Interreg
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DanubeSediment

Sediment Balance Assessment for the Danube

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

Sediments are a natural part of an aquatic system, such as the Danube River, which has been greatly altered by human activities over the past centuries. River-bed straightening, flood protection, and the construction and operation of hydropower dams have led to major changes in the sediment load. The resulting sediment imbalance heightens the risk of flooding and worsens the conditions for shipping and hydropower generation. It also leads to the loss of biodiversity within the Danube Basin.

To tackle these challenges, 14 project partners and 14 strategic partners have come together for the DanubeSediment project. The partnership includes numerous sectoral agencies, higher educational institutions, hydropower companies, international organisations and non-governmental organisations from nine Danubian countries.

Closing the knowledge gaps: In a first step, the project team collected data on sediment transport along the Danube and its main tributaries. These data were used to make a Danube-wide sediment balance assessment, based on an analysis of the sinks, sources and redistribution of sediments along the full length of the Danube – from the Black Forest to the Black Sea. In order to better understand the impacts and risks of a sediment deficit and erosion, the project partners also examined the key drivers and pressures that may cause sediment discontinuity.

Strengthening governance: One of the main project outputs is the Danube Sediment Management Guidance (DSMG). It contains recommendations for alleviating the impact of a disturbed sediment balance on the ecological conditions and flood risks along the river. Together with the Danube River Basin 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 present project directly contributes to transnational water management and flood risk prevention.

International Training Workshops were held to support the transfer of knowledge to the key target groups throughout the Danube River Basin, e.g. to entities in charge of hydropower generation, navigation, flood risk and river basin management, including ecology. The project addressed these target groups individually in the ‘Sediment Manual for Stakeholders’ (the second main project output). This document provides background information and concrete examples for implementing good practice measures in each field.

DanubeSediment was co-funded by the European Union’s ERDF and IPA funds within the scope of the Danube Transnational Programme. Further information on the project, its results, and on related events are available at: www.interreg-danube.eu/danubesediment.

Project Reports

The DanubeSediment project is structured into six work packages (WPs). The main project publications are listed below.

A detailed list of all project activities and deliverables is available on the project's website at: www.interreg-danube.eu/approved-projects/danubesediment/outputs.

- Sediment Monitoring in the Danube River
- Analysis of Sediment Data Collected along the Danube
- Handbook on Good Practices in Sediment Monitoring
- Data Analyses for the Danube's Sediment Balance and Long-term Morphological Development
- Sediment Balance Assessment for the Danube
- Long-term Morphological Development of the Danube in Relation to the Sediment Balance
- Interactions of Key Drivers and Pressures on the Danube's Morphodynamics
- Risk Assessment Related to the Sediment Regime of the Danube
- Sediment Management Measures for the Danube
- Key Findings of the DanubeSediment Project
- Danube Sediment Management Guidance
- Sediment Manual for Stakeholders

Sediment Balance Assessment for the Danube

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This report has been prepared as part of the project called ***Danube Sediment Management*** – *Restoration of the Sediment Balance in the Danube River*. The DanubeSediment project is co-funded by the European Union's ERDF and IPA funds within the framework of the Danube Transnational Programme (Project reference number: DTP-1-1-195-2.1). The overall budget for the project is EUR 3,558,581.62, to which ERDF has contributed EUR 2,827,421.16 and IPA has contributed EUR 197,373.19.

Project duration: 1 January 2017 – 30 November 2019

Website: www.interreg-danube.eu/danubesediment

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1. Introduction

Sediments are a natural part of a river. The Danube and its tributaries have been greatly altered over the past centuries by human interventions made for flood protection, power generation and navigation purposes through the construction of hydraulic engineering structures (e.g. dams and barriers) and the narrowing and shortening of the Danube channel, etc. These interventions have caused changes in the river's sediment transport regime, resulting in a sediment imbalance along the full length of the Danube. Such changes may in consequence increase the risk of flooding, worsen the navigational conditions, reduce the capacity of reservoirs for hydropower production, and cause a loss of biodiversity. Therefore, the basic question of how the sediment balance has changed over time has led the project partners of the DanubeSediment project to make a sediment balance assessment for the Danube and its selected tributaries. In so doing, they focused on establishing a sediment budget, identifying the surpluses (sources) and deficits (sinks) of sediments, and proposing sediment redistribution within various spatial and temporal units.

This report represents one of the outputs of the DanubeSediment Interreg DTP project. It is divided into six chapters. In addition to this introductory chapter, the report contains five more chapters. Chapter 2 presents the basic concept of the sediment balance assessed, its definition and composition. Chapter 3 contains a brief analysis of the basic hydrological conditions in the Danube River Basin, based on the datasets provided for the project. Chapter 4 covers the datasets that were used to establish a setup for the sediment balance. Chapter 5 describes the sediment balance setup. The main results and conclusions are included in Chapter 6. The report has six separate annexes.

2. Sediment balance – general information

A **sediment balance** is the result of accounting for the sources (surpluses), sinks (deficits) and redistribution pathway of sediments within various spatial and temporal units. In Work Package 4, Activity 4.2 focused on quantifying the main components of the sediment balance of the Danube and its major tributaries, using various spatial and temporal scales.

As the scheme in Figure 2.1 of the Rhine River Basin (Frings et al. 2014) shows, the sediment balance equation includes the following components: **a) inputs** – sediments transported from the upstream stretches, sediments transported from the tributaries, sediments from riverbank erosion, sediments fed artificially into the river channel; **b) outputs and storage**: sediments transported to downstream stretches, river-bed sediments removed by dredging, sediments in the floodplains and/or groyne fields, river-bed material abrasion.

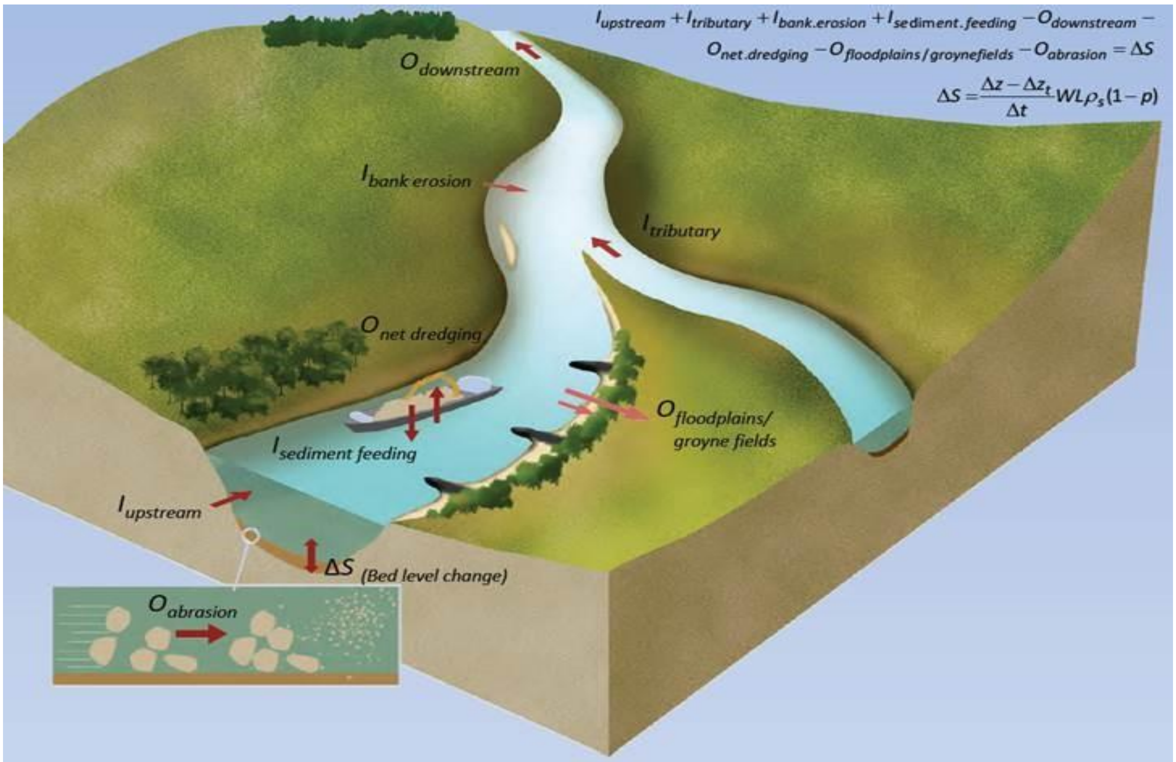

Figure 2.1 Scheme of sediment balance components (Frings et al. 2014)

The full version of the sediment balance equation reads as follows:

$$I_{upstream} + I_{tributary} + I_{bank\ erosion} + I_{sediment\ feeding} - O_{downstream} - O_{dredging}$$

$$- O_{floodplains/groynefields} - O_{abrasion} = \Delta s \qquad (2.1)$$

$\Delta s = ((\Delta z - \Delta z_t)/\Delta t).W.L.\rho_s.(1-p)$ (2.2)

where:

$I_{upstream}$ – sediments transported from the upstream stretches

$I_{tributary}$ – sediments transported from the tributaries

$I_{bank\ erosion}$ – sediments as a product of bank erosion

$I_{sediment\ feeding}$ – sediments artificially fed into the river channel

$O_{downstream}$ – sediments transported to downstream stretches

$O_{dredging}$ – sediments dredged from the river channel

$O_{floodplains/groynefields}$ – sediments deposited in the floodplains and/or groyne fields

$O_{abrasion}$ – river-bed material abrasion caused by sediment transport

Δs – change in the storage of sediments

$\Delta z - \Delta z_t$ – river-bed change during a time interval Δt

W – width of the river channel

L – length of the river stretch

ρ_s – specific weight of sediments

p – porosity of the bed material

In our case, suspended load and bedload data were provided within the scope of WP 3 '*Sediment Data Collection'.* Other components, needed for the sediment balance setup, e.g. river-bed changes, sediment dredging and/or feeding, etc. were collected and quantified within the scope of Activity 4.1. 'Data analyses for the sediment balance and long-term morphological development of the Danube'.

Owing to the lack of data on riverbank erosion (not yet quantified) and river-bed material abrasion, the equation for the Danube River Basin has been modified as follows:

$I_{upstream} + I_{tributary} + I_{sediment\ feeding} - O_{downstream} - O_{dredging} = \Delta s$ (2.3)

3. Hydrological characteristics

Along its course from the spring area in the Black Forest in Germany down to its delta and river mouth at the Black Sea in Romania, the Danube is supplied with water from its tributaries on both sides. The river basin area increases in the longitudinal profile, as it is illustrated in Figure 3.1.

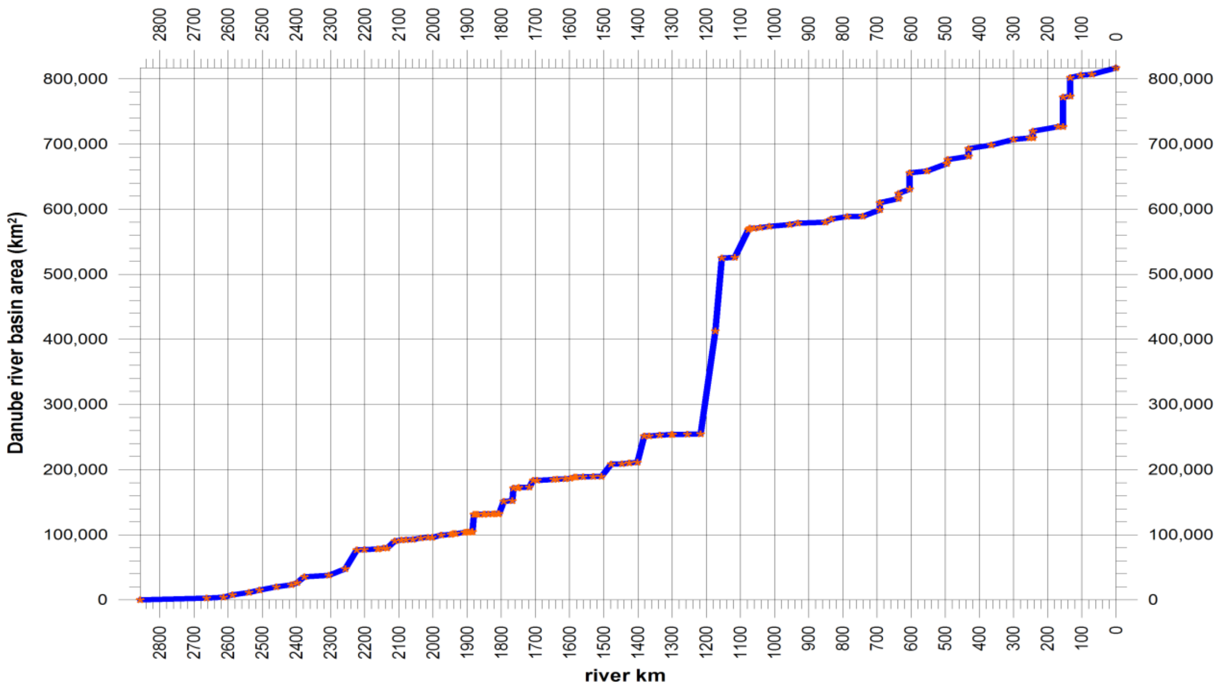

Figure 3.1 Longitudinal development of the Danube River Basin

The longitudinal profile in Figure 3.1 illustrates the contributions of the most important Danube tributaries:

- In the Upper Danube section – the Isar (confluence with the Danube at river km 2,281.710), Inn (rkm 2,225.200), Traun (rkm 2,124.730), Enns (rkm 2,111.830) and Morava/March (rkm 1,880.260) rivers;
- In the Middle Danube section – the Drava (rkm 1,382.500), Tisza/Tisa (rkm 1,214.500), Sava (rkm 1.170.000) and Velika Morava (rkm 1,103.000) rivers;
- In the Lower Danube section – the Jiu (rkm 691.550), Iskar (rkm 637.000), Arges (rkm 432.000), Ialomita (rkm 244.000), Siret (rkm 155.000) and Prut (rkm 134.140) rivers.

There are several characteristic years in the investigated datasets, which determine the method of their analyses:

- 1956 – the initial year of the available historical datasets;
- 1972 – the Iron Gate 1 dam was put into operation;
- 1986 – the first year of the datasets available for project;
- 1992 – the Gabčíkovo dam was put into operation;
- 2014, 2015, 2016 – the last years of the available project datasets.

The mean annual discharge was computed for gauging stations with complete datasets for the following periods, respecting the characteristic years listed above:

- 1956-2014 (59 years), 1956-1972 (17 years), 1973-1992 (20 years), 1993-2014 (22 ys).

The length of three partial time periods is almost the same, varying between 17 and 22 years. The mean annual discharge of the Danube is illustrated in the longitudinal section (between Neu Ulm and the Danube Delta) in figures 3.2 to 3.5. An overview of the values for selected gauging stations is available in Table 3.1.

Table 3.1 Mean discharges of the Danube at selected gauging stations in different time periods

Gauging station	river km	Qa ($m^3.s^{-1}$)			
		1956-2014	1956-1972	1973-1992	1993-2014
Neu Ulm	2,586.700	124	120	127	124
Ingolstadt	2,457.850	314	300	325	316
Engelhartszell	2,200.660	1,412	1,433	1,407	1,401
Hainburg	1,886.860	1,921	1,906	1,922	1,933
Bratislava	1,868.750	2,052	2,026	2,047	2,077
Komárno	1,767.800	2,205	2,280	2,250	2,107
Nagymaros	1,694.600	2,286	2,301	2,242	2,314
Mohács	1,446.900	2,350	2,366	2,278	2,404
Iron Gate 1	943.000	incomplete data	incomplete data	incomplete data	5,477
Turnu Severin	931.000	incomplete data	5,692	5,454	5,459
Zimnicea	553.230	incomplete data	6,231	5,821	5,929
Braila	167.000	6,223	6,275	6,132	6,265

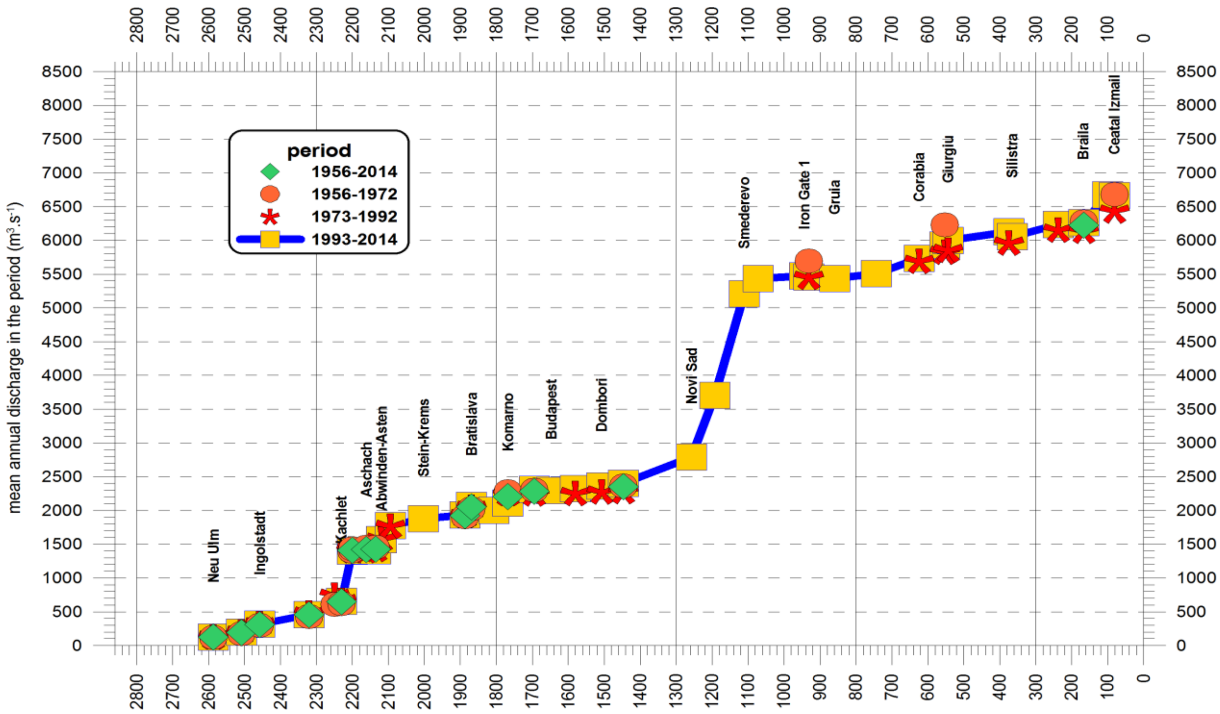

Figure 3.2 Longitudinal profile of the mean annual discharge in different time periods

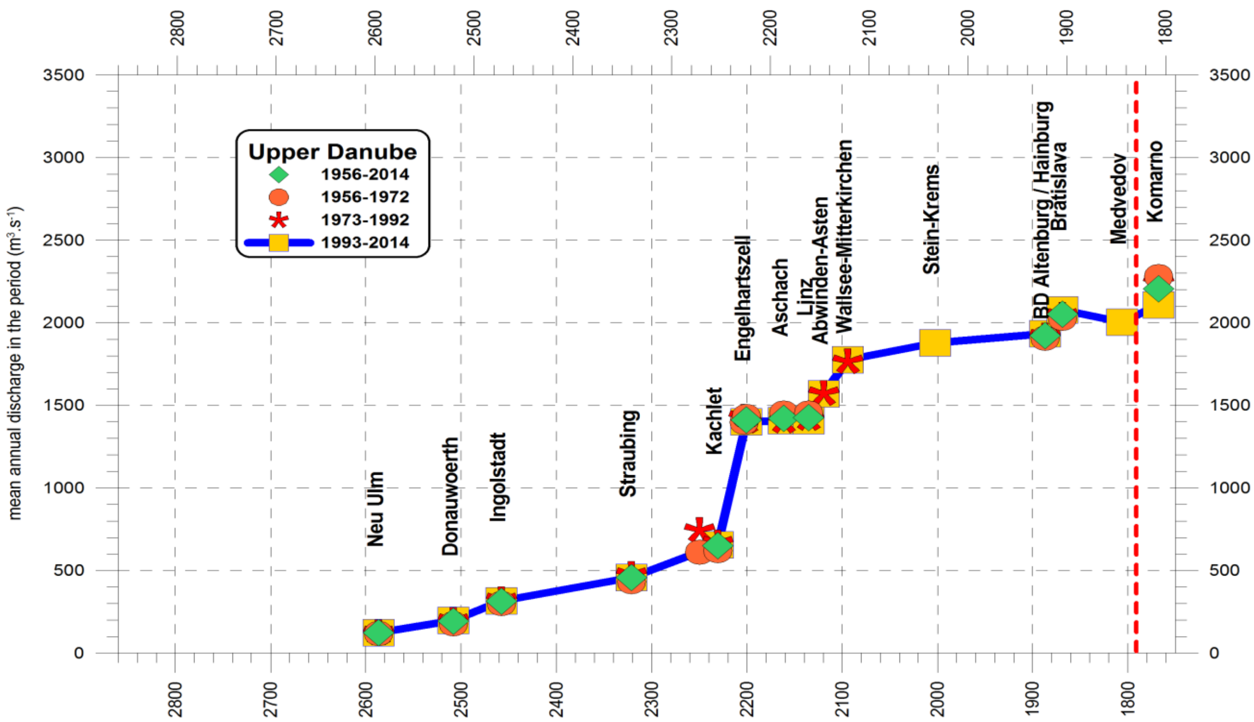

Figure 3.3 Longitudinal profiles of the mean annual discharge in different time periods – Upper Danube

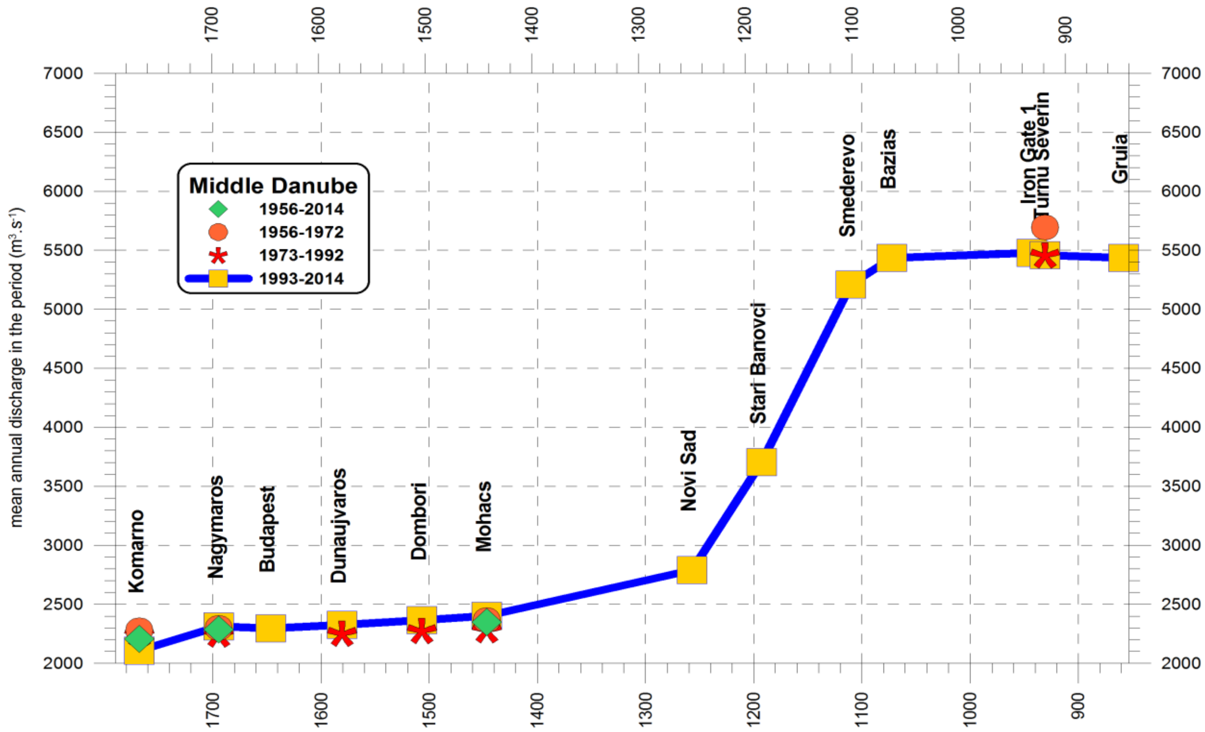

Figure 3.4 Longitudinal profile of the mean annual discharge in different time periods – Middle Danube

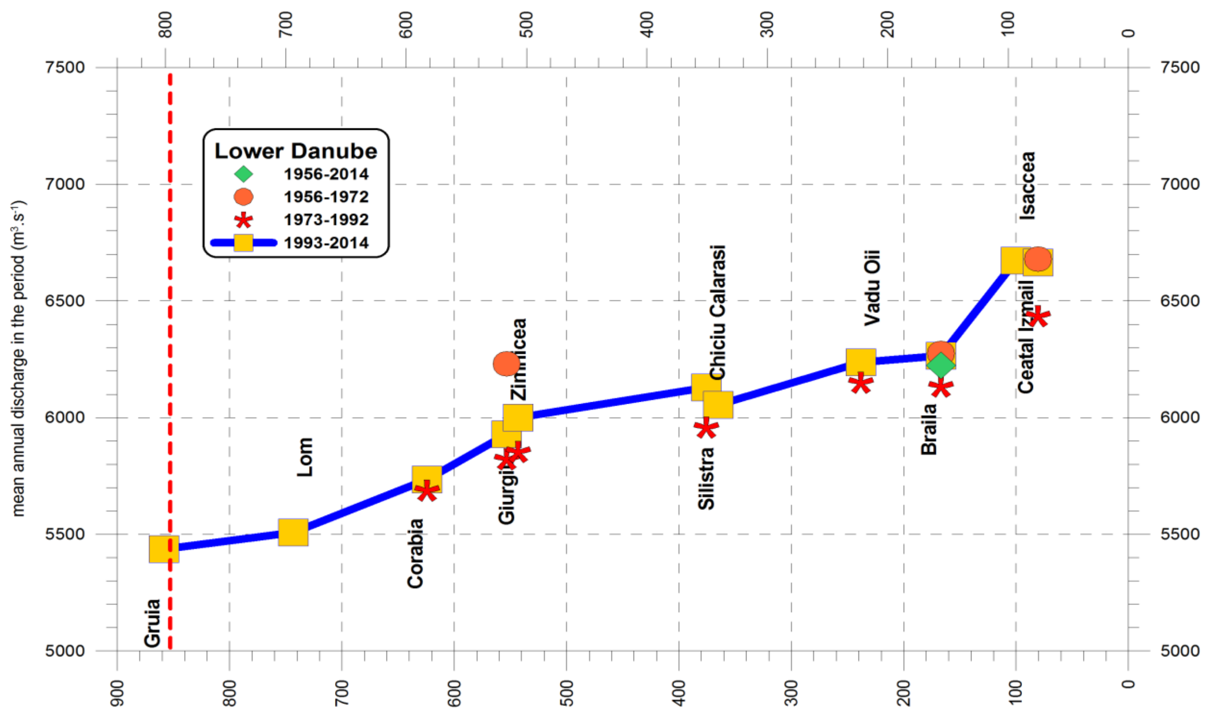

Figure 3.5 Longitudinal profile of the mean annual discharge in different time periods – Lower Danube

The mean annual discharges in the main tributaries of the Danube are given in Table 3.2.

