

Field measurements in hydromorphology

Riverine hydromorphological field
measurement course for MSc students
in civil engineering and geophysics

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Foreword

This lecture notes was prepared within the Inter-institutional Cooperation Projects in Higher Education of the EEA Grants Scholarship Programme. The project called 'Elaboration of hydromorphology field course for civil engineer and geophysicist students', shortly EEA HydroCourse was supported by the EEA Grants and Norway Grants.

In the frame of the EEA project the elaboration of new field measurement courses is proposed for hydraulic engineer and geophysicist students at the partner institutes. The main goal of the field courses will be to provide state-of-the-art knowledge on fluvial hydromorphological monitoring techniques for the participating students. The project partners are all well recognized institutes in the research field of river hydro- and morphodynamics:

- Budapest University of Technology and Economics (BME), Faculty of Civil Engineering, Department of Hydraulic and Water Resources Engineering
- Norwegian University of Science and Technology (NTNU), Department of Hydraulic and Environmental Engineering
- Eötvös Loránd University (ELTE), Faculty of Science, Institute of Earth Science, Department of Geophysics and Science

Although significant scientific research developments have been achieved in the last decade in the area of riverine flow- and sediment transport measurement methods, the developments have not yet been implemented in university curricula on a practical level. In fact, such a knowledge transfer to MSc education level has become necessary by now, as the fulfillment of the Europe-wide adopted Water Framework Directive is largely based on the hydromorphological conditions. Monitoring hydromorphology in its known interdisciplinary complexity, however, needs adequate, up-to-date instrumentation, the lack of which has been the primary obstacle for its full scale introduction in university framework. The EEA HydroCourse project supported the establishment of such a comprehensive field course, through a well-structured preparatory work and capitalizing the joint efforts of hydraulic engineer and geophysicist researchers in the two countries. Coupling up-to-date instrumentation and river monitoring methodologies would provide well trained engineers and geophysicists, the significantly improved knowledge of whom is urgently needed in a number of practical riverine activities at e.g. water and environmental agencies, national parks, fluvial navigation companies can be significantly improved.

The field course is included in the Master's programme at the Faculty of Civil Engineering at the Budapest University of Technology and Economics in the course entitled Hydromorphology. The course will be an optional course at the partner institutes.

1

Introduction

The research field of hydromorphology is relatively new, which is, similarly to the relationship between geology and geomorphology, a subfield of hydrology (Vogel, 2011). Hydromorphology deals with the origins, movement, morphological changes of waters, together with the natural and anthropogenic processes. Hydromorphology is also connected to numerous fields of natural and social sciences, such as geography, urban planning and environmental economics. The relevancy of hydromorphology has been clearly enhanced in the last century by the increasing anthropogenic impacts on water bodies. It also plays an essential role in the Water Framework Directive of the European Union, one of the most important tasks of which is the hydromorphological characterization of water bodies.

From the civil engineering and geophysics point of view the following processes and the interactions among them are relevant in hydromorphology:

- water flow,
- sediment transport,
- river morphology,
- river bed structure,
- main channel and floodplain interactions,
- influence of vegetation,
- habitat

Monitoring of river morphology, as a main feature of hydromorphology, is essential from several aspects. The morphological conditions and its changes can affect fluvial navigation, flood conveyance capacity, habitat conditions, operation of hydraulic structures as well as water quality. Consequently, not only water management directorates and agencies have interest in morphological surveys but activities related to economics, society, environmental protection, research all connect to issues related to hydromorphology.

The other essential feature of hydromorphological characterization of water bodies are the hydrological and hydraulic conditions.

The hydrological description of water bodies reveals typical and extreme water levels, discharges together with quantitative information on frequency and duration of these parameters. Finer scale hydrodynamic analysis of flow, on the other hand, can describe discharge, areal, cross-sectional and vertical changes of flow velocities based on which spatial flow features, sediment erosion and transport capacity can be derived.

Besides the morphological and flow characterization, hydromorphological measurements focus on the physical assessment of the bed material and the transported sediment in the water column. The following parameters are considered: bed material composition, stratification, rate and grain size distribution of bedload, particle size distribution and concentration of suspended sediment. The permanent development of sediment transport measurement methods leads to increasingly detailed, both on spatial and temporal scale, and more reliable sediment data compared to the conventional methods used a few decades ago. The more detailed and accurate information contribute to more reliable hydromorphological characterization.

Based on such hydromorphological assessment the varying sediment transport conditions resulted by extreme floods or human impacts, spatial and temporal behavior of morphological changes on the main channel and in the floodplain, negative processes for navigation, sedimentation of reservoirs and the interaction with riverine habitat can be estimated.

Numerous instruments can be found on the market to support hydromorphological measurements. All of the instruments certainly have their limitation though. Therefore, the selection of the adequate equipment is essential. The reliable measurement range depends on the physical parameters of the measured feature. For instance, the characteristic flow depth and flow velocity determine the suitable acoustic Doppler current profiler (ADCP), or the typical particle size and concentration determine the well-applicable optical and acoustic sediment measurement devices. Besides the measurement devices, the measurement and data analysis methods also play an essential role at the assessment. There are no standardized methods for hydromorphological measurements, but the required space and time resolution of the results suggest different procedures.

The curriculum of the field course was developed considering all the above described points. In this lecture notes the study sites, both the Hungarian and Norwegian ones, chosen for the field surveys will be first introduced. Next, the different measurement and data analysis methods will be described. The lecture notes also deals with the large scale morphological assessment of rivers and sample measurement protocols will be shown.

2

Measurement sites

2.1 River Danube, Hungary (Göd)

The measurement site in the river Danube was chosen near Göd, Hungary at the river reach between 1670 and 1664 rkm (2.1). In the 50's both the river reaches of Vác (1683-1678 rkm) and Göd (1666-1657 rkm) have been regulated. The prescribed depth and width parameters of the shipping route was *produced* through river trainings e.g. construction of groynes. River bank protection was also applied after the regulations. Between 1970 and 1982, more than 17 million m³ of gravel was dredged out upstream from Budapest, mostly in the area of Nagymaros and Vác. This resulted in about 50-110 cm decrease in the bed level and low water levels. The beginning and interruption of the construction of the dam at Nagymaros resulted in a completely new situation in this involved river reach. Significant regulation works have been completed, e.g. a new hydraulic river bed and shipping route, the river bank protection in both the right and left banks, a tunnel for the public utilities under the river or the construction of the galleries. At the moment this reach is under the control of the Middle-Danube Valley Water Directorate. The mean discharge at the studied river reach is about 1500 m³/s, the mean slope is 5 cm/km.



Figure 2.1: The measurement site at Göd

At the measurement site a smaller shallows developed, which de-

crease the water depth in the whole width of the Danube resulting in poor navigational conditions in a part of a year. In Figure 2.2 the location of this shallows is presented according to the surveys of the Directorate. Areas having the appropriate water depth are colored blue and it is well observable that the shallows results in a 80 meters wide narrowing in a 1400 m long reach. Two settlements are at the both sides of the river (left bank: Göd, right bank: Horány) which have direct connections to the river banks.

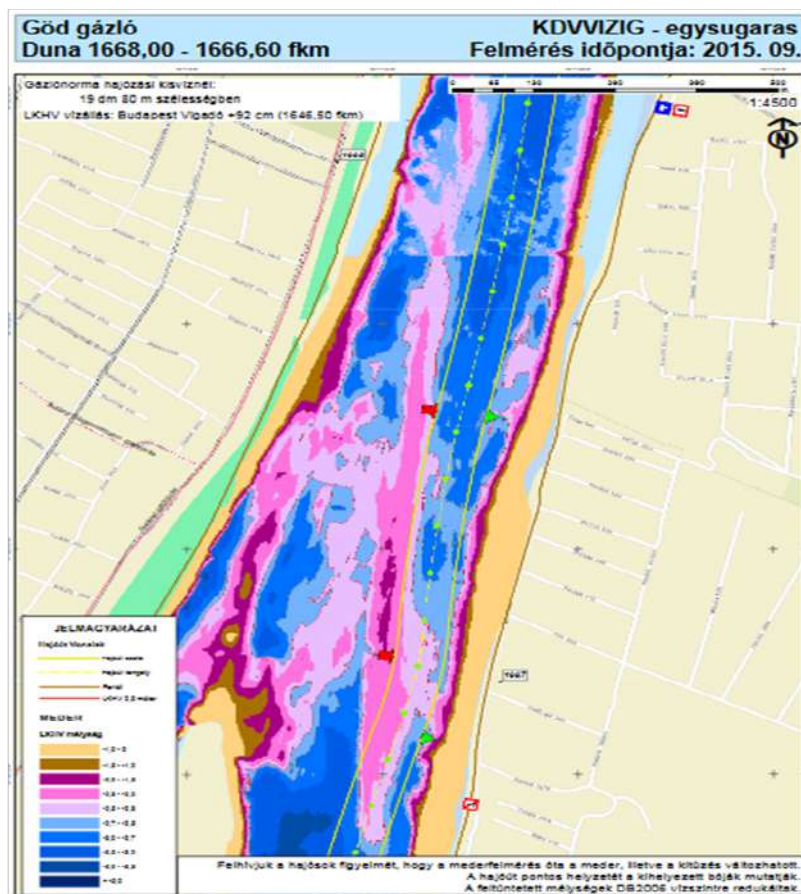


Figure 2.2: The shallows at Göd

According to the combined ADCP and RTK-GPS water depth surveys, Figure 2.3 presents a map of interpolated water depth data. The sediment deposition between the river training works and the scour hole at the 'nose' of the groins are well observable.

