Interreg
EUROPEAN UNION
Danube Transnational Programme
DanubeSediment

Sediment Monitoring in the Danube River

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

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/IWHW-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 and can be found here on our project website.

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

Sediment Monitoring in the Danube River

Imprint

Publisher*:* Budapest University of Technology and Economics (BME)

Date: September 2018

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

Project duration: 01.01.2017-30.06.2019

Website: www.interreg-danube.eu/danubesediment

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1 Goal and structure of this report

This report has been prepared in the frame of the DanubeSediment Interreg DTP project. The report is one of the two deliverables within Work Package 3 (Sediment Data Collection) of the project.

The goal of this report is twofold: i) to give a thorough overview of the past and current sediment sampling methods, the laboratory methods as well as the sediment load calculation methods used by the Danubian countries and ii) to give recommendations for improvements of the sediment monitoring network along the Danube River. The introduction of methods currently applied along the Danube will support the understanding of uncertainties, which inherently characterize the collected sediment data. These uncertainties are systematized and analysed in the follow-up deliverable “Sediment Data Analysis in the Danube River”. Also, this report clearly highlights the most critical sections of the Danube River in terms of available data and data quality. Building on this information, the report recommends locations, where the improvement of the monitoring methods is crucial. In order to understand the good practice methods for sediment measurements, an overview of the techniques applied these days will be given. Based on this, concrete methods and monitoring procedures, i.e. protocols will be recommended. The main findings of this report will be included in the synthesis work package (WP 6) of the project as well as in the Danube Sediment Management Guidance and the Sediment Manual for Stakeholders, which will be the two final products of the project.

This report is divided into three large chapters. Chapter 2 tackles the monitoring methods applied in the different countries. We introduce the methods for suspended sediment and bedload transport monitoring separately. Not only the Danube River will be considered but the methods applied in the most important tributaries, in terms of sediment input, will also be described. However, only those stations located closest to the confluence are included. In order to demonstrate the methodological evolution at the institutes responsible for sediment monitoring in the different countries, this report presents not only the methods currently applied but also the past methods. Chapter 3 gives an overview about the most widely used monitoring methods, as well as the most recent techniques in order to support the selection of good practices, which are considered as the most adequate ones for the Danube River. Chapter 4 will show a few good examples of existing sediment monitoring networks and based on Chapter 2 and 3, concrete recommendations will be given for future improvements on a country-by-country basis. The report will also make suggestions for the establishment of new monitoring stations. Finally, practical messages will be provided for basin-wide sediment data management, as well as for stakeholders in the field of sediment monitoring.

2 Sediment monitoring methods in the Danube countries

2.1 Introduction

The goal of this chapter is to introduce the sediment monitoring methods applied along the Danube River and in the most important tributaries regarding sediment transport. For the tributaries, we only consider the stations closest to the Danube confluence.

In order to understand, to assess and to give potential solutions for sediment related problems in rivers, the amount of the transported sediments, varying both in time and space, has to be known. For this purpose, sediment monitoring stations are operated along the Danube River in all the countries that the river flows through. Based on the nature of sediment transport in rivers, the monitoring methods can be divided in two larger groups, focusing on either suspended sediment (SS) or bedload transport (BL). Suspended sediment is the finer fraction, which is moved with the water, and mixed up in the whole water column. Bedload transport takes place at the riverbed, where the coarser particles are rolling, sliding or saltating (*Figure 1*). This chapter will introduce both monitoring methods. However, in case of the Danube River, the relatively high number of suspended sediment monitoring stations stands in contrast to the few stations where bedload monitoring is continuously performed. In total, there are 55 SS stations in the Danube and 20 in the tributaries, whereas for BL, there are 19 and one, respectively.

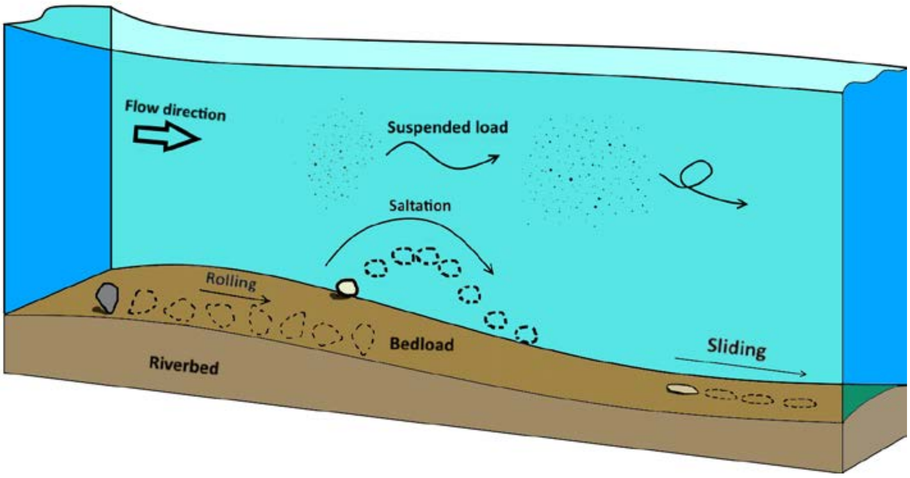


Figure 1 Transport modes of sediments in rivers

The information provided in this chapter is based on the results of a high number of web-based questionnaires completed by the project partners. The goal of the questionnaires was to collect metadata about the monitoring stations all along the Danube River and in the most important tributaries. The questionnaire forms consisted of four main topics: i) Basic information of the monitoring station, ii) Hydrological monitoring, iii) Suspended sediment monitoring, iv) Bedload monitoring. In *Basic information*, the name and the location of the station, data owner, typical hydrological and sediment parameters as well as photos, maps, illustrations of the station are given. *Hydrological monitoring* focused on the stage and discharge measurement methods at the sediment monitoring station. *Suspended sediment monitoring* collected information about the purpose of the monitoring, the applied measurement method, the frequency, the time period of the operation, the laboratory analysis methods as well as the sediment load calculation methods. *Bedload monitoring* collected the same sort of information about bedload measurements. In this report, we describe the information related to the sediment transport monitoring network in detail, whereas all other relevant characteristics of the sediment data were collected in a metadatabase, implemented in a GIS environment and provided as separate results in later reports of the project.

The structure of the chapter is the following: introduction of the SS and BL monitoring stations, which are divided into two separate sections. Within each section, the methods are presented country by country, beginning upstream in Germany to downstream Romania. In countries, where several institutes are responsible for the sediment measurements, each is described separately. Also, if the methods were changed in the past, both the past and the current methods are presented. If the methods applied in the tributaries differ from the ones applied in the Danube, these are also presented separately. For both monitoring techniques, the report presents the sampling techniques, laboratory analysis techniques and discharge calculation methods.

In general, the main purpose of the sediment monitoring stations is to determine the sediment load at characteristic sections of the Danube River as well as in the tributaries. As shown later on, the Danube countries use different techniques for both suspended sediment and bedload transport. Suspended sediment monitoring stations can be found in all Danubian countries, whereas bedload monitoring is not performed everywhere. This report clearly illustrates the differences in sediment sampling methods of the countries along the river in terms of applied technique, sampling frequency, sediment analysis and the resulting data quality. This inhomogeneity of monitoring methods makes it clear that a harmonized sediment monitoring system is needed. This system must provide consistent and comparable sediment datasets that serve as a basis for assessing sediment-related problems in the Danube Basin.

2.2 Suspended sediment monitoring system

According to the assessable data provided by the project partners, the suspended sediment monitoring system consists of 55 stations along the Danube and 20 in the tributaries (considering only the ones closest to the Danube confluence, except at the Inn and Morava Rivers, where two stations were taken into account from the neighbouring countries). In terms of applied methods, several different techniques are used, such as physical sampling with bottle, physical sampling with point-integrating sampler, physical sampling with depth-integrating sampler, pump sampling, optical sensors as well as acoustic sensors. The frequency of the sampling as well as the laboratory analysis methods also differ between countries. These characteristics, together with information about the sediment data owners are summarized in

Table 1 for each country.

The list of the monitoring stations, indicating the country, the river's name, the name and location of the sites is shown in *Table 2, Table 3* and *Figure 2* for the Danube and for the tributaries. Note that only the tributaries, which play a major role in the sediment balance of the Danube, are listed here.

Table 1 Main features of the current suspended sediment monitoring system in the Danube and relevant tributaries

Country	**Data owner**	**Monitoring performed by**	**No. of stations (Danube + trib.)**	**SS measure-ment method**	**Frequency**	**SSC analysis method**
Germany	Bavarian Environment Agency (LfU), Bavarian Hydrological Service (GKD)	Regional water authorities	3+2	Acoustic devices	1 time per year	Filtration
				Optical backscatter point sensor	4 times per hour	
				Physical sampling	1 time per week	
	Federal Waterways and Shipping Administration (WSV)	Federal Waterways and Shipping Administration (WSV), Federal Institute of Hydrology (BfG), BAW	4+0	Physical sampling	1 time per day	Filtration

Country	**Data owner**	**Monitoring performed by**	**No. of stations (Danube + trib.)**	**SS measure-ment method**	**Frequency**	**SSC analysis method**
Austria	via donau - Österreichische Wasserstraßen-Gesellschaft mbH	via donau - Österreichische Wasserstraßen-Gesellschaft mbH	2+0	Physical sampling, isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	Flow-dependent, from 1/2 weeks to more than 1 time per day	Filtration
	via donau - Österreichische Wasserstraßen-Gesellschaft mbH	via donau - Österreichische Wasserstraßen-Gesellschaft mbH	4+1	Physical sampling (bottle)	Flow-dependent, from 1/2 weeks to more than 1 time per day	Filtration
	Verbund Hydro Power GmBH (VHP)	Verbund Hydro Power GmBH (VHP)	7+0	Pump sampling, automatized bottle sampling	Flow-dependent, from 3 times per week to 6 times per day	Filtration
	Hydrographic service of Upper Austria	Hydrographic service of Upper Austria	0+3	Physical sampling (bottle), isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	Flow-dependent, from 1 time per week to more than 1 time per day	Filtration

Country	Data owner	Monitoring performed by	No. of stations (Danube + trib.)	SS measurement method	Frequency	SSC analysis method
Slovakia	Slovak Hydrometeorological Institute (SHMU)	Slovak Hydrometeorological Institute (SHMU)	3+0	Physical sampling, isokinetic sampling (depth-integrating)	Flow-dependent, from 1 time per day to more than one time per day	Filtration
	Water Research Institute (VUVH Bratislava)	Water Research Institute (VUVH Bratislava)	3+2	Physical sampling, isokinetic sampling (depth-integrating)	Flow-dependent, from 1 time per day to more than one time per day	Filtration
Hungary	General Water Directorate (OVF)	North-Trans-Danubian Water Directorate (ÉDUVIZIG)	4+1	Physical sampling, pump sampling	5 times per year	Evaporation
	General Water Directorate (OVF)	Directorate of Water Management of Central Danube Basin (KDVVIZIG)	2+0	Pump sampling	5 times per year	Evaporation
	General Water Directorate (OVF)	Lower-Danube-Valley Water Directorate (ADUVIZIG)	3+0	Pump sampling	5 times per year	Evaporation
Croatia	Meteorological and Hydrological Institute of Croatia (DHMZ)	Meteorological and Hydrological Institute of Croatia (DHMZ)	0+1	Physical sampling (bottle), pump sampling, acoustic devices	1 time per day, cross-sectional measurements 6 times per year	Filtration
Serbia	PE Electric Power Industry of Serbia - Branch HPP Djerdap	Jaroslav Černi Institute for the Development of Water Resources (JCI)	4+3	Pump sampling	1-3 times per year	Evaporation
				Physical sampling	1 time per day	

Country	**Data owner**	**Monitoring performed by**	**No. of stations (Danube + trib.)**	**SS measure-ment method**	**Frequency**	**SSC analysis method**
Romania	National Administration "Apele Romane" (ANAR)/National Institute of Hydrology and Water Management	National Administration "Apele Romane" (ANAR)/River Basin Administrations	12+5	Physical sampling	Flow-dependent, ca. 6 times per year	Turbidity meter
Bulgaria	National Institute of Meteorology and Hydrology (NIMH)	National Institute of Meteorology and Hydrology (NIMH)	4+2	Physical sampling, isokinetic sampling (depth-integrating)	1 time per day	Filtration

Table 2 List of the currently operating suspended monitoring stations along the Danube River

Country	**River**	**Name of monitoring site**	**Location (rkm)**
Germany	Danube	Neu-Ulm Bad Held	2 586.70
Germany	Danube	Donauwörth	2 508.13
Germany	Danube	Ingolstadt Luitpoldstrasse	2 457.85
Germany	Danube	Straubing gauging station	2 321.30
Germany	Danube	Vilshofen	2 249.50
Germany	Danube	Kachlet	2 230.70
Germany	Danube	Jochenstein	2 203.10
Austria	Danube	Engelhartszell	2 200.66
Austria	Danube	Donaukraftwerk Aschach	2 161.96
Austria	Danube	Aschach Strombauleitung	2 161.27
Austria	Danube	Linz	2 135.17
Austria	Danube	Donaukraftwerk Abwinden - Asten	2 119.20
Austria	Danube	Donaukraftwerk Wallsee - Mitterkirchen	2 094.21
Austria	Danube	Donaukraftwerk Ybbs - Persenbeug	2 060.20
Austria	Danube	Stein-Krems	2 002.69
Austria	Danube	Donaukraftwerk Altenwörth	1 979.58
Austria	Danube	Donaukraftwerk Greifenstein	1 948.88
Austria	Danube	Donaukraftwerk Freudenau	1 920.67
Austria	Danube	Bad Deutsch-Altenburg (Bauleitung)	1 886.86
Austria	Danube	Hainburg Straßenbrücke*	1 886.24
Slovakia	Danube	Devín	1 878.15
Slovakia	Danube	Bratislava, Lafranconi bridge	1 871.30

Country	River	Name of monitoring site	Location (rkm)
Slovakia	Danube	Bratislava	1 868.75
Hungary	Danube	Dunaremete	1 825.50
Slovakia	Danube	Medveďov Bridge**	1 806.30
Hungary	Danube	Vámosszabadi	1 805.60
Slovakia	Danube	Komárno Bridge	1 767.80
Hungary	Danube	Dunaalmás	1 751.80
Hungary	Danube	Esztergom	1 718.50
Hungary	Danube	Nagymaros	1 694.60
Hungary	Danube	Budapest	1 646.50
Hungary	Danube	Dunaújváros	1 580.60
Hungary	Danube	Dombori	1 506.80
Hungary	Danube	Mohács	1446.90
Serbia	Danube	Novi Sad	1 257.10
Serbia	Danube	Stari Banovci	1 192.75
Serbia	Danube	Smederevo	1 110.40
Romania	Danube	Bazias	1 072.50
Serbia	Danube	HPP Đerdap 1 dam	943.00
Serbia	Danube	Kladovo	932.90
Romania	Danube	Drobeta Turnu Severin	931.00
Bulgaria	Danube	Novo Selo	866.60
Bulgaria	Danube	Lom	743.30
Romania	Danube	Corabia	624.20
Bulgaria	Danube	Svishtov	554.30
Romania	Danube	Zimnicea	553.23
Romania	Danube	Giurgiu	493.05
Romania	Danube	Chiciu Calarasi	379.58
Bulgaria	Danube	Silistra	375.50
Romania	Danube	Vadu Oii	238.00
Romania	Danube	Braila	167.00
Romania	Danube	Ceatal Izmail	80.50
Romania	Danube/Branch Chilia	Periprava	20.00
Romania	Danube/Sfantu Gheorghe branch	Sfantu Gheorghe Harbour	8.00
Romania	Danube	Sulina	2.50

*The data from Bad Deutsch-Altenburg (Bauleitung) and Hainburg Straßenbrücke stations are combined in the data assessment.

**SHMU and VUVH both perform sediment monitoring.

Table 3 List of the currently operating suspended monitoring stations in the most important tributaries of the Danube River (at the confluence)

Country	River	Name of monitoring site	Location (rkm)
Germany	Isar	Plattling	9.12
Germany	Inn	Passau Ingling	3.10
Austria	Inn	Schärding (Schreibpegel)	16.25

Country	River	Name of monitoring site	Location (rkm)
Austria	Traun	Wels-Lichtenegg	33.25
Austria	Enns	Steyr (Ortskai)	30.88
Austria	Morava	Angern	31.89
Slovakia	Morava	Záhorská Ves	32.52
Slovakia	Morava	Moravský Ján	67.15
Hungary	Rába	Győr	14.5*
Croatia	Drava	Donji Miholjac	80.50
Serbia	Tisa	Titel	4.90
Serbia	Sava	Belgrade	5.20
Serbia	Velika Morava	Ljubičevski Bridge	21.83
Romania	Jiu	Zaval	8.00
Bulgaria	Iskar	Oriahovitza	340.50**
Bulgaria	Iantra	Karantzi	208.00**
Romania	Arges	Budeşti	2.00
Romania	Ialomita	Tandarei	29.00
Romania	Siret	Lungoci	77.00
Romania	Prut	Oancea	79.20

*River Rába flows into Danube through River Mosoni-Duna.

**River kilometre values in Bulgaria at the tributaries indicate the distance from the source instead of the mouth.

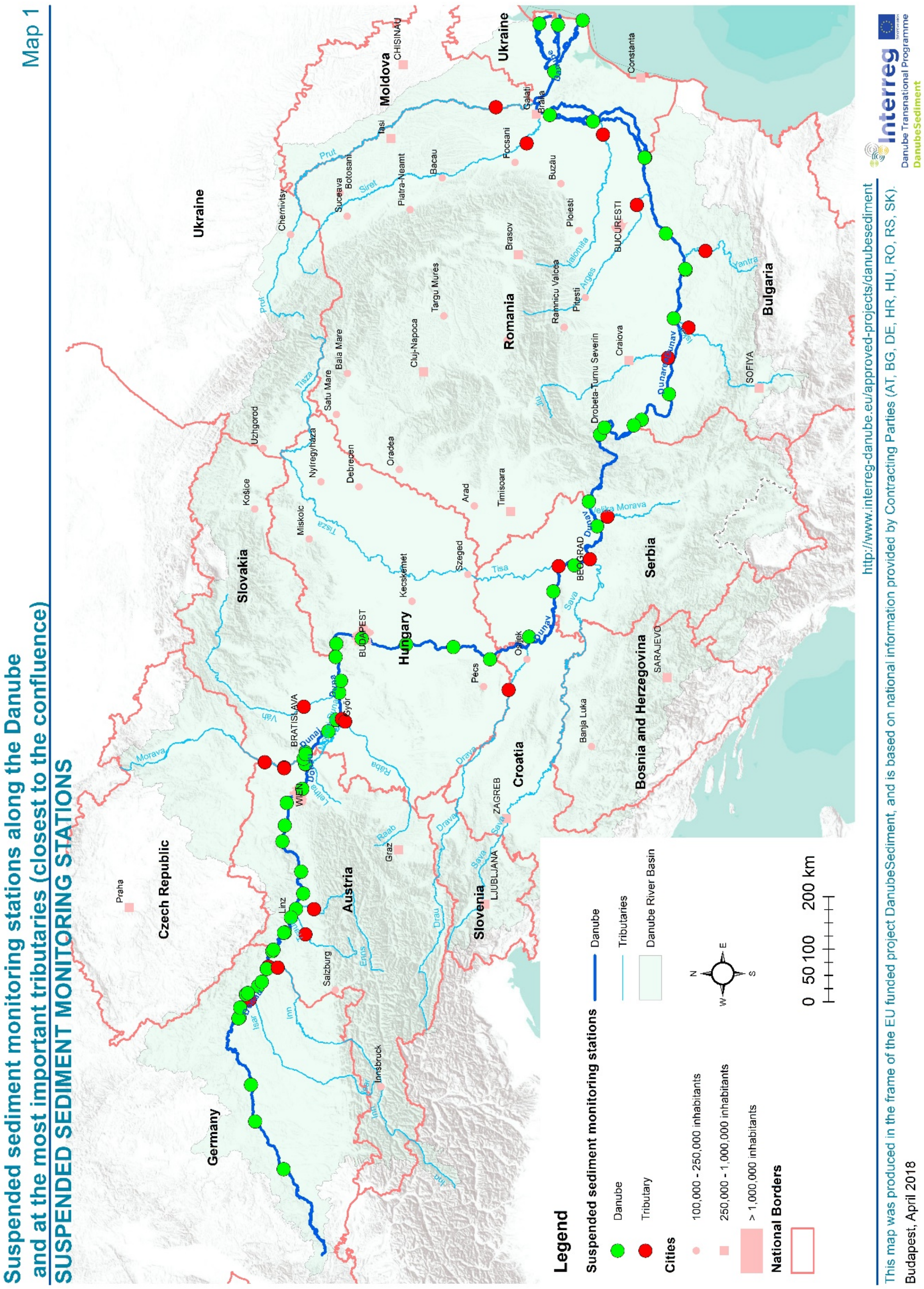


Figure 2 Suspended sediment monitoring stations along the Danube and its important tributaries

2.2.1 Germany

2.2.1.1 Present (2011-, 1966-)

Bavarian Environment Agency (LfU) (2011-)

Table 4 Present SS monitoring stations in Germany (LfU)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Neu-Ulm Bad Held	Danube	2 586.70	Wasserwirtschaftsamt Donauwörth	2011-
Donauwörth	Danube	2 508.13	Wasserwirtschaftsamt Donauwörth	2014-
Ingolstadt	Danube	2 457.85	Wasserwirtschaftsamt Ingolstadt	2011-
Plattling	Isar	9.12	Wasserwirtschaftsamt Deggendorf	2011-
Passau Ingling	Inn	3.10	Wasserwirtschaftsamt Deggendorf	1970-

The purpose of the suspended sediment monitoring at the LfU monitoring stations is the assessment of water management/hydraulic engineering issues (monitoring), assessment of sediment budget and to determine suspended sediment concentration (SSC) (mg/l), SS load (SSL) (kg/s) or annual SSL (t/y) and SS yield (SSY) (t/km^2y) (see the list of abbreviations). The main measurement device is a Solitax ts-line optical backscatter sensor. Acoustic devices and physical sampling methods are also used during reference measurements.

The Solitax ts-line optical backscatter point sensor from the Hach-Lange company is permanently fixed near the bank (*Figure 3*). It continuously measures the concentration of the suspended sediment right in front of the instrument. For calibration and referencing of the continuous measurements, reference samples are also taken. The probe uses an infrared-backscatter method.

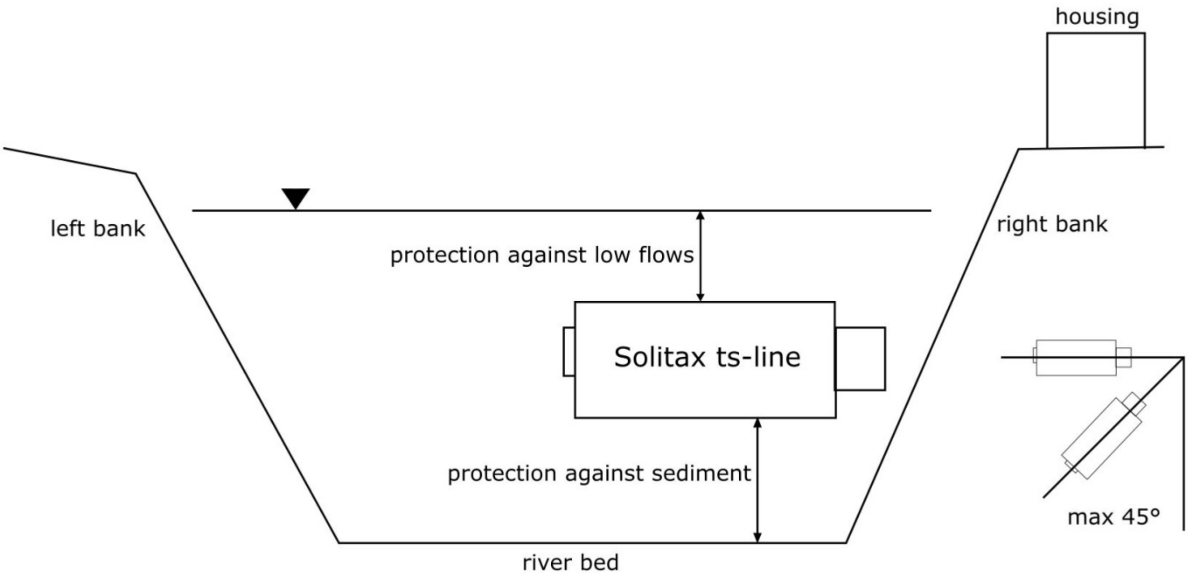


Figure 3 Schematic illustration of measurements with a Solitax ts-line sensor (LfU, 2012)

Using an automatic wiping method, the sensor stays clean for a long time. Therefore, the quality of the measurements does not change over time. The data from the probe is transmitted to a controller. The controller (*Figure 4*) passes the information to a data collector.

Figure 4 The probe and the controller (LfU, 2012)

In order to prevent the sensor from damages due to sediment transport, sun, and algae growths, it is surrounded by a protection case (*Figure 5*).

Figure 5 Protection case for Solitax ts-line optical backscatter (LfU, 2012)

Physical sampling is performed as a reference measurement for the optical backscatter sensor. The one-point sampling with a 500-ml wide-mouth bottle takes place next to the location of the sensor. The bottle is installed on a telescopic bar to guarantee a reaching of the location of the sensor in times of high water levels. The setup is shown in *Figure 6*.

Figure 6 Reference bottle sampler (LfU, 2012)

Information about the discharge is also determined by the gauging station (Q/h relationship). Therefore, discharge multiplied by suspended sediment concentration results in the suspended sediment discharge. Additionally, a correction factor *k* could be applied to the result. This correction factor is determined with a multi-point measurement and is used to adapt the one-point measurement to the whole cross-section.

Together with the multi-point measurements, an acoustic device is also used. The applied instrument is the StreamPro ADCP (*Figure 7*), from RDI.

Figure 7 StreamPro ADCP (Teledyne RD Instrument StreamPro ADCP official photo)

The StreamPro uses a Broadband Doppler signal-processing technology. The calibration and data processing are done with the ViSea software from Aqua Vision (*Figure 8*).

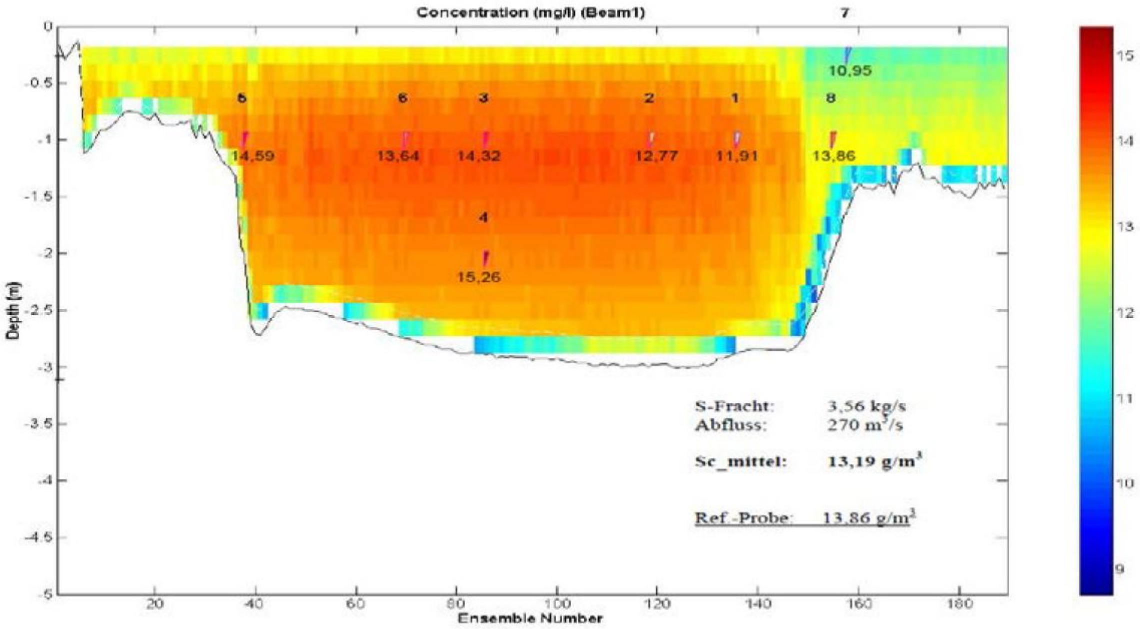


Figure 8 Processed SS concentration results from an ADCP measurement (LfU, 2012)

The laboratory analysis is performed only after the physical sampling. The suspended sediment concentration (SSC) measurement is done with a vacuum filter, which filters suspended particles from 0.45 µm.

Federal Waterways and Shipping Administration (WSV) (1966-)

Table 5 Present SS monitoring stations in Germany (WSV)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Straubing gauging station	Danube	2 321.30	WSV, BfG, BAW	1982-
Vilshofen	Danube	2 249.50	WSV, BfG, BAW	1966-
Kachlet	Danube	2 230.70	WSV, BfG, BAW	1975-
Jochenstein	Danube	2 203.10	WSV, BfG, BAW	1974-

The purpose of the physical sampling at the WSV monitoring stations is to determine the SS transport and the SS load. During monitoring, a 5-l bucket is used. Personnel take the suspended sediment sample.

Afterwards, the sample is filtered. The concentration of fine materials is derived and the suspended sediment discharge is determined taking into account the concentration and the flow discharge (assuming that measured concentration is representative for the concentration in the whole cross-section).

As mentioned above, the laboratory analysis contains the suspended sediment concentration measurement using the filtering method. After the separation of < 0.063 mm fraction through filtering (using filter paper), the fraction is dried and weighed to gain the concentration.

2.2.1.2 Past (1966-2011)

Table 6 Past SS monitoring stations in Germany (LfU)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Neu-Ulm Bad Held	Danube	2 586.70	Wasserwirtschaftsamt	1966-2011
Ingolstadt Luitpoldstrasse	Danube	2 457.85	Wasserwirtschaftsamt Ingolstadt	1966-2011
Plattling	Isar	9.12	Wasserwirtschaftsamt Deggendorf	1966-2011

In the past, the purpose of the physical sampling at the LfU monitoring stations was to assess the water management/hydraulic engineering issues (monitoring), to assess the sediment budget and to determine SSC, SSL, SSY.

Normally, one-point bucket measurements were applied. Once a year a multi-point sampling was additionally performed. For this method, the cross-section was split into a measurement raster. A six-bottle sampler (volume each: 1-2 l) was used to take the suspended sediment samples. The evaluation of the samples was the same as for the one-point measurement.

The frequency of the one-point measurements depended on the water level in the river, and the variations in rising and falling water levels occurring at that time. The number of measurements ranged from once a week to 8 times per day. If the water was highly turbid, the number of measurements also increased (3 times per day).

A filtration method was used to gain the SSC concentration during the laboratory analysis. After the precise cleaning of the bottle - to make sure that every bit of suspended load is taken into account - the sample was filtered (6.1 µm). If fine suspended load was expected, the personnel checked to see if material got lost using dense paper-, synthetic-, glass-filter, or vacuum filters. After filtering, the filter was dried (105°C, until the weight did not change anymore) and then sent to the lab. The sample was weighed in the same humidity conditions as at the station.

2.2.2 Austria

2.2.2.1 Present (2008-; 1928-; 2000-)

viadonau, continuous measurements (2008-)

Table 7 Present SS monitoring stations in Austria (viadonau)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Aschach Strombauleitung	Danube	2 161.27	viadonau	2011-
Hainburg Straßenbrücke	Danube	1 886.24	viadonau	2008-

The purpose of the monitoring at the viadonau stations is to determine SSC (mg/l), SSL (kg/s), annual SSL (t/y), SS yield (t/km^{2}y) and analyse the PSD. The monitoring method, the suspended sediment load calculation method and the suspended sediment concentration measurement method refers to the guideline of surveying suspended sediment load (BMLFUW, 2008; 2017).

The following devices are used during the measurements: US-P63 point-integrating sampler (*Figure 9*, left), US-P61A point-integrating sampler (*Figure 9*, right) and Solitax ts-line turbidity sensor (Hach-Lange) (*Figure 10*).

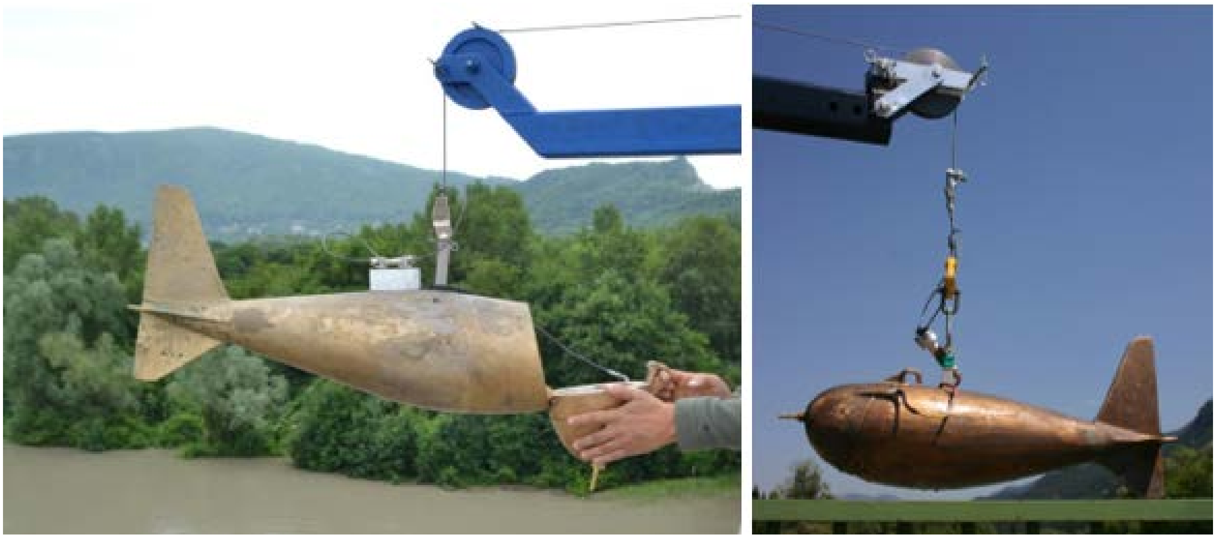


Figure 9 US-P63 (left) and US-P61 A1 point-integrating samplers (right) (IWHW/BOKU)

Figure 10 Solitax ts-line turbidity sensor (viadonau)

A combination of direct and indirect methods is applied to measure the suspended sediment transport. To measure the temporal variability of the suspended sediment transport, an optical sensor is installed, which continuously records the turbidity at one point in the cross-section (near the river bank). The optical sensor is calibrated using a Formazin turbidity standard and the data represent mg/l. The sensor has to be calibrated in-situ using water samples. The sampling frequency of the water samples taken close to the sensor is dependent on the suspended sediment concentration and varies from once a week up to several times a day during flood events.

Additionally, the distribution of the suspended sediment concentration in the cross-section (spatial variability) is considered. To establish the cross-sectional mean concentration, the multi-point method is applied. Using this method, the suspended sediment concentration and flow velocity are measured in various verticals and different depths.

The sampling is undertaken up to 4 times a year using a suspended sediment sampler applied with a trailer and a cable from the bridge. The flow velocities are measured by using an ADCP (Acoustic Doppler Current Profiler), an ADV (Acoustic Doppler Velocimeter) or a current meter. As the ADCP (600 and 1200 kHz) is mounted on a boat, it can only be used up to the highest navigable discharge whereas the ADV and current meter can be applied during all discharge conditions since these instruments are deployed suspended from the bridge by a cable with the equipment mounted on a trailer (*Figure 11*). Thus, the flow velocity is also measured.

Figure 11 The trailer on the bridge with the sediment sampler and the ADV on cable (IWHW/BOKU)

To calculate SS discharge, first the turbidity data has to be calibrated from the water samples. To calibrate the turbidity data, two different methods can be applied, which can also be used in combination. The first method calculates a correction factor between turbidity data and water samples for each occasion when water samples are collected. By using linear interpolation between these time steps, a correction factor (probe factor) is calculated for each turbidity value. The second method uses a simple linear regression (cross-sectional characteristic) between turbidity data and the calibration samples to convert the turbidity data into a record of SSC close to the sensor.

Furthermore, the SS transport and mean SS concentration in the cross-section is determined using the multi-point method, where the SS concentration and flow velocity are measured in various verticals and different depths. Alternatively, the SSC in the cross-section is calculated from the ADCP backscatter signal combined with water samples using the sonar equation

(*Figure 12*). As the ADCP simultaneously measures the flow velocity, the SS transport and mean concentration in the cross-section can be calculated.

Taking into account the relationship (cross-sectional characteristic, *Figure 12*) between the SS concentration close to the sensor and the mean SS concentration from multi-point - or ADCP - measurements, a record of mean suspended sediment concentration in the cross-section is generated. This is combined with the discharge record to provide a record of suspended sediment transport. By integrating the transport over time, the suspended sediment load is determined.

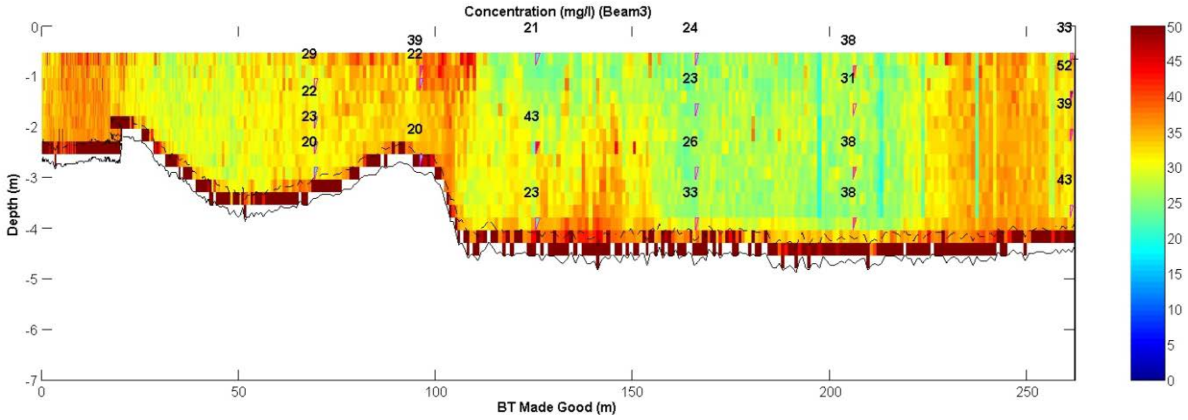


Figure 12 Processed SS concentration results from an ADCP measurement (IWHW/BOKU)

The laboratory analysis contains concentration measurement and particle size distribution analysis as well. The suspended sediment concentration is determined by vacuum filtration (*Figure 13*) using cellulose acetate or cellulose nitrate filters with pore diameters of 0.45 µm. Before filtering, the sample volume is determined. The whole sample volume is filtrated. After filtering, the filter and contents are removed and dried for nearly 2 hours at 105° C. The filter, including the content, is weighed with an analytical balance of an accuracy of ± 0.1 mg. The suspended sediment concentration (mg/l) is calculated by dividing the filter content (mg) by the volume (l).

Figure 13 The vacuum filtration equipment in the laboratory (IWHW/BOKU)

The particle size distribution (PSD) analysis is done with a sieving instrument and a sedimentation instrument. The particle size distribution is determined by combining wet sieving (fraction > 20µm) and automatic sedimentation analysis (fraction < 20 µm) applying the Sedigraph 5000 ET from *Micromeritic*s. Organic matter is removed prior to the particle size analysis by treating the sample with 10% hydrogen peroxide. The sieving is performed with a set of sieves (2 mm, 630 µm, 200 µm, 63 µm and 20 µm). The coarse fraction is dried at 105 °C and specified in mass percent of the weighted sample. The fraction < 20 µm is dispersed in an ultrasonic bath by adding 0.05 % sodium polyphosphate. Afterwards, the fraction < 20 µm is analysed with the Sedigraph using x-rays and applying Stoke's law. Combining the cumulative curves of the Sedigraph results and the sieving data the particle size distribution of the whole sample is determined.

To determine the PSD a minimum of 4-5 g of dry matter is needed. Therefore, the sample volume is dependent on the SSC in the river when the sample is taken.

viadonau, intermittent sampling (1928-)

Table 8 Present intermittent sampling in Austria (viadonau)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Engelhartszell	Danube	2 200.66	viadonau	1954-
Aschach Strombauleitung	Danube	2 161.27	viadonau	1960-
Linz	Danube	2 135.17	viadonau	1928-
Stein-Krems	Danube	2 002.69	viadonau	1991-
Bad Deutsch-Altenburg (Bauleitung)	Danube	1 886.86	viadonau	1956-
Angern	Morava	31.89	viadonau	1957-

The purpose of the monitoring at the viadonau stations (Engelhartszell, Angern, Aschach Strombauleitung, Linz, Stein-Krems, Bad Deutsch-Altenburg) is to determine SSC (mg/l), SS transport (kg/s) and SS load (t/y).

The sampling frequency is dependent on the water level or discharge and varies from once every three days up to four times a day during flood events. Samples are taken with a bottle sampler (*Figure 14*) at one point of the river (usually from the river bank).

Figure 14 Bottle sampler (BMLFUW 2008; 2017)

Although a sample only represents the concentration at a particular instant in time, the values are used to represent the mean daily concentration to calculate the load. When two or more samples are available on the same day, the average of these samples is calculated to obtain the daily mean concentration. For days, where no samples were taken, the concentration is determined by linear interpolation between concentrations of the chronologically closest samples to generate values for these days. By multiplying the SSC with the discharge on a daily basis, the SS transport per day is calculated. The average monthly and annual SSC and SS transport is determined by simply calculating the average of the daily values for the corresponding time period.

The suspended sediment concentration is determined by vacuum filtration using cellulose acetate or cellulose nitrate filters with pore diameters of 0.45 µm. Before filtering, the sample volume is determined. The whole sample volume is filtrated. After filtering, the filter and contents are removed and dried for nearly 2 hours at 105° C. The filter including the content is weighed with an analytical balance of an accuracy of ± 0.1 mg. The suspended sediment concentration (mg/l) is calculated by dividing the filter content (mg) by the volume (l).

Verbund Hydro Power GmbH (2000-)

Table 9 Present SS monitoring stations in Austria (Verbund)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Donaukraftwerk Aschach	Danube	2 161.96	VHP	2000-
Donaukraftwerk Abwinden - Asten	Danube	2 119.20	VHP	2000-
Donaukraftwerk Wallsee - Mitterkirchen	Danube	2 094.21	VHP	2000-
Donaukraftwerk Ybbs-Persenbeug	Danube	2 060.20	VHP	2000-
Donaukraftwerk Altenwörth	Danube	1 979.58	VHP	2000-
Donaukraftwerk Greifenstein	Danube	1 948.88	VHP	2000-
Donaukraftwerk Freudenau	Danube	1 920.67	VHP	2000-

The Verbund Hydro Power GmbH (VHP) is using pump sampling and automatized bottle sampling (*Figure 15, Figure 16*) for suspended sediment monitoring. At the monitoring station Ybbs-Persenbeug an optical sensor is installed, additionally. The purpose of the measurements is to determine the SSC (mg/l).

Figure 15 The automated sediment sampler (Verbund)

The laboratory analysis is performed by viadonau. The suspended sediment concentration is determined by vacuum filtration using cellulose acetate or cellulose nitrate filters with pore diameters of 0.45 µm. Before filtering, the sample volume is determined. The whole sample volume is filtrated. After filtering, the filter and contents are removed and dried for nearly 2 hours at 105° C. The filter including the content is weighed with an analytical balance of an accuracy of ± 0.1 mg. The suspended sediment concentration (mg/l) is calculated by dividing the filter content (mg) by the volume (l).

Figure 16 The place of the measurement (division pier) (Verbund)

Hydrographic Service of Upper Austria (HD OOE) (2008-)

Table 10 Present SS monitoring stations in Austria (HD OOE)

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Schärding (Schreibpegel)	Inn	16.25	HD OOE	2008-
Wels-Lichtenegg	Traun	33.25	HD OOE	2008-
Steyr (Ortskai)	Enns	30.88	HD OOE	2008-

The suspended sediment monitoring method at the tributaries is the same as the method applied at the viadonau stations that provide continuous data and has been described above. The only difference is that only a US-P61A point sampler is used at these stations and that at the monitoring stations Wels-Lichtenegg and Steyr (Ortskai) the equipment to perform cross-sectional measurements is deployed with a cable way.

2.2.2.2 Past (1956-2008)

Table 11 Past SS monitoring stations in Austria

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Aschach Strombauleitung	Danube	2 161.27	viadonau	1960-2011
Bad Deutsch-Altenburg (Bauleitung)	Danube	1 886.86	viadonau	1956-2009
Wels-Lichtenegg	Traun	33.25	HD OOE	1960-2008
Steyr (Ortskai)	Enns	30.88	HD OOE	1984-2008

In the past, the purpose of the physical sampling was to determine the SSC (mg/l), the SS transport (kg/s) and the SS load (t/y). The sampling frequency was dependent on the water level or discharge and varied between once every three days up to four times a day during flood events.

Although a sample only represented the concentration at a particular instant in time, the values were used to represent the mean daily concentration to calculate the load. For stations monitored by viadonau, when two or more samples were available on the same day, the average of these samples was calculated to obtain the daily mean concentration. For days with no sampling, the concentration was determined by linear interpolation between concentrations of the chronologically closest samples to generate values for these days. By multiplying the SSC with the discharge on a daily basis, the SS transport per day was calculated. The average monthly and annual SSC and SS transport was determined by simply calculating the average of the daily values for the corresponding time period.

For those stations monitored by HD OOE, the values for days without sampling were generated through linear interpolation between two concentrations of the chronologically closest measurements. The SSC values are multiplied with the correspondent discharge. On days where more than one sample was taken and more than one SS transport value was calculated (one for each sample), the average of these values was calculated to obtain the daily mean SS transport. The average monthly and annual SS transport was determined by simply calculating the average of the daily values for the corresponding time period. The mean monthly SSC was determined by dividing the SS transport by the discharge, whereas the mean annual SSC was the average of the monthly SSCs of the year.

2.2.3 Slovakia

2.2.3.1 Present (1991-)

Table 12 Present SS monitoring stations in Slovakia

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Bratislava, Lafranconi Bridge	Danube	1 871.30	VUVH	1991-
Medveďov Bridge	Danube	1 806.30	VUVH	1991-
Komárno Bridge	Danube	1 767.80	SHMU	1995-

The purpose of the suspended sediment monitoring is to determine the mean annual suspended sediment transport rate (tons/year). Regular SS monitoring has been performed by the Slovak Hydrometeorological Institute (SHMU; in three stations: Bratislava, Medveďov and Komárno) and Water Research Institute (VUVH; Bratislava - Lafranconi Bridge and Medveďov). Since the Slovak sediment experts consider the VUVH data to be more reliable, the VUVH data will be used, were available. For the monitoring station Komárno Bridge, the project will use the data assessed by SHMU. SHMU measurements are taken daily from the river bank with a bottle sampler (1 sample/day). VUVH uses a depth-integrating sampler (*Figure 17*) for SSC monitoring in Bratislava and at the Medveďov bridge. The sampler is lowered to the river bed and raised to the surface at a uniform rate to accumulate a suspended sediment sample. Sampling frequency depends on actual hydrological conditions in the Danube – normally 3 times in a week during steady flow conditions and daily or a few times per day during increasing/decreasing discharges.

Figure 17 The VUVH-sampler (VUVH)

The suspended sediment load is calculated by using a linear regression, which is derived from direct field measurements of the suspended sediment concentration (SSC) and the actual discharge during measurement.

In the laboratory, the filtering method is used to determine the suspended sediment concentration. During the analysis, 0.2 l from the water sample is extracted during permanent mixing. The 0.2 l volume sample is passed through a filter of a diameter of 0.45 µm. After filtering, the filter is dried at 105°C for 24 hours and weighed.

2.2.3.2 Past (campaigns between 1933-2010)

Table 13 Past SS sampling campaigns in Slovakia

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Devín	Danube	1 878.15	VUVH	1997-1998
Devín	Danube	1 878.15	VUVH	1933-1935
Devín	Danube	1 878.15	VUVH	1952-1960
Devín	Danube	1 878.15	VUVH	1970-1986
Medveďov Bridge	Danube	1 806.30	VUVH	2000-2002
Záhorská Ves	Morava	32.52	VUVH	1993-1997
Moravský Ján	Morava	67.15	VUVH	1993-1997

In the past, the monitoring of sediment regime - bedload and suspended - was always performed by VUVH in the frame of research programmes. In these measurement campaigns, a VUVH depth-integrating sampler (*Figure 18*) was used. The measurements were performed from a ship in several verticals, using the VUVH depth-integrating sampler and an Ott sampler. Shorter monitoring campaigns were also performed by the VUVH at the site of the Medved’ov Bridge (2000-2002. Samples were collected in the way described above.

Figure 18 Measurements for the whole cross-section performed within the wider research programme on sediment transport using Ott-sampler and VUVH sampler (VUVH)

Using the results of field measurements, the linear regression equations were derived. These equations are used to calculate daily average values of suspended load.

The filtering method was used during the laboratory analysis to determine the suspended sediment concentration. The samples in the range of 0.1 l - 0.5 l are extracted after mixing. The water samples are passed through a filter of a diameter of 45 µm, and then the filter is dried at 105 °C for 24 hours and weighed. The particle size distribution analysis was performed with laser diffraction by ANALYSETTE laser device in VUCHT Bratislava.

2.2.4 Hungary

2.2.4.1 Present (1949-)

Table 14 Present SS monitoring stations in Hungary

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Vámosszabadi	Danube	1 805.60	ÉDUVIZIG	1988-
Nagymaros	Danube	1 694.60	KDVVIZIG	1951-
Budapest	Danube	1 646.50	KDVVIZIG	1969-
Dunaújváros	Danube	1 580.60	ADUVIZIG	1950-
Dombori	Danube	1 506.80	ADUVIZIG	1968-
Mohács	Danube	1 446.90	ADUVIZIG	1949-
Győr	Rába*	14.5	ÉDUVIZIG	1988-

*River Rába flows into Danube through River Mosoni-Duna.

The three Water Directorates along the Danube in Hungary perform pump sampling in order to determine SSC, SS transport and PSD. Data has been collected since 1988 at the monitoring stations of the North-Transdanubian Water Directorate (ÉDUVIZIG); since 1951 at the stations of the Middle-Danube-Valley Water Directorate (KDVVIZIG) and since 1949 at the stations of the Lower-Danube-Valley Water Directorate (ADUVIZIG).