Table 3.2 Mean annual discharges in the main tributaries of the Danube in the period 1993-2014

Tributary	Gauging station	Qa ($m^3.s^{-1}$)	Tributary	Gauging station	Qa ($m^3.s^{-1}$)
Isar	Plattling	175	Velika Morava	Ljubicevski bridge	220
Inn	Passau	755	Jiu	Zaval	93
Traun	Wels	124	Iskar	Oriahovitza	44
Enns	Steyr	209	Iantra	Karantzi	47
March/Morava	Angern	107	Arges	Budesti	41
Drava	Donji Miholjac	516	Ialomita	Tandarei	37
Tisa	Titel	843	Siret	Lungoci	203
Sava	Belgrade	1,542	Prut	Oancea	100

The table above clearly indicates that the Sava, Tisa and Inn rivers are the most significant tributaries of the Danube in the terms of discharge.

The variability of the mean annual discharge in the Danube is well demonstrated by figures 3.6 to 3.9. The most significant (the wettest) year in the river's German section was 2002. This year was also important in the Austrian and Slovak river sections, but there were two other years with a higher mean annual discharge – 1965 and 1970. The year 1965 was also the wettest year for the whole Danube section between Bratislava (rkm 1,868.750) and Mohács (rkm 1,446.900). For the Romanian river section, only the time series of discharges from Gruia was available for a whole period under review. The wettest years in that river section were 1970 and 2010.

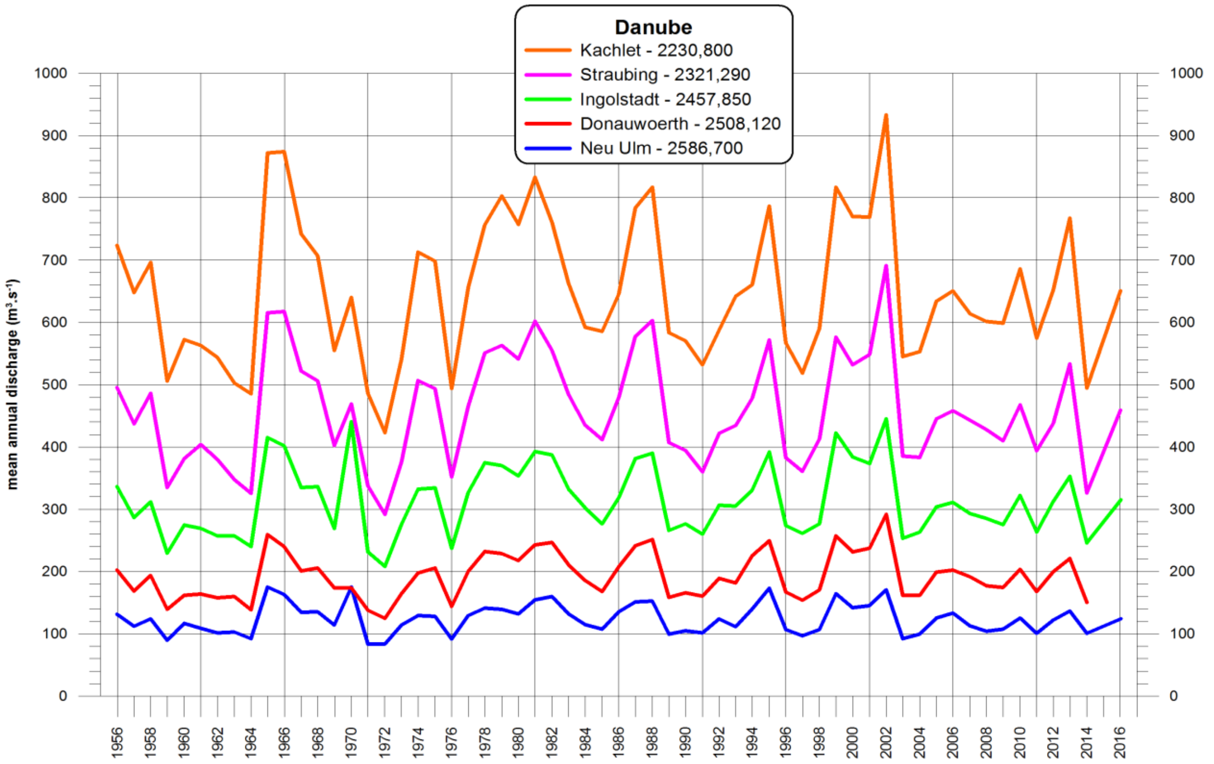

Figure 3.6 Time series of the mean annual discharge in the Danube – Germany

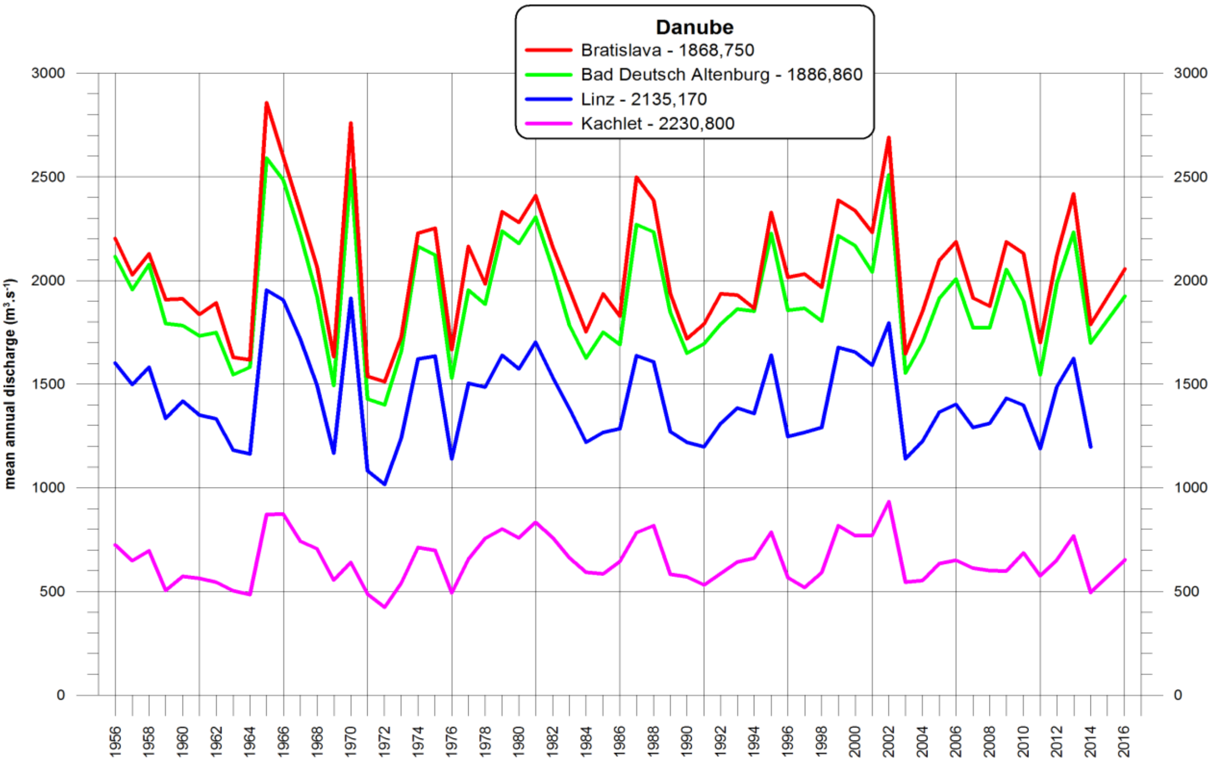

Figure 3.7 Time series of the mean annual discharge in the Danube – Germany, Austria, Slovakia

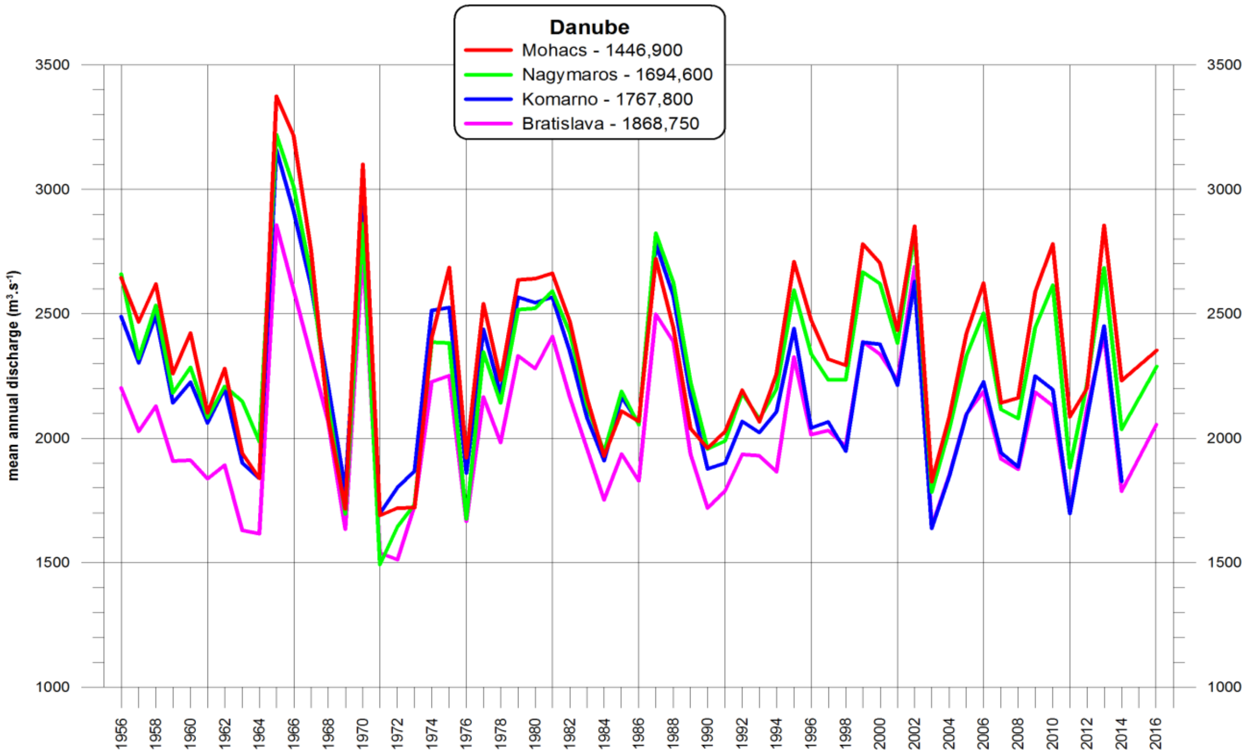

Figure 3.8 Time series of the mean annual discharge in the Danube – Slovakia, Hungary

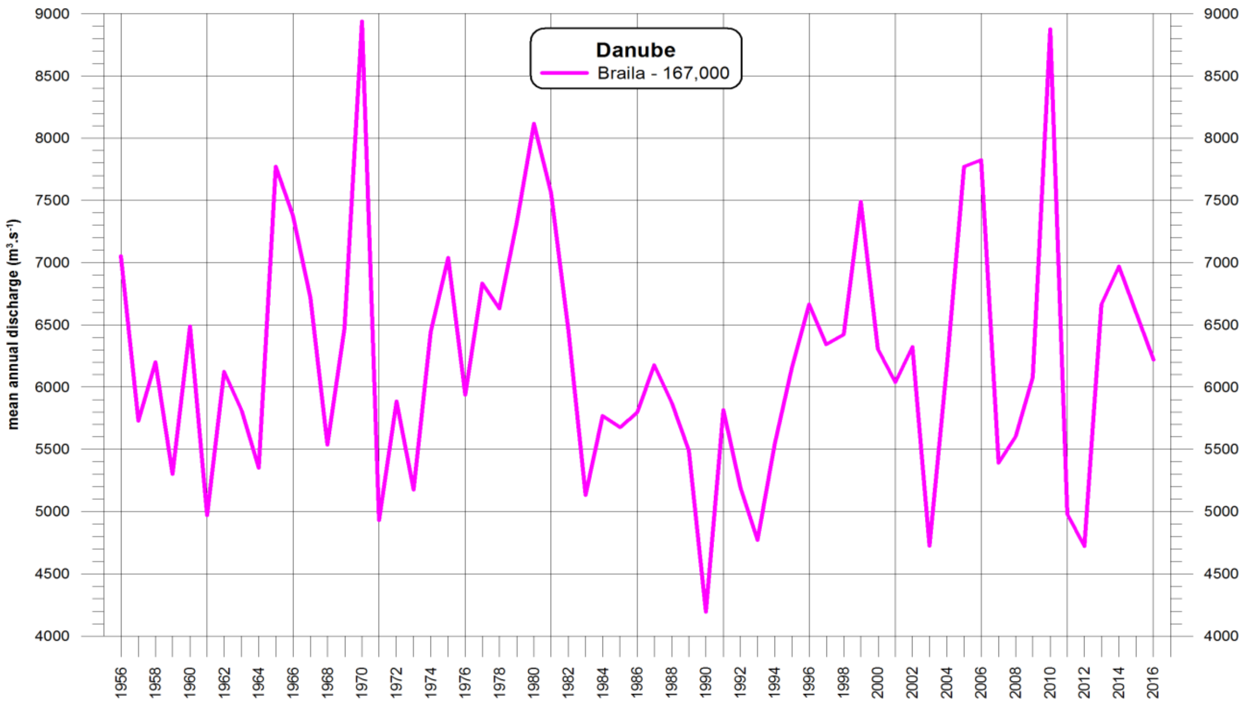

Figure 3.9 Time series of the mean annual discharge in the Danube – Romania

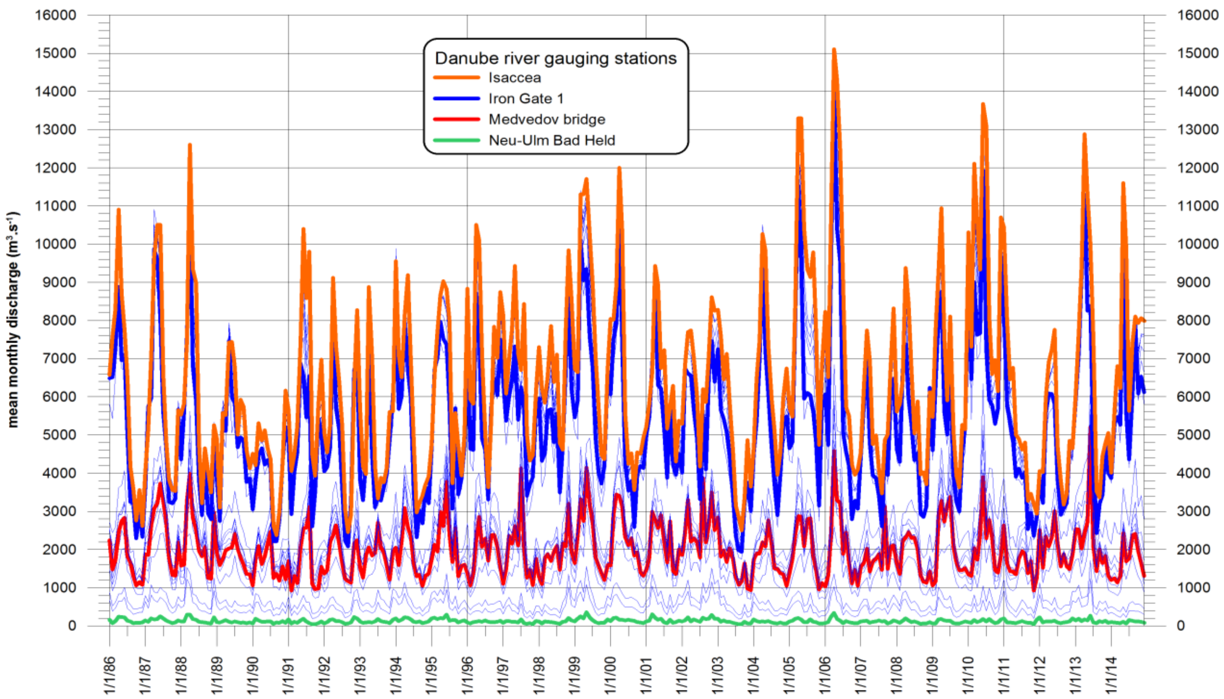

Figure 3.10 Overview of the mean monthly data collected for the project – all gauging stations

The basic time step used in the flow and sediment data collected for the project was one month in the period from 1986 to 2016. An overview of the monthly values of discharges is presented in the series of figures 3.10 to 3.13. The database set up for the project contains data from 42 gauging stations along the main Danube channel and 18 gauging stations along the river's tributaries. The absolute maximum of the recorded mean monthly discharges in the period under review was Q_{MAX} = 15,900 $m^3.s^{-1}$. It was recorded at the Isaccea gauging station during the flood in April 2006.

The wettest months at the Medveďov gauging station (the most downstream station in the Upper Danube section) were June 2013 (with a daily maximum of $Q_{d,MAX}$ = 10,018 $m^3.s^{-1}$ during flooding), April 2006 ($Q_{d,MAX}$ = 7,430 $m^3.s^{-1}$), May 1999 ($Q_{d,MAX}$ = 5,303 $m^3.s^{-1}$) and July 1997 ($Q_{d,MAX}$ = 6,458 $m^3.s^{-1}$).

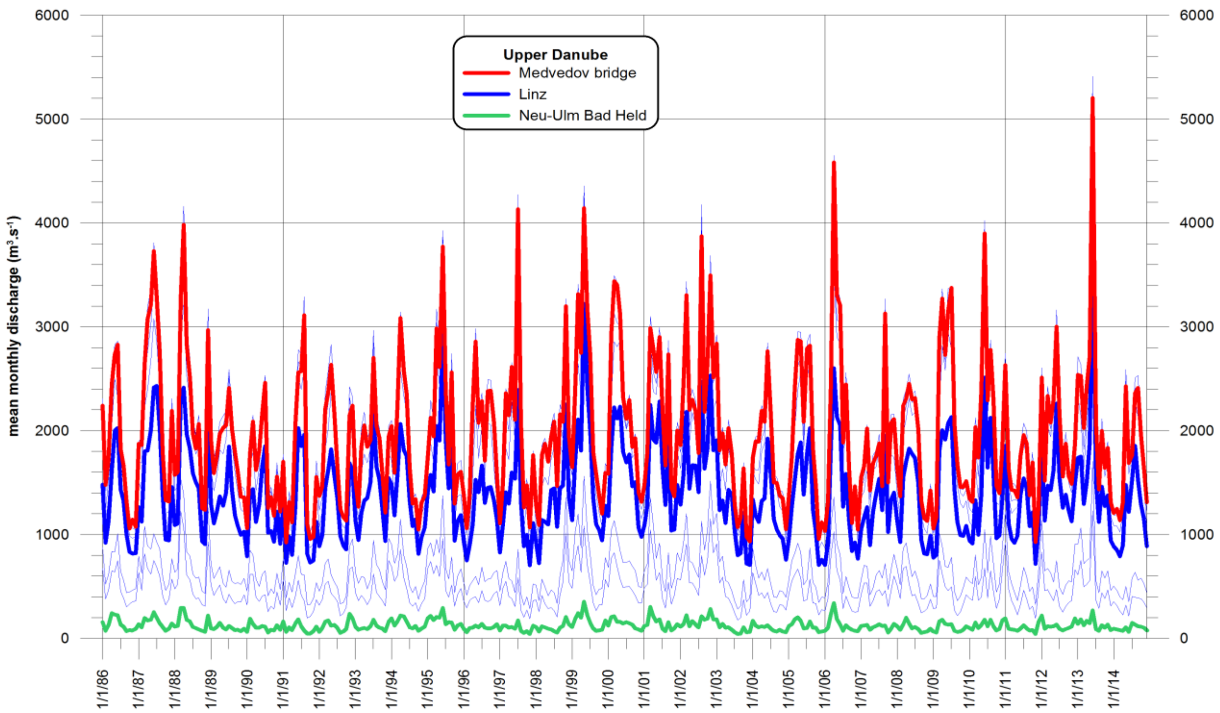

Figure 3.11 Overview of the mean monthly data collected for the project – Upper Danube

The values for the Middle Danube section, measured at the Iron Gate 1 gauging station are: April 2006 – the wettest month ($Q_{d,MAX}$ = 15,760 $m^3.s^{-1}$), followed by June 2010 ($Q_{d,MAX}$ = 13,188 $m^3.s^{-1}$) and April 2005 ($Q_{d,MAX}$ = 12,803 $m^3.s^{-1}$).

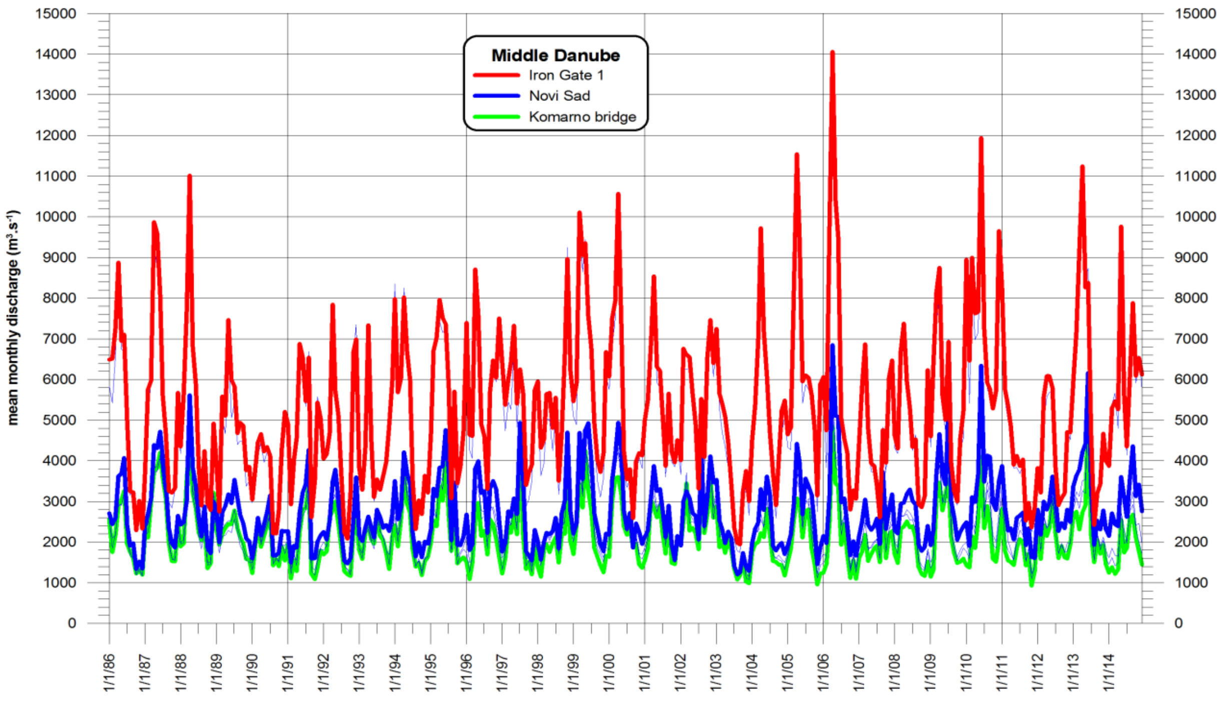

Figure 3.12 Overview of the mean monthly data collected for the project – Middle Danube

The data recorded at the Isaccea gauging station present a realistic picture of the hydrological situation in the Lower Danube section, upstream of the delta area. The wettest month was again April 2006 ($Q_{d,MAX}$ = 16,900 $m^3.s^{-1}$), followed by May 2006 ($Q_{d,MAX}$ = 16,000 $m^3.s^{-1}$) and June 2010 ($Q_{d,MAX}$ = 15,980 $m^3.s^{-1}$).

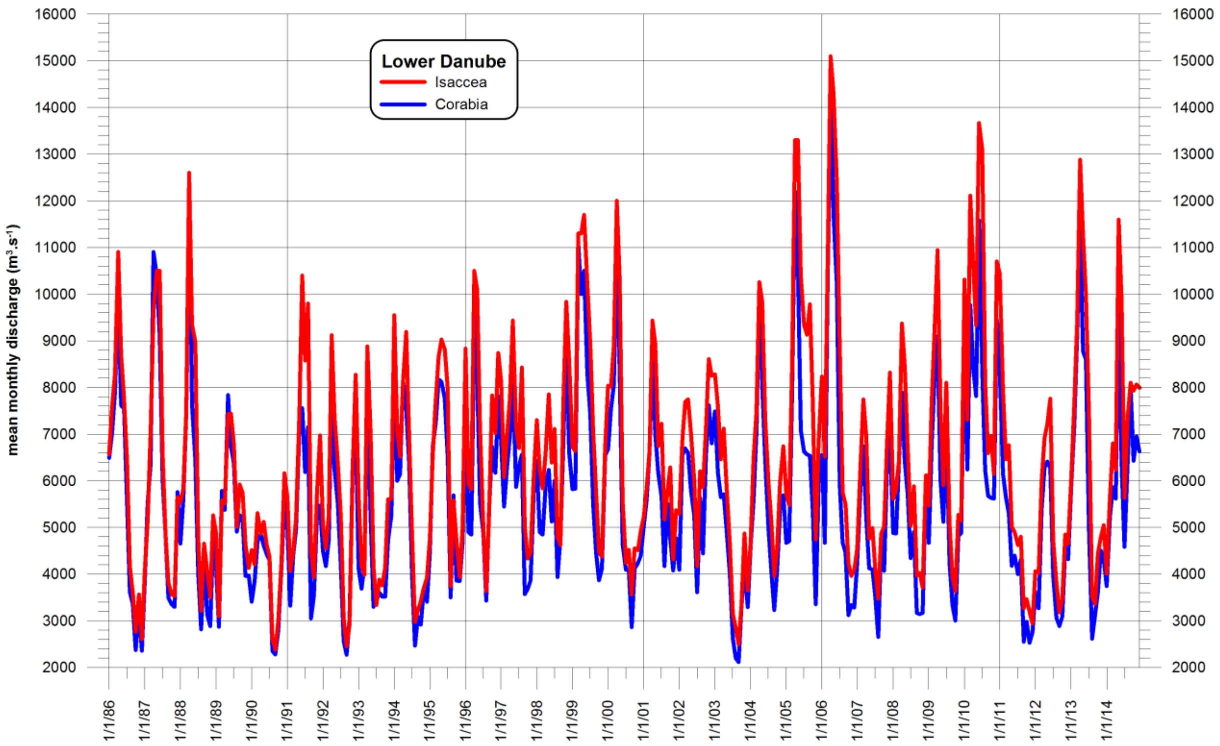

Figure 3.13 Overview of the mean monthly data collected for the project – Lower Danube

4. Datasets for sediment budgets

There are four basic categories of data needed for drawing up partial sediment budgets within the scope of this project:

- data on suspended load;
- data on bedload;
- data on the quantity of dredging;
- data on the morphological changes in the Danube channel, complementing the lack of data on bedload along the Danube.