2.2 Lundesokna, Norway (Lundamo)

Lundesokna is a tributary of the Gaula on its right side. The measurement site is in the near of Lundamo. The stream is highly regulated, not its banks but its range of hydrograph by hydropeaking. The hydropower system of Lundesokna consists of three powerplants and their artificial reservoirs with a total average energy production of 278 GWh per year. The area of the river basin is 243 km². The study site is situated on the downstream side of

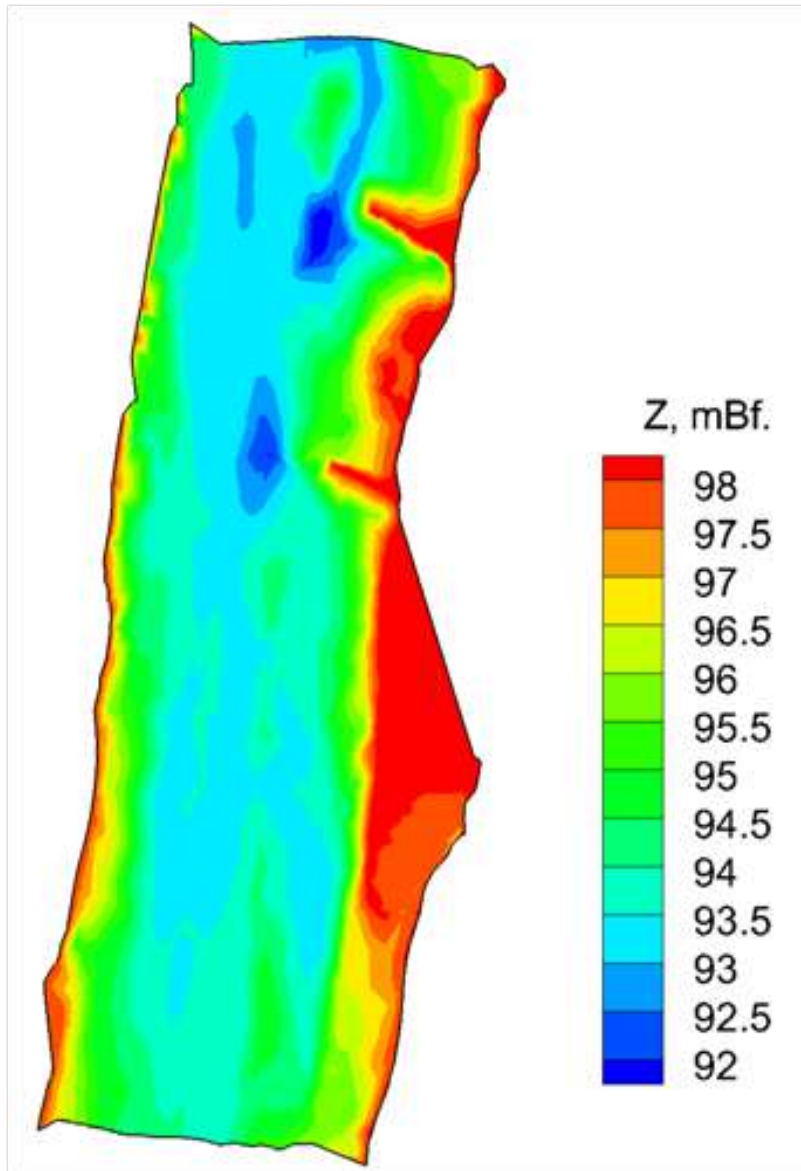


Figure 2.3: Interplated water depth map of Göd measurement site

the last powerplant, before it reaches river Gaula. This reach is 2.1 km long and due to regular hydropeaking operation its average discharge varies between $0.45 \text{ m}^3/\text{s}$ and $20.0 \text{ m}^3/\text{s}$. As it is shown in the Figure 2.4. Lundesokna is the outlet part of a complex hydro-powerplant system. The described river site used to have a very good potential of salmon spawning long time ago, but during the last decades the population of young salmonids decreased here and almost vanished. This is the reason why it is chosen to simulate the long term sediment changing under regulated and natural flow conditions.



Figure 2.4: Satellite photo about the measurement site in Lundesokna

2.3 Gaula, Norway (Kvål)

The river Gaula is located in Sør-Trøndelag region, Central Norway. The source of the river is located around 950 m above sea level, near the Swedish border, and flows through the region until it reaches Trondheimsfjorden. With its 145 km length and 3661 km² catchment area it is one of the largest rivers of the county besides the river Nidelva. The river is not regulated which causes its discharges vary between 1-20 m³/s in winter time and 6-700 m³/s during late-spring, early-summer flood. At mean discharge most of the gravel banks are usually dry, and with the shallow water depth it is easy to get bed material samples. The next figure (Figure 2.5) shows the site where most of the samples were taken in 2010 and in 2015. The sampling site at Gaula is located 8 km downstream of the point where Lundesokna enters river Gaula.



Figure 2.5: Satellite photo about the measurement site in Gaula

A particular characteristic of this measurement site, is that a bridge spans over the river which makes it possible to conduct

proper suspended sediment samplings as well. The next two figures show the views from a bridge over the river Gaula in the upstream and the downstream direction, respectively. (Source: Google Street View).



Figure 2.6: Measurement site Gaula from the bridge, upstream direction



Figure 2.7: Measurement site Gaula from the bridge, downstream direction

3

Measurement of river topography

3.1 Measurement devices

Many measurement devices are available in the market which utilize the Doppler-effect. Manufacturers offer tools with various geometries so one could easily find an adequate device to conduct measurements with in different water bodies, such as rivers, lakes or oceans as well. In the following sections, the instruments possessed by the Department of Hydraulic and Water Resources Engineering of the Budapest University of Technology and Economics will be briefly presented.

3.1.1 Acoustic Doppler Current Profiler (ADCP)

As the name of the device suggests, the ADCP utilizes the Doppler-effect to conduct fast, indirect flow velocity measurements. In order to perform three-dimensional velocity measurements the device needs to have at least three (usually three or four) signal emitters and receivers (Fig. 3.1). In the case of ADCPs, this two structural parts are located at the same place on the device and called the “heads” of the device.

Figure 3.1: Four-headed ADCP device.





Figure 3.2: RTK-GPS and data recording computer.

Since the device is usually fixed to a boat, which also moves in most of the cases, the georeferencing of the measured data is not as straightforward as in case of near-bank measurements, where it is sufficient to gather the spatial coordinates of the device only once during a field campaign. In order to overcome this problem, ADCPs are usually used together with an RTK-GPS, which is located in the vertical axis of the device (Fig. 3.2). This installation ensures that the data collected during both fixed and moving boat measurements are georeferable during post-processing.

The propagation velocity of the signal (sound) may be considered constant with a value of approximately 1500 m/s, if the temperature of the water is between 5 and 22 °C, and the water depth does not exceed 100 meters. Knowing the propagation velocity and measuring the time between the emission and reception of the signal, one could calculate the distance between the emitter and the particles from which the sound was reflected. Using this principle, the device is also able to map the geometry of the riverbed as well: signals coming from the farthest are reflected from the bottom and these distances can be transformed to actual water depths if the angle between the heads and the vertical direction is properly taken into account.

The quick, detailed measurement of the cross sectional velocity distributions and cross section geometries provides the opportunity to conduct fast (5 minutes in Daube scale) discharge measurements, which makes the dives widely employed by the hydraulic engineering and academic society as well.

Theoretical background of acoustic Doppler velocimetry

NOWADAYS, different acoustic measurement devices have a fundamental role in hydraulic engineering practice, both for field and laboratory investigations. Despite these devices are available in various sizes, geometries and offer different sampling rates for different sampled volumes, the physical law they utilize is the same.

