Interreg
EUROPEAN UNION
Danube Transnational Programme
DanubeSediment

Handbook on Good Practices in Sediment Monitoring

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

Project Introduction

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

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.

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

Handbook on Good Practices in Sediment Monitoring

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Website: www.interreg-danube.eu/danubesediment

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Introduction

In the Danube Basin, one can observe an increasing discrepancy between the surplus of sediment (e.g. reservoir sedimentation) and the deficit of sediment (e.g. river bed and coastal erosion). This increases flood risk, reduces navigation possibilities, reduces hydropower production, deteriorates the ecological conditions of the Danube River, and moreover, it decreases the ground water level. In order to improve our understanding of sediment transport related problems in the Danube River, it is of crucial importance to have a clear picture about the spatial and temporal variation of the sediment amount being transported in the river. For this purpose, the quantity of the sediment needs to be monitored at given sections of the river. This handbook gives practical recommendations for good practices in sediment monitoring.

Based on the nature of sediment transport in rivers, the monitoring methods can be divided into 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, mixed up in the whole water column, whereas **bedload** transport takes place at the riverbed, where the coarser particles are rolling, sliding or saltating (Figure 1). Monitoring methods for both sediment transport modes are introduced in the following document.

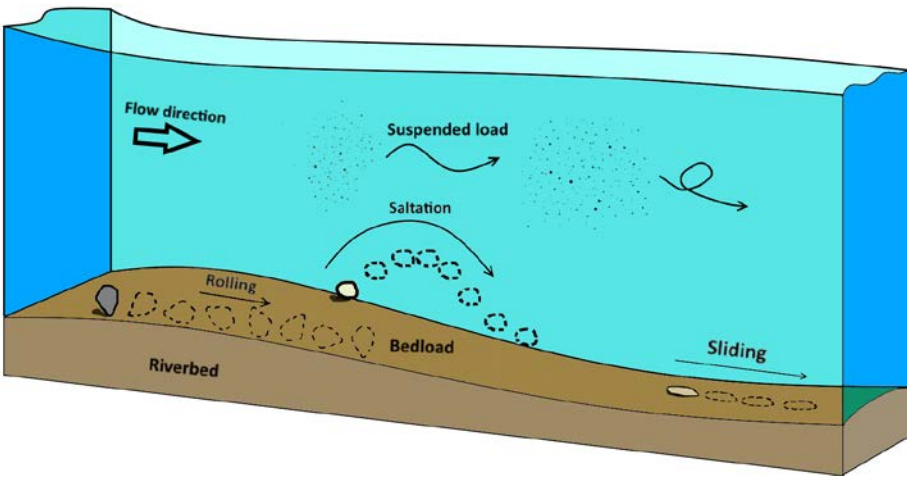


Figure 1 Transport modes of sediments in rivers.

Based on the data analysis performed on historical sediment datasets in the frame of the DanubeSediment project, one can see that the proportion of suspended sediment to the total sediment load is around 80-90%, whereas bedload accounts for around 10-20%. Despite plying a smaller role in the total sediment load and being less decisive e.g. on large scale sediment budget calculations, bedload transport has a steering influence on morphological variations on the scale of river reaches and must therefore also be monitored.

Monitoring of suspended sediment

In order to obtain reliable information regarding the suspended sediment transport, the following parameters/characteristics are to be assessed:

- suspended sediment concentration (SSC) [mg/l],
- suspended sediment load [kg/s],
- annual suspended sediment load [Mt],
- spatiotemporal variability,
- particle size distribution (PSD),
- characteristic particle sizes.

While many methods and devices are available for the quantification of the suspended sediment transport, no single method is sufficient for the reliable temporal and spatial characterization of all the relevant parameters. In the following document, we introduce a monitoring method that applies a combination of different techniques (BMLFUW, 2008, 2017; Haimann et al., 2014).

Where to set up a monitoring site?

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, when selecting the monitoring location and when positioning the equipment in the water, the 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 must be accessible, e.g. for maintenance, throughout the whole year. It is recommended to integrate the sediment monitoring station in an operating hydrographic gauging station, where stage and flow discharge data is inherently available. Otherwise, concurrent hydrographic measurements are necessary.

Figure 2 shows the procedure of the suspended sediment load determination according to the good practice we propose. There are two main pillars of the measurements, i.e. i) continuous measurements to capture the temporal variability of the sediment transport and ii) cross-sectional measurements to capture the spatial variability of the sediment transport. Besides indirect methods that can be easily implemented in the field, physical samplings are also crucial for calibration purposes. These samples have to be analysed in a laboratory following the filtering method (is explained later on). Performing complementary flow velocity measurements, the sediment load, representing the whole cross-section, can be calculated. The main steps of the sediment load determination procedure are explained in the following text.