According to the standard depth-integral method in Hungary, a 1 l water sample is taken at 10 points (evenly distributed in the vertical), in 7 verticals, with a pump lowered from a boat or with a bottle screwed onto the propeller wing and lowered from a boat. The 1-litre samples are then poured together into a 10-litre sample for every vertical. The sample is transported to the laboratory and after 24 hours of sediment settling, 9 litres of water are decanted (with a siphon) and only 1 litre of concentrated sample from the whole sample is analysed. This 1 l sample is dried and weighed. The flow velocity is also measured during the physical samplings with a propeller wing in 13 verticals and 10 points. The sediment discharge is estimated by calculating the specific sediment discharge for the measurement verticals from the product of the depth averaged flow velocity and sediment concentration, then the values are integrated along the cross-section.

After 2005, when flow measurements were performed via ADCP, suspended sediment sampling continued but no sediment load calculations were done.

The laboratory analysis includes both SSC measurements and determination of PSD. After addition of ammonium hyrdoxide (NH_4OH) as a flocculant, the 10-litre bottle samples are left to settle for 24 hours. On the next day, the clear water is carefully decanted with a siphon (*Figure 19*). The remaining sample with all the settled suspended sediment is poured into a drying cup (with known weight) and dried at 105 °C until mass equilibrium. Then, the cup with the dry suspended material is weighed again. The SSC is calculated from the known volume of the original sample and the difference between the two measured weights.

Figure 19 Laboratory analysis in Hungary. From left above: separation of clear water and settled suspended sediment; analytical balance; cups with dried material; oven

In order to determine the PSD, the weight of the dried sample has to be at least 0.1 g. The PSD for particles larger than 0.15 mm is determined by sieving (*Figure 20*, right), but the percentage of finer particles is determined by sedimentation. The sedimentation instrument is called Papfalvy sedimentation instrument (*Figure 20*, left). Before sedimentation, the dried sample is mixed with distilled water and ammonium solution. When the sedimentation is done, the sample is dried and weighed again. From the results of the sieving and sedimentation, the PSD curve can be defined.

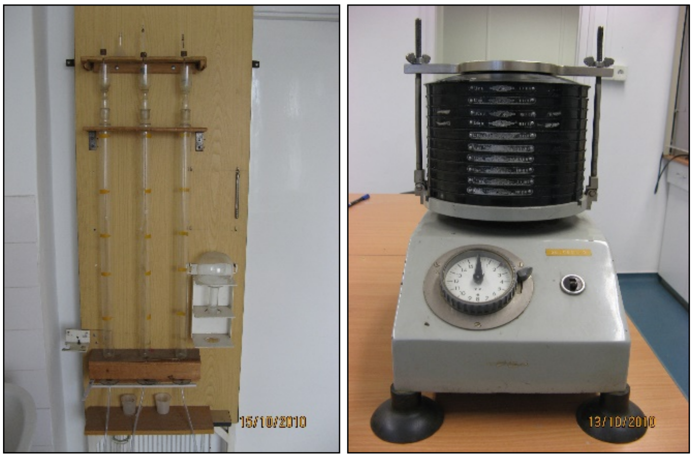


Figure 20 Papfalvy sedimentation instrument (left) and sieving machine (right)

2.2.5 Croatia

2.2.5.1 Present (1993-)

Table 15 Present SS monitoring stations in Croatia

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Donji Miholjac	Drava	80.50	DHMZ	1993-

The purpose of suspended sediment monitoring in Croatia is to determine the SSC and SS transport. During the daily measurements, the physical sampling method is used. Besides that, profile measurements are also performed 6 times per year, when the samplings are done by simultaneous pump sampling and flow measurements using an ADCP.

In order to determine the daily concentrations of suspended sediment, water samples are traditionally collected at a single point near the stream surface. The sample is poured through a 0.45 µm filter paper (*Figure 21*). Sample filtration is done by using Munktell filter paper of a diameter of 320 mm.

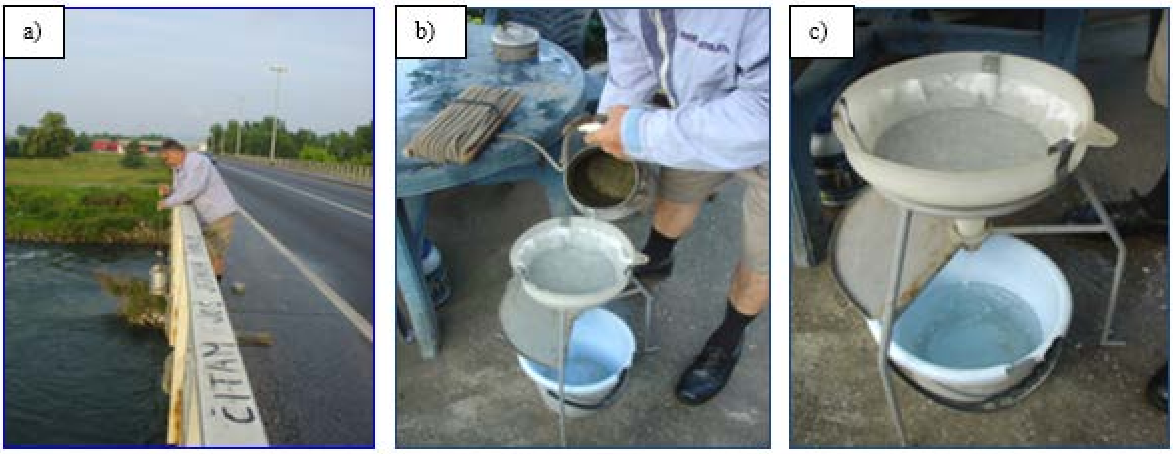


Figure 21 Suspended sediment sampling

At the end of the month, the filters are sent to the Hydrological and Meteorological Service (DHMZ), where they undergo laboratory analysis using a standard method (ISO 4365:2005) that dries the sample at 105 °C, followed by cooling and weighing. Based on the difference in the weight between the empty and full filter paper, the suspended sediment concentrations are calculated and expressed in (g/m^3). The annual overviews of the daily values of SSC and daily, monthly and annual values of SS transport are published every year in the Hydrological Yearbooks.

In order to identify the real concentration value at a cross-section, the DHMZ Department for Hydrology occasionally conducts cross-sectional measurements of the concentration and current transport of suspended sediment at a standard cross-section, i.e. multipoint measurements. The measurement is done according to the ISO 4363:2002 standard. The so-called Van Dorn bottle sampler is lowered from a bridge in 6 evenly distributed verticals (*Figure 22*). Three points per depth are sampled at each vertical (surface, mid-depth, bottom). During the sampling, the flow velocity is measured simultaneously by an ADCP.

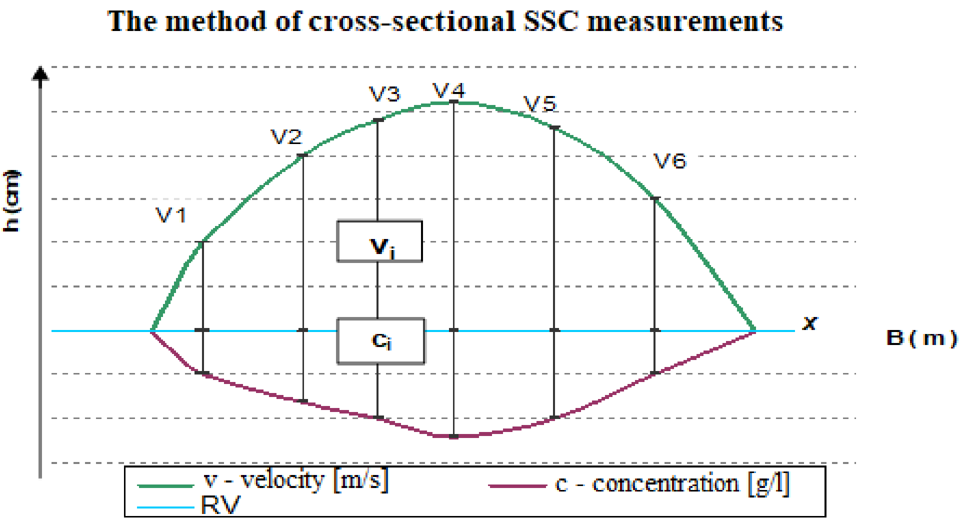
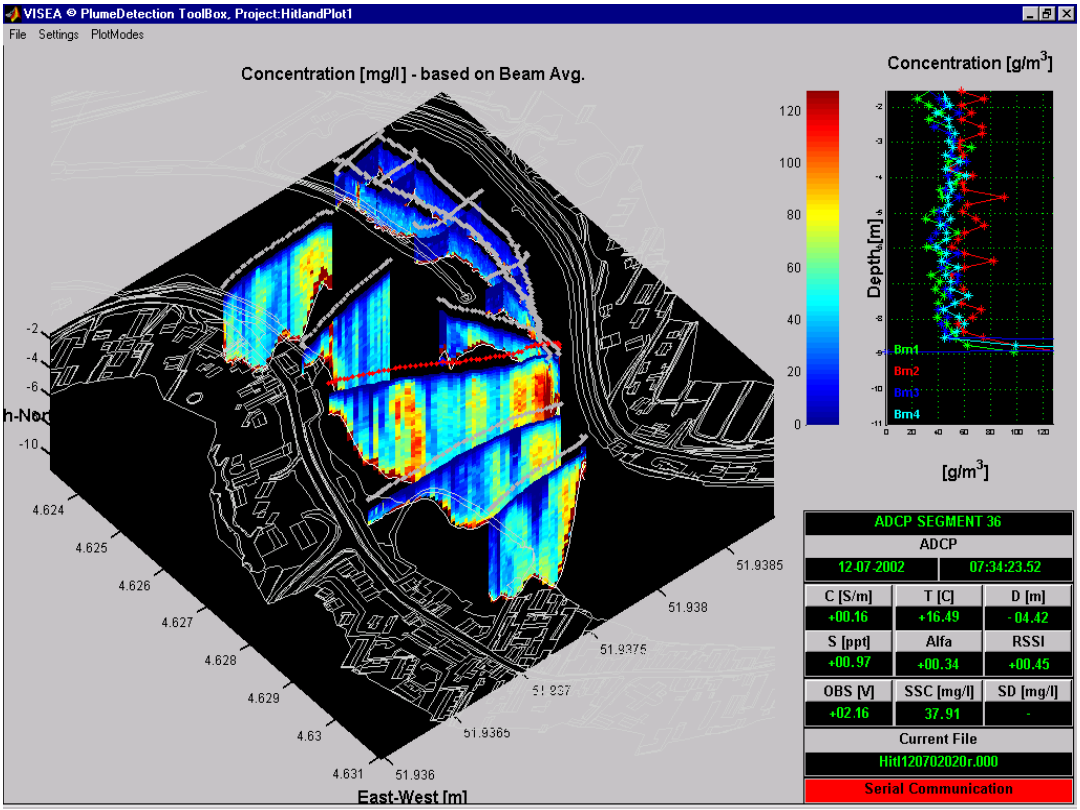


Figure 22 Schematic figure of the measurement method

The current sediment volume that passes the cross-section of height H and width B is defined by a double integral:

$$\text{SS load} = \iint_{00}^{BH} \text{vc dh dx} \left[\frac{\text{kg}}{\text{s}}\right]$$

Since 2012, the cross-sectional suspended sediment concentrations have been analysed with a new method using an additional software package called "ViSea 4.0" developed by the Dutch company AquaVision (*Figure 23*).



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OBS [V] +02.16
SSC [mg/l] 37.91
SD [mg/l] -
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Figure 23 Graphical representation of cross-sectional SSC measurements by the ViSea software

Before the cross-sectional measurement of suspended sediment, it is common practice to collect an integrated 200 l water sample across the entire flow cross-section and store it in a barrel. After a standstill period of one to two days, the sample is decanted and only 10 l of water is taken for a laboratory analysis of the particle-size distribution of suspended sediment.

As the composition of suspended sediment usually ranges from sand to the finest clay fractions, the particle-size analysis is performed using a combined method of sieving and pippetting (or areometering). All *D* > 0.063 mm fractions are first sieved through standard sieves. Since *D* < 0.063 mm fractions cannot be sieved, the dimension of smaller fractions is defined by determining the change in suspension density due to the sedimentation of particles of varying diameters in a liquid. In literature, this procedure is called a sedimentation (settling) experiment.

The suspension sedimentation or the calculation of the settling velocity of solid particles in steady water is tested using the Andreasen pipette (*Figure 24*). The purpose of the analysis is to calculate the size of the particles, which will no longer be found in the analysed part after approximately 24 hours and to determine their share (%) in the overall mass of the initially suspended particles.

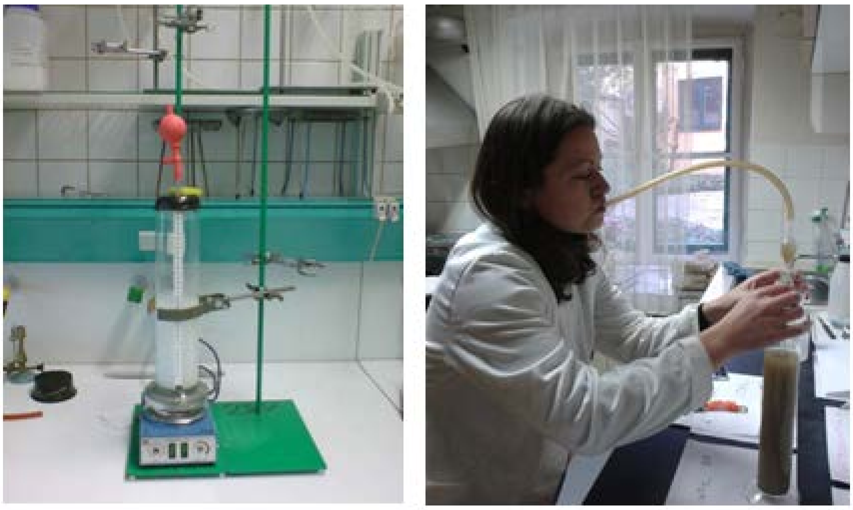


Figure 24 The Andreasen pipette (left) and the pipetting procedure (right)

2.2.6 Serbia

2.2.6.1 Present (1974-)

Table 16 Present SS monitoring stations in Serbia

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Novi Sad	Danube	1 257.10	JCI	1986-
Stari Banovci	Danube	1 192.75	JCI	1986-
Smederevo	Danube	1 110.40	JCI	1986-
HPP Đerdap 1 dam	Danube	943.00	JCI	1974-
Kladovo	Danube	932.90	JCI	1974-
Titel	Tisza	4.90	JCI	1986-
Belgrade	Sava	5.20	JCI	1986-
Ljubičevski Bridge	Velika Morava	21.83	JCI	1986-

In Serbia, physical sampling is done on a daily basis, in order to determine the “surface” suspended sediment concentration. Water samples (10 l) are collected at selected permanent points on the monitoring cross-section.

The “surface” concentrations are converted into cross-sectional average values, by applying empirical relationships established by complete measurements of water and sediment discharge. Daily values of suspended sediment discharge are calculated as the product of average cross-sectional concentration and water discharge measured by the Hydrometeorological Service of Serbia at the closest hydrological station.

Complete field measurements of water and sediment parameters are performed periodically (1-3 times a year). They identify the water flow and sediment characteristics at various points, verticals, and across the monitoring profile. The field activities include: (1) A geodetic survey of the river cross-section; (2) Flow velocity measurements at 7 to 10 verticals, 5 points each, for at least 5 minutes; (3) Pump sampling of water and sediment samples using a vacuum bathometer (5 verticals, 5 points each), approximately 40 l per sample; and (4) Collection of riverbed samples at each vertical, approximately 5 kg per sample.

The purpose of the complete measurements is to identify the correlation between the surface concentration of suspended sediment at a specific point of the monitoring cross-section and the average cross-sectional concentration of suspended sediment. During the monitoring a vacuum bathometer (*Figure 25*) for the suspended sediment sampling and a current meter for the flow velocity measurements are used.

The processing of data includes the evaluation of velocity, SSC, SS load and PSD. From the average vertical values and water discharge, the transport of sediment by grain-size fractions and the average settling velocity of sediment are also calculated. During each measurement, cross-sectional profiles of the investigated values are obtained (*Figure 26*).

The laboratory analysis contains suspended sediment concentration (SSC) measurement and particle size distribution (PSD) analysis as well. In order to determine the SSC, the evaporation method is used on the sample with a volume of 10 l. After the sediment settling process (at least a few days long), 1-1.5 l of concentrated sediment is decanted and transported into the sediment laboratory. After 24 hours of sediment settling, a sample of 100 ml of sediment is taken. The settling process is repeated for another 24 hours, and then all of the sediment is dried at 105°C for 4 hours and weighed. The sediment concentration is calculated based on the known volume of sample and the weight of sediment. For the PSD analysis, a sedimentation instrument and a sieving instrument is used. The particle-size is analysed by fraction-meter (for particle diameter $D > 0.063$ mm) and the pipette-method (for smaller particles). Both methods determine the particle settling velocity.

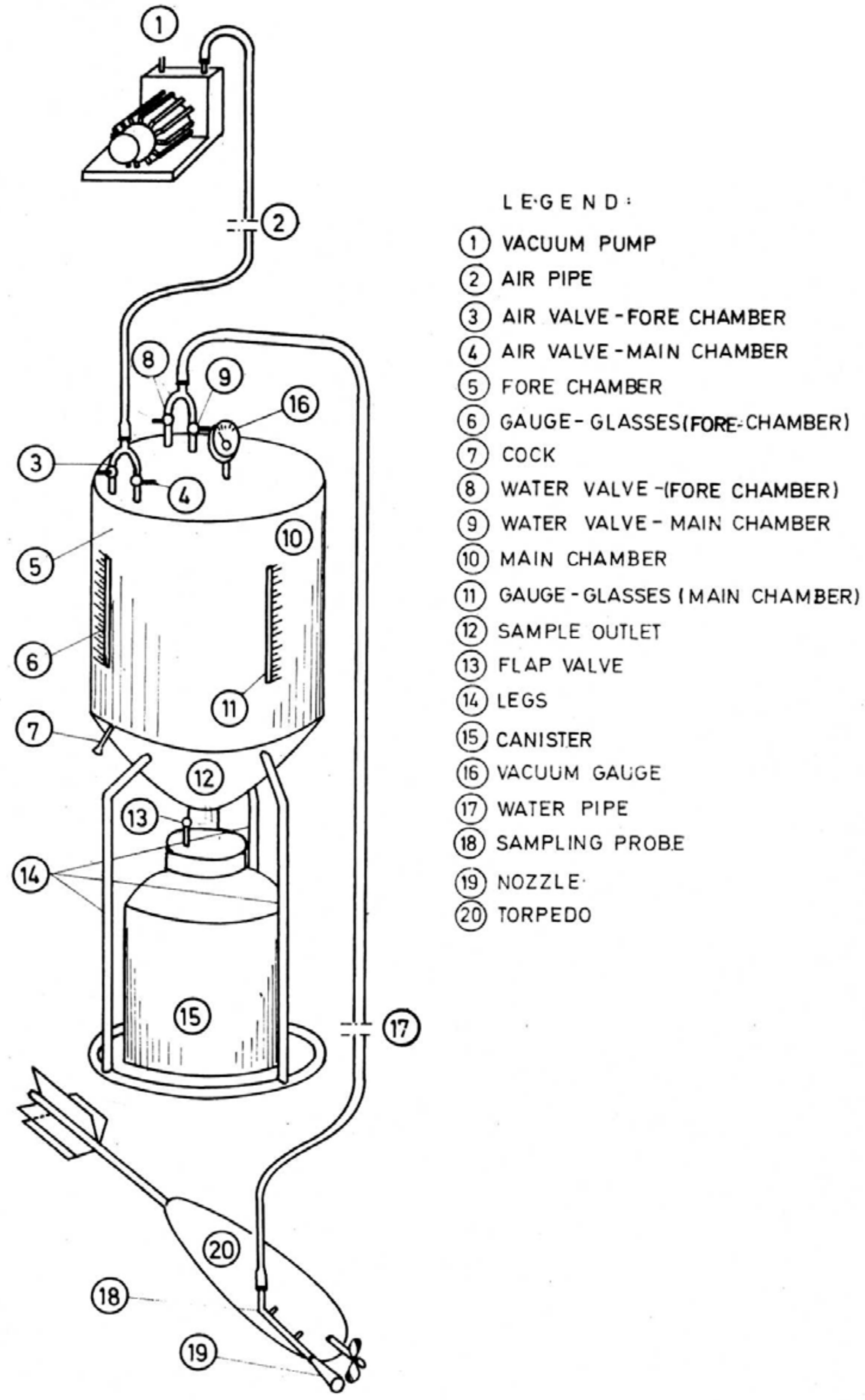
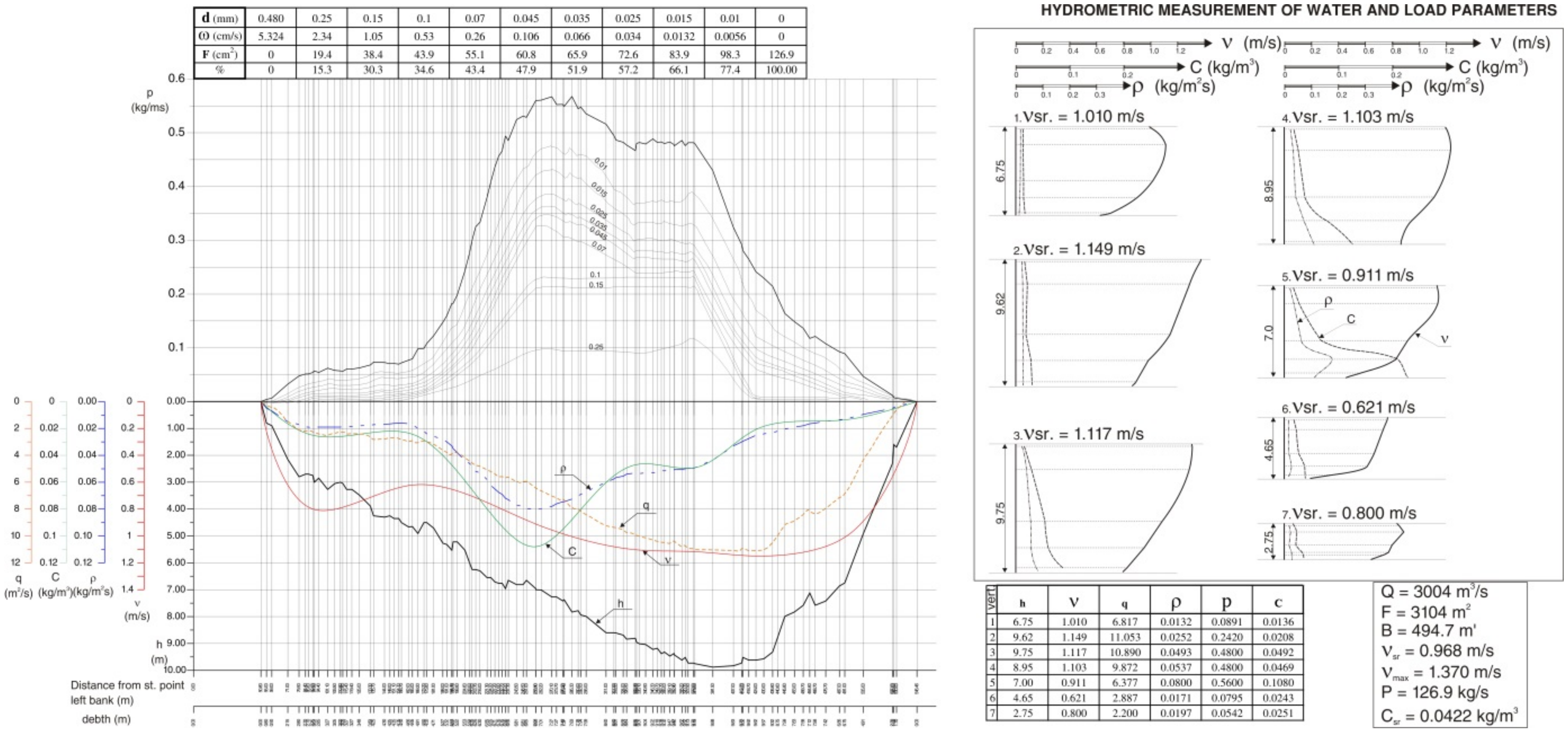


Figure 25 A bathometer used in Serbia



d (mm)	0.480	0.25	0.15	0.1	0.07	0.045	0.035	0.025	0.015	0.01	0
ω (cm/s)	5.324	2.34	1.05	0.53	0.26	0.106	0.066	0.034	0.0132	0.0056	0
F (cm²)	0	19.4	38.4	43.9	55.1	60.8	65.9	72.6	83.9	98.3	126.9
%	0	15.3	30.3	34.6	43.4	47.9	51.9	57.2	66.1	77.4	100.00

vert.	h	v	q	ρ	p	c
1	6.75	1.010	6.817	0.0132	0.0891	0.0136
2	9.62	1.149	11.053	0.0252	0.2420	0.0208
3	9.75	1.117	10.890	0.0493	0.4800	0.0492
4	8.95	1.103	9.872	0.0537	0.4800	0.0469
5	7.00	0.911	6.377	0.0800	0.5600	0.1080
6	4.65	0.621	2.887	0.0171	0.0795	0.0243
7	2.75	0.800	2.200	0.0197	0.0542	0.0251

$Q = 3004\ m^3/s$
$F = 3104\ m^2$
$B = 494.7\ m'$
$v_{sr} = 0.968\ m/s$
$v_{max} = 1.370\ m/s$
$P = 126.9\ kg/s$
$C_{sr} = 0.0422\ kg/m^3$

Figure 26 Results of the complete field measurement in Serbia

2.2.7 Romania

2.2.7.1 Present (1931-)

Table 17 Present SS monitoring stations in Romania

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Bazias	Danube	1 072.50	ANAR /Jiu River Basin Administration	1971-
Drobeta Turnu Severin	Danube	931.00	ANAR /Jiu River Basin Administration	1980-
Corabia	Danube	624.20	ANAR /Arges River Basin Administration	1979-
Zimnicea	Danube	553.23	ANAR /Arges River Basin Administration	1931-
Giurgiu	Danube	493.05	ANAR /Arges River Basin Administration	1931-
Chiciu Calarasi	Danube	379.58	ANAR /Dobrogea-Litoral River Basin Administration	1931-
Vadu Oii	Danube	238.00	ANAR /Dobrogea-Litoral River Basin Administration	1931-
Braila	Danube	167.00	ANAR /Dobrogea-Litoral River Basin Administration	1931-
Ceatal Izmail	Danube	80.50	ANAR /Dobrogea-Litoral River Basin Administration	1931-
Periprava	Danube/ Branch Chilia	20.00	ANAR /Dobrogea-Litoral River Basin Administration ANAR /Dobrogea-Litoral River Basin Administration ANAR /Dobrogea-Litoral River Basin Administration	1961-
Sfantu Gheorghe Harbour	Danube/ Sfantu Georghe	8.00	ANAR /Dobrogea-Litoral River Basin Administration	1979-
Sulina	Danube	2.50	ANAR /Dobrogea-Litoral River Basin Administration	1979-
Zaval	Jiu	2.50	ANAR /Jiu River Basin Administration	1963-
Budeşti	Arges	20.00	ANAR /Arges River Basin Administration	1955-
Tandarei	Ialomita	29.00	ANAR /Ialomita-Buzau River Basin Administration	1977-
Lungoci	Siret	77.00	ANAR /Siret River Basin Administration	1956-
Oancea	Prut	79.20	ANAR /Prut River Basin Administration	1958-

In Romania, physical sampling is used to monitor suspended sediment. The purpose of the monitoring is to determine SS transport (kg/s), SS load (t/y), SSC (mg/l) and PSD. The load quantity passing through a cross-section of the river bed in a certain unit of time constitutes the load, which is expressed in kg/s, t/s, t/y. The measurements of suspended sediment are performed using a specific equipment, the bathometer (*Figure 27*). This instrument was built in 1986 by the Institute of Meteorology and Hydrology (IMH) and has a capacity of 1 litre.

Figure 27 The bathometer used in Romania

Samples must be taken in the year after the major floods. The number of samples shall not be less than four. It is mandatory that the riverbed silt samples be collected in parallel to suspended sediment samples. The suspended sediment discharge is computed by the product of SSC and the flow velocity. The flow velocity is also measured during the entire sediment sampling. Until 2014, these measurements were performed with a propeller wing instrument and after that, both propeller wing and ADCP (*Figure 28*) devices are in use.

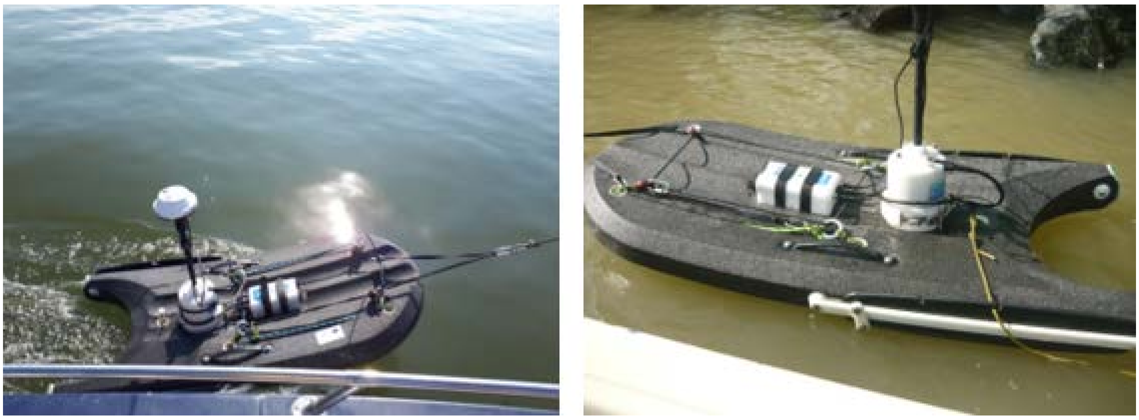


Figure 28 Doppler equipment - River Surveyor M9

The complete flow rate measurement is accomplished by the crossing the water surface with the ADCP mounted on a boat.

The hydrologist executes different measurements at the hydrometric gauge stations. While „complete” load measurements, i.e. multipoint measurements, cover the entire cross-sections, the „simple” load measurements are limited to one point near the river bank. During the latter, single water samples are collected from the water surface, using a bucket or a bottle. This is done twice a day. Therefore, the daily mean SSC represents the average of two values. Suspended sediment concentrations from the “simple” load measurements are obtained in the laboratory, using the standard method based on filtration, drying and weighing.

The frequency of field measurements is variable; it depends on the flow regime. During a year, 4-6 complete measurements are carried out at standard water depth, in a number of verticals of the cross-section. Based on mathematical formulas, a cross-sectional mean SSC is obtained from all values measured in the cross-section. Each year, a correction is established based on the cross-sectional mean and the near-bank point values of SSC. Then, the correction factor is applied to the daily values. The number of verticals (5-9 verticals) depends on the actual width of the cross-section. The distance between the verticals is around 100 m.

Concerning the “complete” load measurements (multipoint measurements), until few years ago the laboratory analysis was based on filtering the water samples to obtain the SSC in mg/l. Currently, a portable turbidity meter provides the SSC values of the water samples directly in mg/l. To perform the calibration of the equipment (Rd. Lange Hach Dr. 890 photocolorimeter, *Figure 29*), the hydrologists use the blank sample of distilled water. Then the specific glass of the equipment is filled with the collected water sample and the SSC is calculated. The water sample is shaken well before being placed in the equipment for reading. After the first reading, the glass is shaken, rotated 180 degrees and the reading is repeated. At least two readings are performed, and the final value is obtained as the arithmetic mean of the readings.

Figure 29 The Hach Lange photocholorimeter

In the Romanian tributaries, concentration measurements are obtained with the filtering method. Before filtering, the filters are prepared and the data is enrolled on envelopes and filters (date, time, vertical number, standard point from which the sample was taken, depth, bottle number). One litre of water sample is mixed and passed through a filter, dried in the oven at 105 °C and then the filter is weighed. The equipment of the filtering method is shown in *Figure 30*. The volume of the water sample depends on the turbidity value. In the past, particle size distribution was analysed sporadically. Currently, there is no particle size distribution analysis.

Figure 30 Oven; balance; dry and weighed filters

2.2.8 Bulgaria

2.2.8.1 Present (1961-)

Table 18 Present SS monitoring stations in Bulgaria

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Lom	Danube	743.30	NIMH	2017-
Svishtov	Danube	554.30	NIMH	1989 -
Silistra	Danube	375.50	NIMH	1989 -
Oriahovitza	Iskar	340.50	NIMH	1961-
Karantzi	Iantra	208.0	NIMH	1964-

In Bulgaria, the main purpose of the suspended sediment monitoring is to determine the SSC (mg/l). The 1 l sampler bottle (*Figure 31*) is lowered from a vertical in the area closer to the Bulgarian bank using the depth-integral method.

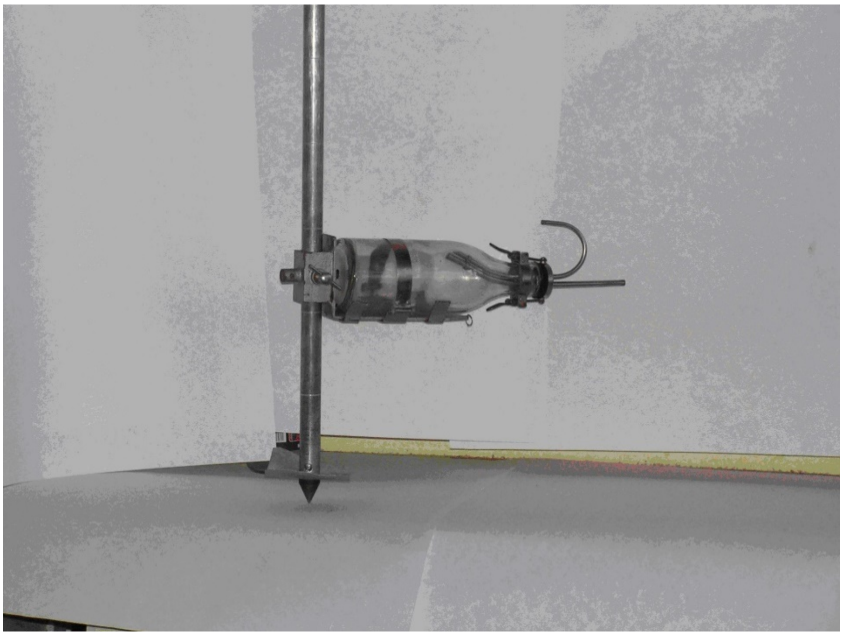


Figure 31 The sediment sampler used in Bulgaria

The sediment discharge (kg/s) is calculated using the determined SSC (after laboratory analysis) and the daily water discharge on the sampling days. The SSC from the collected integral sample is considered as mean SSC for the cross-section of the river. The sampling frequency depends on the hydrological regime of the river aiming the best fit to the hydrograph and especially to the flood periods. A sediment rating curve (suspended sediment discharge/water discharge relationship) is applied to obtain the value of daily sediment discharge. The present scheme of sampling is also applied at the gauging stations located along the Danube tributaries. Along the stations at the Danube River, the sampling measurements are performed at least on a daily basis and the determination of the SSC, as well as the sediment discharge, is obtained by direct calculations using the rating curves.

The National Institute of Meteorology and Hydrology (NIMH) has a specialized laboratory for sediment treatment of samples for the whole country. The laboratory analysis includes concentration measurements and particle size distribution analysis. The filtering method is used for the SSC measurements. The water samples are passed through a filter of a diameter of 2-3 µm at the river stations and are submitted in the Laboratory of NIMH. After filtering, the filter is dried at 105°C for 2 hours and weighed (see the equipment in *Figure 32* and *Figure 33*). The method used in the laboratory is a quantitative analysis by weight. The sample is weighed by analytical balance with an error of 0.1 mg.

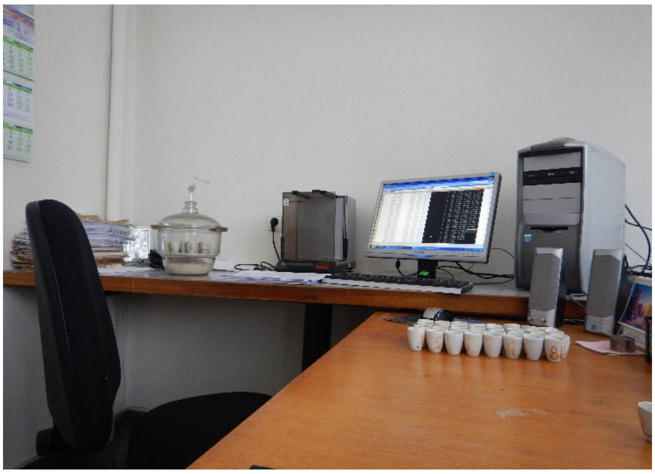


Figure 32 Electronic weigher and sediment weight determination

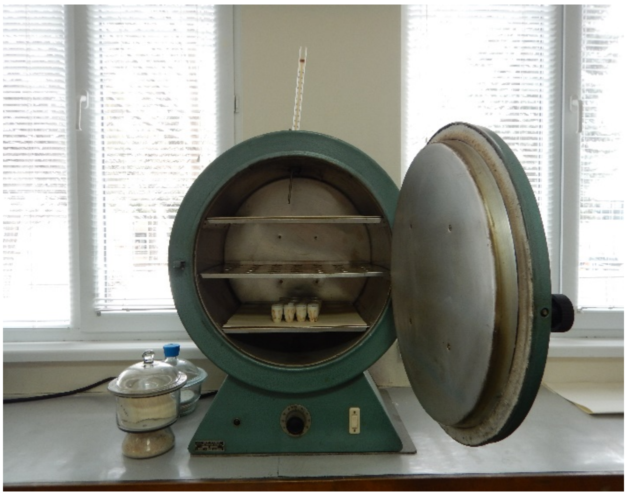


Figure 33 Dryer for sediment samples

Depending on the size, homogeneity of the sediment particles and weight of the sample, different methods can be applied: the sedimentation analysis is used for suspended sediments or the sieve analysis using sieves with round holes for coarser particles (*D* > 0.15 mm) only. The sedimentation analysis is now regularly used and implemented in the frame of project investigations.

The samples for particle size analysis are taken with a sampler bottle and afterwards analysed with a depth-integral method. In the laboratory at NIMH, the collected water samples are treated for determination of different suspended sediment fractions using sedimentation analysis. The treatment of samples consists of “dry” sieve analysis for particles larger than 0.1 mm. The volume of particles smaller than 0.1 mm is determined by hydraulic methods based on the rate of their sinking in calm distilled water at 20 °C (fraction columns). Furthermore, there is a special drying oven (*Figure 34*) for additional treatment of the samples and organic/mineral content determination.

Figure 34 Furnace for organic/mineral content determination

2.3 Bedload transport monitoring system

Bedload transport monitoring is rarely performed in the Danube River. In fact, continuous monitoring can only be found in Austria (one station), Hungary (one station) and in Romania (8 stations). Data quantity is therefore not sufficient for the assessment of the sediment balance but can be used for qualitative analyses at certain locations. Also, bedload data from field measurement campaigns is available at a few sites in Germany (6) and Slovakia (3). The locations and a few characteristics of the bedload monitoring can be found in *Table 19* and *Figure 35*. A more detailed description about the applied methods is given later on a country-by-country basis.

Table 19 List of currently operating bedload monitoring stations along the Danube and its important tributaries

Country	River	Name of monitoring site	Location	Comment
Germany	Danube	Straubing1	2 329.30	campaigns
Germany	Danube	Straubing2	2 321.00	campaigns
Germany	Danube	Pfelling	2 305.50	campaigns
Germany	Danube	Deggendorf	2 283.20	campaigns
Germany	Danube	Halbmeile	2 280.00	campaigns
Germany	Danube	Hofkirchen	2 256.39	campaigns
Austria	Danube	Hainburg Straßenbrücke	1 886.24	monitoring
Slovakia	Danube	Devín	1 878.15	campaigns
Hungary	Danube	Vámosszabadi	1 805.60	monitoring
Slovakia	Danube	Klizska Nema	1 795.58	campaigns
Romania	Danube	Bazias	1 072.50	monitoring
Romania	Danube	Corabia	624.20	monitoring
Romania	Danube	Zimnicea	553.23	monitoring
Romania	Danube	Giurgiu	493.05	monitoring
Romania	Danube	Chiciu Calarasi	379.58	monitoring
Romania	Danube	Vadu Oii	238.00	monitoring
Romania	Danube	Braila	167.00	monitoring
Romania	Danube	Ceatal Izmail	80.50	monitoring
Slovakia	Morava	Moravský Ján	67.15	campaigns

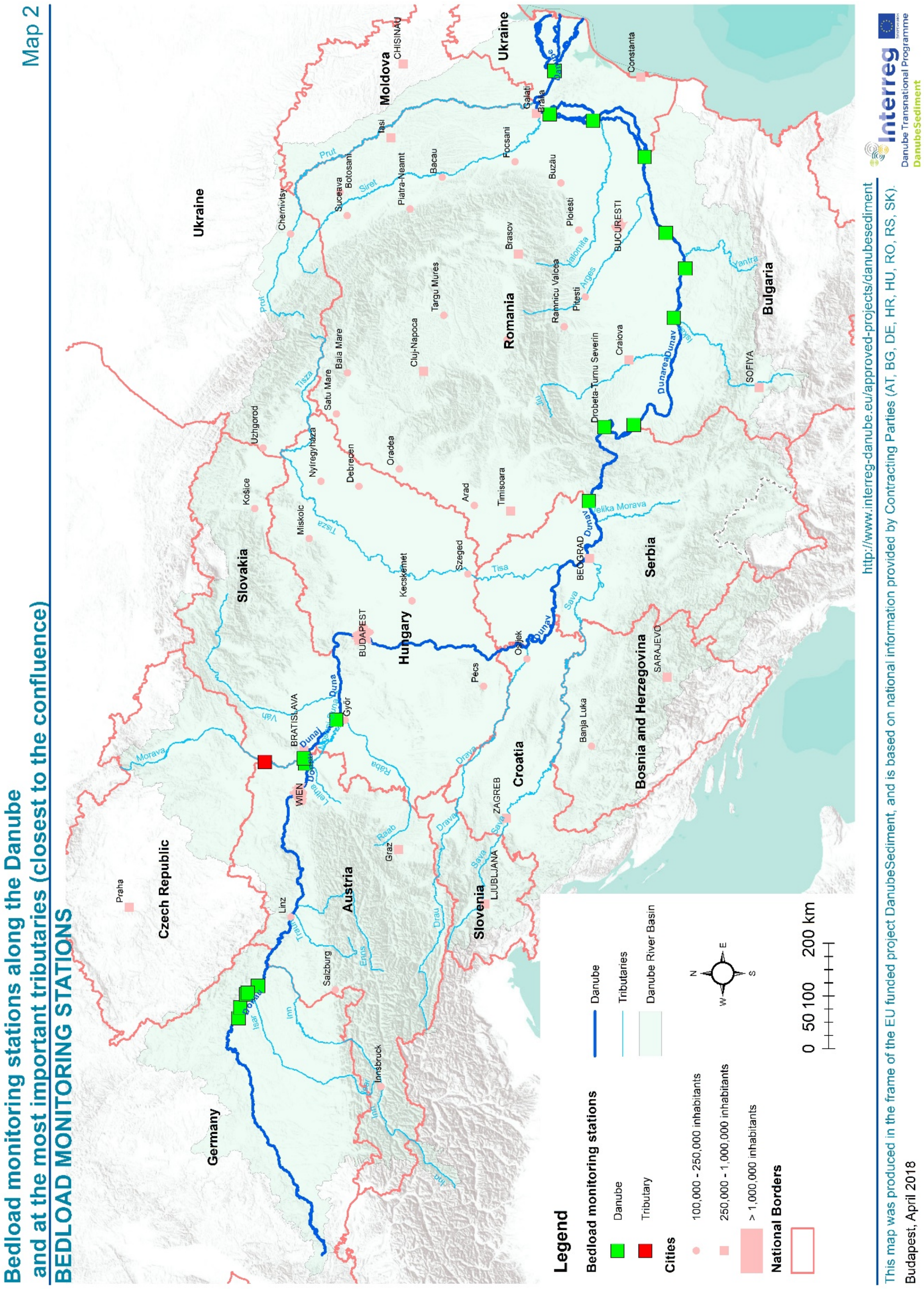


Figure 35 Bedload monitoring stations along the Danube and its important tributaries.

2.3.1 Germany

2.3.1.1 Present (2012-)

At the moment, continuous bedload transport monitoring does not occur in the German reaches of the Danube River. Instead, field campaign measurements are performed.

2.3.1.2 Past (1970-2012)

Table 20 Past BL monitoring stations in Germany

Name of monitoring site	River	Location (river km)	Measurements performed by	Time period
Straubing 1	Danube	2 329.30	WSV, BfG, BAW	2010-2012
Straubing 2	Danube	2 321.00	WSV, BfG, BAW	2010-2012
Pfelling	Danube	2 305.50	WSV, BfG, BAW	1970-2012
Deggendorf	Danube	2 283.20	WSV, BfG, BAW	2008-2012
Halbmeile	Danube	2 280.00	WSV, BfG, BAW	2008-2012
Hofkirchen	Danube	2 256.90	WSV, BfG, BAW	1970-2012

The purpose of bedload monitoring was to determine the bedload transport and load. A so-called BfG-sampler (1.40 x 1.40 mm coarse mesh, 0.16 x 0.10 m nozzle) was used during the measurements. The device was lowered into the water from a boat. The measurements were performed at different verticals (5-7 verticals, depending on the discharge) with 3 measurements per vertical (5 minutes duration each). Then, the data was integrated over the cross-section.

The following parameters were determined with the dry sieving method during the grain size distribution analysis: coefficient of uniformity (U), several grain diameters (D_{10}, D_{16}, D_{50}, D_{84}, D_{90} and D_m), sorting (SO) and skewness (SK).

2.3.2 Austria

2.3.2.1 Present (2006-)

Table 21 Present BL monitoring stations in Austria

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Hainburg Straßenbrücke	Danube	1 886.24	IWHW/ BOKU, viadonau	2006-

The bedload monitoring is done by IWHW/BOKU on behalf of viadonau. The purpose of the monitoring is to determine GSD, bedload transport (kg/s) and annual bedload transport (t/y). For the bedload sampling the so-called BfG-Sampler (*Figure 36)* is used. The original design of the sampler is based on the BTMA (Bedload Transport Meter) of Delft Hydraulics and was improved by the Federal Institute of Hydrology (BfG) in Koblenz, Germany. The slight adaptations for the Danube river were to make the construction more massive and to increase the mass of the instrument to obtain a higher stability during the sampling.

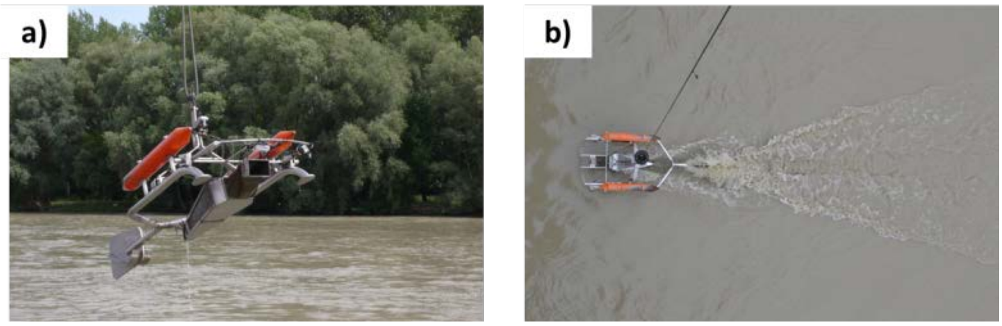


Figure 36 a: BfG-sampler (bedload transport sampler); b: sampler on its way to the river bed (IWHW/BOKU)

The sampler itself is a pressure difference sampler with a mesh size of 1mm, an orifice size of 160 x 100mm and an overall weight of about 200 kg. The overall dimensions of the sampler are 2.5 x 1.2 x 1.0m (length x width x height).

The measurements are performed from the Road Bridge near Hainburg or (less frequently) from a ship (see *Figure 37*). When the measurements are performed from the bridge, the sampler is lowered 30 m from the bridge deck to the river bed via truck, which is fitted with a loader crane and a winch. For ship measurements, an excavator with a steel cable is utilized and during the measurement the ship is immobilized via anchor or stilts.

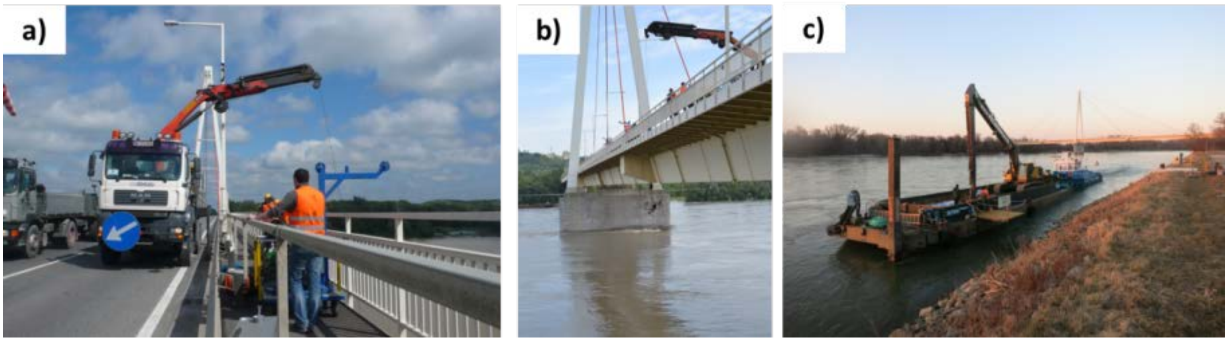


Figure 37 a: Truck with crane; b: lowering the sampler from the bridge; c: ship for the measurements (IWHW/BOKU)

Depending on the discharge and if measured from the bridge or the ship, the measurements in the cross-section are performed in 8 – 15 verticals. They are usually more closely spaced in the main stream (approx. every 20 m) than in the adjacent groyne field, where substantial bedload transport only occurs during higher discharges. In every vertical, the sampler is lowered at least 3 times for 5 minutes. However, the deployment time is reduced during times of intensive bedload transport to avoid overfilling of the sampling basket, as the sample should not exceed 6000 g (*Figure 38*).

Figure 38 a: emptying the sampler after the measurement; b & c: bedload transport samples (IWHW/BOKU)

To obtain the bedload bearing width (most relevant concerning the left part of the section in the groyne field), the measurement is continued until at least one vertical with zero transport is measured. An example for the bedload results can be seen in *Figure 39*.

Bedload transport is measured 3 times per year. This is an average value, since in some years (depending on discharge conditions) up to 5 measurements have been performed.