As the name suggests, the device exploits the Doppler-effect to conduct quick velocity measurements, which is the following: if a source of the signal (sound) moves with a relative velocity compared to the receiver, the frequency of the sound changes. The change of frequency between the receiver (f_r) and the source (f_s) is a linear function of the relative velocity between them (v_{rel}):

$$f_r = \frac{v_{rel}}{c} \cdot f_s \quad (3.1)$$

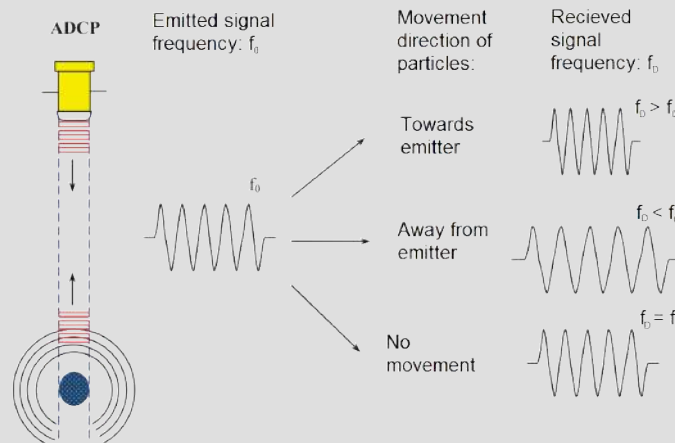


Figure 3.3: Changes in frequency due to the Doppler effect in different cases

Acoustic Doppler velocimeters measure the flow velocity indirectly. The device emits sound signals to the water, which are reflected from particles transported by the fluid flow (microorganisms, suspended sediment, bubbles) and a part of these reflected sound pulses travels back to the receiver of the device. In the majority of the cases, especially in natural conditions, these particles are present in the water with quite high density, therefore, the continuous sampling is ensured. Assuming that the traveling velocity of these particles is equal to the actual flow velocity, the following connection stands:

$$f_r = 2 \cdot \frac{v_{flow}}{c} \cdot f_s, \quad (3.2)$$

where v_{flow} is the relative velocity between the particles and the receiver: the flow velocity.

Aquadopp High Resolution (HR) profiler The Aquadopp is a specific ADCP device, which measures 3D velocity vector profiles along the water column, but in contrast with the regular ADCPs it does with higher spatial and temporal resolution thanks to the high resolution (HR) firmware.¹ The device had been designed to fit a wide range of applications, hence is deployable in lakes, rivers or even in oceans up to a depth of 100 meters. The Aquadopp is relatively small compared to regular ADCPs, and also available in many different geometric configurations to make it suitable for various conditions. This device, is usually not used from boats, but is fixedly deployed at the bottom.

¹ 8 Hz instead of 1 Hz; subcentimeter instead of subdecimeter

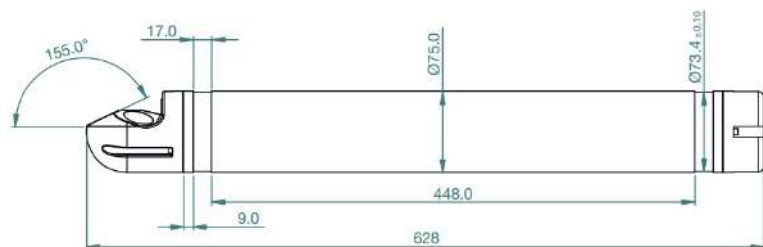
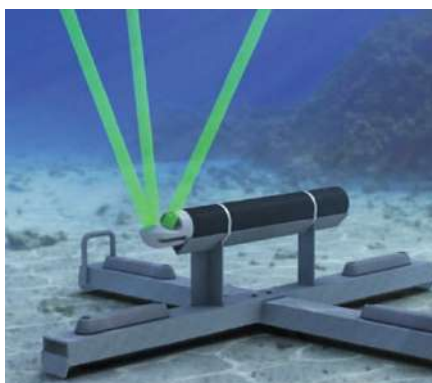


Figure 3.4: Aquadopp high resolution (HR) profiler.

Both the operation and the geometry of the Aquadopp device is very similar to classic ADCPs (Fig. 3.4). In terms of sampling frequency, on the other hand, the device is closer the ADVs, which

are to be presented in the following subsection. The capability to conduct high time resolution velocity measurements (8 Hz) makes the device able to identify turbulence as well, which is of great importance when dealing with turbulence related phenomena. Since one of its main area of use is the measurement of waves, a pressure sensor is also implemented in the device.

Note, that based on the configuration of the device, it also has a blind zone right above the head, where no data is collected (just like as it is with the regular ADCP). Due to the geometry of the device (divergent beams), the further the sampled water volume is from the head, the bigger the spatial averaging is, hence the measured data points along the profile are less and less considerable as single points values.

3.1.2 Acoustic Doppler Velocimeter (ADV)

The ADV, however also exploits the Doppler-effect to perform velocity measurements, comes with a different geometry and serves a different purpose as well. In contrast with the ADCP, where the main goal is to perform quick, usually large scale e.g. cross sectional velocity measurements, the ADV samples only a small (1 cm^3) water volume. ADVs measure three-dimensional flow velocities with high temporal resolution (up to 32 Hz) which makes it a perfect tool for measuring turbulence related parameters in such a small volume, which could also be considered a single point.

The device, similarly to the ADCP has three or four signal receivers which are responsible for receiving the reflected signals, emitted from the vertical axis of the device. Completing the necessary transformations which are implied by the geometry of the device, the 3D velocities are obtained in a Cartesian coordinate system.

The Nortek Vector, which comes with three receivers, is suitable to measure 3D velocity vectors in a single point, however, due to its geometry (Fig. 3.5) it is rather sensitive to the components with the direction parallel to its main vertical axis. In order to prevent bad quality measurements, it should be deployed with respect to this weakness, if possible. In most of the cases, however, the device can be still properly employed as the vertical velocity is usually of less interest to us, than the horizontal components. The Vector also comes with a pressure gauge, which is very practical when conducting wave related flow measurements.

The Nortek Vectrino is very similar to the Vector, however, it is much smaller and comes with four receivers (Fig. 3.6). This additional head comes with an important advantage over the Vector: at every sampling, it has an additional velocity value measured, which can be used to improve the quality of the otherwise weak, vertical velocity component. The Vectrino is basically designed to conduct laboratory measurements, however, in areas of lower velocities such as lakes, or the littoral zone of a river, its field application is also



Figure 3.5: The Vector



Figure 3.6: The Vectrino

possible.

ADV's are usually operated at high sampling rates (8-32 Hz), so turbulence related velocity fluctuations could appear in the time-series. This, on the other hand, necessary comes with more erroneous measured data, which are to be removed prior any further post-processing. Further details and information about the presented instruments can be found on webpages of the manufacturers: <http://www.teledynemarine.com/>, <http://www.nortek-as.com/en>.

3.2 *Flow measurements with the ADCP device*

The quick spreading of the ADCP in the hydraulic engineering society was induced by its applicability in fast and efficient discharge measurements. This popularity also resulted in the fact, that a number of scientists and researches started to develop methods to derive further parameters and values from the measurements beyond the originally offered water depth and flow velocity. The calculation of these generally hydromorphological parameters is not included in the software offered by the manufacturers of these devices, as these methods are still subjects of ongoing research and development. ADCP measurements for example can be utilized to estimate the bed load or the suspended sediment load of rivers (Baranya and Józsa, 2010). Such methods are going to be presented in detail in further chapters.

In the following subsections, the different ADCP measuring techniques will be presented. The presented measurement and post-processing methods all support the proper hydromorphological surveying of a river reach, hence the ADCP device plays a fundamental role in the field course.

A usual measurement goes like as follows: given is an ADCP device, an RTK (Real Time Kinematic) GPS and a portable computer (Figures 3.1. and 3.2). The GPS is firmly and carefully fixed above the ADCP in its vertical axis to ensure the highest possible accuracy for the georeferencing. The ADCP is firmly fixed to the boat from which the measurements are conducted and is set to have its head underwater, approximately 20-30 cm from the water surface. This is necessary in order to ensure that the device remains under water at all conditions, otherwise erroneous data will corrupt the measurements. However, the device should also not be too far from the free surface, as it cannot perform measurement above its head. The device also has blank zones, right under the head, and in the close proximity of the river bed. This, however, does not mean that these empty areas are completely neglected from the measurements, as the data recording software extrapolates plausible values to these regions as well. Similarly, in case of cross sectional measurements, extrapolation is used to estimate the velocity and bed geometry as well for the near bank regions, which are not approachable with the measurement boat (due to low water depths or vegetation). The cross-sectional area of these regions is approximated with a right-

angled triangle, whose legs are the distance from the bank and the actual water depth at the point.