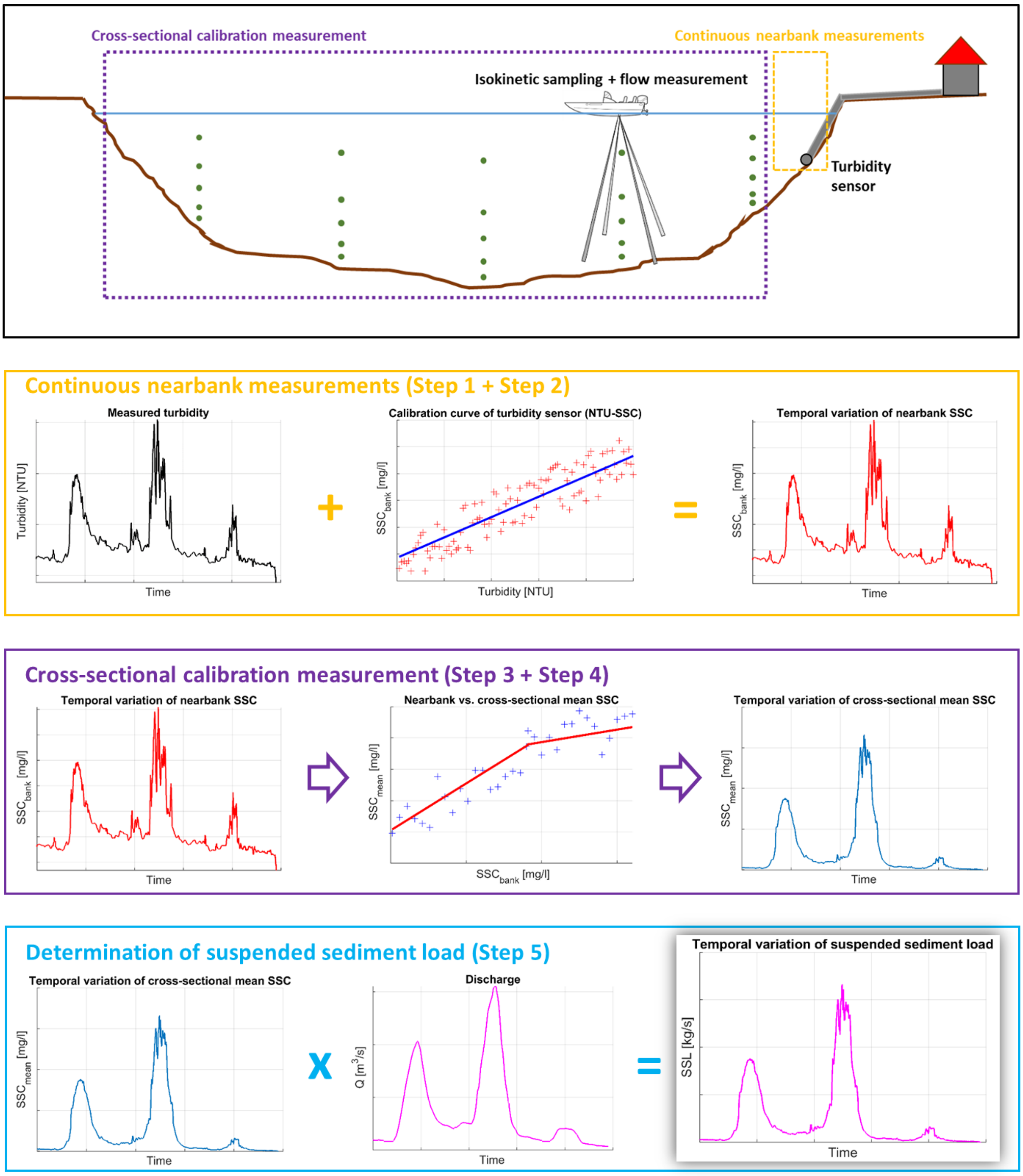


Figure 2 Sketch of suspended sediment load monitoring

How often to measure?

Whether talking about continuous data logging or a field measurement campaign, we can give recommendations regarding the sampling frequencies (Table 1).

Table 1 Recommended sampling frequencies for the different suspended sediment measurements (based on BMLFUW, 2008; 2017)

Parameter	Methods	Sampling frequency
Turbidity	Turbidity sensor	Continuous
Suspended sediment concentration (SSC)	Single-point sampling with bottle sampler	*High water* – daily *Mean water* – 1-2 times per week *Low water* – less often
Cross-sectional distribution of SSC	Multi-point sampling, or sampling combined with ADCP	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

Step 1: Turbidity measurements

Required equipment

- Optical or acoustic backscatter sensor mounted on the river bank, bridge pier or lowered from a floating pontoon
- Power supply (generator, battery)
- Data logger

In order to assess the temporal variability of turbidity, and more importantly the suspended sediment concentrations, indirect measurement devices are required that are capable of conducting measurements with at least a temporal resolution of 15 minutes (mean or instantaneous) (Figure 3 and Figure 4). In order to obtain reliable data, the measurement device must be chosen carefully, according to the local concentration and grain size characteristics. Especially for optical sensors, regular cleaning and maintenance of the device must be ensured. In addition to locally storing the collected data, their remote transmission is recommended. Turbidity and acoustic sensors always have to be calibrated based on single-point suspended sediment concentration (SSC) measurements.

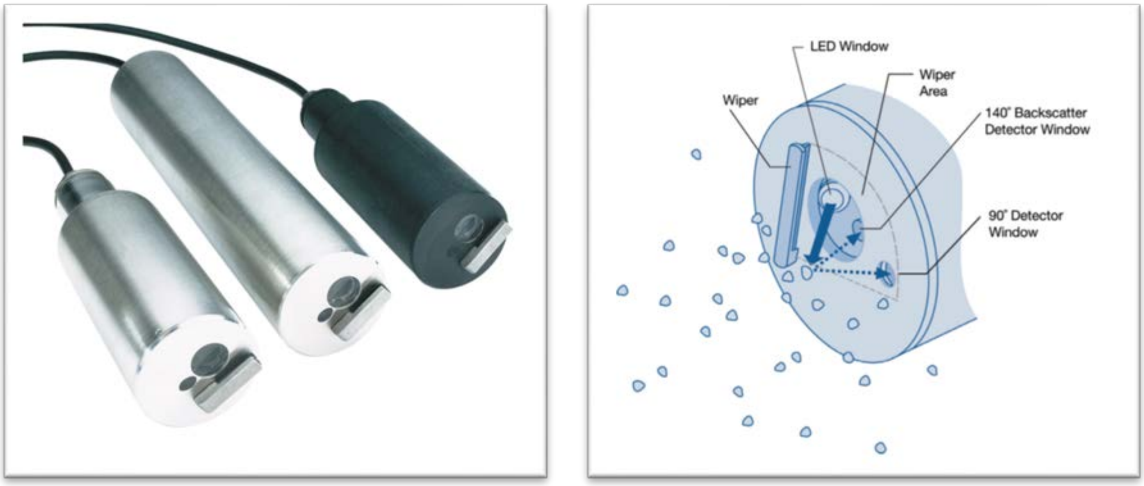


Figure 3 Solitax sensors from Hach and measurement principle (www.hach.com)

Figure 4 Turbidity sensor mounted on the river bank (source: viadonau)

Step 2: Calibration of turbidity sensors

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

It is advised to generalise 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 changing of the sensor.