After determining the dry weight of the samples, the bedload transport is calculated across the section after Dröge et al. (1992).:

1. Division of the mass (g) of the single samples and the sampling duration (s)
2. Calculation of the arithmetic mean from the result of 1. --> bedload transport rate in g/(s·b) where b is the width of the sampler orifice

3. Conversion of the result from 2. into the width of one meter with the width of the sampler inlet --> bedload transport rate in g/(m·s)
4. If the mass of the sample exceeds 6000 g the sampling time is reduced to an equivalent mass of 6000 g
5. If the sample mass exceeds 2500 g, the rate of efficiency has to be taken into account by multiplying with a conversion factor, which is dependent on the mass of the sample --> result is the corrected bedload transport rate in g/(m·s); the conversion factor is based on an empirically developed function, taking into account the rate of efficiency based on the sampled mass
6. Plotting of the calculated transport rates of the verticals in respect to their distance from the river banks
7. Connection of the points with a spline over the bedload bearing width (determined from the measured verticals with zero transport at the right and left side of the cross-section)
8. Integration of the area under the curve from 7. over the bedload bearing width --> bedload transport in kg/s of the whole cross-section in relation to the discharge during the time of sampling.

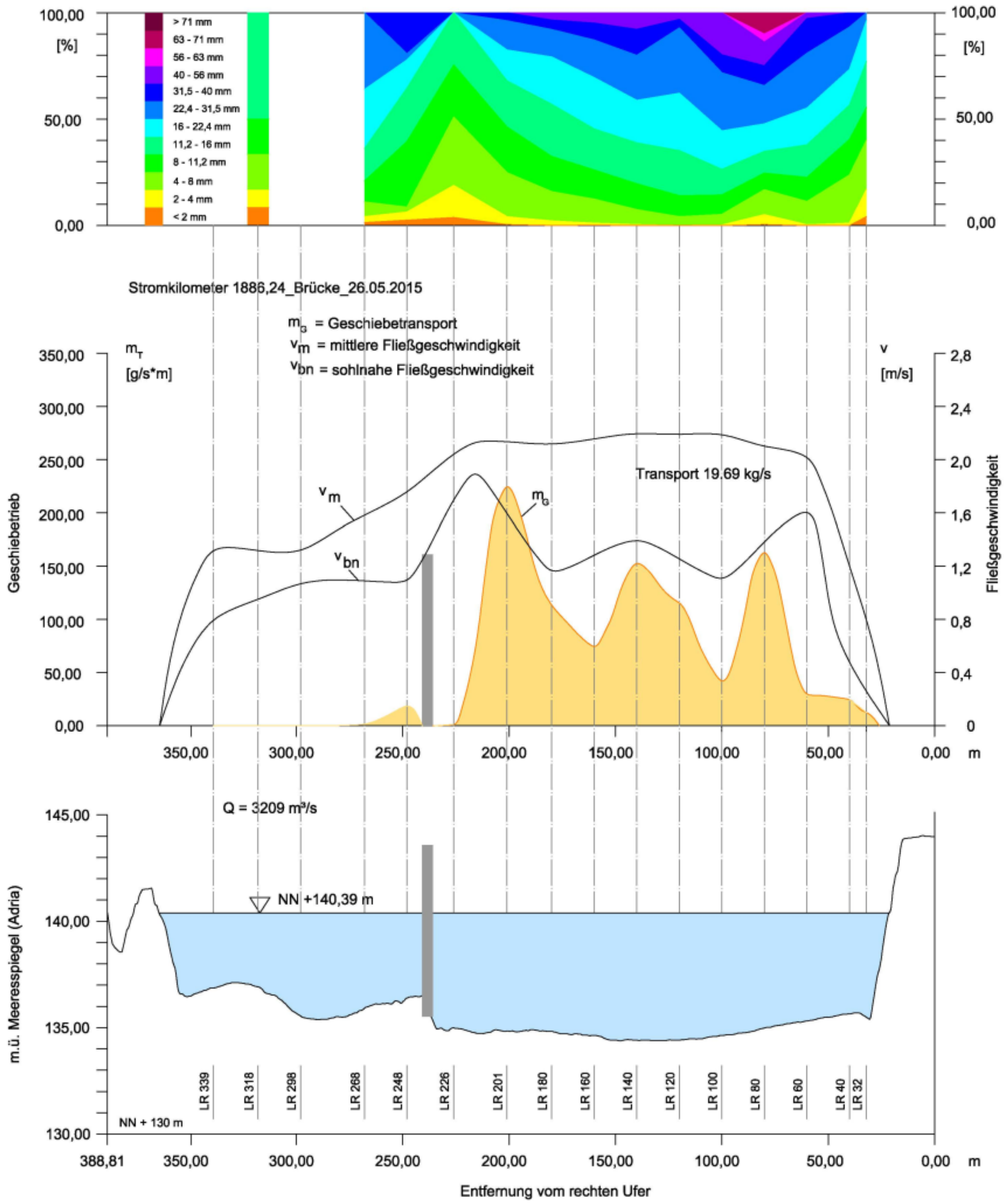


Figure 39 Example of a bedload transport calculation: Bedload texture, transport rates in each vertical (including bedload transport – shaded area middle panel), cross-section measurement (IWHW/BOKU)

After air drying the samples, the dried sample is weighed prior to sieving, to obtain the weight for the bedload transport calculation.

The dry sieving is performed with square hole sieves; prior to sieving the empty sieves are weighed with an analytical balance of an accuracy of ± 1 g; then the sample is sieved for 10 minutes; and afterwards each sieve plus the retained part of the sample is weighed with an analytical balance of an accuracy of ± 1 g. The sieves are then emptied, cleaned and weighed, before proceeding with the next sample. The mass of each fraction is calculated as the difference of the retained mass (including sieve mass) and the mass of the empty sieve.

Mesh sizes (mm): 125, 90, 63, 56, 31.5, 22.4, 16, 11.2, 8, 4, 2, 1, 0.5, 0.25 and pan (finer than the smallest sieve).

The results are the following: cumulative grain size distribution and characteristic grain sizes (D_{10}, D_{20}, D_{30}, D_{40}, D_{50}, D_{60}, D_{70}, D_{80}, D_{90}, D_{16}, D_{84}, D_m, D_{max} and b-axis which is the so-called intermediate axis or width, and is perpendicular to the longest axis).

2.3.2.2 Past (1930-1931 and 1956-1957)

Table 22 Past BL monitoring stations in Austria

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Vienna	Danube	1 930.80	Staatliche Versuchsanstalt für Wasserbau	1930-1931
Bad Deutsch-Altenburg	Danube	1 885.90	Bundesstrombauamt	1956-1957

In the past, the bedload monitoring was performed by Staatliche Versuchsanstalt für Wasserbau in 1930/1931 (Ehrenberger, 1931 and Ehrenberger, 1942) and the Bundesstrombauamt (predecessor company of viadonau) in 1956-1957. The purpose of the monitoring was to determine GSD, bedload transport (kg/s) and annual bedload transport (t/y). The measurements by Ehrenberger 1930-1931 als assessed the temporal variation of bedload transport. For the bedload sampling of both campaigns the Ehrenberger sampler (*Figure 40*) was used. The original design of the sampler is based on the Muehlhofer sampler used by Muehlhofer (1933) at the river Inn and was modified by Ehrenberger.

The sampler was a basket sampler with an intake size of 50 x 25 cm (width x height) and a length of 100 cm. The size of the wire mesh was approx. 4.5 mm with the bottom of the sampler made of ring chains to have a flexible sampler bottom, which can adjust to the river bed.

The measurements in both cases (1930/1931 and 1956-1957) were performed from a ship, which was fixed in position with anchors during the measurements.

Figure 40 Ehrenberger sampler (Ehrenberger, 1942)

2.3.3 Slovakia

2.3.3.1 Present (2006-)

At the moment, there is no continuous bedload transport monitoring along the Slovak reach of the Danube River.

2.3.3.2 Past (1996-2005)

Table 23 Past BL monitoring stations in Slovakia

Name of monitoring site	River	Location (river km)	Measurement performed by	Time period
Devín	Danube	1 878.15	VUVH	1997-2003
Klizska Nema	Danube	1 795.58	VUVH	2000-2002
Moravský Ján	Morava	67.15	VUVH	1996-2005

In the past, bedload measurements were performed by the Water Research Institute (VUVH).

Morava: Moravsky Jan monitoring site (1996-2005)

The bedload measurements were performed from a large vessel. The so-called Helley-Smith sampler (modified by VUVH) was used during for bedload monitoring (

Figure 41). The purpose of the monitoring was to determine the mean annual bedload transport rate (t/y).

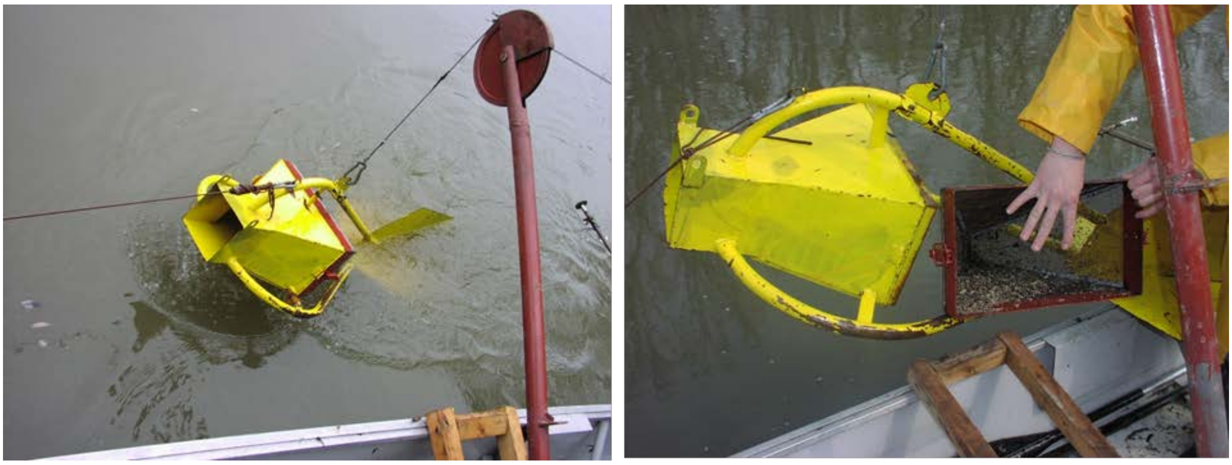


Figure 41 Helley-Smith sampler (modified by VUVH)

Bedload measurements were occasionally performed according to the actual hydrological situation. Field campaigns were performed during the flood discharges in 1996 and bedload monitoring continued during the period 2004-2005. Data from both periods are used to develop regression type equations.

Danube: Devin monitoring site (1997-1998 and 2003) and Klizska Nema monitoring site (2000-2002)

At Devin, the samplers of Helley-Smith, Novak sampler and Swiss type were tested to select an appropriate sampler for the Danube conditions. As a result, the Swiss type was chosen (*Figure 42*, *Figure 43* and *Figure 44)*.

The purpose of the measurements was the monitoring of the sediment regime, both bedload and suspended. The measurement campaigns were performed by VUVH within different research programs (2 - 3 years). The measurements were performed from a ship; the sampler was lowered on the river bed using a crane fixed on the board. The Swiss type sampler (based on Ehrenberger sampler) was used for the measurements in 5-6 verticals; from 5 to 10 times in each vertical bedload transport was repeatedly measured, and mean value was used to calculate total transported volumes. The time taken for each sampling was between 2-5 minutes depending on bedload transport intensity. The measurements were performed in two periods: June 1997-November 1998 (23 whole-profile measurements), 10 June 2003-28 Nov 2003 (23 whole-profile measurements).

Figure 42 Swiss-type sampler

Figure 43 Swiss-type sampler

Figure 44 Bedload sample

Using the field measurements, the equation of the bedload rating curve was derived as:

$$G_S = a \cdot Q^b \qquad (2)$$

where: G_s bedload discharge (kg/s)

Q discharge (m^3/s)

a, b determined coefficients, see *Table 24* for each monitoring station:

Table 24 Table of coefficients

Name of monitoring site	**a**	**b**
Moravský Ján	0.00013754	1.8277
Devín	0.00000016628	2.3386
Klizska Nema	0.0000012683	2.1

The daily or annual bedload transport amounts were estimated using this equation.

The results of the sieving analysis were different grain diameters (D_{10}, D_{16}, D_{20}, D_{50}, D_{84}, D_{90} on the Morava, and D_{50}, D_{90} on the Danube).

2.3.4 Hungary

2.3.4.1 Present (1978-)

Table 25 Present BL monitoring stations in Hungary

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Vámosszabadi	Danube	1 805.60	ÉDUVIZIG	1978-

Bedload sampling is done by ÉDUVIZIG. The purpose of the bedload monitoring is to estimate bedload discharge. The Károlyi-sampler (*Figure 45*) is used in 7 verticals in the measurement section. The sampler is lowered from the Vámosszabadi Bridge and kept for 15 minutes at one point.

Figure 45 Károlyi-sampler

The collected samples are taken to the laboratory. Drying is performed at 105°C for 24 hours, and then a sieving analysis is carried out. Based on this, the grain size distribution curve is prepared and characteristic grain diameters, such as D_{10}, D_{50}, D_{90} as well as geometric standard deviation are determined.

Specific bedload discharge values are calculated for each measurement vertical based on the weight of the collected sample, the sampling time and the width of the instrument's opening. To provide cross-sectional sediment discharge, the specific discharge values are numerically integrated along the cross-section.

2.3.5 Croatia

No bedload monitoring.

2.3.6 Serbia

No bedload monitoring.

2.3.7 Romania

2.3.7.1 Present (1969-)

Table 26 Present BL monitoring stations in Romania

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Corabia	Danube	624.20	ANAR /Arges River Basin Administration	1992-
Zimnicea	Danube	553.23	ANAR /Arges River Basin Administration	1972-
Giurgiu	Danube	493.05	ANAR /Arges River Basin Administration	1970-
Chiciu Calarasi	Danube	379.58	ANAR /Dobrogea-Litoral River Basin Administration	1980-
Vadu Oii	Danube	238.00	ANAR /Dobrogea-Litoral River Basin Administration	1970-
Braila	Danube	167.00	ANAR /Dobrogea-Litoral River Basin Administration	1971-
Ceatal Izmail	Danube	80.50	ANAR /Dobrogea-Litoral River Basin Administration	1969-

Bedload monitoring is done by the National Administration "Apele Romane" (ANAR)/National Institute of Hydrology and Water Management.

The purpose of the bedload monitoring is to determine bedload transport (kg/s). The nozzle of the sampler is 10 cm wide and 10 cm high. The sampling is performed from the vessel, using a crane. The sampling time is 10 minutes. The so-called IMH bedload equipment is used (*Figure 46. and Figure 47.*). The equipment was built in 1986 by the IMH (Institute of Meteorology and Hydrology). The equipment is wedge-shaped in longitudinal direction and it is located so that the point of the wedge cuts the current. It contains baffles and slots to catch the transported solid particles.

The bedload monitoring is performed together with suspended sediment monitoring. The sampling frequency is varying, depending on the flow regime. The samplings are performed in the same verticals, where SS measurements are carried out. The number of verticals (5-9 verticals) is chosen taking into account the width of the cross-section and the distance between verticals, which is around 100 m.

Figure 46 The IMH bedload sampler

Figure 47 The IMH bedload sampler

The bedload discharge is calculated from the amount of sediment trapped in a sampler located at the stream bed in a unit of time. In general, 10 minute-long samplings are performed, which can change according to the intensity of bedload transport. The measurement time is noted for each vertical. If the volume of the collected sample is not sufficient, the measurement is repeated. The sample is weighed on site and then taken to the laboratory for further analysis. The bedload discharge is calculated integrating the specific values along the cross-section.

The laboratory analysis consists of the separation through a set of sieves, with mesh diameters of 50 mm to 0.063 mm. Before sieving, the sediment samples are dried at a temperature of 105°C for 6 hours. After drying and sieving, the samples are weighed using a scale to determine the total amount.

2.3.7.2 Past (1971-1984)

Table 27 Past BL monitoring stations in Romania

Name of monitoring site	River	Location (river km)	Monitoring performed by	Time period
Bazias	Danube	1 072.50	ANAR /Jiu River Basin Administration	1971-1984

See 2.3.7.1.

2.3.8 Bulgaria

No bedload monitoring.

3 Good practices on sediment transport monitoring

3.1 Introduction

The goal of this chapter is to introduce good practices for riverine sediment transport measurement methods. The main reason for preparing this chapter is that, as was introduced above, many different sediment monitoring techniques are used along the Danubian countries, which inherently result in heterogeneous quality and quantity of sediment data. As an important step towards a harmonized sediment management concept for the Danube River, it is essential to understand the advantages and disadvantages of the different monitoring techniques and to aim at a standardized, common sediment monitoring methodology. In this way, the data homogeneity could be ensured, which decreases the uncertainty of the sediment data, which will be further analysed when assessing the sediment budget of the Danube River.

This chapter will first give an overview about the sediment measurement methods used for both suspended sediment and bedload transport. Next, based on a literature review combined with experiences from the project partners as well as utilizing the results of the comparative analysis performed in this project, the chapter will provide recommendations for monitoring the sediment transport, for the laboratory analysis of sediment samples and for calculating the sediment load. Methods for both suspended sediment and bedload transport measurement will be addressed.

3.2 Review of sediment measurement techniques

3.2.1 Suspended sediment

To determine suspended sediment concentration and particle size distribution, various methods are available (Wren et al., 2000; Gray and Gartner, 2009; Rai and Kumar, 2015). These methods can be divided into direct monitoring methods (water samples) and indirect methods (e.g. optical and acoustical tools). Water samples represent the traditional monitoring method and comprise, besides collecting samples in the field, the analyses of suspended sediment properties (concentration, particle size, etc.) in the laboratory. In the past centuries, surrogate technologies that measure substitute parameters such as light scattering, light transmission or sound attenuation, have advanced rapidly. These devices have the capability of more frequent data collection compared to traditional methods. Although the number of samples can be reduced with these methods, samples still have to be taken because all surrogate technologies require calibration and verification of the data recordings. So, the results of the indirect methods can only be as good as the calibration method. An overview about some suspended sediment measurement techniques is provided in *Table 28*.

Table 28 Suspended sediment measurement techniques (based on Wren et al., 2000 and Rai and Kumar, 2015)

Technology	**Operating principle**	**Advantages**	**Disadvantages**
Sampling:			
Bottle	Water-sediment sample is taken isokinetically by submerging container in streamflow and is later analysed.	Accepted, time-tested technique, allows determination of concentration and size distribution, most other techniques are calibrated against bottle samplers	Poor temporal resolution, flow intrusive, requires laboratory analysis to extract data, requires on-site personnel
Pump	Water-sediment sample is pumped from stream and later analysed.	Accepted, time-tested technique, allows determination of concentration and size distribution	Poor temporal resolution, intrusive, requires laboratory analysis, does not usually sample isokinetically
Acoustic	Sound backscattered from sediment is used to determine size distribution and concentration.	Good spatial and temporal resolution, measures over wide vertical range, nonintrusive	Backscattered acoustic signal is difficult to translate, signal attenuation at high particle concentration
Laser diffraction	Refraction angle of laser incident on sediment particles is measured.	Measures both SSC and PSD, no particle-size dependency	Expensive, flow intrusive, point measurement only, limited measurement range

Technology	Operating principle	Advantages	Disadvantages
Optical (backscatter / transmission	Backscatter or transmission of visible or infrared light through water-sediment sample is measured.	Simple and mature technology, good temporal resolution, allows remote deployment and data logging, relatively inexpensive	Dependency on size and shape of particles, flow intrusive, point measurement only, instrument fouling

3.2.1.1 Physical sampling methods

Suspended sediment samplers are used to collect a representative sample of the water-sediment mixture of rivers and streams. In order to obtain this representative suspended sediment sample, the sampler should meet certain requirements as defined in ISO / TS 3716 (2006). Despite the fact that there are several indirect methods to assess suspended sediment concentration in rivers, physical sampling is still essential. The main reason for taking physical samples is that it is the only accepted reference technique and it must be used as for calibrating and validating all the indirect methods (Aberle at al., 2017).

The weight of the applied suspended sediment sampler shall be adequate to minimize deflection of the supporting cable from the vertical due to the current drag, but the sampler still has to be portable. The sampler shall have a streamlined form to reduce drag and to minimize disturbances of the flow. The intake of the sampler shall be outside the zone of the disturbances of the flow induced by the sampler and its operating gear, and the disturbance of the flow lines shall be kept to a minimum, especially near the intake. At the sampling point, the intake of the sampler shall always be directed into the current. The applied sampler shall be isokinetic, i.e. the sampler takes water samples in a nonintrusive way as the velocity of water that is flowing into the instrument is adjusted to the velocity of the flow. The difference between the two velocities must be minimized thus the water sample obtained with the sampler will have the same SSC as the original flow. If the sampling velocity is lower than the original flow, the sample taken will have a higher SSC value; on the contrary, if the sampling velocity is higher, the SSC is lower than the one in the original flow (Garica, 2008). This effect is schematically presented in *Figure 48*. The error due to the differences between velocities can be seen in the *Figure 48* depending on the mean particle sizes. The horizontal axis shows the relative sampling value , i.e. the ratio of the velocities of the inflowing water and the flow, while the vertical axis shows changes in the SSC values.

The sampler shall contain a container that can be easily removed and sealed, so it can be easily transported to a laboratory without loss of contents. If the sampling container forms part of the sampler, special care has to be taken when draining the content as material can adhere to the container walls. The volume of the sample shall be sufficient for determining the concentration of the sample, so a minimum sample size of 0.5 l is recommended (ISO / TS 3716, 2006). The sampling time has to be selected properly for the particular situation and sampler type to avoid an overfilling of the container, and thus an artificial increase of sediments in the sample.

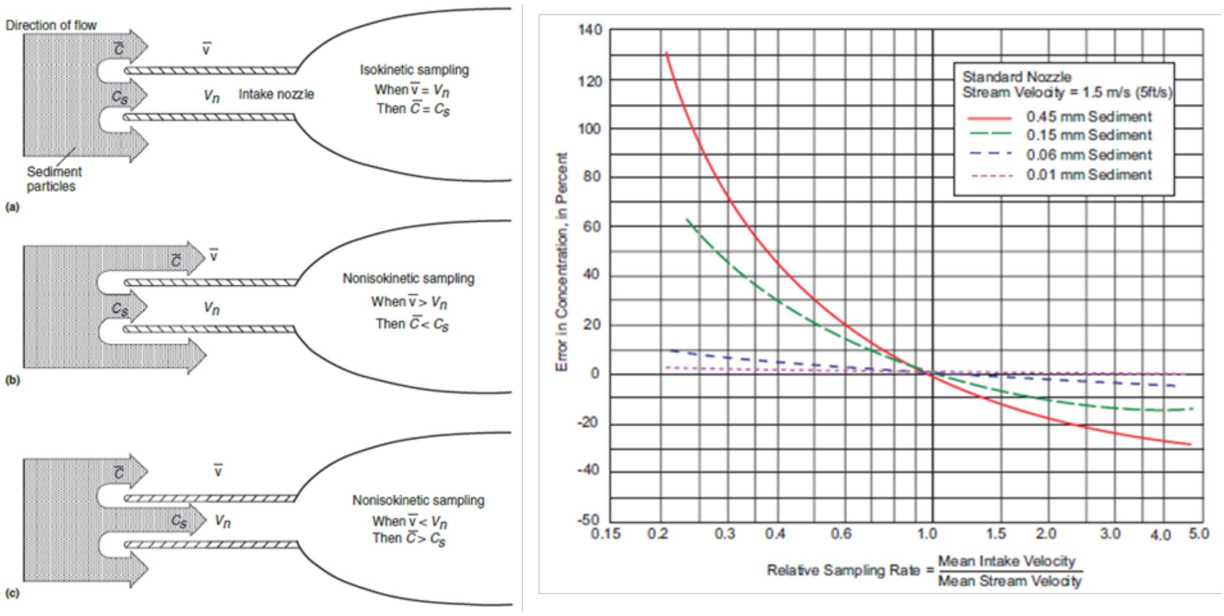


Figure 48 Relation between intake velocity and sample SSC for (a) isokinetic and ((b) and (c)) nonisokinetic sample collection of particles ((Garcia, 2008); Effect of sampling rate on measured sediment concentration for four sediment size distributions (Garcia, 2008)

There are so-called depth integrating and point integrating samplers (*Figure 49*). Depth integrating samplers are typically used in smaller rivers or streams. These instruments collect water samples continuously throughout a water column, during lowering and raising of the sampler. The final sample will provide representative concentration for the measured vertical of the river. Depth integrating sampling requires less time compared to point sampling, however, no vertical variation of the SSC can be assessed. On the other hand, point integrating samplers can be remotely opened and closed to collect water sampler from any point of the cross-section. It takes more time to collect representative samples in the study section, compared to the depth integrating method, but at the same time, it provides the spatially varying nature of SSC distribution. In practice, several types of both sediment samplers are used. For instance, see the detailed report on sediment sampling methods by Edwards and Glysson (1999).

Figure 49 D49 depth integrating sampler (left) (https://www.hyquestsolutions.com) and US P-61-A1 point integrating sampler (https://water.usgs.gov/).

Typical error sources of physical samplings are the followings (Aberle et al., 2017):

- Lack of isokinetic sampling
- Errors in elevation and depth measurement
- Scooping from the bed for depth integrating samplers
- Unequal transit time error for depth integrating samplers
- Errors introduced in sample analysis

3.2.1.2 Optical methods

The very basic principle for optical instruments is that when light propagates through any kind of media and reaches an object with a different (in our case usually higher) density than the original media, by the optical laws of physics, the light beam scatters, refracts (Hulst, 1957). These optical based devices can be divided into the following groups: instruments that measure the small angled forward scattering of the light and the devices that measure the backscatter or transmission of the light. In the following, the properties of laser instruments will be briefly introduced and then backscattering and transmission devices are presented.

Laser diffraction

The first introduced group is the one that analyses the forward scattering pattern of the laser light that is diffracted in multiple angles. The mathematical solutions for scattering light used by these instruments is the so-called Mie's solution (Hulst, 1957), which is the exact solution to Maxwell's equations (Czuba et al, 2015). Laser diffraction provides particle size distributions and concentration of the sediment in the water sample and such instruments are widely used in laboratory environments. However, a few instruments can be used in-situ.

The working principle of laser diffraction is that the laser beam propagates through the water sample with a known volume containing the particles; it reaches the collecting lens that transmits the scattered light onto concentric detector rings. The pattern of the detected light determines the size distribution in the sample, then by the transmitted power the volumetric concentration can be calculated (*Figure 50*). Simpler descriptions of principles are available in e.g. the study of Agrawal et al. (1991) and a more up-to-date description of the technology and its application is provided by Agrawal & Pottsmith (2000).

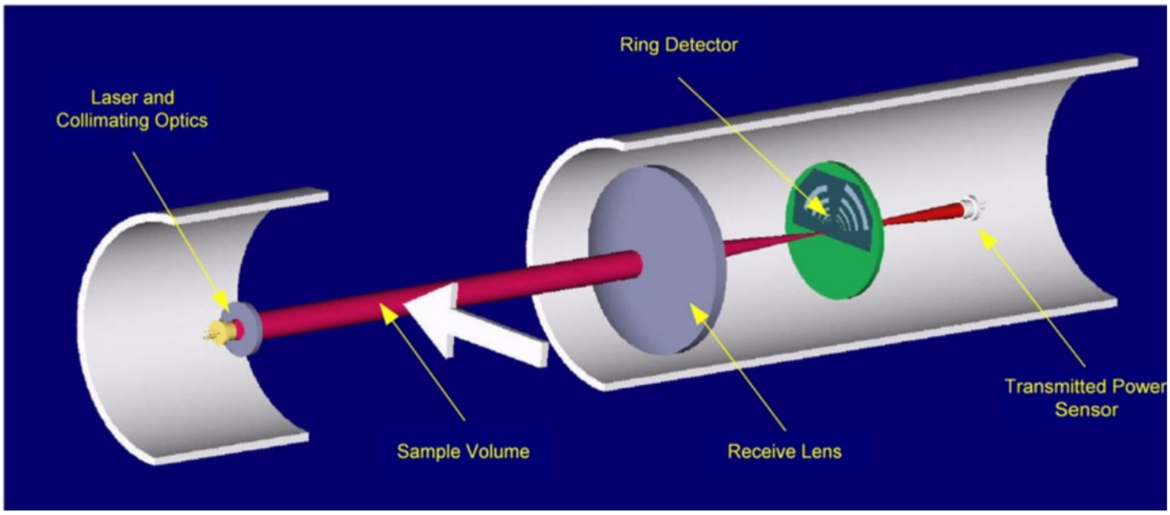


Figure 50 The working method of the LISST (Sequoia Scientific Inc.)

The measurement range of a widely applied laser diffraction instrument (called LISST-100X from Sequoia Scientific) is up to 2 g/l for 10 µm sized particles and 40 g/l for sand (Rai and Kumar, 2015). The measurement range can be varied by using different optical path length and extended up to a factor of 10 by diluting the sample by adding clean water.

Optical backscattering

Optical backscattering devices (OBS) have been widely used to estimate SSC time series in the last few decades (Downing et al, 1981, Rai and Kumar, 2015) in various environments such as bays, rivers, and estuaries (Kienke & Steinberg, 1992) (Schoellhamer, 1996).

The working method for any optical backscattering sensors is that the instrument emits infrared (IR) light and measures the strength of the backscattered signal from the suspended material in the sampling volume (Gartner et al, 2001). The detectors can be situated at different angles (90°, 140-165°) with respect to the source beam (Rai and Kumar, 2015). The detected light is converted to photocurrent by the photodetectors. The amount of photocurrent mainly depends on the area of the solid particles in the sample, but it is also affected by their shape, reflectivity and other characteristics. At constant PSD and relatively low concentrations (<5000 mg/l) the measured turbidity by the OBS is proportional to the SSC (Downing, 2006). Therfore, with a suitable calibration, the SSC can be estimated. Because of this dependence on the PSD, the instrument has to be recalibrated according to the actual circumstances (Baranya et al, 2016). There are OBS sensors available that are able to determine suspended sediment concentration up to several 100 g/l (range is dependent on the sample property).

The instrument is unaffected by the natural light during the measurements. An advantage of the method is that the meteorological circumstances do not affect the results whether it is sunny or cloudy.

OBS sensors provide real-time output as well as the option of remote deployment and data recording. When permanently installed at a monitoring site, the sensor should be equipped with a cleaning system (e.g. wiper) to keep the optic clean. This helps to prevent or to retard the growth of algae (biofouling) that can adulterate the measurement result (Lewis and Eads, 2008). The parameters introduced in the followings are valid for the Ponsel NTU digital turbidity meter. A photo of the instrument can be seen in the figure below (*Figure 51*). The validated concentration range with reliable results lies between 1-4500 mg/l. One of the biggest advantages of this instrument is that it has WIFI connection (if the necessary software and hardware is available). Thus, it does not need wires to communicate with the operator and the duration of the measurement can be set remotely.

Figure 51 Ponsel NTU digital turbidity meter

The Solitax ts-line and Solitax hs-line sensors (*Figure 52*) operate with dual-beam optics and added backscatter detector. The LED light source transmits light at 45° to sensor face. The nephelometric photoreceptors detect the light at 90° to the transmitted light beam, whereas the backscatter photoreceptor detects the light at 140° to the transmitted light beam (*Figure 52*). Thus, the sensors are able to measure suspended solids in clear water conditions (0.001 mg/l) and in heavily loaded streams up to 50 g/l (Solitax ts-line), or 500 g/l (Solitax hs-line), however the upper range is dependent on the sample property.

The sensor can be equipped with a wiper to keep the optic clean *(Figure 52*). This helps to prevent or to retard the growth of algae (biofouling) that can adulterate the measurement result .

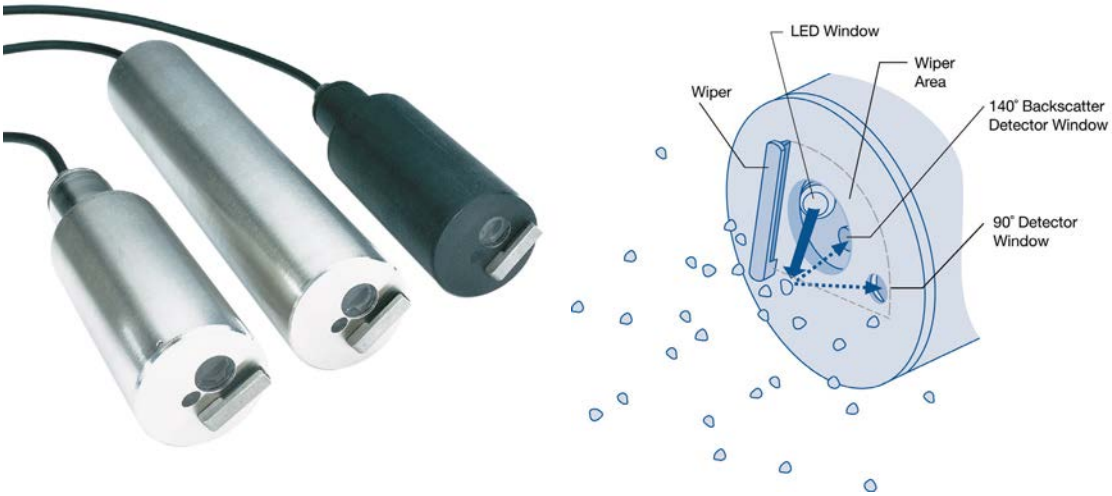


Figure 52 Solitax sensors from Hach and measurement principle (www.hach.com)

Optical transmission

In optical transmission sensing, light is directed into the sample volume and detected by a sensor located opposite of the light source. Sediment present in the sample volume will absorb and/or scatter a portion of the light and by determining the degree of attenuation of the light beam the sediment concentration can be calculated (Wren et al., 2000).

Advantages and disadvantages of optical transmission instruments are very similar to those of OBS instruments. Optical transmission sensors allow very good temporal resolution and are generally more sensitive to low particle concentrations than OBS instruments. Furthermore, the particle-size dependency is somewhat less severe than with OBS (Wren et al., 2000). The performance of turbidity meters depends on the amount of signal received. Since a transmitted signal reduces and a backscattered signal increases with higher SSC, the performance of transmissometers decreases compared to OBS sensors (Rai and Kumar, 2015). Optical transmission instruments show a nonlinear response to increasing particle concentrations with disproportionately small changes in output being produced by large changes in sediment concentration in the upper range of the instrument.

For laser diffraction sensors, also optical transmission instruments are available with different optical path length (e.g. Spectro::lyser^{TM}, *Figure 53*). Using a shorter optical path length, the nonlinear response to increasing particle concentrations in the upper range of the instrument can be corrected. A shorter optical path length furthermore increases the measuring range up to several g/l (e.g. Felix et al., 2012: 20 g/l). However, the accuracy of the measurement decreases at high concentrations.

Figure 53 left: Spectro::lyserTM of s::can, right: optical path of Spectro::lysers (pictures: Bittner, 2008)

3.2.1.3 Acoustic devices

Optical devices have been used efficiently to investigate suspended sediment in different environments, but a few studies revealed that in some particle size ranges acoustic devices obtained better results. Also, a disadvantage of optical tools is that they provide data only at one elevation at a time. Acoustic instruments might provide better quality data in some size ranges and they are able to create profiles of the sediment at one time. Another advantage of the backscattering devices is that they can be totally nonintrusive, yet provide a high degree of temporal and spatial resolution of the SSC (Thorne et al, 1990).

The principle for these instruments is analogous to the previously introduced working method of the optical devices. “A very short pulse of high frequency sound is emitted from a transducer and sediment in suspension scatters some of the acoustic energy back to the transducer.“ The magnitude of the detected backscattering signal is in relation with the concentration and the size of the sediment and the time delay between the emitting and the receiving linearly proportional to the distance of the location of the scattering (Thorne et al, 1990). A schematic figure of the process can be seen on the next figure (*Figure 54*).

As the detected backscattering signal is dependent on the concentration and the size of the sediment, samples have to be taken to calibrate the measurements and to be able to determine suspended sediment concentrations.

Furthermore, acoustic devices are less exposed to biofouling (Rai and Kumar, 2015).

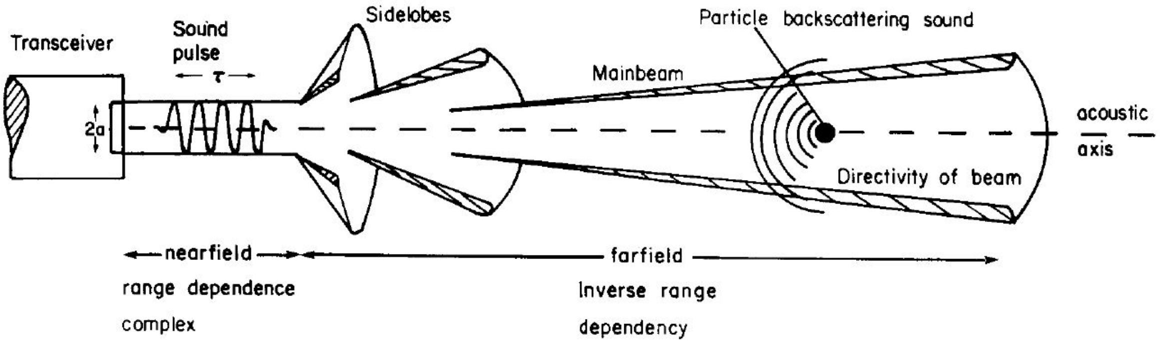


Figure 54 Scheme of the working principle of acoustic devices (Thorne et al, 1990)

Point-like suspended sediment measurements

The acoustic backscattering sensors (ABS), like the LISST-ABS (Sequoia Scientific Inc., *Figure 55* and *Figure 56*) have been designed to carry out point-like suspended sediment measurements. As any other acoustic device, ABS also emits sound pulse into the water. The difference is that the frequency of this sound can be very high (e.g. 8 MHz) compared to the other acoustic devices and the analysed point can be very close to the transducer (approx. 5 cm), thus the attenuation in the water is insignificant and the properties of water such as the temperature does not affect the calibration of the ABS. In this manner, this device is more like the optical backscattering ones but tries to overcome some of the optical tool's shortcomings. Unlike the OBS, it sees coarser particles very well (Sequoia Scientific Inc., 2016). Another advantage is that due to the short path of the signal the attenuation due to the sediment is also not significant, thereby the device may be used in very high concentration (up to 30 g/l) as well (Sequoia Scientific Inc., 2016).

Figure 55 LISST-ABS (http://www.sequoiasci.com/product/lisst-abs/)

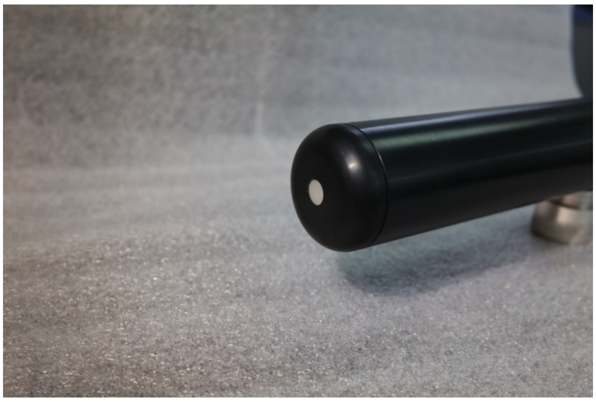


Figure 56 LISST-ABS sensor face (http://www.sequoiasci.com/product/lisst-abs/)

The next figure illustrates the comparison of the relative responses against the sediment mean diameter of the two measuring approach (*Figure 57*).

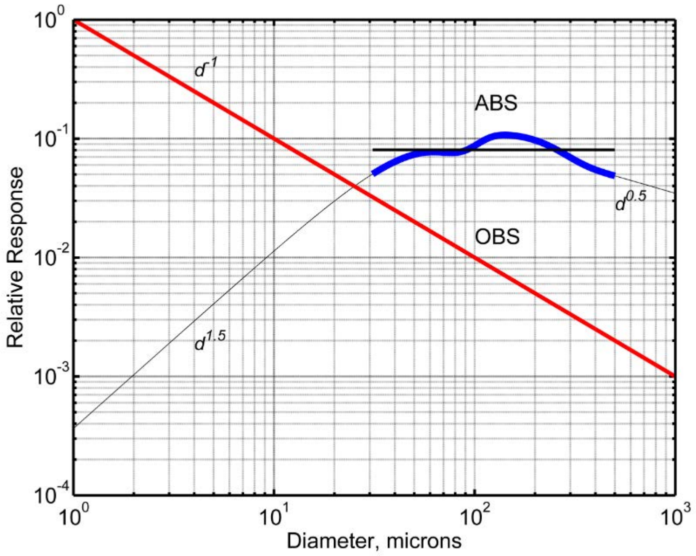


Figure 57 Comparison between OBS and ABS responses (Agrawal et al, 2016)

The figure also shows that the response of the ABS, thus the calibration of it, is less sensitive to the change in the PSD during the measurements (in the recommended particle size range, i.e. 30 to 400 microns) than the OBS is. However, in the finer regions the optical method appears to be more reliable (Agrawal et al, 2016).

ADCP

The Acoustic Doppler Current Profiler (ADC) is a well-known hydroacoustic current meter similar to sonar. The ADCP transmits ultrasonic sound into the water in different directions (differ from each other in small angles), then detects the signal scattering back from the particles in the water. It uses the Doppler-shift that relates the change in frequency of a source to the relative velocities of the source and the observer to determine the velocities in the water. By using the duration of travelling of the pulse, it can estimate the depth of the particles that scattered the sound (Mueller & Wagner, 2009).

The reason why ADCP was introduced in addition to other SSC measuring devices, is that the backscattering signal that ADCP receives might be converted into relevant SSC data, since the scattering is proportional to the concentration (see before). The high temporal and spatial resolution and the easy operation make the instrument suitable for such measurements (*Figure 58*).

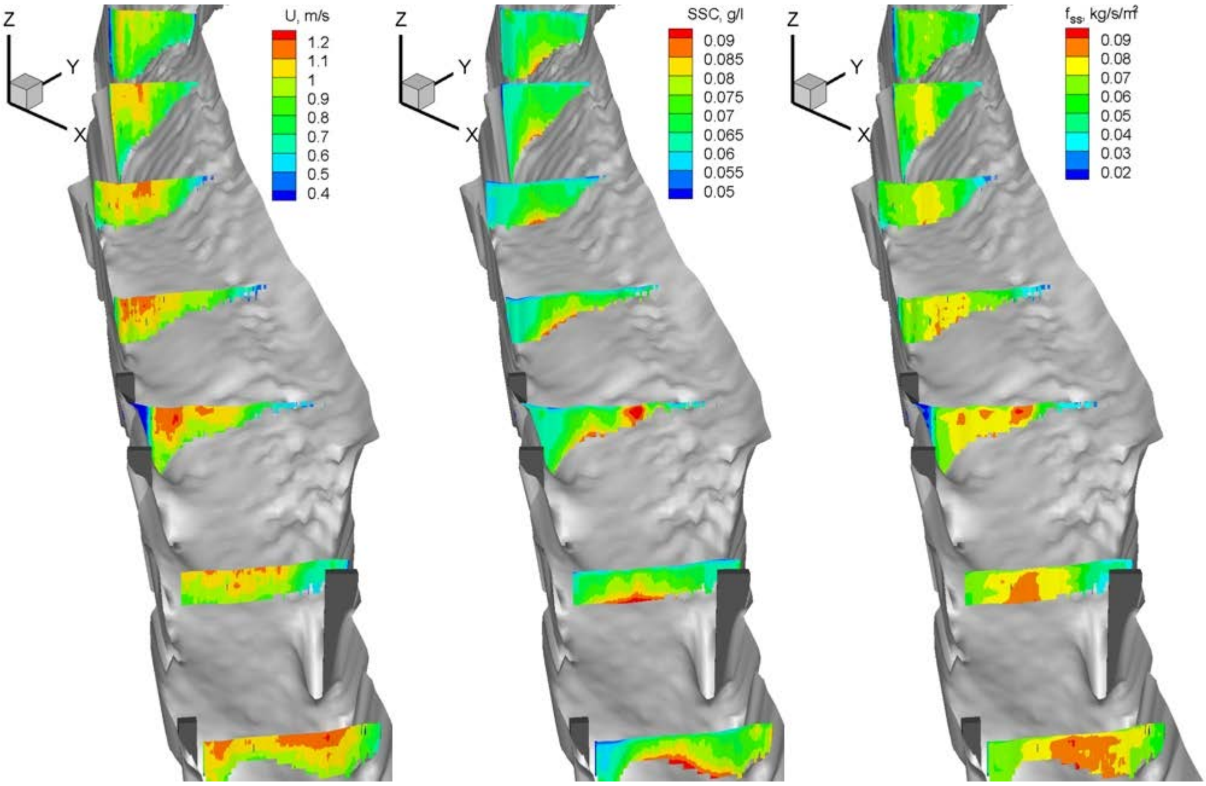


Figure 58 Spatial distribution of a) flow velocity, b) SSC and c) sediment flux in the Danube (Baranya and Józsa, 2013)

ADCPs operate at different frequencies (between 300 kHz and 2 MHz), thus are suitable for different water depths and flow velocities. In dependency of the PSD, the higher the frequency of the device, the lower the concentration range that can be measured. The framework and the estimation procedure of SSC from ADCP backscatter is introduced e.g. in Baranya and Józsa (2013).

ADCPs are conventionally used for measuring flow discharge, and the instrument is generally mounted vertically on a measurement vessel. This means that suspended sediment concentration mapping, with this equipment, can be performed during measurement campaigns and will provide an instantaneous picture of the measured situation. There are, however, other methods, which can support the continuous detection of SSC. Horizontal ADCPs (H-ADCPs), for instance, are designed to be installed at a fixed location of the river, pointing horizontally from the bank towards the centreline of the river. Recently, some papers have been published that show the strong potential in H-ADCPs for monitoring suspended sediment transport, even in larger rivers, see e.g. Moore et al. (2012).

Single frequency ADCPs can only be used for SSC measurements using calibration data from complementary samplings, e.g. physical samples, since besides the knowledge of the instrument frequency, the grain size distribution of the sediment is needed. To overcome this limitation of acoustic measurements, the performance of two-frequency methods has been introduced recently by e.g. Guerrero et al. (2013). Using several instruments of different operating frequency in parallel, it is possible to assess the influence of both the variation of SSC and the particle size from the backscattered signal, which, in theory, yields an estimation method, where no concurrent data is needed (*Figure 59*).

Figure 59 Parallel deployment of a 600 KHz and 1200 KHz ADCPs (photo: S. Baranya)

3.2.1.4 Remote spectral reflectance

The amount of sediment in water directly affects the reflectance of solar radiation in the visible and near-infrared portions of the spectrum. In general, the more sediment that is in suspension, the higher the reflectance (Long and Pavelsky, 2012). There are, however, other parameters, which directly influence the relationship between SSC and the reflectance, such as mineralogy, colour, as well as the size of the sediments. The remote observation of the reflectance, complemented with in situ samplings, can therefore contribute to the remote sensing of SSC in riverine environment. There are several studies published in this topic already (e.g. Long and Pavelsky, 2012; Carniello et al., 2014), which illustrate the capabilities of this method very well (*Figure 60*).

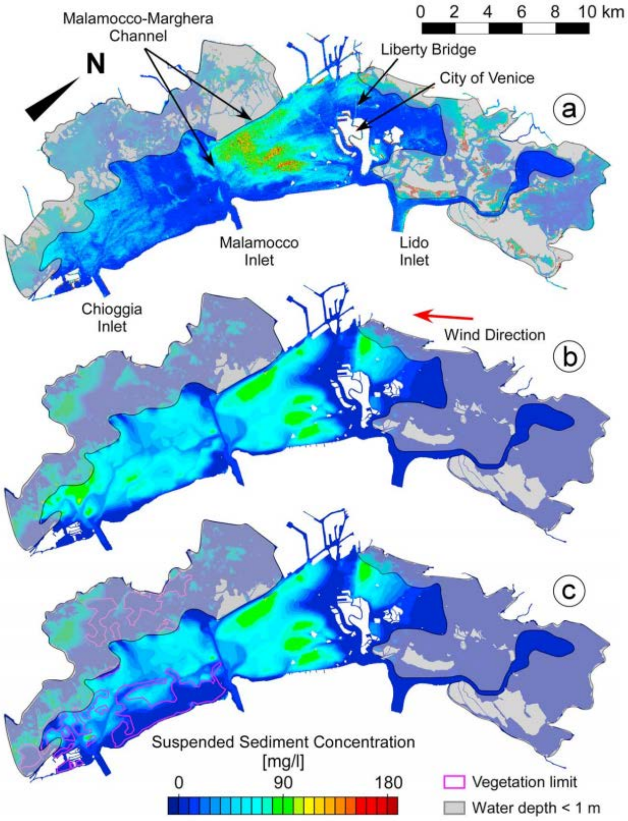


Figure 60 SSC maps reconstructed from spectral reflectance (source: Carniello et al., 2014)

3.2.2 Bedload

The main reason for bedload transport measurements is that bedload transport is a fundamental factor in determining the morphological development of alluvial river reaches (Habersack et al., 2017). Bedload as part of the total transport represents net erosion from upstream parts of the watershed (Diplas et al., 2008), which is transferred downstream and deposited. It also represents a major process link between hydraulic and material conditions that govern river-channel morphology (Gomez, 2006). Fluvial problems associated with sediment transport are related to a lack or surplus of bedload and/or to negative influences produced by anthropogenic interference with natural processes (Habersack, 1997).

Knowledge about bedload transport in rivers is needed by engineers, geomorphologists, ecologists and river managers (Frings and Vollmer, 2017). The purpose of bedload measurements is that field data are often needed to develop reliable sediment budgets, to record and explain causes and consequences of channel changes (eroding and degrading reaches, bank erosion, and grain size changes), reservoir sedimentation or for the selection, calibration and validation of transport formulae and numerical models, respectively.

Overall, this information is essential for sound decision-making regarding sediment management in rivers and reservoirs, river engineering and maintenance, water way management, flood protection, river restoration purposes, ecosystem and habitat dynamics (Diplas et al., 2008; Droege et al., 1992; Wilcock, 2001; Habersack et al, 2013).