The basic data are described in the reports of WP 3 *('Analysis of Data on Sediments in the Danube')* and WP 4 – Activity 4.1 *('Data analyses for the sediment balance and long-term morphological development of the Danube').* This chapter describes the basic datasets used in connection with the preparation of sediment budgets.

4.1 Suspended sediments

Data on suspended sediments (SS) represent the most extensive dataset used in this project. These data have provided a basis for drawing up sediment budgets for the river stretches under investigation.

A graphical interpretation of the values of mean monthly suspended load is presented in Annex 1. The values in the series of graphs are given for the time period from January 1993 to December 2000. In this period, complete suspended load data were available in all the gauging stations involved in this project.

For a more detailed description of the contributions of tributaries, we have selected several graphs for each section of the Danube – the Upper, Middle and Lower sections.

The most upstream tributary in the database is the Isar River. Its confluence with the Danube is situated at rkm 2,282.000, between the monitoring stations at Straubing (rkm 2,321.290) and Vilshofen (rkm 2,249.470). A comparison of SS load values at these two stations is presented in Figure 4.1.1. The contribution of the Isar River can be seen in Figure 4.1.2. In almost each case, the monthly SS load values are lower than those of the Danube at the aforementioned two stations. On the other hand, in some cases, especially during floods (June 1995, July 1997, May 1999), the Isar values are higher than the Danube values at the Straubing monitoring station upstream.

The next set of graphs for the Upper Danube section (Figure 4.1.3) are based on data from the Kachlet (rkm 2,230.609) and Jochenstein (rkm 2,203.300) gauging stations. The mouth of the Inn River (rkm 2,225.200) is situated between these stations. The Inn represents the most significant Danube tributary in the Upper Danube section. This is also evident from Figure 4.1.3, where the SS load values at Kachlet and Jochenstein downstream are compared. This comparison is illustrated in Figure 4.1.4. The values for the Inn River are usually higher than those for Kachlet, in some cases (July 1996, July 1997, May 2000) even higher than the Danube values at Jochenstein. Such situation was typical mainly for the flood events that occurred in the Inn River Basin.

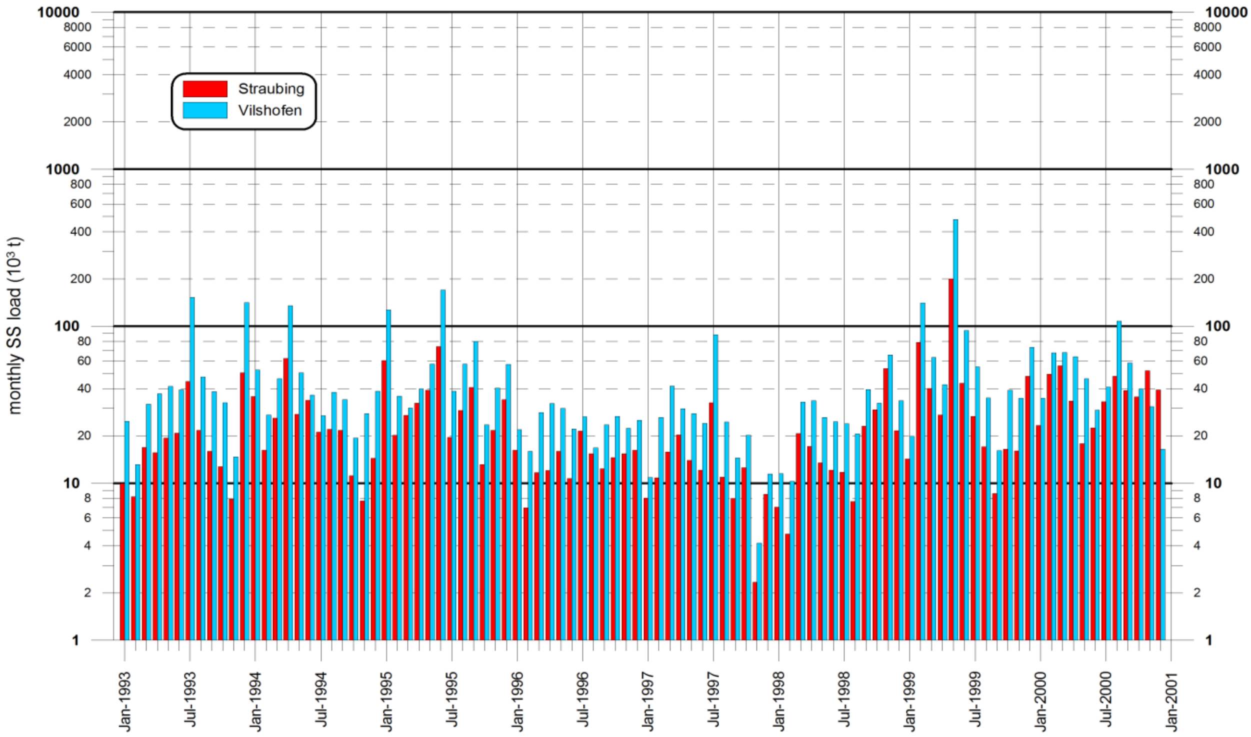

Figure 4.1.1 Values of monthly SS load at the Straubing and Vilshofen monitoring stations

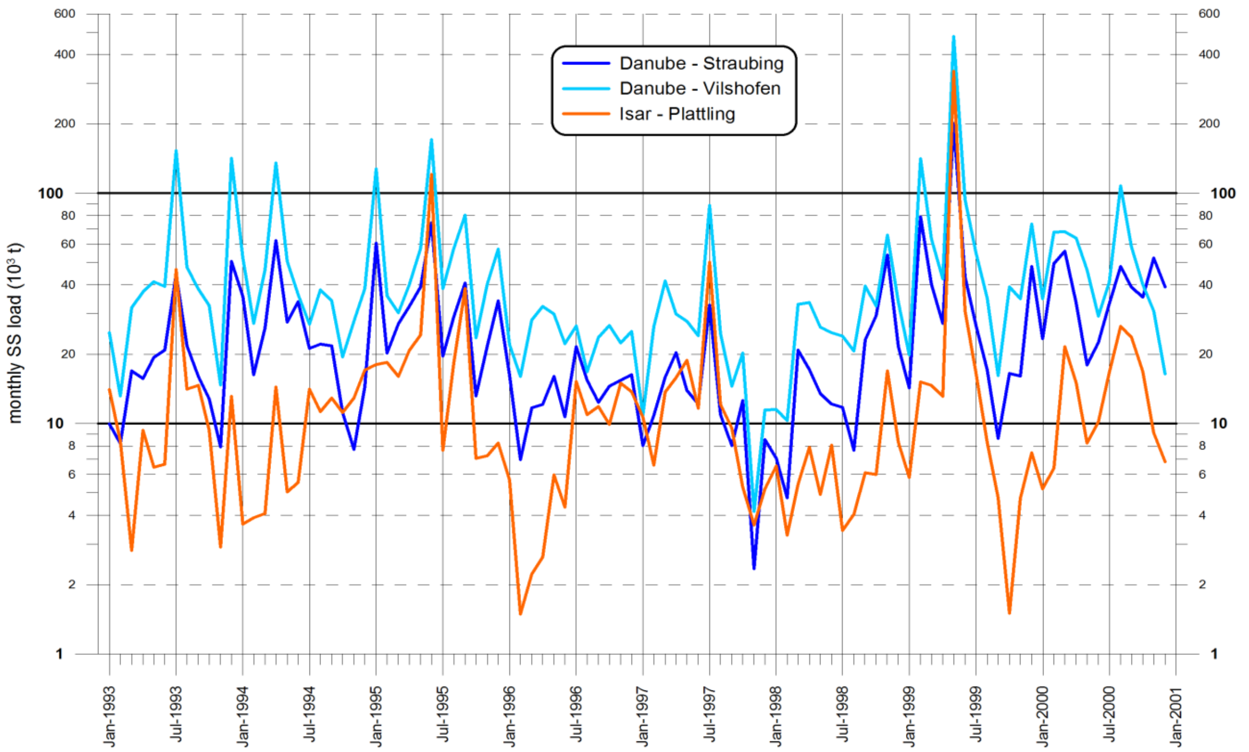

Figure 4.1.2 Values of monthly SS load in the Isar River, compared with those in the Danube at the closest monitoring stations

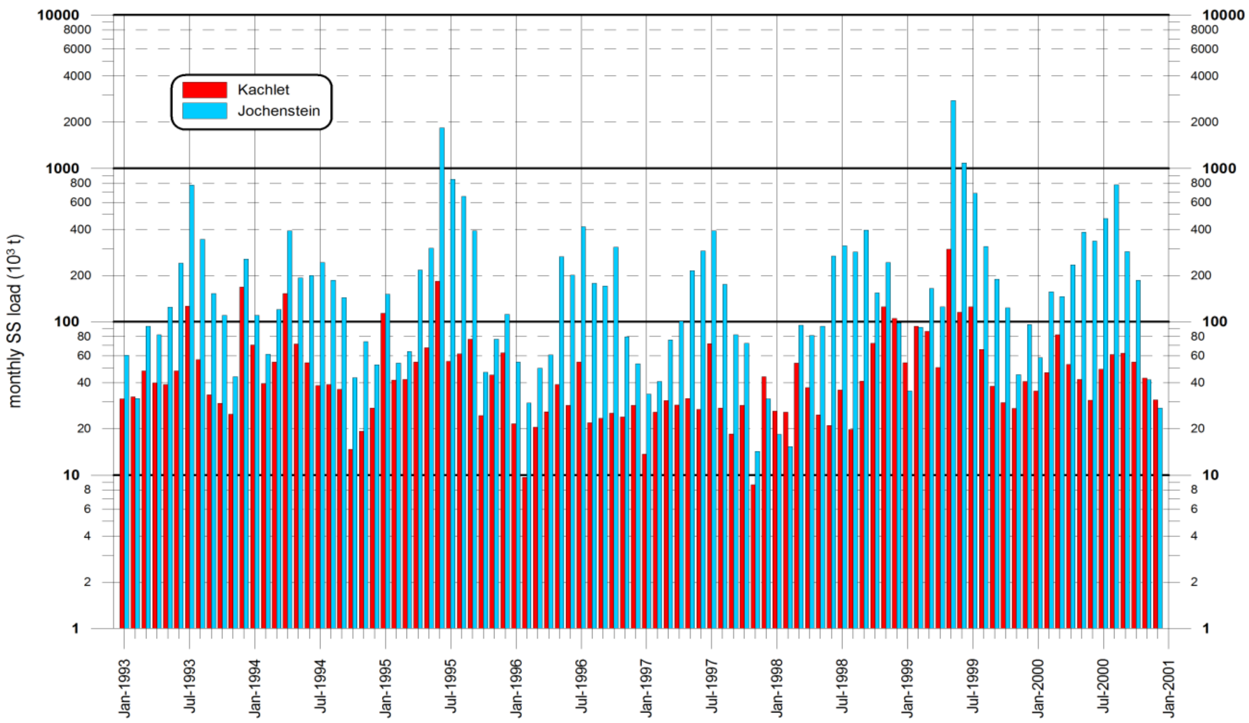

Figure 4.1.3 Values of monthly SS load at the Kachlet and Jochenstein monitoring stations

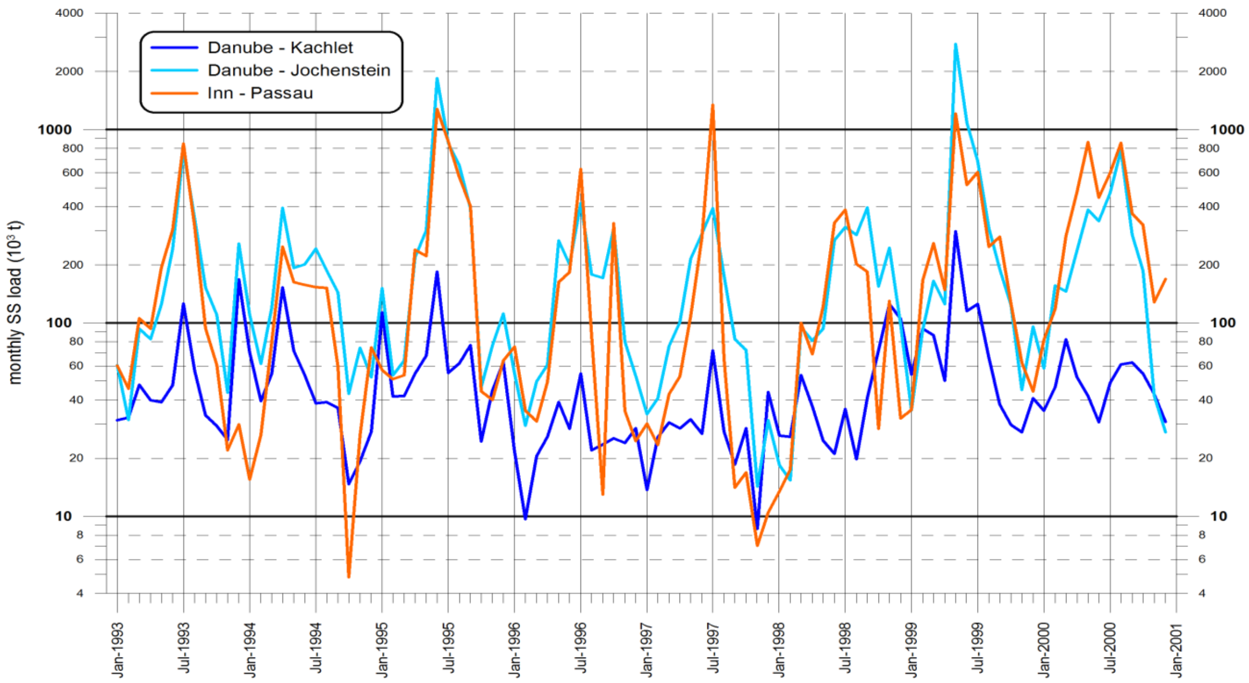

Figure 4.1.4 Values of monthly SS load in the Inn River, compared with those in the Danube at the closest monitoring stations

Other important Danube tributaries in Austria are the Traun (rkm 2,125.000) and Enns (rkm 2,112.000) rivers. A comparison of the monthly SS load in these rivers with that in the Danube is shown in figures 4.1.5 and 4.1.6.

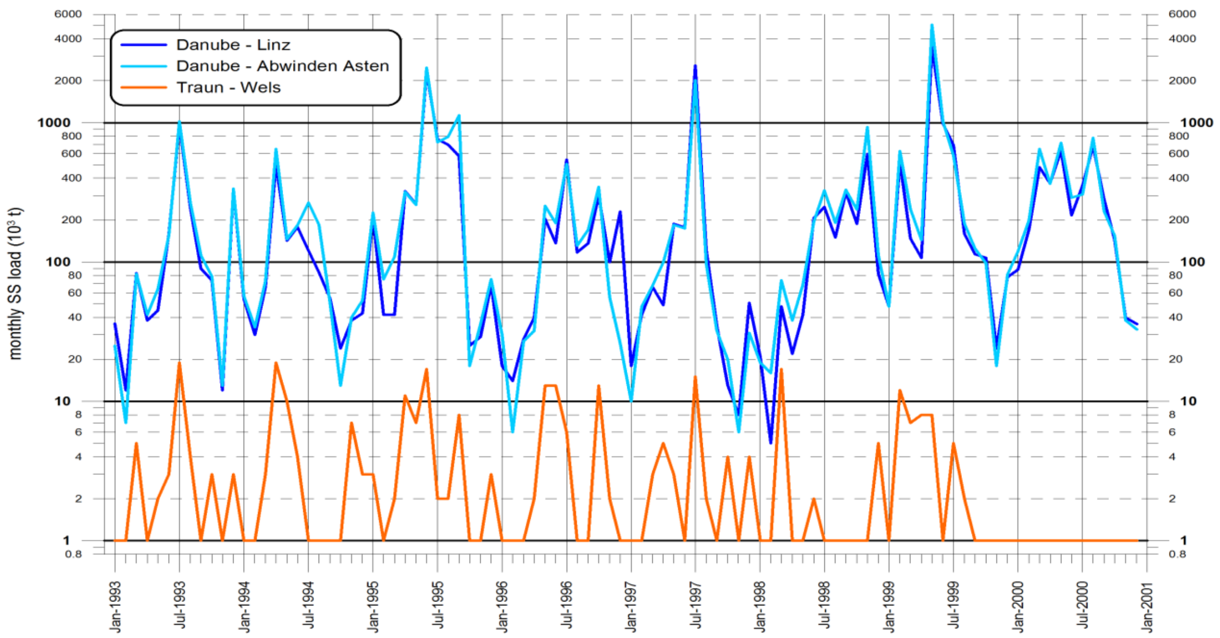

Figure 4.1.5 Values of monthly SS load in the Traun River, compared with those in the Danube at the closest monitoring stations

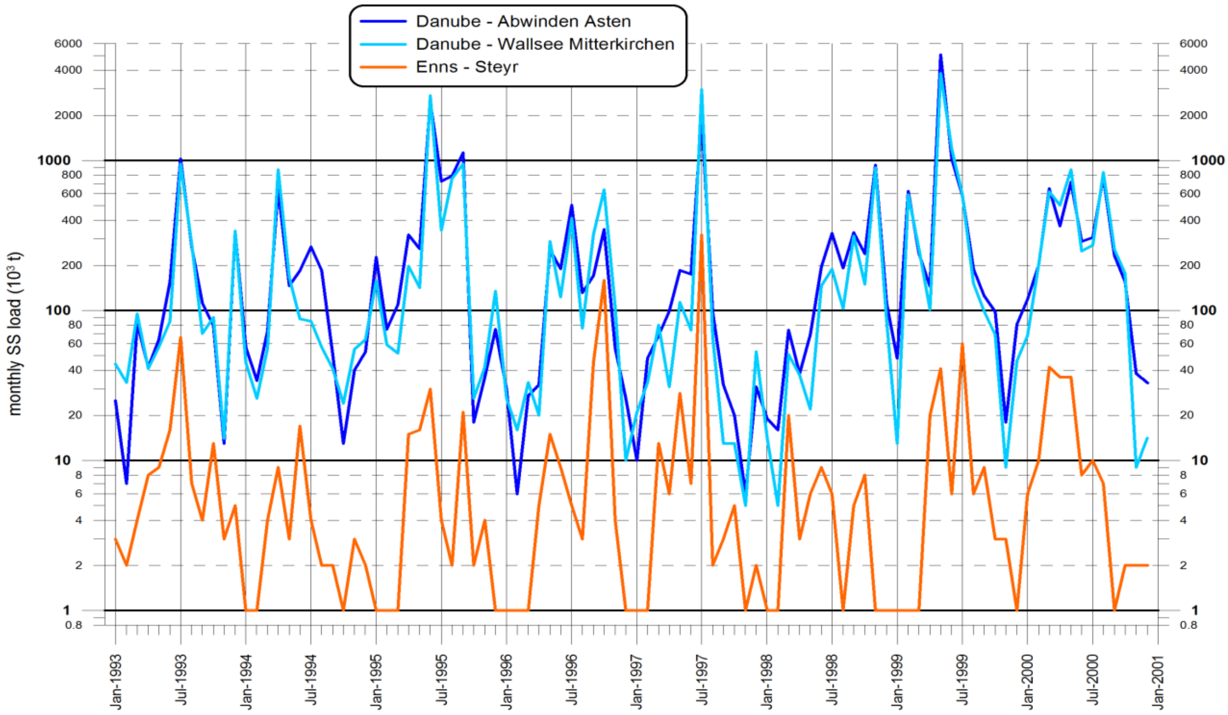

Figure 4.1.6 Values of monthly SS load in the Enns River, compared with those in the Danube at the closest monitoring stations

In all cases, the SS load values for these two tributaries are lower than the corresponding values for the Danube at the closest monitoring stations – Linz (rkm 2,135.170), Abwinden Asten (rkm 2,119.940) and Wallsee-Mittenkirchen (rkm 2,094.210).

Downstream of Bratislava, the Hrušov reservoir (rkm 1,851.750) traps a significant amount of suspended sediments. This fact is evident from a comparison of the monthly SS load values measured at the Bratislava (rkm 1,871.300) and Medveďov (rkm 1,806.300) stations. The Bratislava values are always higher than those measured at Medveďov (Figure 4.1.7).

The values of monthly SS load, depending on the discharge, for the tributaries of the Upper Danube are illustrated in Figure 4.1.8.

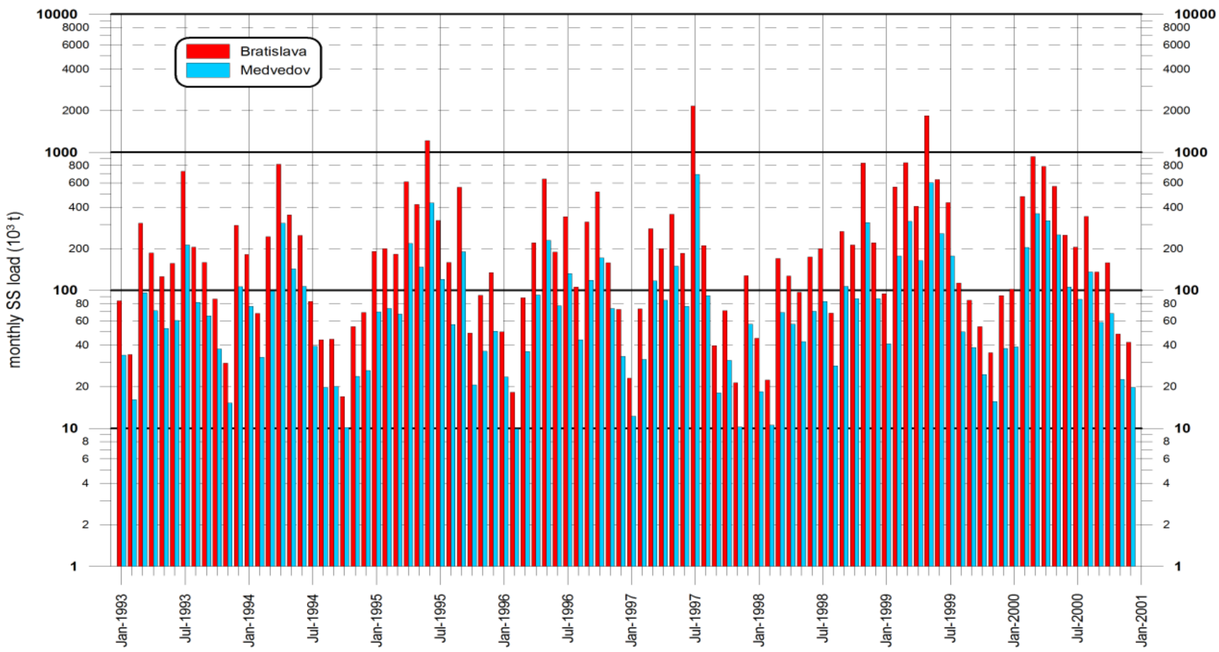

Figure 4.1.7 Values of monthly SS load at the Bratislava and Medveďov monitoring stations

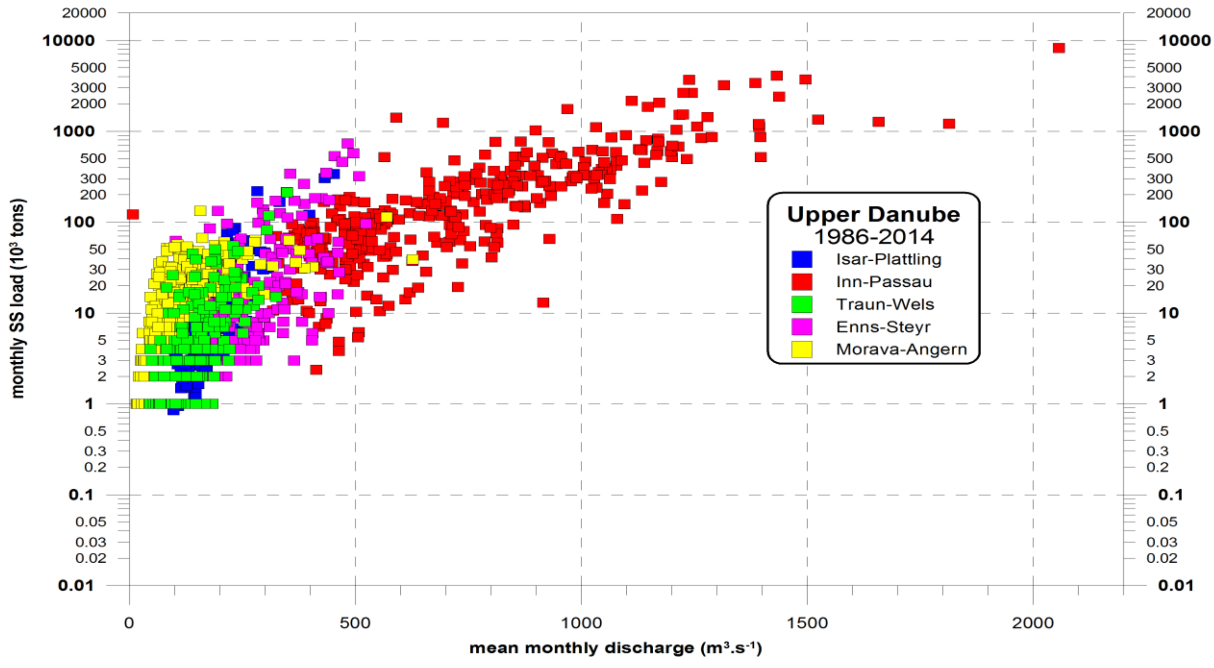

Figure 4.1.8 Values of monthly SS load in the tributaries of the Upper Danube

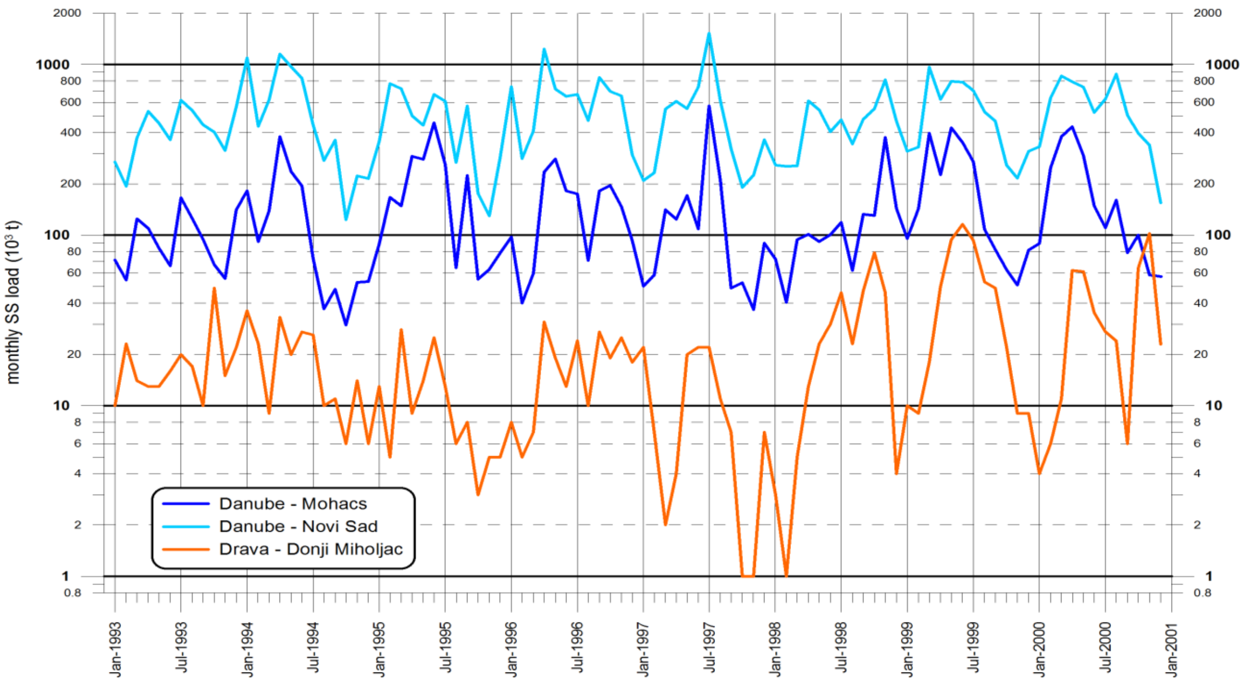

Figure 4.1.9 Values of monthly SS load in the Drava River, compared with those in the Danube at the closest monitoring stations

The Middle Danube section starts downstream of the Medveďov monitoring station. There is no significant tributary in the Hungarian section of the Danube. The mouth of the Drava River (rkm 1,382.000) is situated between the Mohács (rkm 1,446.900) and Novi Sad (rkm 1,257.100) stations (see Figure 4.1.9). The SS load values at the Donji Miholjac station are almost always lower than those at Mohács.