Required equipment

- Sampling device (e.g. bottle sampler) + necessary accessories
- Clear, closable bottles to store water samples (min. volume of 1 litre)

Calibration measurement conducted with a sampler on a rope

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

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 for the cable of the sampler. This 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 at least 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, 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 1000 ml) is mounted on a telescopic rod and lowered to close proximity of the turbidity sensor (Figure 5).
2. The sampler must be emerged 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 entered into the measurement protocol, along with the measured turbidity value and the actual water stage.

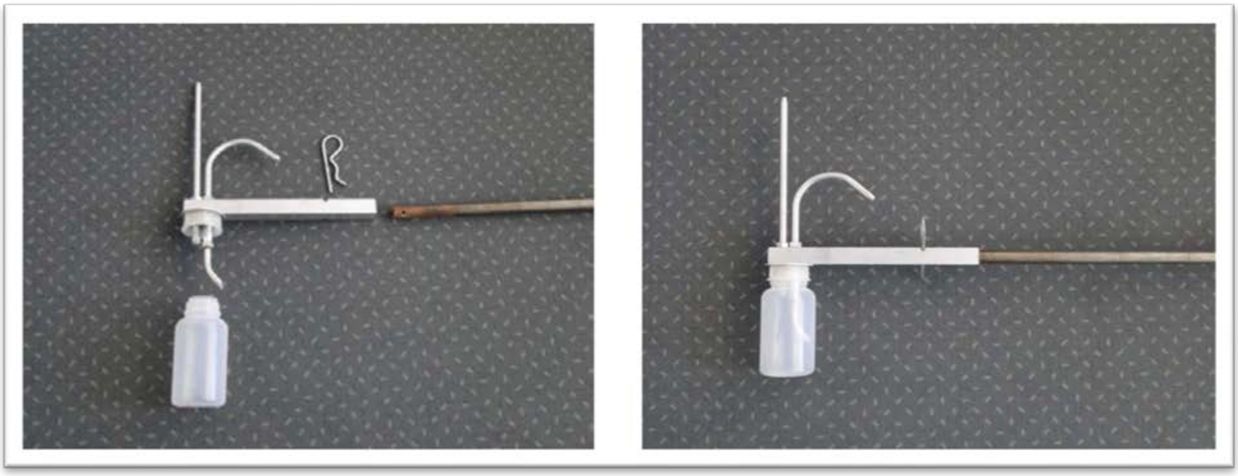


Figure 5 Reference bottle sampler (LfU, 2012)

Step 3: Cross-sectional calibration

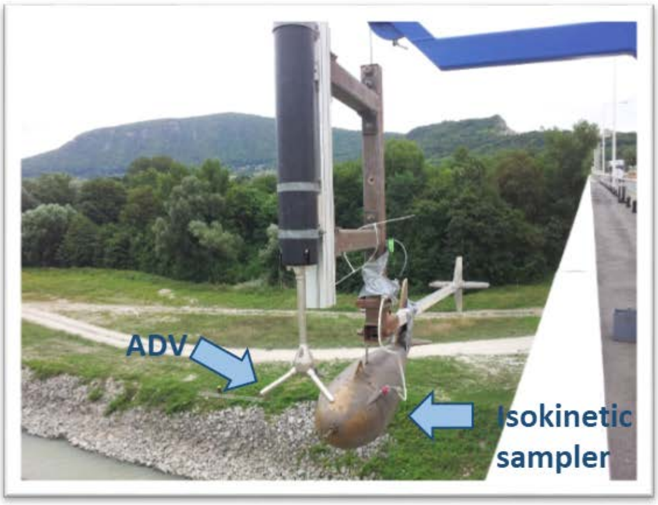
Repeated single-point measurements along a vertical or through a whole cross-section, which aims to determine the spatial distribution of suspended sediment concentrations. In these cases, the samplings must be complemented by velocity measurements, in order to quantify SS load.

Required equipment

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

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 simultaneously. It is advised to conduct such measurements several times per year, preferably in different flow conditions. This can be done with multi-point sampling measurements or in combination with ADCP measurements (Figure 6). If ADCP is used, we recommended performing long-term, e.g. lasting 3 minutes, fixed boat measurements, from which the time-averaged flow velocity distribution can be derived and be used for the follow-up steps. Figure 7 shows an example of a cross-sectional measurement plan including the sampled points (5 verticals, 4 points in each vertical).



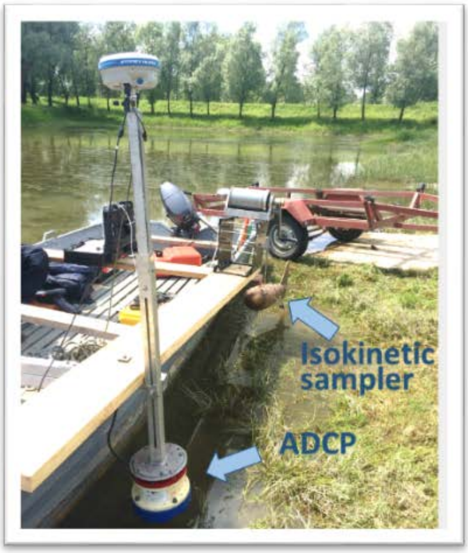


Figure 6 Setup of parallel sediment sampling and flow velocity measurement (left: IWHW/BOKU, right: BME)

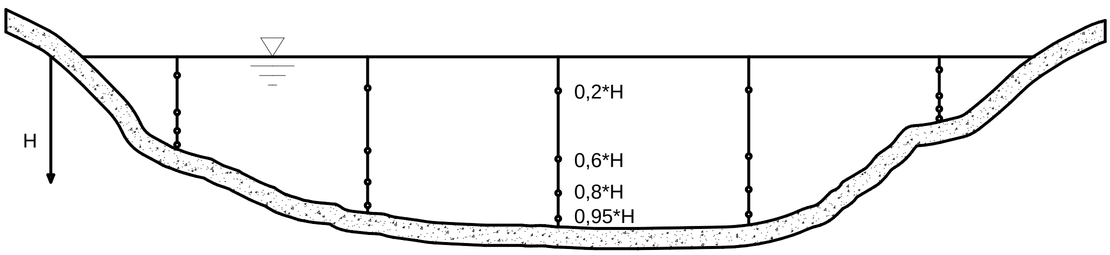


Figure 7 Scheme of a cross-sectional measurement in 5 verticals and 4 measuring points per vertical (based on BMLFUW, 2008; 2017)