Nonetheless, bedload transport measurements in rivers are still a challenging task, as for instance stated by Edwards and Glysson (1999):

"Bedload is difficult to measure for several reasons. Any device placed on or near the bed may disturb the flow and rate of bedload movement. More importantly, bedload transport rate and the velocity of water close to the bed vary considerably with respect to both space and time. Therefore, any sample obtained at a given point may not be representative of the mean transport rate for a reasonable interval of time because the bed particles move intermittently at a mean velocity much less than that of the water. Thus, a bedload sampler must be able to representatively sample, directly or indirectly, the mass or volume of particles moving along the bed through a given width in a specified period of time if bedload discharge is to be accurately determined"

In general, the accuracy of the bedload measurements in rivers is highly dependent on the choice of the sampler and the methodology used. This is the reason why a wide variety of sampling techniques exist, which were usually adapted to local conditions, e.g. bed material at the river bed and in transport, water depth and flow velocity.

Bedload monitoring methods can be divided into direct monitoring methods and indirect methods (Habersack et al., 2010), which are sometimes integrated (combined) to overcome the limitations of the individual monitoring methods.

Despite the wide variety of bedload measurement devices, they are basically grouped into three categories (Hubbell, 1964; Gray et al., 2010; Habersack et al., 2010):

- Direct methods (quantitative):
    - Mobile bag samplers (box, basket and pressure difference samplers)
    - Slot or pit samplers
    - Vortex and conveyor-belt samplers
- Indirect / Surrogate methods (qualitative):
    - Active or passive acoustic (e.g. ADCP, plate geophones, (pipe) hydrophones)
    - Tracer (e.g. radiotracer - active or passive, radioactive tracer, magnetic tracer, geological tracer / exotic particles, luminophoric tracer, painted stones)
    - Optical (e.g. particle tracking)
    - Morphological methods:
        - Bed form tracking (Echo-sounders, ADCP)
        - Bathymetry measurements (Echo-sounders, ADCP) – mass balance / variation of sediment storage
- Other methods:
    - Dredged volume (e.g. backwater of a reservoir, sediment trap)

A comparison of the advantages and disadvantages of bedload monitoring methods by Habersack et al. (2001) in *Table 29* shows that the different measurement techniques negatively or positively influence flow, show high or low mobility / flexibility, entail long or short sample duration, and have different hydraulic and sampling efficiencies. Some techniques allow grain size and transport path to be determined. Considerable differences are also evident with respect to automation and costs.

Table 29 Advantages and disadvantages of bedload monitoring methods with respect to relevant criteria (Habersack et al., 2001)

Method	Flow disturbance	Mobility/ Flexibility	Sample duration	Hydraulic and sampling efficiency	Grain size determination	Transport path	Auto-mation	Costs
Basket sampler	---	+++	--	--	+++	---	---	-
Trap	+-	---	++	+++	++	---	++	--
Radiotracer	+-	+++	++	+-	+++	+++	++	-
Geophones	-	---	+++	+-	---	---	+++	---
Sonar	-	++	+++	+-	---	+	+	-

+++	significantly positive, high
++	positive, high
+	slightly positive, high
+-	neutral, no effect, unknown
-	slightly negative, low, low costs
--	negative, low, medium costs
---	significantly negative, low, high costs

Figure 61 depicts the suitability of some of the individual bedload monitoring techniques with respect to specific parameters gained from bedload transport measurements.

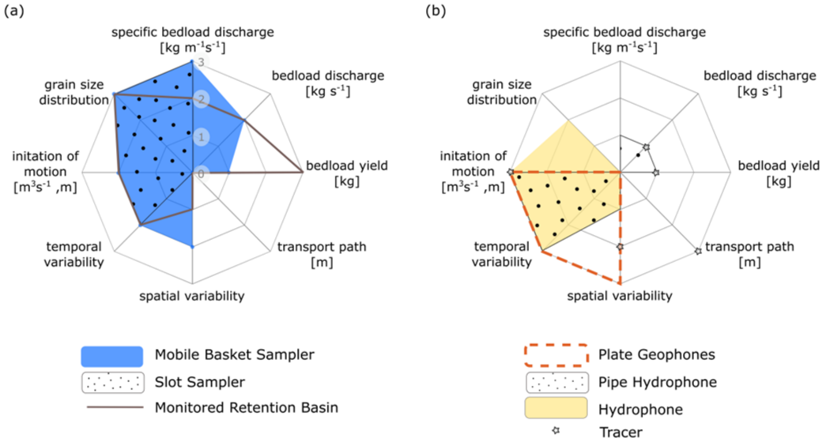
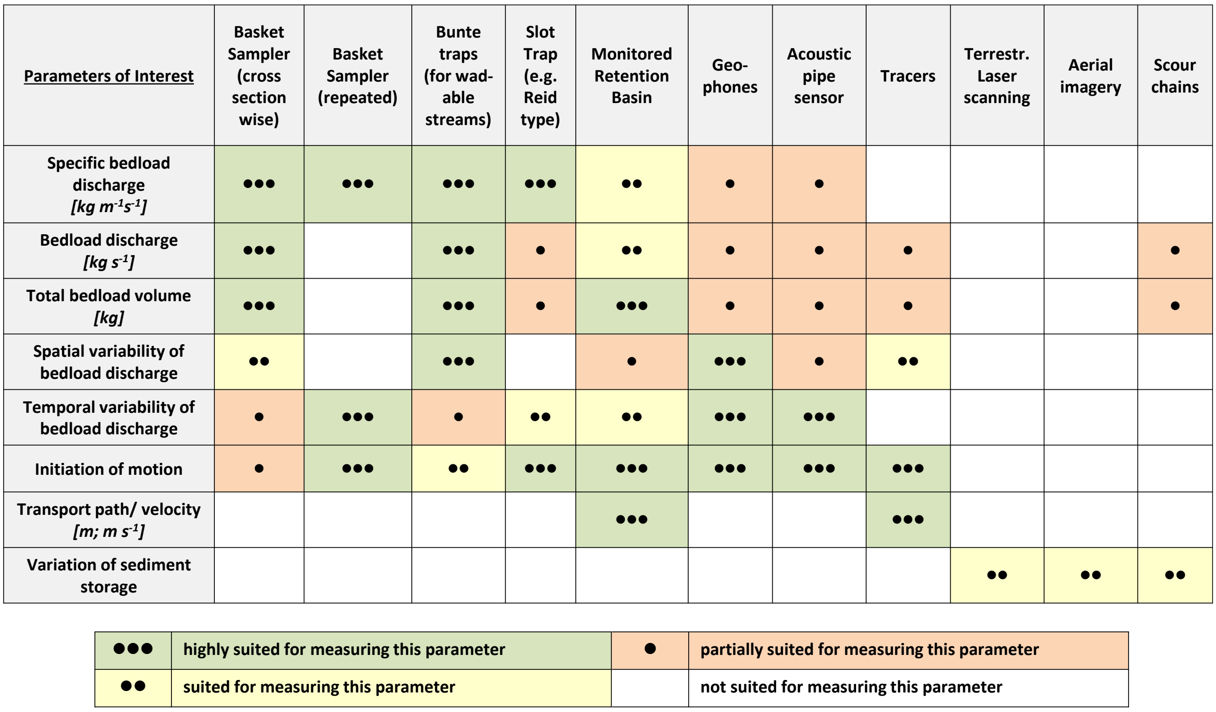


Figure 61 Suitability of individual bedload monitoring devices (mobile bag samplers, slot samplers, retention basins (a); plate geophones, acoustic pipe sensor, hydrophones, tracers (b)) concerning specific parameters; 3 = highly suitable for measuring this parameter, 2 = suitable, 1 = partially suitable, 0 = unsuitable to measure this parameter; based on practical experience and an expert exchange in the project SedAlp. (Habersack et al., 2017)

Another overview of the suitability of bedload monitoring devices concerning specific parameters is given in the final report on sediment monitoring of the EU-funded project SedAlp (Habersack et al., 2015) (*Figure 62*).



Parameters of Interest	Basket Sampler (cross section wise)	Basket Sampler (repeated)	Bunte traps (for wad-able streams)	Slot Trap (e.g. Reid type)	Monitored Retention Basin	Geo-phones	Acoustic pipe sensor	Tracers	Terrestr. Laser scanning	Aerial imagery	Scour chains
Specific bedload discharge *$[kg\ m^{-1}s^{-1}]$*	●●●	●●●	●●●	●●●	●●	●	●				
Bedload discharge *$[kg\ s^{-1}]$*	●●●		●●●	●	●●	●	●	●			●
Total bedload volume *[kg]*	●●●		●●●	●	●●●	●	●	●			●
Spatial variability of bedload discharge	●●		●●●		●	●●●	●	●●			
Temporal variability of bedload discharge	●	●●●	●	●●	●●	●●●	●●●				
Initiation of motion	●	●●●	●●	●●●	●●●	●●●	●●●	●●●			
Transport path/ velocity *$[m;\ m\ s^{-1}]$*					●●●			●●●			
Variation of sediment storage									●●	●●	●●

●●●	highly suited for measuring this parameter	●	partially suited for measuring this parameter
●●	suited for measuring this parameter		not suited for measuring this parameter

Figure 62 Suitability classification of bedload monitoring devices concerning specific parameters (Habersack et al., 2015)

As illustrated in *Figure 61* and *Figure 62*, each of the monitoring systems is best suited for a certain parameter or parameter set, but none of it is able to measure all the parameters with the same quality. Therefore, it is advisable to combine different methods to achieve a high degree of confidence in the measured bedload transport in view of a spatio-temporal variable process, with a fair amount of stochastic behaviour.

Overall, basket samplers are among the oldest and most frequently used methods for sampling bedload transport in gravel bed and sand bed rivers (Edwards and Glysson, 1999; Diplas et al., 2008; Liedermann et al., 2017). Slot, pit, vortex, conveyor-belt samplers and plate geophones are not applicable due to the width and depth of large rivers. According to Liedermann et al. (2017), dredged sediment traps could only give a time and flow discharge integrated value for bedload transport and visual methods often cannot be considered due to the turbidity of the Danube. Using ADCP devices for the determination of bedload transport (Rennie and Church, 2010) shows promise but has not been developed to the extent that it can be considered a standard technique as calibration relations depend on bed material and ADCP operating parameters (Rennie et al., 2017). Depending on the size and velocity of bedforms dune tracking with echo sounders, like singlebeam, multibeam or ADCP, is a viable option in larger rivers (e.g. Gaeuman and Jacobson, 2006) which can contribute to an integrated bedload monitoring approach. Nonetheless basket samplers are currently still one of the best methods to assess bedload quantities (Habersack et al., 2017) and the associated parameters in large rivers (Liedermann et al., 2017). Therefore, the focus on the chapters concerning bedload transport is on the direct bedload measurement with mobile bag samplers (basket or pressure difference samplers).

3.2.2.1 Direct methods

Direct measurement methods are basically physical sampling methods of the transported bedload. The samplers can be handheld, cable suspended or fastened on the channel bed in the case of mobile bag samplers. Alternatively, they are installed in the river bed in the case of slot, pit, vortex or conveyor-belt samplers (Edwards and Glysson, 1999; Habersack et al., 2017; Rickenmann et al., 2017). The relative low setup cost and the comparable easy handling makes mobile bag samplers the most common method for bedload sampling. However, sampler deployment might be difficult and requires experienced personnel being on site during the measurement; especially ship traffic on the river Danube ship traffic can be an additional source disturbance. The installation and maintenance of slot and pit samplers is rather laborious and cost intensive but they are deemed the most accurate type of samplers (Diplas et al., 2008).

During the sampling procedure, the bedload is trapped in a given point of the bed surface by a selected sampling method. The trapped sediment is then analysed in laboratory conditions (dried, weighted and sieved). So, in combination with the known measuring period, the intake width and a calibration factor one can derive the specific bedload discharge (kg/sm). Further quantitative properties of the bedload that can be calculated are for instance the cross-sectional discharge Q_b (kg/s), the total bedload mass (kg) and its grain size distribution. Direct methods are considered more reliable compared to indirect methods, which are still in the research stage. Furthermore, the validation of indirect methods always needs directly measured values as well (similarly to suspended sediment measurement methods).

Basket-type bedload samplers

As already pointed out the most widely used direct bedload measurement tools are the basket-type devices (*Figure 63* and *Figure 64*). Important aspects in the use of basket type samplers are the hydraulic and the trapping efficiency, as well as possible sampling errors (over- and undersampling) resulting from an improper use of the device (e.g. Van Rijn and Gaweesh, 1992; Gaudet et al., 1994, Habersack and Laronne, 2001; Vericat et al., 2006).

The main operating principle is the trapping of the bedload for a given time in a given point of the bed surface. A net or a wire mesh is fixed on a frame and the basket is lowered to the river bed. Bedload that passes the frame is trapped in the net or wire mesh, which also defines the smallest captureable sediment size. The intake size in turn limits the maximum sediment size a basket sampler is able to capture. Due to the tail fin of the device, the flow orients the intake towards the main flow direction. Thus, the water and the bedload are transported through the opening, and the grains get trapped in the basket. The free water flow through the basket is ensured by the perforated basket sides. Internationally, the best-known type is the Helley-Smith sampler. At larger rivers like the Danube the instruments are usually lowered by a winch or crane, from a bridge or a larger vessel.

Figure 63 Basket samplers – from left to right: Mühlhofer sampler (Hubbell, 1964), sampler in use by the VUVH (SK) and sand bed sampler in use by NIHWM (RO).

As different types of rivers require different types of samplers, for a bedload sampler to operate correctly, it should be used within the range of conditions for which it was designed. The most restrictive of these design elements include bedload particle sizes as compared to the inlet opening of the sampler; bedload rates as compared to the size of the captured volume; water depth according to whether the sampler was designed for wading or cable suspension; and flow velocities as related to resistance of the sampler in the flow and range of calibration velocities. (Diplas et al., 2008)

As stated in many publications dealing with bedload measurements (e.g. Ehrenberger, 1933; Einstein, 1937; Novak, 1957; Hubbell, 1964; Helley and Smith, 1971; Emmett, 1980; Edwards and Glysson, 1999; Vericat et al., 2006) the placement of any type of bedload sampler onto the bed alters the local flow conditions and the quantity and composition of the sampled bedload. Which means the ideal bedload sampler does not exist and therefore the sampler needs to be calibrated to get an estimate of the true bedload transport from the measured samples.

The degree of disturbance depends on the sampler shape itself as well as the local flow conditions (velocity and bed shear stress), the characteristics of the bed material and the presence or absence of bed forms. The reduction of flow velocity resp. bed shear stress in the vicinity of the sampler leads to a slowdown resp. accumulation of the grains in front of the sampler. The elimination of this reduction and the counterbalance of blocking effects is part of the design of pressure difference samplers.

Figure 64 Pressure difference samplers – from left to right: Helley-Smith sampler, Karoly sampler and BfG-sampler (pictures by: Baranya/BME, Haimann IWHW/BOKU, Gmeiner IWHW/BOKU)

The pressure difference samplers are generally designed that the cross-sectional area of the inlet gap is smaller than the outlet. With this design the velocity in the sampler is made equal to that of the flow by creating a decrease in pressure at the exit of the sampler nozzle by having a gradual increase in area (Diplas et al., 2008). This design also results in the decrease of flow velocity inside the sampler, which promotes the trapping of the bedload particles (Helley and Smith, 1971). The hydraulic efficiency (ratio of flow velocity in the sampler to flow velocity for the same location without sampler) is about one or greater (Hubbell et al. 1985). According to Diplas et al. (2008) one key parameter in the design of pressure-difference samplers is to make the hydraulic efficiency large enough to prevent sediment from depositing in front of the sampler, but not so large as to cause scouring of the bed and oversampling.

The device allows the measurement of the time-averaged bedload transport rate in a point of the bed surface, based on the ratio of the trapped sediment mass and the sampling period:

$$q_b = \frac{\Delta m}{\Delta t} \cdot \frac{1}{s} \tag{3}$$

where q_b is the specific bedload discharge (kg/(m·s)), Δm (kg) is the mass of the trapped bedload sample, Δt is the time (s) and s (m) is the width of the opening.

Sampler design: Efficiency

Knowledge about the efficiency of the sampler is essential, as it is needed for the operation of the sampler and the correct calculation and interpretation of the results (DVWK 127, 1992).

According to Druffel (1976) there are two measures of sampler performance:

1. Hydraulic efficiency: Ratio of the mean velocity in the sampler mouth to the mean undisturbed velocity (i.e. without the sampler) (*Figure 65*).

$$\alpha_H = \frac{v_m}{v_{ms}} \tag{4}$$

   where α_H denotes the hydraulic efficiency, v_m the undisturbed mean flow velocity and v_{ms} the flow velocity in the sampler intake.

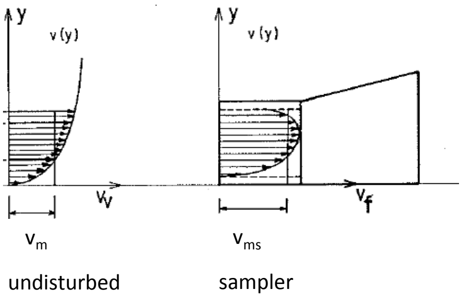


Figure 65. Flow velocity distribution without a sampler and with a sampler (adapted from: DVWK 127, 1992)

   To improve the sediment-sampling efficiency of portable samplers, pressure difference nozzles were designed (Helley and Smith 1971) to increase the flow of water through the sampler (Diplas et al., 2008). Thus, hydraulic efficiency in pressure difference samplers is designed to be equal to or greater than 100% (Druffel et al. 1976). Hydraulic efficiencies are readily measured in laboratory flumes.

2. Sampling / Trapping efficiency: Ratio of the Mass of the bedload collected by the sampler to the bedload that passed the area occupied by the sampler if the sampler has not been there (Druffel, 1976). Or in other words the ratio of the sampled bedload to the true bedload.

$$\alpha_S = \frac{q_{bs}}{q_b} \tag{5}$$

   where α_s denotes the sampling efficiency, q_{bs} the measured specific bedload transport and q_b the true bedload transport.
   There is still an ongoing discussion about the ideal way to assess the sampling efficiency, nonetheless all the relevant sources agree that a calibration coefficient is needed to correct the sampled rate to the actual rate (Diplas et al., 2008). Not incorporating the sampling efficiency leads to a systematic error, this is not averaged out.

Sampler operation: Measurement errors

There are several typical problems one encounters when measuring with a mobile bag sampler. Most of them can be avoided by properly operating the sampler and choosing an adequate sampler and sampling duration for the conditions prevailing in the river (flow conditions, bedload transport intensity, bedload particle size). This is important because those sources of error are systematic errors, which are not averaged out.

During the operation of the samplers, the following typical problems can occur resulting in over- or undersampling (the listed points 1., 3a and 4a are directly taken from: Van Rijn and Gaweesh, 1992; additional sources: Ehrenberger, 1931; Emmett, 1980; Beschta, 1981; Carey, 1985; Gaweesh and Van Rijn, 1994; Gaudet et al., 1994; Childers et al., 1999; Vericat et al., 2006; Camenen et al., 2012; own experience):

1. The initial effect: Sand and gravel particles may be stirred up and trapped when the instrument is placed on the bed (oversampling).
2. The gap effect (*Figure 66a* and *Figure 66b*): A gap between the bed and the sampler mouth may be present initially or generated at a later stage under the mouth of the sampler due to migrating ripples or erosion processes, a large grain in front of the sampler or the sampler is perched due to bed roughness (undersampling).
3. The blocking effect (*Figure 66c*):
    a. Blocking of the bag material by sand, silt, clay particles and organic materials will reduce the hydraulic efficiency and thus the sampling efficiency (undersampling).
    b. Blocking of the sampler mouth with one or several large particles reduces the sampling efficiency (undersampling).
    c. Blocking of the sampler mouth by an approaching sand or gravel dune (undersampling).
4. The scooping (shovelling) effect:
    a. The instrument may drift downstream during lowering to the bed and may be pulled forward (scoop) over the bed when raised again so that it acts as a grab sampler (oversampling).
    b. The instrument slides over the bed during sampling, either due to ship movements or due to improper handling of the suspension and tether lines
5. The subsidence effect (*Figure 66d*): The sampler sinks into the overloose sediment. Depending on the sediment (sand or gravel), the orientation of the sampler around its centreline axis and the amount of the intake that is buried this results in sediments entering the sampler that are not part of the transport or the transported sediment might not be able to enter the sampler anymore (over- or undersampling).
6. The overfilling effect: The sampler losses its ability to trap the transported sediment properly as the hydraulic efficiency is reduced (undersampling). But the efficiency to

trap sediments in suspension might increase significantly, with the effect of oversampling this part of the transported sediment.

The orientation effect (*Figure 66e*): Misalignment of the sampler and the mean near bed flow velocity leads to a decrease of the sampled material. This might be a problem in complex flow situations, when the sampler is lowered to fast to the river bed, not giving it time to align with the near bed flow velocity direction or when the tail of the sampler touches the river bed much earlier than the intake, acting as a pivot point. (undersampling).

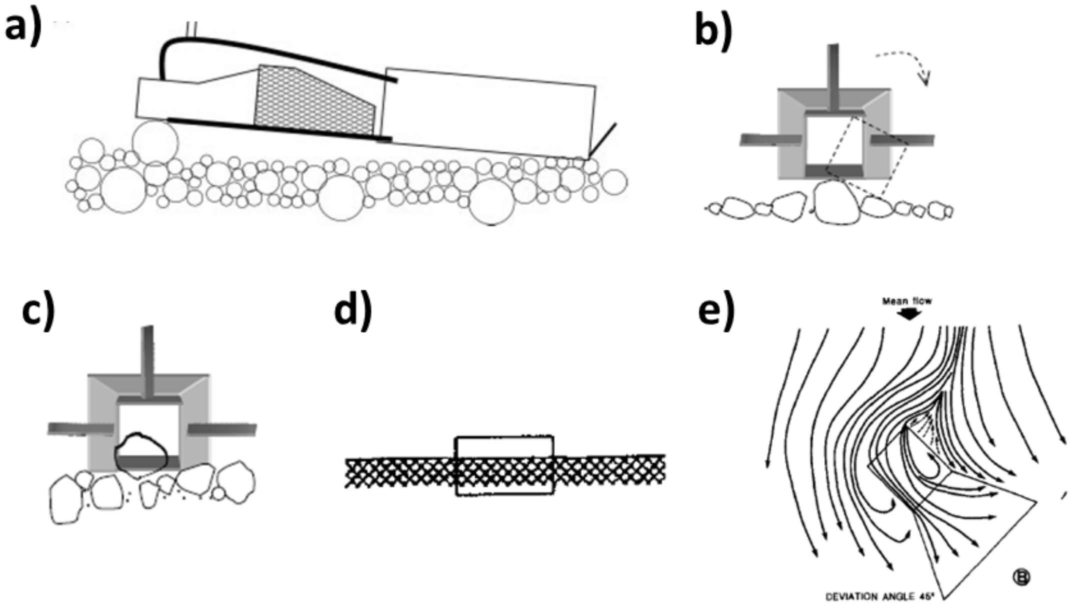


Figure 66 Typical problems and sources of error when operating a bedload sampler: a) gap effect; b) sampler perched - gap effect; c) blocking effect; d) subsidence effect; e) orientation effect. (Sources: a) Camenen et al., 2012; b) and c) Vericat et al., 2006; d) Gaweesh and Van Rijn, 1994; e) Gaudet et al., 1994)

The effects of these potential problems are examined by researchers. For a more reliable sampling purpose, the possible symptoms can be eliminated by the use of e.g. a flexible bottom sampler, steering wings, larger basket, underwater cameras (Garcia, 2008), heavier basket, reduced sampling duration, different sampler design.

Sediment traps - direct

More expensive methods are the trap- and pit sampling methods which also require major infrastructure (Garcia, 2008). The main operating principle is to place a trap in the river bottom to capture the bedload. The trap or pit can be quite a simple construction, but it can be supplemented by weighing and data recording functions (*Figure 67*). The main benefit is the high representativeness of the samples. The disadvantages are that these kinds of sampling methods can be installed mainly on smaller streams and the construction is quite expensive.

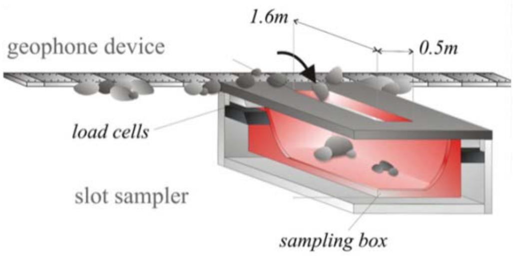


Figure 67 Slot sampler (Kreisler et al., 2016)

3.2.2.2 Indirect bedload measurement methods

Indirect methods to measure bedload transport can provide high-resolution data of sediment transport and they have the additional advantage of minimizing local and temporal changes in the flow field (Habersack et al., 2017; Rickenmann et al., 2017). The need for and advantages and limitations of indirect (surrogate) non-invasive techniques have been discussed extensively in international workshops (e.g. Gray, Laronne and Marr, 2010; Rickenmann et al., 2013).

The indirect or surrogate methods do not measure directly the required parameter of the bedload (e.g. mass and grain size), but it is estimated based on other, measurable features of a physical process. Thus, the direct sampling can be integrated (combined) with indirect methods. This kind of method is e.g. the bedload movement mapping by acoustic technique. In this case, the bedload velocity is estimated as a function of the reflected sound intensity. Indirect methods are under continuous development, especially in the past few years. Nowadays, the integrated use of direct and indirect techniques is the most appropriate way in gaining high resolution bedload transport data. As the accuracy of any indirect technique still relies on the quality of the calibration data (directly measured bedload), the use of the most appropriate bedload sampler is a prerequisite for an adequate indirect bedload transport monitoring (Gray et al., 2010). Based on reliable direct bedload measurements the indirect methods can be calibrated and validated, which provides the opportunity to qualitatively analyse the bedload conditions in a larger and more continuous space and time frame.

Tracers

Since the first bedload tracing experiments with painted particles (e.g. Einstein, 1937; Leopold et al., 1966), radioactive (e.g. Sayre and Hubbell, 1965; Stelczer, 1968), magnetic and fluorescent tracers, the tracing of sediments has become a popular tool to investigate bedload transport in streams and rivers (Hassan and Ergenzinger, 2003; Liedermann et al., 2013, Lajeunesse et al., 2017). Tracers are marked / tagged particles (similar in size, shape and density to sediment in the river) that are introduced into rivers to obtain general information on the movement resp. the fluvial transport of sediments in rivers (Hassan and Ergenzinger, 2003). Tracers can be used e.g. to obtain information on the rate and direction of sediment transport, particle entrainment, the virtual velocity, rest periods and step lengths, distances travelled, sediment sources and depositional areas.

In the recent past the application of high-frequency radio transmitters, either active or passive (RFID) has become quite popular (e.g. Habersack, 2001; Bradley and Tucker 2012; Liedermann et al., 2013; Phillips and Jerolmack, 2014). As stated by Liedermann et al, (2013) only the active radio transmitters are applicable in larger rivers, because RFID tags have a rather limited detection range (approx. 1 m or less). *Figure 68* shows the elements of the system which allows for the triangulation of the tracer position.

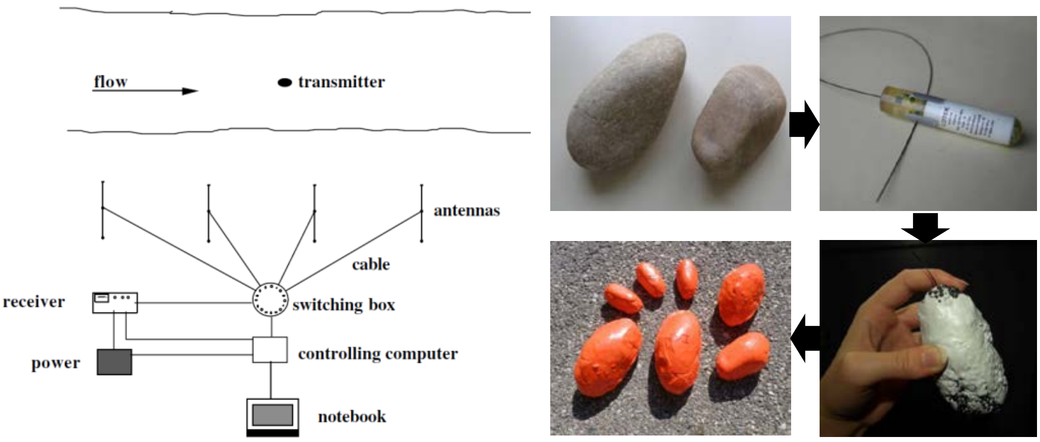


Figure 68 Left picture: Elements of a radio tracer system (Habersack et al., 2001); right picture: tracer stone assembly (Liedermann et al., 2013)

A more feasible method for larger rivers is the tracking of the particles from a boat and the logging of the actual position with a GPS (*Figure 69*). The main experiences regarding to the radio transmitters:

- The tracking of the gravels significantly contributes to the investigation of the bedload transport.
- The motion paths of the gravels can be determined.
- The tracking methods can be used for the investigation of larger gravel particles.

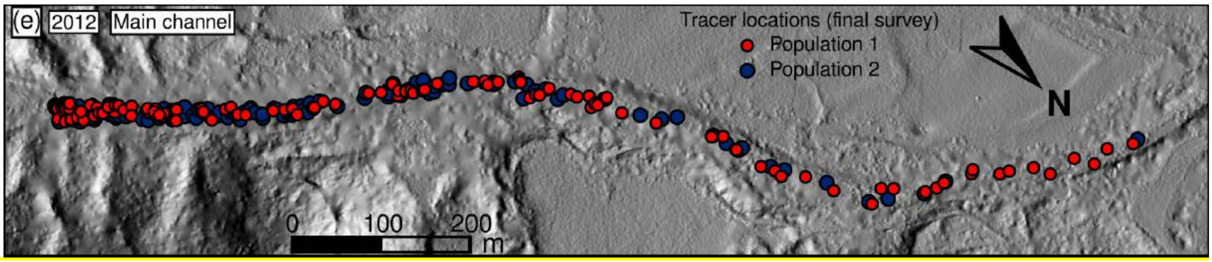


Figure 69 Distribution of transported tracer particles after the final search (Phillips and Jerolmack, 2014)

The use of tracers has proved to be an important method in studying the general characteristics of sediment movement under differing flow conditions, as they reveal the long-term action of a fluvial system under varying flow conditions, sediment supply and channel morphology (Hassan and Ergenzinger, 2003), enabling an explanation of the interactions between sediment transport and river morphology (Habersack, 2001). Further they can be used to evaluate the success of river restoration projects, help in optimizing bedload management and sediment augmentation strategies (e.g. Arnaud et al., 2017; Goelz, 2002; Liedermann et al., 2013).

Acoustic-based bedload measurements

The primary areas of application of acoustic devices are the indirect measurement of flow conditions (e.g. ADCP and Acoustic Doppler Velocimeter (ADV)) and the bed geometry (e.g. Multibeam echosounder). Besides the primary functions of the acoustic devices, the application of an ADCP or echosounder provides the opportunity to estimate the sediment velocity in the vicinity of the bed surface. As it was already introduced, the flow velocity can be estimated by the ADCP instrument based on the reflected beam from the suspended solid particles. According to the reflected beam, the velocity of the particle can be calculated. Inasmuch as there is no bedload transport on the bed surface, the velocity and direction of the vessel can be estimated using the same principle, through the ostensible movement of the bed. This method is called Bottom Tracking, which means that the velocity of the vessel is estimated based on the tracking of the bed surface. However, if bedload transport is present, hence the bed is moving, the calculated velocity by the Bottom Tracking becomes the vectorial sum of the vessel velocity and the bed moving velocity of the bed surface (*Figure 70*).

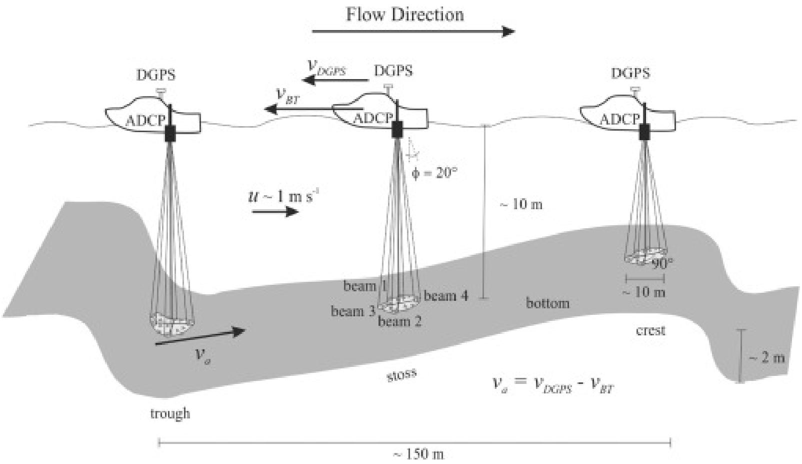


Figure 70 Principle of the estimation of the apparent bedload velocity via ADCP bottom tracking. When bedload transport is occurring the bottomtracking velocity (v_{BT}) and the actual boat velocity (v_{DGPS}) are not identical. (Graphic taken from: Latosinksi et al., 2017)

If the vessel is standing still and is not moving, or the movement of it can be determined independently (e.g. a real-time kinematic (RTK) GPS), then the velocity calculated by the Bottom Track can be corrected, as the vectorial value of the boat velocity will be either zero or known. *Figure 71* shows an example, when the vessel is standing still and there is considerable bedload transport.

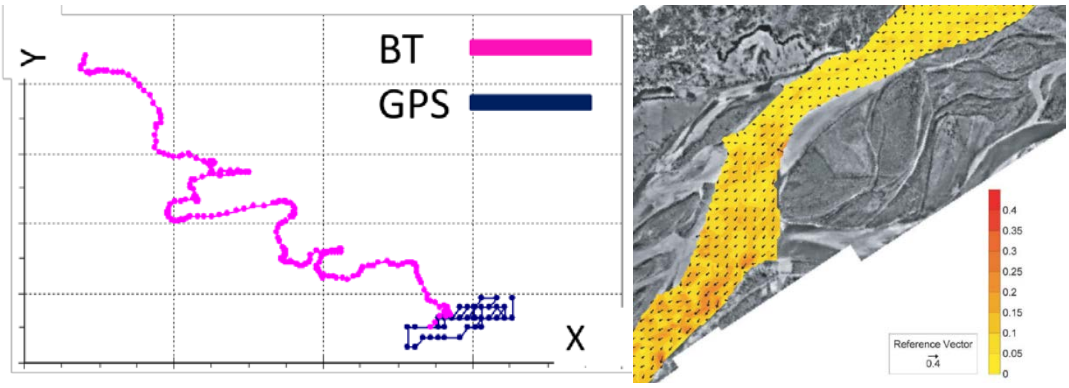


Figure 71 Left picture: Route of the vessel estimated by the Bottom Track (pink dots) and by the RTK GPS (blue dots). Bottom Tracking suggests the movement of the vessel in the upstream direction, which is the effect of the bedload motion (source: Baranya). Right picture: Interpolated apparent bedload velocity measured with an ADCP (Rennie and Church, 2010).

The pink line represents the estimated movement calculated by the Bottom Track. The blue dots show the real coordinates of the vessel, determined by an RTK GPS. The positions calculated by the two methods (the pink and blue dots) do not match because of the effect of the bedload movement.

The instantaneous bedload sediment velocity vector can be calculated by the following formula (Rennie et al., 2002; Rennie and Villard, 2004; Gaeuman and Jacobson, 2006; Gaeuman and Rennie, 2006):

$$\mathrm{v_a} = \mathrm{v_{GPS}} - \mathrm{v_{BT}} \tag{6}$$

where v_a [m/s] is the sediment velocity on the bed surface, v_{GPS} [m/s] is the actual vessel velocity calculated from the real GPS positions and v_{BT} [m/s] is the vessel velocity estimated by the Bottom Tracking method. If the actual mean bedload particle velocity $\mathrm{v_b}$ is known the specific bedload transport can be calculated using the kinematic relation:

$$\mathrm{q_b} = \rho_s \mathrm{v_b} \mathrm{d_a} (1 - \lambda) \tag{7}$$

with ρ_s the sediment density, $\mathrm{d_a}$ the active layer thickness and λ the porosity of the active layer. According to Rennie et al. (2017) the relations between $\mathrm{v_a}$, $\mathrm{v_b}$, and $\mathrm{q_b}$ depend on a number of factors (e.g. concentration and grain size of the moving particles, the bedload layer thickness, and the backscatter strength). This at the moment leaves two options to relate $\mathrm{q_b}$ to $\mathrm{v_a}$: (1) a site-specific calibration or (2) an assumed linear relation between $\mathrm{q_b}$ and

v_a. The other option is in using v_a as an uncalibrated relative measure of bedload transport intensity (Rennie and Church 2010).

As shown by Rennie et al. (2017) calibration relations between directly measured bedload and the apparent bedload velocity measured with an ADCP have proven to be site-specific, varying as a function of the bedload grain size distribution and several ADCP operating parameters. Overall the technique using ADCPs seems to be promising, but it is still in the phase of research and has not been developed to the extent that it can be considered a standard technique

Other acoustic methods as plate geophones and pipe hydrophones are not further explored in this context, due to the width and depth of larger rivers (in case of the Danube also in combination with ship traffic), which are a limiting factor for the application of those techniques.

Bed form tracking

The basic principle of bed form tracking is the computation of the bedload transport from a repeated scan of the same longitudinal profile (singlebeam or ADCP) or the same area (multibeam) under comparable flow conditions (*Figure 72*). The minimum requirements to estimate the specific bedload transport are the bed form dimensions and the migration velocity of the bed forms (Gaeuman and Jacobson, 2007). In combination with a shape parameter this allows for the calculation of the bedload transport.

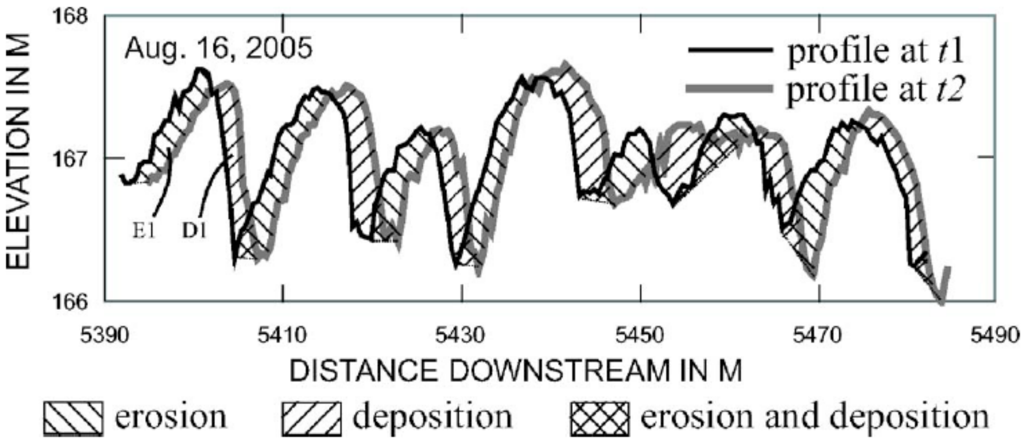


Figure 72 Pair of bathymetry profiles showing the erosion and deposition (Gaeuman and Jacobson, 2007)

Instead of relying on estimates of a shape factor the specific bedload transport can also be derived by calculating the bed form volume numerically (Gaeuman and Jacobson, 2007). This is done by calculating the erosion, deposition and the intersecting deposition-erosion volume. This approach can be applied as long as the dunes do not migrate more than one wavelength between consecutive bathymetry measurements.

For the transformation of the calculated bedload transport from a volume into units of mass the porosity of the transported material is needed – either via an assumption or by measuring it.

As the use of echosounding instrumentation (ADCP, single- or multibeam echosounders) is nowadays quite wide-spread, this technique has great potential in being applied on a larger scale in rivers where dunes are occurring.

Sediment trap - indirect

Another option for a sediment trap which is more applicable at larger rivers is the dredging of a sediment trap (*Figure 73*), which can deliver an estimate of the transported material when the filling stage is monitored with echo sounding instruments (indirect approach) or the dredging volume (other approach) is documented. The drawback is that an assumption regarding the pore volume is needed to calculate the transported mass and that sediment which is transported through the trap between echo soundings or dredging works leads to an underestimation of the transported amount.

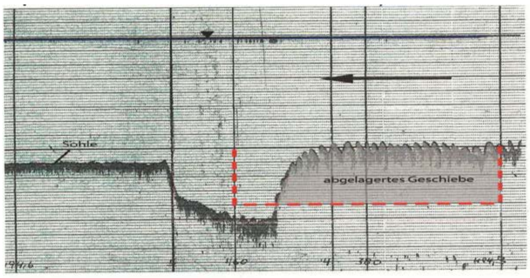


Figure 73 Sediment trap at the river Rhine (DWA-M 525, 2012)

3.3 Good practice examples

3.3.1 Suspended Sediment

3.3.1.1 Monitoring

Suspended material parameters

The following parameters can be used for the reliable characterization of suspended sediment transport:

- suspended sediment concentration (mg/l),
- suspended sediment load (kg/s),
- suspended sediment yield (t),
- spatio-temporal variability,
- particle size distribution,
- characteristic particle size.

Concentration is defined as the ratio of the mass of total solid particles in a water sample, and the volume of the sample itself. The mass of the solid particles is determined after the sample is dried and has reached a constant mass.

Suspended sediment load is the flux of the suspended sediments through a selected cross-section per unit time. The suspended sediment load may significantly change over time. Integrating the suspended sediment load over a specific period of time (e.g. a year) gives the total amount of sediment transported through the studied cross-section.

Suspended sediments not only change significantly over time, but in space as well i.e. the cross-sectional distribution of the suspended sediments is rather inhomogeneous.

Suspended materials consisting of particles of different particle sizes can be characterized with specific particle sizes (e.g. mean grain size) or with the particle size distribution curve as well.

Monitoring methods/strategies

Various methods are available for the determination of suspended sediment concentration (Wren et al., 2000; Gray and Gartner 2009). It can be stated, that a single method is not sufficient for the characterization of all relevant parameters. Developing and maintaining reliable suspended sediment monitoring calls for the parallel implementation of both direct and indirect methodologies (Haimann et al., 2014) and their combination during post processing (*Figure 74*). The monitoring strategy described in the following chapter is mainly based on the guideline for suspended sediment monitoring “Schwebstoffe im Fließgewässer – Leitfaden zur Erfassung des Schwebstofftransportes” (BMLFUW 2008; 2017).

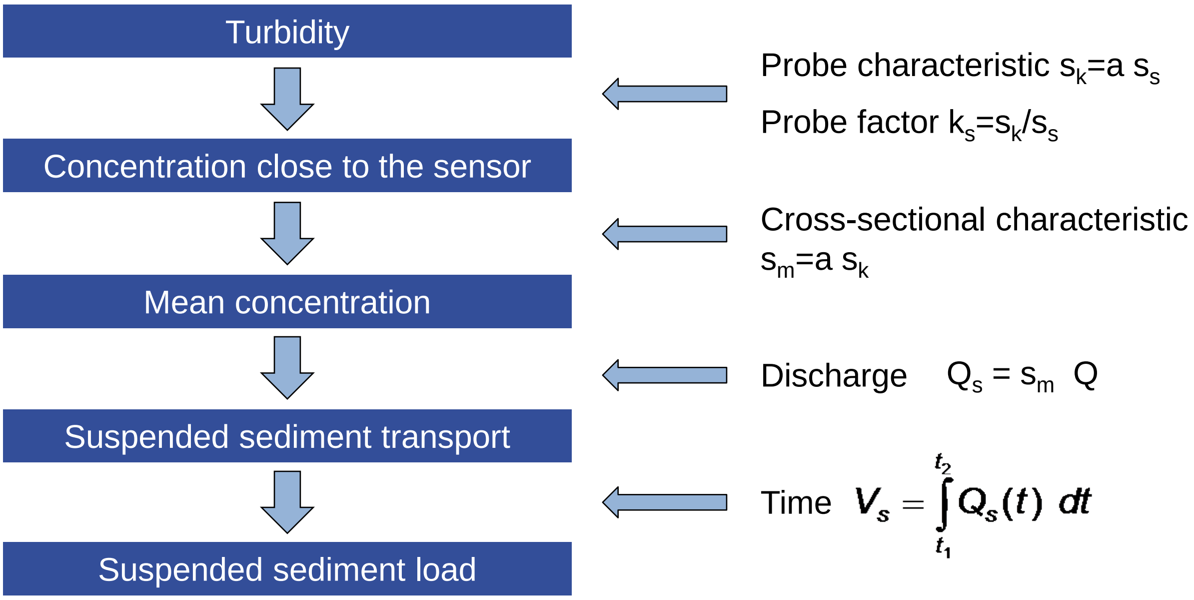


Figure 74 Flow chart of the suspended sediment data processing (Habersack et al., 2013)

The temporal variation of the suspended sediment transport can be assessed with methods/devices which offer continuous operation, such as turbidity sensors installed in a vertical close to the bank. As the turbidity values measured by these sensors strongly depend on the size and shape of suspended particles, the preliminary calibration of these devices is necessary with water samples taken in the close proximity of the vertical where the sensors operate. Optimal sampling interval depends on the concentration and on the flow velocity as well.

Another important monitoring task is to reveal the cross-sectional distribution of the suspended sediment yield, which can be achieved through multi-point samplings usually combined with ADCP measurements. This combined methodology offers the determination of the cross-sectional distribution of suspended sediment concentration and its load as well. Due to the temporal variations, it is recommended to perform such combined measurements multiple times a year, preferably in different flow conditions.

By combining these measurements with conversion factors, a time series of mean suspended sediment concentration can be established. Taking the discharge into account, the suspended sediment transport can be determined. By integrating the time series of suspended sediment transport over time, the suspended sediment load can be determined for any period of time (years, months, events).

The different measurement methods and the related, recommended sampling frequencies are summarized in *Table 30*.

Table 30 Suspended sediment measurement methods (BMLFUW, 2008;2017)

Parameter	**Method**	**Sampling frequency**
Turbidity	Turbidity sensor	Continuous
Suspended sediment concentration	Single-point sampling with bottle sampler or pump (close to the probes for calibration)	High water – daily; mean water – 1-2 times per week; low water – less often
Cross-sectional distribution of suspended sediment concentration	Multi-point sampling, or sampling combined with ADCP measurements	Several times per year, at different flow rates
Particle size	Water sample with sufficient amount of suspended solids	Recommended: at least every year during high water condition.

3.3.1.2 Monitoring site selection and infrastructure

Permanently operating suspended sediment monitoring stations shall be constructed and operated in a way that the monitoring of suspended sediments is possible throughout the whole year and that the measurement results can be considered as representative for the section of the river. Therefore, even when selecting the monitoring location as well as the positioning of the equipment in the water, flow conditions, tributaries or inlets, sedimentation and erosion tendencies, ice formation, (bio-) fouling and weeds have to be taken into account. Equipment that is permanently installed at the monitoring site shall be accessible for e.g. maintenance throughout the whole year.

For the calculation of the suspended sediment load, the flow discharge must be determined continuously at the measurement site too.

3.3.1.3 Measurement methods

Determining the temporal variation of single-point sediment concentrations

Required equipment

Equipment necessary for the assessment of temporal variations:

- Indirect measurement device for continuous data recording + data logger
- Sampling device (e.g. cable sampler)
- Clear, closable bottles to store water samples (volume of min. 1 litre)

- Waterproof marker to make labels
- Measurement protocol and writing tool

Continuous data recording

In order to assess the temporal variability of turbidity or concentration, indirect measurement devices are required which are capable to conduct measurements at least with the temporal resolution of 15 minutes (mean or instantaneous). In order to obtain reliable data, the measurement device must be chosen carefully, according to the local concentration and grain size characteristics. The regular cleaning and maintenance of the device most be ensured. In addition to locally storing the collected data, their remote transmission is recommended.

Calibration measurements

Since the continuous monitoring of suspended sediments is only feasible with indirect methods, their calibration must be conducted with water samples taken from their close proximity.

It is advised to generalize a consistent measurement report sheet on which one can record the identification number of every sample with the date and time of the sampling and the relevant turbidity measurement as well. It is also recommended to record every maintenance work done on the probe e.g. cleaning or change of sensor.

Calibration measurement conducted with a sampler on a rope

Based on previous experiences the calibrating measurements are advised to be conducted from a bridge.

1. The lowered point sampler usually starts swinging. When the sampler gets close to the free surface, one has to wait until the main axis of the device and its swinging motion gets aligned (parallel) with the flow direction. At this moment, the device can be submerged and one must wait until the rope is tensed so the swinging motion can stop.
2. It is recommended to use a reel with the cable of the sampler which can ensure precise operation and the straightforward measurement of vertical lengths as well (position of the sampler along the vertical).
3. It is not necessary to fill the sampler bottle entirely, however, it is advised to fill it at least to the half.
4. The sampling bottle must be labelled for clear identification (sample ID; place and time of sampling).
5. Identification data must be logged in the measurement protocol as well, along with the measured turbidity value and the actual water stage.

Calibration measurement conducted with a sampler on a rod

The rod sampling is usually performed from the river bank.

1. The sampler (capacity of 1 litre) is mounted on a telescopic rod and lowered to the close proximity of the turbidity sensor.
2. The sampler must be pulled out from the water with a quick move before it is completely full.
3. The sampling bottle must be labelled for clear identification (sample ID; place and time of sampling).
4. Identification data must be logged in the measurement protocol as well, along with the measured turbidity value and the actual water stage.

Determination of cross-sectional (spatial) distribution of sediment concentration

Required equipment

Devices necessary for the assessment of spatial concentration distribution:

- Sampling device (e.g. US-P61-A1 type sampler or pump sampler; *Figure 75*) + necessary accessories
- Reel, crane
- Clear, closable bottles to store water samples (volume of min. 1 litre)
- Waterproof marker to make labels
- Stopwatch
- Measurement protocol and writing tool
- Calibrated device for velocity measurements (ADCP, ADV, etc.)
- Power supply (generator, battery)

In order to calibrate the indirect device employed for the assessment of temporal changes the followings are needed:

- Sampling device (e.g. hand sampler)
- Clear, closable bottles to store water samples (volume of min. 1 litre)
- Waterproof marker to make labels
- Measurement protocol and writing tool

Figure 75 Suspended sediment samplers: a) US P61 A1 type sampler (BMLFUW, 2008; 2017); b) pump sampler (picture Haimann IWHW/BOKU).

Cross-sectional measurement

In order to obtain a reliable estimation of the suspended sediment flux in a cross-section, one must determine the spatial distribution of suspended sediment concentration and flow velocities in the assessed cross-section. It is advised to conduct such measurements several times per year, preferably in different flow conditions. It can be done with multi-point sampling measurements or with its combination with ADCP measurements. *Figure 76* shows an example of a cross-sectional measurement plan, with the sampled points (5 verticals, 4 points in each vertical).