The computer is not only responsible for collecting and saving the ADCP and GPS data, but the software used for the measurements (WinRiver) also continuously performs their synchronization, moreover, visualizes the raw, instantaneous measured data.

Fig. 3.7 presents the Dunube in the area of Sződliget, where an extensive ADCP survey had been conducted. The figure also presents the three most common types of measurements: fixed, general moving boat, and cross-sectional measurements (Baranya et al., 2008).

Figure 3.7: Path of ADCP measurements conducted in the Danube in the area of Sződliget.



3.2.1 Moving boat measurements

The most common way to use the ADCP device, is to perform moving boat measurements, usually along cross-sections of the river. This method reveals the cross-sectional distribution of velocities, the thalweg can be identified, and zones with recirculating flow features can also be easily identified. Simultaneously with the velocity measurements, the ADCP also measures the water depth at every sampling, hence the profile of the river bed is also obtainable, which implies the determination of the discharge as well. Raw velocity data from a cross-sectional measurement is presented in Fig. 3.8.

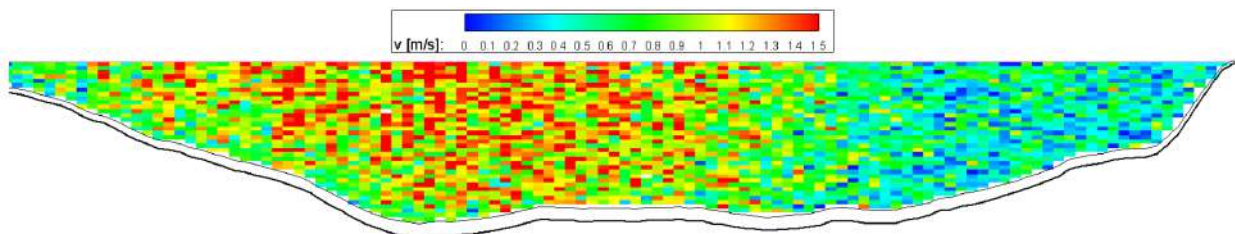


Figure 3.8: Raw cross-sectional velocity distribution measured with ADCP.

A mosaic nature of the measured velocities points (cells) is observed on the figure presented above. The vertical resolution of the measurements can be adjusted by the user with the data recording software (WinRiver); the horizontal resolution is the function of

the sampling frequency (in this case 1 Hz) and the velocity of the measuring boat. If the sampling frequency is f [Hz] (f samplings per sec) and the boat travels with a constant velocity of v [m/s], then the horizontal side of the sampled cells will be v/f [m] wide. This means that the proper choice of travel velocity with the boat is important, as too high speed may reduce spatial resolution and also can result in worse quality data. Beyond the mosaic nature of the measurements, the inconsistency of the velocity distribution is observed as well. This noise, however, does not a result of bad measurements or some device error, but is a manifestation of turbulence (fluctuating velocities). These fluctuations, however, can be time-averaged, if we measure a single vertical for 1-2 minutes, which is the main idea behind fixed boat measurements (to be discussed later). In order to get a smoother velocity distribution from the raw data presented in Fig. 3.8, (spatial) moving averaging can be applied (Fig. 3.9).

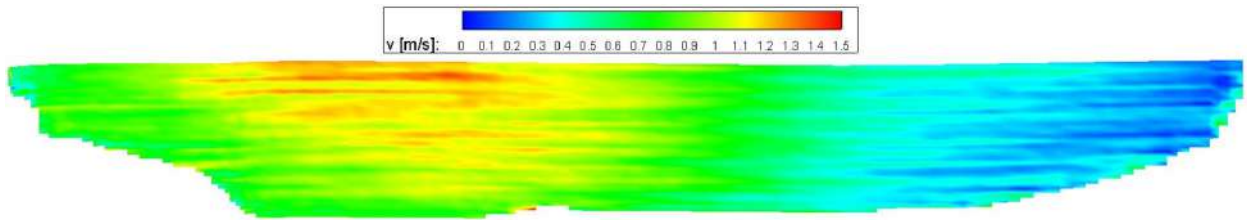


Figure 3.9: Smoothed velocity distribution achieved by the moving averaging of the raw data presented in Fig. 3.8.

In the possession of digital elevation model of the river bed, and more of the above presented cross sectional velocity distributions, the proper post-processing (visualization) software may take us a step further towards understanding the local connections between the observed flow features and the morphology of the river bed. The topological model of the study site (interpolated from the depth measurements of the ADCP), and the cross-sectional velocity distributions are presented in Fig. 3.10 for different flow rates.

If cross-sectional or other general moving boat measurements are available for a studied reach in high spatial density, depth-averaged, horizontal velocity distributions can be evaluated with the interpolation of the gathered data to a triangulated mesh. Fig. 3.11 presents such interpolated velocity fields for different flow rates. The thalweg is well represented in the velocity fields, moreover, in the proximity of the groins, the low velocity zones are also could be observed.

The presented velocity distributions (both in two- and three-dimensional view) all well support the calibration and verification (Baranya and Józsa, 2006) of computational fluid mechanics (CFD) models.

Previously only the magnitude of the velocities have been presented, however, as it has been mentioned earlier, the device actually measures three-dimensional velocity vectors. These vectors obtained by moving boat measurements can also be interpolated

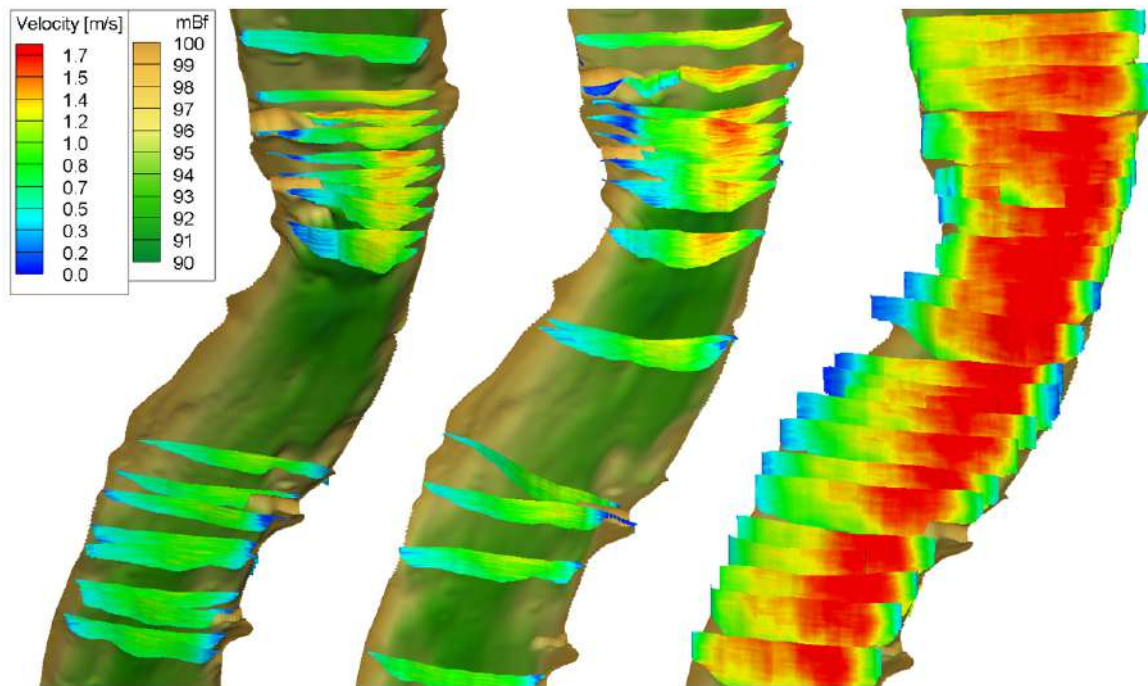


Figure 3.10: Three-dimensional view of cross-sectional velocity distributions at different flow rates.

