6 Vertical reference systems

Within the scope of the DanubeSediment project, data were collected from the countries sharing the waters of the Danube River. These countries use different horizontal and vertical coordinate systems. For GIS data, the common ETRF89 coordinate system was used. A national *vertical* coordinate system is defined by a geodetic point network, vertical datum at sea tide gauges, kinds of heights and network levelling. Therefore, it was necessary to harmonise the national data, which are given in meters above sea level (e.g. elevation of the riverbed's deepest point for evaluating the longitudinal profile or the low-flow water levels). For this purpose, the European Vertical Reference Frame 2007 (EVRF2007) was used to harmonise the elevation data collected. The objectives of EVRF2007 were to fulfil the EU requirement for harmonised, seamless vertical data, and to prepare recommendations for the European Commission for the adoption of a common EVRF to be proposed in the INSPIRE Directive (Infrastructure for Spatial Information in Europe).

The datum of EVRF2007 is the Normaal Amsterdams Peil (NAP), which is formed by 13 datum points distributed over the stable part of Europe (Sacher et al., 2009). The results of adjustment are given in geopotential numbers and normal heights, which are reduced to the zero tidal system. Table 3.7 contains the vertical datums used in the DanubeSediment partner countries, kinds of heights, and the transformation parameters (in cm) used to transform national data into the EVRF2007 system, which was used to combine the data provided by the project partners into consistent datasets.

Table 3.10: Reference tide gauges in the DanubeSediment countries and the parameters used to transform the national heights to EVRF2007

Country	Vertical datum	Kind of height	Transformation parameter (cm)
Germany	Amsterdam	normal (Molodenski)	+1
Austria	Triest Adria (1875)	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, hence the average value for Croatia–Slovenia is used.

** Historical data in Romania referred to Sulina stage gauge (Black sea)

4 Data collection, sorting and basic analysis

Collected data were also provided by the project partners for quantification of the key sediment balance components (surpluses and deficits) for the Danube River and its main tributaries, and for clarification of the long-term morphological development of the Danube in relation to the sediment balance. These data also included the results of basic analyses carried out in respect of the national river stretches. The methodologies of data processing were presented, discussed and approved at the project meetings. The results were submitted to the work package leader in the required forms (templates – excel files, GIS layers) for more detailed analyses. The main groups of the additional data covered following areas:

- **Riverbed bathymetry** – assessment of riverbed changes through a comparison of cross-sections from several periods (raw data from cross-sections were not provided); typical cross-sections affected by erosion and/or sedimentation;
- **Longitudinal profiles** – profiles along the thalweg (the deepest points of cross sections) or the mean/average elevations of the riverbed;
- **Dredging, feeding, disposal** – spatial and temporal distribution of the amounts of riverbed sediments dredged (removed from the river channel), sediments refed into the river channel (in order to compensate for bedload deficits – downstream of hydropower dams), sediments disposed (sediments dredged from the riverbed and replaced within the river channel for the purpose of the river restoration, navigation, etc.);
- **Composition of riverbed sediments** – grain size distribution curves showing the composition of the bed material in the Danube and in its main tributaries;
- **Low-flow water level** – minimum water level for navigation, estimated on the basis of calculations (numerical modelling) and/or measurements;
- **Historical maps showing the reference conditions** (from the period before the river channel was regulated) **and the present state**.

Data were provided on the national stretches of the Danube for all three periods (I, II and III) considered in this project, depending on the data availability. Additional data were also provided for sediment balance assessment for the Danube's main channel and selected tributaries and for determining the spatial and temporal variations (long-term, mid-term, short-term) in the river channel's morphology in relation to modifications in the hydromorphological conditions (river regulation, dam construction, etc.) and in the sediment budget.

4.1 Morphological changes in the river channel – assessment methods

Changes in the river processes (sediment transport – erosion/sedimentation and flow dynamics) are the consequences of human interventions in the river system. The resulting changes in sediment transport and flow dynamics have induced morphological changes of the river channel (mainly in the riverbed in stretches where the river banks are fixed). For this reason, the quantification of morphological changes in the riverbed is of key importance in assessing the temporal and spatial changes in the sediment budget.

Riverbed changes in the Danube were assessed by the project partners (see Annex 3) on the basis of data from cross-sections analysed and compared for several time periods. The aim of this analysis was to locate the areas of erosion and/or sedimentation in the riverbed (bank erosion was not considered owing to the unavailability of sufficient data) along the entire length the Danube River, for the three periods considered in this project.

The riverbed changes can be evaluated by several methods:

- Low-flow water level changes – on the basis of long-term changes in the low-flow water levels (decrease: erosion (-), increase: sedimentation (+));
- Changes of the riverbed bathymetry – on the basis of changes in cross-sectional areas assessed for several different periods;
- Changes of the riverbed bathymetry – on the basis of high-resolution DTMs using GIS.

The method applied in this project is based on an analysis of **changes of the riverbed bathymetry.** This includes cross-sectional area calculations for two (or more) cross-sections measured in the same locality but in different periods. A cross-sectional area is delimited by the riverbed and the water level (i.e. low-flow water level or a predefined water level assuming that the left and right boundaries of the riverbed are fixed within the cross sections). The area of erosion (-) or sedimentation (+) is calculated as the product of the difference between two cross-sectional areas and the distance between the cross-sections (e.g. 100 m).

There are several approaches used to estimate the cross-sectional area. Three of them, specifically German (using a uniform reference elevation), Slovak (low-flow water level), and the Austrian approach are presented below.

a) An example of the German approach

Cross section measurements are usually performed every 200 m along the German section of the Danube. Only the points of a mobile riverbed are of interest for sediment balance assessment; they are used to calculate the mean bottom level. The width of a movable riverbed is defined by the left and right boundary points and is fixed for the entire analysis (Figure 4.1).

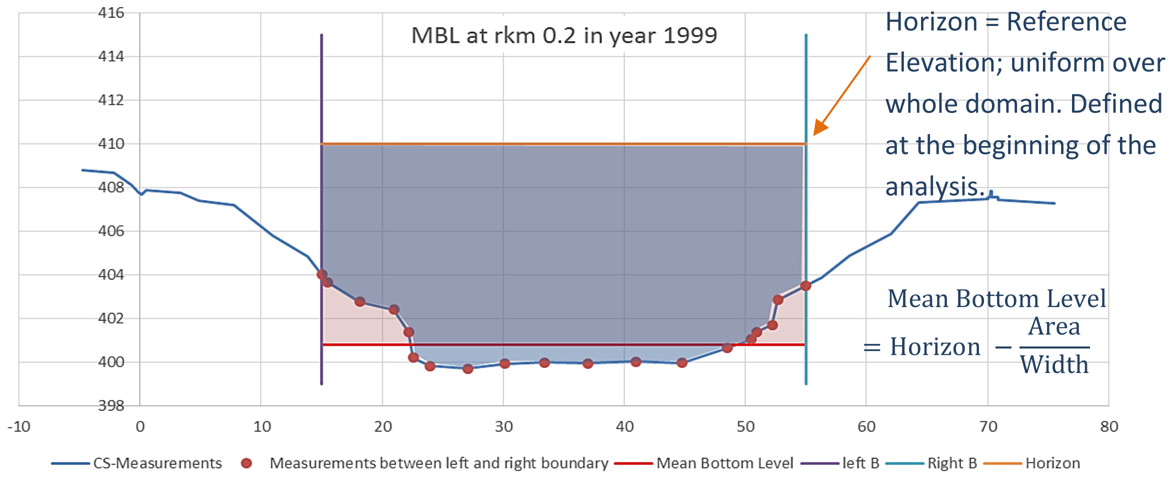

Figure 4.1: Scheme of cross-sectional area assessment based on a mean bottom level (TUM)

This approach is applicable where the river banks are fixed. For natural river banks, the method needs to be modified. The mean measurement points are calculated using an algorithm, which can easily be applied for assessing any future measurements. Erosion or sedimentation (±) in the given river stretch is calculated as the difference between cross-sectional areas from different periods (Figure 4.2), multiplied by the distance between the cross sections.

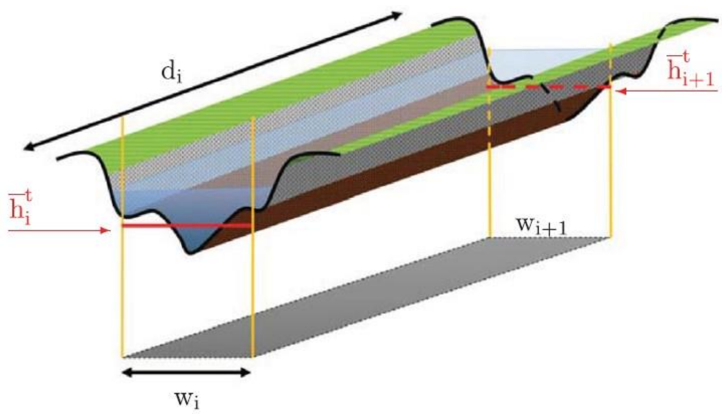

Figure 4.2: Evaluation of riverbed volume at a certain time *t* between the cross section *i* and the upstream located one *i+1* using the width *w* between the evaluation boundaries, the distance *d*, and the mean riverbed elevation *h* (Reisenbüchler et al., 2019)

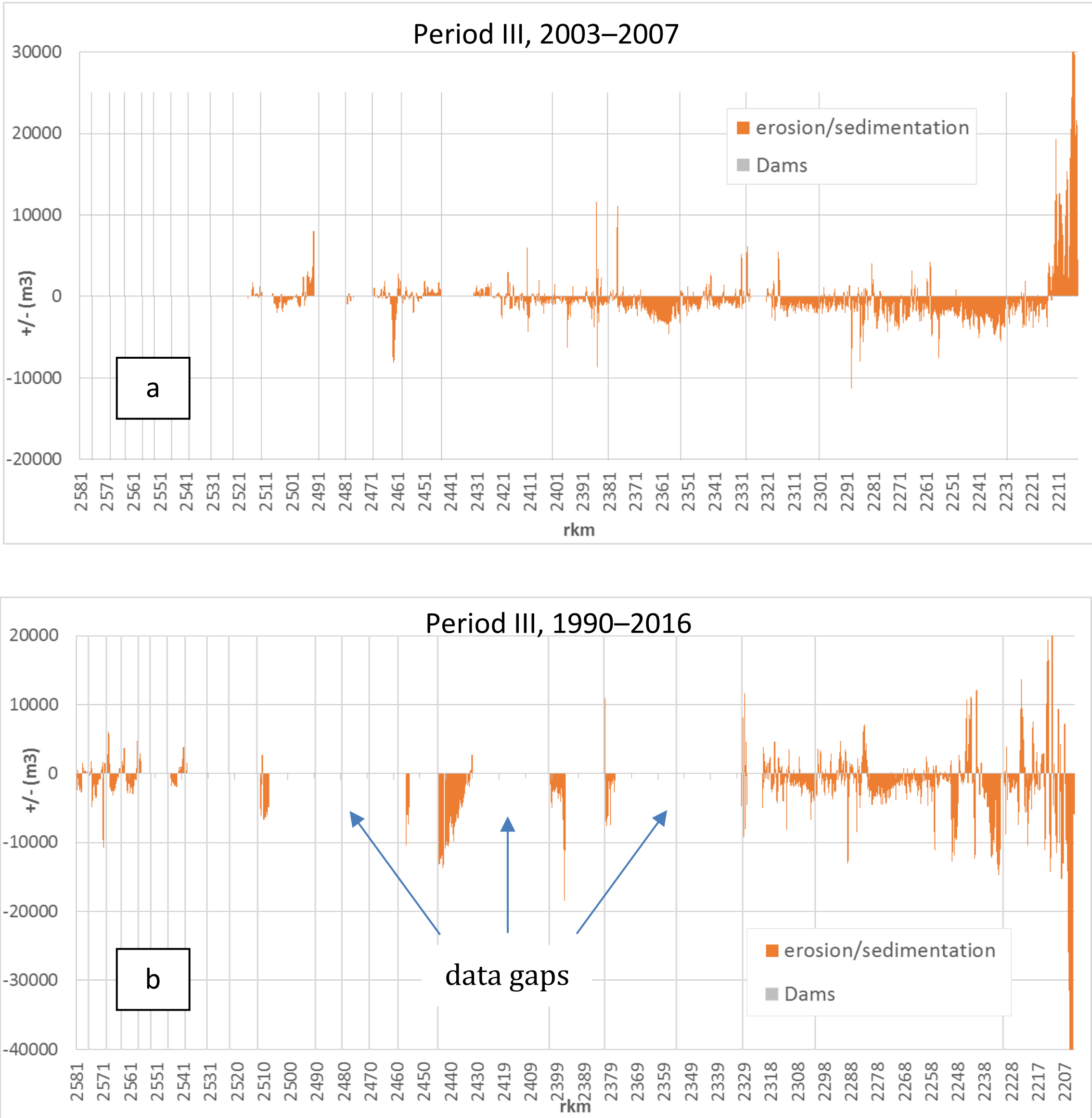

Figure 4.3: Preliminary assessment of the areas of erosion/sedimentation for shorter (a) and longer periods (b)