1. The following data must be entered into the measurement protocol:
   Type of sampling and velocimeter device, time, measurement team, location, project name, type of measurement, parallel measurements, water stage, temperature, turbidity.
2. The cross-section is to be divided into several segments of equal width, called verticals. The number of verticals shall not be less than seven for a cross-sectional width larger than 300 m, and not less than five for a width smaller than 300 m. *In case ADCP measurements are conducted as well, a fewer number of vertical could be sufficient.*
3. Determination of measurement points along the verticals: in general, 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
4. Once the sampler is lowered to the depth of interest, the sampling is performed as presented for the single-point measurements. Relevant identification data must be protocolled!
5. Determination of flow velocity at the sampling point.
6. Steps 4-5 are repeated for all points/verticals.
7. After the measurement, the following data needs to be entered into the protocol:
   Water stage, discharge, temperature, time of measurements, any additional relevant information regarding the measurement (e.g. that a vessel passed).
8. Samples are later analysed in laboratory conditions (determination of SSC). The samples are to be kept in dry, cold place (refrigerator), but should not be frozen. The samples should be post-processed as soon as possible.

Step 4: Laboratory analysis of water samples

Following the field measurements, the collected samples are to be analysed in laboratory conditions as soon as possible.

The filtering of the samples can be done under pressure or with vacuum filtering as well. In order to get comparable results, a filter of 0.45 µm pores has to be used for all samples. 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 (Figure 8)

- 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 for the determination of the sample volume (precision of 0.5%)
- wash bottle
- tweezers
- adjustable dryer cabinet

Figure 8 Membrane filter (left); filtering of samples at the laboratory of viadonau in Aschach (right) (pictures: IWHW/BOKU).

Determination of dry matter content

The steps to determine the dry matter content are as follows:

1. The membrane filter placed on the plate is dried at 105 °C until it reaches a constant weight (min. 10 minutes, max. 3 hours). The 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. The water used for rinsing 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 the combined mass reaches a constant value.
7. The plate and the membrane filter (with the dry matter on it) are weighed 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: $s_0=m_T/V_p$ [mg/l].

Laser diffraction

The SSC measurement range of the LISST Portable XR device (Figure 9) lies between 30 to 1900 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 careful dilution. This makes the analysis of samples containing very fine particles in high concentration possible. In addition to the basic equipment, LISST-Portable has an auxiliary ultrasonic sensor, with the aid of which the measurements of the PSD can be obtained more accurately (see the manual of the device). As mentioned before, the determination of the PSD is done by the amount of light detected on the different detector rings. The LISST Portable has 44 concentric rings, thus it can provide a PSD in 44 logarithmic size classes between 0.34-500 µm. The device has built-in batteries so it can be easily used during field measurements and not only in the laboratory.

Figure 9 LISST Portable XR (http://www.sequoiasci.com/product/lisst-portable-xr/)

Step 5: Determination of suspended sediment load

SSC load 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 that the areas of triangular, rectangular and trapezoid objects are summed up (Figure 10). The calculation of vertical and cross-sectional specific sediment loads is presented below.