There are three very important tributaries in the Middle Danube section of the Serbian Danube – the Tisa (rkm 1,214.000), Sava (rkm 1,170.000) and Velika Morava (rkm 1,103.000) rivers. Figures 4.1.10 and 4.1.11 show that the values of monthly SS load in the Tisa and Sava rivers were in several cases higher than those measured in the Danube at the closest monitoring stations.

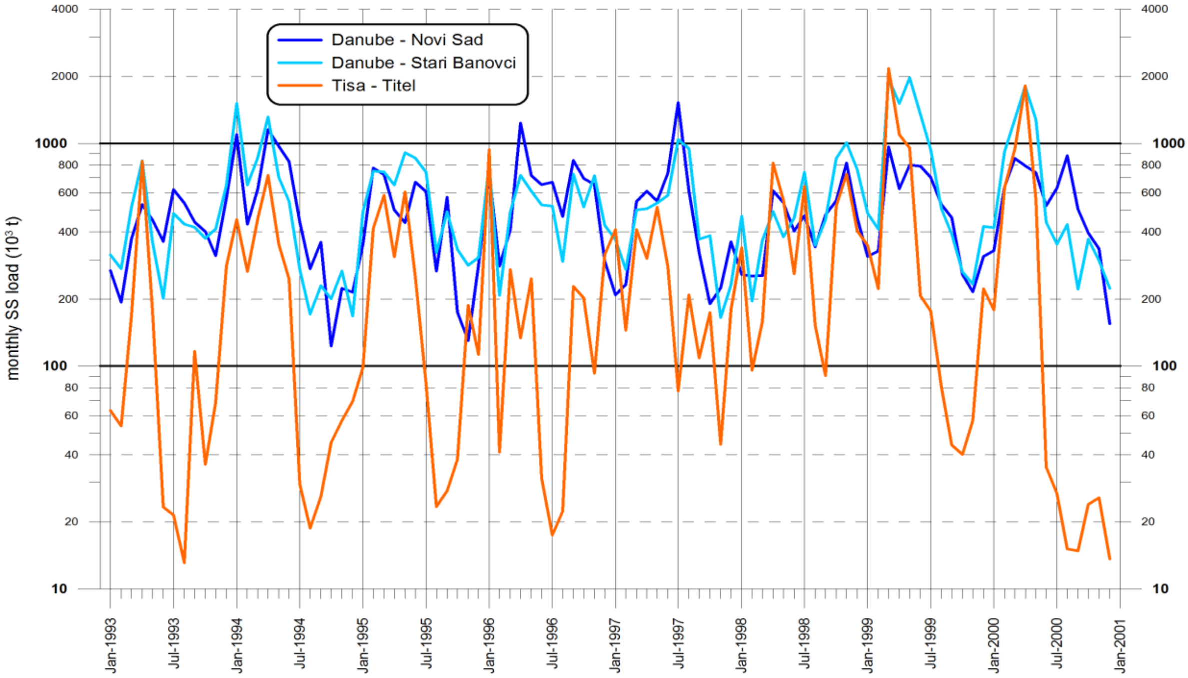

Figure 4.1.10 Values of monthly SS load in the Tisa River, compared with those in the Danube at the closest monitoring stations

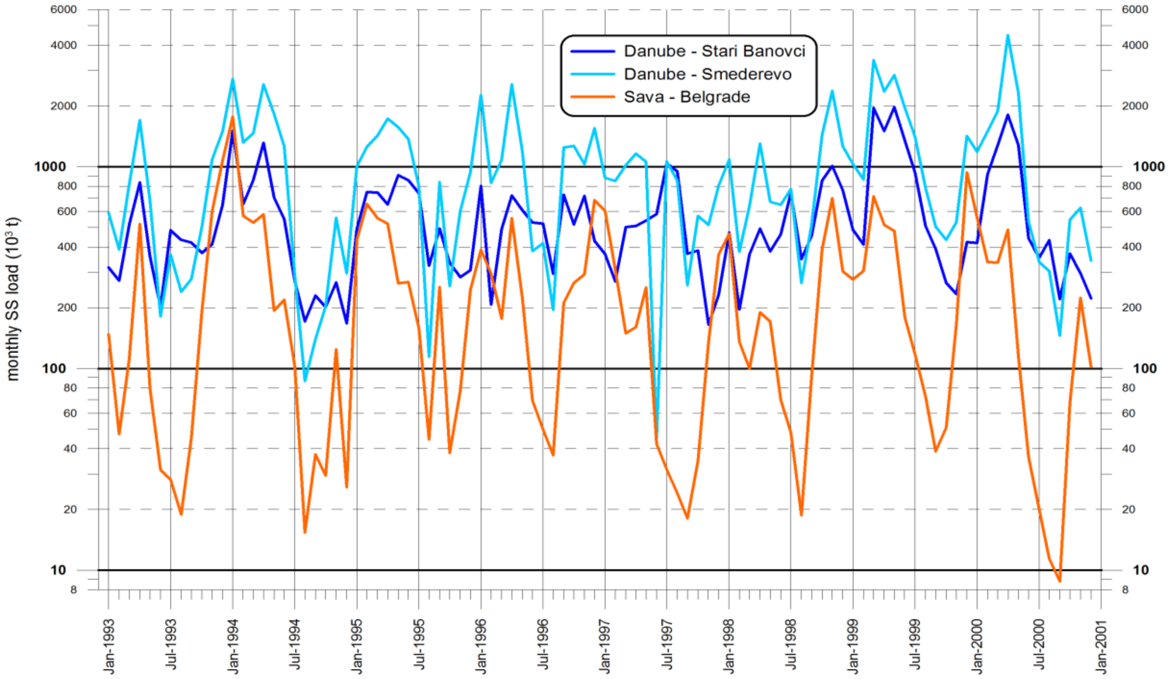

Figure 4.1.11 Values of monthly SS load in the Sava River, compared with those in the Danube at the closest monitoring stations

A comparison of SS load values from the Iron Gate 1 monitoring station with those from the nearest upstream (Smederevo) monitoring station is shown in Figure 4.1.12.

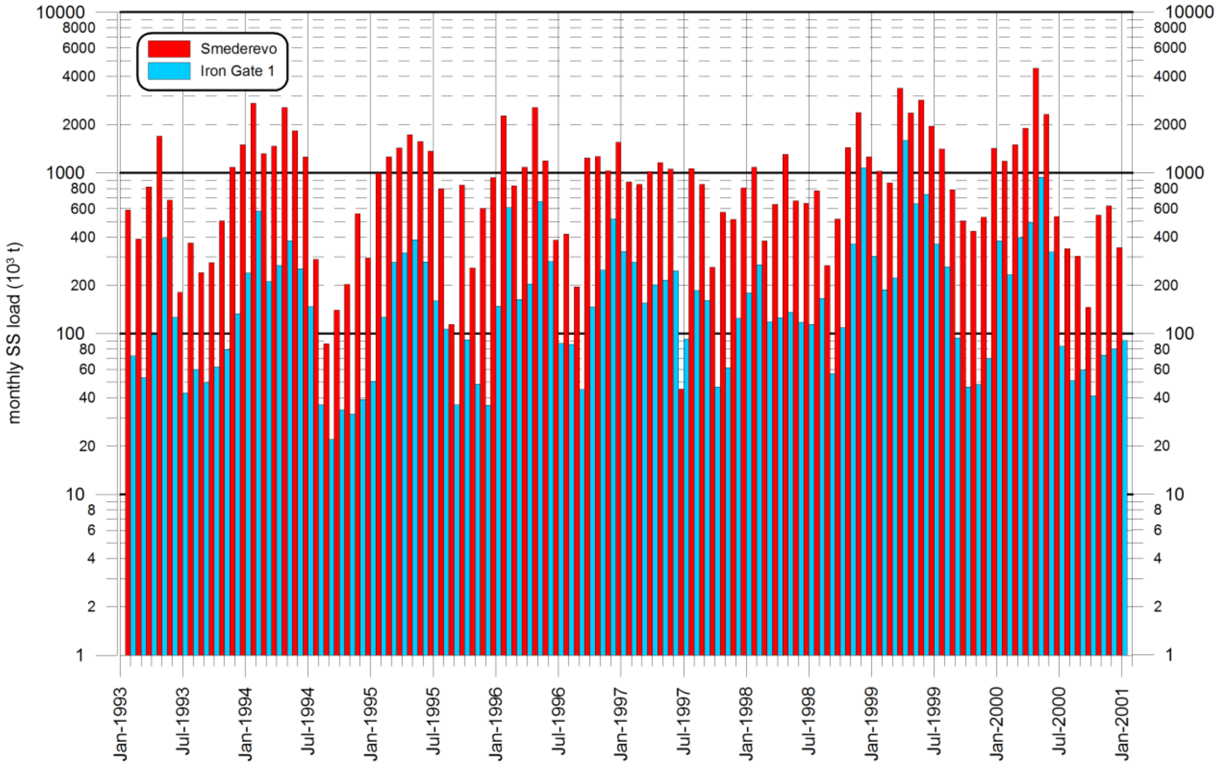

Figure 4.1.12 Values of monthly SS load from the Smederevo and Iron Gate 1 monitoring stations

Figure 4.1.12 indicate prevailing sedimentation in the Iron Gate 1 reservoir. The values of monthly SS load in the tributaries of the Middle Danube are illustrated as a function of discharge in Figure 4.1.13.

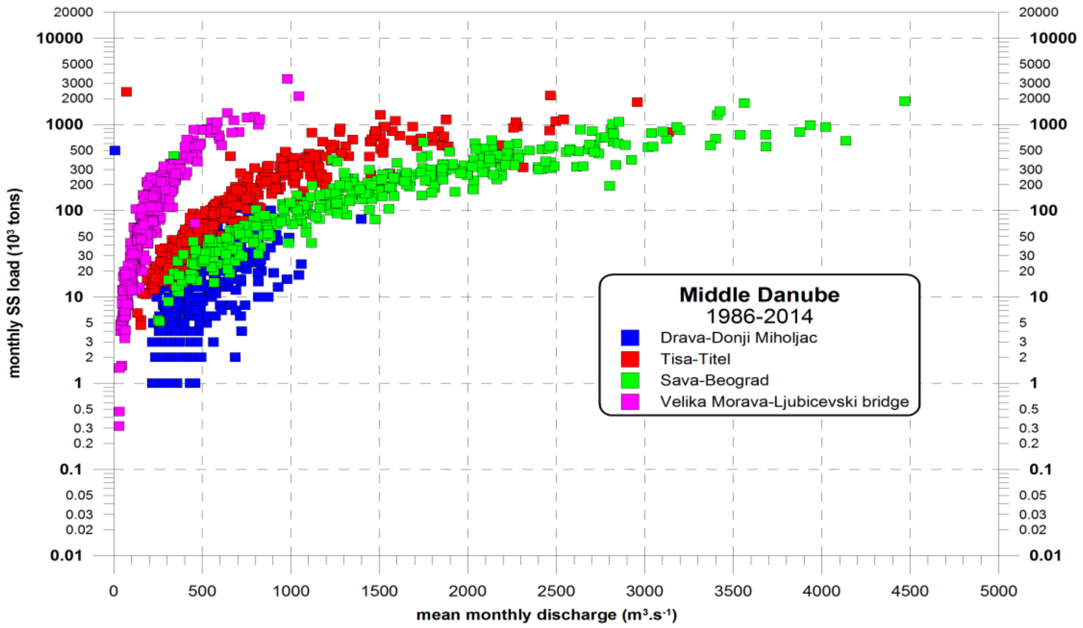

Figure 4.1.13 Values of monthly SS load in the tributaries of the Middle Danube

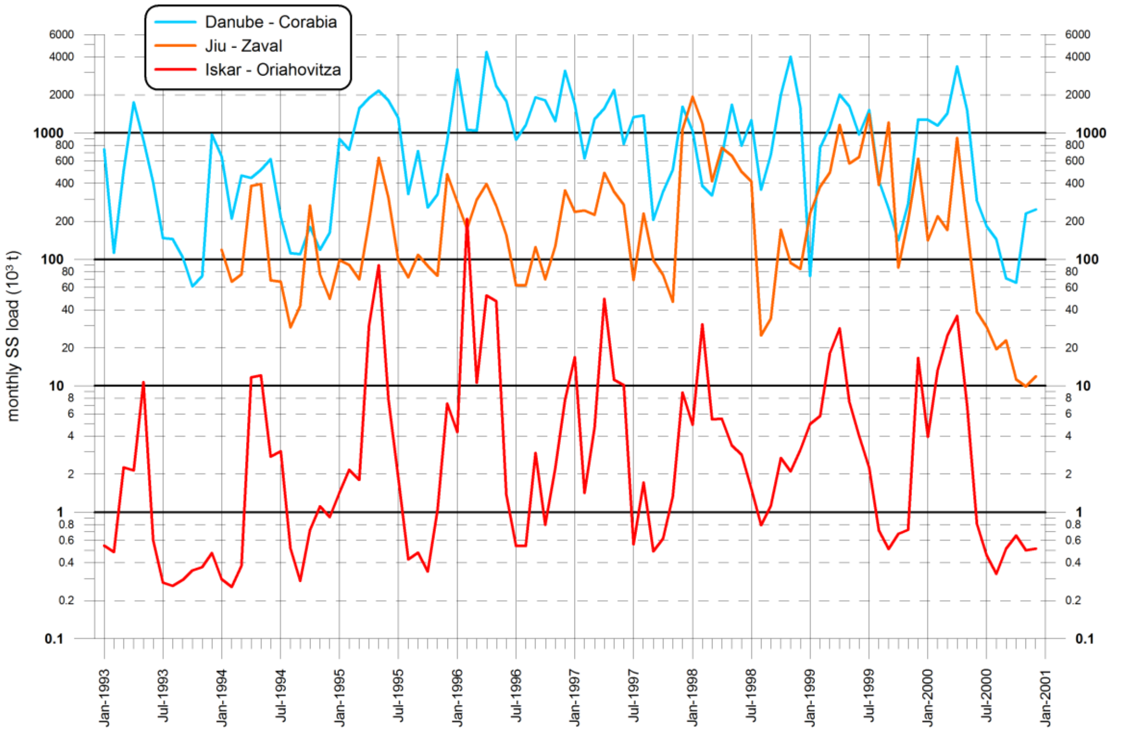

Figure 4.1.14 Values of monthly SS load in the Jiu and Iskar rivers, compared with those in the Danube at the closest monitoring stations

The contribution of the Jiu River (mouth at rkm 694,000), a Danube tributary in Romania, is exceptional (see Figure 4.1.14). The monthly SS load in this river is, in several cases, higher than that in the Danube. The contribution of the Iskar River (mouth at rkm 636,000), a Bulgarian tributary, is much smaller, except in a few cases.

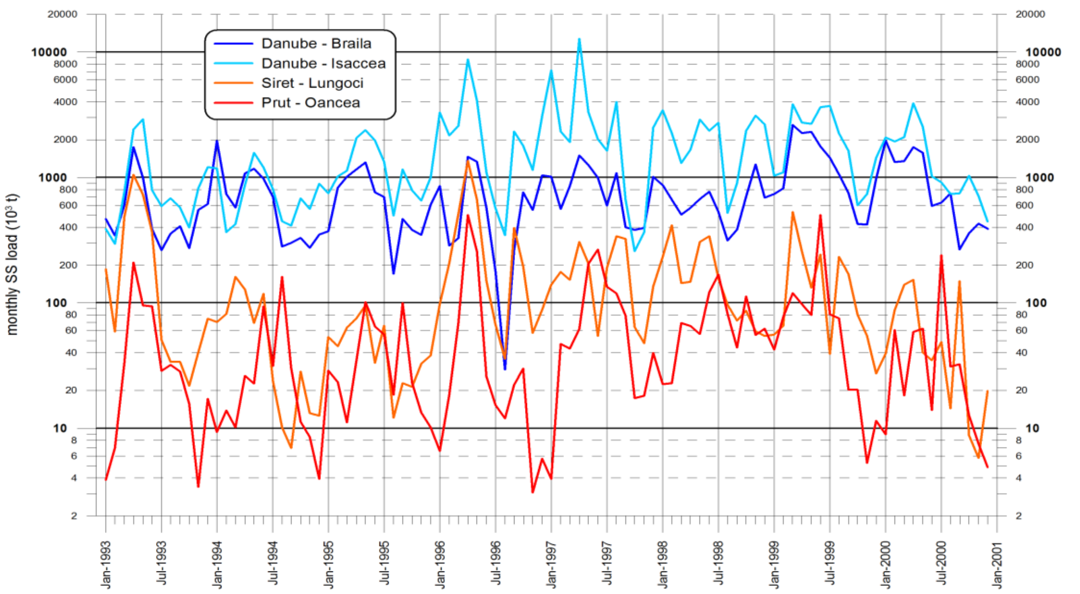

Figure 4.1.15 Monthly SS load in the Siret and Prut rivers, compared with that in the Danube

Other significant tributaries in terms of the SS load are situated further downstream, between the Braila (rkm 167,000) and Isaccea (rkm 100,200) monitoring stations. These are the Siret (mouth at rkm 155,000) and Prut (rkm 132,000) rivers. The corresponding time series of the monthly SS load are shown in Figure 4.1.15.

The values of monthly SS load, depending on the discharge, for the tributaries of the Lower Danube are illustrated in Figure 4.1.16.

Except for the monitoring stations in the Danube delta, the time series of SS load values measured at the Isaccea (rkm 100,200) and Ceatal Izmail (rkm 80,500) stations represent the most downstream river stretch. These values are illustrated in Figure 4.1.17, which shows that the values from Isaccea are usually higher than those from Ceatal Izmail.

Monthly SS load data are also available from the delta area, from three major tributaries, i.e. the Chilia (monitoring station at Periprava, rkm 20,000), S. Gheorge (S. Gheorge station, rkm 8,000) and Sulina (Sulina station, rkm 2,500) rivers – see Figure 4.1.18. The highest SS load values are from the Chilia branch and the lowest from Sulina branch, but there are a few exceptions to this typical pattern.

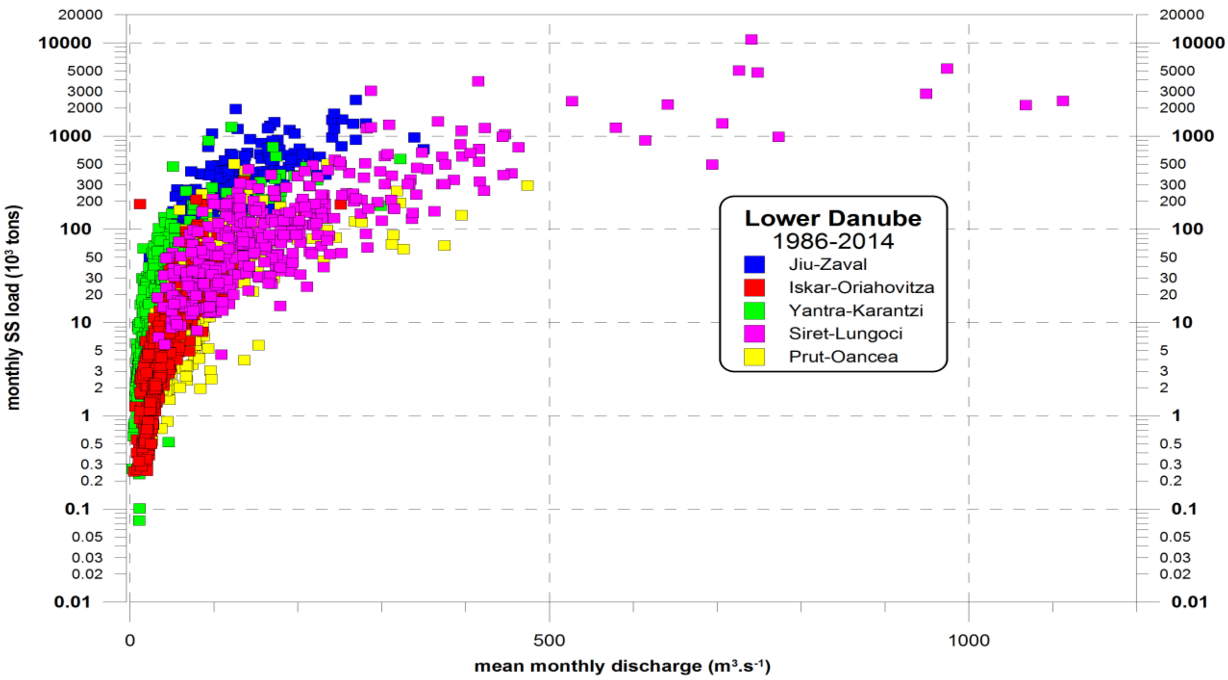

Figure 4.1.16 Values of monthly SS load in the tributaries of the Lower Danube

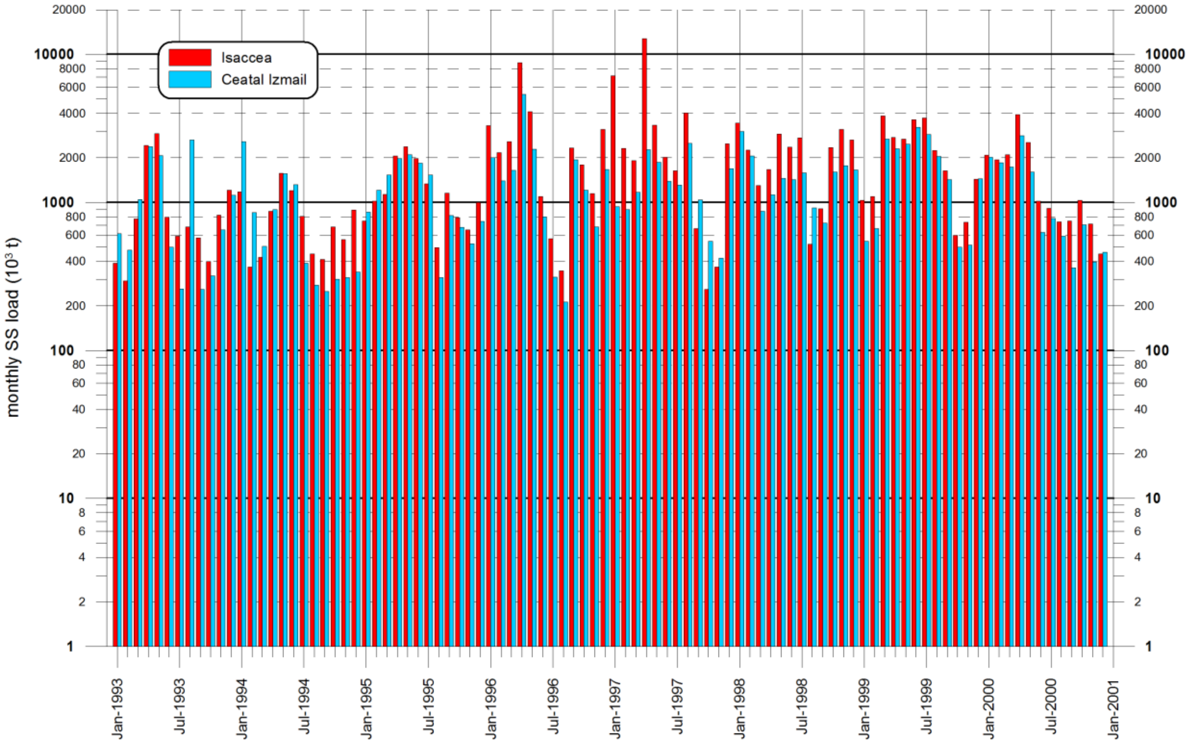

Figure 4.1.17 Values of monthly SS load from the Isaccea and Ceatal Izmail monitoring stations

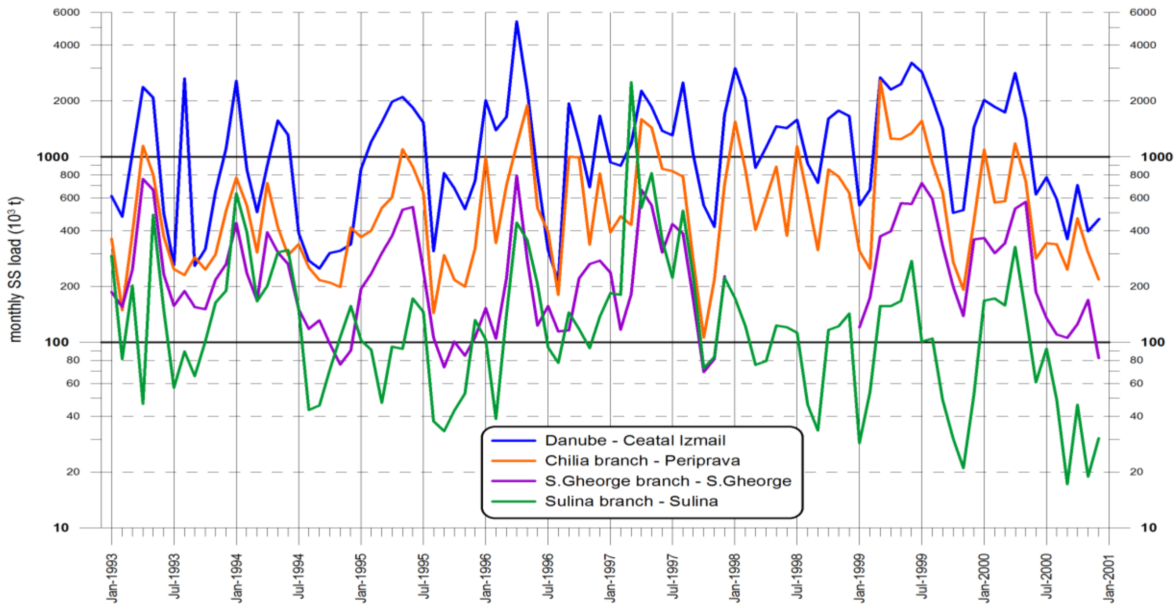

Figure 4.1.18 Values of monthly SS load at Ceatal Izmail, compared with those measured in the Danube Delta

4.2 Bedload

Data on bedload are only available from several stations along the Danube River. The list of these stations with the corresponding values of mean annual bedload transport from measurements is available in Table 4.2.1. The values refer to the period when the Danube hydropower plants were already in operation.