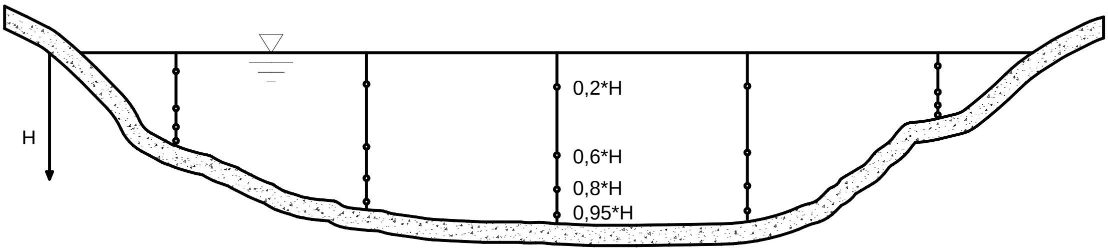


Figure 76 Scheme of a cross-sectional measurement in 5 verticals and 4 measuring points per vertical (based on BMLFUW, 2008; 2017)

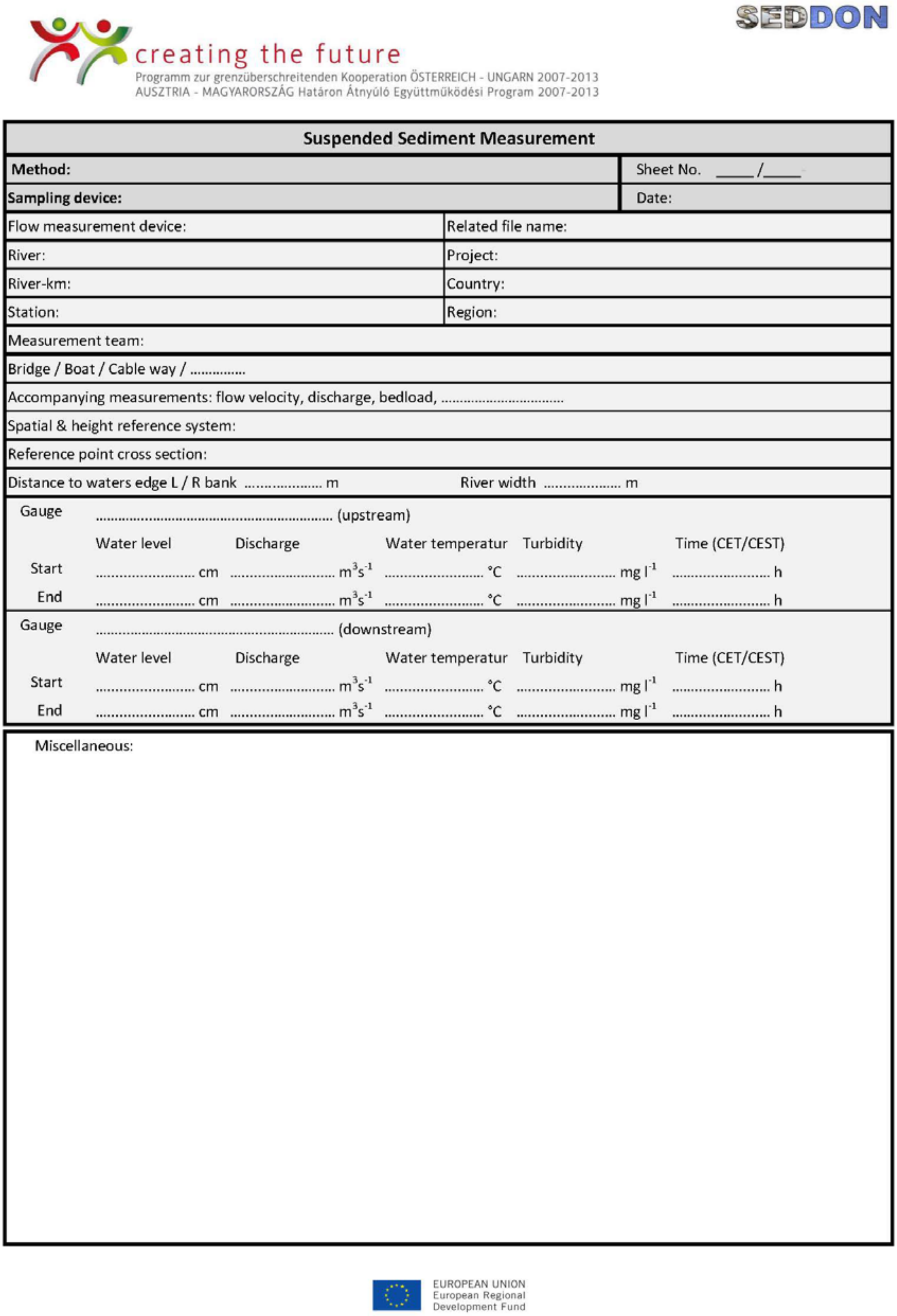
1. The following data must be logged to the measurement protocol (an example for a protocol is provided in *Figure 77* and *Figure 78*):
   Type of water sampling and velocimeter device, time, measurement team, location (river, river kilometre, gauging station, country), project name, type of measurement (vessel mounted, from bridge, from bank, etc.), every parallel

measurement (flow measurement, bed bacterial sampling, etc.), water stage, water temperature, turbidity.

2. The cross-section must be divided into several segments of equal width. The number of verticals shall not be less than seven for a water surface width larger than 300 m and not less than five for a surface width smaller than 300 m (ISO4363; 2002). The measurement verticals are then in the midpoint of these sections. In the case when ADCP measurements are conducted as well, a fewer number of verticals is sufficient.
3. The determination of the water depths in the verticals can be done with the velocimeter (ADCP) or with the suspended sediment sampler. In case when the cable of the sediment sampler is used for the estimation of the water depth, the sweeping effect of the flow should be taken into account (the measured depth can be larger than the actual), hence the use of ADCP is justified. All designated verticals must be logged in the measurement protocol.
4. Determination of measurement points along the verticals: in general, it is suggested to measure 3-5 points in the same relative depths. The relative depths in which measurements have to be conducted based on the total depth (H) with different number of points are the following:
    a. 5-pointed method: 0.05×H, 0.20×H, 0.60×H, 0.80×H, 0.95×H
    b. 4-pointed method: 0.20×H, 0.60×H, 0.80×H, 0.95×H
    c. 3-pointed method: 0.20×H, 0.60×H, 0.80×H
    d. 2-pointed method: 0.20×H, 0.80×H
    e. 1-pointed method: 0.60×H
5. The sampler is lowered to the depths determined in the previous step. It is recommended to use an isokinetic sampler, so the measurement is the most representative and reliable as possible. It is not necessary to fill the sampler bottle entirely, however, it is advised to take a sample of at least 0.5 l. The stopwatch is used the measure the net time of the measurement.
6. The sampling bottle most be labelled for clear identification (sample ID; place and time of sampling).
7. The time, location (distance from bank, depth), time and the length of the measurement must be logged on the protocol along with the ID of the sample. If possible, turbidity and water stage must be noted as well.
8. Determination of flow velocity in the sampled point.
9. Steps 5-8 are repeated to all the verticals.
10. After the measurement, the following data have to be logged into the protocol:
    Water stage level, discharge, temperature, measured turbidity value and time of measurement.
11. The samples are later analysed in laboratory conditions (determination of suspended solid concentration). The filled sample bottles are to be kept in dry, cold place (refrigerator), but should be not frozen. The samples should be post-processed as soon as possible.

Similarly to the determination of the temporal alteration of sediment concentration from indirect measurements, the following steps have to be taken for the cross-sectional measurements as well:

1. The calibration requires a water sample from the close proximity of the indirect device. The sample can be collected with cabled, rodded or pump sampling.
2. The sampling bottle most be labelled for clear identification (sample ID; place and time of sampling).
3. The water stage and the turbidity value measured with the indirect device have to be logged to the measurement protocol at the time of the water sampling.
4. These steps (1-3) have to be performed repeatedly during the cross-sectional measurements.



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SEDDON

Suspended Sediment Measurement

Method:
Sheet No. ____/____
Sampling device:
Date:
Flow measurement device:
Related file name:
River:
Project:
River-km:
Country:
Station:
Region:
Measurement team:
Bridge / Boat / Cable way / ……………
Accompanying measurements: flow velocity, discharge, bedload, ……………………………
Spatial & height reference system:
Reference point cross section:
Distance to waters edge L / R bank ………………… m
River width ………………… m

Gauge ……………………………………………………… (upstream)

	Water level	Discharge	Water temperatur	Turbidity	Time (CET/CEST)
Start	…………………… cm	…………………… m^3s^{-1}	…………………… °C	…………………… $mg\,l^{-1}$	…………………… h
End	…………………… cm	…………………… m^3s^{-1}	…………………… °C	…………………… $mg\,l^{-1}$	…………………… h

Gauge ……………………………………………………… (downstream)

	Water level	Discharge	Water temperatur	Turbidity	Time (CET/CEST)
Start	…………………… cm	…………………… m^3s^{-1}	…………………… °C	…………………… $mg\,l^{-1}$	…………………… h
End	…………………… cm	…………………… m^3s^{-1}	…………………… °C	…………………… $mg\,l^{-1}$	…………………… h

Miscellaneous:

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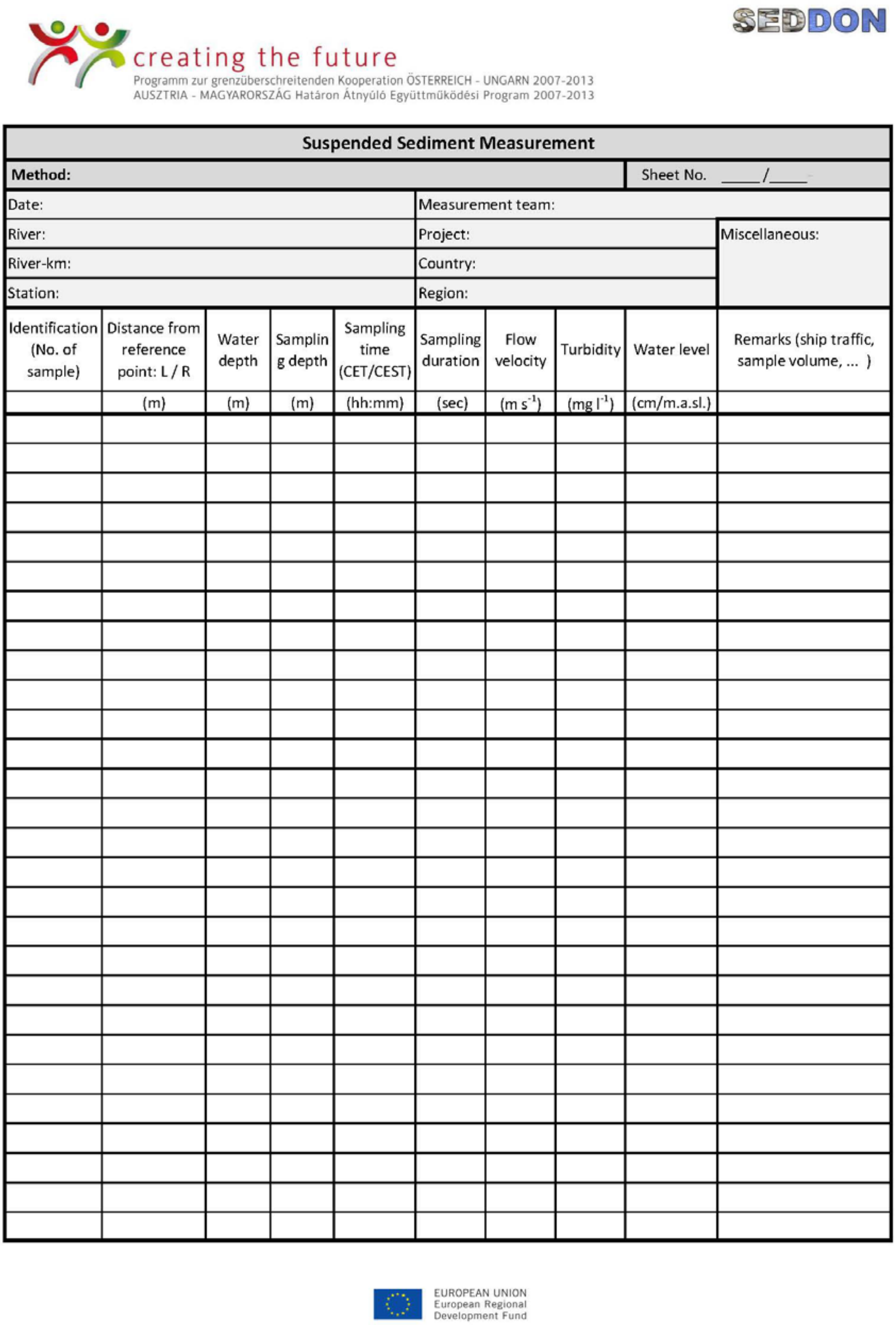
Figure 77 Field measurement data sheet for suspended sediment measurements (SEDDON, 2014)



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SEDDON

Suspended Sediment Measurement

Method:
Sheet No. _____/_____
Date:
Measurement team:
River:
Project:
Miscellaneous:
River-km:
Country:
Station:
Region:

Identification (No. of sample)	Distance from reference point: L / R	Water depth	Samplin g depth	Sampling time (CET/CEST)	Sampling duration	Flow velocity	Turbidity	Water level	Remarks (ship traffic, sample volume, ...)
	(m)	(m)	(m)	(hh:mm)	(sec)	($m\ s^{-1}$)	($mg\ l^{-1}$)	(cm/m.a.sl.)	

EUROPEAN UNION
European Regional
Development Fund

Figure 78 Field measurement data sheet for suspended sediment measurements (SEDDON, 2014)

3.3.1.4 Determination of SSC

Laboratory analysis (Filtration)

The filtering of the samples can be done under pressure or with vacuum filtering as well. In order to get well comparable results, a filter of 0.45 µm pores have to be used for all samples (*Figure 79*). The concentration of suspended solids comes from the ratio of the dry matter mass and the original volume of the sample. The steps of laboratory analysis are presented in detail in the handbook "Schwebstoffe im Fliessgewaesser – Leitfaden zur Erfassung des Schwebstofftransportes" (BMLFUW, 2008; 2017) (Suspended sediments in rivers – manual for the assessment of suspended sediment transport).

Required equipment

The determination of dry matter content requires the following equipment:

- analytical weight (precision of 0.1 mg)
- membrane filter (pore size of 0.45 µm) (cellulose-acetate or cellulose-nitrate)
- filtering device (vacuum or pressurized)
- volumetric measuring cylinder (precision of 0.5%) for the determination of the sample volume
- slide
- bottle
- forceps
- adjustable dryer cabinet

Figure 79 a) Membrane filter; b) Filtering of samples at the laboratory of viadonau in Aschach (pictures Haimann IWHW/BOKU).

Determination of dry matter content

The steps of the determination of dry matter content are the following:

1. The membrane filter placed on the plate is dried at 105 °C until it reaches constant weight (min. 10 minutes, max. 3 hours). Mass is considered constant when it does not change more than 0.1 mg between consecutive drying periods.
2. Combined mass of the plate and the membrane filter is measured immediately after the drying (m_a).
3. Membrane filter is placed into the filtering device.
4. Sample is poured into the filtering device and its volume is measured precisely (V_p). The sample bottle has to be rinsed carefully along with the volumetric measuring device, this water is also poured into the filtering device.
5. During the filtering process, the funnel has to be washed carefully in order to force the stuck particles towards the membrane filter.
6. After the filtering process, the membrane filter is placed on a plate. The plate and the membrane filter are then dried (105 °C, usually at least 30 minutes) until they combined mass reaches a constant value.
7. The plate and the membrane filter (with the dry matter on it) is weighted again, immediately after the drying process (m_b).
8. The dry matter content is: $m_T=m_b-m_a$ [mg].
9. The suspended matter concentration of the sample is: $s_o=m_T/V_p$ [mg/l].

Portable laser device

The working principle of the instrument has been already introduced briefly in chapter 3.2.1.2 and the references for detailed descriptions have been provided.

Figure 80 LISST Portable XR (http://www.sequoiasci.com/product/lisst-portable-xr/)

The SSC measurement range is from 30 to 1,900 mg/l but the range is significantly affected by the mean size of the sediment. When measuring finer particles, the range drops to 30-170 mg/l. This shortcoming can be solved by a careful dilution, thus samples containing very fine particles in high concentration can also be analysed. Beside the basic equipment LISST-Portable (*Figure 80*) has an auxiliary ultrasonic. When it is used during the measurements, the PSD can be obtained more accurately (Sequoia Scientific Inc., LISST-Portable|XR). As it was mentioned before, the determination of the PSD is done by the amount of light detected on the different detector rings. The LISST-Portable|XR has 44 concentric rings thus it can provide a PSD in 44 logarithmic size classes between 0.34-500 µm (Sequoia Scientific Inc., LISST-Portable|XR. The device has inner batteries, so it easily can be used during field measurements and not only in the laboratory.

3.3.1.5 Determination of suspended sediment load

Temporal variation

Based on the checked and/or corrected turbidity time series and the analysis of the calibration data, the relationship between turbidity (indirect) and suspended sediment concentration can be determined, so the temporal variation of suspended sediment concentration can be assessed. Two methods are presented in the followings.

Probe coefficient

The probe coefficient (k_s) comes from the ratio of the analytically determined suspended sediment concentration (s_k) and suspended sediment concentration calculated from turbidity (s_s), that is: $k_s=s_k/s_s$. The factor is calculated for each available sample. For the time where no coefficient is available, linear interpolation is performed between two consecutive values. This time series is then multiplied with the turbidity data to get a time series of concentration close to the sensor.

Probe curve

This method is based on the regression analysis of measured turbidity values and related concentration measurements (SSC of the water sample). Different regression equations can be parametrized for different water regimes (e.g. rising and falling limb of a flood). The method is suitable for those gauging stations and/or water regimes where the correlation for the calibration (turbidity – concentration) is strong.

Cross-sectional distribution

Multipoint sampling and its combination with ADCP measurements is presented in the followings.

Analysis based on multipoint measurements

Using this method, the cross-sectional distribution of suspended sediment concentration is approximated based on single-point concentration (water samples) and velocity measurements. The product of the coherent velocities and concentrations gives the specific sediment discharge (g/sm^2) in the vicinity of the sampled points. The total sediment load comes from the integration of this product along the whole cross-section (kg/s) or (t/year). The interpolation of such discrete data means the summation of the areas of triangular, rectangular and trapezoid objects (*Figure 81*). The calculation of vertical and cross-sectional specific sediment loads is presented below.

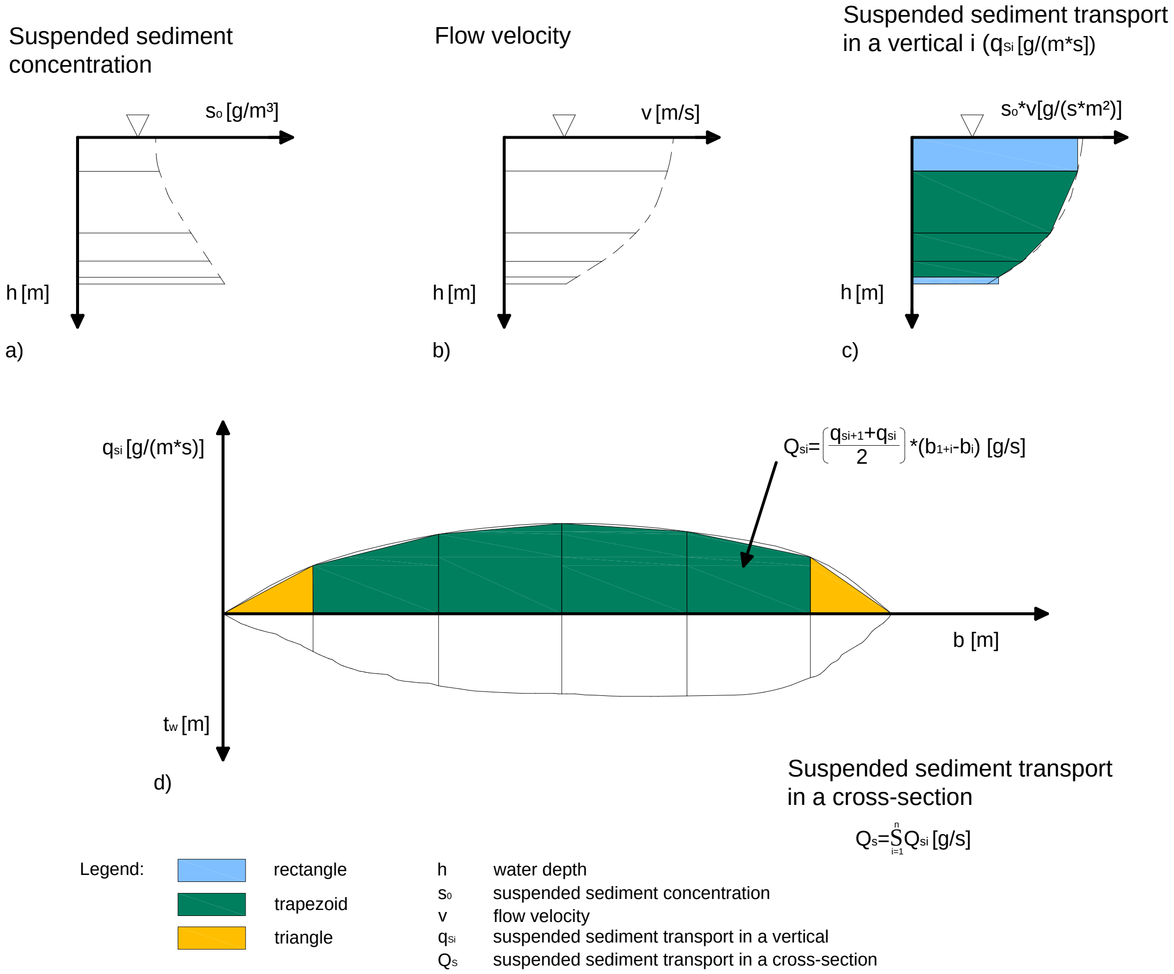


Figure 81 Cross-sectional analysis based on conventional multi-point sampling. (after BMLFUW 2008; 2017 and DVWK 125, 1986).

1. Prior the calculation of the sediment yield, general data regarding the measurements and the laboratory analysis of the samples have to be logged into the measurement protocol (Table 31, letterhead).

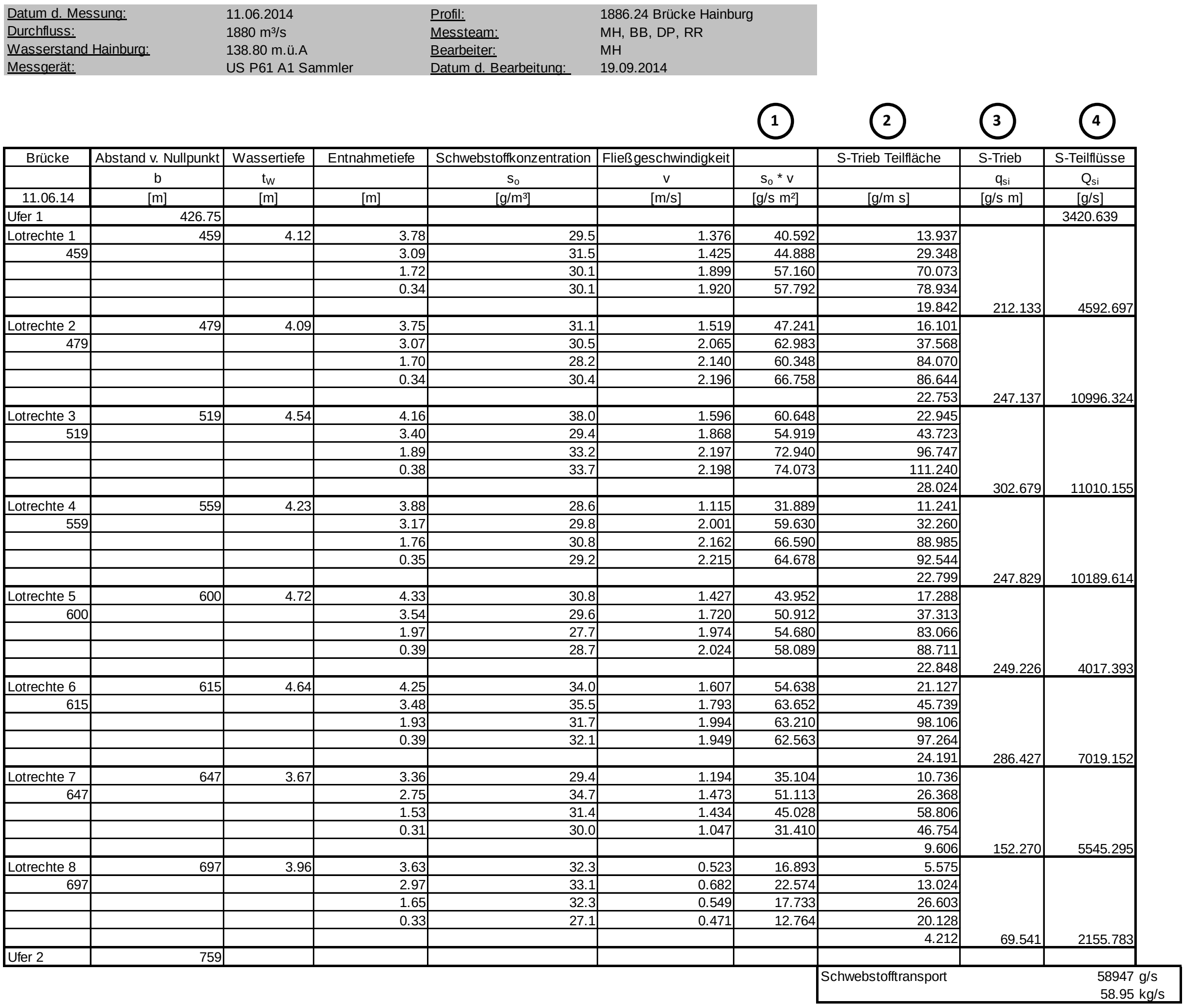
   The following information should be indicated: time and location of measurement, stage, applied devices, measurement team and evaluation.

2. The ID of the sample, the horizontal distance of the vertical from the reference point (either side of the bank), the total depth in the vertical, the distance of the sampled

point from the surface, the flow velocity and the sediment concentration in the sampled point is logged into the measurement protocol (*Table 31*).

3. The product of velocity (v) and sediment concentration (s_0) (specific discharge, ($g/(s\cdot m^2)$)) is calculated for every point. The calculated values are integrated along each vertical separately; the numerical integration is done with the trapezoid rule (green areas in *Figure 81*), while the areas close to the surface and the bed, where no measurements are available are approximated with rectangles (blue areas in *Figure 81*). The specific load in the vertical is the sum of these areas (g/m·s).
4. The total suspended sediment load comes from the width-wise integration of the vertical-wise specific discharges, which is the lower half of *Figure 81*. At the bank, the load is zero, so the two sections close to the bank are approximated with triangles, (yellow areas in *Figure 81*), while the rest is approximated as trapezoids (green in *Figure 81*). The sum of the areas gives the total suspended sediment load in the verticals (Q_s (kg/s)).

Table 31 Measurement protocol for suspended sediment load (IWHW/BOKU)



Datum d. Messung:	11.06.2014	Profil:	1886.24 Brücke Hainburg
Durchfluss:	1880 m³/s	Messteam:	MH, BB, DP, RR
Wasserstand Hainburg:	138.80 m.ü.A	Bearbeiter:	MH
Messgerät:	US P61 A1 Sammler	Datum d. Bearbeitung:	19.09.2014

						①	②	③	④
Brücke	Abstand v. Nullpunkt	Wassertiefe	Entnahmetiefe	Schwebstoffkonzentration	Fließgeschwindigkeit		S-Trieb Teilfläche	S-Trieb	S-Teilflüsse
	b	t_W		s_o	v	$s_o * v$		q_{si}	Q_{si}
11.06.14	[m]	[m]	[m]	[g/m³]	[m/s]	[g/s m²]	[g/m s]	[g/s m]	[g/s]
Ufer 1	426.75								3420.639
Lotrechte 1	459	4.12	3.78	29.5	1.376	40.592	13.937		
459			3.09	31.5	1.425	44.888	29.348		
			1.72	30.1	1.899	57.160	70.073		
			0.34	30.1	1.920	57.792	78.934		
							19.842	212.133	4592.697
Lotrechte 2	479	4.09	3.75	31.1	1.519	47.241	16.101		
479			3.07	30.5	2.065	62.983	37.568		
			1.70	28.2	2.140	60.348	84.070		
			0.34	30.4	2.196	66.758	86.644		
							22.753	247.137	10996.324
Lotrechte 3	519	4.54	4.16	38.0	1.596	60.648	22.945		
519			3.40	29.4	1.868	54.919	43.723		
			1.89	33.2	2.197	72.940	96.747		
			0.38	33.7	2.198	74.073	111.240		
							28.024	302.679	11010.155
Lotrechte 4	559	4.23	3.88	28.6	1.115	31.889	11.241		
559			3.17	29.8	2.001	59.630	32.260		
			1.76	30.8	2.162	66.590	88.985		
			0.35	29.2	2.215	64.678	92.544		
							22.799	247.829	10189.614
Lotrechte 5	600	4.72	4.33	30.8	1.427	43.952	17.288		
600			3.54	29.6	1.720	50.912	37.313		
			1.97	27.7	1.974	54.680	83.066		
			0.39	28.7	2.024	58.089	88.711		
							22.848	249.226	4017.393
Lotrechte 6	615	4.64	4.25	34.0	1.607	54.638	21.127		
615			3.48	35.5	1.793	63.652	45.739		
			1.93	31.7	1.994	63.210	98.106		
			0.39	32.1	1.949	62.563	97.264		
							24.191	286.427	7019.152
Lotrechte 7	647	3.67	3.36	29.4	1.194	35.104	10.736		
647			2.75	34.7	1.473	51.113	26.368		
			1.53	31.4	1.434	45.028	58.806		
			0.31	30.0	1.047	31.410	46.754		
							9.606	152.270	5545.295
Lotrechte 8	697	3.96	3.63	32.3	0.523	16.893	5.575		
697			2.97	33.1	0.682	22.574	13.024		
			1.65	32.3	0.549	17.733	26.603		
			0.33	27.1	0.471	12.764	20.128		
							4.212	69.541	2155.783
Ufer 2	759								

Schwebstofftransport	58947 g/s 58.95 kg/s

ADCP measurements

The main idea behind the estimation of suspended sediment concentration from ADCP measurements is that the backscattered signal strength and the suspended sediment concentration is strongly correlated. The backscattered signal strength is a function of the amount of suspended matter in the water column (the more suspended sediments are in the water, the stronger the backscattered signal is). In order to determine the relationship, simultaneous ADCP measurements and water samplings are necessary. After determining the SSC of the water samples, the regression analysis of the coherent concentrations and signal strengths can be done, with which the relationship can be formed. Using this relationship, the total cross-sectional distribution of suspended sediment concentration can be approximated from the ADCP measurements (*Figure 82*).

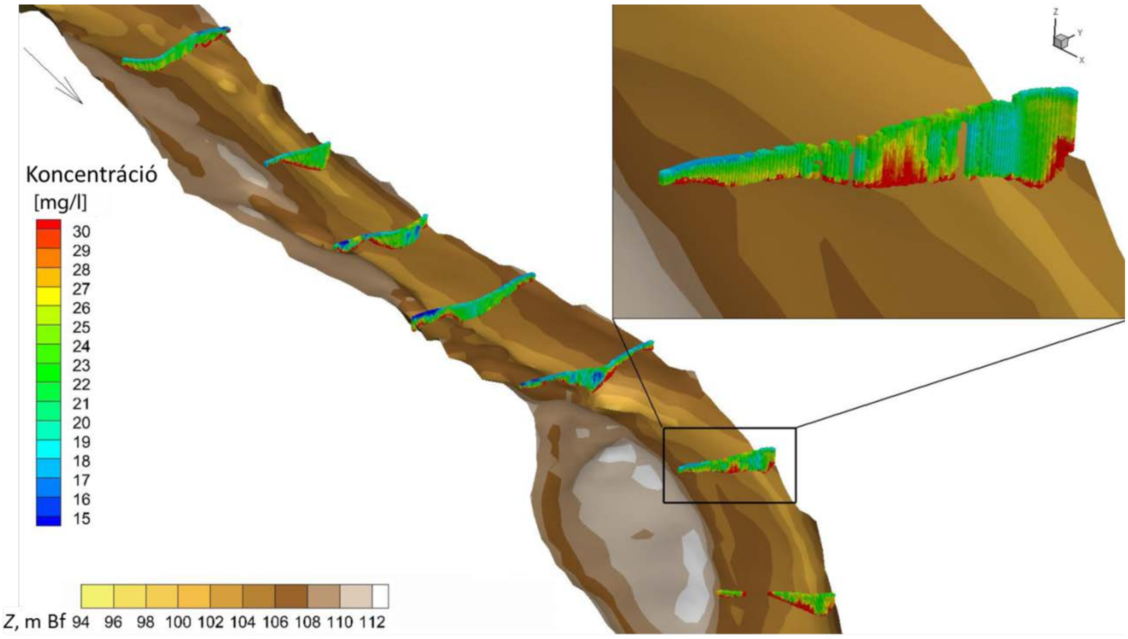


Figure 82 Cross-sectional distribution of suspended sediment concentrations, calculated from ADCP measurements (source: SEDDON II AT-HU Interreg project).

A brief theoretical description is given in the following, introducing the main steps of the estimation procedure and the parameters, playing a role in the physical processes (taken from Baranya and Józsa, 2013).

In contrast with flow velocity measurements, where the frequency of backscattered sound is postprocessed to determine three-dimensional velocity data, the strength of the reverberated sound is analysed when assessing SSC. The relationship between SSC and the so-called relative acoustic backscatter (*RB*) can be expressed as (e.g. Gartner, 2004):

$$\mathrm{SSC} = 10^{(\mathrm{A}+\mathrm{B}\cdot\mathrm{RB})} \tag{8}$$

The relative backscatter is the measured acoustic backscatter corrected for transmission losses in units of dB. Following Thevenot et al. (1992) the RB can be derived from

$$\mathrm{RB} = \mathrm{RL} + 2 \cdot \mathrm{TL} \tag{9}$$

where RL is the reverberation level and 2·TL is the two-way transmission loss, both expressed in dB. *A* and B in the first equation are empirical parameters that can be derived from known SSC and RB data pairs using e.g. least squares fitting, this is why concurrent calibration data is necessary.

Based on the sonar equation (Urick, 1983) the reverberation level (RL) is

$$\mathrm{RL} = \mathrm{SL} - 2 \cdot \mathrm{TL} + \mathrm{TS} \tag{10}$$

where SL is the source level (the sonar transmits the signal with this strength), whereas TS is the target strength of suspended sediment, which is a function of particle shape, size, rigidity, and acoustic wavelength. In the sonar equation all terms are in dB. When measuring with an ADCP the reverberation level comes from

$$\mathrm{RL} = \mathrm{K_c}(\mathrm{E} - \mathrm{E_r}) \tag{11}$$

where K_c is the received signal strength indicator scale factor, E is the echo strength (in counts) measured by the ADCP and E_r is the reference level for echo intensity (in counts), i.e. the echo baseline value when no signal is present. K_c is a conversion factor from instrument counts to echo intensity which is instrument-specific and temperature dependent (DRL Software Ltd, 2003). It can be estimated using the following formula:

$$\mathrm{K_c} = \frac{127.3}{\mathrm{T_e} + 127.3} \tag{12}$$

where T_e is the real-time temperature of the amplification circuits in °C. It generally has a value between 0.35–0.55 (Deines, 1999). The ADCP reference level E_r is the thermal noise of the amplifiers, which is transducer-specific as well as sensitive to temperature (DRL Software Ltd, 2003) and can be measured in the field. The term ‘transmission loss’ consists of losses accounted for by spherical spreading of the beam (first term on the right side) and losses due to absorption (second term):

$$\mathrm{TL} = 10 \cdot \Psi \cdot \log(\mathrm{R}) + \alpha * \mathrm{R} \tag{13}$$

where R is the slant range from transducer head to measured bin (in meters), while α is a coefficient describing the absorption of energy by water (α_w) and attenuation from suspended sediments (α_s), i.e. $\alpha = \alpha_w + \alpha_s$ (all in dB/m). When calculating the effect of spherical spreading close to the transducer, a near-field correction factor ψ has to be introduced, according to Downing et al. (1995). This correction can be calculated based on the so-called critical range $R_{critical,}$ where $R_{critical} = \pi a_t^2/\lambda$. Here a_t is the transducer radius in cm, and λ is the acoustic wavelength. The correction factor for near-field spreading loss is:

$$\Psi = \frac{[1 + 1.35Z + (2.5Z)^{3.2})}{[1.35Z + (2.5Z)^{3.2})} \tag{14}$$

where Z equals to R/ $R_{critical}$. In this study, the above presented correction factor was used for near-field calculations of spreading losses. For the estimation of energy dissipation by absorption in the water the formula of Schulkin and Marsh (1962) can be used as follows:

$$\alpha_w = 8.687 \frac{3.38 \cdot 10^{-6} \cdot f^2}{f_T} \tag{15}$$

where f is the instrument frequency, and f_T is the so-called Relaxation Frequency, both in Hz. The latter depends on the water temperature, T (in °C) as:

$$f_T = 21.9 \cdot 10^{\left(6 - \frac{1520}{273+T}\right)} \tag{16}$$

Attenuation from suspended sediment (α_s) is caused by both scattering and absorbing the energy. It is shown that energy dissipation depends mainly on particle size and sound frequency (DRL Software Ltd, 2003), and under certain conditions one or both of them can be neglected.

Substituting the above detailed terms into Eq. (8) the following relation can be written:

$$SSC = 10^{A + B(K_c(E - E_r) + 2(10 \cdot \log(R) + \alpha \cdot R))} \tag{17}$$

Here, echo intensity (*EI*), slant distance (*R*) and reference level (E_r) can be measured with ADCP, K_c and α are estimated, whereas *A* and *B* parameters can be derived with e.g. least squares fitting, if complementary SSC data are available.

There are two widely used commercial software, which apply the above theoretical background and enable the determination of the suspended sediment load based on ADCP measurements:

- ViSea Aqua Vision (http://aquavision.nl/services/sediment-monitoring/)
- Sediview (http://www.drl.com/drl_software/drl_software.html)

Calculation of average cross-sectional concentration from single-point turbidity measurements

The idea behind this method is to find correlation between cross-sectional averaged (calculated form multi-point samplings and/or ADCP measurements; for details see previous sections) suspended sediment concentrations (s_m) and a single-point sediment concentration measured in a fix point, preferably near the bank (s_k). In order to set up such relationships, both values have to be measured simultaneously in during different water regimes. Having sufficient data pairs, the relationship can be formed, from which the temporal variation of the cross-sectional mean suspended sediment concentration can be continuously approximated from near-bank turbidity measurements.

Assessment of suspended sediment transport

The total suspended sediment load can be calculated as the product of the cross-sectional average SSC (see previous section) and the actual discharge (Q_s (kg/s)). Continuous discharge measurements (e.g. approximated by a rating curve) coupled with calculation of average sediment concentration as mentioned before, provide the opportunity to assess the temporal variation of suspended sediment transport in a cross-section, from which the total sediment mass ($V_{s,m}$ (kg) or (t)) can be approximated with an integration over time.

3.3.2 Bedload

3.3.2.1 Monitoring

Regarding the transport of the bedload, two schools can be distinguished. From the Eulerian view, the bedload is assessed in a cross-section with direct or indirect methods such as the geophone, sediment sampler or the bedload trap. These measurement methods can provide the specific or total yield of sediments along with their spatial and temporal variation (Habersack et al., 2012). On the contrary, the Lagrangian approach studies the movement of individual particles in the flow field. Active and passive tracking techniques are available for the investigation of these stochastic processes (Habersack, 2003; Phillips and Jerolmack, 2014), which offers the quantitative determination of various parameters e.g. initiation of the bedload, the path of the particles, the total transported length, individual paths, resting phases or the sediment layer thickness (Hassan and Ergenzinger, 2003; Habersack et al., 2012; Liedermann et al., 2013, Lajeunesse et al., 2017).

Bedload parameters

The following bedload sediment related parameters should be determined when dealing with bedload transport:

- specific bedload transport (kg/ms)
- bedload transport (kg/s)
- bedload mass (kg)
- grain size distribution of the bedload
- initiation of bedload transport
- spatial and temporal variability

Additional parameters that should be measured for later use of the measured bedload are:

- flow velocity
- bed material at the measurement site
- discharge and water level (stage)

The specific bedload transport (q_b) is the sediment flux projected to unit cross-sectional width. By integrating (summing) this value over the whole active cross-section, the total bedload transport (Q_b) is calculated. The integration of Q_b over time gives the total amount of bedload transported (bedload transport) through the cross-section ($V_{b,m}$) in the time interval used for integration.

Bedload grains being a mixture of particles of different sizes, can be well characterized with grain size distribution, which can be determined via sieving. The sieving results are usually presented in a graphical form of a summation function or can be described with a characteristic grain size.

The initiation of the bedload transport is usually defined as a discharge or water stage during which the bedload grains get into motion.

Due to the temporal variation of the water regime, bedload transport rates also show high temporal and spatial variations as well.

Monitoring methods and strategies

In terms of larger rivers, such as the Danube, the assessment of the bedload transport can be performed with bedload samplers deployed from a bridge or a vessel. The measurement device/method has to be chosen with respect to the actual type of sediment movement (particle size and transport intensity) and flow conditions. The opening of the sediment sampler must be larger than the largest bedload grains, moreover, their saltation height and distance also have to be taken into account (DVWK 127, 1992). Further the mesh or wire frame size must be adequate for the sediment in transport. It should be small enough to capture the relevant sizes, but large enough to prevent it from clogging.

Some of the potential operation errors and some ways to avoid them are listed below.

1. The initial effect: Slow touchdown of the sampler onto the river bed, opening of the sampler intake after positioning on the river bed.
2. The gap effect: Sampler design, control with video camera
3. The blocking effect: Correct mesh size, correct size of the sampler intake, video control
4. The scooping (shovelling) effect: Use of stayline / sounding weight / anchor and a tether line or increase the weight of the sampler; avoid ship movement
5. The subsidence effect: Metal or plastic plate under the sampler intake to reduce the pressure towards the river bed; video control
6. The overfilling effect: Reduce the sampling time; larger sampling basket
7. The orientation effect: proper balancing of the sampler; give the sampler time to adjust to the direction of the near bed flow velocity – avoid too fast lowering

In general, observe the behaviour of your sampler and evaluate the sampled bedload material during measurement, to see if any of the above-mentioned problems is occurring.

For further details, see the point “Sampler operation: Measurement errors”.

Bedload sampling has to be repeated several times per year under different flow conditions (stage). The whole discharge range from low flow to high flow conditions has to be sampled to be able to calculate a reliable estimate of the bedload transport and to avoid extrapolation into those unmeasured regions (the question marks in *Figure 83*).

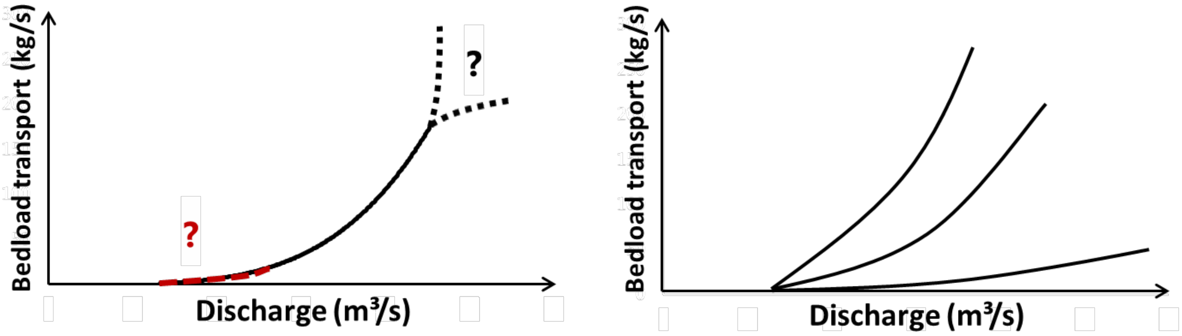


Figure 83 Left: Sample the whole discharge range to avoid extrapolation of the rating curve into unknown regions; Right: Assess if bedload relation is changing. (IWHW/BOKU)

Strong bedload transport – flow discharge relationship can only be expected in rivers, where the long-term balance of sediment transport is steady. Due to different external effects (e.g. hysteresis of rating-curves, bed armouring, etc.) measurements usually show large deviations, thus the required relationship is not evaluated as an explicit curve, rather a band for which a balancing function can be applied (DVWK 127, 1992). In case of larger rivers, usually, these are the only reliable measurements regarding the bedload transport, hence sufficiently high number of samplings (performed at different flow conditions) can be used to assess the relationship between discharge and sediment flux for long-term analysis (e.g. calculation of total mass per year) (Habersack et al., 2009). It is further advisable to evaluate from time to time if a bedload-discharge relation has to consider changes in transport patterns, due to other external effects (*Figure 83* – right panel) (Aigner et al., 2017).

3.3.2.2 Measurement methodology

Measurement with bedload sampler

Bedload measurements with a mobile bag sampler are conducted either at several measurement verticals in the cross-section (cross-section measurement) or can be repeated at one single vertical (permanent measurement). Cross-section measurements enable the determination of the total bedload transport in cross-section. Permanent measurements are used mainly to measure and analyse the temporal variability of the specific bedload transport. This means they are also a good tool to get an idea about the optimal sampling period and the number of samples per vertical at a specific measurement site.

Demands regarding the sampling

Generally, for a bedload sampler to operate properly it must be used within the range of conditions it was designed for. This is necessary to achieve meaningful results. Additional requirements regarding the sampling are:

- Calibration coefficient to correct the sampled rate to the actual rate
- Sampler intake large enough to catch the coarse particles
- Mesh size small enough to catch the fine particles
- Sampler volume large enough to cover transport fluctuations or easy handling of the sampler for frequent sampling
- Heavy sampler that rests stable on the river bed or use of tetherlines in combination with a sounding weight / anchor; avoid ship movement
- Sampling over the whole active width to avoid extrapolation
- Appropriate number of sampling verticals to capture the cross-sectional variability of the bedload transport

- Sufficient number of sampling points resp. duration in one vertical to capture the temporal variability of the bedload transport
- Sufficient mass of the collected bedload sediment for the subsequent sieve analysis; remark: this might not always be achievable in gravel bed rivers due to low transport rates resp. time constraints during the measurements

Equipment necessary for measurement with bedload sampler and the process of the sampling is described in the following.

Required equipment

Tools and equipment necessary for the bedload sampling:

- Suitable bedload sampler (e.g. *Figure 84* and *Figure 85*)
- crane truck, trailer and reel
- clean, closable sample containers (adequate in size for the samples material)
- waterproof marker for labelling
- stopwatch
- measurement protocol
- toolbox
- security equipment (helmet, visibility vest)

Optionally:

- container (for intermediate storing)
- waterproof video camera

Figure 84 Cross-sectional Bedload samplers: Károlyi-type sampler (left (picture: Haimann / IWHW-BOKU); modified BfG sampler (right (picture: Liedermann / IWHW-BOKU)

Figure 85 Basket samplers – from left to right: Sampler in use by the VUVH (SK) and sand bed sampler in use by NIHWM (RO (pictures: Gmeiner / IWHW-BOKU)

Methodology of bedload sampling

The following steps have to be conducted when sampling bedload:

1. The following data have to be noted into the measurement protocol (*Figure 87* and *Figure 88*) at the beginning of the measurement:

   Type of measurement; employed measurement device with its relevant dimensions (e.g. size of the opening of the device; date; measurement crew; location of measurement (name of the river, river km, competent water directory, country); project; where from the device is lowered (bridge/vessel); simultaneous measurements (e.g. discharge, suspended sediment load); coordinate system; if possible: water stage; discharge; water temperature; turbidity; time of measurement; measured stage at the neighbouring gauging stations.

2. Bedload samplings have to be conducted in multiple (equidistant) verticals per cross-section. If possible, all areas have to be covered (*Figure 86*) with the measurements where bedload transport is expected (e.g. in the proximity of river training works such as groins). If bedload transport differs strongly between two verticals it is advisable to insert an additional vertical to achieve a higher accuracy.

   The number of verticals which are necessary strongly depend on the cross-sectional variation of bedload transport. Sand bedded rivers are often active over the full width, were as in a gravel bed river often just a part of the river width is active. If the active area is unknown more verticals (approx. 10 - 20) are needed and if the active area is known less verticals (approx. 5 - 7) are needed (Emmett, 1980; Edwards and Glysson, 1999; Gaweesh and Van Rijn, 1994; Gomez and Troutman, 1997; Kleinhans and Ten Brinke, 2001; Frings and Vollmer, 2017).

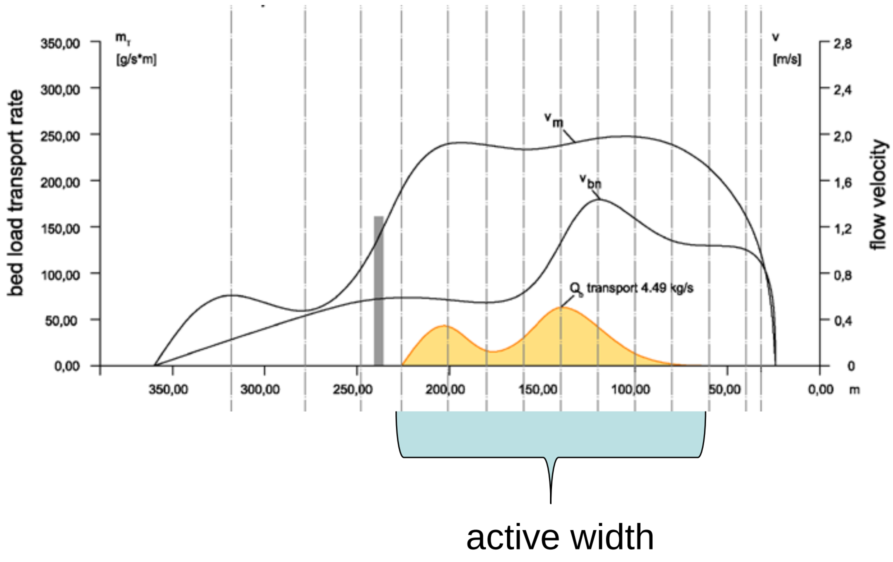


Figure 86 Example of the active width covered with a cross-section wise bedload transport measurement; joint measurement at the Danube in Bad Deutsch-Altenburg, Austria (IWHW/BOKU)

3. The sampler is lowered with a crane and/or a reel to the river bed. Sampling time have to be chosen with respect to the spatial variability of the bedload transport, however, too long sampling time results in the overfilling of the sampler, which is to be avoided. In case of low water condition, a single measurement of 15 minutes could be sufficient, while in case of larger discharges, the sampler should at least be lowered three times per vertical (approx. 3 x 5 minutes), especially when the measurement time needs to be reduced. If the sampled mass in one point differs strongly it is advisable to repeat the sampling more often.