Figure 4.3 a, b shows results of preliminary assessment of the volumes of erosion and deposition for shorter and longer time period. Even though the German data are very detailed, the riverbed scanning was not performed over the whole reach in the same year. Therefore certain “data gaps” occurred, because two specific years are compared with this methodology, e.g. 1990 and 2016. This approach was used due to its simplicity for application to the entire reach. Despite its limitations, the overall processes of sedimentation and erosion over a period are represented.

b) An example of the Austrian approach

Cross-sections are measured at least every 100 m in geodetically fixed profiles, ensuring that the locations of the measured cross-sections are coherent. Except at the profile start and end points the measured points usually are deviating from the predefined profile with +/- 1m or smaller (Figure 4.4). Nonetheless the points are first projected onto the measurement profile, prior to the volume calculation.

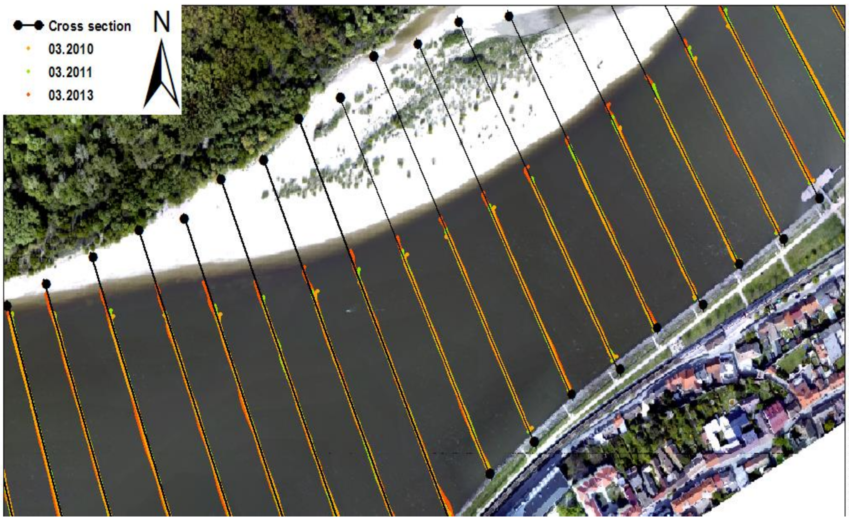

Figure 4.4: Example of measured cross-sections (orange, red and green dots) from the predefined cross-sections (black lines) (Data source: viadonau)

For the calculation of the cross sectional area (grey area in Figure 4.5) the width is delimited based on the common width (i.e. the smallest common multiple) for two or more measured years. The vertical extend is delimited by an arbitrary reference datum well above the measured cross sections. This reference datum is constant over the whole evaluated domain (e.g. the Danube River) like in the German approach.

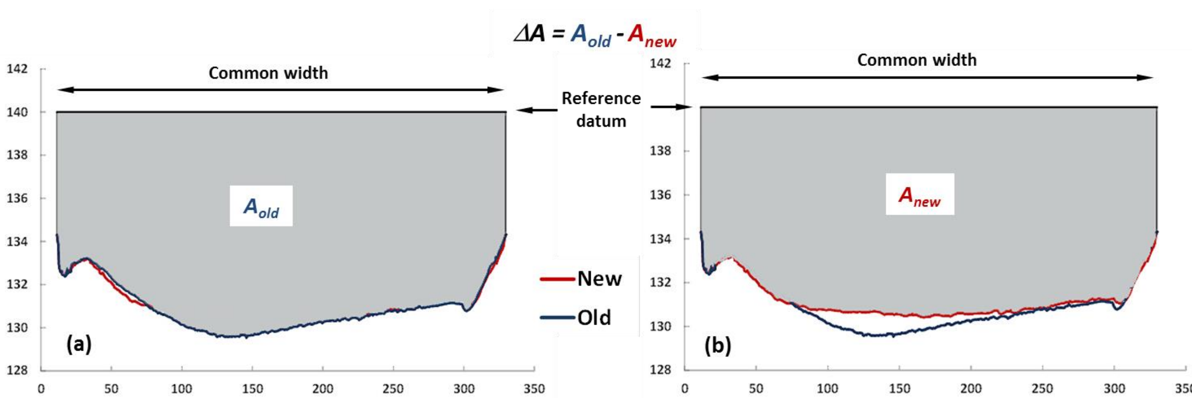

Figure 4.5: Calculation of the cross sectional areas for the old (picture a) and the new measurement (picture b) for one cross section.

The calculated areas A_{old} and A_{new} in Figure 4.3 b yield positive values therefore the difference area ΔA due to erosion or deposition is calculated as follows:

$$\Delta A = A_{old} - A_{new}$$

where a positive ΔA means deposition and a negative ΔA means erosion.

The volume change ΔV (erosion or deposition) between two profiles and years (Figure 4.6) is calculated as the product of the average areal change between two cross-sections and the distance between those two cross sections:

$$\Delta V = (\Delta A_i + \Delta A_{i+1})/2 * \Delta L$$

with ΔL denoting the distance between two cross sections. The resulting value of the area change ΔA_i and ΔA_{i+1} is either positive (sedimentation) or negative (erosion).

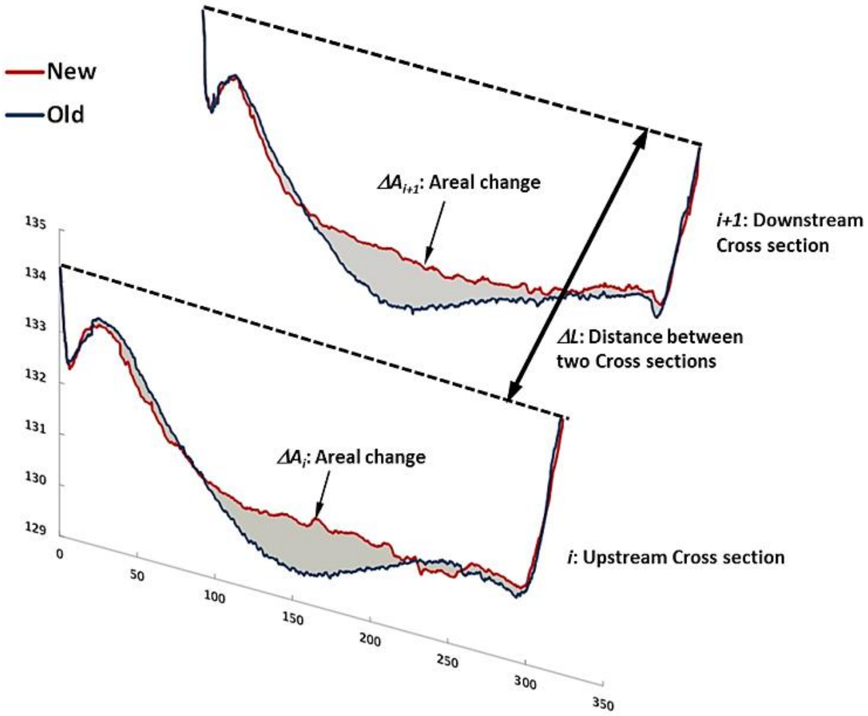

Figure 4.6: Calculation of the volume change ΔV between two profiles and years.

c) An example of the Slovak approach

Cross-sections are usually measured every 50 to 200 m. A comparison of cross-sections from different periods requires that the measured values are projected into the nearest straight line, because cross-sections are not always measured along the same and straight line (a scheme of this approach is shown in Figure 4.7).

The margins of a mobile riverbed are delimited within a cross section by the low-flow water level (minimum water level for navigation, corresponding to a discharge with an annual exceedance probability of 94%). The total cross-sectional area is calculated as the sum of the partial areas given by the individual points measured and the low-flow water level (Figure 4.8: A1, A2, etc.). The calculation is performed using a simple algorithm in Excel (an approach similar to the German method).

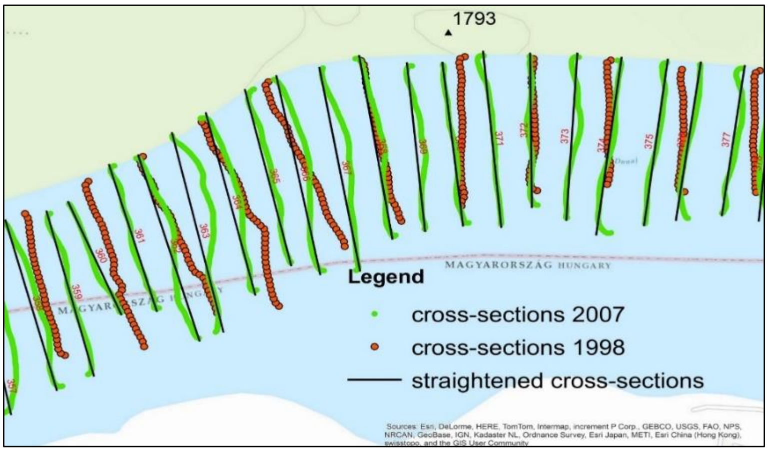

Figure 4.7: Examples of cross-sections straightened for the differences

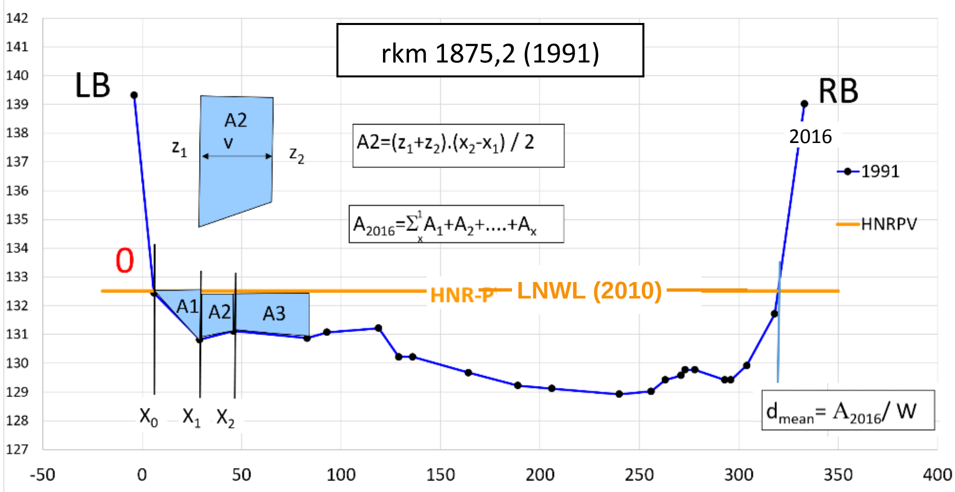

Figure 4.8: Calculation of the cross-sectional area between the riverbed and the low-flow water level (2016)