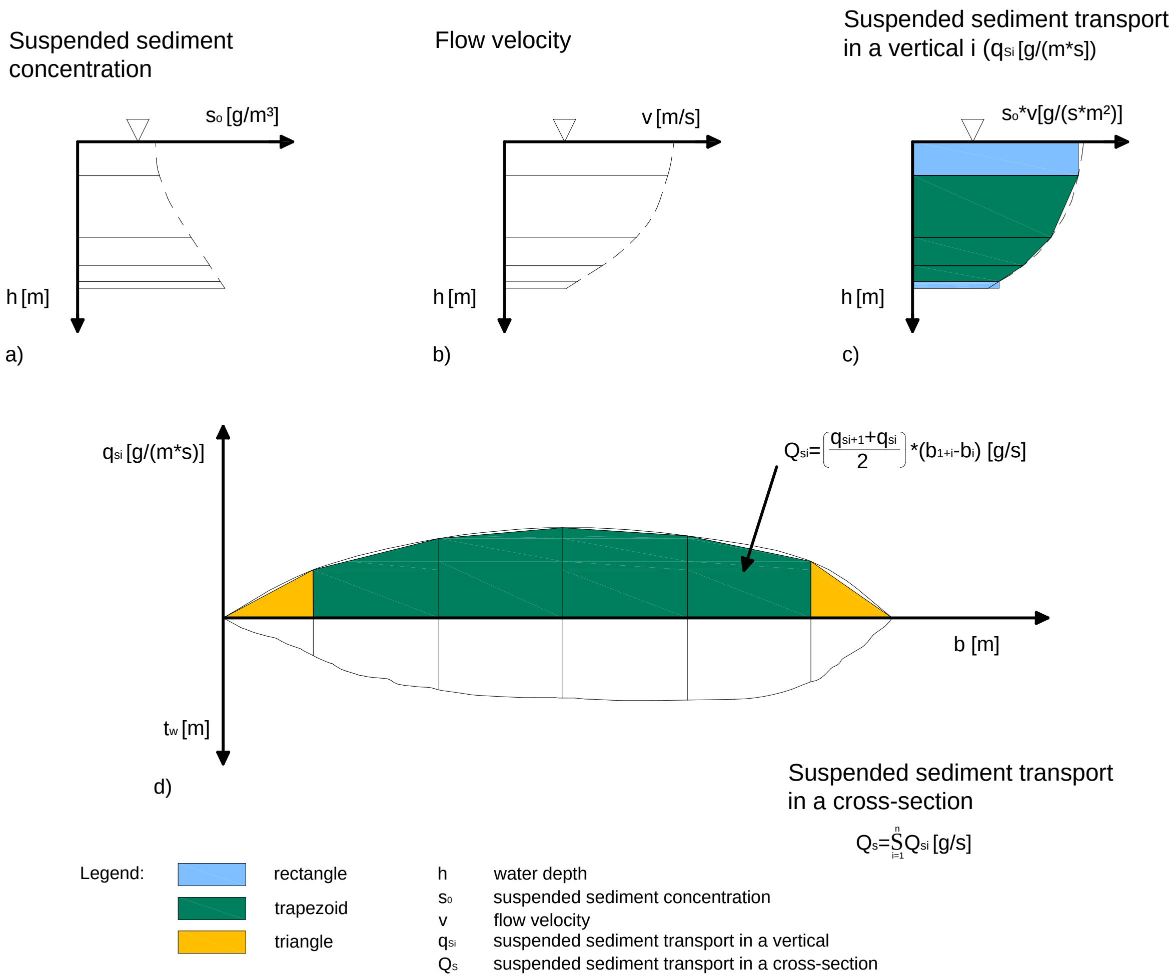


Figure 10 Cross-sectional analysis based on conventional multi-point sampling (after BMLFUW 2008; 2017 and DVWK 125, 1986)

Calculation of sediment load

1. Prior to the calculation of the sediment load, general data regarding the measurements and the laboratory analysis of the samples have to be entered into a measurement protocol. Information to be indicated is: time and location of the measurement, stage, applied devices.
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 protocolled.
3. The product of velocity (v) and sediment concentration (s_0) (specific discharge, [g/(s 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 10), while the areas close to the surface and the bed, where no measurements are available are approximated with rectangles (blue areas in Figure 10). The specific load in the vertical is the sum of these areas [g/s m].
4. The total suspended sediment load is calculated by integrating the vertically measured specific discharges along the width, which is shown in the lower half of Figure 10. At the bank, the load is zero, so the two sections close to the bank are approximated with triangles, (yellow areas in Figure 10), while the rest is approximated as trapezoids (green in Figure 10). The sum of the areas gives the total suspended sediment load in the verticals (Q_s [kg/s]).

SSC load based on the combination of multi-point sampling and 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 11). The theoretical background of this method is given in Baranya and Józsa (2013).

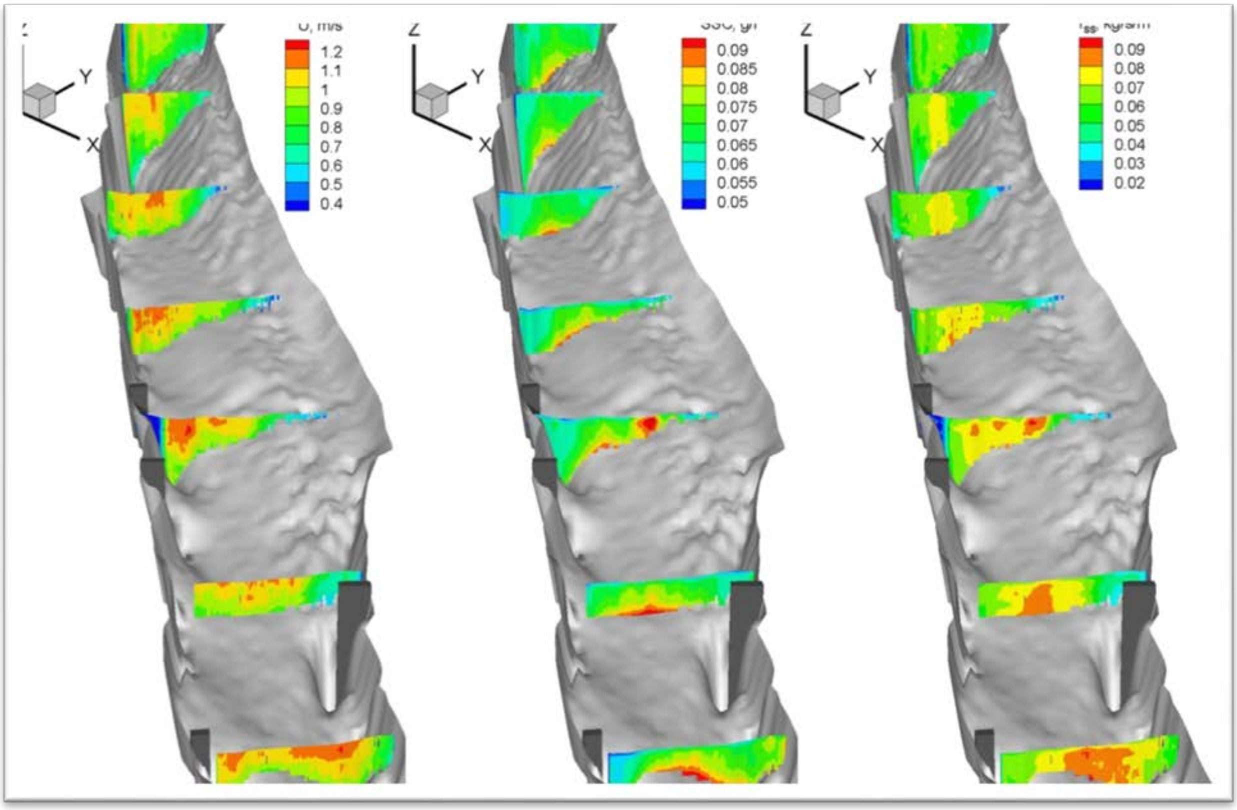


Figure 11 Spatial distribution of a) flow velocity, b) SSC and c) sediment flux in the Danube (Baranya and Józsa, 2013)

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

The idea behind this method is to find a correlation between suspended sediment concentrations (s_c) averaged along the cross-section (calculated from multi-point samplings and/or ADCP measurements; for details see previous sections) and a single-point sediment concentration measured at a fixed point, preferably near the bank (s_k). In order to set up such relationships, both values have to be measured simultaneously at 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.

The total suspended sediment load can be calculated as the cross-sectional average SSC 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.