Table 4.2.1 List of bedload data provided by the project partners

Location	River km	Mean annual bedload transport (Kt.year^{-1})
Straubing 1	2,329.300	1.06
Straubing 2	2,321.000	10.98
Pfelling	2,305.500	7.04
Deggendorf	2,283.200	1.89
Halbmeile	2,280.000	22.04
Hofkirchen	2,256.390	29.56
Bad Deutsch Altenburg	1,886.240	438.64
Devin	1,878.150	320.91
Vamosszabadi	1,805.600	14.43
Klizska Nema	1,795.580	550.16
Bazias	1,072.500	54.47
Drobeta Turnu Severin	931.000	18.23
Gruia	858.350	370.84
Corabia	624.200	209.77
Zimnicea	553.230	250.50
Giurgiu	543.000	210.70
Chiciu Calarasi	379.580	212.38
Vadu Oii	238.000	116.56
Braila	167.000	41.48
Isaccea	100.200	56.63
Ceatal Izmail	80.500	35.73

4.3 Data on dredging

The project partners provided information on the quantity of dredged material for the individual national and bilateral river sections. The amounts of sediments dredged from, and fed into, the river channel are one of the main components of the sediment balance equation. Therefore, the related spatial and temporal data are of great importance for the sediment balance assessment, as well as for an analysis of the morphological changes in the river bed (erosion/sedimentation). The terms used are defined as follows: **dredging** means the amount of sediments dredged from the river bed 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/hydropower plants (sediment balance surplus); and **disposal** means the amount of sediments dredged from the river bed 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.

The most complete data were collected for the third period (1991-2016). Some of the partner countries provided detailed data on dredging with smaller or no data gaps, but some countries provided only the total volume of sediments dredged in longer river stretches in selected years. Other countries provided somewhat incomplete data for periods in which certain years are not covered (e.g. HU – limited data) or where a whole period is missing (RS – Period II is covered, but the data for Period III are missing in the national databases and were estimated by Serbian experts for this project). The data collected were sorted by year and river kilometre. In border sections, the data were checked and harmonised to avoid doubling of the dredged quantities.

As the data on dredging enter the sediment balance equation and in order to correctly display the dredged quantities in graphs, the data were harmonised for all countries, using the same methodology. The collected dredging data were summed up every 5 kilometres. For longer sections, the data were evenly distributed along the section where the dredging works were carried out and are summed up in volume every 5 river kilometres. This gave us an overview of the localities and amounts of dredging.

The processed data were sorted into three main sections, namely the Upper, Middle and Lower Danube, and the total volumes of dredging were calculated for these sections in the defined time periods. Metadata on the dredging data provided are summarised in Annex 2 of the Report titled *'Data analyses for the sediment balance and long-term morphological development of the Danube'.*

An overview of the amounts dredged along the Danube in the periods under review is presented in Tables 4.3.1 and 4.3.2 and in Figures 4.3.1 and 4.3.2. As mentioned above, not all the dredging amounts were collected for this project, hence the absolute figures may be incomplete, especially in the historical periods. Detailed graphs showing the dredging localities in the Danubian countries are available in Annex 3 of the Report *'Data analyses for the sediment balance and long-term morphological development of the Danube'*.

Table 4.3.1 Overview of the dredging amounts in the individual river sections and periods

Dredging	Period I	Period II	Period III	∑ (m³)
Upper Danube	3,118,407	30,131,670	16,340,906	**49,590,983**
Middle Danube	2,000,000	200,345,835	46,129,959	**248,475,794**
Lower Danube	2,615,572	55,016,909	36,355,615	**93,988,096**
∑	**7,733,979**	**285,494,414**	**98,826,480**	**392,054,873**

Sediment dredging along the Danube has been performed mainly for water management (river training, navigation and flood protection), hydropower dam construction, and/or for commercial purposes (sale of gravel and sand for construction). Over-dredging for commercial purposes has often caused river bed 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 with the aim of reducing the impact of river-bed degradation, only in several stretches of the Danube in Germany and Austria.

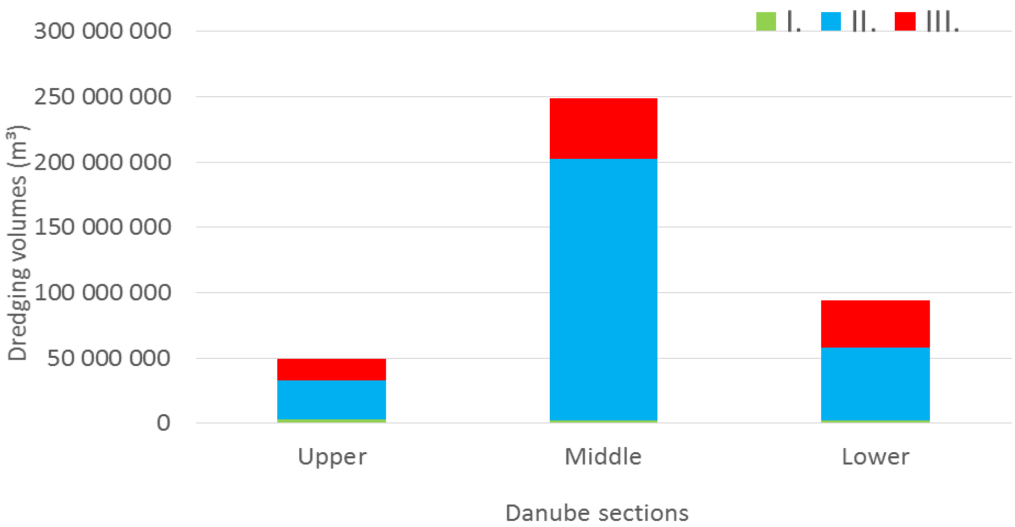

Figure 4.3.1 Dredging in the Upper, Middle and Lower Danube in periods I, II and II

Over the periods under review (I, II, III), from 1920 till 2016, sediments were dredged from the Danube channel in the total amount of almost 400 million m^3 (Table 4.3.1). The largest amount was dredged in Period II (285 million m^3) in connection with the construction of major projects on the Danube, such as the Gabčíkovo and Iron Gates HPPs (Table 4.3.1). The largest amounts were dredged in the Middle Danube section, mainly in Serbia (Figure 4.3.2). In Period III, the volume of dredging rapidly decreased to less than 100 million m^3 along the whole Danube, owing to a decline in construction in the Danubian countries, coupled with legislative changes forbidding commercial dredging and bed material removal out of the river channel.

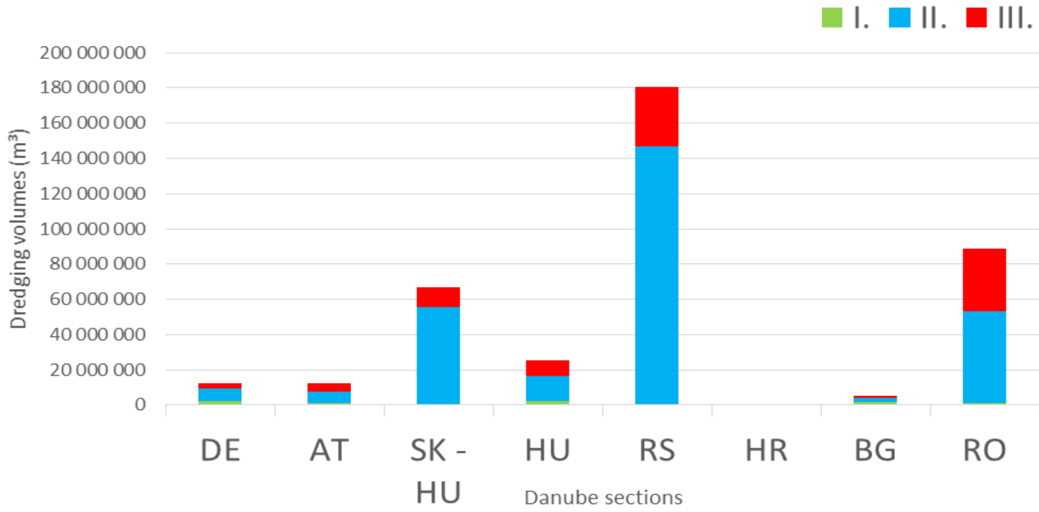

Figure 4.3.2 Volumes of sediments dredged in the Danubian countries in periods I-III

Table 4.3.2 Volumes of sediments dredged broken down by country and period

Dredging	Period I	Period II	Period III	∑ (m³)
DE	2,223,044	7,122,568	3,199,806	12,545,418
AT	895,363	6,473,359	4,942,592	12,311,314
SK - HU		55,725,743	11,354,255	67,079,998
HU	2,000,000	14,295,835	9,197,897	25,493,732
RS		146,860,000	33,458,859	180,318,859
HR			317,456	317,456
BG	1,508,572	2,768,188	1,048,358	5,325,118
RO	1,107,000	52,248,721	35,307,257	88,662,978
∑	7,733,979	285,494,414	98,826,480	392,054,873

At the present time, sediment dredging is performed mostly for improving flood protection, maintaining the navigational channel, and increasing the storage capacity of reservoirs upstream of hydropower plants, and at the mouths of tributaries in impounded river stretches and in harbours.

4.4 Data on morphological changes in the Danube channel

Within the scope of Work Package 4.1, morphological data were collected, sorted and analysed. Their analysis has revealed 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 for the national stretches of the Danube. Table 4.4.1 provides an overview of the availability of data on morphological changes in the Danube channel, based on bathymetric measurements in cross sections.

The above table indicates that there is very wide temporal variety of cross sections and of data on morphological changes occurring in the river channel, which limits the applicability of the sediment budget approach.

The data on river-bed changes in the Danube (erosion and sedimentation) received from the partner countries were different in quality, format, density and structure. Data from the Middle (Hungary) and Lower Danube (Romania) were corrected and modified several times, which made the process of quantification of the river processes in this part of the Danube rather time-consuming. Data provided by countries on erosion (-) and sedimentation (+) were calculated for river stretches of various distances depending on the available (measured) cross sections, which formed a basis for the evaluation of river-bed changes. (More information about the methodology used to evaluate erosion/sedimentation from the cross sections is available in the Report *'Data analyses for the sediment balance and long-term morphological development of the Danube' – Chapter 4.1).* The length of the evaluated stretches ranged from 100 m to several kilometres. As the calculated volume of erosion and sedimentation represented stretches of different lengths, it was necessary to harmonise the data with comparable stretches and volumes.

Table 4.4.1 Availability of data on erosion/sedimentation (E/S) in the river channel

from rkm	to rkm	Data on E/S		from rkm	to rkm	Data on E/S
2,581	2,557	1990-2016		2,146	2,120	2001-2007
2,556	2,546	2010-2017		2,119	2,039	2001-2014
2,545	2,540	1990-2016		2,038	2,011	2001-2016
2,539	2,513	2007-2010		2,010	1,980	2001-2013
2,512	2,509	1990-2016		1,979	1,950	2001-2017
2,508	2,471	2007-2010		1,949	1,873	2001-2016
2,470	2,456	2003-2007		1,880	1,861	1991-2017
2,455	2,445	2010-2017		1,860	1,843	no data
2,444	2,432	1990-2016		1,842	1,812	1991-2013

from rkm	to rkm	Data on E/S	from rkm	to rkm	Data on E/S
2,431	2,402	2003-2017	1,811	1,709	1993-2013
2,401	2,397	1990-2016	1,811	1,584	2003-2016
2,396	2,382	2007-2010	1,583	1,581	2003-2007
2,381	2,378	1990-2016	1,580	1,433	2003-2016
2,377	2,355	2007-2010	1,433	1,175	2008-2015
2,354	2,330	2010-2017	1,174	943	1988-2014
2,329	2,203	1990-2016	942	937	no data
2223	2,204	2002-2017	936	846	1985-2014
2203	2,147	2001-2015	850	80,6	2008-2017

Therefore, the river stretches had to be divided into 100 m-long sections with corresponding erosion/sedimentation. In the next step, the values for 10 sections were summed up and thus provided the total volume of erosion/sedimentation for every river kilometre. It is clear that the length of the sections has a great influence on the results and that too long sections can cause uncertainties and errors in the sediment balance. However, in order to complete the balance for the whole Danube, this uncertainty must be accepted.

The dredging data provided (Chapter 4.3) were all coupled with the data on morphological changes (erosion and sedimentation volumes) in the respective stretches and periods, and are also illustrated in the graphs showing the morphological changes.

Overview of data density and coverage of the Danube stretches in the years 1991-2016

Germany

Period III - In Germany, there is no consecutive dataset from one specific year for the whole Danube. Owing to the federal approach to management in Germany, several authorities are responsible for different stretches of the river. However, owing to the length of the river and the time-consuming measurement procedure, no coordinated campaign has so far been conducted for the whole river. Therefore, several sub-periods are used (1990-1995, 1995-2000, 2000-2003, 2003-2007, 2007-2010, 2010-2017) to evaluate the process of erosion/ sedimentation in the individual river stretches. For example, the longest period evaluated (1990-2016) covers only about 55% of the German section of the Danube. In general, the data are of good quality, and the responsible entities calculate erosion/sedimentation in 100-200 m-long stretches. This makes the volumetric analysis very accurate, but spatially limited owing to the shortness of the river stretches under analysis. For details about the evaluation procedure, see the report on *'Data analyses for the sediment balance and long-term morphological development of the Danube – Chapter 4.1'.*

Austria

Period III – the best available data on river-bed changes in the Austrian Danube cover the period from 1991 to 2001 along the river section between rkm 2,203.2 and rkm 1,872.7 – erosion/sedimentation volumes are evaluated every 500 m. Also available are datasets from the periods 1991-2002, 2002-2017, 2001-2017, 2001-2008, 2001-2016, 2001-2015, 2001-2014, 2001-2013, and 2008-2016 with the erosion/sedimentation volumes calculated every 500 m, but only short river stretches are covered within the given years (20 to 80 km) – see Figure 4.4.1 (already published in the report titled *'Long-term Morphological Development of the Danube in Relation to the Sediment Balance'*).

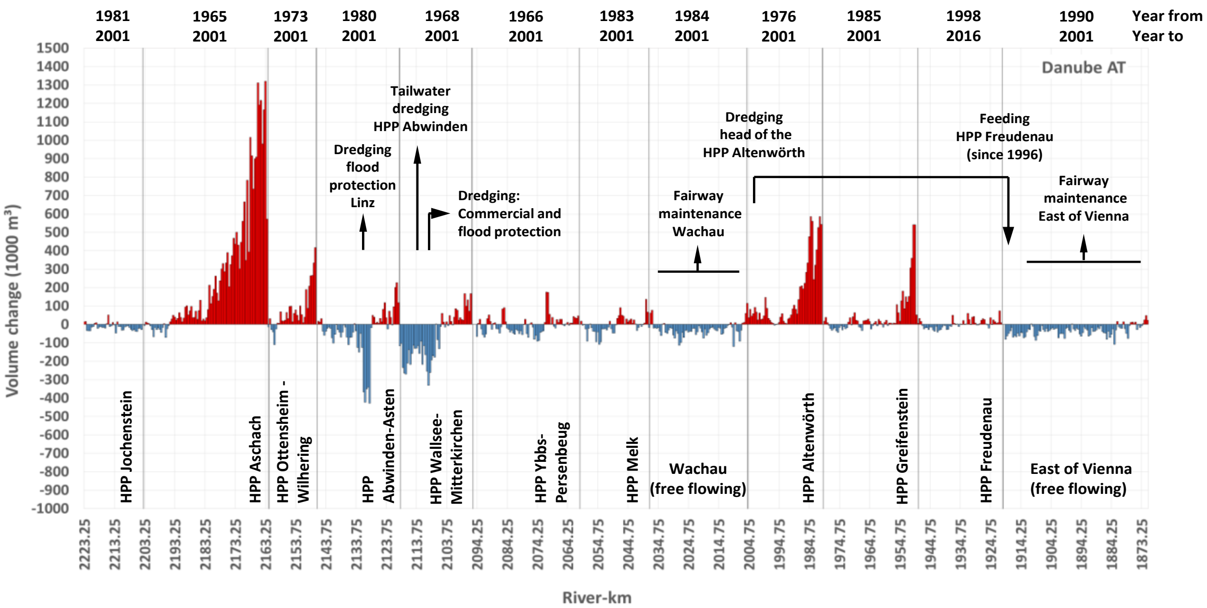

Figure 4.4.1 Bathymetry: Erosion (blue) and sedimentation (red) in 500 m-long stretches from the first measurement until 2001 (for the stretch including the Freudenau HPP since 1998)

Slovakia

Period III – the evaluation of erosion and sedimentation in volume terms covers almost the entire Slovak section of the Danube, except for a stretch between rkm 1,861 and rkm 1,843. The Slovak Danube is covered as follows: rkm 1880-1861 in the years 1991-2017 and rkm

1842-1709 in the years 1993-2013 (Figure 4.4.2, already published in the report *'Long-term Morphological Development of the Danube in Relation to the Sediment Balance'*).

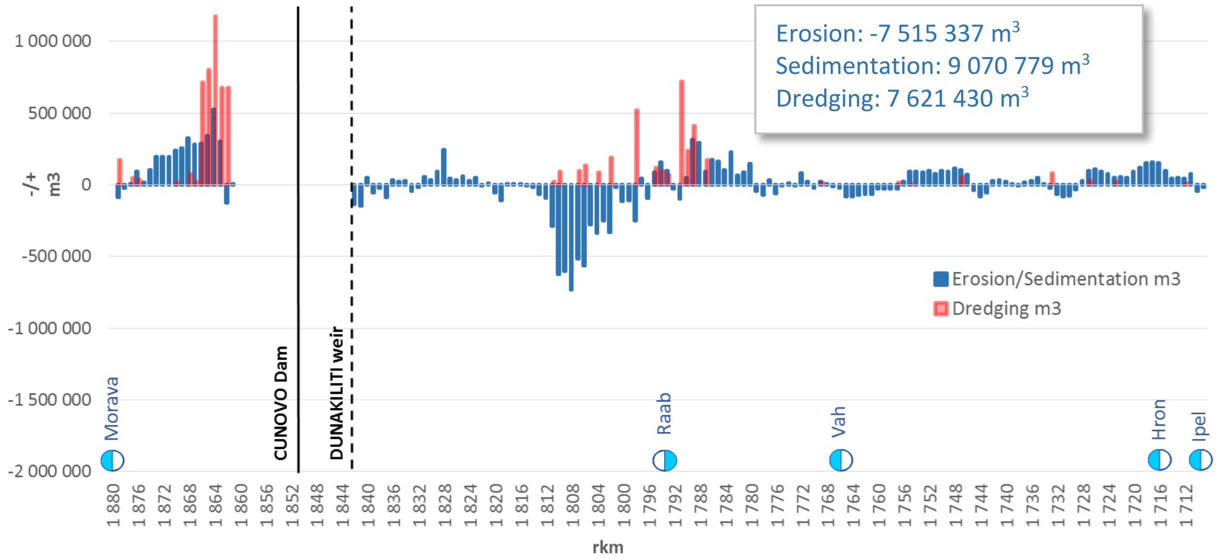

Figure 4.4.2 Bathymetric changes in the river bed (erosion/sedimentation) recalculated for 1 km-long stretches of the Danube and sediment dredging in its Slovak section in Period III

Hungary

Period III – the full length of the Hungarian Danube (rkm 1,811-1,433) was first covered by datasets from 2003-2007 and 2007-2016. Later, the quality of source data used for evaluating the river-bed changes was verified and different datasets were provided to achieve more reliable results. The new datasets covered only the river section in Hungarian territory (rkm 1,708-1,433) and were from different periods (1996-2004, 2004-2013 a 2013-2016) with 1 km-long evaluation stretches. As the data from these consecutive periods cover the entire Hungarian section, the river-bed changes were also evaluated for a longer period, i.e. from 1996 to 2016 (see Figure 4.4.3, already published in the report titled *'Long-term Morphological Development of the Danube in Relation to the Sediment Balance'*).

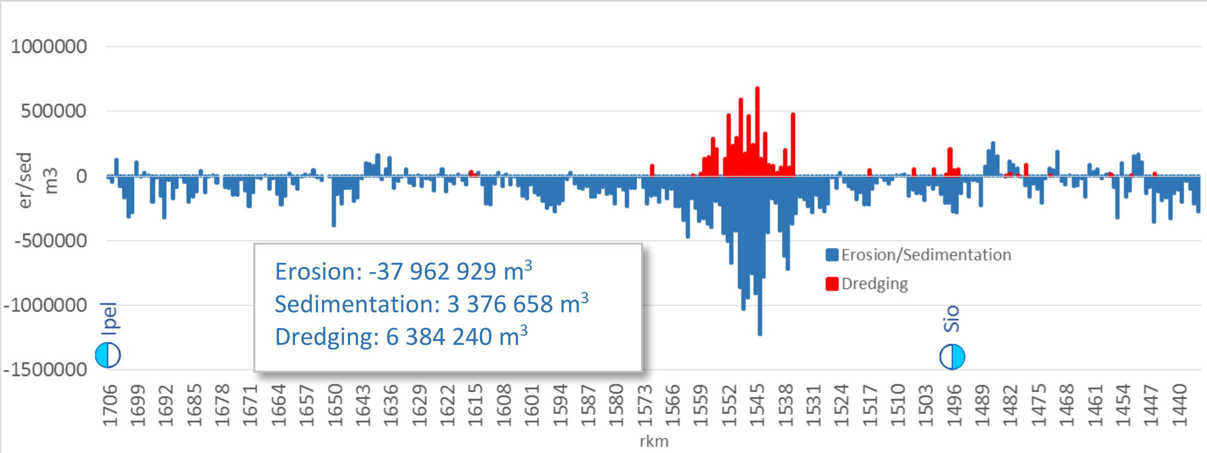

Figure 4.4.3 Bathymetric changes in the river bed (erosion/ sedimentation) recalculated for 1 km-long stretches of the Danube and sediment dredging in its Hungarian section in Period III

Croatia

The river-bed changes in the Croatian section of the Danube (from rkm 1,427 to rkm 1,298) were quantified only for a short period (2011-2016) and the evaluated stretches were too long (5 to 13 km). Therefore, the Serbian datasets were used for this Danube section in a further analysis.

Serbia

Period III – erosion and sedimentation in the Serbian section of the Danube were evaluated for three periods: 2008-2015 (rkm 1,433-1,174), 1988-2014 (rkm 1,174-943) and 1985-2014 (rkm 936-846). The evaluated stretches were 100 to 1000 meters long. The volumes of erosion and sedimentation along the Serbian Danube in Period III are shown in Figure 4.4.4 (already published in the report titled *'Long-term Morphological Development of the Danube in Relation to the Sediment Balance'*).

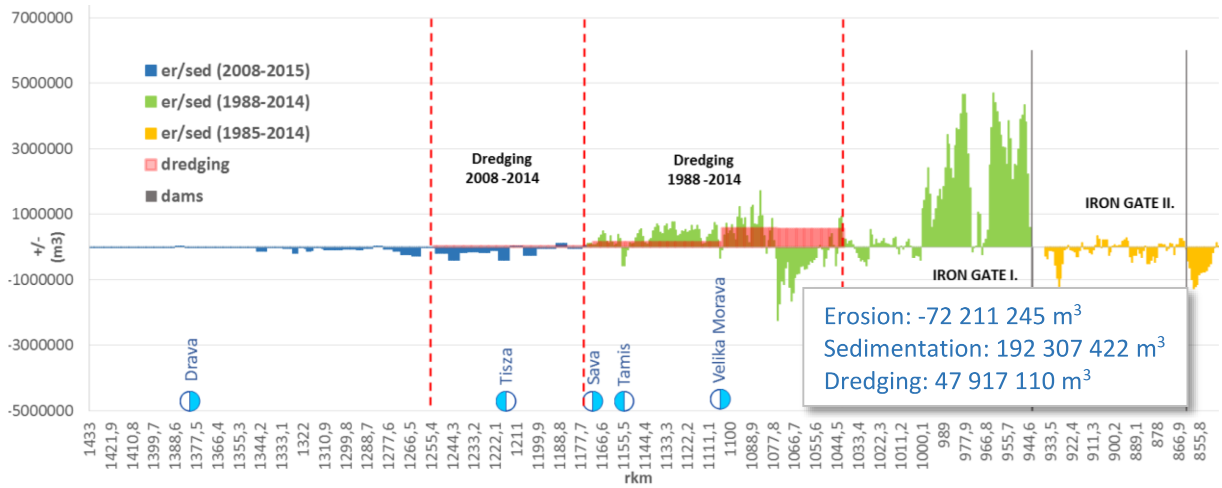

Figure 4.4.4 Bathymetric changes of the river bed (erosion/sedimentation) including dredging in the Serbian/Croatian, Serbian, and Serbian/Romanian sections of the Middle Danube (rkm 1,433-849) in Period III (volumes calculated for 100 m-long stretches)

Romania

Period III – Initially, data on river-bed changes provided for the Romanian section of the Danube (rkm 1,072 to rkm 80) were evaluated for the period 1991-2004. The volumes of erosion/sedimentation were, however, evaluated from only 11 cross sections for a distance of 20 to 232 kilometres, which do not enable a correct quantification of the river-bed changes along the Lower Danube. After long discussions, denser data were prepared by our Romanian colleagues for the Danube from rkm 850 to rkm 80 and the sedimentation/ erosion volumes were calculated for the period 2008-2017. These volumes were calculated from cross sections covering a distance 300 meters up to 67 kilometres. Further attempts to improve the data quality and the methodology used for evaluating the erosion and sedimentation volumes resulted in a dataset (final version) covering the Danube channel from rkm 865.5 to rkm 80.5 (period 2008-2017). But unfortunately, the river stretch between rkm 375 and rkm 80 was evaluated on the basis of cross sections with long distances between them (up to 30 km in some cases; i.e. 8.5 km on average). It can be stated that the data downstream of rkm 375 are not precise enough for evaluating the erosion and sedimentation processes. Moreover, only river-bed changes comparing two years (2008 and 2017) were evaluated and no historical data were available for the Lower Danube with appropriate spatial resolution.