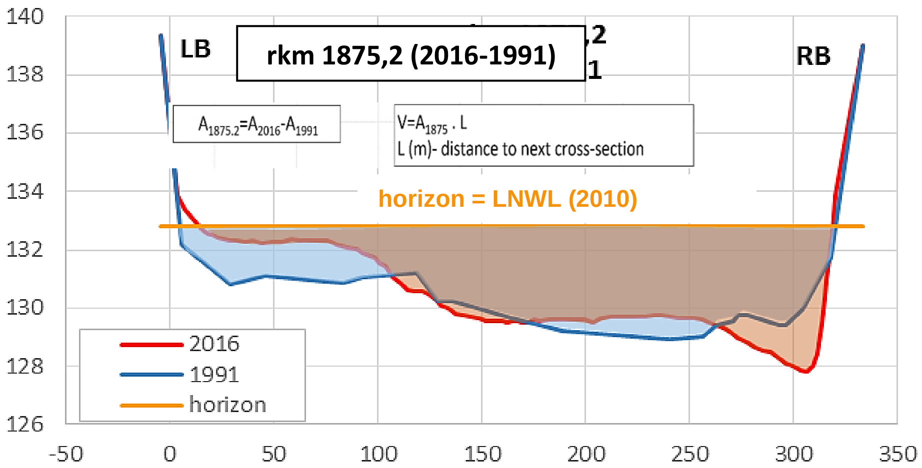

Figure 4.9: An example of cross-sections overlapping for the estimation of erosion/sedimentation

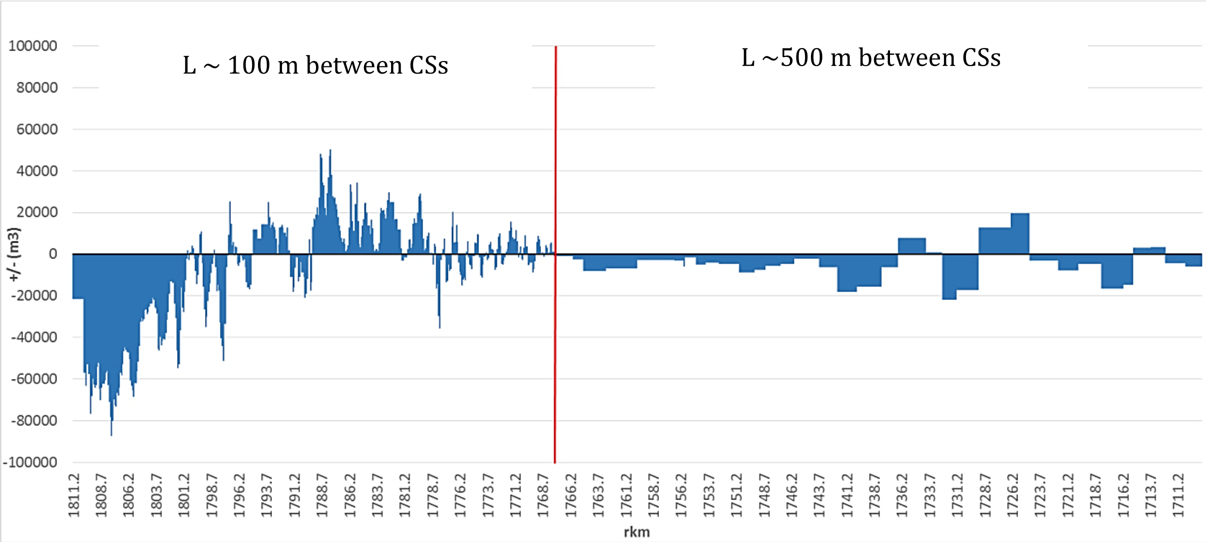

Figure 4.10: Riverbed changes (m^3) assessed in the Danube's SK-HU section (rkm 1,810–rkm 1,709) in Period III (1991/2016)

Erosion or sedimentation (±) volume (V) within a river stretch is calculated as a change in the areas of cross-sections (e.g. A_{2016} and A_{1991} from two or more different years) multiplied by the distances between the cross-sections (L): $\Delta V = (A_{2016} - A_{1991}) \times L)$ as shown on Figure 4.9. This approach was used by most of the project partners.

The values of riverbed changes (erosion/deposition) along the national and shared sections of the Danube (SK-AT, SK-HU) were calculated for partial river reaches and for three periods depending on the data available. The riverbed changes calculated for Period III (2016/1991) along the SK and SK-HU sections of the Danube are shown in Figure 4.10.

Summary 4.1: The collection and basic evaluation of bathymetric data were arranged by the project partners (using series of cross-section measurements from different years of Periods I, II and III). The initial analysis of the results showed big differences in the quality and quantity of data (data gaps), which resulted in high spatial and temporal inhomogeneity. While the assessment of areas exposed to erosion or sedimentation using bathymetric data are broadly comparable, the measurement methods are highly variable (e.g. technical aspects, including the equipment used, the frequency of cross-section measurements and the distances between the cross-sections – ranging from 50 to 2,000 m, or more in certain cases). This underlines the need for formulating common rules or recommendations for measuring the river channel's bathymetry and for assessing the morphological changes in the Upper, Middle and Lower Danube sections. The main aim is to provide higher-quality data and data compatible along the entire Danube River.

4.2 Longitudinal profile – long-term evolution of the riverbed

Longitudinal profiles of the riverbed represent another major source of information about the long-term morphological development of the river channel. The changes in the Danube's longitudinal profiles (aggradation/degradation) observed since the beginning of the last century reflect changes in the sediment transport and discharge conditions, caused by various pressures (flood protection, navigation, hydropower, etc.).

The analyses of changes in the river channel's bathymetry (erosion/deposition) and in longitudinal profiles (aggradation/degradation) are closely related, because they are based on the same data, i.e. cross-sections. Except for the general assessment of the river's longitudinal profile (aggradation/degradation), including changes in the riverbed slopes, the results of these analyses provide important additional information for identifying and explaining the spatial and temporal changes in the river channel's bathymetry (erosion/deposition), in particular in stretches with poor or no bathymetric data (lower Danube). Following figures (Figure 4.11., 4.12., 4.13., 4.14.) show examples of longitudinal profiles available in some of the Danube countries. More detailed analysis of longitudinal profiles is covered in Report on "*Long-term morphological development of the Danube River in relation to the sediment balance*".

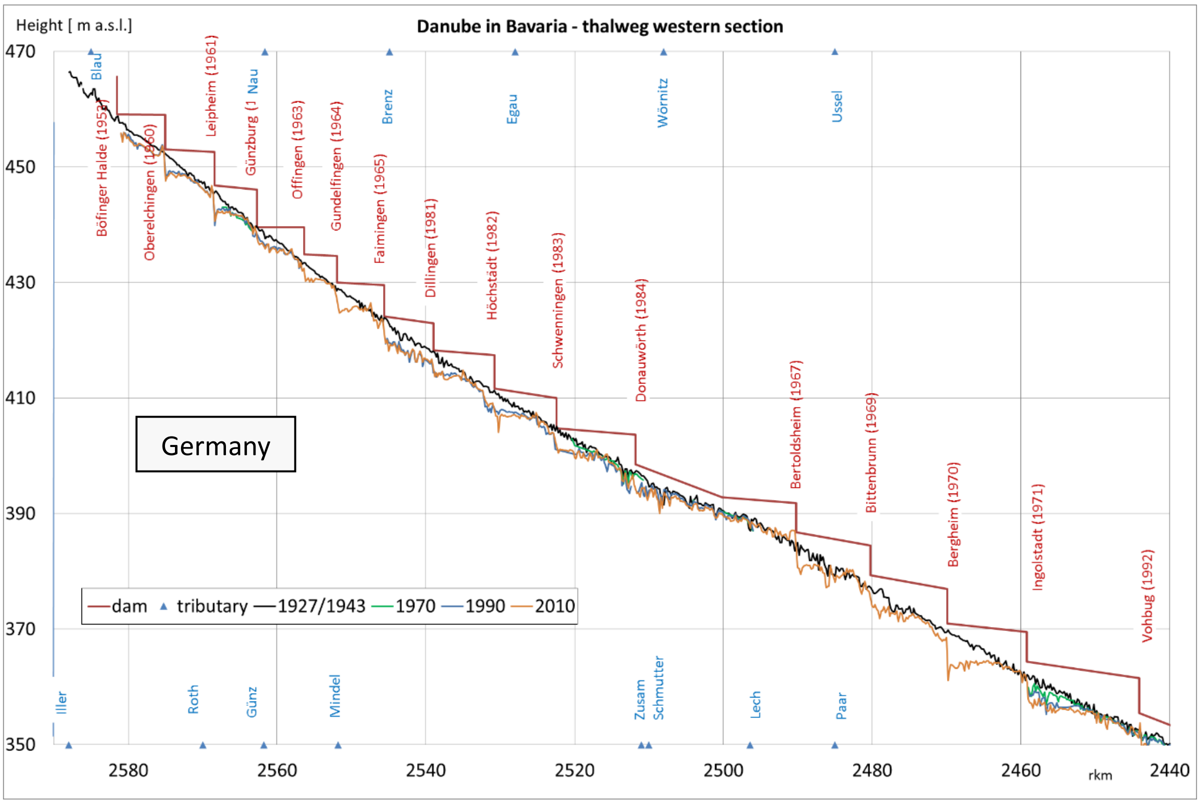

Figure 4.11: Longitudinal profile of the western German section of the Danube along the thalweg

Data of the longitudinal profiles of the Danube were collected for the thalweg (the deepest points of cross sections) and/or the mean depth (the mean levels of the riverbed in the cross sections) from three periods (I, II, III). The main objective was to compile a longitudinal profile for the entire length of the Danube River, on the basis of real data from three periods (for the first time ever). Since the Danube countries use different coordinate and vertical systems, the common coordinate system ETRF 1989 and EVRF 2007 were applied (for details see chapter 3.6).