Practical recommendations for suspended sediment monitoring

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),
- 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 maintenance of the monitoring stations, the following practical issues shall be considered:

Optical and acoustic sensors

- The instruments shall be able to measure suspended sediment concentration up to 50 g/l so that they can 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 (e.g. weekly) and therefore access is needed to operate them,
- Sensors 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 of sensors 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 daily 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, shape).

Monitoring of bedload

According to Lagrangian, particle based methods are a good choice for the scientific investigation of bedload movement, in the case of bedload monitoring, the Eulerian approach, which is the use of bedload traps, is more practical and convenient.

In bedload monitoring, the following parameters are to be determined:

- specific bedload transport [kg/sm],
- bedload mass [kg],
- grain size distribution of the bedload,
- initiation of bedload transport,
- spatial and temporal variability.

Additional parameters that should be determined for better interpretation of the bedload measurements are:

- flow velocity respectively bed shear stress
- spatial distribution of bed material characteristics 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.

Monitoring methods and strategies

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

- *Initial effect* – slow touchdown of the sampler onto the river bed, open the mouth of the sampler only after it is properly positioned on the bed.
- *Gap effect* – proper sampler design, use underwater video stream to oversee sampler operation.
- *Blocking effect* – correct mesh size, correct size of the sampler intake, video control.
- *Scooping (shoveling) effect* – use of stayline/sounding weight/anchor and a tether line or increase the weight of the sampler; avoid ship movement.
- *Subsidence effect* – metal or plastic plate under the sampler intake to reduce the pressure towards the river bed; video control.

- *Overfilling effect* – reduce sampling time; larger sampling basket.
- *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, the underwater behaviour of the sampler should be continuously observed.

Bedload sampling is to be repeated several times per year during different flow conditions so that bedload yield values are available for the whole discharge range, reducing the uncertainties from extrapolations. Having sufficient amount of measured data, relationships between discharge (Q) and bedload yield (Q_{BL}) can be established. These relationships need to be checked from time to time, since external (or even internal) effects can alter the transport patterns (Figure 12).

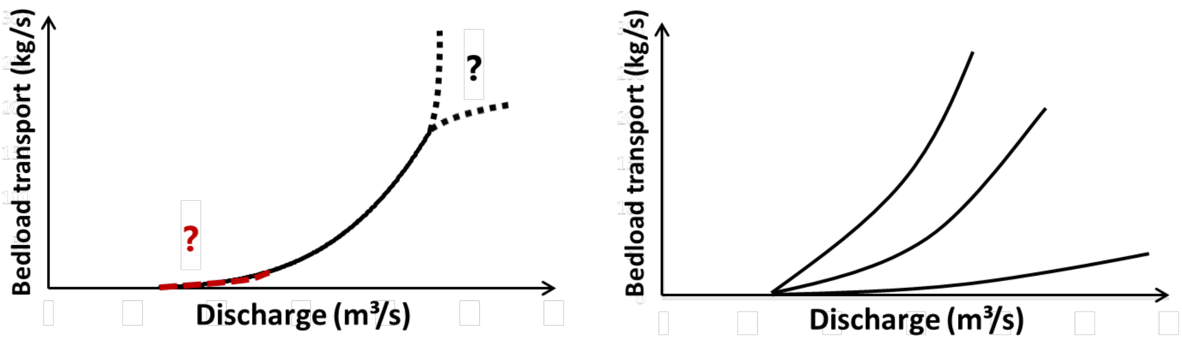


Figure 12 Uncertainty of extrapolations (left); example of the change of bedload relation with time (right (IWHW/BOKU))

Step 1: Bedload measurements

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 the 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. In order to obtain credible measurement results, the bedload sampler of choice has to be operated within the range of conditions it was designed for.

Required equipment

- suitable bedload sampler (Figure 13)
- crane, reel
- clean, closable sample containers (adequate in size for the sampled material)
- waterproof marker for labelling
- stopwatch
- measurement protocol
- toolbox
- security equipment
- underwater camera (optional but recommended)


Figure 13 Bedload samplers: Károlyi-type (left); modified BfG sampler (right) (IWHW/BOKU).

Bedload sampling methodology

1. The following data must be entered into the measurement protocol:
   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; location that the device is lowered from (i.e. 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 sampling is to be conducted in multiple (equidistant) verticals per cross-section. A special focus should be placed on the areas where the majority of the bedload transport is expected. 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 necessary strongly depends on the cross-sectional variation of bedload transport. Sand-bedded rivers are often active over the full width, whereas in a gravel bed river, usually only a part of the river width is active. More verticals (approx. 10-20) are required if the active area is unknown, while less verticals (5-7) are sufficient if its location is known.

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. 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. Sampling time is to be measured with a stopwatch.
4. The collected samples are emptied into the designated containers. If possible, take a photo of the sample including a ruler as size reference. Material loss should be avoided. Relevant information (sample ID., distance from null-point, sampling duration, etc.) is to be marked on the containers.
5. The previous steps are repeated for all verticals.
6. After the measurements, the following data should be protocolled: *water stage, discharge, water temperature, turbidity, neighbouring gauging stations, etc.*
7. The collected samples are to be analysed in laboratory conditions after drying.

Step 2: Evaluation of the measurements

Laboratory analysis

The analysis of the bedload samples is performed through sieving. Test sieving should be performed prior to the analysis, in order to determine the appropriate set of sieves (applied grain sizes). The smallest sieve sizes should also be determine based on the net or 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 consulting one of the various national or international standards on particle size analysis.

Required equipment

- Scale with precision of 0.1%
- Round-holed and square-holed sieves in psi and half psi units (e.g. 0.125 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, etc.) + additional sieves if necessary
- sieving machine (Figure 14)
- collecting pot
- sieving protocols

Figure 14 Sieving machine (IWHW/BOKU)

The sieving procedure

1. Sample weight is measured prior sieving (m_s), to reduce error of potential mass loss.
2. If necessary, merge samples from same vertical to meet the mass criteria.
3. Empty sieves are weighed (m_1).
4. Sample is sieved through the selected series of sieves. Note that particles smaller than 0.5 mm often need external help for proper sieving, which can be done with a fine brush.
5. After sieving, the sediment retained on the bottom pot (m_r) and the individual sieves (m_2) are weighed. The following equation must hold true: $m_r+(m_2-m_1)=m_s$ (mass conservation).
6. The size and weight of the largest particle (d_{max}) is determined.