   Duration of the sampling is measured with a stopwatch and the sampling time starts when the sampler touches the river bed and stops when the sampler is raised from the river bed.

4. The collected samples are emptied into the designated containers. Check if the mesh of the sampler is clean and not clogged, else clean it. If possible, take a photo of the sample (including a ruler as size reference). Containers should be clean and closable. The following information are marked on the containers: location of measurement, vertical, distance from the null-point of the cross-section (e.g. left bank), date and time, sample ID and duration of sampling.

   As far as possible, the taken samples should be poured into the designated containers as soon as possible. All the collected material has to be carefully taken out of the sampler. In case of larger samples, it is possible, that the sample has to be poured into a collector container first, and then to the designated containers. In these cases, material loss can occur, which should be avoided.

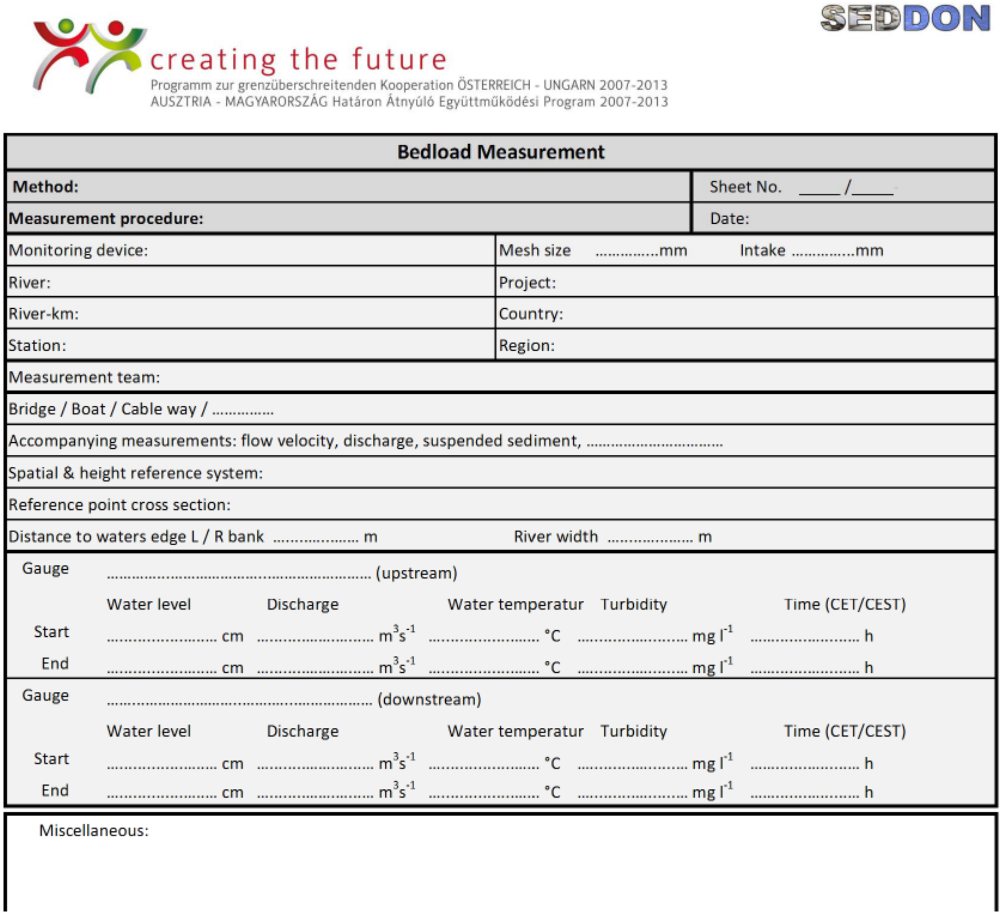
5. The location of the vertical (ID of the vertical), time of the sampling, duration of the sampling in seconds and ID of the samples have to be logged in the measurement protocol.

6. The previous steps are repeated for all verticals.

7. After the measurement, the following data (if known) is to be noted into the measurement protocol:

   water stage, discharge, water temperature, turbidity, time of the measurement and measured stages at the neighbouring gauging stations.

8. The collected samples are later analysed in laboratory conditions after drying. First the samples are weighed and then the grain size distribution of the samples is determined via sieving.



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SEDDON

Bedload Measurement

Method:	Sheet No. _____ / _____
Measurement procedure:	Date:
Monitoring device:	Mesh size ....mm Intake ....mm
River:	Project:
River-km:	Country:
Station:	Region:

Measurement team:

Bridge / Boat / Cable way / ....

Accompanying measurements: flow velocity, discharge, suspended sediment, ...

Spatial & height reference system:

Reference point cross section:

Distance to waters edge L / R bank .... m River width .... m

Gauge .... (upstream)

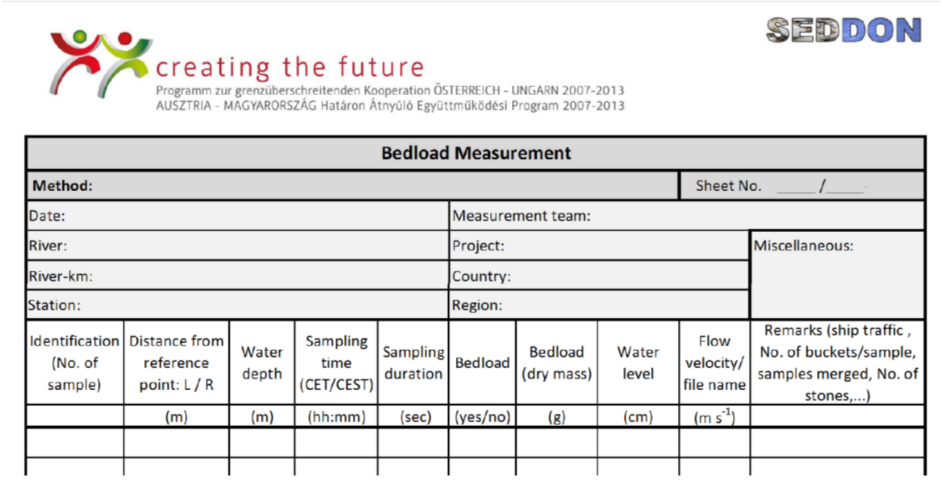
	Water level	Discharge	Water temperatur	Turbidity	Time (CET/CEST)
Start	.... cm	.... m^3s^{-1}	.... °C	.... $mg\ l^{-1}$	.... h
End	.... cm	.... m^3s^{-1}	.... °C	.... $mg\ l^{-1}$	.... h

Gauge .... (downstream)

	Water level	Discharge	Water temperatur	Turbidity	Time (CET/CEST)
Start	.... cm	.... m^3s^{-1}	.... °C	.... $mg\ l^{-1}$	.... h
End	.... cm	.... m^3s^{-1}	.... °C	.... $mg\ l^{-1}$	.... h

Miscellaneous:

Figure 87 Measurement protocol template for bedload measurements: Summary table (SEDDON, 2014)



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SEDDON

Bedload Measurement

Method: Sheet No. ____/____

Date:	Measurement team:		
River:	Project:	Miscellaneous:	
River-km:	Country:		
Station:	Region:		

Identification (No. of sample)	Distance from reference point: L / R	Water depth	Sampling time (CET/CEST)	Sampling duration	Bedload	Bedload (dry mass)	Water level	Flow velocity/ file name	Remarks (ship traffic , No. of buckets/sample, samples merged, No. of stones,...)
	(m)	(m)	(hh:mm)	(sec)	(yes/no)	(g)	(cm)	(m s^{-1})	

Figure 88 Measurement protocol template for bedload measurements: Measurement table (SEDDON, 2014).

3.3.2.3 Evaluation

Laboratory analysis

The analysis of the bedload samples is performed through sieving. Test sieving should be performed prior the analysis, in order to determine the appropriate set of sieves (applied grain sizes). The smallest sieve sizes should also determine based on the net resp. wire mesh size of the sampler. As a result of the sieving, the sampled sediments can be ordered into different size ranges determined by the selection of sieves. Based on the mass of material in the different size ranges, the grain size distribution curve can be determined. The largest characteristic particle size (D_{max}) also gets evaluated through the sieving process. Regarding the details of the sieving procedure we recommend the consultation of one of the various national resp. the international standard on particle size analysis.

Required equipment

The followings are required for the determination of the gran size distribution curve:

- weight with precision of 0.1%
- round hole or square hole sieves in psi or half psi units e.g. with the following: 0.125 m, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, 31.5 mm, 45.3 mm, 63 mm
- further sieves if necessary
- sieving machine (*Figure 89*)
- collecting pot
- Sieve protocols

Figure 89 Sieving machine (IWHW/BOKU).

The sieving procedure

The sieving of the dried sample material is done as follows:

1. Bedload samples are dried until constant mass, and then each sample is weighted before sieving, to reduce the error of a potential mass loss during the sieving procedure.
2. If necessary, merge samples from the same vertical to meet the mass criteria (usually based on the largest particle in the catch) for obtaining a representative grain size distribution.
3. The empty sieves are weighed
4. The sampled material is sieved through the selected series of sieves (manually or with sieving machine). Depending on the sieving machine the samples might need to be split into subsamples. The sieving time usually takes approx. 10 minutes, based on the composition and amount of the sample.
   Particles smaller 0.5 mm often need external help for proper sieving, which can be done with a fine brush or else wet sieving needs to be applied.
5. After sieving the sediment retained and the sieve are weighed
6. The sum of these weights (excluding the sieve weights) and plus the mass retained in the pan under the last sieve cannot differ from the weight of the sample determined in point 1.
7. Determination of the size and weight of the largest particle (D_{max}).

Evaluation of sieving results

The evaluation of the sieving results is as follows:

1. The ratio (%) of the mass of the material gathered on each sieve and the total mass is calculated.
2. The grain size distribution curve (*Figure 90*) comes from the cumulating of these consecutive ratios. The results are plotted on an x-wise semi-logarithmic coordinate system, where size class is the x-axis. The curve shows the percentage finer (the proportion of the sample (mass) that fell through each sieve (size class)).
3. Calculation of the characteristic grain sizes (e.g. D_{10}, D_{16}, $D_{20,}$ D_{30}, D_{40}, D_{50}, D_{60}, D70, D_{80}, D_{84}, D_{90}). Percentage finer is used to describe the characteristic grain sizes, usually presented as D_{xx}, with xx denoting an integer between 1 and 99. D_{10} for instance denotes the grain size in mm at a percentage finer than 10%. The calculation is performed in a semi-logarithmic space.

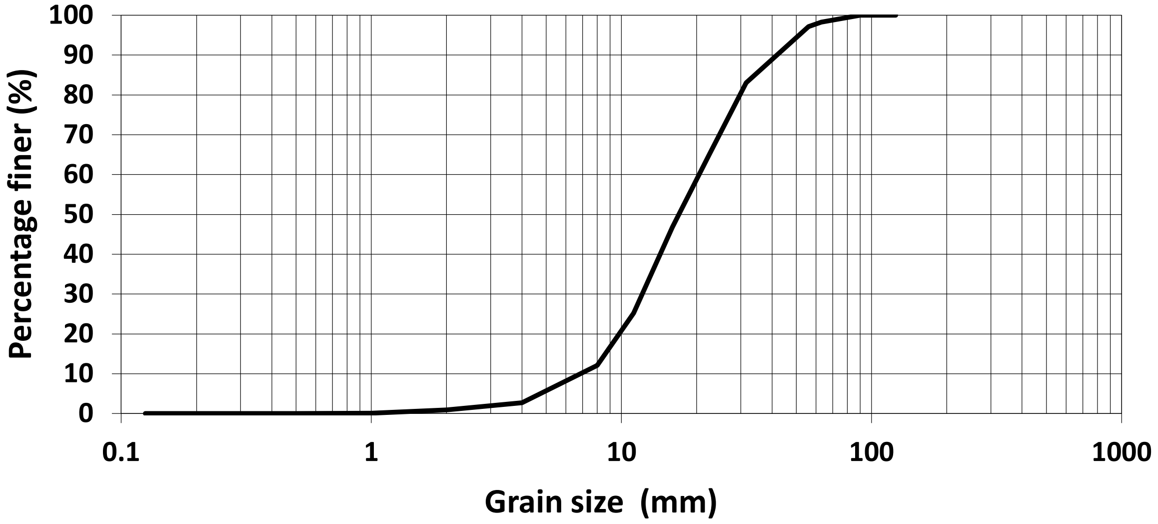

Figure 90 Grain size distribution from the joint measurement at the Danube in Bad Deutsch-Altenburg, Austria (IWHW/BOKU)

Determination of bedload sediment yield

Bedload transport expresses the amount of bedload transported through a selected cross-section (flux) over unit time, which can be determined based on the weight of the samples, sample duration, the width of the sampler, a calibration coefficient for the sampler and the distance between the measured verticals (*Figure 91*). The specific bedload discharge is calculated for each of the assessed verticals as the ratio of the weight of the sample and the duration of the sampling. Having calculated these values for all of the verticals, the cross-sectional distribution of the specific bedload transport is determined. Integrating this function over the whole cross-section, the total bedload transport can be determined (kg/s).

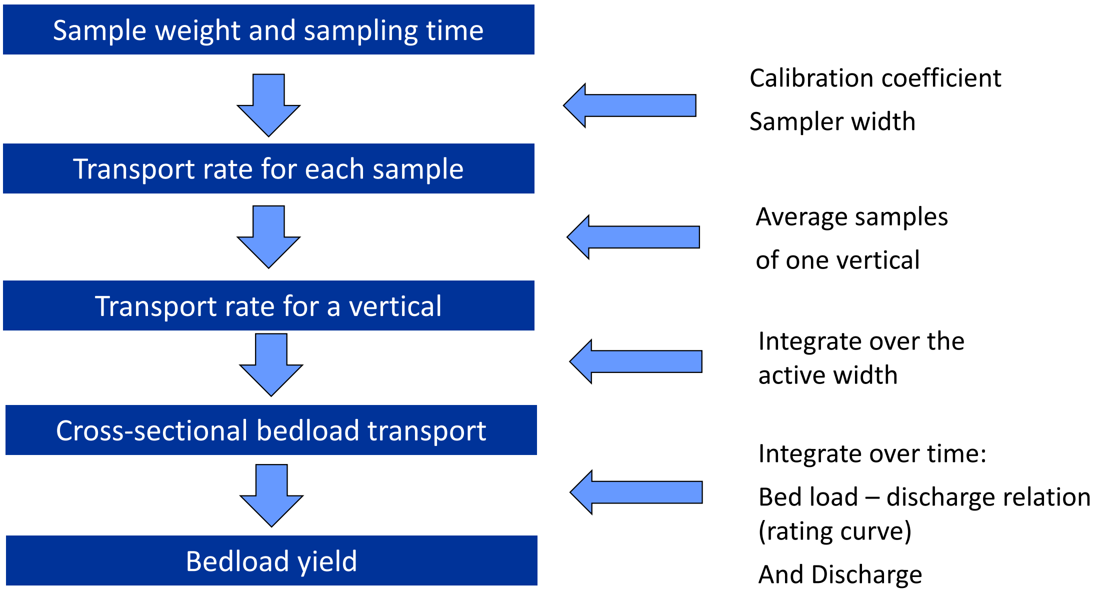

Figure 91 Steps to calculate the bedload transport and the bedload yield from a cross-sectional bedload measurement. (IWHW/BOKU)

Determination of specific bedload transport

The determination of the specific bedload transport in a vertical is as follows:

1. Prior the calculation of the sediment load, general data regarding the measurements and the laboratory analysis of the samples have to be noted into the analysis protocol.

   The following data have to be noted: date, location, discharge, water stage, applied measurement device, measurement crew, date of laboratory analysis and the name of the analyser.

2. The ID of the sample, the location of the verticals (distance from reference point), total water depth, duration of the sampling and total mass of the samples have to be logged into the evaluation protocol.
3. The mass of the samples has to be divided by the sampling time
4. Apply the calibration coefficient to each sample
5. For each vertical, the values calculated in the previous point is averaged for, which gives the specific bedload transport projected onto the width of the opening (b) of the sampler [kg/sb].
6. Dividing by the width of the sampler intake the specific bedload transport is calculated for each vertical (kg/sm).

Determination of total bedload yield

The total bedload transport in a cross-section is calculated as follows:

7. The cross-sectional distribution of the specific bedload transport can be plotted as a function of the distance from the reference point (e.g. left bank) (kg/sm) (*Figure 92* – middle).
8. The total bedload transport is calculated as the numerical integration of this discrete function (specific bedload transport) over the whole active width of the cross-section. If not, the complete active width was measured the start point of the active area needs to be approximated. Ideally, the number of sampled verticals is sufficient to give a good approximation of the cross-sectional distribution of the sediment transport.
9. If available also the depth averaged and the bottom near flow velocity should be indicated in the plot.
10. The area below the curve (*Figure 92* – middle, sand coloured graph) shows the actual bedload transport (g/s) or (kg/s), which is a function of discharge and water stage.
11. The calculated total bedload transport is noted into the evaluation protocol.

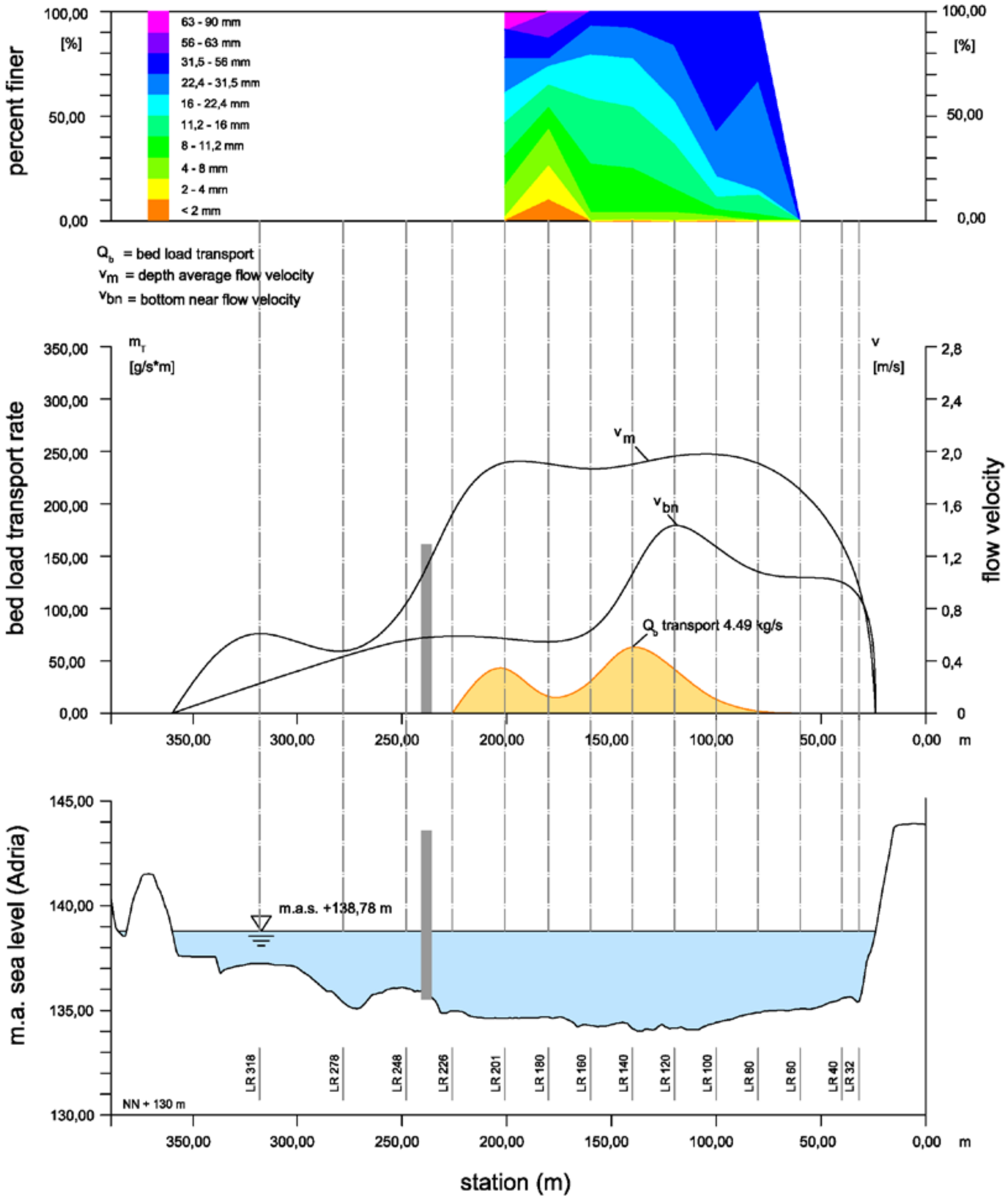

Figure 92 Cross-sectional distribution of hydromorphological parameters; the joint measurement at the Danube in Bad Deutsch-Altenburg, Austria (IWHW/BOKU); source of the bathymetry: viadonau

Determination of bedload yield

The previously presented bedload sampling method cannot provide with transient information, hence the variation of the bedload transport with discharge resp. stage has to be estimated with a bedload rating curve ((specific) bedload transport – discharge regression relationship).

1. Measured (specific) bedload transport values are paired with the discharge at the time of measurement. The paired values can be assessed performing a regression analysis, and their relationship can be described with a fitted function (e.g. power function) (*Figure 93*).

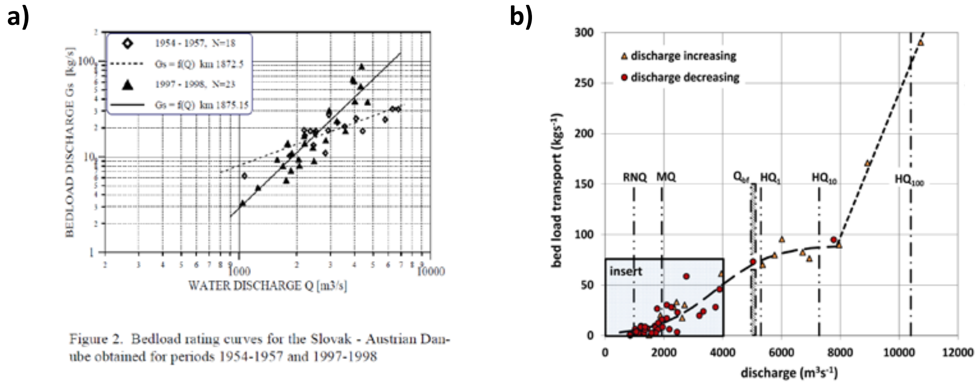

Figure 93 Two examples of bedload rating curves (bedload –discharge relation) from the Danube. a) Slovak-Austrian Danube (Holubova et al,. 2004); b) Austrian Danube Bad Deutsch-Altenburg (Liedermann, et al., 2017)

According to Gaeuman et al. (2015) the most common form used for sediment rating curves a simple power function:

$$Q_b = aQ^b \tag{18}$$

where Q_b is the predicted (specific) sediment transport, Q the water discharge and a and b are adjustable parameters.

Alternatively, some investigators prefer to fit a three-parameter model (shifted power function) that integrates a water discharge threshold (Q_c) below which no sediment transport occurs:

$$Q_b = a(Q - Q_c)^b \tag{19}$$

A not so common form is the sigmoid function used by Liedermann et al. (2017). This form was used to account for the deviation of the bedload transport from a power function when the discharge is above bankfull and utilized for the calculation of a rating curve.

2. Using the discharge time-series and the previously determined function in the investigated cross-section, a bedload transport time-series can be derived.
3. Integration (summation) of the bedload transport time series over time gives the total amount of bedload transported through the cross-section over the integrated time period, i.e. the bedload yield.

4 Proposal for a harmonized transnational sediment monitoring network

4.1 Introduction

The goal of this chapter is to give concrete recommendations for the establishment of an improved sediment monitoring system for the Danube River and the most important tributaries, which would be based on a harmonized methodological approach. In such a way, a data collection protocol could be set up, which ensures comparable sediment datasets all along the Danube River, with an adequate spatial and temporal resolution on a long-term. The improved sediment monitoring system could contribute to the establishment of a high-quality sediment database, which could be utilized in scientific research, in practical river engineering activities as well as in policy making related to the use of Danube River.

As shown in the previous chapters, there is already a quite high number of existing sediment monitoring stations along the Danube and the important tributaries. It was, however, also shown that due to the very heterogeneous monitoring methods (e.g. in terms of sampling method, sampling frequency, laboratory analysis of sediment samples, sediment load calculation methods) the available information about the sediment transport also shows reasonable uncertainties, as well as discrepancies at places, as discussed at the data assessment related report of this project. Also, a significant issue is the sediment monitoring at reservoirs. Despite the fact that there are numerous hydropower plants in the Upper-Danube (Germany, Austria, Slovakia) and two large reservoirs in the Lower-Danube (Iron Gate I and II at the common Romanian-Serbian reach), the quantification of the sediment trapping effect of the reservoirs is still not straightforward, due to insufficient quantity and/or quality of sediment data. Furthermore, the influence of the tributaries in the Danube River could be better revealed, if the stations close to the tributary inflows were systematically chosen. Most of the monitoring stations collect information on suspended sediment concentration, however, bedload transport at the same time is rarely monitored. From the available datasets it could be shown, that the contribution of bedload to total load is quite low (<10% on average), but on the other hand, the reach scale morphological changes are rather resulted by the rearrangement and transport of the coarse material. Therefore, the monitoring of bedload transport also calls for significant development.

4.2 Objectives of an improved Danube-wide sediment monitoring network

There are several reasons to establish a monitoring network for the sediment transport. As to the Danube River Basin, an increasing discrepancy between sediment surplus, e.g. reservoir sedimentation, and sediment deficit, e.g. river bed and coastal erosion, can be observed. This change of the sediment balance leads to an increase of flood risk, reduction of navigation possibilities and hydropower production and deterioration of the ecological conditions in the Danube River. The lack of coordinated transnational sediment management has been recognized by the First and Second Danube River Basin Management Plan (DRBMP) in 2009 and 2015, respectively. The DRBMP evidently indicates the need for a change and calls for a relevant, concrete answer. As shown in the Annex of this report, first examples of basin-wide sediment management plans for European rivers exist, for example for the Sava. However, despite the fact that the Danube plays an essential role in the economy and the society of the Danube Region, a sediment management strategy for the Danube River does not exist. It is clear that sediment transport along the Danube River has an immediate impact on water management activities and flood risk. There is a strong need to bridge knowledge gaps and to improve sediment management in order to directly contribute to strengthening transnational water management and flood risk prevention.

The sediment monitoring network is one of the key elements of a basin-wide sediment management plan. The main objective of a sediment monitoring network is to collect quantitative information of the amount of the transported solid material in the rivers through continuous sampling. In this proposal, we only focus on the routine monitoring, but not the expeditionary, specific measurement campaigns. Also, despite the fact that sediments act as a potential sink for many hazardous chemicals (Brils, 2008) and as such, have a direct influence on aquatic environment, sediment quality related monitoring is not proposed herein, however, there must be a certain overlapping, or even integration with such a system.

Besides the general issues related to the transport of sediments mentioned above, the sediment monitoring network in the Danube River has to be able to provide quantitative information in order to assess the following issues:

- Spatial and temporal variation of sediment transport both on short and long term
- Influence of hydropower plants on the sediment regime, i.e. sediment trapping influence of reservoirs and downstream erosion effects
- Influence of floodplains on the sediment regime, i.e. floodplain sedimentation
- Influence of tributaries on the sediment regime, i.e. the amount of sediment input at the tributary inlets

- Changes in sediment transport due to climate change
- Coastal erosion at the Danube Delta due to the reduction of fine sediment reaching this region
- Influence of river restoration measures on the sediment regime
- Influence of population growth, land clearance and land use change, infrastructure development and resource exploitation on sediment regime
- Influence of sediment transport on natural aquatic habitats
- Influence of sediment transport on the waterways and vice versa, the influence of waterway maintenance on sediment transport
- Influence of floods on the sediment regime

Considering the goals of the sediment monitoring network, it is clear that the sediment load has to be measured with an adequate frequency and spatial density. Moreover, to ensure comparable, standard sediment datasets, a harmonized approach is crucial, which certainly requires the improvement of existing monitoring stations, as well as the setup of new stations. We tackle the following points:

- Short description of the proposed sediment monitoring stretegy
- Evaluation of the current sediment monitoring network in the Danube River and at the most important tributaries
- Recommendations for the improvement of existing sediment monitoring stations
- Recommendations for the setup of new sediment monitoring stations

4.3 Proposed sediment monitoring strategy

The currently applied sediment monitoring methods along the Danube are very heterogeneous as shown in Chapter 2. In order to ensure an intercomparable sediment dataset, provided by state-of-the-art monitoring methodologies, we propose a harmonized sediment monitoring network, where all the monitoring stations apply the same procedures, i.e., the utilized instruments use the same working principles, the measurement protocols are the same, and also the sediment load calculation methods are the same. In such a way the sediment information could be characterized with similar data quality and temporal resolution. The monitoring system has to be able to meet the requirements of the main objectives, described in Chapter 4.2.

4.3.1 Suspended sediment

The proposed monitoring strategy applies direct and surrogate technologies. The key steps and the theoretical background are described in Haimann et al. (2014) and BMLFUW (2008; 2017). This methodology enables the quantification of SSC (mg/l), SS load (kg/s), annual SS load (t/y), SS yield (t/km^{2}y) and the analysis of the particle size distributions (Suspended material parameters to be monitored in Subchapter 3.3.1.1).

The following devices are used in a combination: isokinetic point-integrating sampler, turbidity sensor as well as acoustic profilers. To measure the temporal variability of the suspended sediment transport, the turbidity sensor is installed which continuously records the turbidity at one point in the cross-section (near the river bank). The sensor has to be calibrated based on water samples taken at the sensor. The sampling frequency of the water samples is dependent on the suspended sediment concentration and varies from once a week up to several times a day during flood events.

Additionally, the distribution of the suspended sediment concentration in the cross-section (spatial variability) is considered. To establish the cross-sectional mean concentration, the multi-point method is applied (Cross-sectional measurement methods in 3.3.1.3). Using this method, the suspended sediment concentration and flow velocity are measured in various verticals and different depths (see examples for the sampling instruments in *Figure 94*). The sampling is undertaken up to 3-5 times a year using an isokinetic suspended sediment sampler. The flow velocities are measured by using acoustic profilers, i.e. an ADCP (Acoustic Doppler Current Profiler), acoustic point velocimeters, i.e. ADV (Acoustic Doppler Velocimeter) or current meters.

Figure 94 Measurement setup for suspended sediment sampling.

To calculate SS load, first the turbidity data has to be calibrated by the water samples. To calibrate the turbidity data, two different methods can be applied, which can also be used in combination. The first method calculates a correction factor between turbidity data and water samples for each occasion when water samples are collected. By linear interpolation between these time steps the correction factor is calculated for each turbidity value. The second method uses a simple linear regression (cross-sectional characteristic) between turbidity data and the calibration samples to convert the turbidity data into a record of SSC close to the sensor.

Furthermore, the SS transport and mean SS concentration in the cross-section is determined using the multi-point method, where the SS concentration and flow velocity are measured in various verticals and different depths. Alternatively, the SSC in the cross-section is calculated from the ADCP backscatter signal combined with water samples using the sonar equation. As the ADCP simultaneously measures the flow velocity, the SS transport and mean concentration in the cross-section can be calculated. Calculation methods are more detailed in 3.3.1.4.

The laboratory analysis contains concentration measurement and particle size distribution analysis as well. The suspended sediment concentration is determined by vacuum filtration (see 3.3.1.4). The PSD analysis is done with a sieving instrument and a sedimentation instrument (see 3.3.1.4). It is important to note that PSD analysis should not be operatively carried out, since the necessary infrastructure for such an analysis could be cost demanding. However, a reasonable number of water samples, representative for different flow regimes, is recommended to assess even at external laboratory facilities, occasionally.

The technical descriptions about the instruments to be utilized within the monitoring strategy introduced above are detailed in Chapter 3.2 (Physical samplers as the isokinetic sampler in 3.2.1.1, Optical tools as OBS, ABS in 3.2.1.2 and Acoustic devices as ADCP in 3.2.1.3).

4.3.2 Bedload

The proposed monitoring methodology for the quantification of bedload transport applies physical bedload traps. Even though there are several innovative, surrogate techniques are under development for bedload transport measurements, in practical applications it is still the conventional sampling, which can be easily implemented and assessed.

To determine the cross-sectional bedload transport, the samplings can be performed with bedload samplers deployed from a bridge or a vessel. The measurement device/method has to be chosen with respect to the actual type of sediment movement (particle size and transport intensity) and flow conditions. The opening of the sediment sampler must be larger than the largest bedload grains, moreover, their saltation height and distance also have to be taken into account (DVWK 127, 1992). Further the mesh or wire frame size must be adequate for the sediment in transport. It should be small enough to capture the relevant sizes, but large enough to prevent it from clogging. For the necessary equipment, see Chapter 3.3.2.2. Using the proper sampling device, the local, specific bedload transport can be measured. Performing samplings in several verticals (5-10 along the cross-section), repeating the sampling at least three times in a vertical, the integration of the specific bedload transport will result in the cross-sectional bedload transport. The recommended procedure for the samplings together with measurement protocol samples is detailed in Chapter 3.3.2.2.

The evaluation of the bedload samples has to be performed in laboratory, where the grain size distribution together with the mass of the samples can be determined. After calculating the specific bedload transport for the single verticals, and integrating them over the cross-section, the cross-sectional bedload transport can be calculated. However, the determination of bedload yield, i.e. the total amount of bedload transported through a cross-section in a given time frame requires the knowledge of the relationship between the flow discharge and the bedload transport, i.e. the bedload rating curve. Different kinds of empirical curves can be set up based on measured bedload transport values for which, together with the bedload evaluation methods Chapter 3.3.2.3 provides concrete suggestions.

4.3.3 Practical recommendations

4.3.3.1 Suspended sediment monitoring

As to suspended sediment, the most relevant elements of the proposed system are:

- Optical or acoustic backscatter sensors (OBS or ABS), that are able to measure point SSC with high temporal resolution (e.g. 15 minutes),
- Isokinetic samplers that are needed to calibrate the OBS or ABS and to perform multipoint physical sampling to provide cross-sectional data,
- Acoustic velocity profilers or point velocimeters to provide flow velocity information for sediment load calculations,
- Laboratory facilities for SSC analysis (filtering, drying, weighing) and PSD analysis or laser diffraction based instruments.

Regarding the set-up, the operation and the maintenance of the monitoring stations, the following practical issues shall be considered:

Optical or acoustic sensors:

- The instruments shall be able to measure suspended sediment concentration up to 50 g/l, to cover extreme flood situations,
- Optical sensors are more sensitive to changes in particle shape, composition or water colour compared to acoustic sensors,
- Optical sensors need cleaning, and therefore access is needed for operation,
- Sensor should be deployed in a protective pipe to decrease exposition to flow, ice, debris, …
- Sensors need power, but generally batteries or solar panels can provide adequate electricity,
- Operation needs manpower, e.g. for maintenance and data download from logger, however, this can also be managed remotely if the instrument is connected to an online monitoring system,
- Manpower is also needed to perform calibration samplings close to the sensor.

Isokinetic sampling:

- A measurement vessel, a trailer or a suitable frame, mounted on a bridge is necessary for the sampling,
- Manpower is needed for the measurement campaigns, such as boat driver and sampling personnel,
- The sampler has to be deployable in flood conditions, which must be considered when choosing the appropriate sampler (volume, weight).

4.3.3.2 Bedload monitoring

- Capture the temporal and spatial variability in the measurements
- Suitability of the bedload sampler must be ensured
- Defined hydraulic and sampling efficiency
- Cover full range of discharges (from initiation of motion to floods)
- Establishment of rating curves, i.e. Q-Q_{BL}, τ- Q_{BL} relationships
- Surrogate techniques (e.g. acoustic based, sonar, tracer) can contribute → integrated approach
- Sample bed material at the bedload monitoring site
- Define standard bedload monitoring approach for the gravel bed and sand bed reaches of the Danube
- Integrate bedload monitoring data into National Hydrographic Data Bases and guarantee quality and access for practical application to improve planning of engineering measures

4.4 Proposed improvements in the sediment monitoring network

However, to realize this ambitious plan of a harmonized monitoring network, significant improvements are necessary in several countries, either with upgrading existing stations and/or setting up new ones. In the following, we shortly introduce the proposed methodology both for suspended sediment and bedload transport monitoring, then we address where and what sort of improvements are needed, country by country.

As shown in Chapter 2, the sediment monitoring methodologies can significantly vary along the Danube River country by country, or even within countries. Moreover, besides the sediment sampling methods, the laboratory analysis techniques as well as the sediment transport calculation methods can differ. When suggesting improvements for the sediment monitoring methodologies along the Danubian countries, the limitations and uncertainties of the currently applied methods have to be known.

4.4.1 Evaluation of the existing monitoring stations

Our proposal was to define a classification of the different methods, considering the applied technique, the sampling frequency, if the provided sediment data is directly measured or estimated based on statistics, also taking into account the experiences of sediment experts. Instead of quantifying the uncertainty in the datasets, a qualitative evaluation will be performed, eventually providing three classes for the sediment data quality. The assessment is carried out both for suspended sediment and bedload monitoring.

4.4.1.1 Suspended sediment

In order to implement the classification on the data quality the applied methods have been overviewed. As already presented, the following field measurement techniques are currently applied at the institutes responsible for the sediment data collection:

1. Calibrated Optical Backscatter Sensor (OBS) based continuous (15 min sampling frequency) suspended sediment concentration monitoring (in one point of the cross-section), together with isokinetic physical sampling and acoustic suspended sediment concentration mapping over the whole cross-section (complementary multipoint measurements). The multipoint measurements are performed 1-5 times a year and are used to calibrate the near-bank suspended sediment concentration with the cross-sectional mean concentration. The daily suspended sediment load is calculated using the calibration curves.

2. Automatized pump sampling or bottle sampling with a flow discharge dependent sampling frequency (from 6 times a day to 3 times a week) in one point of the cross-section. When estimating the suspended sediment load, it is assumed that the measured sediment concentration is representative for the whole cross-section.
3. Isokinetic, depth-integrating physical sampling on daily basis in one point of the cross-section. The sampling is performed in a carefully chosen vertical, which provides suspended sediment concentration representative for the whole cross-section. The daily suspended sediment load is calculated based on the product of the measured concentration and the actual flow discharge.
4. Physical, non-isokinetic sampling on daily basis in one point of the cross-section, with complementary multipoint measurements 4-6 times a year. The multipoint measurements are used to calibrate the near-bank suspended sediment concentration with the cross-sectional mean concentration. The daily suspended sediment load is calculated based on the product of the mean cross-sectional concentration and the actual flow discharge.
5. Physical, non-isokinetic sampling on daily basis in one point of the cross-section. When estimating the daily suspended sediment load, it is assumed that the measured sediment concentration is representative for the whole cross-section. The daily sediment load is calculated based on the product of the concentration and the actual flow discharge.
6. Physical, non-isokinetic multipoint sampling 4-6 times a year. A regression curve is set up for the mean cross-sectional concentration and the flow discharge, then the monthly suspended sediment load is calculated based on this regression and the characteristic flow discharge.

As to the suspended sediment concentration determination methods, there are basically three methods applied by the responsible institutes:

1. Filtering method: the suspended sediment concentration is determined by vacuum filtration using cellulose acetate or cellulose nitrate filters with pore diameters of 0.45 µm. Before filtering, the sample volume is determined. The whole sample volume is filtrated. After filtering, the filter and contents are removed and dried for nearly 2 hours at 105° C. The filter, including the content, is weighed with an analytical balance of an accuracy of ± 0.1 mg. The suspended sediment concentration is calculated by dividing the filter content by the volume of the sample.
2. Evaporation method: This method uses a sample of 10 l. After a settling process (at least a few days long), 1-1.5 l of concentrated sediment is decanted and transported into the sediment laboratory. After 24 hours of sediment settling, a sample of 100 ml of sediment is taken. The settling process is repeated for another 24 hours, and then all of the sediment dried on 105°C for 4 hours and weighed. The sediment

concentration is calculated on the basis of known volume of sample and the weight of sediment. For the PSD analysis a sedimentation instrument and a sieving instrument is used.

3. Turbidity method: a portable turbidity meter provides the concentration values of the water samples directly in mg/l. To perform the calibration of the equipment, a blank sample of distilled water is used. Then the specific glass of the equipment is filled with the collected water sample and the SSC will be given. The water sample is shaken well before being placed in the equipment for reading. After the first reading, the glass is shaken, rotated 180 degrees and the reading is repeated. At least two readings are performed, and the final value is obtained as the arithmetic mean of the readings.

The decisive parameter at the classification of the above presented methods was the sampling frequency. Sediment data collected on a daily basis or even with higher frequency (the optical sensors collect data in every 15 minutes) provides high time resolution datasets and contributes to a more accurate sediment load calculation on a long term, compared to monthly or less frequent data collection frequency. With daily datasets it is ensured that the widest range of flow regimes is measured in contrast with less frequent sampling, when extreme situations can be easily omitted. Also, the influence of dynamic flood waves, and the hysteresis effect can be captured with frequent sampling. Besides the sampling frequency, the cross-sectional representativeness of the collected data was taken into account, because at many stations the near-bank data is used without cross-sectional calibration, which inherently decreases the accuracy of the calculated sediment load. It was also considered if the calculated sediment load is based on measured data or derived from statistical analysis, where the former is considered to be more accurate.

As to the laboratory analysis, the experiences suggest that the filtering method provides more reliable data compared to the evaporation method. In fact, the latter can easily consist of dissolved parts, which can bias the resulted concentration values. The turbidity method can be an acceptable and straightforward manner of sample analysis, however, the proper calibration of the applied instruments is of primary importance.

Combining the above aspects, the following classification was established. In *Table 32*, the green boxes indicate the good practices of suspended sediment monitoring. The methods indicated with yellow provide less accurate datasets and improvement is suggested for those. The improvements, as will be discussed later on, should focus on the sampling technique (upgrade from non-isokinetic to isokinetic), the cross-sectional calibration and/or the applied laboratory analysis method. The methods indicated with red boxes need significant improvement. At these monitoring stations, the sediment load calculation is based on a regression analysis, set up from data collected in the past. This method, therefore, does not consider the long-term temporal changes of the sediment transport dynamics and neglects the unsteady effects of dynamic flood waves.

Table 32 Classification of suspended sediment monitoring methods

	Filtering method	**Evaporation method**	**Turbidity method**
Continuous point OBS (4/hour) + complementary multipoint sampling with isokinetic physical and acoustic methods (1-5/year)	GE: Wasserwirtschaftsamt Donauwörth, Wasserwirtschaftsamt Ingolstadt, Federal Waterways and Shipping Administration (WSV), Federal Institute of Hydrology (BfG), Federal Waterways Engineering and Research Institute (BAW) AT: viadonau (Aschach Strombauleitung, Hainburg Straßenbrücke), Hydrographic Service of Upper Austria (HD OEE) (Schärding, Wels-Lichtenegg, Steyr (Ortskai))		
Automatized pump sampling in a point (Flow-dependent, from 3/week to 6/day)	AT: Verbund Hydro Power (VHP) (Aschach, Abwinden-Asten, Wallsee-Mitterkirchen, Altenwörth, Greifenstein, Freudenau)		
Automatized pump sampling in a point (Flow-dependent, from 3/week to 6/day) plus Continuous point OBS (4/hour)	AT: Verbund Hydro Power (VHP) (Ybbs-Persenbeug)		
Physical point sampling (Flow-dependent, from 3/week to 4/day)	AT: viadonau (Engelhartszell, Linz, Stein-Krems, Angern)		

	Filtering method	Evaporation method	Turbidity method
Physical sampling, isokinetic sampling in a vertical (depth-integrating) Flow-dependent, from 1/day to 1+/day	SK: Water Research Institute Bratislava (VUVH) (Bratislava)		
Physical point sampling 1/day + complementary physical, multipoint sampling (1-3/year)		RS: Jaroslav Černi Institute for the Development of Water Resources (JCI) CR: Meteorological and Hydrological Institute of Croatia (DHMZ)	RO: National Administration "Apele Romane" (ANAR)/River Basin Administrations
Physical point sampling 1/day	SK: Slovak Hydrometeorological Institute (SHMU) BG: National Institute of Meteorology and Hydrology (NIMH)		
Physical, multipoint sampling (4-6/year)	SK: Water Research Institute Bratislava (VUVH) (Devín, Medveďov Bridge, Záhorská Ves, Moravský Ján)	HU: North-Transdanubian Water Directorate (ÉDUVIZIG), the Middle Danube Valley Water Directorate (KDVVIZIG), Lower Danube Valley Water Directorate (ADUVIZIG)	

Based on this classification, in Germany and Austria (at stations where the monitoring is performed by viadonau and the Hydrographic Service of Upper Austria (HD OOE)), the suspended monitoring is done following good practices. At the remaining Austrian sites (monitoring performed by Verbund Hydro Power GmBH (VHP)), one Slovak station (monitoring performed by the Slovak Hydrometeorological Institute (SHMU)) and in Croatia, Serbia, Romania and Bulgaria, improvements are suggested. At most of the Slovak sites (monitoring performed by the Water Research Institute (VUVH)) and in Hungary, significant improvement is needed.

4.4.1.2 Bedload

Characterizing the bedload data quality is even more difficult than for the suspended sediments. There are no generally well-applicable methods, which would provide high accuracy and representative bedload data and in fact, the development of proper bedload monitoring techniques is still an active research topic. Based on the experiences of the sediment experts involved in this project it can be stated that the bedload samplings performed with well-tested, pressure difference samplers, such as the Helley-Smith or the BfG type of sampler provide reliable information in the gravel bed sections. In sandy environment, however, the bedload transport can be characterized with very complex dynamics, which can hardly be detected by physical samplers. In such conditions, the bedload transport can mainly be represented by the movement of bedforms and therefore, a bedform tracking should be used instead, or the combination of different techniques (Hoekstra et al., 2004). In case of the Danube River, currently only physical bedload samplers are applied both in the gravel and sand bed reaches.

Bedload data was provided in 5 countries: Germany, Austria, Slovakia, Hungary and Romania. The dataset provided by the German partners come from expeditionary bedload measurement campaigns and in most of the cases the data cannot be considered representative in terms of the measured flow range as high flow conditions were not sampled. Even though the sampling technique (using a BfG sampler) would suggest reliable data, an improvement of the monitoring, to cover high flow regimes, is necessary. The bedload monitoring performed in Austria is based on a well-tested methodology (using a BfG sampler) and covers wide range of flow conditions from low flow to extreme floods. This data is considered as good-quality information. However, only one monitoring station is operated and therefore only the local behaviour of the bedload transport can be assessed. The bedload data provided by Slovakian and Hungarian partners represents also a shorter reach of the Danube River. Also, the measured flow regimes do not cover high flow conditions, where most probably a significant sediment transport takes place. Furthermore, there are substantial data discrepancy issues between the datasets of the two countries, despite the fact that the monitoring stations are located close to each other. The applied monitoring methods therefore need further improvements and the data provided by the partners are questionable.

Table 33 Classification of bedload monitoring methods

Country	Applied technique	Comments
Germany	BfG sampler	Well-tested pressure-difference sampler. The measured flow range does not cover high flows. Field campaigns in high flow conditions are needed.

Country	Applied technique	Comments
Austria	BfG sampler	Well-tested pressure-difference sampler. The measured flow range covers low flow to extreme flood
Slovakia	Swiss-type sampler	Basket sampler. The measured flow range does not cover high flows. Data shows significant discrepancy with HU data. Further tests and improvement are needed.
Hungary	Károlyi-type sampler	Well-tested pressure-difference sampler. The measured flow range does not cover high flows Data shows significant discrepancy with SK data. Further tests and improvement are needed.
Romania	IMH bedload equipment	The provided data covers a wide flow range. Due to the complex nature of bedload transport in sand bed rivers, this technique might not be suitable here. Further tests and improvement are needed.

4.4.2 Improvement of existing monitoring stations

Aiming at a harmonized sediment monitoring network, we propose to upgrade the existing monitoring stations applying the same monitoring strategy, introduced above. This, however, means that at several stations, significant improvements are needed. Overall, several already existing stations in Germany and Austria are equipped with the necessary instrumentation. There are several already successfully operating monitoring stations, e.g. at Hainburg Straßenbrücke in Austria, the experiences of which can greatly contribute to the planning and implementation of the improved, integrated sediment monitoring strategy.

Also, it has to be noted that in most of the countries, the frequency of the cross-sectional, multipoint surveys, i.e. 4-6 times a year, fits well to the methodology suggested here. In most of the cases, therefore, it is rather instrumental improvement which is essentially needed, instead of the whole operative monitoring strategy.

One large group of the necessary improvements is the upgrade to an indirect optical or acoustic based backscatter sensor, which should be fixed at a certain point, e.g. at the bank, of the monitoring cross-section. Again, there are several good examples for the construction, operation and maintenance of such equipment. Moreover, these good practices are introduced in details in Chapter 3.

Regarding the multipoint surveys, which should be based on i) detailed flow measurements (using acoustic instruments) and ii) isokinetic sediment sampling, the acoustic flow measurement methods are, in fact, already available at most of the responsible institutes and are used in the daily operative work in hydrography. On the other hand, the isokinetic sampling is not generally applied so far. According to the experiences of the involved sediment experts, the disadvantage of this sort of sampler is the weight of the device, which, for instance in case of the US-P-61-A1 can be 47 kg. Due to its size, the handling of the instrument, e.g. the mounting to a small measurement vessel, can be problematic. In this regards, we also showed suitable solutions, both for deploying the sampler from a boat and from a bridge.

The laboratory analysis methods used to determine the suspended sediment concentration from the water samples are, in general, adequate, where the filtering method is used. However, at most of the responsible institutes, no particle size distribution analysis is performed, which could contribute to the better understanding of the fine sediment transport e.g. with revealing what can be the source of the sediment transported at given sections of the Danube River.

In the followings, the recommendations for the improvements will be shown for each country involving all the existing stations.

4.4.2.1 Germany

In Germany, two organizations are responsible for the sediment data collection: i) Regional water authorities (data is owned by Bavarian Environment Agency (LfU) and Bavarian Hydrological Service (GKD)), ii) Federal Waterways and Shipping Administration (WSV), Federal Institute of Hydrology (BfG), Federal Waterways Engineering and Research Institute (BAW) (data is owned by Federal Waterways and Shipping Administration (WSV). As shown above (see chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**), these two organizations apply different methods, therefore the recommendations for the improvements also differ.