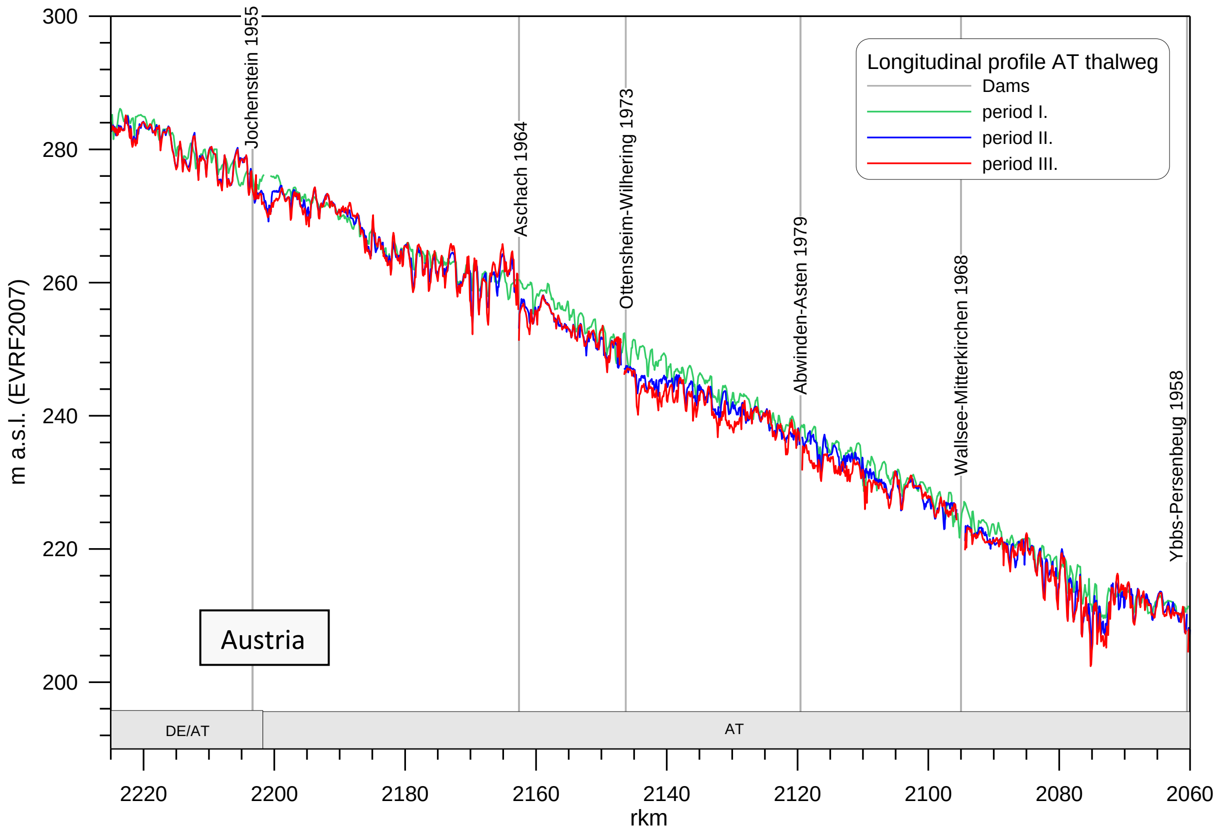

Figure 4.12: Longitudinal profile of the Danube's riverbed (thalweg) along western Austrian section (Periods I, II and III)

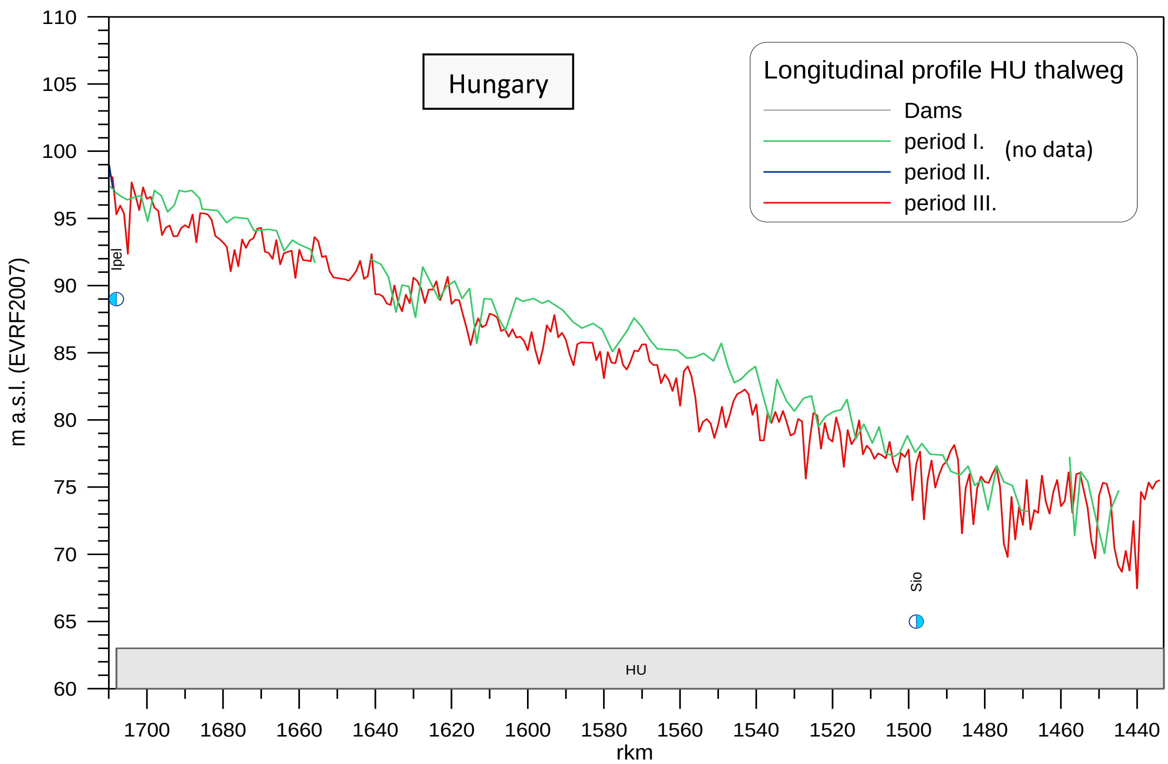

Figure 4.13: Longitudinal profile of the Danube's riverbed along Hungarian section

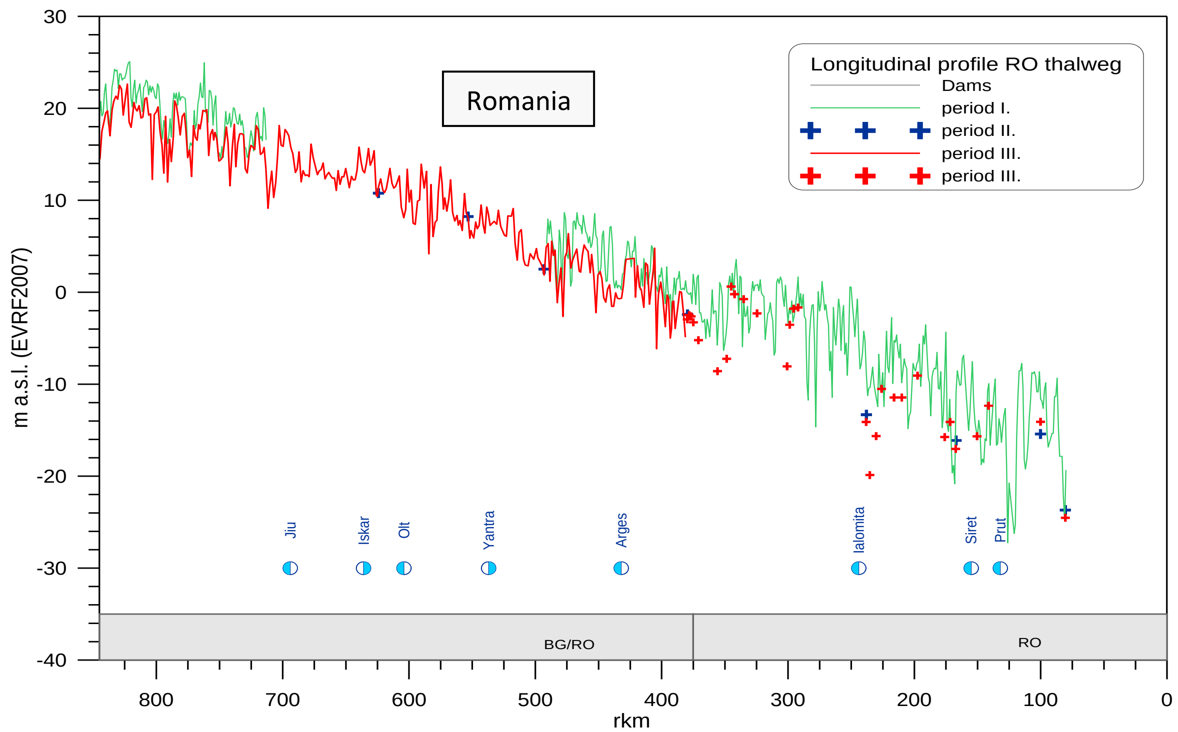

Figure 4.14: Longitudinal profile of the Danube‘s riverbed along Romanian/Bulgarian and Romanian section incl. scarce parts of the dataset interpreted by point values (local data only)

Depending on the data available, the longitudinal profiles of the Danube have been compiled for three periods along the national river sections, as well as for the Upper, Middle and Lower Danube sections. As in the previous case, the results of basic analyses show differences between the countries, mainly in the availability of data (data gaps). Nevertheless, the data collected have made it possible to compile a complete longitudinal profile for the present state (Period III), as well as for Period II with some smaller data gaps. The morphological development of the Danube channel over the three periods as illustrated in the river's longitudinal profiles has enabled us to understand and explain the erosion and sedimentation processes along the entire length of the Danube River in the long term (see report *"Long term-morphological development of the Danube in relation to the sediment balance"*).

4.3 Dredging, feeding and disposal

The amounts of sediments dredged from and fed into the river channel are one of the main components of a **sediment budget equation.** Therefore, the related spatial and temporal data are of great importance for sediment balance assessment (Activity 4.2), as well as for an analysis of the morphological changes in the riverbed (erosion/sedimentation). The terms used in the headline are defined as follows: ***dredging*** means the amount of sediments dredged from the riverbed and removed from the river channel *(sediment balance deficit)*; ***feeding*** means the amount of sediments (gravel/sand) artificially fed into the river channel to compensate for a bedload deficit caused by the trapping effect of dams or hydropower plants *(sediment balance surplus); and* ***disposal*** means the amount of sediments dredged from the riverbed and replaced within the relevant river stretch. As sediments disposed remain in the river channel, they affect the river channel's morphology and sediment balance only locally.

Sediment dredging along the Danube River has been performed mainly for water management (river training works, navigation and flood protection), construction of hydropower plants and/or commercial purposes (sale of gravel and sand for construction). Over-dredging for commercial purposes has often caused riverbed degradation leading to a fall in the surface and ground water levels in certain stretches of the Danube. Sediment feeding has been performed downstream of the hydropower plants in order to reduce the impact of riverbed degradation, only in several stretches of the Danube in Germany and Austria. Thus, one of the most important data is those on dredging.

Data collected on sediment dredging, feeding and disposal cover three periods and all the years from which data are available. The most complete data were collected for the third period (1991-2016). Some of the partner countries provided fairly detailed data on dredging (Germany, Austria, Slovakia, Hungary), including the annual volume, locality and purpose of dredging with smaller or no data gaps. By contrast, some countries provided only the total volume of sediments dredged in longer river stretches in selected years (RO). Other countries provided somewhat incomplete data for periods in which certain years are not covered (HU – limited data) or where a whole period is missing (RS – Period II is covered, but the data for Period III are missing in national databases and were estimated by Serbian experts within the project).

Examples of evaluated dredging data recorded in the German, Austrian, Serbian, Romanian, Romanian-Bulgarian Danube sections in Periods I, II and III are shown in Figures 4.15, 4.16, 4.17 and 4.18. For the purpose of comparable graphical interpretation and as an input to sediment balance, the collected dredging data were evenly distributed along the section where the dredging was recorded and its summed up volume was attributed to every river kilometre. Feeding/disposal data are not depicted in graphs as it is performed only in a few localities along the Danube in small amounts.