Evaluation of the sieving results

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 15) comes from cumulating the 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}, D_{70}, 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.

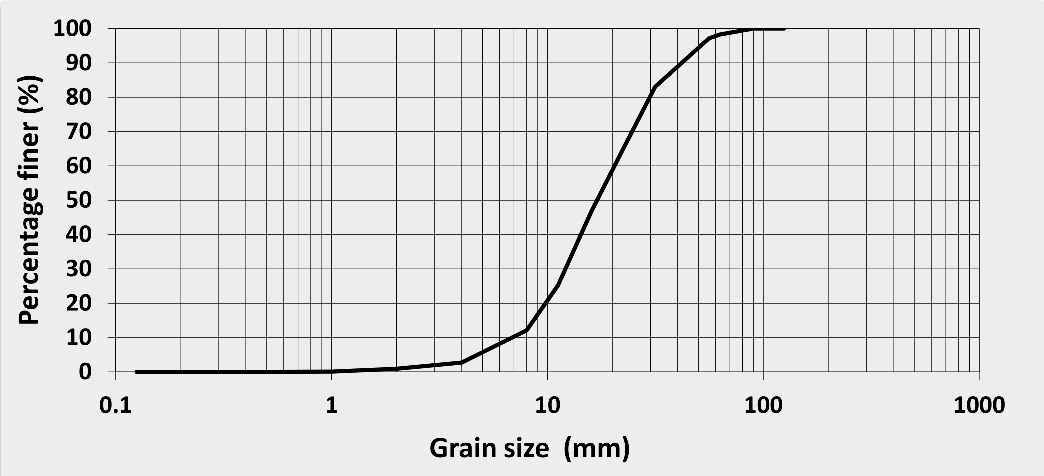


Figure 15 Grain size distribution of bedload sample (IWHW/BOKU)

Step 3: Determination of bedload sediment yield

Bedload transport expresses the amount of bedload transported through a selected cross-section (flux) over time unit, 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 16). 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).

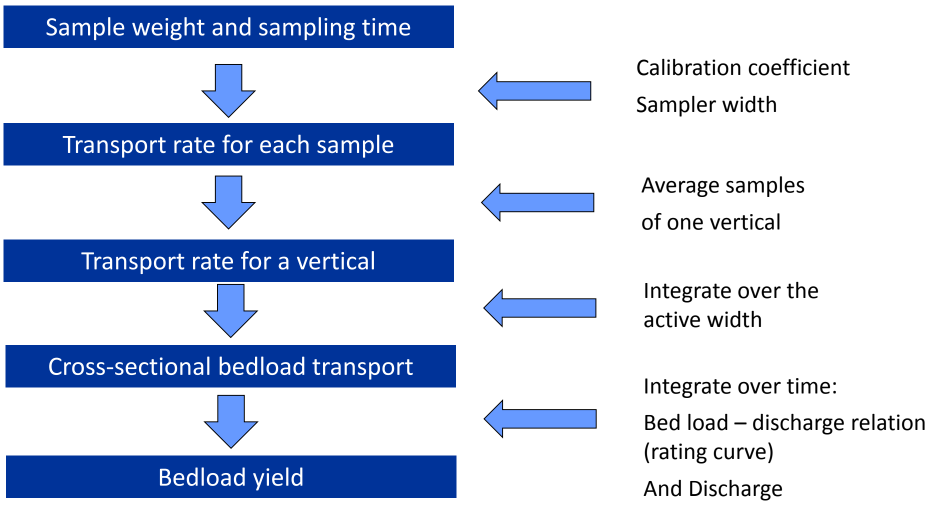


Figure 16 Steps to calculate the bedload transport and the bedload yield from cross-sectional bedload measurements (IWHW/BOKU)

Determination of total bedload yield

1. 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 17).
2. 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 the complete active width was not 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.
3. If available, the average depth averaged and the flow velocity near the river bottom should be indicated in the plot.
4. The area below the curve (middle of Figure 17, sand coloured graph) shows the actual bedload transport (g/s) or (kg/s), which is a function of discharge and water stage.
5. The calculated total bedload transport is noted into the evaluation protocol.