5. Sediment balance assessment

Sediment balance assessment is accounting for the sources (surpluses) and sinks (deficits) of sediments within the spatial and temporal scales under investigation. Work Package 4, in particular Activity 4.2 'Sediment Balance Assessment', focuses on quantifying the surplus or deficit of sediments along the Danube.

The report on *'Sediment Data Analysis in the Danube River'* published by the Budapest University of Technology and Economics (BME) within the scope of the DanubeSediment project's previous phase contains the results of a basic analysis of data on suspended sediments.

The river's longitudinal profile showing the variations in the mean annual suspended sediment load has been compiled for the period 1986-2016, along with a comparison with the data from the period before the HPPs were constructed (Figure 5.1). These data were used as input data in estimating the sediment budget and identifying the river stretches with a suspended sediment deficit and surplus.

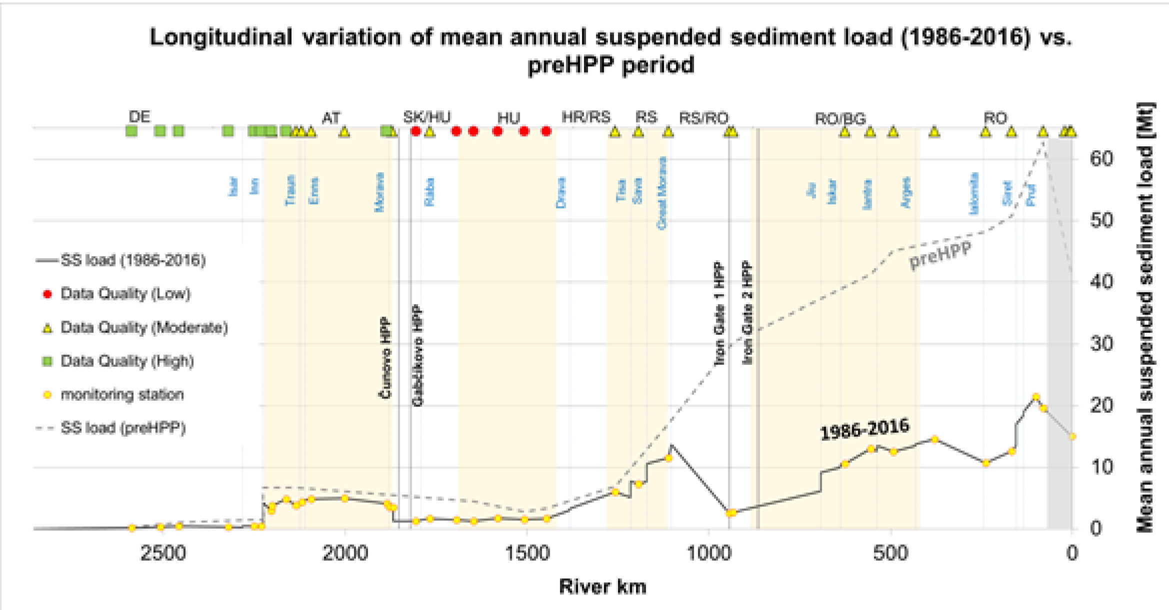

Figure 5.1 Longitudinal variations in the mean annual suspended sediment load along the Danube in the long term (1986-2016), compared with the period when the hydropower plants were not yet in operation (Author: Sándor Baranya, BME)

Bedload transport along the Upper Danube has been restricted by the construction of a chain of HPPs and sediment input reduced by the damming of the tributaries. Therefore, local changes in the river bed occur only in free-flowing stretches. Depending on the availability of data and their spatial and temporal consistency, two approaches were used to assess the sediment balance:

- suspended sediment balance (deficit and surplus) calculated for the whole Danube;
- extended sediment budget for the pilot stretch between the Čunovo weir (Gabčíkovo HPP) and Iron Gate 1 (rkm 1,842 to rkm 943), which includes the suspended sediment load, erosion/sediment deposition in the river bed, and dredging (sediment storage).

Surpluses and deficits of suspended sediments, including the contributions of tributaries, were identified along the whole Danube for the most complete time series (1993-2000). An extended sediment budget was estimated for the free-flowing part of the Danube, from the Hrušov reservoir (Čunovo weir) to Iron Gate 1 (rkm 1,842 to rkm 943) for Period III (1991-2016). Unfortunately, some of the components of the sediment balance equation (Eq. 2.1) are not monitored in the Danubian countries and are therefore not available. Such components are the sediment input from bank erosion, sediment deposits in the floodplains and groyne fields, and river-bed material abrasion. Moreover, bedload monitoring along the Danube is rather scarce (there are only a few monitoring sites) and performed irregularly during measurement campaigns. Therefore, the quantification of river-bed changes from bathymetric data supplements the sediment balance equation's known components and provides information on the sediment storage Δs (Eq.2.1), reflecting the morphological changes, as the river bed in the pilot section under evaluation (Čunovo-Iron Gate 1) is shaped by bedload transport. The volumes of river-bed changes (erosion and sedimentation) were used for calculating the average annual river-bed changes in the river stretch under investigation, as well as in the partial stretches between the monitoring stations.

Within the scope of the sediment balance analyses, the Danube channel was divided into partial stretches, in view of the locations of the stations that form a monitoring network for suspended sediments. The partial river stretches are delimited simply by the neighbouring monitoring stations. These river stretches are listed in the Table 5.1.

Table 5.1: List of the partial Danube stretches used in the analyses

River stretch	rkm upstream	rkm downstream	length (km)
Neu Ulm – Ingolstadt	2,586.700	2,457.850	128.850
Ingolstadt – Straubing	2,457.850	2,321.290	136.560
Straubing – Vilshofen	2,321.290	2,249.470	71.820
Vilshofen – Kachlet	2,249.470	2,230.800	18.670

River stretch	rkm upstream	rkm downstream	length (km)
Kachlet – Jochenstein	2,230.800	2,203.300	27.500
Jochenstein – Engelhartszell	2,203.300	2,200.660	2.640
Engelhartszell - Aschach	2,200.660	2,161.270	39.390
Aschach – Linz	2,161.270	2,135.170	26.100
Linz – Abwinden Asten	2,135.170	2,119.940	15.230
Abwinden Asten – Wallsee-Mittenkirchen	2,119.940	2,094.210	25.730
Wallsee-Mittenkirchen – Stein-Krems	2,094.210	2,002.690	91.520
Stein-Krems – Bad Deutsch-Altenburg	2,002.690	1,887.000	115.690
Bad Deutsch Altenburg – Devin	1,887.000	1,878.150	8.850
Devin – Bratislava	1,878.150	1,871.300	6.850
Bratislava – Medveďov	1,871.300	1,806.300	65.000
Medveďov – Komárno	1,806.300	1,767.800	38.500
Komárno – Nagymaros	1,767.800	1,694.600	73.200
Nagymaros – Budapest	1,694.600	1,646.500	48.100
Budapest – Dunaújvaros	1,646.500	1,580.600	65.900
Dunaujváros – Dombori	1,580.600	1,506.800	73.800
Dombori-Mohács	1,506.800	1,446.900	59.900
Mohács – Novi Sad	1,446.900	1,257.100	189.800
Novi Sad – Stari Banovci	1,257.100	1,192.350	64.750
Stari Banovci – Smederevo	1,192.350	1,110.400	81.950
Smederevo – Iron Gate1	1,110.400	943.000	167.400
Iron Gate1 – Corabia	943.000	624.200	318.800
Corabia – Zimnicea	624.200	553.230	70.970
Zimnicea – Giurgiu	553.230	543.000	10.230

River stretch	rkm upstream	rkm downstream	length (km)
Giurgiu – Chiciu Calarasi	543.000	379.580	163.420
Chiciu Calarasi – Vadu Oii	379.580	238.000	141.580
Vadu Oii – Braila	238.000	167.000	71.000
Braila – Isaccea	167.000	100.200	66.800
Isaccea – Ceatal Izmail	100.200	80.500	19.700

5.1 Assessment of the suspended sediment balance

As mentioned above, incomplete data allow sediment balance assessment only for suspended sediments. For the partial stretches of the Danube listed in Table 5.1, the deficits and surpluses of the river's suspended sediment load (SS load, monthly values) were calculated from the values measured at the neighbouring monitoring stations, where sediment inputs from the tributaries are also taken into account. For the partial river stretches, we calculated the differences in the annual SS load (dSSL) by simply subtracting the values measured upstream from those measured downstream:

$$dSSL = SSL_{DS} - SSL_{US} \tag{5.1}$$

where:
SSL_{DS} – SS load at the monitoring station situated downstream
SSL_{US} – SS load at the monitoring station situated upstream

A positive value of dSSL indicates a suspended sediment **surplus**, whereas a negative value indicates a suspended sediment **deficit** for the river stretch under analysis. The resulting maximum and minimum dSSL values and the cumulative dSSL are summarised in Table 5.1.1 and are graphically illustrated in Annex 3.

The spatial distribution along the Danube of river stretches with a surplus (marked green) or deficit (marked orange) of suspended sediments (average annual values for the period 1993-2000), based on the results summarised in Table 5.1.1, is displayed in the map in Figure 5.1.1.

Table 5.1.1 Differences in the annual SS load for the partial river stretches calculated from monthly values

River stretch	Period 1993 – 2000			
	dSSL – MAX (10^3t)	dSSL – MIN (10^3t)	SUM dSSL (10^3t)	Average annual value (10^3t)
Neu Ulm – Ingolstadt	1,249.8	-12.8	3,251.7	406.5
Ingolstadt – Straubing	41.4	-1,151.4	-2,100.6	-262.6
Straubing – Vilshofen	277.1	-22.9	2,082.1	260.3
Vilshofen – Kachlet	71.7	-180.7	429.4	53.7
Kachlet – Jochenstein	2,472.4	-18.7	18,187.4	2,273.4
Jochenstein - Engelhartszell	1,628.6	-84.5	5,068.2	633.5
Engelhartszell - Aschach	4,935.0	-227.0	4,372.0	546.5
Aschach – Linz	190.0	-4,534.0	-6,692.0	-836.5
Linz – Abwinden-Asten	1,520.0	-561.0	3,455.0	431.9
Abwinden-Asten – Wallsee-Mittenkirchen	954.0	-1,253.0	-1,656.0	-207.0
Wallsee-Mittenkirchen – Stein-Krems	1,233.0	-555.0	5,216.0	652.0
Stein-Krems – Bad Deutsch Altenburg	696.0	-1,032.0	-6,167.0	-770.9
Bad Deutsch Altenburg – Devin	583.2	-1,724.0	762.9	95.4
Devin – Bratislava	111.9	-34.2	-659.1	-82.4
Bratislava - Medveďov	-6.8	-1,470.9	-16,702.7	-2,087.8
Medveďov – Komárno	821.4	-100.8	5,600.1	700.0
Komárno – Nagymaros	99.9	-788.0	-3,553.0	-444.1
Nagymaros – Budapest	-1.8	-129.7	-1,467.3	-183.4
Budapest – Dunaujváros	299.8	1.3	4,208.2	526.0
Dunaujváros – Dombori	2.8	-89.8	-1,991.5	-248.9
Dombori – Mohács	42.3	-30.8	1,179.9	147.5
Mohács – Novi Sad	998.3	67.0	35,434.1	4,429.3
Novi Sad – Stari Banovci	1,173.1	-514.8	6,949.6	868.7
Stari Banovci – Smederevo	2,668.6	-538.4	42,548.5	5,318.6
Smederevo – Iron Gate1	47.0	-3,535.7	-77,853.1	-9,731.6
Iron Gate1 – Corabia	3,717.3	-479.4	73,893.5	9,247.9
Corabia – Zimnicea	3,053.4	-915.0	32,256.4	4,032.1
Zimnicea – Giurgiu	1,716.9	-2,892.7	-8,673.0	-1,084.1
Giurgiu – Chiciu Calarasi	1,982.0	-2,177.5	-1,384.4	-173.1
Chiciu Calarasi – Vadu Oii	1,140.5	-4,458.2	-43,368.3	-5,421.0
Vadu Oii – Braila	1,644.5	-766.0	2,521.6	315.2
Braila – Isaccea	11,283.0	-779.4	99,427.3	12,428.4
Isaccea – Ceatal Izmail	1,961.7	-10,513.2	-51,531.3	-6,441.4

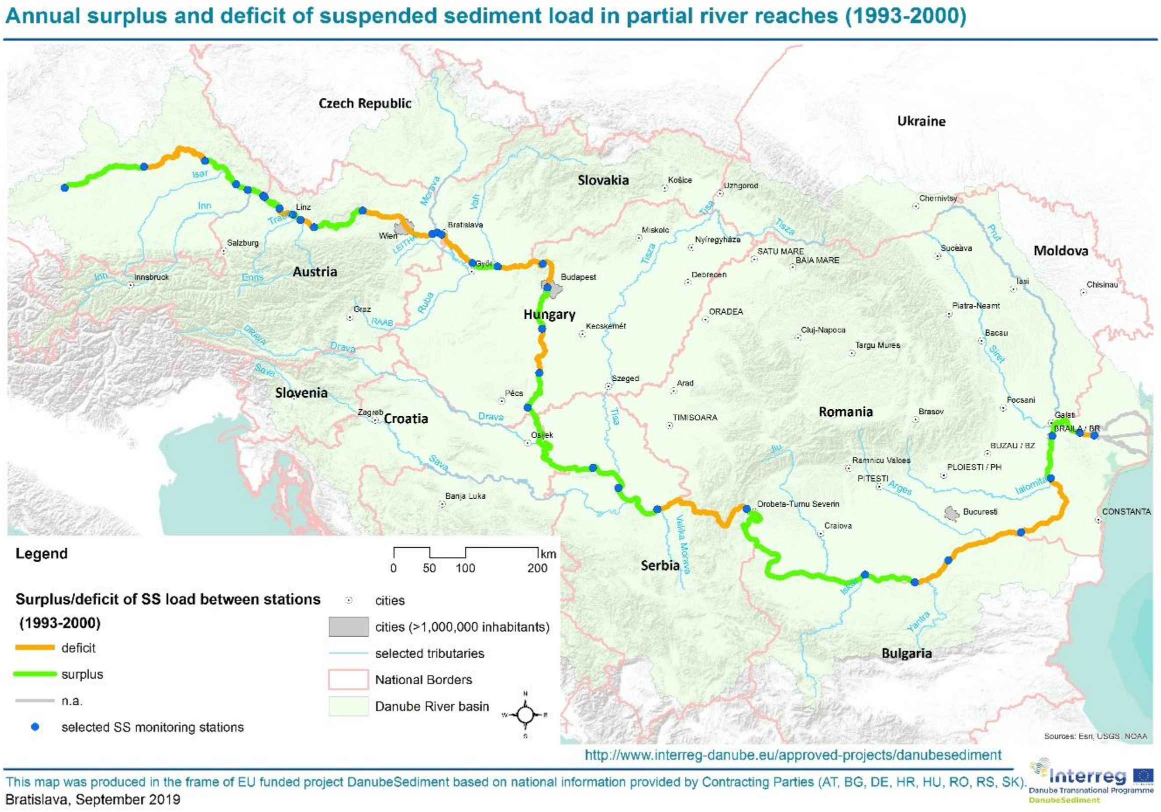

Figure 5.1.1 Annual surplus or deficit of suspended sediments in the partial river stretches (measured at the downstream station)

The largest suspended sediment deficits in the period 1993-2000 were measured at the downstream stations of the following river stretches:

- Smederevo – Iron Gate 1 (-77.9 Mt cumulated value, vs -9.7 Mt annually);
- Isaccea – Ceatal Izmail (-51.5 Mt, vs -6.4 Mt);
- Chiciu Calarasi – Vadu Oii (-43.4 Mt, vs -5.4 Mt);
- Bratislava – Medveďov (-16.7 Mt, vs -2.1 Mt);

The large deficit in the stretch between Smederevo and Iron Gate reflects sediment deposition in the Iron Gate 1 reservoir (see Figure 5.1.2). The impact of the Gabčíkovo hydropower scheme, i.e. sedimentation in the Hrušov reservoir downstream of Bratislava, is evident from the values for the Bratislava–Medveďov river stretch. The largest sediment deficit recorded in the Upper Danube section can be found in this river stretch.

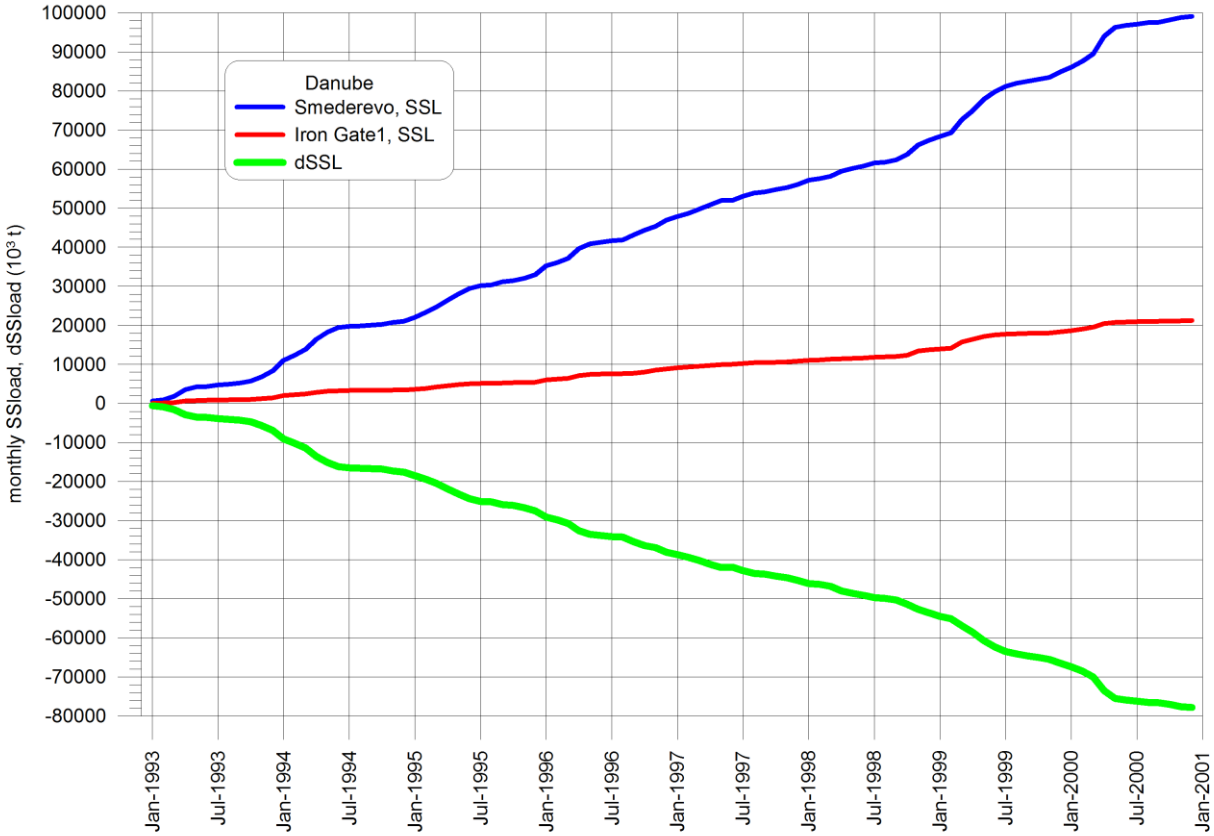

Figure 5.1.2 Deficit of suspended sediments in the Smederevo–Iron Gate 1 river stretch

On the other hand, the river stretches with the largest surplus of suspended sediments at the downstream station in the period 1993-2000 were the following:

- Braila – Isaccea (99.4 Mt cumulated value, vs 12.4 Mt annually) – see Figure 5.1.3;
- Iron Gate 1 – Corabia (73.9 Mt, vs 9.2 Mt);
- Stari Banovci – Smederevo (42.5 Mt, vs 5.3 Mt);
- Mohács – Novi Sad (35.4 Mt, vs 4.4 Mt);
- Corabia – Zimnicea (32.3 Mt, vs 4 Mt); and
- Kachlet – Jochenstein (18.2 Mt, vs 2.3 Mt annually).

A large sediment surplus is usually connected with the contribution of a significant Danube tributary (tributaries) in a partial river stretch, such as:

- the Siret and Prut rivers, between Braila and Isaccea;
- the Jiu and Iskar rivers, between Iron Gate and Corabia;
- the Sava River, between Stari Banovci and Smederevo;
- the Drava River, between Mohács and Novi Sad; and
- the Inn River, between Kachlet and Jochenstein.

For several river stretches, it was also possible to compare the historical data (from the period 1975-1992) with data from the recent period (1993-2014) in the database. The length of the compared periods was almost identical, 18 and 22 years. We compared the cumulated surplus or deficit of the annual suspended sediment load. The graphical illustration of this comparison is available in Annex 4. As a result of data gaps, the river stretches are sometimes different from those in Annex 3. The differences in the annual SS load between the periods compared are particularly significant in the Middle (downstream of Novi Sad) and Lower Danube sections.

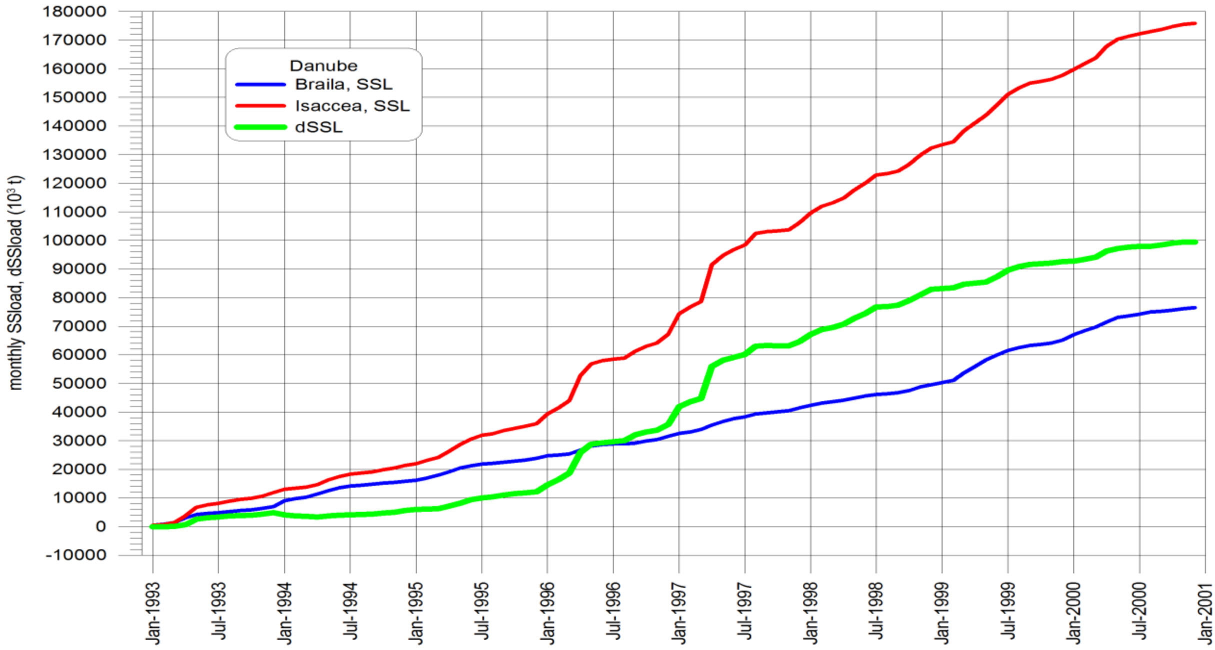

Figure 5.1.3 Surplus of suspended sediments in the Braila-Isaccea river stretch

The longitudinal profiles of the SS load for the individual years of the period 1986-2014 are summarised in a graphical form in Annex 5 – see an example from 2002 in Figure 5.1.4.

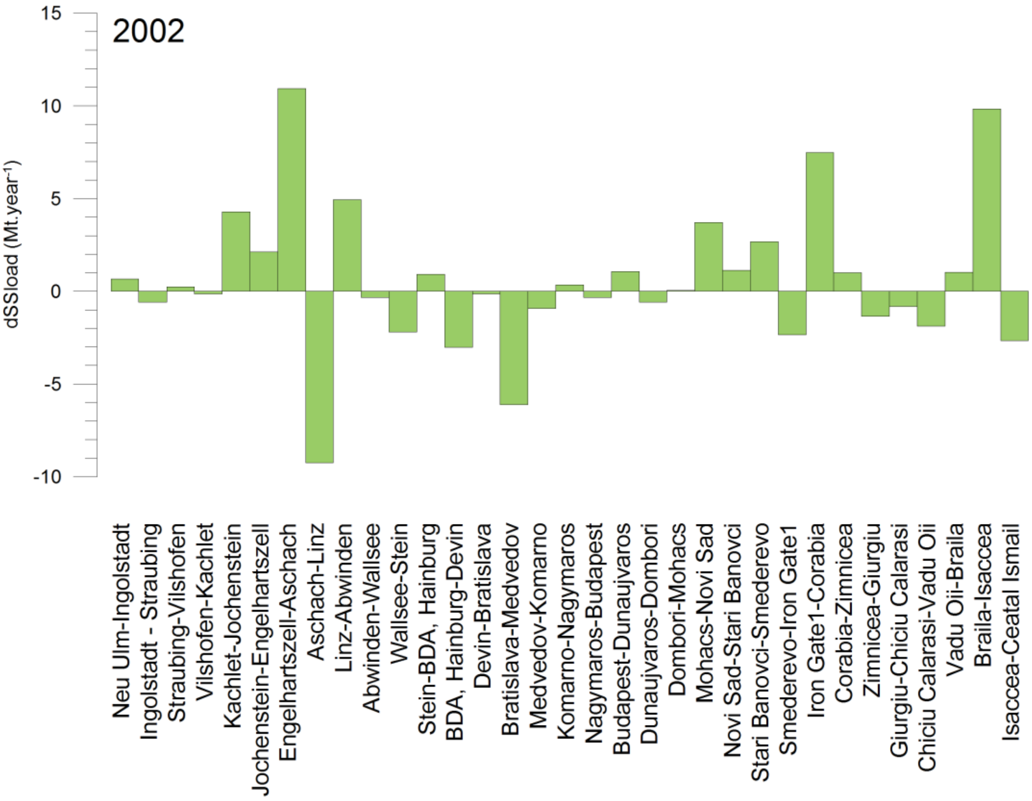

Figure 5.1.4 Suspended sediment load surplus/deficit in 2002

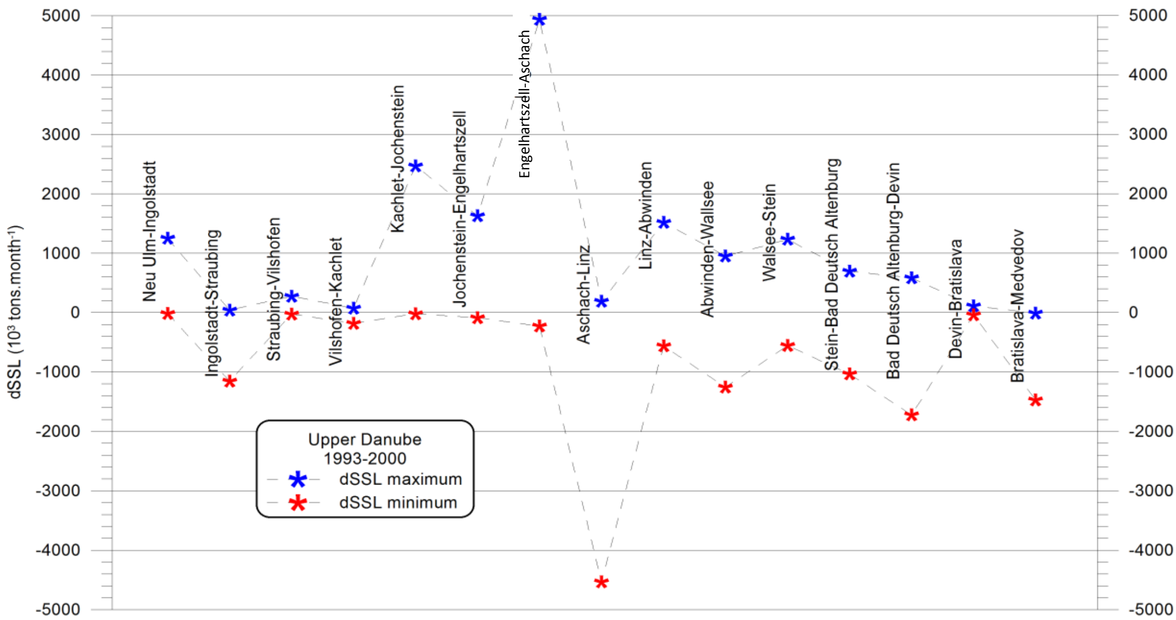

Figure 5.1.5 Range of monthly dSSL values – Upper Danube

The range of monthly dSSL values (minimum vs maximum values) in selected partial stretches of the Upper, Middle and Lower Danube in the period from 1993 to 2000 are illustrated in figures 5.1.5 to 5.1.7.