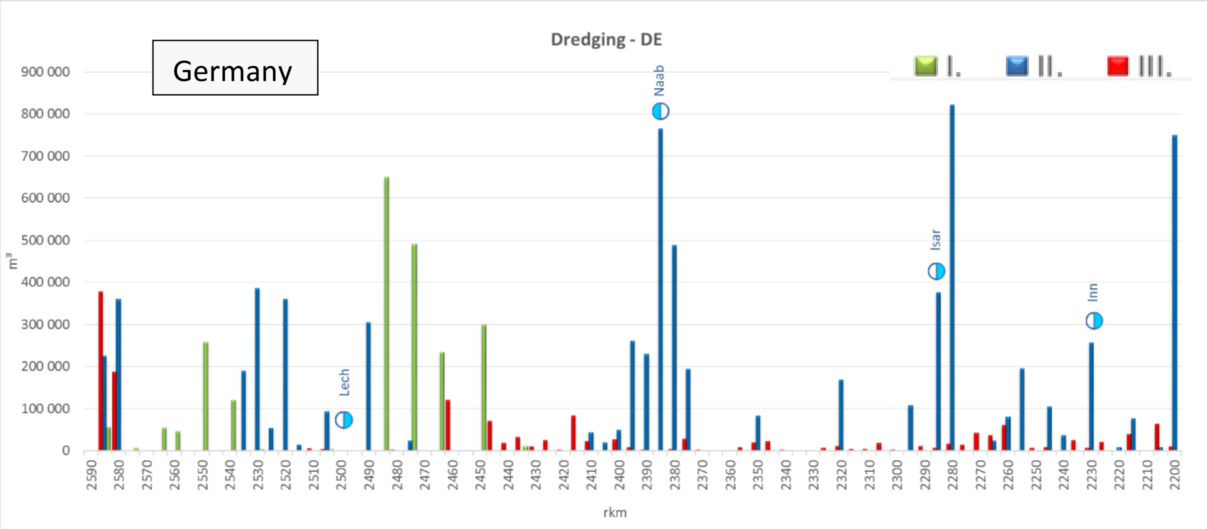

Figure 4.15: Volumes of riverbed sediments dredged along the German section of the Danube in Period I., II. and III.

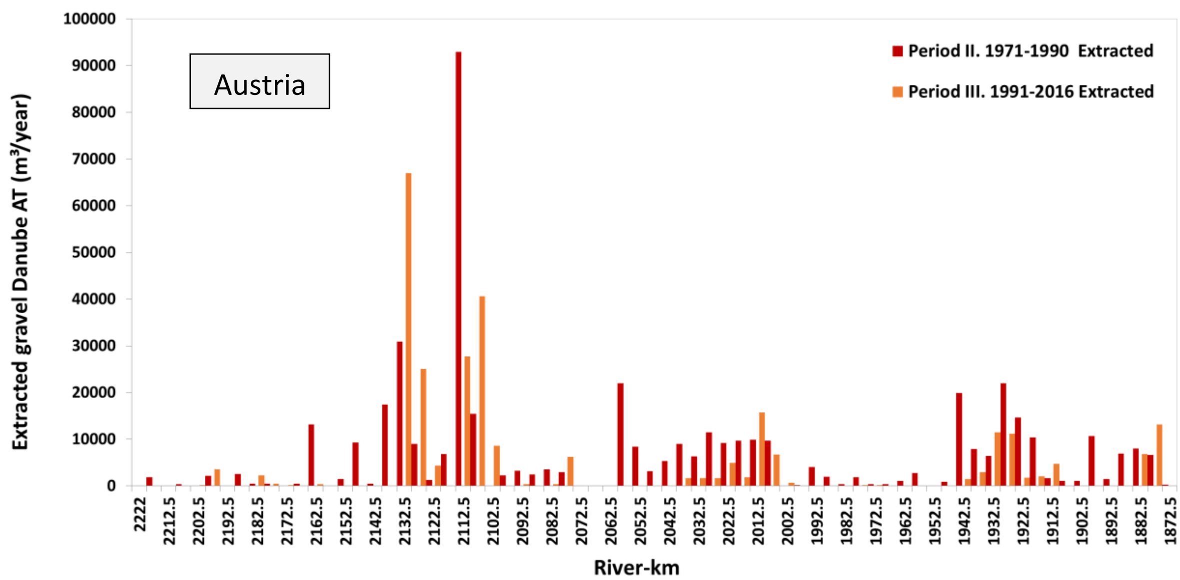

Figure 4.16: Volumes of riverbed sediments dredged along the Austrian Danube. Note that in the Austrian Danube the dredging for flood protection near Krems (rkm 2003 - 1999) is not included as it is fed back downstream of the HPP Freudenau between rkm 1921 and 1910. Also not included are dredging works for the HPP constructions.

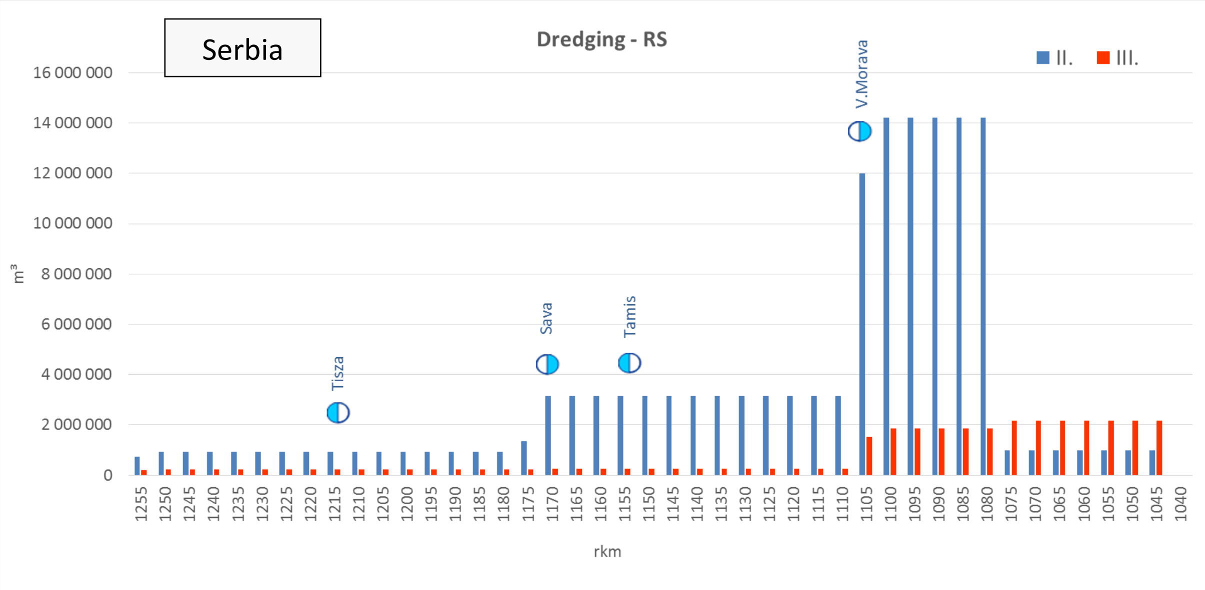

Figure 4.17: Volumes of riverbed sediments dredged along along the Serbian Danube within the Period II and Period III. based on expert estimation

Besides national data sources, the project partners also used data obtained from the Danube Commission as an additional data source (Austria, Romania, Hungary). Data on dredging volumes were analysed for the national river sections, as well as for the Upper, Middle and Lower Danube sections in the context of morphological changes in the riverbed (Activity 4.3). The results of these analyses are of high importance for the sediment balance (Activity 4.2).

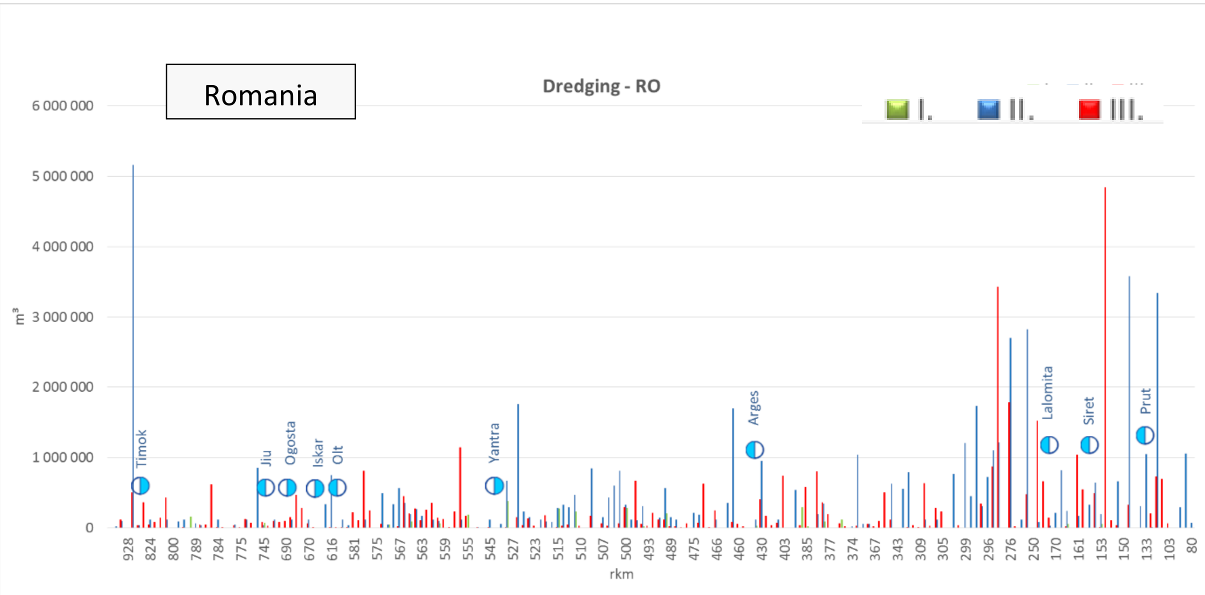

Figure 4.18: Volumes of riverbed sediments dredged along the Romanian and Romanian – Bulgarian Danube within the three periods based on Romanian data obtained from Danube Commission records

4.4 Riverbed sediments – sediment size variations

The composition of riverbed sediments is one of the key morphological characteristics of the Danube channel. Changes in riverbed sediments reflect the changes in the physical processes caused by human pressures, especially by the construction of dams and hydropower plants (higher content of fine sediments in impoundments, clogging, armouring downstream of dams and hydropower plants, etc.).

The data collected by the project partners covered the Danube and its selected tributaries, and provided information on the D_{50} grains (the median particle size in a distribution curve).

Figure 4.19: Riverbed sediment samples taken from the Danube between rkm 1,740 and rkm 1,700

Where grain size distribution curves were available, further characteristics were also evaluated (i.e. D_{16}, D_{53}, D_{65}, D_{84} and D_{90}). All these values were estimated mostly from surface layer samples of bed sediments taken from the middle part of the river channel (Figure 4.19, 4.20, 4.21). Except for data collected by the project partners, data from JDS3 were also used (grain size distribution curves derived from bed sediment samples taken and analysed by the Water Research Institute, SK, Figure 4.22, 4.23).

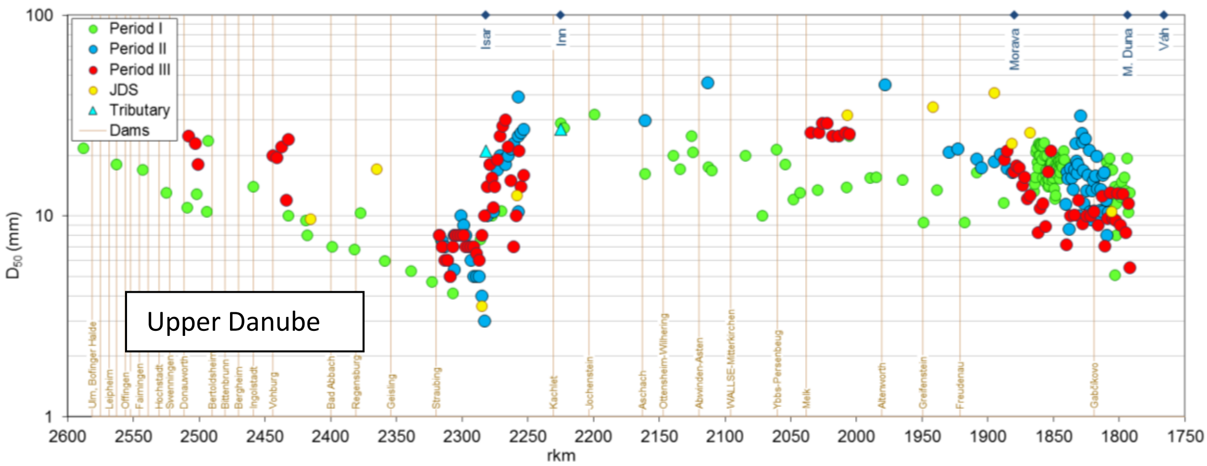

Figure 4.20: Grain size of bed sediments in the Upper Danube and its tributaries, represented by the value of D_{50} for Period I., II. and III.