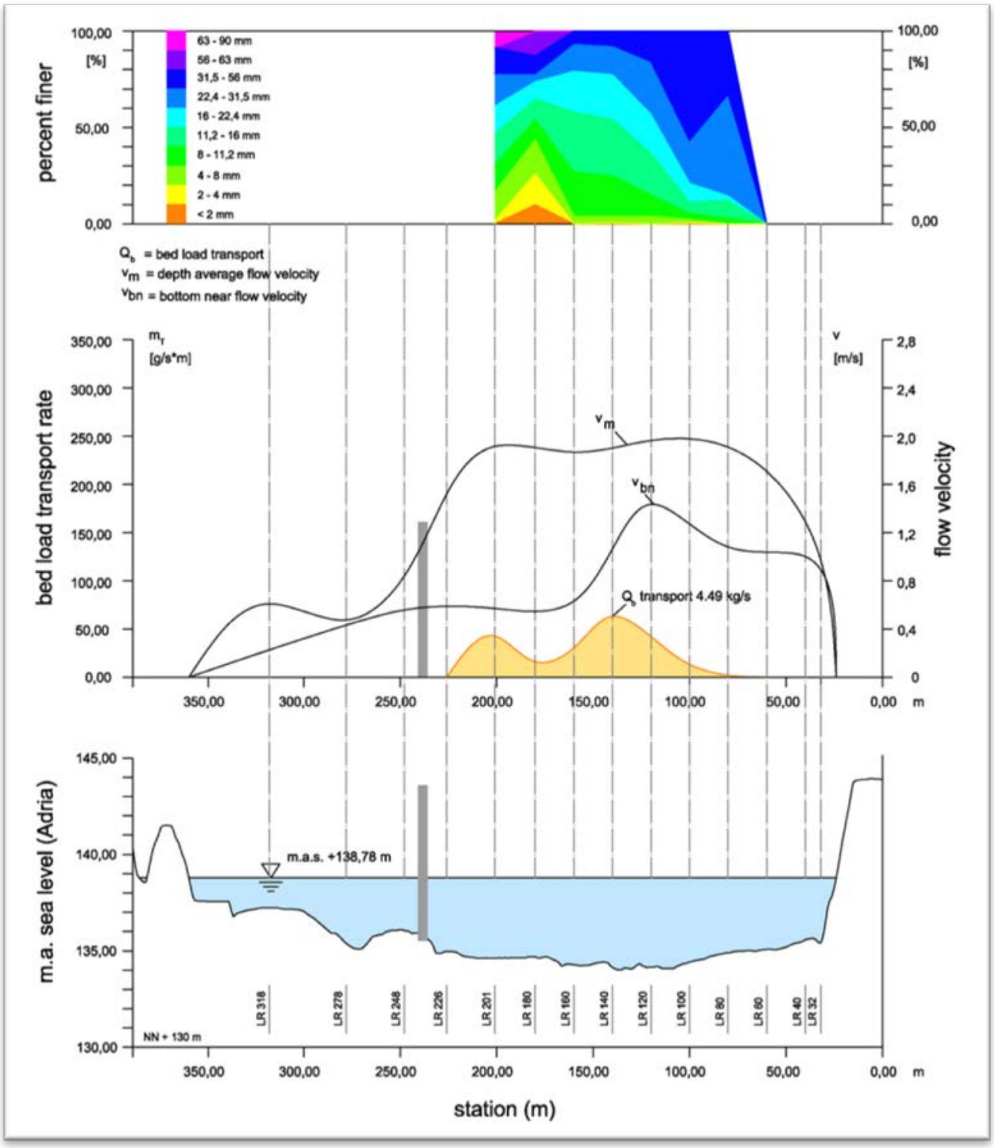


Figure 17 Cross-sectional distribution of hydromorphological parameters (IWHW/BOKU)

Determination of the bedload rating curve

The previously presented bedload sampling method cannot provide 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 18).

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

$$Q_{BL} = aQ^b$$

where Q_{BL} is the predicted specific sediment transport, Q is the water discharge, 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:

$$Q_{BL} = a(Q - Q_c)^b$$

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.

2. Using the discharge time-series and the previously determined function in the investigated cross-section, the (predicted) 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.

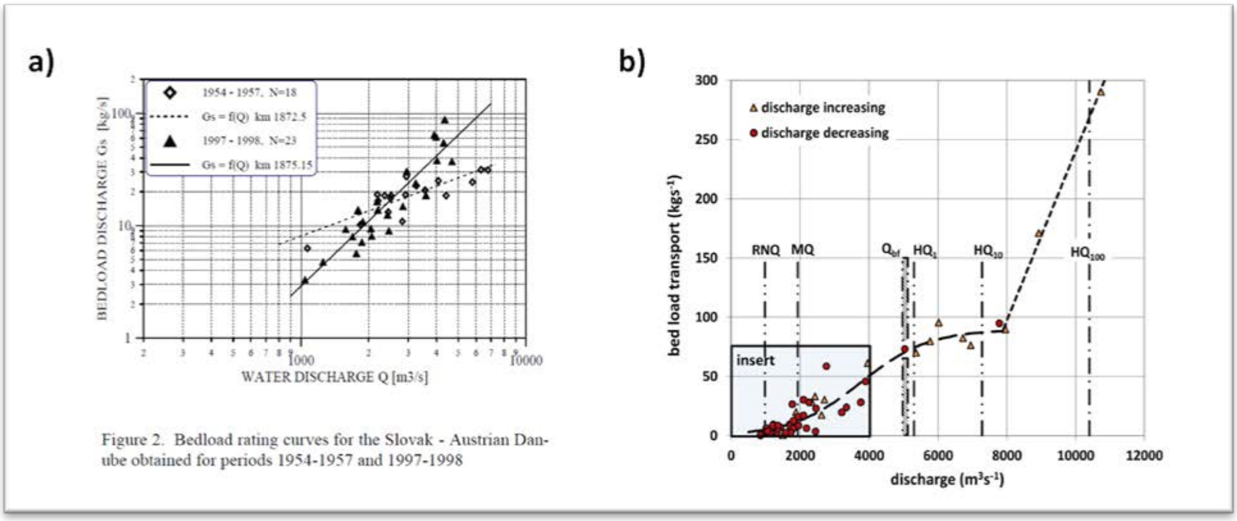


Figure 18 Two examples of bedload rating curves (QBL-Q relation) for the Danube. a) Slovak-Austrian Danube (Holubová et al., 2004); b) Austrian Danube, Bad Deutsch-Altenburg (Liedermann et al., 2017)

Practical recommendations for 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.

List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
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)
GSD	Grain Size Distribution
IWHW	Institute of Water Management, Hydrology and Hydraulic Engineering
LfU	Bavarian Environment Agency (Germany)
PSD	Particle Size Distribution
SS	Suspended Sediment
SSC	Suspended Sediment Concentration
SSL	Suspended Sediment Load
VUVH	Water Research Institute (Slovakia)

List of Symbols

B	Width of the Cross-Section
a, b	empirical parameters for bedload rating curves
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%)
H	Vertical depth
m_s	Sample weight is measured prior sieving
m_1	Weight of empty sieve
m_2	Weight of sieve with sediment
m_r	Weight of sediment retained on the bottom pot
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_{BL}	Bedload Transport
Q_C	Water discharge threshold (Q_c) below which no sediment transport occurs
q_{si}	Suspended Sediment Transport in a Vertical
s	Width of the Opening of the Bedload Sampler
s_k	Analytically Determined Suspended Sediment Concentration
s_0	Suspended Matter Concentration
$V_{b,m}$	Cross-sectional Bedload Discharge
V_p	Sample Volume
$V_{s,\,m}$	Suspended Sediment Load
Ψ	Grain Size on Base-2 Logarithmic Scale (in particle size analysis)

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