Monitoring stations of Bavarian Environment Agency (LfU)

The currently applied field monitoring methods need no further improvements, however, regarding the laboratory analysis of the sediment samples, we recommend to perform Particle Size Distribution (PSD) analysis for different flow regimes.

Monitoring stations of Federal Waterways and Shipping Administration (WSV)

The following improvements are recommended:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data

- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary (acoustic) flow measurements
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.2.2 Austria

In Austria several organizations are responsible for the sediment data collection. Verbund Hydro Power GmbH (VHP) collects data at the Danube River. viadonau operates monitoring stations at the Danube River and at the tributary Morava and the hydrographic service of Upper Austria is i.a. responsible for the data collection at the tributaries Inn, Traun and Enns. The organizations apply different methods, therefore the recommendations for the improvements also differ.

In Austria, already a high number (12) of monitoring stations exists along the Danube River. Thus, it doesn’t seem necessary to have a full monitoring at all of these stations. Anyway, at least a number of three stations distributed along the Austrian Danube River should be equipped with this integrative monitoring system.

Monitoring stations of viadonau

There are two different methods applied at the viadonau monitoring stations. At Aschach Strombauleitung, Hainburg Straßenbrücke and Angern (Morava) stations, the integrated monitoring strategy is applied, which need no further improvements. On the other hand, at the stations Engelhartszell, Linz, as well as Stein-Krems, only one-point physical sampling is performed. At these stations, we suggest implementing the following upgrade:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary (acoustic) flow measurements
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

Monitoring stations of Verbund Hydro Power GmBH (VHP)

At all the monitoring stations of VHP, i.e. Donaukraftwerk Aschach, Donaukraftwerk Abwinden – Asten, Donaukraftwerk Wallsee – Mitterkirchen, Donaukraftwerk Altenwörth, Donaukraftwerk Greifenstein, Donaukraftwerk Freudenau the same methodology is used, such as automatized pump sampling. At the monitoring site Donaukraftwerk Ybbs-Persenbeug an optical sensor is installed additionally. The sediment concentration values are very sensitive to the local hydrodynamic features at the sampling site, which result at some of the monitoring stations in unreliable datasets which were not used in the project. In order to ensure good quality sediment data, we suggest implementing the following upgrade:

- Relocation of some of the existing stations for a more accurate assessment of the suspended sediment transport regime
- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary (acoustic) flow measurements
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

Monitoring stations of Hydrographic service of Upper Austria

The currently applied methods need no further improvements.

4.4.2.3 Slovakia

In Slovakia two organizations are responsible for the sediment data collection: i) Slovak Hydrometeorological Institute (SHMU) and, ii) Water Research Institute (VUVH Bratislava). Different methods are applied by the institutes, moreover, there are overlapping among the monitoring sites. At two sites, Bratislava and Medvedov, both institutes perform sediment monitoring. We recommend sharing the available sediment measurement resources and rather set up new stations, instead of duplicating sediment data. We, however, recommend improvements for both institutes at all the monitoring stations:

Monitoring stations of Slovak Hydrometeorological Institute (SHMU)

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

Monitoring stations of Water Research Institute (VUVH Bratislava)

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements

- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.2.4 Hungary

In Hungary the regional water directorates are responsible for collecting sediment data. The currently applied methods are very limited and provide uncertain quantitative information on the sediment load. At all the existing monitoring sites, we recommend the same improvements:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements
- Laboratory analysis of the suspended sediment samples, following the filtration method instead of the evaporation method, or the utilization of laser-diffraction methodology
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.2.5 Croatia

In Croatia the Meteorological and Hydrological Institute of Croatia (DHMZ) is responsible for collecting sediment data. The currently applied method requires the following improvements:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- The multipoint sampling should be performed using isokinetic sampler

4.4.2.6 Serbia

In Serbia the Jaroslav Černi Institute for the Development of Water Resources (JCI) is responsible for collecting sediment data. The data is owned by the PE Electric Power Industry of Serbia - Branch HPP Djerdap. The same methodology is used at all the monitoring stations. We recommend implementing the following improvements:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements
- Laboratory analysis of the suspended sediment samples, following the filtration method instead of the evaporation method, or the utilization of laser-diffraction methodology
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.2.7 Bulgaria

In Bulgaria the National Institute of Meteorology and Hydrology (NIMH) is responsible for collecting sediment data. The same methodology is used at all the currently operating monitoring stations. We recommend implementing the following improvements:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements
- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.2.8 Romania

In Romania the National Institute of Hydrology and Water Management of the National Administration "Apele Romane" (ANAR) is responsible for collecting sediment data. The same methodology is used at all the currently operating monitoring stations. We recommend implementing the following improvements:

- Installation of optical or acoustic backscatter sensors at the bank to provide high temporal resolution sediment concentration data
- Multipoint measurements 3-5 times a year at different flow regimes using point-integrating isokinetic sampler and complementary acoustic flow measurements
- Laboratory analysis of the suspended sediment samples, following the filtration method instead of using the turbidity sensor, since the calibration of the sensor needs careful and comprehensive data analysis procedure, involving the size of the sediment particles as well as the organic matter content

- Particle Size Distribution (PSD) analysis of suspended sediment samples for different flow regimes.

4.4.3 Set up of new monitoring stations

The improvement of existing monitoring stations will contribute to reach a higher quality of the collected sediment data, moreover, the temporal variation of the sediment regime can be more accurately assessed. However, analysing the spatial coverage of the monitoring network, it could be concluded that additional monitoring locations are needed to have a better understanding on unique local features of the sediment transport, such as the sedimentation at hydropower plant reservoirs, role of significant tributaries, and also to support future sediment data assessment activities for more reliable sediment budget calculations.

Based on the sediment data assessment performed within this project and the experiences of the involved partners, suggestions were made for new stations both in terms of suspended sediment and bedload monitoring. In general, the measurement, laboratory analysis and sediment load calculation methods presented in the previous sections are recommended for the new monitoring stations, therefore, methodological and infrastructural features will not be detailed here. Instead, the location and short explanations are listed in the following table.

Table 34 Proposed monitoring stations

Country	Name, location	Type of monitoring station	Comments
Germany	-	-	No new sediment monitoring station is proposed in Germany.
Austria	Wachau	Suspended sediment Bedload	The new station should be established in the free-flowing section at Wachau.
Austria	East of Vienna	Bedload	Set up of an additional station in the free flowing section east of Vienna about 10 km downstream of the feeding section.
Slovakia	Sturovo	Suspended sediment	Proposed new sediment monitoring station in Sturovo is close to the downstream end of the common Slovak-Hungarian river section of the Danube river. Data on SS transport from Sturovo monitoring station can contribute to improvement of overall SS budget in this river section.

Country	Name, location	Type of monitoring station	Comments
Hungary	Szigetköz region (Rajka)	Suspended sediment	The Szigetköz region, as a secondary branch system of the Danube River, can alter the sediment regime, especially during floods, when a significant amount of the total discharge is led here from Slovakia. The proposed station could support the better understanding of the role of the secondary branch system on the sediment regime.
Hungary	Esztergom	Bedload	Esztergom is located at the downstream end of the common Slovakian-Hungarian Danube reach within a transition zone, in terms of bed material. The bedload monitoring station could contribute to the better understanding of morphological changes and could support the spatial extension of the bedload budget along the Danube.
Hungary	Dunaföldvár	Bedload	Dunaföldvár is a critical section of the Hungarian Danube due to the continuous bed erosion. Bedload monitoring could support the explanation of this unfavourable process.
Hungary	Mohács	Bedload	Mohács is located close to the downstream end of the Hungarian section. Due to the clear sand bed conditions here, bedload monitoring could support the understanding of sediment transport processes in a transition zone of the river.
Serbia	Bezdan (rkm 1425.59)	Suspended sediment	A new monitoring station at the upstream end of the Croatian-Serbian section of the Danube could contribute to decrease the uncertainty in sediment data discrepancy due to the possibly different methods of the neighbouring countries (HU-CR-RS).
Serbia	Radujevac	Suspended sediment	This station would be located at the downstream side of HPP Iron Gate 2 and will contribute to the assessment of the sediment blocking effect of the reservoir
Croatia	Batina	Suspended sediment	Batina is the first hydrological station in the Danube in Croatia. It currently measures water stage, discharge and temperature. This monitoring station would be located also at the

Country	Name, location	Type of monitoring station	Comments
			upstream end of the common Croatian-Serbian section of the Danube, with Bezdan on the other side, therefore, only one of the proposed two stations should be established, either on the CR or RS side.
Croatia	Ilok	Suspended sediment	Ilok is the last hydrological station in the Danube in Croatia. It currently measures water stage, discharge and temperature. The monitoring station could decrease sediment data uncertainty at the common Croatian-Serbian section and possible data discrepancy between CR-RS sediment datasets.
Croatia	Belišće (Drava River)	Suspended sediment	The last station on the Drava before the joining the Danube. It currently measures water stage, discharge and temperature. The monitoring of suspended sediment is proposed to better quantify the influence of the Drava River on the sediment budget of the Danube.
Croatia	Bijelo Brdo (Drava River)	Suspended sediment Bedload	A station on the Drava immediately before its discharge into the Danube, under the backwater effect of the Danube. Due to strong sedimentation processes and formation of sand bars, continuous measurement of suspended sediment concentration, occasional particle size distribution of bed sediment and measurement of bedload should be established.
Romania	Turnu Magurele	Suspended sediment Bedload	This new location is located closer to the Olt River tributary inflow, than Zimnicea gauge station, therefore, a more accurate sediment budget could be set up locally. On the other hand, between Turnu Magurele and Zimnicea it is the Belene island, which is a critical area for navigation, due to frequent alluvial deposition phenomena, which could also better be assessed.
Bulgaria	-	-	No new sediment monitoring station is proposed in Bulgaria.

4.5 Danube-wide sediment data management

Sediment data are collected, stored and managed in different ways in the Danubian countries. In most of the countries, except from Germany and Austria, the sediment data is not available for public use, but is generally collected and stored by regional institutions and no data exchange is managed on a transnational level among the countries either (see the responsible institutes in sediment data management in

Table 1).

In Germany, the real-time sediment concentration values at the monitoring stations are published for selected river sections in the following webpage: https://www.gkd.bayern.de/en/rivers/suspended-sediment

In Austria, sediment data for several monitoring stations are published in the hydrographic yearbooks:
https://www.bmnt.gv.at/wasser/wasser-oesterreich/wasserkreislauf/hydrographische_daten/jahrbuecher.html

and in ehyd: https://ehyd.gv.at/

Based on the sediment data collected within this project a database has been setup, consisting of quality checked annual sediment load data for 44 stations along the Danube and 19 at the most important tributaries. The covered time period is varying, starting from 1928 at a few locations and ending with 2016 (see the relevant information on the sediment monitoring stations in the Annex). The collected data is not public but is planned to be handled by ICPDR.

As for the future sediment data management, it is questionable if it can be implemented on a transnational level in a centralized way, due to several reasons, such as data inhomogeneity, different data rights, or the amount of data. It has to be noted that there are good examples for the establishment of centralized sediment data management on river basin level, for instance, at the Sava River Basin (see ISRBC, 2015). According to the proposal of the International Sava River Basin Commission an on-line free database on sediment will be established to be implemented in a web-based application in the Sava River Basin. The Hydrological Information System of the International Sava River Basin Commission (Sava HIS) provides an adequate tool for collecting storing, analysing and reporting a sufficiently high-quality data hydrological and meteorological data, including sediment data. The implementation of SavaHIS as integrated module of the SavaGIS web application gives the data management based on GeoServer software which implements OGC standards for publishing spatial data (*Figure 95*).

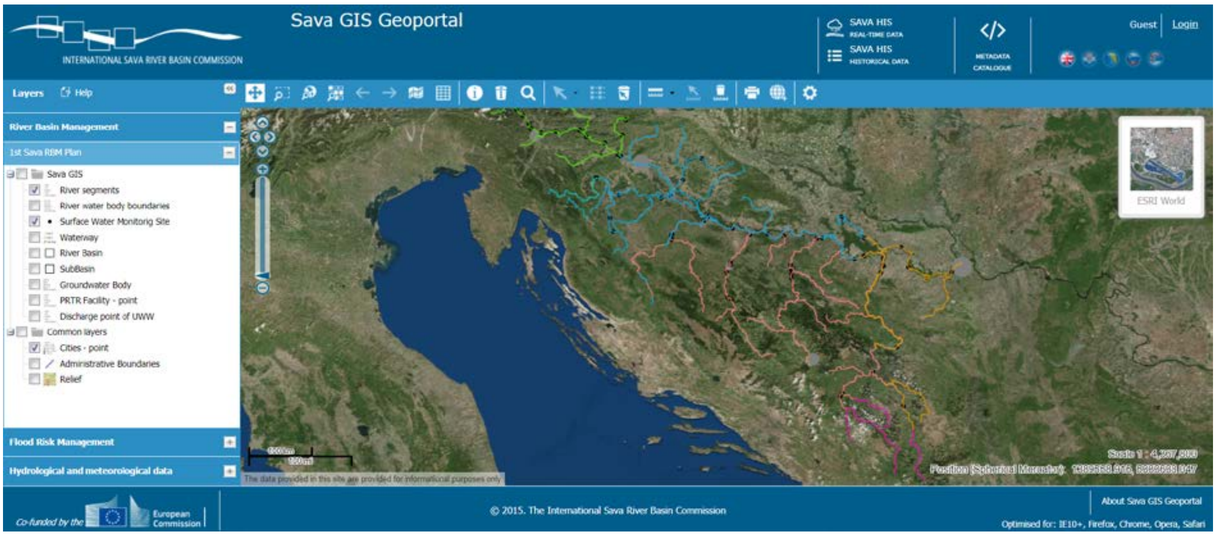

Figure 95 Screenshot from SavaGIS geoportal (http://www.savagis.org/)

No such centralized information system exists for the Danube River, however, there is currently a strong intention to setup the so-called Danube Hydrological Information System (Danube-HIS) within the DARREFORT project, implemented within the Danube Transnational Programme. The following scope was agreed on regarding the Danube-HIS: “Providing Danube basin-wide level basic hydrological and meteorological near real time data in a standard format, and, if possible, the validated long-term data series, for flood risk management or for any water related scientific activities in DRB” (Gombás, oral comm.). Also, “Danube HIS shall display data on the water level, discharge (indication value with an explanatory disclaimer), water temperature and precipitation (from the station closest to the gauging station). None of these data are mandatory, countries will submit only what is available. For water level data, the alarm degrees will be shown for comparison. The data will be shown for the Danube and its major tributaries.” (Gombás, oral comm.).

Based on this information it could be recommended to include sediment data also in the new Danube-HIS. However, in contrast with water stage and flow discharge data, the raw sediment information, such as measured concentration by a turbidity sensor, is not suitable for real-time publishing. As introduced in the chapter of good practices in sediment monitoring, there is a certain calibration and post-processing procedure for the determination of the sediment load, which is, in fact, the most relevant parameter. Accordingly, it is important to continuously perform, update and re-calibrate the sediment load calculation method and to rather publish processed data on e.g. a yearly basis in the hydrological system.

5 Recommendations for stakeholders

A list of recommendations is given in the followings to be considered when implementing the proposed improvements in terms of sediment transport in the Danube River. The points are grouped for three different levels of the potential stakeholders of the project, i.e. i) policy makers on the highest level, who are playing a major role in decision making; ii) practitioners, who are actually applying the measurements methods provided here and responsible for good quality data collection and iii) researchers, who are capable to develop innovative methods for sediment monitoring and responsible for transferring the knowledge towards the practice.

5.1 Recommendation for policy makers

- There are still several sediment data related issues to be addressed, which calls for a harmonized sediment monitoring system on a transboundary level
- This intention should be coordinated on high level (e.g. ICPDR)
- Most of the herein recommended infrastructure are already available at the relevant institutions, and only slight improvements are needed
- Mainly the improvement of already existing monitoring stations is needed
- Long-term, historical sediment data should be stored in a central database at e.g. ICPDR and should be made available for stakeholders (practitioners, administration, water managers, researchers, …)
- Recommendation on good practices in sediment monitoring should be included in a future Sediment Management Plan of the Danube
- Theoretical and practical training of sediment monitoring should be ensured
- Sediment monitoring activities during flood situations have to be implemented in water management tasks and priority should be given

5.2 Recommendation for practitioners

- Harmonized protocols along the Danube countries are expected to be implemented in sediment monitoring
- Understanding the relevance of sediment monitoring is of primary importance and can improve the quality of the measurements
- Continuous, automatized sediment monitoring greatly improves the understanding of sediment transport processes in a cost-efficient manner

- Adequate calibration of monitoring stations is of great importance, with a special attention of high-water regime and floods (planning of measurement campaigns has to be somewhat flexible)
- Calibration and, continuous validation of the monitoring stations is necessary and re-calibration might also be needed
- Qualified laboratories have to be involved in sediment analysis
- Surrogate techniques both in suspended sediment and bedload transport monitoring are increasingly developed, tested and applied in research and could be taken over (ADCP backscatter-based SSC estimation, ADCP based BL estimation, dune tracking, …)
- Well-trained personnel are crucial for performing adequate sediment monitoring → theoretical, practical training
- Automatized sediment monitoring stations, such as other hydrographic stations, need maintenance
- The establishment of sediment balance on local and regional scale should be implemented by water management institutions and relevant stakeholders (e.g. HPPs)
- River restoration measures have to be planned with the consideration of sediment transport processes on local and regional scale
- Numerical flow and sediment transport models have to be thoroughly parameterized, calibrated and validated against field data
- Involvement of researchers in the development of monitoring strategies, monitoring stations, planning and implementation of restoration measures is recommended

5.3 Recommendation for researchers

- Continuous collaboration with relevant practitioners and joint improvement of monitoring protocols have to be performed
- Development of numerical models with improved sediment transport modelling requires good quality field data
- Thorough laboratory and field testing of new sediment measurement methods are necessary
- Researchers are expected to ensure the theoretical and practical background of new monitoring methods via university curricula, workshops, field courses

List of Abbreviations

ABS	Acoustic Backscattering Sensors
ADCP	Acoustic Doppler Current Profiler
ADUVIZIG	Lower-Danube-Valley Water Directorate (Hungary)
ADV	Acoustic Doppler Velocimeter
ANAR	National Administration "Apele Romane" (Romania)
ASTM	Acoustic Sand-Transport-Meter
AT	Austria
BAW	Federal Waterways Engineering and Research Institute (Germany)
BfG	Federal Institute of Hydrology (Germany)
BG	Bulgaria
BL	Bedload
BME	Budapest University of Technology and Economics
BMLFUW	Federal Ministry of Agriculture, Forestry, Environment and Water Management (Austria)
BOKU	University of Natural Resources and Life Sciences (Austria)
BTMA	Bed Load Transport Meter
DE	Germany
DFRMP	Danube Flood Risk Management Plan
DHMZ	Hydrological and Meteorological Service (Croatia)
DRB	Danube River Basin
DRL	Dredging Research Limited
DRBMP	Danube River Basin Management Plan
DRMP	Danube River Management Plan
DSMG	Danube Sediment Management Guidance
DTP	Danube Transnational Programme
DVWK	German Association for Water Research
DWA	German Association for Water, Wastewater and Waste
DWS	Department of Water and Sanitation (South Africa)
ERDF	European Regional Development Fund
ÉDUVIZIG	North-Transdanubian Water Directorate (Hungary)
GIS	Geographic Information System
GKD	Bavarian Hydrological Service (Germany)
GPS	Global Positioning System
GSD	Grain Size Distribution
H-ADCP	Horizontal Acoustic Doppler Current Profiler
HD OOE	Hydrographic Service of Upper Austria (Austria)
HIS	Hydrological Information System

HPP	Hydropower Plant
HR	Croatia
HU	Hungary
ICPDR	Internal Commission for the Protection of the Danube River
ICPER	Internal Commission for the Protection of the Elbe River
IMH	Institute of Meteorology and Hydrology (Romania)
IPA	Instrument for Pre-Accession Assistance
IR	Infrared
ISO	International Organization for Standardization
ISRBC	International Sava River Basin Commission
IWHW	Institute of Water Management, Hydrology and Hydraulic Engineering
JCI	Jaroslav Černi Institute for the Development of Water Resources (Serbia)
KDVVIZIG	Middle-Danube-Valley Water Directorate (Hungary)
LED	Light Emitting Diode
LfU	Bavarian Environment Agency (Germany)
LISST	Laser In Situ Scattering and Transmissometry
ME	Hungarian Technical Specifications
NIMH-	National Institute of Meteorology and Hydrology (Bulgaria)
NIWA	National Institute of Water and Atmospheric Research
NRWQN	New Zealand National Rivers Water Quality Network
OBS	Optical backscattering
OGC	Open Geospatial Consortium
OVF	General Water Directorate (Hungary)
PE	Public Enterprise (Serbia)
PSD	Particle Size Distribution
RFID	Radio Frequency Identification
RHMZ	Republic Hydrometeorological Service of Serbia
RO	Romania
RS	Serbia
SHMU	Slovak Hydrometeorological Institute (Slovakia)
SK	Slovakia
SS	Suspended Sediment
SSC	Suspended Sediment Concentration
SSL	Suspended Sediment Load
SSY	Suspended Sediment Yield
USGS	U.S. Geological Survey
VHP	Verbund Hydro Power GmbH (Austria)
VUCHT	Research Institute of Chemical Technology (Slovakia)
VUVH	Water Research Institute (Slovakia)

WARM	Water and Atmospheric Resources Monitoring Program
WIFI	Wireless Fidelity
WSV	Federal Waterways and Shipping Administration (Germany)

List of Symbols

A, B	Empirical Parameters (from e.g. Least Squares Fitting on SSC-RB data)
a, b	Determined Coefficients (Slovakia)
a_t	Transducer Radius
B	Width of the Cross-section
b	Orifice Width (Austria)
c	Suspended Sediment Concentration (Croatia)
d_a	Active Layer Thickness
D_m	Mean Particle Size
D_{max}	Largest Characteristic Particle Size
D_{xx}	Characteristic Grain Size (with xx denoting an integer between 1 and 99; d_{10} for instance denotes the grain size in mm at a percentage finer than 10%)
E	Echo Strength
E_r	Reference Level for Echo Intensity
f	Instrument Frequency
f_T	Relaxation Frequency
G_s	Bedload Discharge (Slovakia)
H	Total Water Depth
h	Water Depth
K_c	Received Signal Strength Indicator Scale Factor
k_s	Probe Coefficient
m_a	Combined Mass of the Plate and the Membrane Filter (measured immediately after the drying)
m_b	Combined Mass of the Plate and the Membrane Filter with the Dry Matter on it (measured immediately after the drying)
m_T	Dry Matter Content
NTU	Nephelometric Turbidity Units
Q	Water Discharge
q_b	True Bedload Transport
q_{bs}	Measured Specific Bedload Transport
Q_s	Cross-sectional Suspended Sediment Discharge
q_{si}	Suspended Sediment Transport in a Vertical
R	Slant Range
RB	Relative Acoustic Backscatter
$R_{critical}$	Critical Range
RL	Reverberation Level
s	Width of the Opening of the Bedload Sampler
SK	Skewness Parameter (Germany)

s_k	Analytically Determined Suspended Sediment Concentration
SL	Source Level
s_m	Mean Suspended Sediment Concentration
SO	Sorting Parameter (Germany)
s_o	Suspended Matter Concentration
s_s	Suspended Sediment Concentration Calculated from Turbidity
T_e	Real-time Temperature of the Amplification Circuits
TL	Transmission Loss
TS	Target Strength of Suspended Sediment
U	Uniformity Parameter (Germany)
v	Velocity
v_a	Sediment Velocity on the Bed Surface
v_b	Actual Mean Bedload Particle Velocity
v_{BT}	Vessel Velocity Estimated by the Bottom Tracking Method
$V_{b,m}$	Cross-sectional Bedload Discharge
v_{GPS}	Actual Vessel Velocity Calculated from the Real GPS Positions
V_i	Verticals (Croatia)
v_m	Undisturbed Mean Flow Velocity
v_{ms}	Flow Velocity in the Sampler Intake
V_p	Sample Volume
V_s	Suspended Sediment Load
α	Coefficient Describing the Absorption of Energy
α_H	Hydraulic Efficiency
α_w	Absorption Coefficient (by water)
α_s	Attenuation Coefficient (from suspended sediment) (in acoustic theory)
α_s	Sampling Efficiency (in bedload calculation)
Δm	Mass of Trapped Bedload Sample
Δt	Time
λ	Porosity of the Active Layer (in bedload calculation)
ρ_s	Sediment Density
τ	Bed shear stress
Ψ	Grain Size on Base-2 Logarithmic Scale (in particle size analysis)

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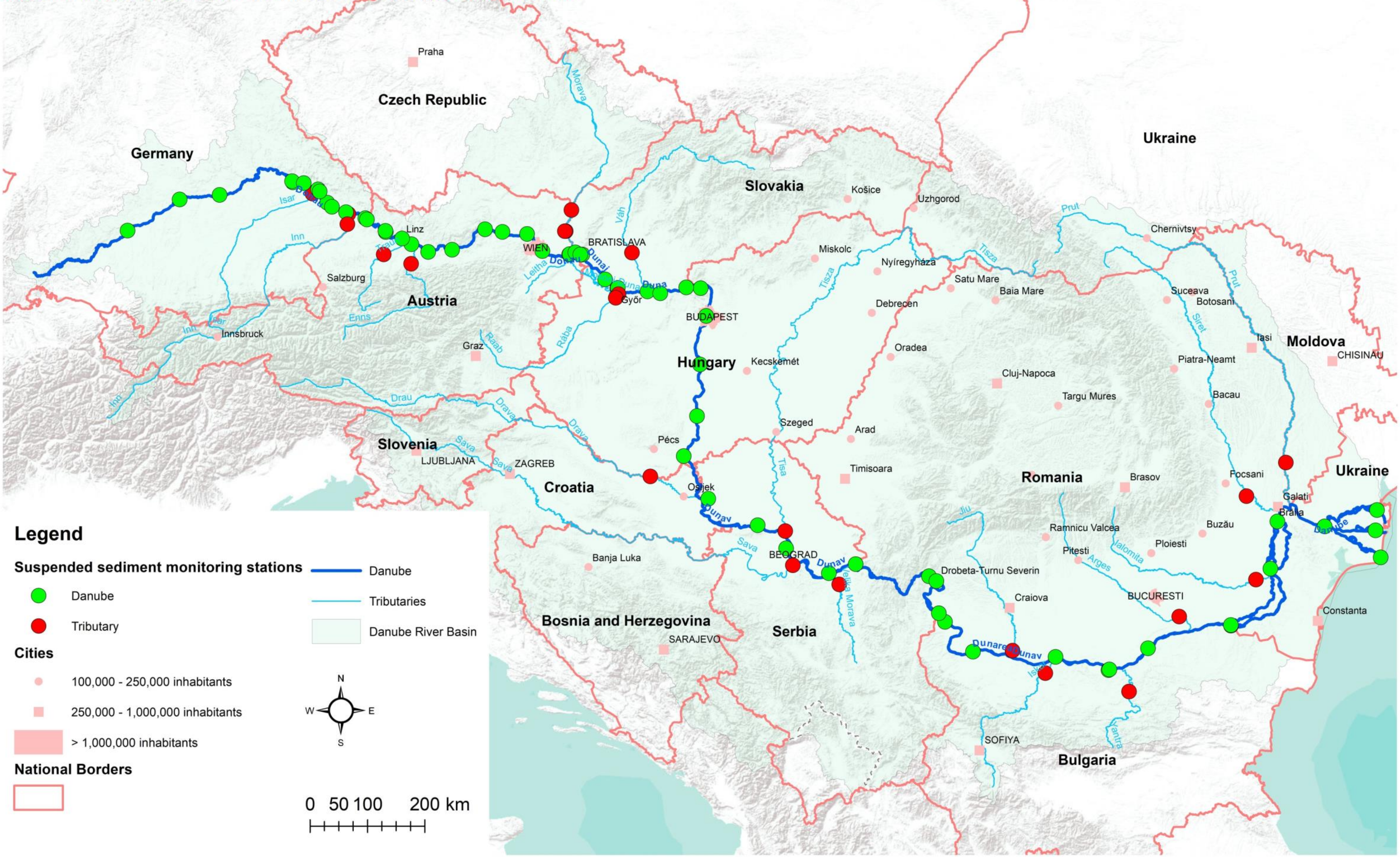
Annexes

Annex 1: Maps of the sediment monitoring system in the Danube River and its most important tributaries

Suspended sediment monitoring stations along the Danube and at the most important tributaries (closest to the confluence)

Map 1

SUSPENDED SEDIMENT MONITORING STATIONS



http://www.interreg-danube.eu/approved-projects/danubesediment

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

Budapest, April 2018

Interreg
Danube Transnational Programme
DanubeSediment

Bedload monitoring stations along the Danube and at the most important tributaries (closest to the confluence)

Map 2

BEDLOAD MONITORING STATIONS

http://www.interreg-danube.eu/approved-projects/danubesediment

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

Budapest, April 2018

Interreg
Danube Transnational Programme
DanubeSediment

Suspended sediment monitoring stations along the Danube and at the most important tributaries (closest to the confluence)

Map 3

SUSPENDED SEDIMENT ANALYSIS METHODS

http://www.interreg-danube.eu/approved-projects/danubesediment

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

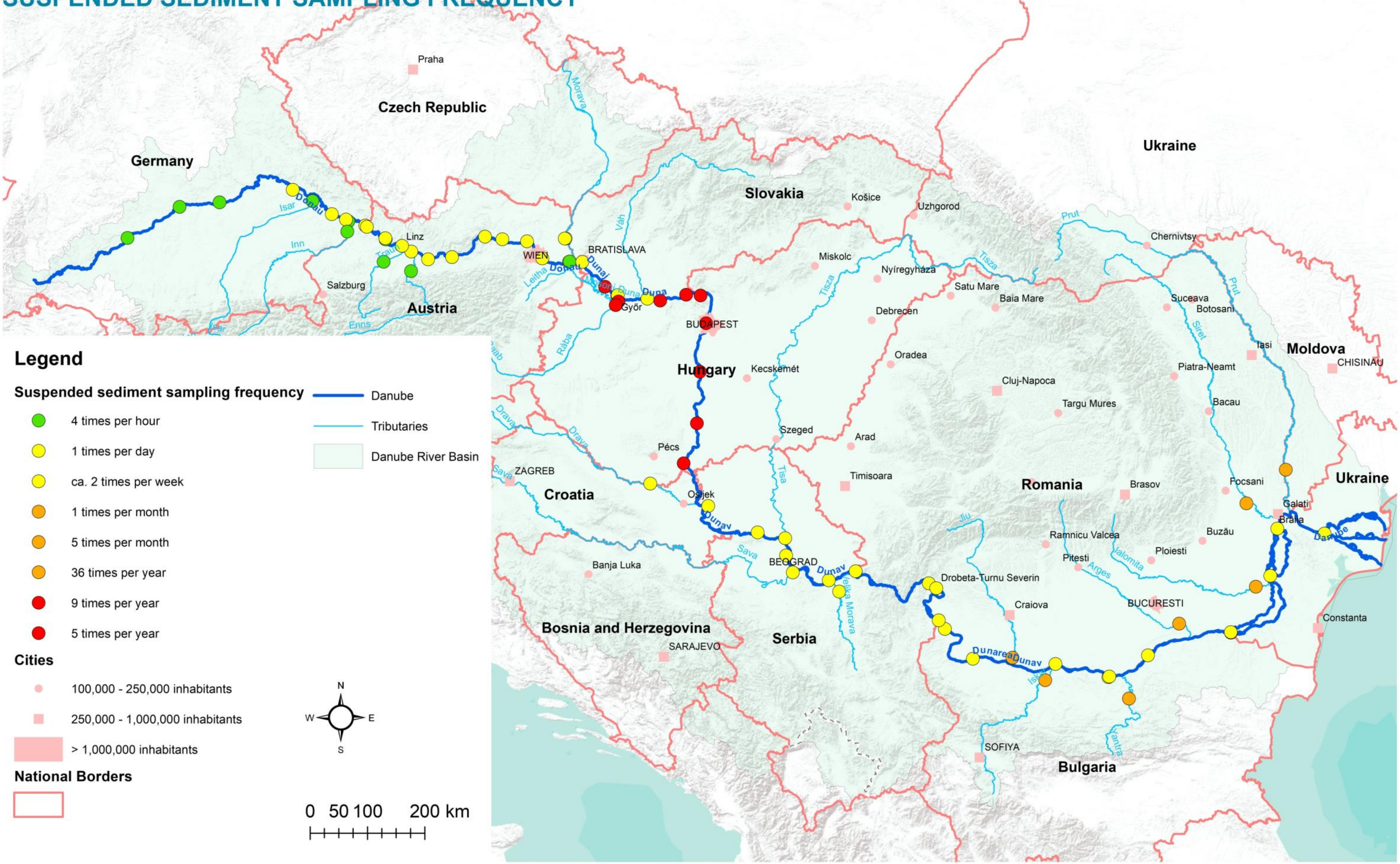
Budapest, April 2018

Interreg
EUROPEAN UNION
Danube Transnational Programme
DanubeSediment

Suspended sediment monitoring stations along the Danube and at the most important tributaries (closest to the confluence)

Map 4

SUSPENDED SEDIMENT SAMPLING FREQUENCY



http://www.interreg-danube.eu/approved-projects/danubesediment

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

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Annex 2: Summary tables of the sediment monitoring system in the Danube River and its most important tributaries

Summary tables of the suspended sediment monitoring system in the Danube River

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Germany	Danube	Neu-Ulm Bad Held	2586.70	LfU, GkD	Wasserwirtschafts-amt Donauwörth	2011-	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour (1 time per year, 1 time per week)	Filtration	NO
Germany	Danube	Neu-Ulm Bad Held	2586.70	LfU, GkD	Wasserwirtschafts-amt Donauwörth	1966-2011	Physical sampling (bottle)	Flow-dependent, from 1/w to 8/d	Filtration	NO
Germany	Danube	Donauwörth	2508.13	LfU, GkD	Wasserwirtschafts-amt Donauwörth	2014-	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour (1 time per year, 1 time per week)	Filtration	NO
Germany	Danube	Ingolstadt Luitpoldstrasse	2457.85	LfU, GkD	Wasserwirtschafts-amt Ingolstadt	2011-	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour (1 time per year, 1 time per week)	Filtration	NO
Germany	Danube	Ingolstadt Luitpoldstrasse	2457.85	LfU, GkD	Wasserwirtschafts-amt Ingolstadt	1966-2011	Physical sampling (bottle)	Flow-dependent, from 1/w to 8/d	Filtration	NO
Germany	Danube	Straubing gauging station	2321.30	WSV	WSV, BfG, BAW	1982-	Physical sampling (bottle)	1 time per day	Filtration	NO
Germany	Danube	Vilshofen	2249.50	WSV	WSV, BfG, BAW	1966-	Physical sampling (bottle)	1 time per day	Filtration	NO
Germany	Danube	Kachlet	2230.70	WSV	WSV, BfG, BAW	1975-	Physical sampling (bottle)	1 time per day	Filtration	NO
Germany	Danube	Jochenstein	2203.10	WSV	WSV, BfG, BAW	1974-	Physical sampling (bottle)	1 time per day	Filtration	NO
Austria	Danube	Engelhartszell	2200.66	viadonau	viadonau	1956-	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Austria	Danube	Donaukraftwerk Aschach	2161.96	VHP	VHP	2000-	Pump sampling, automatized bottle sampling	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Danube	Aschach Strom-bauleitung	2161.27	viadonau	viadonau	1960-2011	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Danube	Aschach Strom-bauleitung	2161.27	viadonau	viadonau	2011.	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour	Filtration	NO
Austria	Danube	Linz	2135.17	viadonau	viadonau	1961-	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Danube	Donaukraftwerk Abwinden - Asten	2119.20	VHP	VHP	2000-	Pump sampling, automatized bottle sampling	Flow-dependent, from 3/w to 4/d	Filtration	NO
Austria	Danube	Donaukraftwerk Wallsee - Mitterkirchen	2094.21	VHP	VHP	2000-	Pump sampling, automatized bottle sampling	Flow-dependent, from 3/w to 4/d	Filtration	NO
Austria	Danube	Donaukraftwerk Ybbs - Persenbeug	2060.20	VHP	VHP	2000-	Pump sampling, Automatized bottle sampling, Optical backscatter point sensor	Flow-dependent, from 1/w to 6/d	Filtration	NO
Austria	Danube	Stein-Krems	2002.69	viadonau	viadonau	1991-	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Danube	Donaukraftwerk Altenwörth	1979.58	VHP	VHP	2000-	Pump sampling, automatized bottle sampling	Flow-dependent, from 3/w to 6/d	Filtration	NO
Austria	Danube	Donaukraftwerk Greifenstein	1948.88	VHP	VHP	2000-	Pump sampling, automatized bottle sampling	Flow-dependent, from 3/w to 6/d	Filtration	NO

Country	**River**	**Name of mon. site**	**Location (rkm)**	**Data owner**	**Monitoring performed by**	**Time period**	**Applied method**	**Frequency**	**SSC analysis method**	**PSD analysis**
Austria	Danube	Donaukraftwerk Freudenau	1920.67	VHP	VHP	2001-	Pump sampling, automatized bottle sampling	Flow-dependent, from 3/w to 6/d	Filtration	NO
Austria	Danube	Bad Deutsch-Altenburg (Bauleitung)	1886.86	viadonau	viadonau	1956-2009	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Danube	Hainburg Straßenbrücke	1886.24	viadonau, BOKU	viadonau, BOKU	2008-	Physical sampling (bottle), isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	4 times per hour	Filtration	YES
Slovakia	Danube	Devín	1878.15	VUVH	VUVH	1997-1998	Isokinetic sampling (depth-integrating, point-integrating)	19 whole profile measurements	Filtration	YES
Slovakia	Danube	Devín	1878.15	VUVH	VUVH	1933-1986	Physical sampling (bottle), isokinetic sampling (depth-integrating, point-integrating)	Irregular	Filtration	NO
Slovakia	Danube	Bratislava, Lafranconi Bridge	1871.30	VUVH	VUVH	1956-	Isokinetic sampling (depth-integrating)	Flow-dependent, from 3/w to 1+/d	Filtration	YES
Slovakia	Danube	Bratislava	1868.75	SHMU	SHMU	1991-	Physical sampling (bottle) Isokinetic sampling (depth-integrating)	Flow-dependent, from 1/d to 1+/d	Filtration	NO
Hungary	Danube	Dunaremete	1825.50	ÉDUVIZIG	ÉDUVIZIG	1988-	Physical sampling (bottle), pump sampling	5 times per year	Evaporation	YES
Slovakia	Danube	Medveďov Bridge	1806.30	VUVH	VUVH	2000-2002	Isokinetic sampling (depth-integrating)	n/a	Filtration	NO
Slovakia	Danube	Medveďov Bridge	1806.30	SHMU	SHMU	1991-	Physical sampling (bottle) Isokinetic sampling (depth-integrating)	Flow-dependent, from 1/d to 1+/d	Filtration	NO

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Hungary	Danube	Vámosszabadi	1805.60	ÉDUVIZIG	ÉDUVIZIG	1988-	Physical sampling (bottle), pump sampling	5 times per year	Evaporation	YES
Slovakia	Danube	Komárno Bridge	1767.80	SHMU	SHMU	1995-	Physical sampling (bottle)	Flow-dependent, from 1/d to 1+/d	Filtration	NO
Hungary	Danube	Esztergom	1718.50	ÉDUVIZIG	ÉDUVIZIG	2011-	Physical sampling (bottle), pump sampling	5 times per year	Evaporation	YES
Hungary	Danube	Nagymaros	1694.60	KDVVIZIG	KDVVIZIG	2008-	Pump sampling	5 times per year	Evaporation	YES
Hungary	Danube	Nagymaros	1694.60	KDVVIZIG	KDVVIZIG	1951-2008	Physical sampling (bottle)	5 times per year	Evaporation	YES
Hungary	Danube	Budapest	1646.50	KDVVIZIG	KDVVIZIG	2008-	Pump sampling	5 times per year	Evaporation	YES
Hungary	Danube	Budapest	1646.50	KDVVIZIG	KDVVIZIG	1969-2008	Physical sampling (bottle)	5 times per year	Evaporation	YES
Hungary	Danube	Dunaújváros	1580.60	ADUVIZIG	ADUVIZIG	1950-	Pump sampling	5 times per year	Evaporation	YES
Hungary	Danube	Dombori	1506.80	ADUVIZIG	ADUVIZIG	1968-	Pump sampling	5 times per year	Evaporation	YES
Hungary	Danube	Mohács	1446.90	ADUVIZIG	ADUVIZIG	1949-	Pump sampling	5 times per year	Evaporation	YES
Serbia	Danube	Novi Sad	1257.10	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle)	1 time per day	Evaporation	NO
Serbia	Danube	Novi Sad	1257.10	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Pump sampling	1-3 times per year	Evaporation	YES
Serbia	Danube	Stari Banovci	1192.75	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle)	1 time per day	Evaporation	NO
Serbia	Danube	Stari Banovci	1192.75	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Pump sampling	1-3 times per year	Evaporation	YES
Serbia	Danube	Smederevo	1110.40	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle)	1 time per day	Evaporation	NO

Country	**River**	**Name of mon. site**	**Location (rkm)**	**Data owner**	**Monitoring performed by**	**Time period**	**Applied method**	**Frequency**	**SSC analysis method**	**PSD analysis**
Serbia	Danube	Smederevo	1110.40	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Pump sampling	1-3 times per year	Evaporation	YES
Romania	Danube	Bazias	1072.50	NARW/NIHWM	NARW /Jiu River Basin Administration	1971-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	NO
Serbia	Danube	HPP Đerdap 1 dam	943.00	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1974-	Physical sampling (bottle)	1 time per day	Evaporation	NO
Romania	Danube	Drobeta Turnu Severin	931.00	NARW/NIHWM	NARW /Jiu River Basin Administration	1980-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	NO
Bulgaria	Danube	Lom	743.30	NIMH-BAS	NIMH-BAS	2017	Physical sampling (bottle)	1 time per day	Filtration	YES
Romania	Danube	Corabia	624.20	NARW/NIHWM	NARW / Arges River Basin Administration	1979-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES
Bulgaria	Danube	Svishtov	554.30	NIMH-BAS	NIMH-BAS	1989-	Physical sampling (bottle)	1 time per day	Filtration	YES
Romania	Danube	Zimnicea	553.23	NARW/NIHWM	NARW / Arges River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	NO
Romania	Danube	Giurgiu	493.05	NARW/NIHWM	NARW / Arges River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES
Romania	Danube	Chiciu Calarasi	379.58	NARW/NIHWM	NARW / Dobrogea-Litoral River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Bulgaria	Danube	Silistra	375.50	NIMH-BAS	NIMH-BAS	1989-	Physical sampling (bottle)	1 time per day	Filtration	YES
Romania	Danube	Vadu Oii	238.00	NARW/NIHWM	NARW / Dobrogea-Litoral River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES
Romania	Danube	Braila	167.00	NARW/NIHWM	NARW / Dobrogea-Litoral River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES
Romania	Danube	Ceatal Izmail	80.50	NARW/NIHWM	NARW / Dobrogea-Litoral River Basin Administration	1931-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	YES
Romania	Danube/ Branch Chilia	Periprava	20.00	NARW/NIHWM	ANAR /Dobrogea-Litoral River Basin Administration	1961-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	n/d
Romania	Danube	Sfantu Gheorghe Harbour	8.00	NARW/NIHWM	ANAR /Dobrogea-Litoral River Basin Administration	1979-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	n/d
Romania	Danube	Sulina	2.50	NARW/NIHWM	ANAR /Dobrogea-Litoral River Basin Administration	1979-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Turbidity meter	n/d

Summary tables of the suspended sediment monitoring system in the most important tributaries of the Danube River

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Germany	Isar	Plattling	9.12	LfU, GkD	Wasserwirtschafts-amt Deggendorf	2011-	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour (1 time per year, 1 time per week)	Filtration	NO
Germany	Isar	Plattling	9.12	LfU, GkD	Wasserwirtschafts-amt Deggendorf	1966-2011	Physical sampling (bottle)	Flow-dependent, from 1/w to 8/d	Filtration	NO
Germany	Inn	Passau Ingling	3.10	LfU, GkD	Wasserwirtschafts-amt Deggendorf	2011-	Optical backscatter point sensor, calibrated by acoustic devices and physical sampling (bottle)	4 times per hour (1 time per year, 1 time per week)	Filtration	NO
Germany	Inn	Passau Ingling	3.10	LfU, GkD	Wasserwirtschafts-amt Deggendorf	1970-	Physical sampling (bottle)	Flow-dependent, from 1/w to 8/d	Filtration	NO
Austria	Inn	Schärding (Schreibpegel)	16.25	Hydrographic service of Upper Austria	Hydrographic service of Upper Austria	2008-	Physical sampling (bottle), isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	4 times per hour	Filtration	YES
Austria	Traun	Wels-Lichtenegg	33.25	Hydrographic Service of Upper Austria	Hydrographic service of Upper Austria	2008-	Physical sampling (bottle), isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	4 times per hour	Filtration	YES
Austria	Traun	Wels-Lichtenegg	33.25	Hydrographic Service of Upper Austria	Hydrographic service of Upper Austria	1950-2005	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Austria	Enns	Steyr (Ortskai)	30.88	Hydrographic Service of Upper Austria	Hydrographic service of Upper Austria	2006-	Physical sampling (bottle), isokinetic sampling (point-integrating), optical backscatter point sensor, acoustic devices	4 times per hour	Filtration	YES
Austria	Enns	Steyr (Ortskai)	30.88	Hydrographic Service of Upper Austria	Hydrographic service of Upper Austria	1984-	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Austria	Morava	Angern	31.89	viadonau	viadonau	1998-	Physical sampling (bottle)	Flow-dependent, from 1/every 3 days to 4/d	Filtration	NO
Slovakia	Morava	Záhorská Ves	32.52	VUVH	VUVH	1993-1997	Physical sampling (bottle), isokinetic sampling (depth-integrating)	Flow-dependent, cca. 2 times per week	Filtration	NO
Slovakia	Morava	Moravský Ján	67.15	VUVH	VUVH	1993-1997	Physical sampling (bottle), isokinetic sampling (depth-integrating)	n.a.	Filtration	NO
Hungary	Rába	Győr	14.50	ÉDUVIZIG	ÉDUVIZIG	1988-	Physical sampling (bottle), pump sampling	5 times per year	Evaporation	YES
Croatia	Drava	Donji Miholjac	80.50	DHMZ	DHMZ	1993-	Physical sampling (bottle), pump sampling, acoustic devices	1 time per day, plus cross-sectional measurements 6 times per year	Filtration	NO
Serbia	Tisza	Titel	4.90	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle); pump sampling	1 time per day; 1-3 times per year	Evaporation	NO; YES
Serbia	Sava	Belgrade	5.20	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle); pump sampling	1 time per day; 1-3 times per year	Evaporation	NO; YES
Serbia	Velika Morava	Ljubičevski Bridge	21.83	PE Electric Power Industry of Serbia - Branch HPP Djerdap	JCI	1986-	Physical sampling (bottle); pump sampling	1 time per day; 1-3 times per year	Evaporation	NO; YES

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	SSC analysis method	PSD analysis
Romania	Jiu	Zaval	8.00	NARW/NIHWM	NARW/Jiu River Basin Administration	1963-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Filtration	NO
Bulgaria	Iskar	Oriahovitza	340.50	NIMH-BAS	NIMH-BAS	1961-	Physical sampling (bottle)	Flow-dependent, average: 14/y	Filtration	YES
Bulgaria	Iantra	Karantzi	208.00	NIMH-BAS	NIMH-BAS	1964-	Physical sampling (bottle)	Flow-dependent, average: 60/y	Filtration	YES
Romania	Arges	Budeşti	2.00	NARW/NIHWM	NARW/Arges River Basin Administration	1955-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Filtration	NO
Romania	Ialomita	Tandarei	29.00	NARW/NIHWM	NARW/Ialomita-Buzau River Basin Administration	1977-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Filtration	NO
Romania	Siret	Lungoci	77.00	NARW/NIHWM	NARW/Siret River Basin Administration	1956-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Filtration	NO
Romania	Prut	Oancea	79.20	NARW/NIHWM	NARW /Prut River Basin Administration	1958-	Physical sampling (bottle)	2 times per day, expeditionary measurements 4-6 times per year	Filtration	NO

Summary tables of the bedload monitoring system in the Danube River

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	GSD analysis method
Germany	Danube	Straubing 1	2329.30	WSV	WSV, BfG, BAW	2010-2012	BfG-sampler	3 sampling campaigns	Dry sieving
Germany	Danube	Straubing 2	2321.00	WSV	WSV, BfG, BAW	2010-2012	BfG-sampler	3 sampling campaigns	Dry sieving
Germany	Danube	Pfelling	2305.50	WSV	WSV, BfG, BAW	1970-2012	BfG-sampler	16 sampling campaigns	Dry sieving
Germany	Danube	Deggendorf	2283.20	WSV	WSV, BfG, BAW	2008-2012	BfG-sampler	9 sampling campaigns	Dry sieving
Germany	Danube	Halbmeile	2280.00	WSV	WSV, BfG, BAW	2008-2012	BfG-sampler	9 sampling campaigns	Dry sieving
Germany	Danube	Hofkirchen	2256.90	WSV	WSV, BfG, BAW	1970-2012	BfG-sampler	1 time per day, 17 sampling campaigns	Dry sieving
Austria	Danube	Vienna	1930.80	Staatliche Versuchsanstalt für Wasserbau	Staatliche Versuchsanstalt für Wasserbau	1910, 1921, 1925-1931	Ehrenberger sampler	4 measurements 1930/1931	Dry sieving
Austria	Danube	Bad Deutsch-Altenburg	1885.90	via donau - Österreichische Wasserstraßen-Gesellschaft mbH	Bundesstrombauamt (predecessor of the viadonau)	1951-1957	Ehrenberger sampler	1 campaign with several measurements 1956/1957	Dry sieving
Austria	Danube	Hainburg Straßenbrücke	1886.24	viadonau; BOKU	viadonau; BOKU	2005-2015	BfG-sampler	cca. 3 times per year	Dry sieving
Slovakia	Morava	Moravský Ján	67.15	VUVH	VUVH	1990-2016	Helley-Smith sampler	campaigns	Dry sieving
Slovakia	Danube	Devín	1878.15	VUVH	VUVH	1991-2016	Helley-Smith, Novak sampler, Swiss type sampler	46 full-profile measurement campaigns	Dry sieving
Hungary	Danube	Vámosszabadi	1805.60	ÉDUVIZIG	ÉDUVIZIG	1998-2014	Károlyi-sampler	5 times per year	Dry sieving
Slovakia	Danube	Klizska Nema	1795.58	VUVH	VUVH	1992-2016	Swiss type sampler	54 full-profile measurement campaigns	Dry sieving
Romania	Danube	Bazias	1072.50	NARW/NIHWM	NARW/Jiu River Basin Administration	1971-1984	Bedload bathometer	4 times per year	Dry sieving
Romania	Danube	Corabia	624.20	NARW/NIHWM	NARW /Arges River Basin Administration	1992-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving

Country	River	Name of mon. site	Location (rkm)	Data owner	Monitoring performed by	Time period	Applied method	Frequency	GSD analysis method
Romania	Danube	Zimnicea	553.23	NARW/NIHWM	NARW/ Arges River Basin Administration	1985-1996, 2007-2008, 2010-2012, 2014-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving
Romania	Danube	Giurgiu	493.05	NARW/NIHWM	NARW/ Arges River Basin Administration	1970-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving
Romania	Danube	Chiciu Calarasi	379.58	NARW/NIHWM	NARW/ Dobrogea-Litoral River Basin Administration	1980-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving
Romania	Danube	Vadu Oii	238.00	NARW/NIHWM	NARW/ Dobrogea-Litoral River Basin Administration	1970-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving
Romania	Danube	Braila	167.00	NARW/NIHWM	NARW/ Dobrogea-Litoral River Basin Administration	1971-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving
Romania	Danube	Ceatal Izmail	80.50	NARW/NIHWM	NARW/ Dobrogea-Litoral River Basin Administration	1969-	Bedload bathometer	Flow-dependent freq., cca. 4 times per year	Dry sieving

Annex 3: GIS metadatabase

1. Introduction

The web-based questionnaires which were completed by the project partners contain basic information about the different monitoring methods used by the project partners and both historical and present data. The collected metadata about the monitoring stations all along the Danube River and at the most important tributaries consist of basic information about:

- the monitoring stations,
- hydrological monitoring,
- suspended sediment monitoring and
- bed load monitoring.