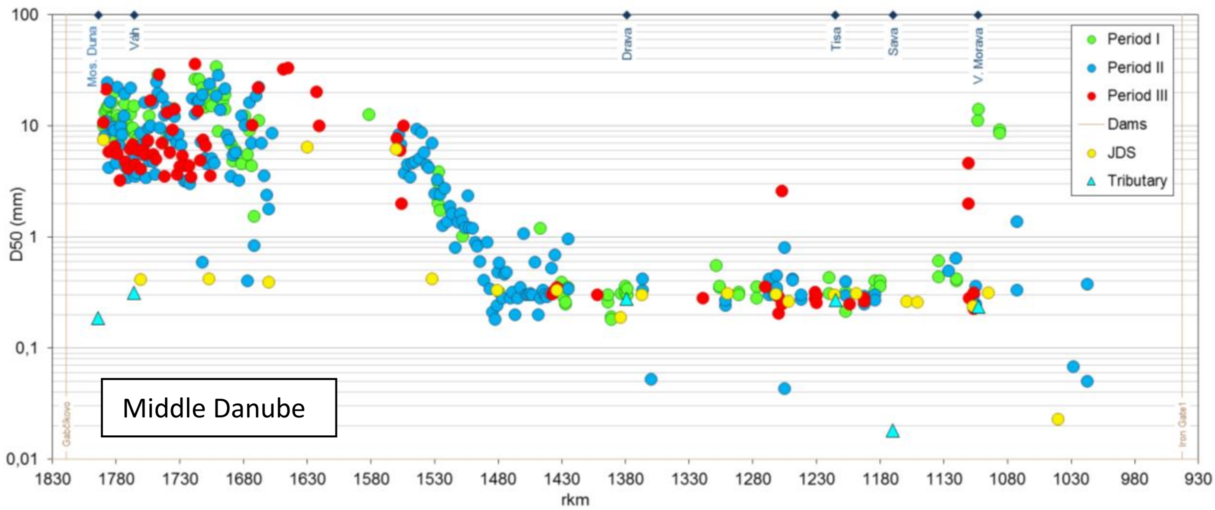

Figure 4.21: Grain size of bed sediments in the Middle Danube and its tributaries, represented by the value of D_{50} for Period I., II. and III.

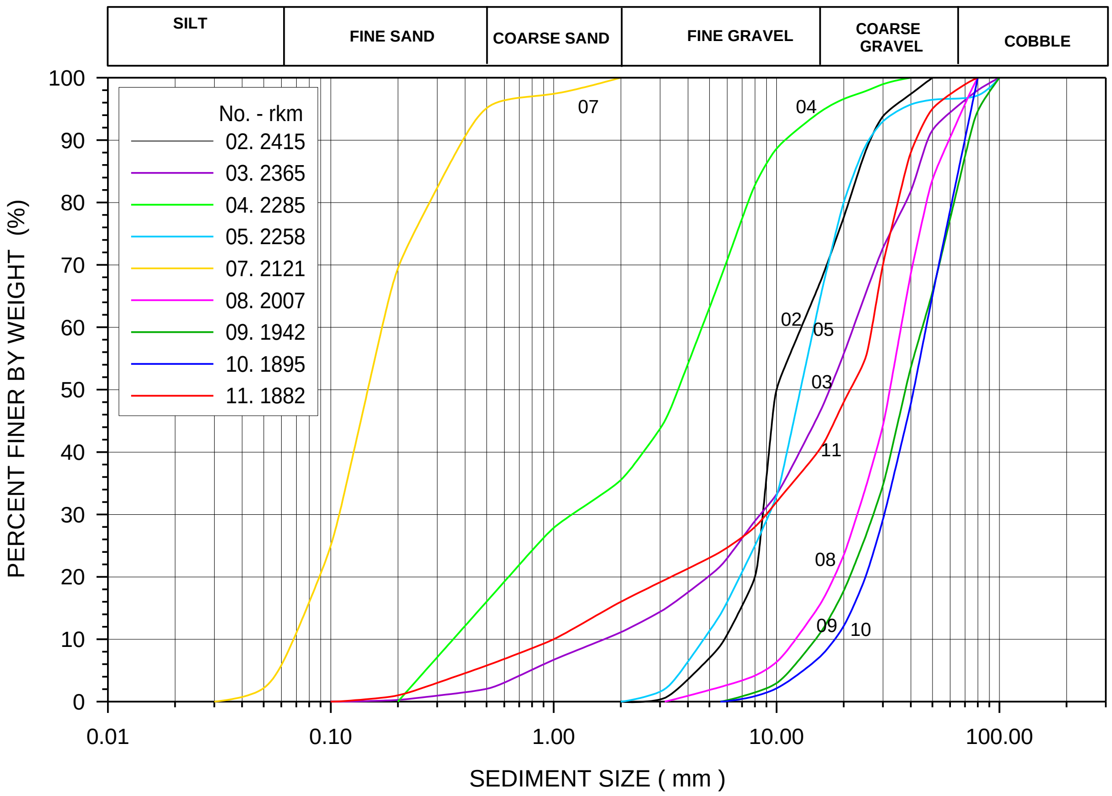

Figure 4.22: Grain size distribution curves for the Upper Danube (JDS3)

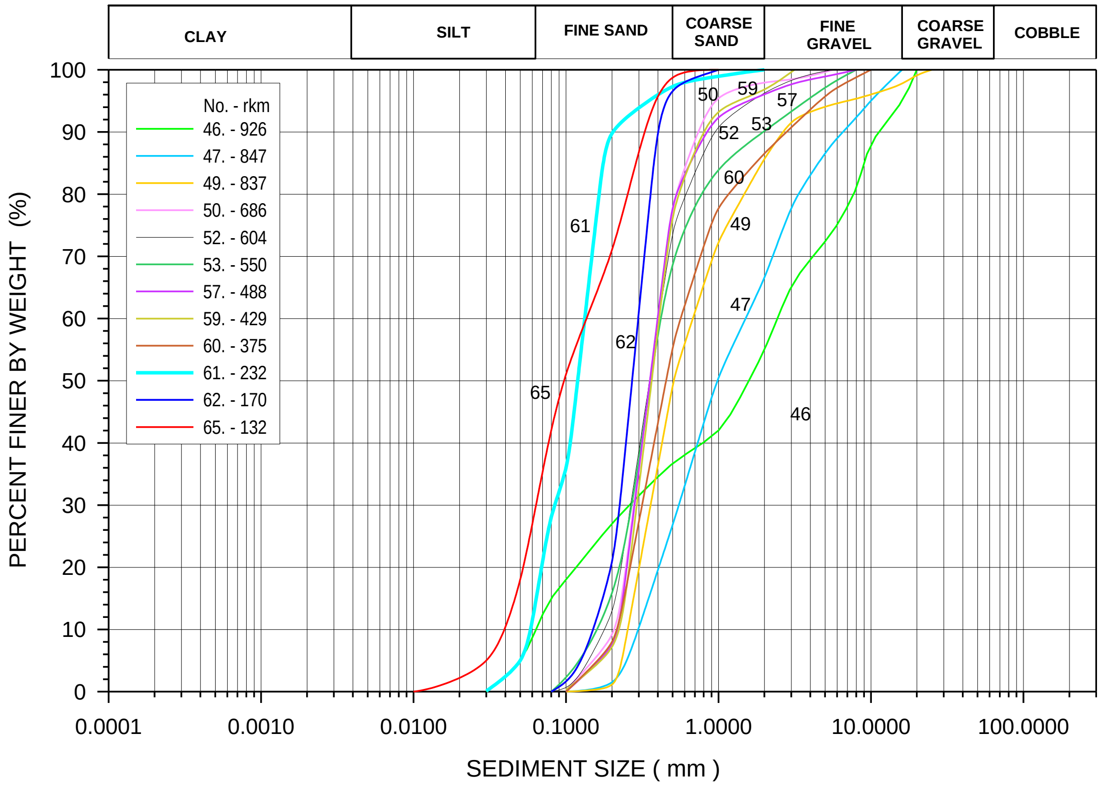

Figure 4.23: Grain size distribution curves of the bed material in the Lower Danube (JDS3)

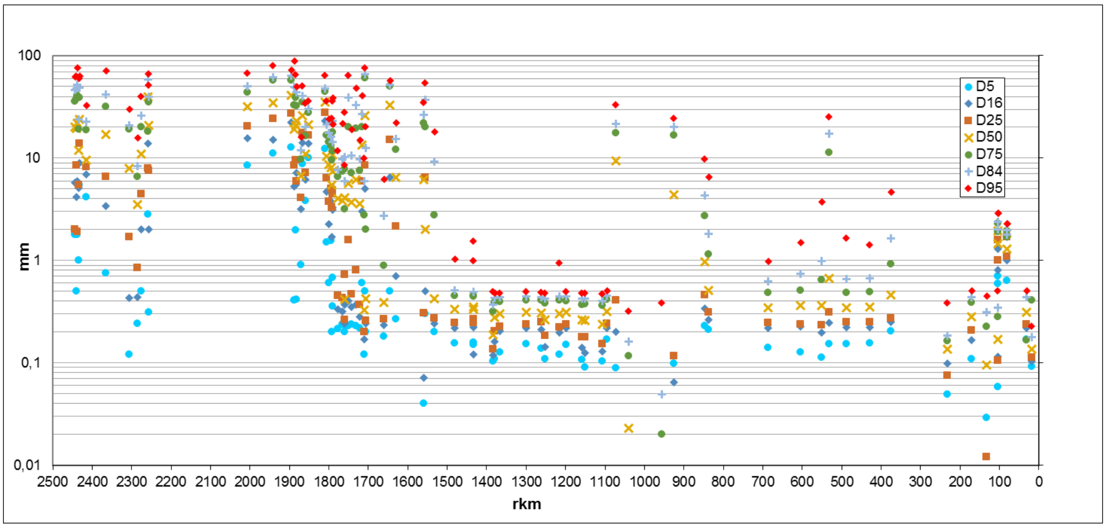

Figure 4.24: Characteristic grain sizes (D_{16}, D_{35}, D_{50}, D_{65}, D_{84}, D_{90}) of the bed sediments along the Danube (Period III.)

The composition of the Danube riverbed varies from coarse gravel to fine sand and silt, and in the tributaries, from coarse gravel to fine gravel and sand.

Data on the bed material grain size were collected to identify the changes that occurred in the composition of the riverbed material during the periods under review. The characteristic grain sizes were estimated from the relevant grain size distribution curves (Figure 4.22, 4.23, 4.24) and evaluated in the context of the Danube channel’s morphological development. These data were used in statistical analyses to evaluate the short-term and long-term changes in the composition of bed sediments (Activity 4.3).