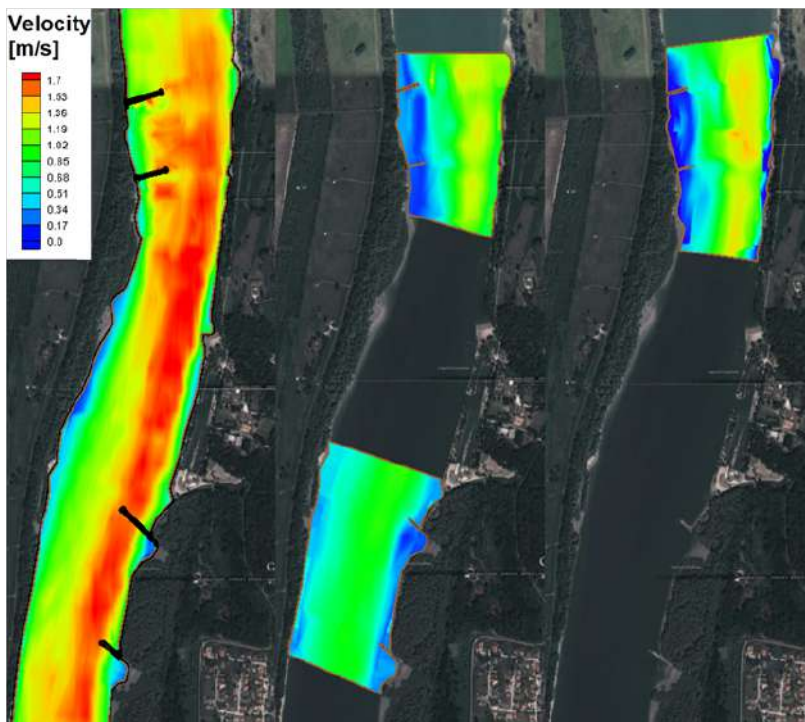


Figure 3.11: Depth averaged velocity distributions at different flow rates.

to a triangulated mesh, so one could achieve a smoother and continuous velocity vector field. In this case, we are usually not that interested in depth averaged vectors, but in the changes along the vertical axis. Fig. 3.12 presents interpolated surface velocity vectors in the proximity of two groins, which highlights the recirculation appearing between these structures and the displacement of the thalweg as well. In conclusion, it is clear that the vector-type representation of the measured data provides a rather clear and spectacular overview of the flow features.

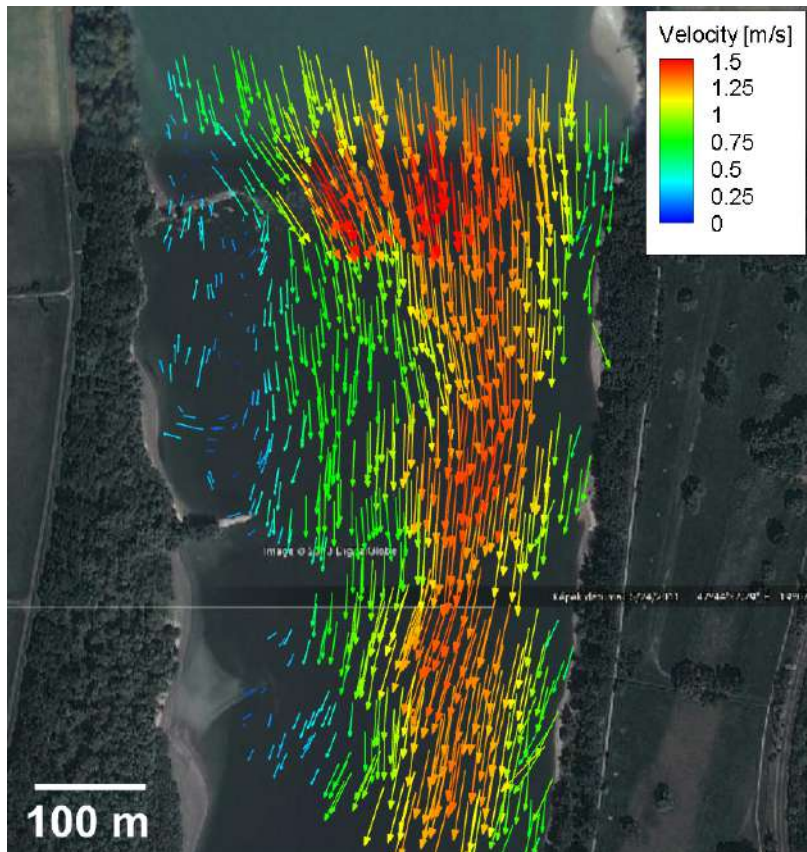


Figure 3.12: Velocity vector field near the surface, interpolated from the ADCP measurements.

It often happens, that one is not only interested in the cross-sectional velocities, but special focus is required on areas with high complexity (e.g. in the proximity of structures built in the flow or river confluences, etc.). In these cases, supplementary moving boat measurements are to be completed to scan the whole area of special interest. In Fig. 3.7, a path of such scanning measurements were presented as “general moving boat” measurements.

3.2.2 Fixed boat measurements

Fixed boat measurements are usually conducted to evaluate different hydromorphological parameters (e.g. shear velocity, hydrodynamic roughness height) from time averaged velocity profiles measured in a single vertical. As the name suggests, this is achieved by

fixing the boat in the very close proximity of a horizontal coordinate through anchoring for example. The main idea behind fixed boat measurements is to eliminate the effect of turbulent velocity fluctuations from the measurements (these were observed at the moving boat measurements in Fig. 3.13) through time-averaging. It has been reported that approximately 2-3 minutes of continuous sampling is sufficient to eliminate these effects, so the measured, time-averaged velocity profile is in very good correlation with the theoretical profile given by the law of the wall (Schlichting, 1955):

$$U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \quad (3.3)$$

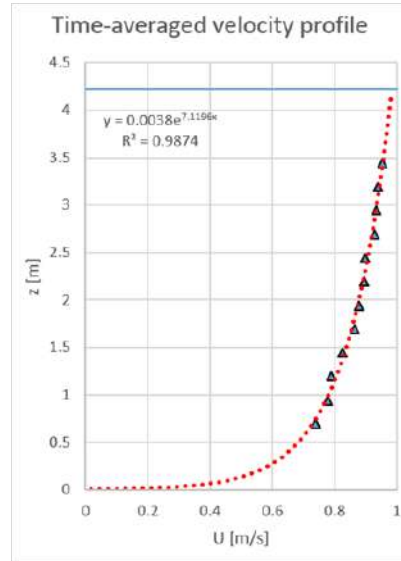
where $U(z)$ is the flow velocity at z distance from the bed, u_* is the bed shear velocity, κ is the von Kármán-constant² and z_0 is the hydrodynamic roughness height

² $\kappa \sim 0.4$

As it has been presented before, due to the blind zones of the ADCP device, it cannot provide velocity data in the close proximity of the surface, or close to the bed. However, adequate fixed boat measurements can be used to fit a logarithmic regression curve to available data, so velocity estimations can be made to these areas as well (Fig. 3.13).

Figure 3.13: Logarithmic regression curve fitted to time-averaged velocity data collected with fixed boat ADCP measurements.

Note, that due to the conventional representation of the velocity profile ($z(U)$ instead of $U(z)$), the profile presented in Fig. 3.13 is actually an exponential function.



Knowing the exact equation of the velocity profile, the opportunity rises to approximate the two unknown parameters of the equation: bed shear velocity and hydrodynamic roughness height. These parameters play a major role in bed-load transport, hence it is essential to have a good assumption to their values. Their evaluation from the equation can be easily performed through plotting the function in a semi-logarithmic coordinate system. In this representation, the logarithmic function becomes a linear function (Fig. 3.14) with two parameters to be evaluated: steepness (m) and the y -intercept (a).

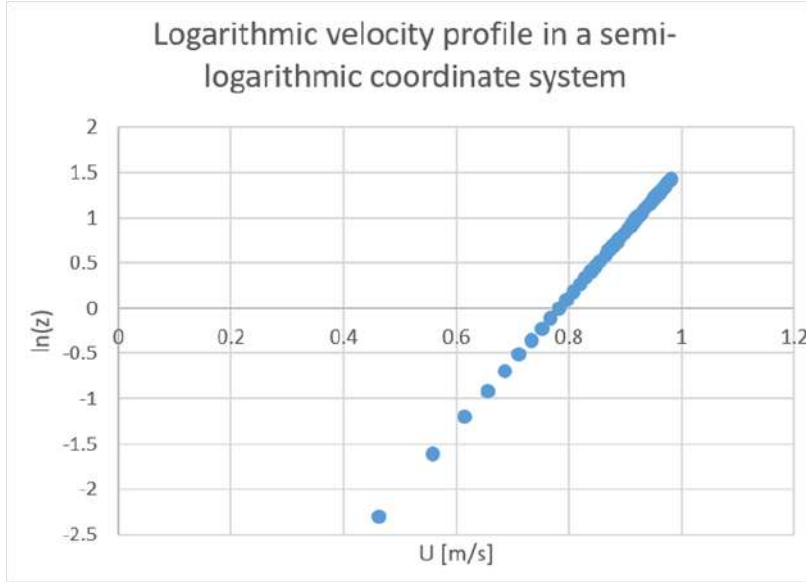


Figure 3.14: Logarithmic velocity profile in a semi-logarithmic coordinate system.