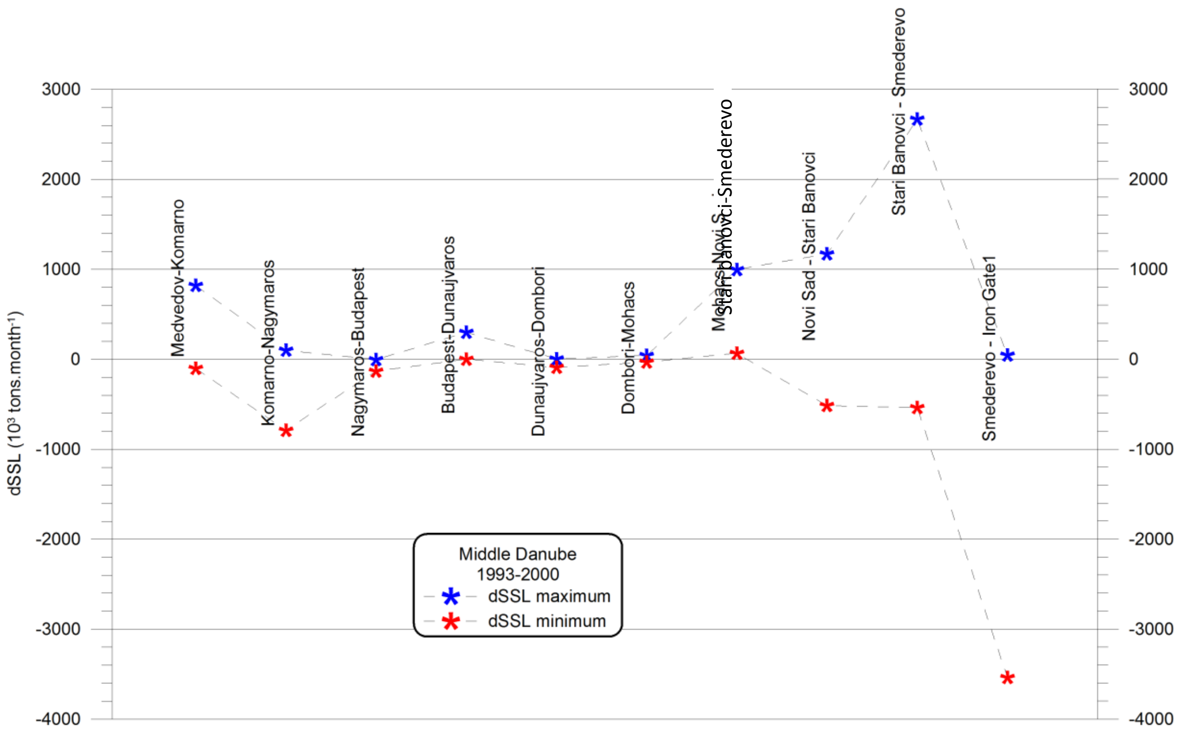

Figure 5.1.6 Range of monthly dSSL values – Middle Danube

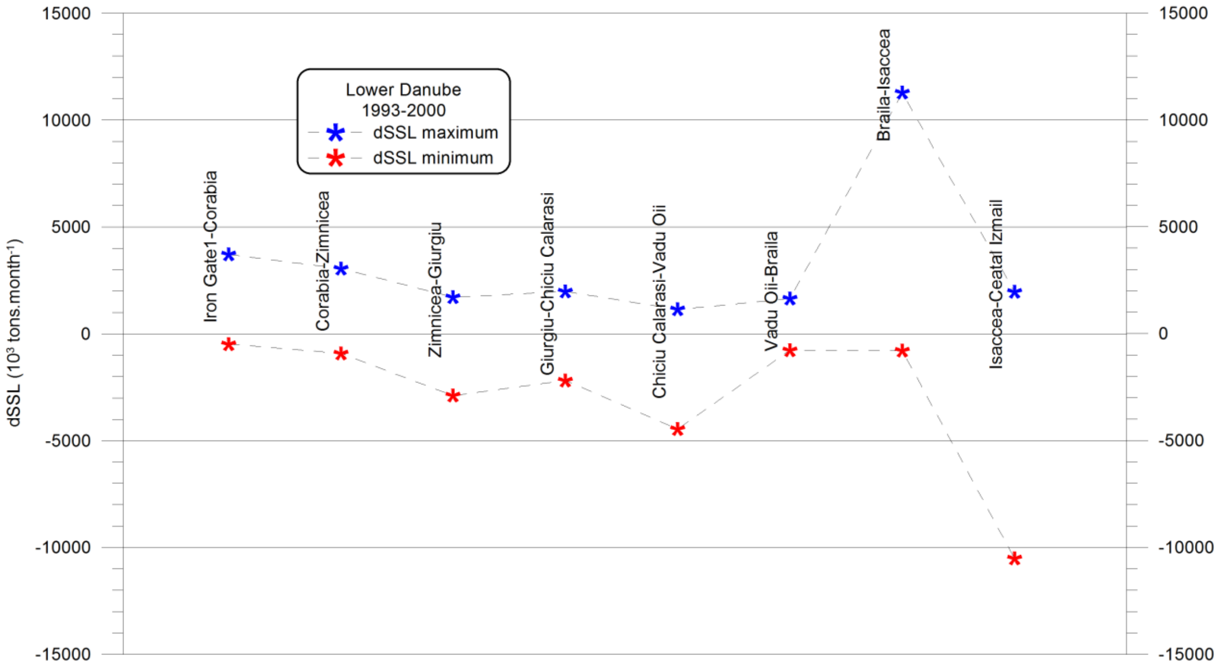

Figure 5.1.7 Range of monthly dSSL values – Lower Danube

Figures 5.1.8 and 5.1.9 show the amounts of suspended sediment load in partial river stretches during the 2006 and 2013 floods (surpluses (+) and deficits (-) between the monitoring stations), based on monthly data from the time when the flood events occurred. The 2006 flood had a stronger impact on the SS load in the Lower Danube section. This is indicated by stretches of increased sedimentation upstream of the Iron Gate 1 dam and downstream of the Svishtov–Zimnicea station (marked red in Figure 5.1.8).

On the other hand, the largest suspended sediment deposits in the Upper Danube were formed by the 2013 flood (in the river stretch between the Stein-Krems and Medveďov stations – marked red in Figure 5.1.9). This can be seen more clearly in higher-resolution maps in Annex 6.

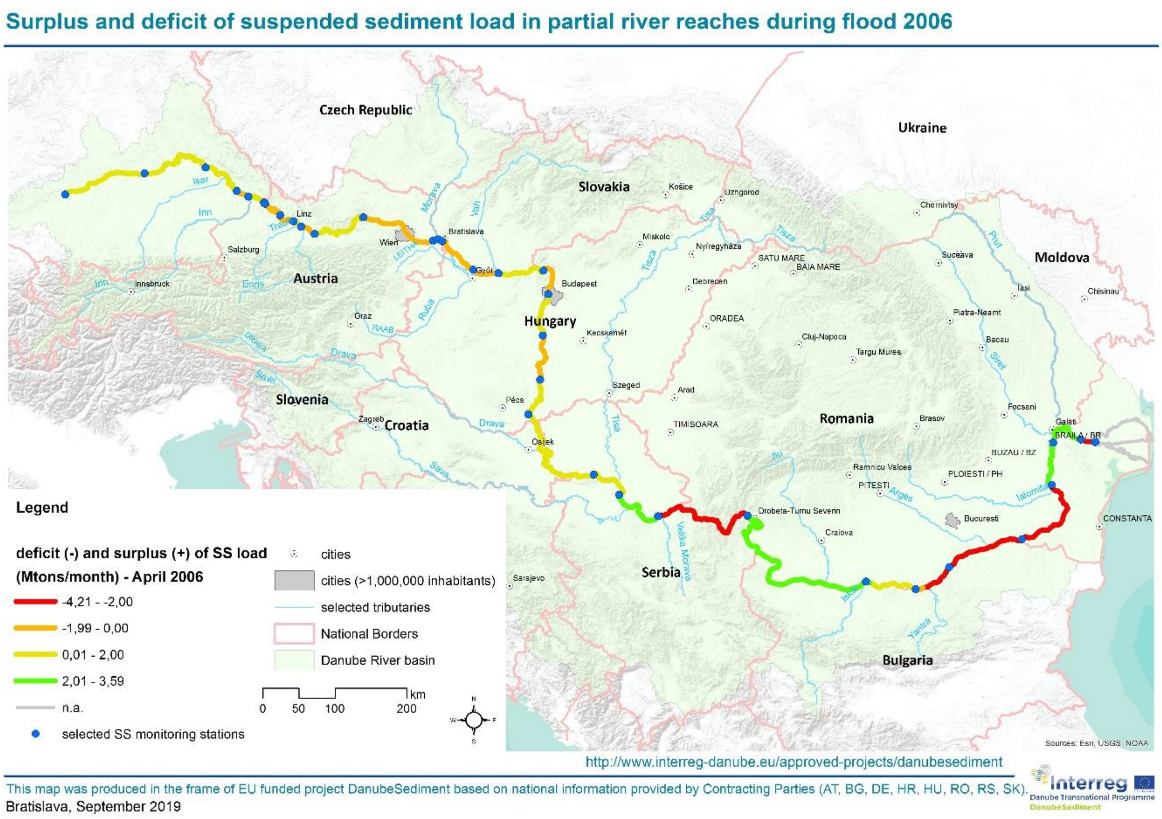

Figure 5.1.8 Suspended sediment load surplus or deficit in partial river stretches during the 2006 flood

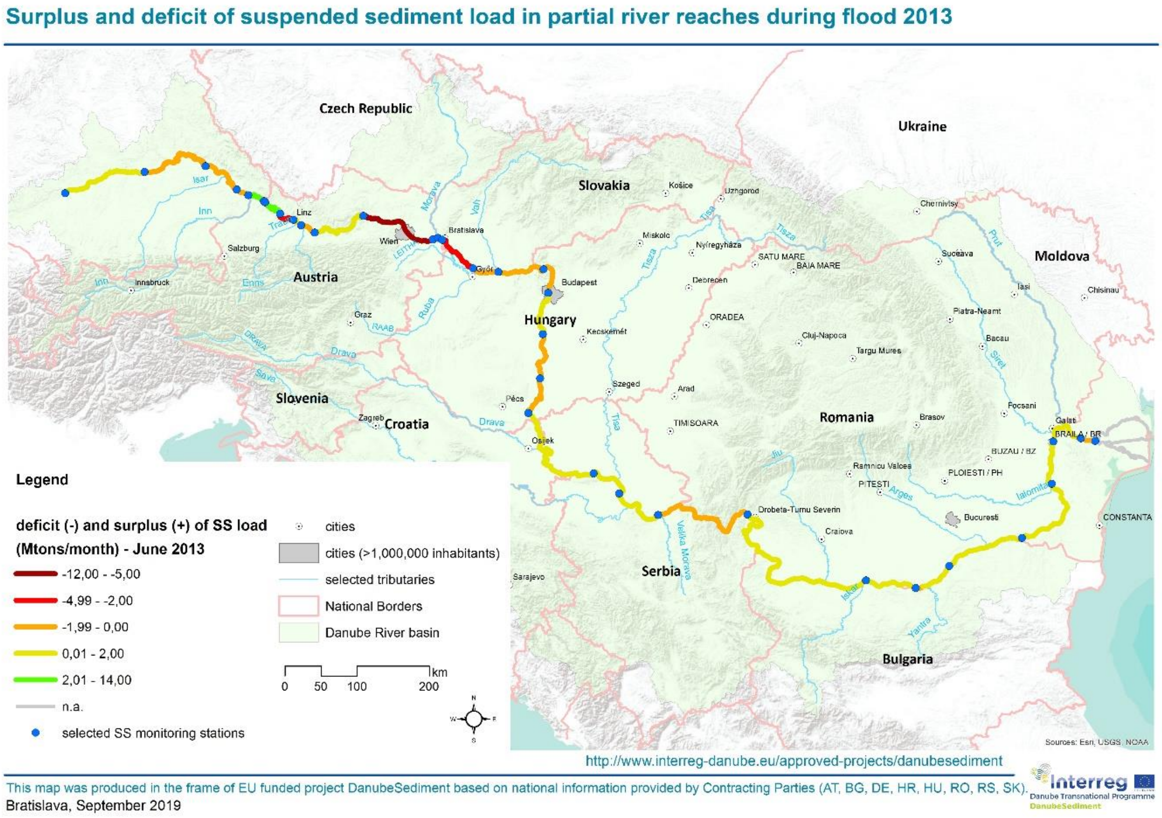

Figure 5.1.9 Suspended sediment load surplus and deficit in partial river stretches during the 2013 flood

5.2 Quantification of the contributions of tributaries

The contributions of individual tributaries to the suspended sediment load in the Danube have been analysed, too. Table 5.2.1 provides an overview of the contributions of tributaries, i.e. the average and maximum percentage of suspended sediments supplied from the individual tributaries. The SS load in the tributaries was compared with that in the Danube, measured at the closest monitoring station.

Table 5.2.1 Average and maximum percentage of SS load from the individual tributaries

Tributary	Danube profile	Average percentage	Maximum percentage
Isar	Vilshofen	47.4	132.4
Inn	Jochenstein	197.0	1,756.2
Traun	Abwinden Asten	2.4	6.1
Enns	Wallsee-Mitterkirchen	5.9	13.7

Tributary	Danube profile	Average percentage	Maximum percentage
Morava/March	Devin	3.6	7.3
Drava	Novi Sad	4.4	12.6
Tisa/Tisza	Stari Banovci	47.8	110.6
Sava	Smederevo	25.5	45.3
Velika Morava	Smederevo	18.4	46.6
Jiu	Corabia	28.7	71.0
Iskar	Corabia	1.6	5.0
Iantra	Chiciu Calarasi	4.7	14.4
Ialomita	Vadu Oii	35.1	102.9
Siret	Isaccea	14.9	73.9
Prut	Isaccea	2.6	5.5

The dominant role of the Inn River is clear from Table 5.2.1. It accounts for almost 200% of the SS load in the Danube, on average. Its maximum contribution is roughly 1,750 times higher than the figure for the Danube. An average contribution above 40% is made by three tributaries (Isar, Inn, Tisa) and a maximum exceeding 70% by the following tributaries: Isar, Inn, Tisa, Jiu, Ialomita and Siret.

Changes in the sediment balance, based on the data collected on suspended sediments for the periods before and after the construction of hydropower plants, were analysed for both the Danube and its major tributaries. Based on the datasets from Work Package 3 covering the collection and analysis of data on sediments and data found in literature (UNESCO, 1993), schemes on Figure 5.2.1 depict the suspended sediment balance for the current state and for the conditions before the construction of HPPs. Before the construction of HPPs on the tributaries, the Inn, Tisa, Sava, Gt. Morava, Olt and Siret rivers had significantly contributed to the transport of suspended sediments in the Danube – the Siret in the Lower Danube contributing the most with about 12 Mt of mean annual suspended load in period 1965-1985 (UNESCO, 1993). Mean annual suspended load in the historical period 1956-1985 from the Inn was about 5 Mt, from the Tisza about 5 Mt, from Sava about 5.5 Mt, from Great Morava about 6.9 Mt and from the Olt about 6.8 Mt (UNESCO, 1993). Additionally, another major tributary important for the sediment balance was the Drava (data displayed in Figure 5.2.1 were already influenced by first HPPs).

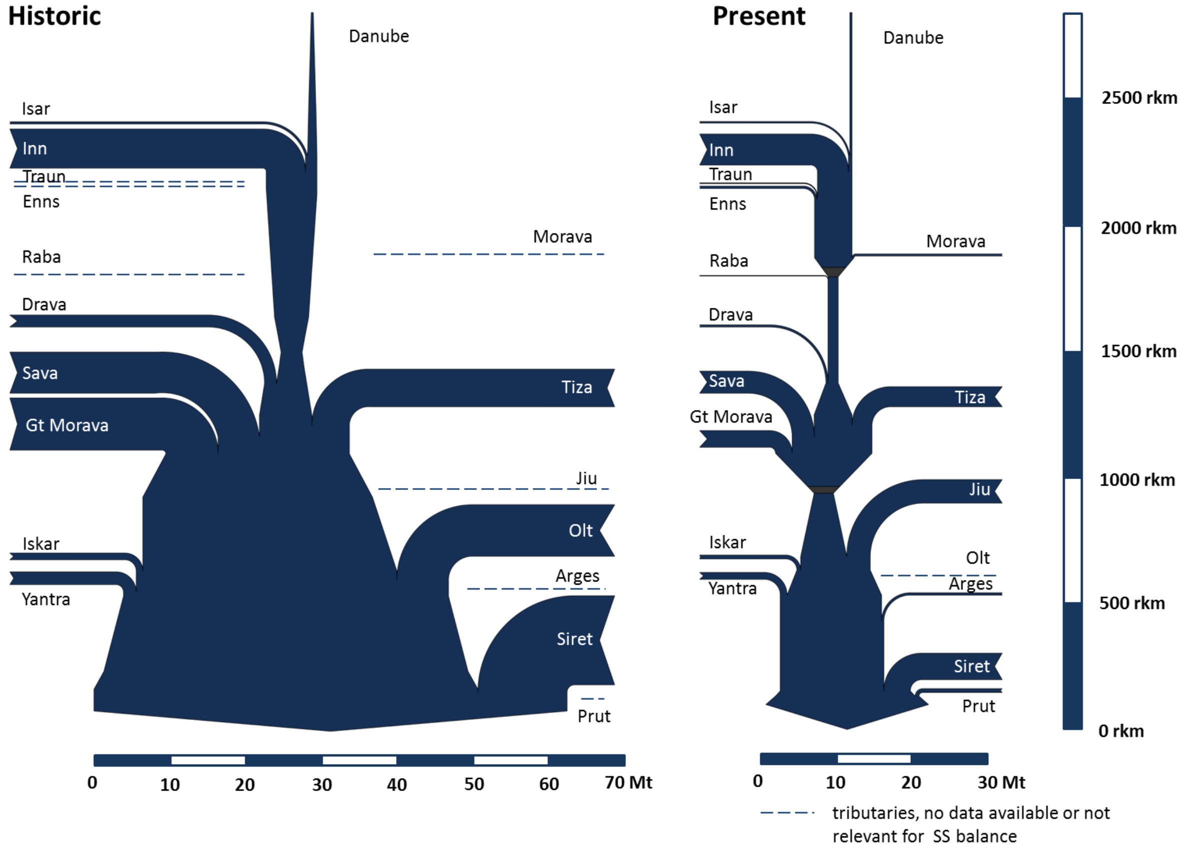

Figure 5.2.1 Suspended sediment balance of the Danube and its major tributaries before (left) and after (right) the construction of HPPs (dashed lines: tributaries, where no data are available) (Authors: Haimann, Gmeiner, Habersack)

Under the current conditions, suspended sediment transport in the Danube is reduced considerably, owing to the trapping effect of the Gabčíkovo and Iron Gate 1 reservoirs (Figure 5.2.1 – right-side picture). According to the report “Sediment data analysis in the Danube River”, 60% (Gabčíkovo) and 80% (Iron Gate 1) of suspended sediments are trapped in these reservoirs, comparing the data from monitoring stations upstream and downstream of the HPPs. Moreover, the suspended sediment input from the tributaries into the Danube channel has been reduced by 20-70% due to their damming. In recent time period from 1986-2016, the most important tributaries in terms of suspended sediment transport (mean annual loads) were the Inn (about 4.1 Mt) for the Upper Danube, the Sava (about 2.9 Mt) and the Tisza (about 2.6 Mt) for the Middle Danube and the Romanian tributaries Jiu (about 3 Mt) and Siret (about 3.5 Mt) for the Lower Danube. As a result, the decrease of suspended sediment input from the tributaries, especially in the Middle and Lower Danube, leads to a reduction of suspended sediment transport in the Danube River. The total suspended sediment input to the Danube Delta and the Black Sea decreased by more than 60%, from ca. 60 and 40 Mt/year historically to ca. 20 and 15 Mt/year nowadays. From Ceatal Izmail to the Black Sea, the suspended sediment load is decreasing (see Figure 5.1), although there are also uncertainties at the last monitoring stations due to tidal influence from the Black Sea.

5.3 Sediment budget for the Danube between the Gabčíkovo and Iron Gate 1 reservoirs

Taking into account the complicated hydraulic and operational conditions in the German and Austrian sections of the Danube, the marked temporal variations in the data available, the lack of data in certain river stretches, and the reduced bedload transport in the Upper Danube (owing to the chain of HPPs), it was decided that an extended sediment budget should be compiled for the section between Gabčíkovo (Čunovo weir) and the Iron Gate 1 reservoirs.

As mentioned above, some of the components of the sediment budget equation (Eq. 2.1) are not available for the Danube, such as sediment input from riverbank erosion, sediment output in the form of deposits in the floodplains and groyne fields, and river-bed material abrasion. Unknown (uncertain) data had to be supplemented with data on river-bed changes from bathymetric measurements.

Consequently, the sediment budget analysis in the river section under investigation for which the most complete data are available focused on the evaluation of river-bed changes and the quantification of sediments in the defined partial river stretches (Table 5.1), which are geographically located within the investigated section between rkm 1,842 and rkm 943. In addition to the average annual suspended sediment load, the average annual sediment storage change Δs (erosion/sedimentation) was calculated in the defined river stretches between the monitoring stations (Table 5.3.1) to estimate the extended sediment budget. The average river-bed change in meters/year was calculated from data on erosion/ sedimentation (river-bed changes) (Table 5.3.2).

The input dataset from the data on the Danube channel's morphological development was used to estimate the sediment storage change Δs (Eq.2.2). There were six different basic datasets, covering the entire time period from 1985 to 2016. Figure 5.3.1 shows the longitudinal distribution of eroded and deposited river stretches along the section under investigation, along with the dredging sites and volumes. The total volume of erosion reached -93,203,872 m^3 in the stretch between Čunovo and Iron Gate 1, and the volume of sedimentation was 196,277,575 m^3 in Period III, according to the evaluation of the morphological processes. The volume of sediments dredged in the investigated Danube section reached 57,501,539 m^3 in Period III.

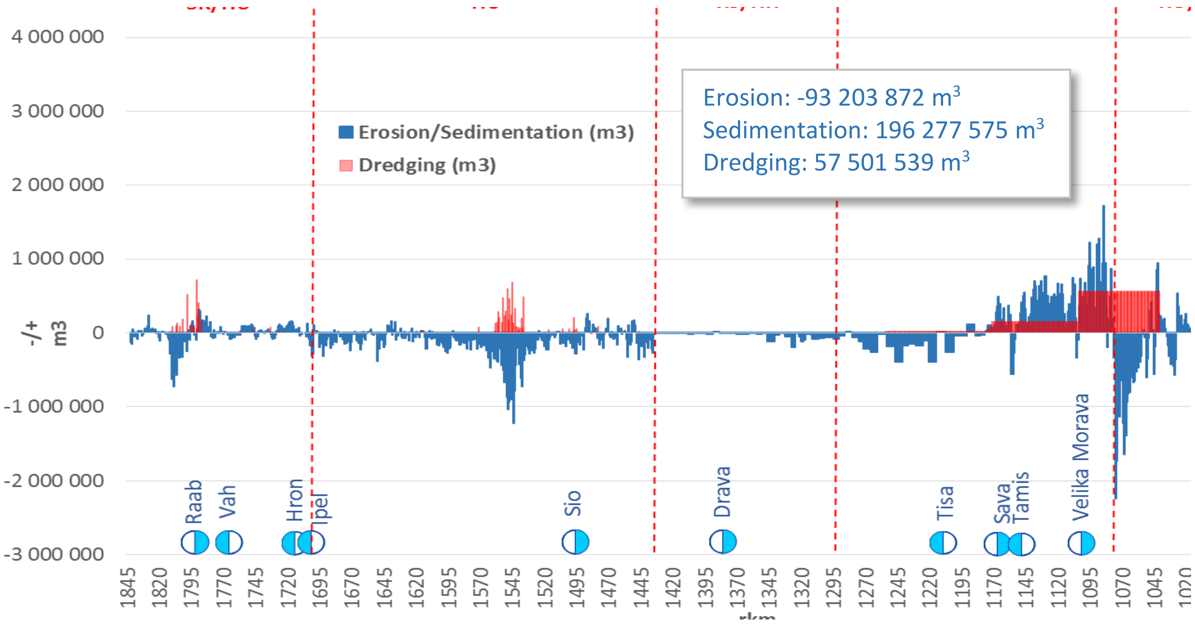

Figure 5.3.1 Erosion, sedimentation and dredging volumes in the investigated section between the Čunovo weir and Iron Gate 1

The cumulative erosion/sedimentation volume curve in Figure 5.3.2 shows the variability of sediment storage Δs (m^3) between the Čunovo weir and the Iron Gate dam. Each point on the line shows the sum of volumes (prevailing processes) in the upstream stretch. The curve indicates that the dominant river-forming process is erosion (river-bed degradation) down to the mouth of the Sava River, where the total (cumulative) volume of erosion amounts to almost 60 million m^3. Sedimentation clearly prevails in the following river stretch down to the Iron Gate 1 dam.