4.5 Low navigable water levels

The low-flow navigable water level (LNWL), defined as the minimum water level for navigation (at a discharge with an exceedance probability of 94%/30 years), is required by the Danube Commission to be determined for the international Danube waterway (except for impounded river stretches where the water level is regulated by dams, e.g. the chains of hydropower dams in Germany and Austria; the Gabčíkovo HPP in Slovakia, and the Iron Gates in Serbia/Romania). LNWLs were calculated using numerical modelling for the Danube’s national sections (Austria, Slovakia, Hungary) or for selected cross sections, i.e. at the gauging stations (Serbia, Romania). The calculation of LNWLs is recommended to be repeated at regular intervals (5 years) and/or after higher floods.

Since the LNWL well reflects the morphological changes occurring in the riverbed along the free-flowing sections of the Danube, national data on LNWLs can be used as an indicator of the long-term morphological development of the Danube channel (Figure 4.25 shows an example from the Slovak-Hungarian Danube section). Thus, LNWLs provide important additional information for the identification of river stretches with significant riverbed degradation (Figure 4.26).

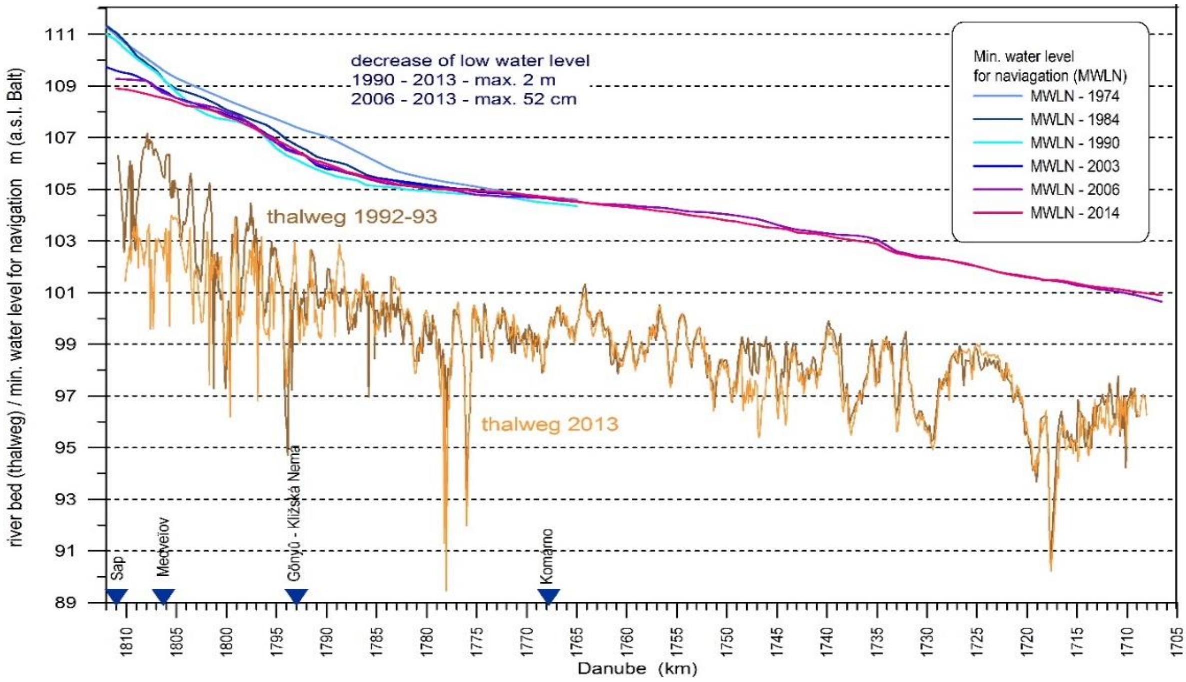

Figure 4.25: Long-term changes in the LNWL along the Slovak-Hungarian Danube section (period 1957-2014)

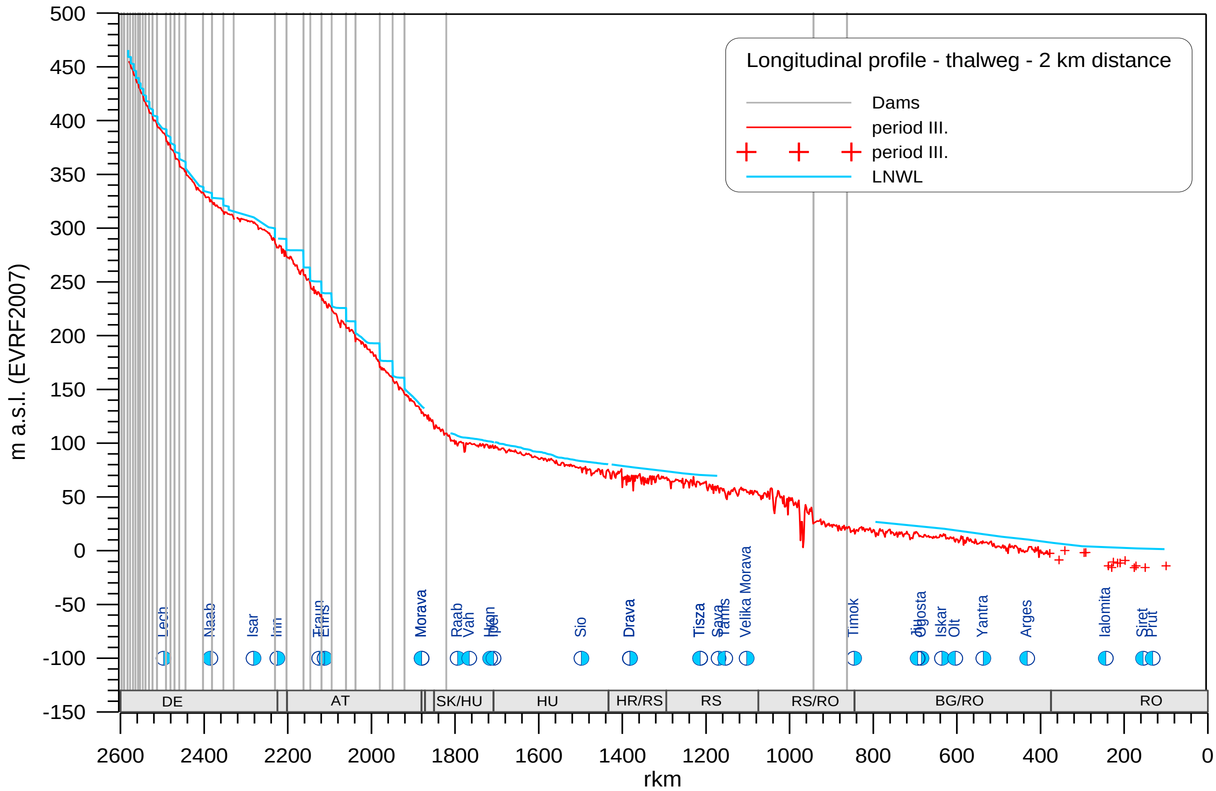

Figure 4.26: Actual low-flow navigable water levels along the Danube River (light blue) and the riverbed (red)

4.6 Historical maps showing the reference conditions

The project partners have developed GIS layers for the Danube channel pattern to illustrate its present state, as well as the reference conditions (historical maps with details are summarised in Table 3.9). Inputs from the project partners were merged into single shapefiles for the whole Danube River solving overlaps in the border sections. Examples of historical and present maps of the Danube channel are shown in Figures 4.27, 4.28, 4.29 and 4.30.

The GIS layers were used to identify the morphological type of the river channel (past & present) and the long-term morphological changes of the Danube river by comparing the key morphological characteristics of the river channel (width, length, sinuosity index – straightening, meandering, anabranching). The results are presented in the report *"Long-term morphological development of the Danube River in relation to the sediment balance"*.

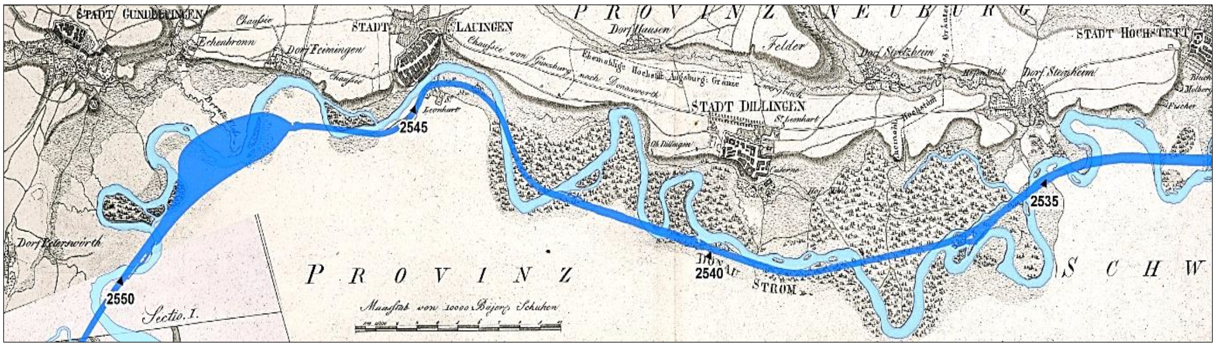

Figure 4.27: GIS layers showing the present (dark blue) and reference state (light blue) of the German Danube in the background of a historical map

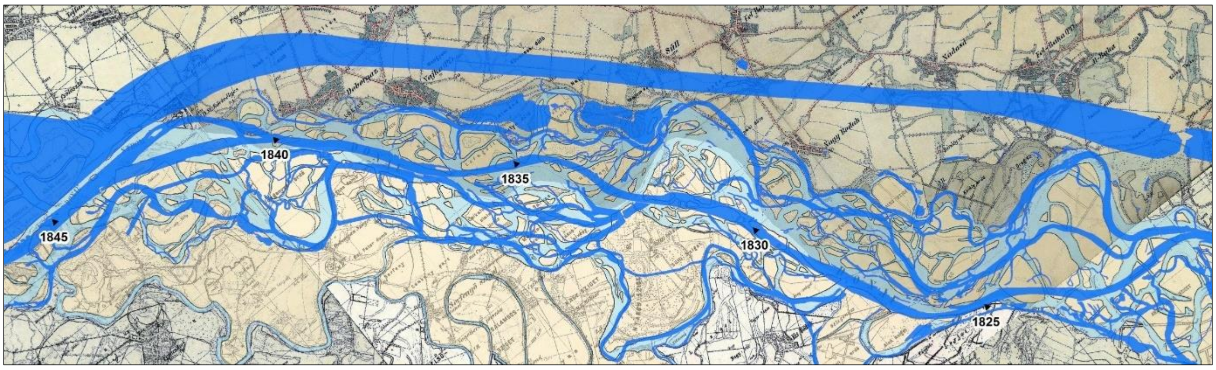

Figure 4.28: GIS layers showing the present (dark blue) and reference state (light blue) of the Slovak-Hungarian Danube in the background of a historical map

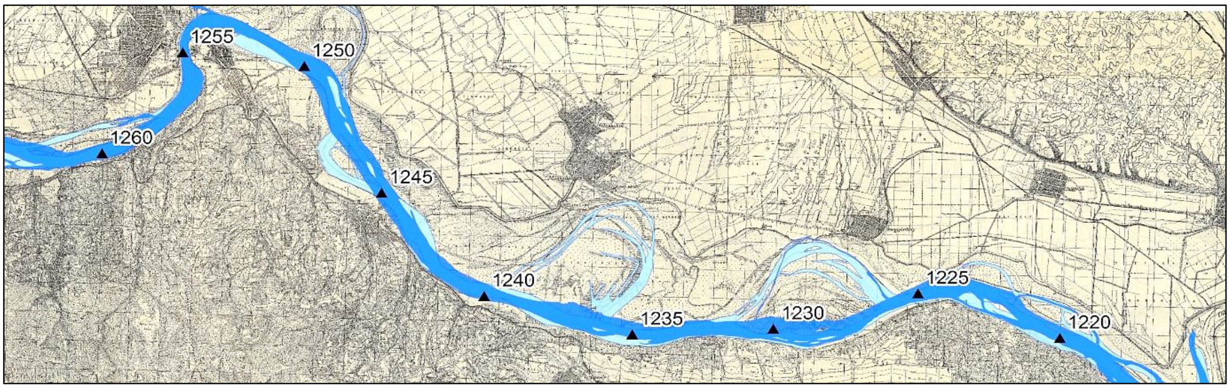

Figure 4.29: GIS layers showing the present (dark blue) and reference state (light blue) of the Serbian Danube in the background of a historical map