Based on the steepness, the bed shear velocity can be derived:

$$u_* = \frac{\kappa}{m} \quad (3.4)$$

from which, the bed shear stress, which is the main driving force of bed load transport, can be calculated as follows:

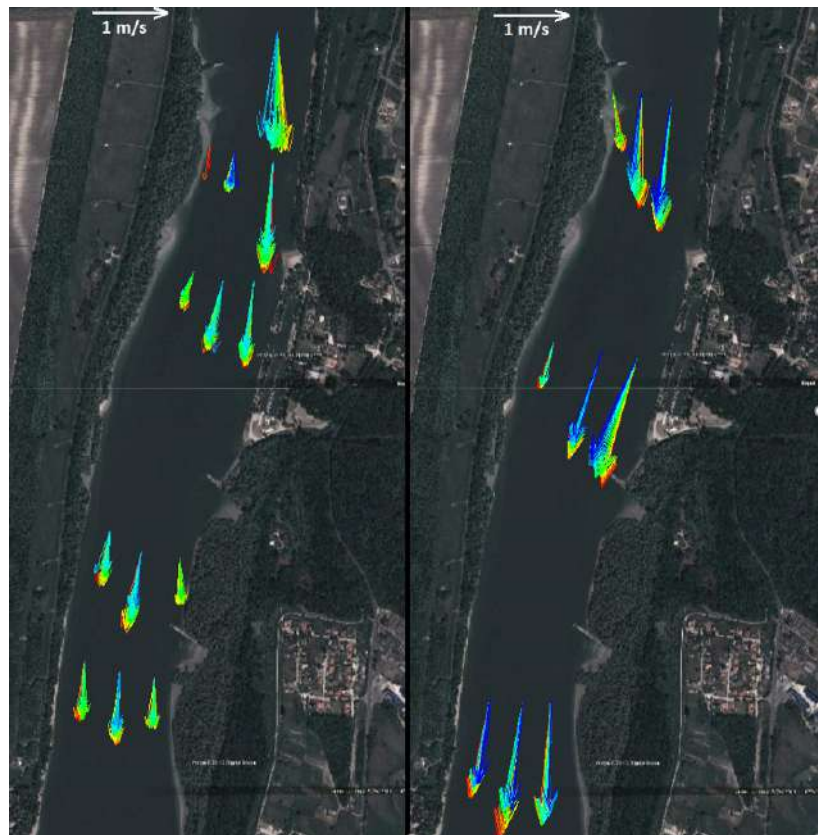
$$\tau = u_*^2 \cdot \rho \quad (3.5)$$

where ρ is the density of water. The hydrodynamic roughness height can be evaluated based on the y -intercept:

$$z_0 = e^a. \quad (3.6)$$

Plotting the time-averaged velocity vectors from different water layers in the same vertical may reveal the presence of secondary flow features. Plotting these vector groups for all fixed boat measurements on a plan view map of the investigated river reach, one might assess the three-dimensional nature of the flow (Fig. 3.15). Considering the curvature of the river, the expected secondary flow features do appear in the measurements. It is observed, that the intensity of these three-dimensional nature is locally different in the two conditions, hence these features not only depend on the topology of the riverbed, but on the flow rate as well.

Figure 3.15: Time-averaged velocity vectors in different water layers from fixed boat measurements at mean (left) and high (right) flow rates. Vectors are colored based on their distance from the bed: blue – near-bed; red – near-surface.



4

Geodesic and bottom morphological surveys

4.1 Introduction

IN HYDROMORPHOLOGICAL ANALYSIS it is essential to have measured data regarding the bed topology. The main aim of the surveying determines the required spatial resolution of the elevation model. Needlessly lowering the spatial scale of the measurements will result in higher resolution and more dense data, however, the duration of the field campaign may increase significantly, as well as the amount of data to be processed. Considering these factors, the suitable resolution has to be selected.

In riverine settings, two main morphological units have to be distinguished. The so called main channel, which determines the primary route of the flow and the floodplain which only gets under water during high water conditions and floods. The surveying of these different morphological units usually requires the employment of different measuring techniques.

4.2 Main channel survey

4.2.1 Horizontal positioning

Horizontal positioning of the measurements can be easily achieved by using up-to-date instruments. GPS¹ devices may provide centimeter accurate positioning, which is more than enough for hydromorphological investigations.

¹ Global Position System

The most widespread method for obtaining horizontal coordinates is using the GNSS². This procedure results in approx. 30 meters of accuracy which might be further improved (up to ± 1 m) with an amplifying satellite system. This accuracy is, however, not suitable for riverbed surveying, thus additional corrections must be carried out. To do so, auxiliary measurements are to be done. RTK³ GPS tools perform this correction automatically, through using real time data provided by transmitting bases on the ground. This way, the RTK GPS may provide coordinates with an accuracy of a

² Global Navigation Satellite System

³ Real Time Kinematic

⁴ Ultra-Short Wave

few centimeters. Data transmission can be done via satellite system, USW ⁴ radio, GPRS data transfer or through a GSM modem. The data processing is automatically done by the instrument, thus the correction of the ground bases does not mean an additional task for the user. In case of real time correction, not only the accuracy of the measurement can be improved but the precision of the process may also be derived. However, the GPS system provides with the opportunity to obtain not only the horizontal, but the vertical location of the measured point as well, in case of the surveying of the river bed the vertical location is obtained with different methods, because of obvious reasons.

4.2.2 Vertical positioning

Determining the vertical coordinates of the riverbed is always done simultaneously with the horizontal positioning. It is achieved indirectly through three different steps as follows. The altitude of the water surface and the water depth can be measured at each point with an RTK-GPS for example. The altitude of the riverbed then can be evaluated with the following equation:

$$z_{bed} = z_{surface} - d \quad (4.1)$$

where z_{bed} is the altitude of the riverbed, $z_{surface}$ is the altitude of the water surface and d is the water depth at the given point.

It is noted, that the water-level and the water depth must be measured at the same time. Since the continuous measurement of the free surface is not feasible, simplifications can be made. In case of very short river sections (up to app. 1 km) the water surface should be measured in a single point then the assumption of a horizontal free surface can be made. For longer river reaches, the water surface should be measured in several points (longitudinally) so the elevation of the surface then could be determined with linear interpolation. In most cases this procedure is adequate to define the water surface for longer sections. The water-levels can be measured using an RTK GPS, but most of the time it is sufficient to check a verified water gauge. The changes in the water level during the measurements (e.g. during flooding) also have to be taken into account, as these temporal changes might result in high inaccuracies.

Synchronizing the horizontal and the vertical geodesic measurements, the x , y , z coordinates of each point of the river geometry can be defined properly.

Several methods are available to measure the water depth, from which the most widespread ones are acoustic techniques. The principle of operation of these devices are based on emitting sound waves in the direction of the river bed and receiving the reflected signals as well. Measuring the time-span between the emission and the reception of the signal, and knowing the propagation velocity of the sound in water, one could easily derive the water depth. Figure

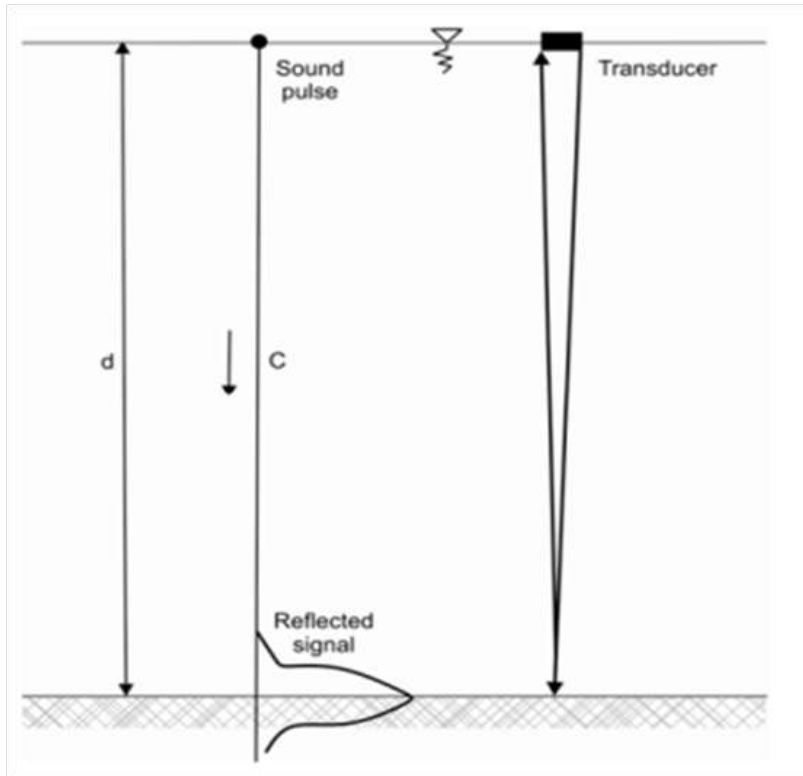


Figure 4.1: Principle of operation of the acoustic depth measuring instruments (Muste, 2012)

4.1 presents the schematic strength profile of a refracted signal. These profiles typically have their maximum values right at the riverbed. Using the strongest sound signal, the water depth can be calculated as follows:

$$d \approx 0.5 \cdot c \cdot t \quad (4.2)$$

where d is the depth of the water column, c is the propagation velocity of sound and t is the time-span between the emission and detection. (Muste, 2012)

Acoustic water depth measuring instruments can be separated into three different groups based on the number of sound signals emitted by them simultaneously. The so called single beam echo sounder instruments emit only one beam of sound at a time, hence the water-depth can be measured only at one point at that given moment. Thereby, during moving boat measurements, the water-depth is measured at discrete points of the path of the boat. A schematic figure of such a measurement is illustrated on the left side of Figure 4.2.