The total volume of dredging in the investigated river stretch has been 57.5 million m^3 in the recent period. Figure 5.3.3 provides information on the pattern of cumulated dredging in the stretch between the Gabčíkovo (Čunovo weir) and Iron Gate 1 reservoirs. Dredging activities were mainly performed in the stretch between rkm 1,250 and rkm 1,040 (the Iron Gate's impoundment) for flood protection purposes.

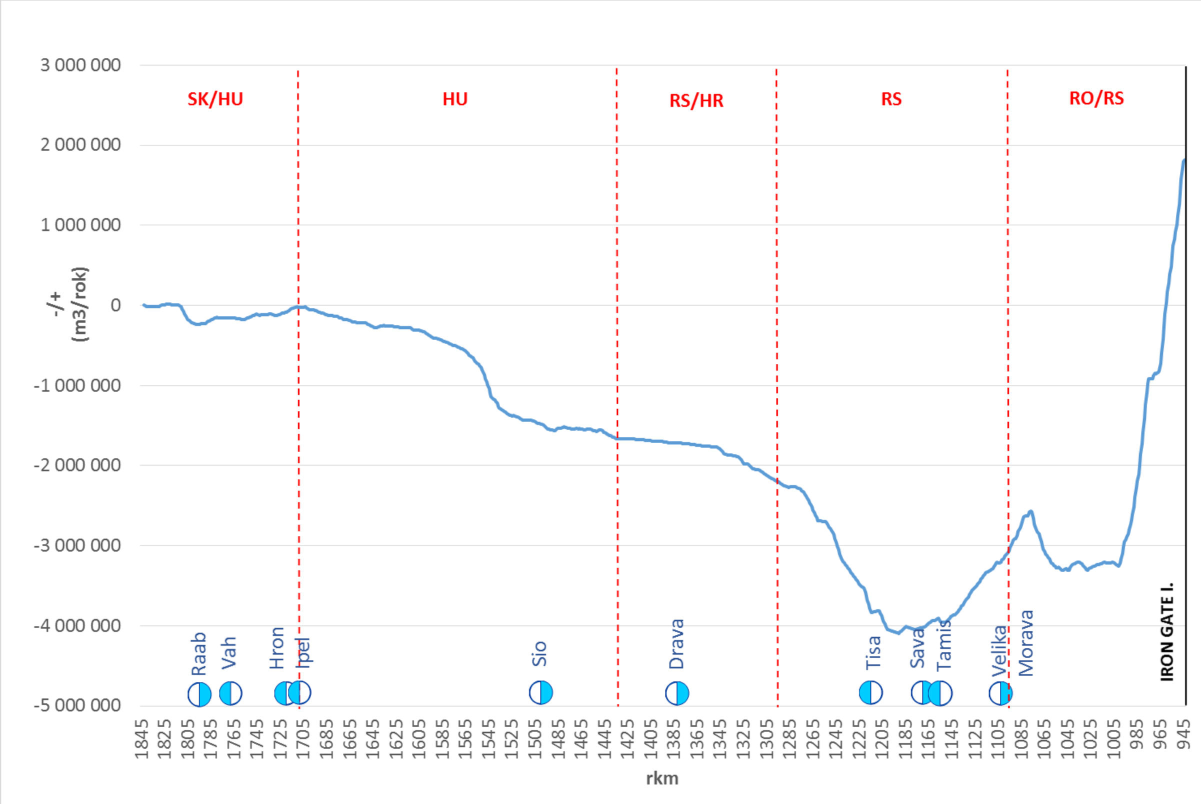

Figure 5.3.2 Cumulative erosion/sedimentation volume curve

It should be noted that, even though the dredging sites and the quantity of sediments dredged were investigated within the scope of this analysis, the data on river-bed changes (volumes of erosion/sedimentation) already included the amounts of sediments dredged (the impact of dredging is reflected in the channel bathymetry). Thus, the amounts dredged are indirectly included in the sediment budget. Dredging causes a sediment deficit in the river stretch concerned, thus it directly affects the river-bed morphology and determines the degree of its modification.

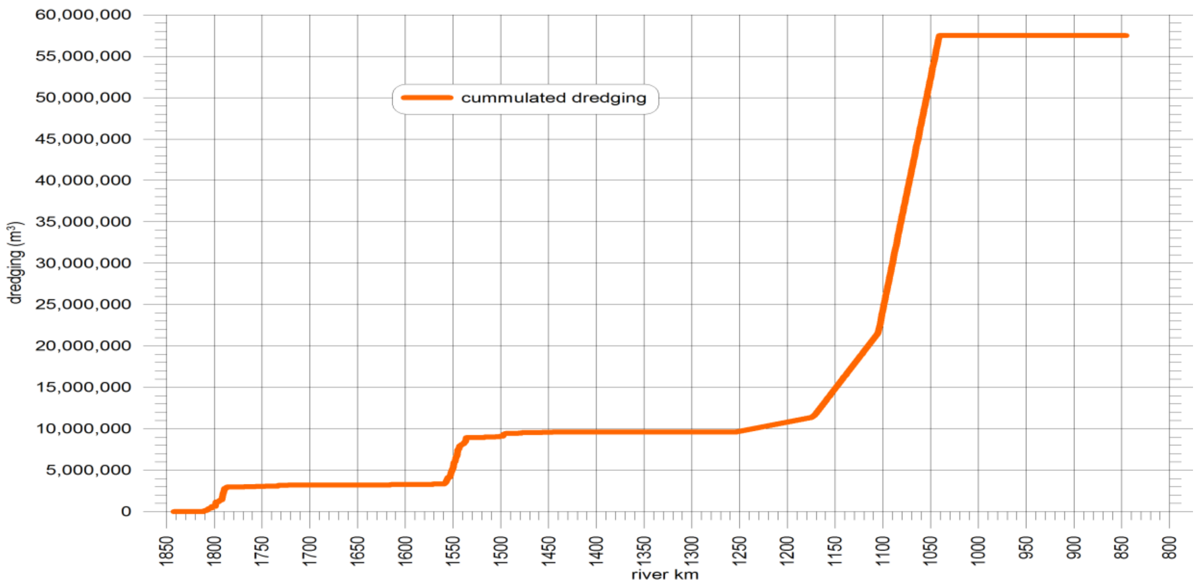

Figure 5.3.3 Quantity of dredging between the Hrušov and Iron Gate reservoirs

The volumes of erosion and sedimentation within the partial river stretches between the monitoring stations were used to calculate the average annual sediment storage changes (Δs) and to compile an extended sediment balance (Table 5.3.1). The average annual sediment storage changes (Δs) in the partial river stretches ranged from -2.3 million tons/year (erosion) in the stretch between Novi Sad and Stari Banovci to 8.4 million t/year (sedimentation) in the stretch between Smederevo and Iron Gate 1.

The prevailing process in the Danube section under investigation is river-bed degradation, except in a short stretch at the lower edge of the section (downstream of Smederevo), where sedimentation prevails.

Table 5.3.1 Calculated values of the average annual SS load and sediment storage change (Δs) in the defined partial stretches within the Danube section between the Čunovo weir and Iron Gate 1

River stretch	Rkm upstream	Rkm downstream	Average annual SS load (million t/year)	Average annual sediment storage change Δs (mil. t/year)
Čunovo weir - Medveďov	1,842.000	1,806.300	-2.087*	-0.221**
Medveďov - Komárno	1,806.300	1,767.800	0.7	-0.032
Komárno - Nagymaros	1,767.800	1,694.600	-0.444	0.163
Nagymaros - Budapest	1,694.600	1,646.500	-0.183	-0.335

Budapest - Dunaujváros	1,646.500	1,580.600	0.526	-0.333
Dunaujváros - Dombori	1,580.600	1,506.800	-0.248	-1.612
Dombori - Mohács	1,506.800	1,446.900	0.147	-0.204
Mohács – Novi Sad	1,446.900	1,257.100	4.429	-1.871
Novi Sad – Stari Banovci	1,257.100	1,192.350	0.868	-2.297
Stari Banovci - Smederevo	1,192.350	1,110.400	5.318	1.303
Smederevo – Iron Gate 1	1,110.400	943.000	-9.731	8.442

* calculated for the stretch between the Bratislava (rkm 1,871.3) and Medveďov stations

** calculated from the Čunovo weir

The average river-bed change in meters/year was calculated from the average annual volume of sediments in the period 1993-2016, considering the distance between the cross sections and the river widths. The average annual river-bed change in the Danube ranges from -0.035 to 0.026 m/year in the individual river stretches (Table 5.3.2, Figure 5.3.6). River-bed incision in the old channel downstream of the hydraulic structures at Čunovo, damming the Old Danube channel to create the Gabčíkovo reservoir, is moderate (0.01 m.year^{-1}). River-bed incision up to -3.5 cm.year^{-1} is evident in the stretch between Novi Sad and Stari Banovci and -2.8 cm.year^{-1} in the stretch between Dunaujváros and Dombori. These rather high values of river-bed incision are induced by river-bed dredging in both cases. The largest river-bed aggradation (+2,6 cm.year^{-1}) occurs in the stretch between Smederevo and the Iron Gate 1 dam in the time period under review.

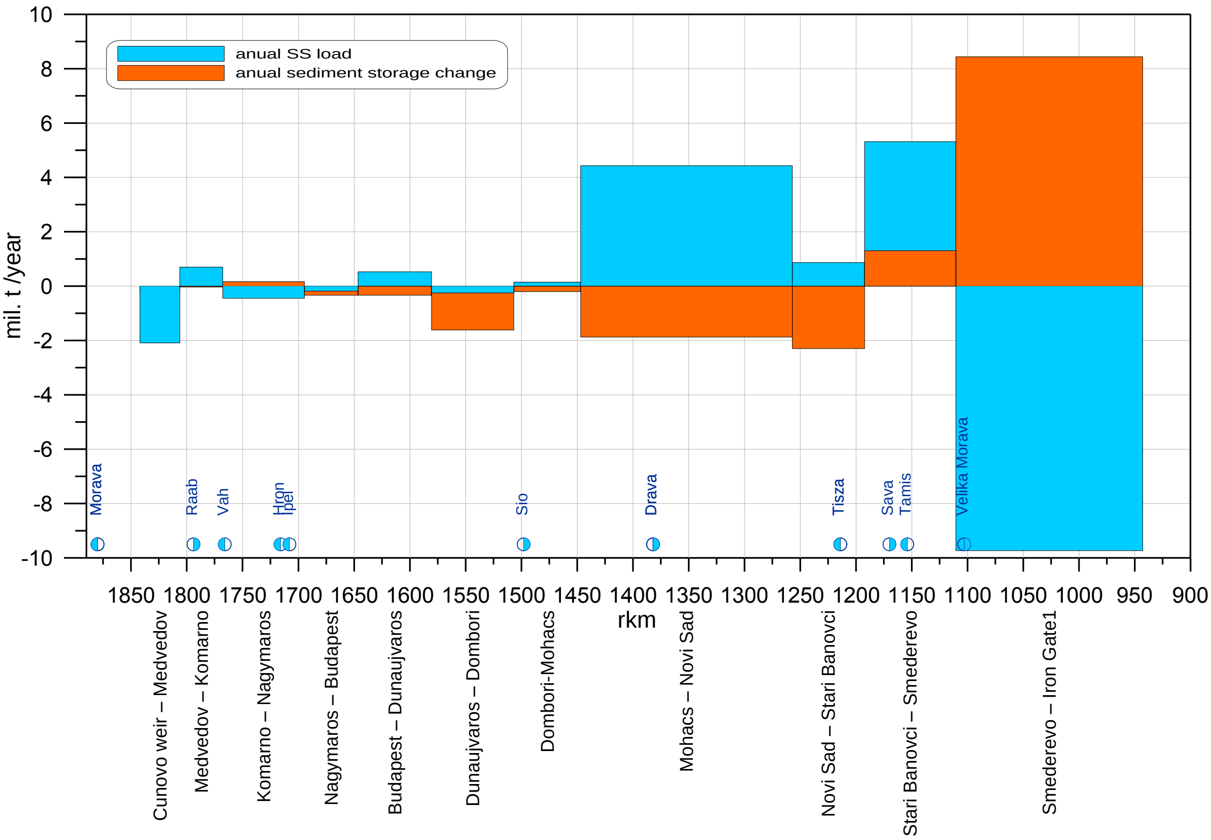

Figure 5.3.4 Average annual SS loads and sediment storage changes (Δs) in the defined partial stretches and time periods (1993-2000, 1993-2016)

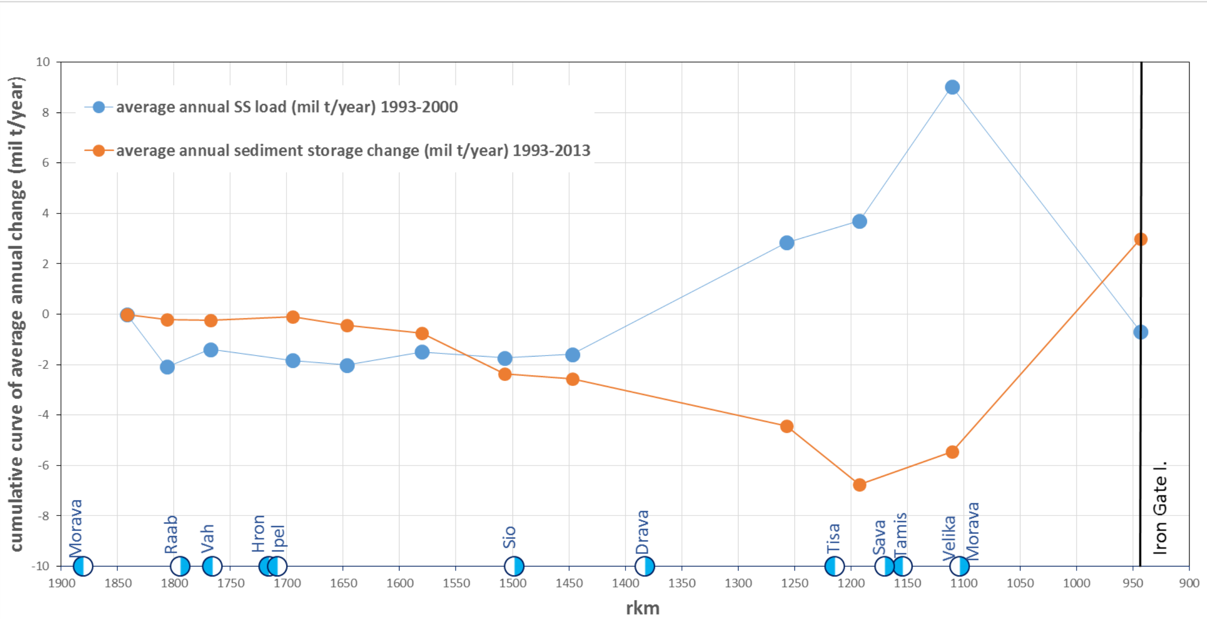

Figure 5.3.5 Cumulative curve of the average annual SS loads (1993-2000) and sediment storage changes Δs (1993-2016) in the defined partial stretches and time periods

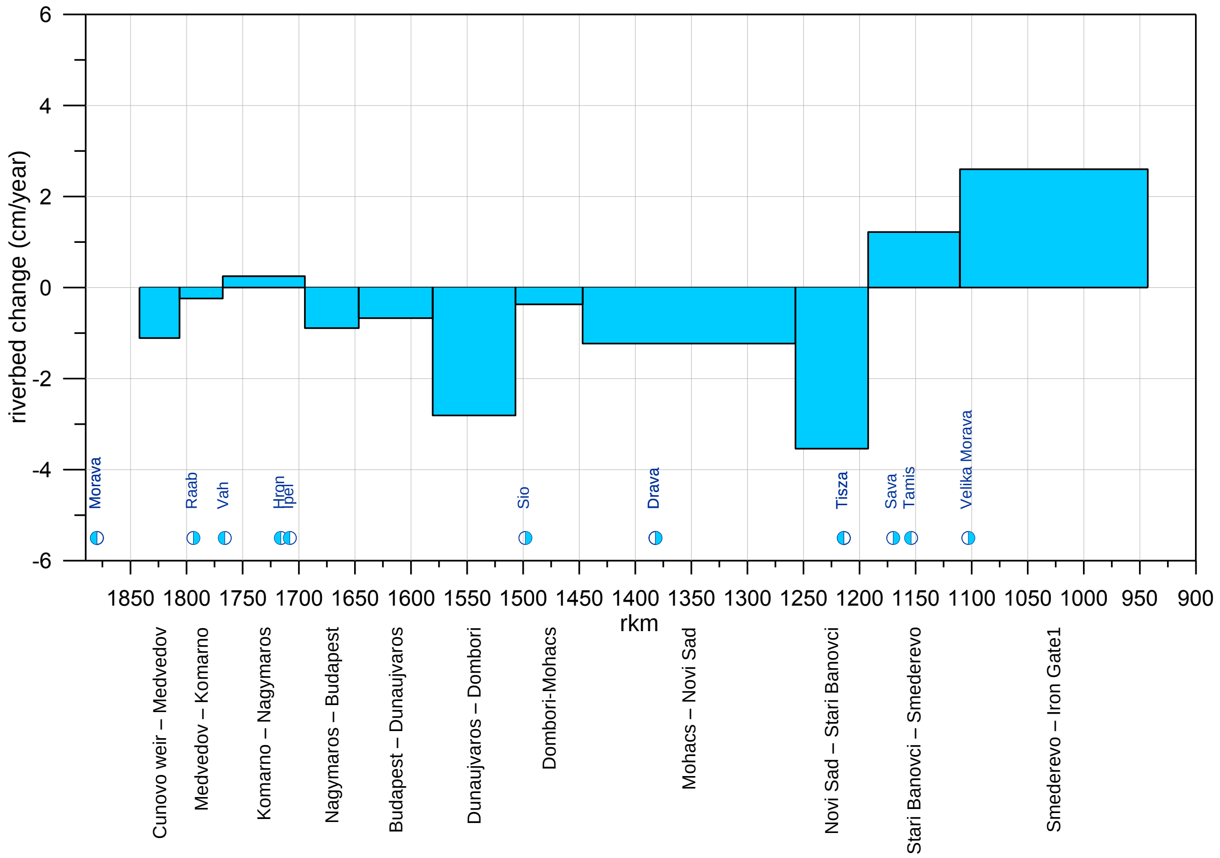

Figure 5.3.6 Average annual river-bed changes in selected stretches between the monitoring stations in the period 1993-2016

Table 5.3.2 Average annual river-bed changes in selected stretches between the monitoring stations in the period 1993-2016

River stretch	Rkm upstream	Rkm downstream	Average annual river-bed change dZ ($m.year^{-1}$)
Čunovo weir – Medveďov	1,842.000	1,806.300	-0.011
Medveďov - Komárno	1,806.300	1,767.800	-0.002
Komárno - Nagymaros	1,767.800	1,694.600	0.003
Nagymaros - Budapest	1,694.600	1,646.500	-0.009
Budapest - Dunaujváros	1,646.500	1,580.600	-0.007
Dunaujváros - Dombori	1,580.600	1,506.800	-0.028
Dombori - Mohács	1,506.800	1,446.900	-0.004

River stretch	Rkm upstream	Rkm downstream	Average annual river-bed change dZ (m.year^{-1})
Mohács – Novi Sad	1,446.900	1,257.100	-0.012
Novi Sad – Stari Banovci	1,257.100	1,192.350	-0.035
Stari Banovci - Smederevo	1,192.350	1,110.400	0.012
Smederevo – Iron Gate1	1,110.400	943.000	0.026

5.4 Summary

Since we had incomplete datasets, we could not compile a complete sediment balance in accordance with Equation 2.1. The dataset of suspended sediment load in the time period 1993-2000 enabled an analysis of suspended sediment deficits and surpluses for the entire length of the Danube. The spatial distribution of deficits and/or surpluses was calculated and displayed in a various graphical forms, i.e. graphs and maps.

The highest values of suspended sediment deficits (-9,7 Mt annually) were measured in the partial river reach between Smederevo and Iron Gate 1. The largest suspended sediment surplus (12,4 Mt annually) was found in the river reach between Braila and Isaccea. The longitudinal profiles of the suspended sediment load for the individual years within the period 1986-2014 were summarised in graphical form.

GIS maps were used to demonstrate the different character of floods (in 2006 and 2013) from the viewpoint of the suspended sediment load. The 2006 flood had a stronger impact on the suspended sediment load in the Lower Danube, while the 2013 flood deposited most of the suspended sediments in the Upper Danube.

The contribution of the Danube's tributaries to sediment transport was analysed in a separate section of this report. The Inn river plays a dominant role in the Upper Danube, while the Drava, Tisa, Sava and Velika Morava rivers are the most significant tributaries of the Middle Danube. The Jiu, Ialomita, Siret and Prut rivers are the most significant tributaries of the Lower Danube. The schemes illustrating the roles of these tributaries were compiled in view of the historical and present conditions. The dominant roles of large hydropower plants such as Gabčíkovo and Iron Gate 1, which trap large amounts of sediments, is well demonstrated. The damming of the tributaries has also reduced the sediment input into the Danube (by 20% to 70%).

In view of the complicated hydraulic and operating conditions in the German and Austrian river sections, the wide temporal variations in the data available, the lack of data in several river stretches, as well as the reduced bedload transport in the Upper Danube caused by a chain of HPPs, it was decided that an extended sediment budget should be drawn up for the Danube in the section between the Gabčíkovo (Čunovo weir) and Iron Gate 1 reservoirs.

Besides the average annual suspended sediment load, the average annual sediment storage change was also calculated for the defined river stretches between the monitoring stations to estimate the extended sediment balance. The average river-bed change was calculated from data on erosion/sedimentation for the given stretches. Erosion (river-bed degradation) is the dominant process between the Čunovo weir and the confluence with the Sava River in the upstream part of the Iron Gate 1 reservoir. Sedimentation clearly prevails in the following river stretch towards the Iron Gate 1 dam.

The average annual river-bed change in the Danube channel ranges from -0.035 to 0.026 $m.year^{-1}$ in the individual river stretches. The largest river-bed aggradation (+2,6 $cm.year^{-1}$) in the time period under review occurred in the stretch between Smederevo and Iron Gate 1.

6. Conclusions

This report deals with the works performed within the scope of Activity 4.2 'Sediment Balance Assessment.' The general concept of sediment balance is explained briefly in the first chapters. This is followed by a basic description of the river section under analysis, which provides an overview of the hydrological conditions in the Danube Basin in the section between Neu Ulm and the Danube Delta (almost 2,500 km). The next chapter presents the basic datasets that were used to compile and evaluate the sediment budget, i.e. data on suspended load, bedload and on the erosion and sedimentation processes, including bed sediment dredging. The fifth chapter focuses on a quantitative assessment of the extended sediment balance within the selected Danube section stretching from Bratislava (Čunovo weir) to the Iron Gate I dam. The extended sediment balance (still only partial) consists of the average annual suspended sediment load and the average annual sediment storage change. The main results obtained within this activity can be summarised as follows:

- Over the recent decades, a major change has occurred in the suspended sediment regime owing to the damming of the Danube and its main tributaries.

- The disruption of sediment continuity has resulted in an overall sediment deficit along the Danube, which is also indicated by the distribution of the suspended sediment load along the river under the current conditions and under those before the construction of HPPs on the Danube (Fig 5.2.1).

- An analyses of the suspended sediment balance along the entire Danube has revealed that the largest suspended sediment deficit in the time period 1993-2000 (9.4 Mt annually at the downstream station) occurred in the river stretch between Smederevo and Iron Gate 1. The largest suspended sediment surplus (12.4 Mt annually) was calculated for the stretch between Braila and Isaccea, owing to the supply of suspended sediments from the Siret and Prut rivers.

- In the river stretch under review, for which an extended sediment budget has been compiled, river-bed degradation is the prevailing process down to the mouth of the Sava River (rkm 1,190). In the stretch downstream of Smederevo, sedimentation prevails.

- The mean annual river-bed changes in the Danube range from -0.035 to 0.026 m.year^{-1} in the individual river stretches. River-bed degradation can be observed between the Čunovo weir (rkm 1,842) and Stari Banovci (rkm 1192.35), with a maximum value of -3.5 cm.year^{-1} in the stretch between Novi Sad and Stari Banovci and -2.8 cm.year^{-1} between Dunaujváros and Dombori. The largest increase in the river bed (+2.6 cm.year^{-1}) was recorded in the stretch between Smederevo and Iron Gate 1.

Unfortunately, some of the sediment budget equation's components (Equation 2.1) are not monitored in the Danubian countries and are therefore not available. These components are sediment input from river-bank erosion, sediment output in the form of deposits in the floodplains and groyne fields, and river-bed material abrasion. Moreover, bedload monitoring along the Danube is rather scarce.

Although data for a complete sediment balance (in line with the sediment balance equation 2.1) are missing, the results of this study provide interesting and useful information about the river's behaviour under the changed or modified flow and sedimentary conditions.

As the previous results of the DanubeSediment project indicate, it is necessary to monitor the river's sediment regime, including its suspended sediment and bedload regime, and the river-forming processes such as river-bank erosion, sediment deposition in the floodplains and groyne fields, as well as the river's long-term morphological development. The purpose of long-term monitoring is to provide complex data, which would enable the compilation of a more detailed sediment budget for the entire Danube in the future.

In this context, data quality (data acquisition and data processing methods) is an extremely important issue. Therefore, the sediment monitoring methods (suspended load, bedload) and the monitoring methods for channel morphology (bathymetry – changes in the river bed and riverbanks; bed material) ***need to be harmonised along the entire Danube***. This issue was highlighted by the project partners during discussions on data reliability (suspended load, bedload and channel bathymetry) throughout the project period. Therefore, the importance of the methodological aspects of data acquisition and data processing is reflected in all relevant project activities.

List of Abbreviations

AT	Austria
BG	Bulgaria
BME	Budapest University of Technology and Economics
BOKU	University of Natural Resources and Life Sciences (Austria)
DE	Germany
DTP	Danube Transnational Programme
HPP	Hydropower plant
HR	Croatia
HU	Hungary
ICPDR	International Commission for the Protection of the Danube River
JCI	Jaroslav Černi Water Institute (Serbia)
RO	Romania
RS	Serbia
SK	Slovakia
SS	Suspended sediments
SSL	Suspended sediment load
TUM	Technical University of Munich (Germany)
VUVH	Water Research Institute (Slovakia)
WP	Work Package

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