Figure 4.30: GIS layers showing the present (dark blue) and reference state (light blue) of the Romanian-Bulgarian Danube in the background of a historical map

5 Conclusions and recommendations

The morphological data collected showed big differences in both quality and quantity and revealed several data gaps. The first basic analysis indicated high spatial and temporal inhomogeneity between countries and consequently also between the Upper, Middle and Lower Danube sections. The lack of data in the past can be attributed to technical limitations i.e. traditional measuring tools and techniques, data processing methods and storage devices, etc. However, the relatively big data gaps seen in the categories under investigation (riverbed bathymetry; longitudinal profiles; dredging, feeding, disposal; composition of riverbed sediments, low-flow water levels; historical maps) have persisted up to the present time. The current situation is due to a combination of the following factors:

- persisting technical limitations (traditional measuring devices);
- methodological limitations in all categories under review (methods of measurement, data acquisition, processing and evaluation);
- different traditions and experiences in field surveying, morphological monitoring, and in assessing the hydromorphological status and the degree of its modification (lack of knowledge and practice);
- different national rules used in relation to morphological monitoring and to its financing;
- shared responsibility for data collection and storage i.e. there are often several data owners at national levels, including private companies.

An improvement in the current situation can be achieved through the formulation and practical application of methodological principles (manuals) and recommendations for morphological monitoring in the future (field measurements, data collection and processing). A manual of the morphological monitoring based on data collection in this report, more detailed analysis and available scientific knowledge are available in the report *"Long term-morphological development of the Danube in relation to the sediment balance"*.

The harmonisation of monitoring methods by the responsible water management authorities can improve regular morphological monitoring along the Danube River at national levels, particularly in the context of the Water Framework Directive. Morphological monitoring prepared on the basis of common rules is expected to improve the acquisition and provision of fully compatible data of higher quality along the whole Danube River. This will enable a more detailed evaluation of the morphological development of the river and will contribute to a more comprehensive sediment balance assessment in the future.

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)
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)
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)

References

Babic Mladenovic M. (2007). Režim nanosa Dunav/Sediment Regime of the Danube River, Monograph, Zadužbina Andrejević – Posebna izdanja, ISSN 1450-801X, ISBN 978-86-7244-631-9

Babic Mladenovic M., Kolarov V., Damjanovic V. (2013). Sediment regime of the Danube River in Serbia, International Journal of Sediment Research, ISSN 1001-6279, Vol. 28, No. 4, pp. 470-485, 2013.

Bayern Atlas (1860). https://geoportal.bayern.de/bayernatlas/?zoom=6&lang=de&topic=ba&bgLayer=historisch&E=700127.95&N=5425669.56&catalogNodes=11,122

Biszak, S., Timár, G., Molnár, G., Jankó, A. (2007). The Third Military Survey 1869-1887 Digitized maps of the Habsburg Empire, 1: 75 000. Tretie vojenské mapovanie na DVD-ROM, Arcanum Adatbázis Kft., Budapešť.

BMLFUW (2015). TASK FORCE DONAU: FEINSEDIMENTMANAGEMENT AN DER ÖSTERREICHISCHEN DONAU ENDBERICHT. Beilage 28: Sohlgrundaufnahmen Donau und daraus abgeleitete Maßnahmen/ Notwendigkeit ergänzender Messungen oder anderer Erhebungen (Wasserspiegelfixierungen) zum Erkennen von Sohländerungen (Abt. IV/5 - BMLFUW). BUNDESMINISTERIUM FÜR LAND- UND FORSTWIRTSCHAFT, UMWELT UND WASSERWIRTSCHAFT, Sektion IV – Wasserwirtschaft. Wien.

BMNT (2018). SOHLENTWICKLUNG IN DER FREIEN FLIESSSTRECKE UNTERSTROM KRAFTWERK FREUDENAU ENDBERICHT. BUNDESMINISTERIUM FÜR NACHHALTIGKEIT UND TOURISMUS, Abteilung I/2 und Abteilung I/5. Wien.

Bundesstrombauamt (1978). Die kennzeichnenden Wasserstände der österreichischen Donau – 1976 (KWD1976)

Drawing plans (Planurile Directoare de Tragere) (1910): http://www.geo-spatial.org/harti/

Embacher, F. (1969). Stromgrundaufnahmen und Hydrometrie. Österreichische Wasserwirtschaft, Jahrgang 21 – Heft 1/2 - 1969.

Fehr, R. (1987). Einfache Bestimmung der Korngrößenverteilung von Geschiebematerial mit Hilfe der Linienzahlanalyse. Schweizer Ingenieur und Architekt, 38/87: 1104-1109.

Finsterwalder. R. (1995). Adrian von Riedler map (1806-1808) in: 400 Jahre Mercator, 400 Jahre Atlas

Franziszeische Landesaufnahme/Zweite Landesaufnahme (1809-1818). Österreichisches Staatsarchiv (all rights reserved). https://mapire.eu/de/

Frings, R. M., Gehres, N., Promny, M., Middelkoop, H., Schüttrumpf, H. & Vollmer, S. (2013). Today`s sediment budget of the Rhine River channel, focusing on the Upper Rhine Graben and Rhenish Massif. Geomorphologz, 204 (2014), 573-587

Geitner, W. (1969). Die Mittel- und Niederwasserregulierung der Donau in Österreich. Österreichische Wasserwirtschaft, Jahrgang 21 – Heft 1/2 – 1969.

Geitner, W. (1978). Die Erhaltungs- und Regulierungsarbeiten der österreichischen Donau in den Jahren 1968 bis 1977. Österreichische Wasserwirtschaft, Jahrgang 30 – Heft 9/10 – 1978.

Habersack, H., Liedermann, M., Blaschke, A. P., Derx, J., Glas, M., Glock, K., Gmeiner, P., Gullner, J., Haimann, M., Holzapfel, P., Hauer, C., Klösch, M., Pessenlehner, S., Schachenhofer, C., Trettler, P., Tritthart, M. (2016). Endbericht Beweissicherung Postmonitoring Phase. Messprogramm 2014-2016. Band 1 - Abiotik, IWHW, Universität für Bodenkultur, Wien.

Holubova K, Comaj M, Lukac M, Mravcova K, Capekova Z, Antalova M (2015). Danube floodplain rehabilitation to improve flood protection and enhance the ecological values of the river in section between Sap-Szob. Project DuReFlood, HUSK/1001/2.1.2/0060, The final report, Water Research Institute, Bratislava

Holubová, K. –Szolgay, J (1999). Sediment transport and associated changes in the Danube river. International Conference on EU Water Management Framework Directive and Danubian Countries. Water Research Institute, Bratislava, pp. 182 – 190.

Holubová, K., Capeková, Z. & Szolgay,J (2004). Impact of hydropower schemes at bedload regime and channel morphology of the Danube River. River Flow 2004, Naples, Italy, p. 135- 141.

Holubová, K., Lukáč M., Szolgay, J., Matok, P., Capeková, Z. (2003). Analýza zmien režimu splavenín na Dunaji v oblasti pod Devínom, VÚVH, Bratislava.

Hydrographisches Zentralbüro – HZB (1937). Schwebstoff und Geschiebeaufnahmen einiger österreichischer Flüsse. Selbstverlage des Hydrographischen Zentralbüros, Wien.

ICPDR (2015). Joint Danube Survey 3, A Comprehensive Analysis of Danube Water Quality, ICPDR, ISBN: 978-3-200-03795-3

NEWADA duo, 2014a. REPORT ON CURRENT AND FUTURE SURVEYING & MAINTENANCE ACTIVITIES PART 1 - DOCUMENT SCOPE + NATIONAL FAIRWAY PARAMETERS. NEWADA duo Act.6.2 Report 6.2 consolidated Pt-1 final.

NEWADA duo, 2014b. REPORT ON CURRENT AND FUTURE SURVEYING & MAINTENANCE ACTIVITIES. PART 2 - FAIRWAY MONITORING. Act.6.2 Report 6.2 consolidated Pt-2 final.

Rainov, St., Ninov, Il., Vassilev, S., Petschinov, D. (1979). Granulometrische Zusammensetzung der Bodenablagerungen der Donau. X. Konferenz der Donauländer über hydrologische Vorhersagen. Wien, 1979.

Reisenbüchler, M., Duc Bui, M., Skublics, D. & Rutschmann, P. (2019): Enhancement of a numerical model system for reliably predicting morphological development in the Saalach River, International Journal of River Basin Management, DOI:10.1080/15715124.2019.1628034

Sacher, M & Liebsch, G & Ihde, J & Mäkinen, Jaakko. (2009). EVRF2007 as Realisation of the European Vertical Reference System. AGU Spring Meeting Abstracts. 68.

Schmautz, M., Strobl, Th. (2000). Bericht über die Entnahme und Auswertung von Sohlproben aus der Donaustrecke Wachau. Lehrstuhl und Versuchsanstalt für Wasserbau und Wasserwirtschaft, TU München.

Simoner, M. - viadonau (2018). Sedimente und Wasserstraßenmanagement – Probleme und Lösungen. Presentation at the 1st National Stakeholder Workshop of the project DanubeSediment, Vienna.

Szolgay, J. (1982). Vyhodnotenie vplyvu intenzívneho bagrovania z koryta Dunaja pod Bratislavou, VÚVH, Bratislava

Szolgay, J. and Nather, B. Selected knowledge on bedload transport in the Danube. Journal of the Water Management, Slovak Academy of Sciences, No. 1, 1954 (in Slovak)

Szolgay, J., 1961. Hydrological investigation of the Danube river development (in Slovak)

Szolgay, J., Csoma J. (1981). Určenie hladiny nízkej regulačnej a plavebnej vody na Dunaji v úseku Devín – Gonyü, VÚVH, Bratislava

Szolgay, J., Holubová, K., Capeková, Z. (1991). Vodohospodársko – ekologické koncepčné riešenie úprav starého koryta Dunaja a ramenných sústav, VÚVH, Bratislava

Szolgay, J., Stančíková, A. (1984). Určenie hladiny nízkej regulačnej a plavebnej vody dunajskej komisie, VÚVH, Bratislava

Szolgay, J., Stančíková, A., Náther, B., Csoma, J., Laczay, I., (1976). Vyhodnotenie vplyvu uskutočnených úprav na vývoj koryta Dunaja v úseku Rajka – Gonyü, VÚVH, Bratislava

Tschochner, F. (1957). Die Donauregulierung in Österreich. Österreichische Wasserwirtschaft 9, Heft 5/6.

VHP (2013). Donaukraftwerk Altenwörth Kompensationsbaggerungen im Raum Stein-Krems. Kollaudierungsbericht. Verfasser: Schmalfuß, R. and Salamon, J.

viadonau (2012). Die kennzeichnenden Wasserstände der österreichischen Donau – KWD 2010. Vienna, Austria.

Zottl, H., Erber, H. (1987). Grundlagen für die Untersuchungen der Sohlstabilität und zur Stabilisierung der Stromsohle. Wien.