The ADCP (Acoustic Doppler Current Profiler) – as its name suggests to it – is an ultrasonic velocimeter that has been designed to measure flow velocities of water currents. In addition to the velocity measurements, the instrument is also suitable for water depth measurements as well, which implies fast discharge measurements as well, as it has been discussed earlier. The principle of operation of the ADCP has been described in detail in the chapter

Acoustic measurements in riverine conditions. The instrument emits 3 or 4 (depending on the type of the device) different sound waves at a time. These sound beams are emitted not in parallel but in a small angle to each other and the vertical axis of the device. This means that the instrument measures 3 or 4 different water depths simultaneously, however, the points of the bed, where the signals are reflected from are quite close to each other, so from practical point of view there is no significant difference between them. In most of the cases the average of these 3 or 4 different water depth measurements is considered as the actual water depth. Due to this fact, the data provided by the ADCP is more reliable than the data obtained by the single-beam instrument. However, compared to the first one, this method still does not provide additional information about the river bed, the water depth can only be measured in the path of the measuring boat as well.

The Multibeam Echosounder is an ultrasonic instrument designed to measure water depths based on the same principle as the previously introduced devices. The main difference from ADCPs and single-beam tools is that this device does not emit signals only in one direction but in a hand fan shape. The angle in which the device emits the signals is depending on the geometry of the device. The schematic operation of the instrument is illustrated on the right side of Figure 4.2. This up-to-date method provides with the opportunity to conduct areal depth measurements, which may result in a scatter set so dense, that no further interpolation is required anymore. The high resolution topological data obtained with the device also allows the users to assess smaller scale river bed forms and patterns (e.g. dunes) as well. Another advantage of the multibeam tool is that due to the areal scanning, the route of the measuring boat can be significantly shortened, thus the financial and time costs of the measurements can be lowered as well, while maintaining a significantly denser measured data compared to ADCP measurements (Ádány, 2015). However, it is noted that such an instrument is also significantly more expensive than ADCPs or single-beam devices.

4.3 *Floodplain survey*

Several methods are available for the geodesic surveying of the floodplain as well. These measurements ought to be carried out when there is either a low water or a mean water level situation, since the process is more feasible when these areas are not under water.

4.3.1 *GPS*

The most widespread tool for surveying the floodplain of short river section (few kilometers) is the RTK GPS. This instrument has been introduced earlier. The RTK GPS provides sub-decimeter

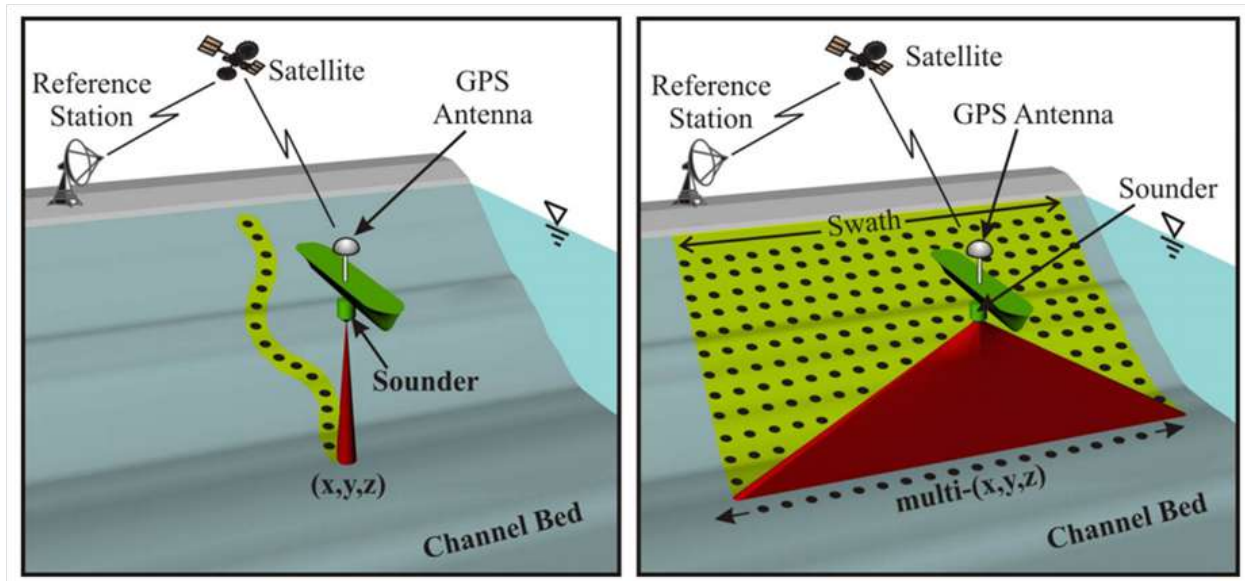


Figure 4.2: Schematic illustration of the operation of the single beam, and the multi beam echo sounders (Muste, M., 2012)

accuracy, which is perfectly sufficient for hydromorphological analysis. For larger scale investigations (e.g. building the geometry of a 1D numerical model for a whole river) even a standalone GPS could be adequate as well. It is noted, that the 'simple' GPS is much cheaper and faster compared to the RTK type.

During such GPS based surveying, the operator must go from point to point and perform measurements with the device. Most of the commercially available instruments come with an interactive graphical user interface as well, which makes both the measuring and data recording fast and easy.

In order to avoid the unnecessarily high amount of data, the resolution of the measurement has to be chosen carefully. It is advised to perform more measurements where the terrain changes quickly and rarefy them where it is more even (e.g. nearly horizontal, flat planes). Surveying linear objects such as groins, dykes must be done carefully, with special focus on their breaking points and characteristic spots. This way the data to be processed can be reduced without losing relevant information. In addition to GPS devices, traditional geodesic tools may also be used for auxiliary measurements. These measuring methods are more time demanding and also require more experience. Moreover, it is mandatory to have at least one fixed reference point with known coordinates (x, y, z) in the surveying area. An advantage of these tools is that they can be used on areas where satellite connection is not available.

4.3.2 Laser scanning

Laser scanning has become more and more popular for creating digital terrain models (DTM) with high scatter density and accuracy. The method can be used both from air⁵ and on the ground as well. The principle of operation of these instruments is the following: the

⁵ Airborne Laser Scanning - ALS LiDAR

device emits a laser beam towards the ground that gets refracted from the surface. The device also detects the reflected signals and records the time-span between the emission and the detection. Depending on the elapsed time between the two events and knowing the propagation velocity of the laser light, the distance of the object from which the signal have been reflected can be easily derived. If the position of the device and the direction of the laser beam are known, the georeferenced coordinates of the examined point can be obtained. The exact position of the instrument can be provided by an extremely precise RTK GPS for example.

The main difference between aerial measurements and the ones that are carried out on the ground is, that the position of the detector is changing more rapidly in case of aerial scanning. Hence, in order to determine the coordinates of the investigated points with the desired accuracy, the positioning of the detector must be done swiftly, and the direction of the emitted signal must be accurately specified. The proper, accurate measurement of the signal direction is crucial, since the laser beam can easily travel even hundreds of meters before getting reflected, hence even the slightest directional inaccuracies may result in highly inaccurate measured coordinates. In case of aerial laser scanning, the instrument is much further from the sampled objects as in case of ground measurements, hence logically, much larger areas can be surveyed with the same time costs. Nowadays, the ALS is the most widespread method for surveying the floodplains or the terrain in general. On one hand this technology provides the opportunity to conduct fast, high quality and very detailed geodesic surveys, but on the other hand obtaining and operating such a device is rather costly. Figure 4.3 presents the elevation model obtained from an ALS LiDAR surveying, for a short section of a river and the surrounding floodplain. It is noted, that the laser beams gets reflected from the water surface, hence the river bed geometry cannot be assessed with this device.