The metadatabase is built based on the scheme of the database structure used by the International Commission for the Protection of the Danube River (ICPDR) and based upon the questionnaires and Excel tables of data gathered about the monitoring stations.

Presumably, after ending the project, the data base will be maintained by the ICPDR. Thus, it seemed to be reasonable to adapt to their system and its structure.

2. DanubeGIS

The GIS- and map-related work of ICPDR is supported by the DanubeGIS platform. It does not contain data for rivers with a river basin less than 4000 km^2 area. Its purpose is to integrate the data of the project partners into a harmonised format and store them in order to help the implementation of the Water Framework Directive and the EU Floods Directive.

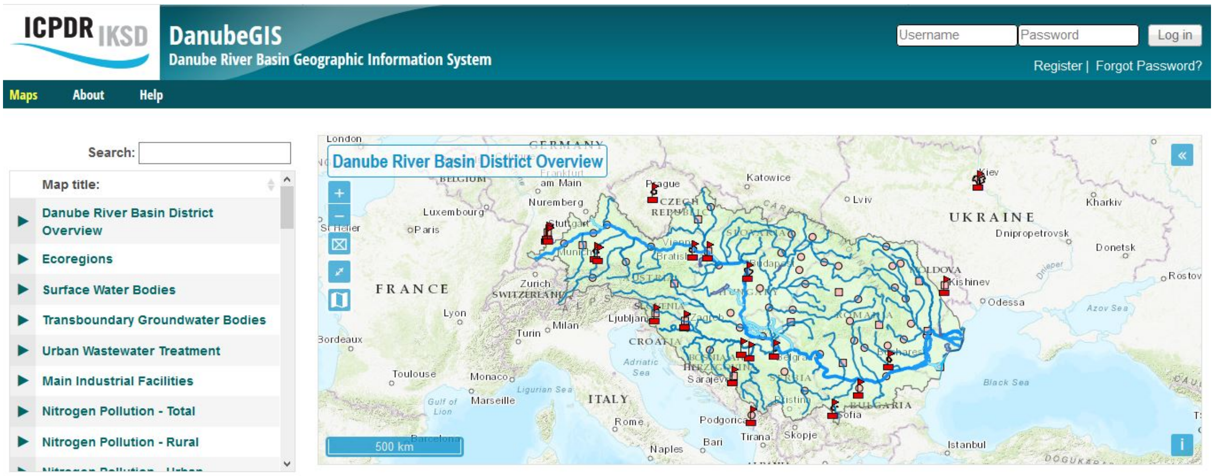

Figure 96 DanubeGIS webpage

On the webpage, over 40 maps of the Danube River Basin Management Plan and the Danube Flood Risk Management Plan could be publicly accessed and downloaded in different – non-editable – formats. All the maps can be downloaded as georeferenced image file or is directly accessible using the Web Map Service (WMS).

After registration, this system provides access to the data of the whole Danube River Basin. However, some of the data could be accessed only with the permission of the partners.

(https://www.danubegis.org/)

3. Sediment Metadatabase

The sediment metadatabase contains the main information from the questionnaires and the data provided by the partners. The data can be divided into two groups:

- information about/data of the monitoring station (location, river geometry, hydrological measurements, statistical data)
- information about/data of the sediment monitoring (applied methods, statistical data)

Table 35 presents the structure of the sediment metadatabase:

Table 35 Structure of the sediment data base

	Field name	Description of the attribute	Units	Field type*
	OBJECTID *	Object ID (automatically generated)		
	SHAPE *	Shape of object (automatically generated)		
	COUNTRY_NAME	Name of the country (to be selected)		Text
BASIC INFORMATION OF THE	**COUNTRY_ID**	Code to identify the country (automatically generated)		Text
	EUCD_SED	European Report Code of monitoring station		Text
	MSCD_SED	National Report Code of monitoring station		Text
	REF_YR	Reference year of the data reported		Integer
	OWNER	Data Owner		Text
	NAME	Name of the monitoring site		Text

	Field name	Description of the attribute	Units	Field type*
	EUCD_RIV	European Report Code of the river		Text
	RIVER	Name of the river		Text
	RKM	Location of monitoring site (river kilometre)	[rkm]	Double
	LONGITUDE	Longitude (decimal degree) in WGS84		Double
	LATITUDE	Latitude (decimal degree) in WGS84		Double
	SLOPE	Average slope of the riverbed where the station is located	[cm/km]	Double
	HYD_MON	Hydrological monitoring at the station (to be selected)	YES/NO	Bool
	DISCHARGE_MEASURE	Flow discharge measurement at the station (to be selected)	YES/NO	Bool
	SUSSED_MON	Suspended sediment monitoring at the station)to be selected)	YES/NO	Bool
	BL_MON	Bed load monitoring at the station (to be selected)	YES/NO	Bool
	VELO_MEASURE	Velocity measure (to be selected)	YES/NO	Bool
	NQ	Low water discharge at the station	[m^3/s]	Double
	MQ	Middle water discharge at the station	[m^3/s]	Double
	HQ	High water discharge at the station	[m^3/s]	Double
	DEPTH	Mean depth at the station	[m]	Double
	WIDTH	Mean width at the station	[m]	Double
	SUSSED_MEAN	Mean suspended load at the station	[t/year]	Double
	BL_MEAN	Mean bed load at the station	[t/year]	Double
	D50	Characteristic D_{50} of the bed surface	[mm]	Double
	D90	Characteristic D_{90} of the bed surface	[mm]	Double
	Danube Sediment	Spreadsheet number		Text
SEDIMENT	**Time Period**	Starting date of suspended sediment monitoring - End date of monitoring	[year]	
	SS_Method	Applied method for suspended sediment monitoring		Text

	Field name	Description of the attribute	Units	Field type*
	SS_Frequency	Frequency of the suspended sediment monitoring	year/hour /day/…	Text
	SSC_Analy_Method	Applied method for suspended sediment concentration (SSC) monitoring		Text
	PSD_Analysis	Particle size distribution analysis of the sample	YES/NO	Bool
	Mean_Annual_SS_Load	Mean annual suspended sediment load	[Mt/year]	Double

*ESRI Field types

Comments:

- The measurement methods are predefined, so the method can be chosen from a drop-down menu for each monitoring site.

- The Country ID is generated automatically when the name of the country is given. The IDs are built-in according to the ICPDR Country IDs. The Country IDs are shown in Table 36.

Table 36 Country IDs

Country ID	Country Name
AT	Austria
BG	Bulgaria
HR	Croatia
DE	Germany
HU	Hungary
RO	Romania
RS	Serbia
SK	Slovakia

- In cases where there has not been any data provided, either <Null> or „-9999” value is set.

Annex 4: Examples for existing sediment monitoring networks

1. Introduction

It is important to study other river-wide sediment monitoring networks in order to minimalize the possible problems and drawbacks. Thus, this point briefly presents examples of existing sediment monitoring networks from other river systems. The extracts of information are collected from the official websites of the related projects.

2. USGS Hudson River Watershed Suspended Sediment Monitoring Network

River: Hudson River
Country: United States of America
Catchment area: 34 000 km^2

The USGS NY Water Science Center maintains a network of near-real-time sensors to monitor the movement of suspended sediment into and through the freshwater reach of the tidal Hudson River. Information from this network helps to quantify the movement of sediment in the watershed to assist resource managers and stakeholders to reduce dredging costs, target resources to mitigate soil loss, and modify land use practices and behaviour that result in sediment-related damage to the ecosystem.

There are 11 continuous monitoring sites and one which was discontinued recently. However, at most of the sites, recording of historical data were occasional. The period of daily recordings is rather varied as well.

Website: https://www.usgs.gov/centers/ny-water/science/usgs-hudson-river-watershed-suspended-sediment-monitoring-network?qt-science_center_objects=0#qt-science_center_objects

3. Sediment Monitoring System for the Sava River Basin

River: Sava River
Countries: Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia
Catchment area: 97 713 km^2

The main objectives of the project have been: (i) establishment of strategic goals and specific objectives of the sediment monitoring and data exchange system; (ii) review of existing sediment monitoring data; (iii) review of technical international standards and technics of monitoring and assessment of their application in the Sava River Basin; (iv) establishment of on-line free database on sediment taking into account the initial functionalities of Sava Geoportal implemented by the International Sava River Basin Commission (ISRBC).

The monitoring system (*Figure 97*) is briefly presented country by country below.

Slovenia:

The number of monitoring sites for suspended load is far from being optimal. Measurements are done continuously using turbidity meters. Sediment concentration is obtained through conventional filtration method. There are no bedload measurements.

Croatia:

Suspended sediment is monitored on 10 gauging stations (4 stations on the Sava River and 6 stations on the tributaries). Point samples at all gauging stations are taken once a day. Profile measurements of sediment concentration and sediment load, at 3 stations on the Sava River, are done periodically. Sediment concentration is obtained through standard vaporization and filtration methods.

There are no bedload measurements.

Bosnia and Herzegovina:

Regular suspended sediment monitoring is not performed by hydrometeorological services Occasional monitoring of sediment is conducted for individual projects.

There are no bedload measurements.

Serbia:

Instruments and methodology should be updated. In the past, the Republic Hydrometeorological Service of Serbia (RHMZ) did regular suspended sediment monitoring on a number of gauging stations in Serbia. The Jaroslav Černi Institute (JCI) conducted yearly programs of the Iron Gate 1 reservoir monitoring, between 1974 and 2014. These encompassed daily monitoring of suspended sediment transport at Beograd and Sremska Mitrovica on the Sava River.

There are no bedload measurements.

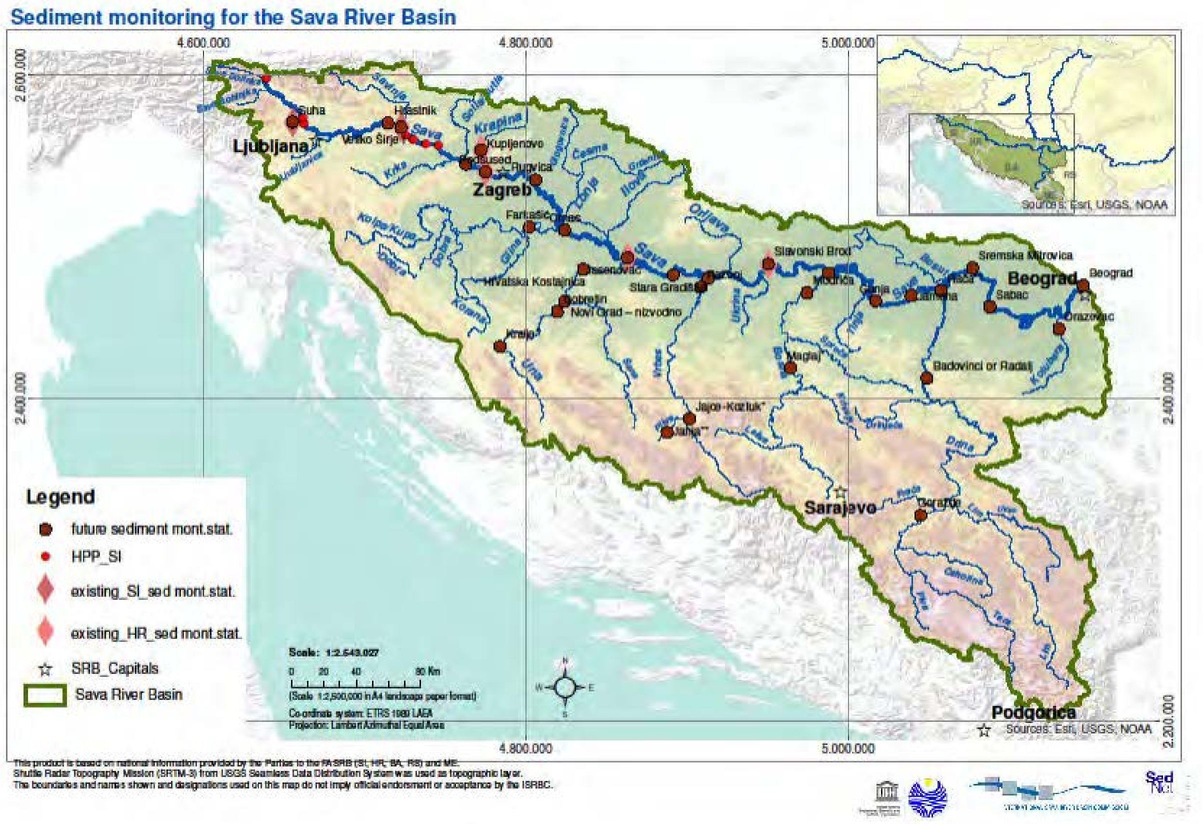

Figure 97 Sediment monitoring for the Sava River Basin (source: see website below)

Website: http://www.unesco.org/new/fileadmin/MULTIMEDIA/FIELD/Venice/pdf/establishment_of_sediment_monitoring_in_srb_final_b.pdf

http://www.savacommission.org/mission

4. Rhine River

River: Rhine River
Countries: Austria, Germany, Switzerland and The Netherlands
Catchment area: 185.000 km²

Sediment transport in the Rhine has various consequences. In the past and present day, the riverbed has been subjected to many hydraulic engineering measures and changes which influence the sediment transport and erosion. Sedimentation and erosion can lead to problems in the navigable depth for shipping, to dehydration, to undermining of structures, as well as to damage to nature and the landscape, for example. The intention is to jointly gather know-how and develop equipment: (i) improvement of the measuring equipment and measuring methods for sediment transport, (ii) quantification of the long-term development of the river bed and (iii) improvement of the model concepts of morphological models for application in the Rhine basin.

The Federal Institute of Hydrology (BfG) has established the research and development project "From the Source to the Mouth: A Sediment Balance of the Rhine", to produce for the first time a sediment balance for the Rhine from the source to the mouth.

The monitoring system (*Figure 98*) is briefly presented country by country below.

Switzerland:

In Switzerland, suspended sediment concentration and sediment deposits in retention basins are surveyed. The suspended sediment observation network consists at the moment of: (i) 13 stations with each two samples per week, (ii) 15 stations with periodic sampling (special campaigns) and (iii) 2 stations with continuous sampling. In addition, the turbidity is continuously measured at 5 monitoring stations.

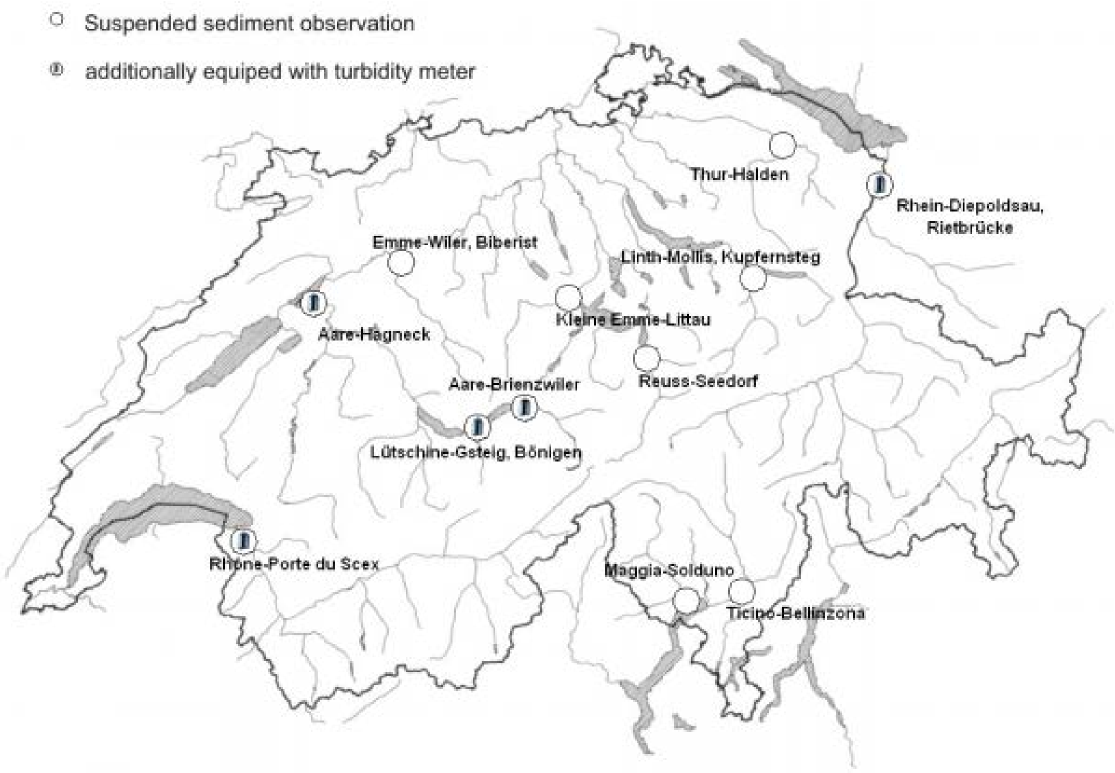

Figure 98 Map of suspended sediment observation network for the Rhine River Basin (LHG 2005)

Suspended sediment concentration can be determined by direct measurements taking some samples. The determination of the sediment concentration in the sample is made by filtration. Since the samples are not taken continuously, larger flood events can be missed, which leads to larger uncertainties by the computation of the suspended sediment load. In order to better interpret the discontinuous concentration measurements, turbidity meters are also used.

The direct measurement of the bedload in torrents is limited today to few test sites. There are three measuring stations with hydrophones (*Figure 99*) in operation in the Swiss Rhine basin. Installations with underwater microphones allow a continuous recording of the bedload discharge.

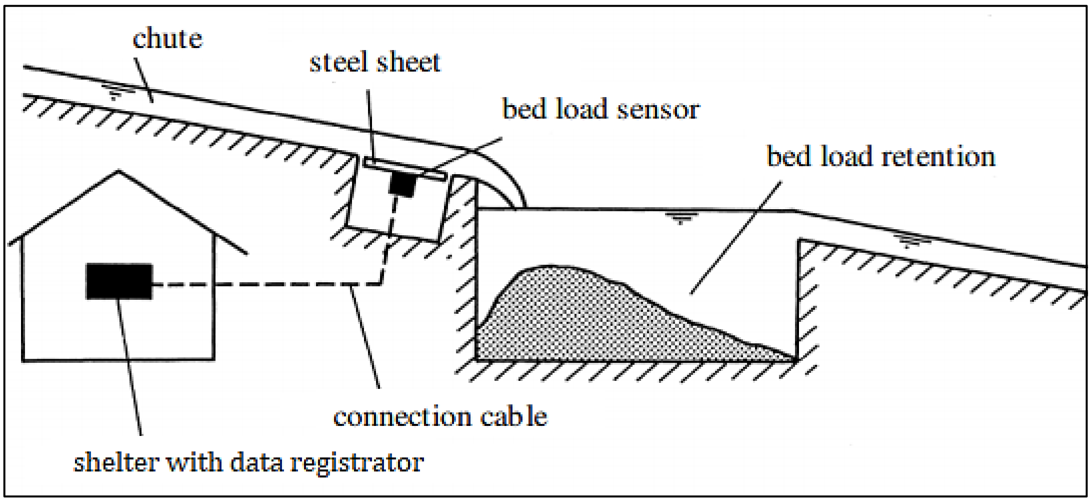

Figure 99 Schematic sketch of a hydrophone installation (BfG, 2008)

Germany:

Beginning with first sediment transport measurements at the Upper Rhine in the late sixties the measurements were extended during the seventies and eighties over the whole free flowing Rhine. Meanwhile cross section measurements of bedload and suspended load are carried out at about 40 stations between Iffezheim and the German Dutch border. At each station sediment transport is measured four to five times a year, which allows to establish sediment balances over the whole reach. Besides the above-mentioned cross-section measurements suspended load is measured at 11 permanent monitoring stations between Lake Constance and the Dutch border.

At the permanent SS stations, monitoring is done by means of 5-litre-samples of water, taken every working day at one point approx. 50 cm below the water surface in the middle of the river (*Figure 100*). The samples are filtrated, and sediment concentration is gravimetrically determined by drying and weighing the solid residuum in a climate constant lab according to the instructions given as German Association for Water Research (DVWK) standard (DVWK, 1986).

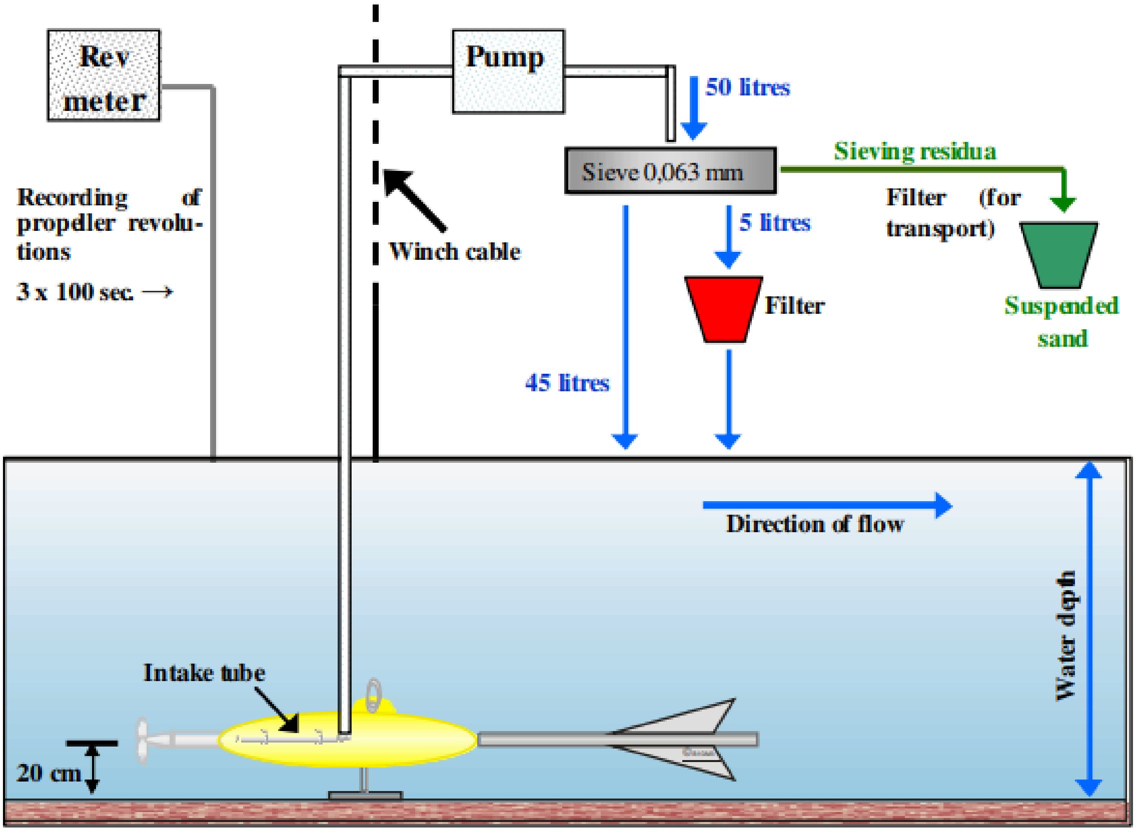

Figure 100 Suspended sediment measurement at cross sections (BfG, 2008)

The measurements are carried out with the bedload sampler "Arnheim-Koblenz" consisting of a heavy frame, a sampling basket with a mobile rectangular mouth (16 to 8 cm) and a so-called diffusor between mouth and basket (see *Figure 101*). When lowered to the riverbed the mobile mouth nestles closely to the bed surface. To control the correct hub of the sampler and the undisturbed inflow of sediment a video camera is mounted directly above the mouth.

Figure 101 Bedload sampler "Arnheim-Koblenz" (BfG, 2008)

The Netherlands:

In the Netherlands, sediment transport measurements are not carried out as a routine, ongoing monitoring program. Instead the measurements are done within research projects that focus on specific river problems at specific locations.

In recent years, the suspended transport of sand has been monitored in the Rhine branches by means of the so-called Acoustic Sand-Transport-Meter (ASTM). The ASTM (*Figure 102)* used in the river consists of a 1-metre long frame with a weight of 220 kg, suspended in the direction of the flow rate by means of fins. The head of the frame contains a sensor with which sound waves are transmitted and two sensors with which the signal is received back again. One of these two sensors is located in line with the sound source.

Figure 102 The Acoustic-Sand-Transport-Meter (ASTM) (left) and the filtering system that is used in The Netherlands to obtain fine-grained sediment samples (right) (BfG, 2008)

The amount of bedload sediment transport is determined by collecting it during a few minutes in a bag placed on the bottom: in The Netherlands this is done with a Helley-Smith bedload sand transport meter (*Figure 103*).

Figure 103 The Helley-Smith bedload sediment transport meter (BfG, 2008)

Website: https://www.chr-khr.org/en/project/sediment
https://www.chr-khr.org/sites/default/files/chrpublications/rapport_ii_-_20_0.pdf

5. Illinois State Water Survey (Water and Atmospheric Resources Monitoring Program (WARM))

River: 12 rivers in Illinois State
Country: United States of America
Catchment area: 68 057 km^2

The Monitoring Program currently consists of 15 sampling sites located throughout Illinois, USA (*Figure 104)*. 14 of the 15 active sampling stations are located at U.S. Geological Survey (USGS) stream gauging stations. The USGS furnishes discharge rating tables for these stations. At most of the stations, sediment data have been recorded since 1981.

The Benchmark Sediment Monitoring Program collects weekly suspended sediment samples at a selected set of Illinois rivers and streams. When the sample is collected the exact date, time, and stream stage are recorded representing an instant in time. Using the instantaneous date, time, and water stage information, water discharge data (collected at the same sites via USGS stream gauges) and the suspended sediment concentration are used to calculate the instantaneous sediment load (in tons per day).

A long-term database such as this can be used to determine long-term trends in sediment transport in Illinois, estimate sediment loads for unmonitored streams, evaluate the effectiveness of watershed management programs and identify watersheds with high soil erosion and sediment delivery rates.

Website: https://www.isws.illinois.edu/warm/sediment/about.asp

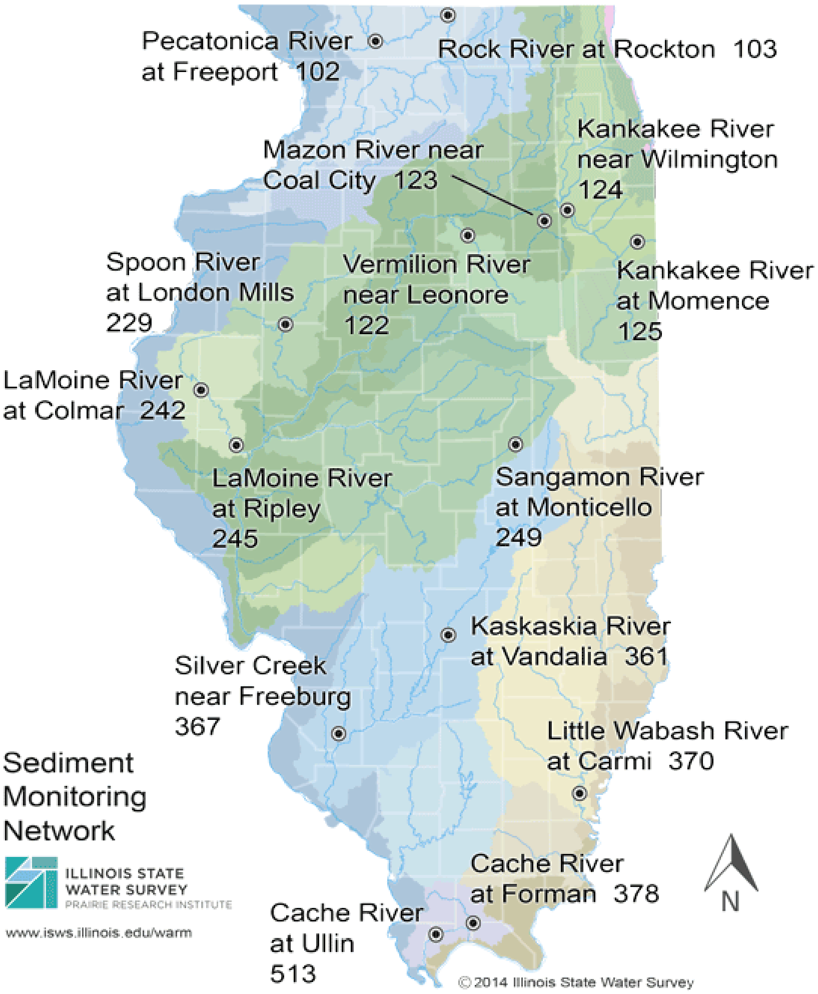

Figure 104 Sediment Monitoring Network – Stations Map (https://www.isws.illinois.edu/warm/sediment/sedmap.asp)

6. International Elbe Monitoring Programme 2017

River: Elbe
Countries: Czech Republic, Germany
Catchment area: 148.268 km^2

The International Elbe Monitoring Programme 2017 currently comprises the analysis of approx. 160 parameters in the water phase and 70 parameters in suspended sediments. Approx. 10 parameters are analysed in the biological part of the monitoring programme. The regular analysis of the Elbe water quality based on a coordinated international monitoring programme makes it possible, among other things, to detect conspicuous substance discharges.

The objectives of this monitoring program are: (i) making the use of water possible, especially promoting the retrieval of drinking water via river bank infiltration and enabling the agriculture to utilise the water and the sediments, (ii) achieving the most natural ecosystem possible; one that can provide for healthy species population and (iii) permanent strategy to decrease the burden imposed on the North Sea by the Elbe River basin.

The water quality within the framework of the International Elbe Monitoring Programme 2017 is monitored at 9 monitoring profiles in Germany and 6 monitoring profiles in the Czech Republic (9 directly at the Elbe and 6 at tributaries) (*Figure 105*). These monitoring profiles are places of surveillance monitoring according to the Water Framework Directive and provide a complete overview of the current situation of the Elbe River basin district.

Updating the plan, proposals for good sediment management practice in the Elbe region (ICPER Sediment Management Concept, published in 2014) were also used. Its suggestion is daily physical sampling (using manual/automated bottle samplers) with the filtration method.

Site: https://www.ikse-mkol.org/en/themen/gewaesserguete/internationales-messnetz-und-internationales-messprogramm/

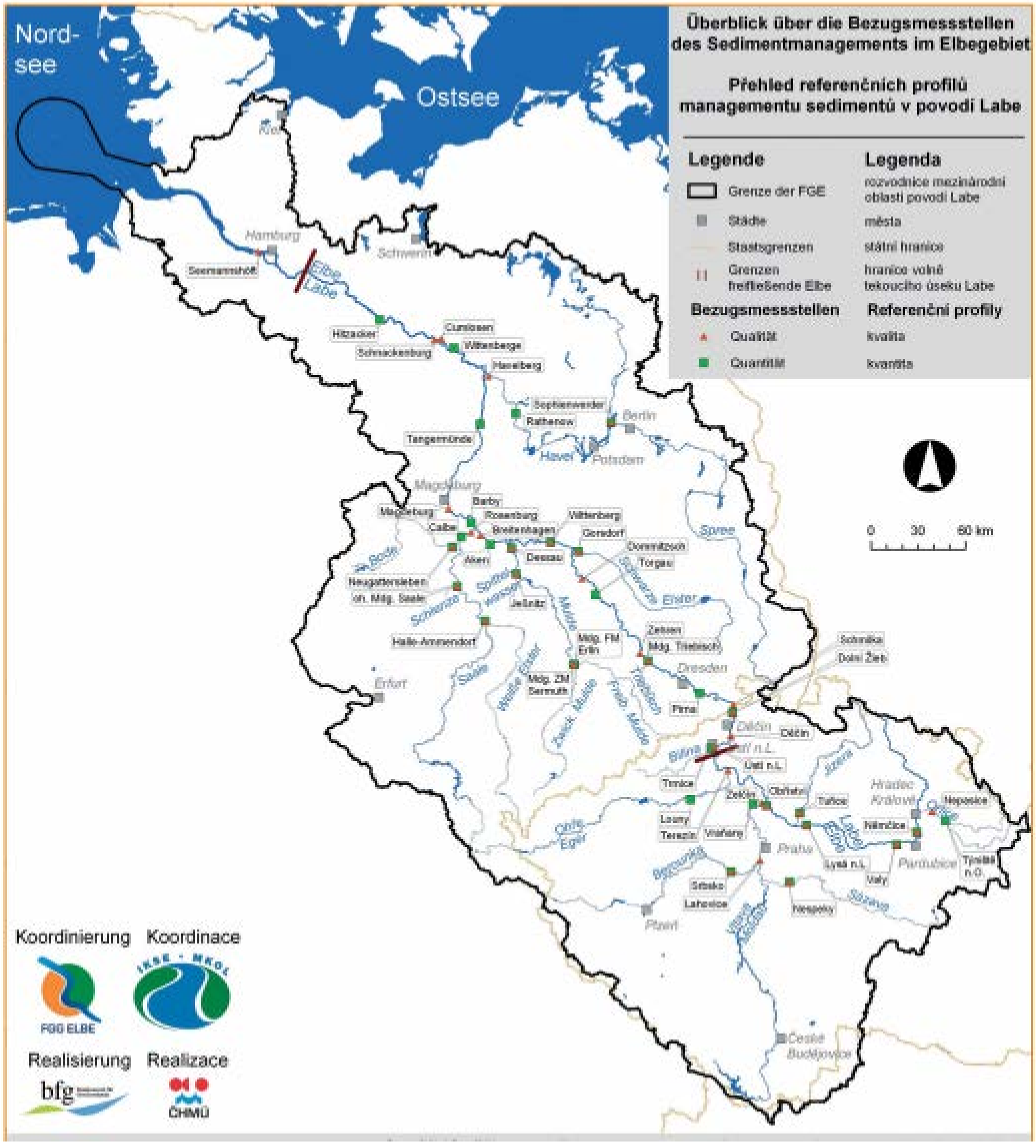

Figure 105 Monitoring system of the Elbe River Basin (https://www.ikse-mkol.org/fileadmin/media/user_upload/D/06_Publikationen/01_Wasserrahmenrichtlinie/2014_IKSE-Abschlussbericht%20Sediment.pdf)

7. New Zealand National Rivers Water Quality Network (NRWQN)

River: 35 rivers over the two main islands of New Zealand

Country: New Zealand

Catchment area: 264 944 km^2

The NRWQN consists of 77 sites on 35 rivers that are evenly distributed over the two main islands of New Zealand (*Figure 106*). The sites and variables measured were carefully selected after reviews of networks in other countries and consideration of their relevance to New Zealand.

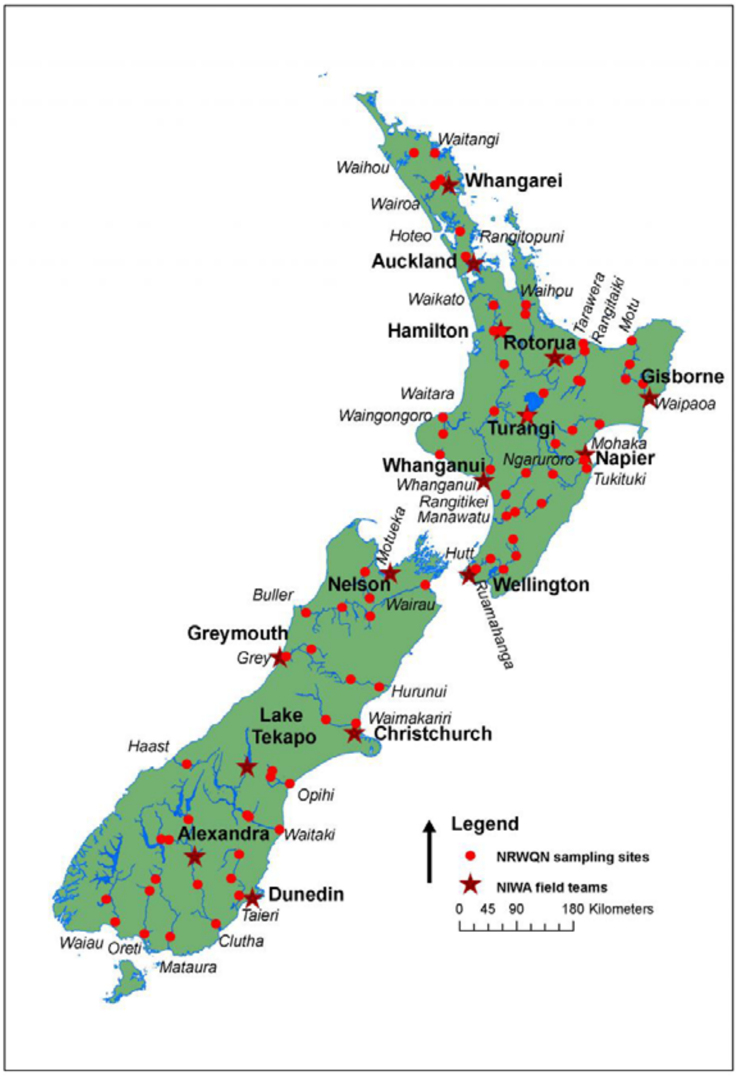

Figure 106 New Zealand National Rivers Water Quality Network (https://www.niwa.co.nz/sites/niwa.co.nz/files/styles/ large/public/sites/default/files/images/0012/110208/NRWQN-monitoring-sites_0.jpg?itok=6CQNukTy

Monitoring commenced in January 1989. Since that, monthly samples have been collected at the NRWQN sites on the major river systems that, together, drain about 50 % of New Zealand's land area. The NRWQN is noteworthy internationally for its stability throughout its history. There have been essentially no changes to monitoring sites and methods of measurement. Sites were selected so that a national perspective of state and trends of water quality could be developed.

Predicting long-term average suspended-sediment loads in rivers and streams is useful for dealing with a variety of issues. These include sediment entrapment rates in potential reservoirs and the vulnerability of estuarine and coastal marine habitats to sediment influxes from the land.

To facilitate this prediction, National Institute of Water and Atmospheric Research (NIWA) have generated a raster-based GIS layer of specific suspended sediment yield (SSY, t/km^2/y) from New Zealand's rivers and streams based on gauged sediment yields at over 200 river stations and an empirical model.

For many years they have used a simple technique for measuring the amount of fine sediment held within the interstitial spaces of the streambed. The quorer (*Figure 107*) utilises an open-ended cylinder that isolates an area of gravel substrates in flowing water, typically in places corresponding to sites suitable for macroinvertebrate sampling (i.e., runs or riffles). After measuring the water depth within the cylinder, the top 5–10 cm of substrate is vigorously disturbed with a stirring rod, and a grab sample of the resulting slurry collected and analysed for the content of organic and inorganic sediments. The quantity of suspended sediment in the surficial substrate (top 5–10 cm) can then be calculated.

Figure 107 Field and laboratory protocol for quorer (NIWA)

Website:https://www.niwa.co.nz/freshwater/water-quality-monitoring-and-advice/national-river-water-quality-network-nrwqn

https://www.niwa.co.nz/our-science/freshwater/tools/estimating-deposited-fine-sediment/quorer-field-and-laboratory-protocol

8. Tsitsa River Catchment

River: Tsitsa River
Country: South Africa
Catchment area: 4000 km^2

In South Africa and globally, agencies involved with catchment management and monitoring require suspended sediment (SS) data to support their decision-making, planning, and interventions. The sampling programme was designed to define and monitor sub-catchment SS sources in the manner described by Collins and Walling (2004). The aim was to determine the relative contribution of the tributary sub-catchments to the overall SS load of the Tsitsa River catchment at the site of the proposed Ntabelanga Dam. 11 sites were established at which channel discharge and SSC were monitored in order to determine SS flux and yield at each site (*Figure 108*).

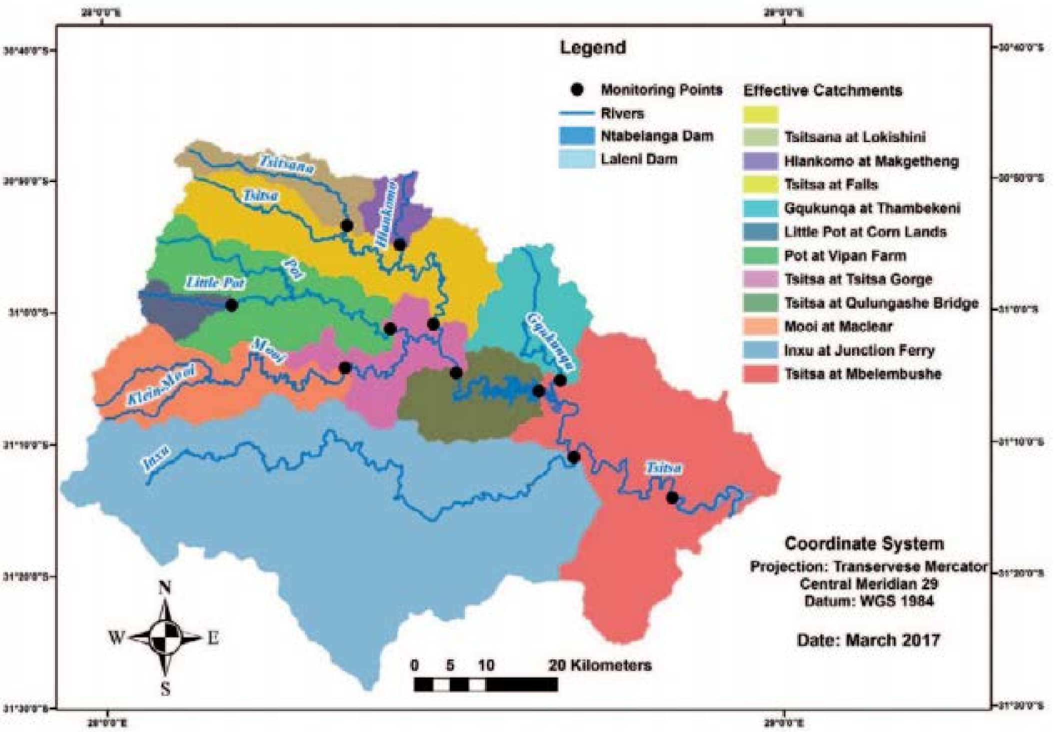

Figure 108 Monitoring sites and effective catchments on the Tsitsa River and its tributaries

A 2-m pole-and-jar isokinetic sampler is used during the measurements (*Figure 109*). Locally resident citizen technicians using basic equipment and Open Data Kit–enabled smartphones have collected flood-focused suspended sediment (SS) samples from 11 sites on the Tsitsa River and its tributaries, in the Eastern Cape Province of South Africa. An acoustic backscatter SSC probe (LISST ABS) was installed at the Department of Water and Sanitation (DWS) gauging station at Xonkonxa to allow the data generated by the citizen technician at that site to be compared against those generated by the probe.

Analysis of the quantitative data collected by the citizen technicians allows high-resolution SSC, flux, and yield data to be produced at sub-catchment scale, which will be benchmarked by an acoustic SSC probe at a downstream DWS gauging weir. Qualitative descriptive and photographic data allows distant researchers to gain a real-time, catchment-wide overview of river and SS levels.

Note, that involving local residents as citizen technicians resulted in significant savings. And the citizen technicians were not only well positioned to sample through flood flows but also, due to their local knowledge, likely to be aware of when such floods might occur.

Figure 109 The wooden pole sampler in use showing the attachment of the sample jar into the head assembly

Website: https://www.ajol.info/index.php/wsa/article/view/159648

Annex 5: Existing sediment monitoring standards

1. Suspended sediment

Standard: ISO 11657:2014(en)
Title: Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques
https://www.iso.org/obp/ui/#iso:std:iso:11657:ed-1:v1:en

This International Standard specifies methods for determination of the concentrations and particle-size distributions of suspended sediment in streams and canals by surrogate techniques.

Standard: ISO 4363:2002(en)
Title: Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment
https://www.iso.org/obp/ui/#iso:std:iso:4363:ed-3:v1:en

This International Standard specifies conventional and simplified methods for the measurement of cross-sectional mean suspended sediment mass concentration and mean particle size distribution.

Standard: ISO 4365:2005(en)
Title: Liquid flow in open channels — Sediment in streams and canals — Determination of concentration, particle size distribution and relative density
https://www.iso.org/obp/ui/#iso:std:iso:4365:ed-2:v1:en

This International Standard specifies methods for determining the concentration, particle-size distribution and relative density of sediment in streams and canals.

Standard: ISO 6420:2016(en)
Title: Hydrometry — Position fixing equipment for hydrometric boats
https://www.iso.org/obp/ui/#iso:std:iso:6420:ed-2:v1:en

The necessity of positioning hydrometric boats arises in several types of measurements on open channels or lakes, reservoirs and estuaries. First, it is necessary to position a boat on a measuring section in order to conduct the appropriate observations of velocity and depth for a discharge measurement. Position fixing also is required for collecting suspended sediment and bedload samples at appropriate verticals on a river cross section.

Standard: ISO/TS 3716:2006(en)
Title: Hydrometry — Functional requirements and characteristics of suspended-sediment samplers
https://www.iso.org/obp/ui/#iso:std:iso:ts:3716:ed-1:v1:en

This Technical Specification specifies the functional requirements and characteristics of the different types of suspended-sediment samplers.

Standard: ISO 5667-1:2006(en)
Title: Water quality — Sampling — Part 1: Guidance on the design of sampling programmes and sampling techniques
https://www.iso.org/obp/ui/#iso:std:iso:5667:-1:ed-2:v1:en

(Part 17: Guidance on sampling of suspended sediments)

This part of ISO 5667 sets out the general principles for, and provides guidance on, the design of sampling programmes and sampling techniques for all aspects of sampling of water (including waste waters, sludges, effluents and bottom deposits). It does not include detailed instructions for specific sampling situations, which are covered in the various other parts of ISO 5667. Also, it does not include microbiological sampling.

Standard: ISO 5667-3:2018(en)
Title: Water quality — Sampling — Part 3: Preservation and handling of water samples
https://www.iso.org/obp/ui/#iso:std:iso:5667:-3:ed-5:v1:en

This document specifies general requirements for sampling, preservation, handling, transport and storage of all water samples including those for biological analyses.

Standard: ISO 13317-4:2014(en)
Title: Determination of particle size distribution by gravitational liquid sedimentation methods — Part 4: Balance method
https://www.iso.org/obp/ui/#iso:std:iso:13317:-4:ed-1:v1:en

This part of ISO 13317 specifies the method for the determination of particle size distribution by the mass of particles settling under gravity in liquid. This method is based on a direct mass measurement and gives the mass distribution of equivalent spherical particle diameter. Typically, the gravitational liquid sedimentation method applies to samples in the 1 µm to 100 µm size range and where the sedimentation condition for particle Reynolds number less than 0,25 is satisfied.

Standard: ISO 772:2011(en)
Title: Hydrometry — Vocabulary and symbols
https://www.iso.org/obp/ui/#iso:std:iso:772:ed-5:v1:en

This International Standard gives terms, definitions and symbols used in standards in the field of hydrometry.

Standard: ISO 6421:2012(en)
Title: Hydrometry — Methods for assessment of reservoir sedimentation

https://www.iso.org/obp/ui/#iso:std:iso:6421:ed-1:v1:en

This International Standard describes methods for the measurement of temporal and spatial changes in reservoir capacities due to sediment deposition.

Standard: ISO 11329:2001(en)
Title: Hydrometric determinations — Measurement of suspended sediment transport in tidal channels
https://www.iso.org/obp/ui/#iso:std:iso:11329:ed-2:v1:en
This International Standard deals with the method and techniques for the sampling of suspended sediment and estimation of sediment transport rates in natural and man-made channels influenced by tidal action.

Standard: ISO/TR 11651:2015(en)
Title: Estimation of sediment deposition in reservoir using one dimensional simulation models
https://www.iso.org/obp/ui/#iso:std:iso:tr:11651:ed-1:v1:en
This Technical Report describes a method for estimation/prediction of sediment deposition within and upstream of a reservoir using numerical simulation techniques through one-dimensional flow and sediment transport equations.

Standard: ISO/TR 24578:2012(en)
Title: Hydrometry — Acoustic Doppler profiler — Method and application for measurement of flow in open channels
https://www.iso.org/obp/ui/#iso:std:iso:tr:24578:ed-1:v1:en
This Technical Report deals with the use of boat-mounted acoustic Doppler current profilers (ADCPs) for determining flow in open channels without ice cover. It describes a number of methods of deploying ADCPs to determine flow. Although, in some cases, these measurements are intended to determine the stage-discharge relationship of a gauging station, this Technical Report deals only with single determination of discharge.

2. Bedload

Standard: ISO/TR 9212:2015(en)
Title: Hydrometry — Methods of measurement of bedload discharge
https://www.iso.org/obp/ui/#iso:std:iso:tr:9212:ed-3:v1:en

This Technical Report reviews the current status of direct and indirect bedload-measurement techniques. The methods are mainly based on grain size distribution of the bedload, channel width, depth, and velocity of flow. This Technical Report outlines and explains several methods for direct and indirect measurement of bedload in streams, including various types of sampling devices.