The advantage of ground scanning is, that the detector moves slowly compared to the aerial method, or even stands still. Hence the positioning is way easier for this technique, and the occurring measurement errors are usually smaller. Vertical positioning errors are typically below 10 centimeters (Kondor, 2016). Ground scanning is usually used for surveying smaller areas e.g. the typical terrain around structures or the riverbanks. Data from such a survey is illustrated in Figure 4.4. The scanning was done by using the instrument presented in the Figure 4.5 (Kondor, 2016).

4.3.3 *Structure from motion*

The Structure from Motion (SFM) method is a new, cost-efficient alternative of laser scanning. The SFM technique recreates a very detailed 3D structure from a series of 2D images taken with a camera moving along a path (Rootwelt, 2014). The algorithm takes a sequence of images as input and outputs a series of 3D points of

Figure 4.3: Complex terrain map of the floodplain created by ALS LiDAR

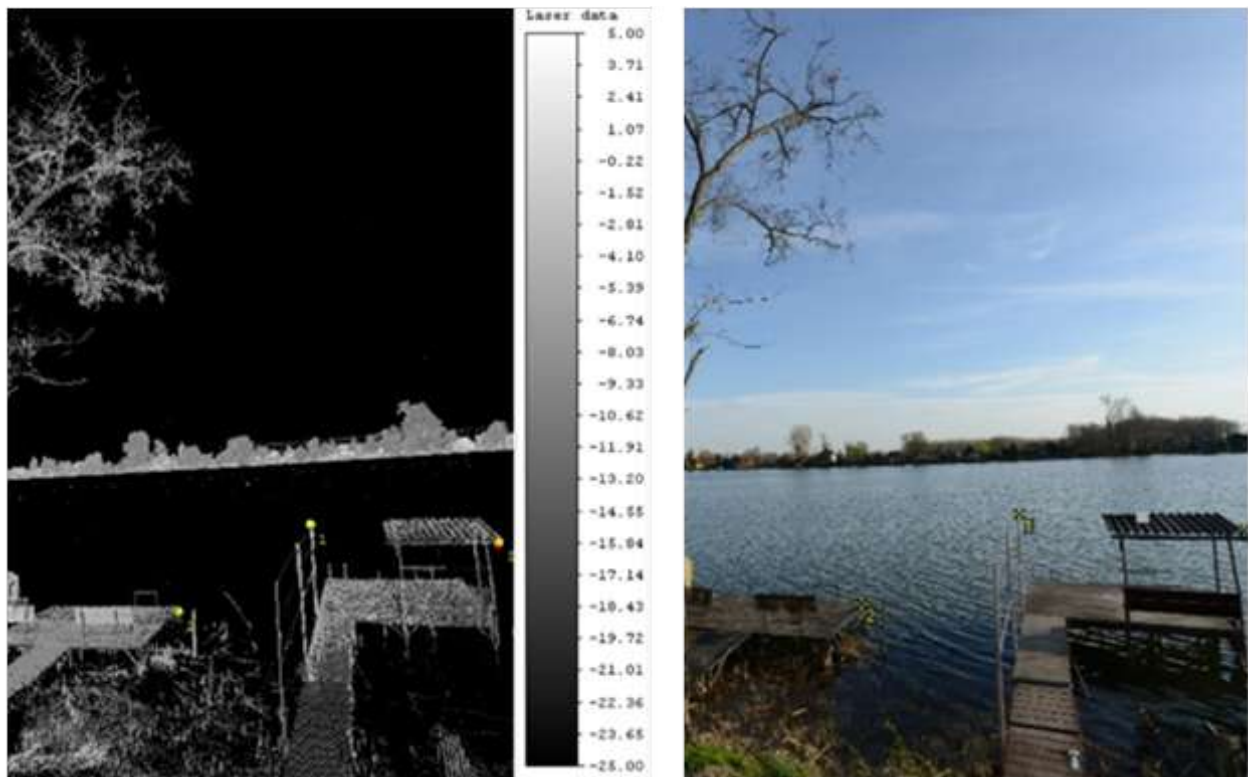


Figure 4.4: DTM by ground laser scanning (left figure), photo of the original location (Kondor, G., 2016)

Figure 4.5: Riegl VZ-1000 ground laser scanner (Kondor, G., 2016)



the structure, called a point cloud. The basic interpretation of the method is described by Equation 4.3, and there are many complex computational methods for solving this problem thus produce the 3D structure from the images captured by the moving camera.

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_f \end{bmatrix} = \begin{bmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_f \end{bmatrix} \begin{bmatrix} X_1 & X_2 & \cdots & X_n \end{bmatrix} \quad (4.3)$$

where $I_1, I_2, \dots, I_f$ are the individual images of the structure, which belong to camera positions $\Pi_1, \Pi_2, \dots, \Pi_f$ and $X_1, X_2, \dots, X_n$ are the 3D coordinates of the individual points of the created cloud.

The adaptation of the SFM method consists of the following steps (Rootwelt, 2014):

1. Camera calibration

All cameras have slight imperfections, such as lens distortions, non-square pixels and varying focal length. Cameras need to be calibrated as part of SFM and it needs to be done before the reconstruction starts.

2. Identify point of interest

SFM outputs a series of points in 3D. These points need to be located in the 2D images before their 3D position can be found. The first step is to identify easily recognizable, characteristic, so called 'good feature' points (Figure 4.6). These points are usually corners or other features that can be pinpointed in 2D.

3. Track points

Once the points of interest have been found in consecutive images, they need to be matched. That means identifying which point in each image is actually the same 3D point. If the camera

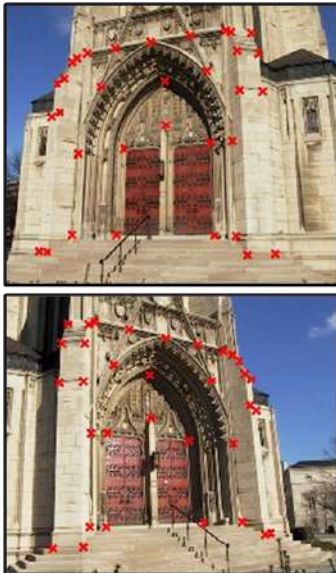


Figure 4.6: Easily recognizable 'good feature' points on images

only moves a little bit, each point will be close to its match in the next image in the sequence.

4. Calculate camera movement

Based on the displacement of the tracked points from one image to another, the relative movement and rotation of the camera can be calculated, from which the so called fundamental matrix F is built.

5. Triangulate points

Once the relative position of the two camera angles are known, the 3D points can be triangulated. The basic principle is drawing a line from each camera center through the 2D points. These lines will intersect in the 3D point.

6. Bundle adjust

Using two consecutive images is one way to get 3D information, but in SFM we generally work with videos. Using information from multiple frames to get a more accurate estimation of the 3D points is called bundle adjustment.

Video recordings for the SFM are usually performed with a camera attached to an UAV⁶. During a survey the UAV flies around the object slowly. The vehicle is controlled remotely by the pilot and another person controls the video recording application from a tablet, starts/finishes the recordings and controls the camera position (forward/downward). Even a user-friendly, hobby UAV can be used for SFM measurements, like the DJI Phantom 3 Standard (Figure 4.7).

⁶ Unmanned Airborne Vehicle

Since the measurement method requires reference points (easily visible points on the recorded videos with known geographical coordinates), an RTK-GPS is to be used to measure the real x , y , z coordinates of the objects. The reference points must be clearly identifiable on the video recordings.



Figure 4.7: DJI Phantom 3 Standard UAV

In order to get a complete georeferenced 3D point cloud out of the recorded video, the following open-source software need to be employed:

- ffmpeg

The ffmpeg software is responsible for converting and cutting the raw video files. The program can be run from the command line.

<https://ffmpeg.org/ffmpeg.html>

- VirtualDub

VirtualDub is used to export a sequence of images from the video with the desired frame rate.

http://www.virtualdub.org/virtualdub_docs.html

- VisualSFM

The VisualSFM software is used to create the 3D point cloud itself, it seeks for the good feature points and matches the images with the same points. It calculates the camera positions and creates the point cloud from the camera motion in a random non-georeferenced coordinate system, where the 3D structure is already recognizable in a good quality.

<http://ccwu.me/vsfm/doc.html>

- Meshlab

Meshlab is used to clean inappropriate objects, such as trees or people from the point cloud and creates a georeferenced point cloud using the real coordinates of the ground reference points. A

<http://www.cyi.ac.cy/system/files/MeshLab%20Documentation1.pdf>

Detailed image processing protocol has been created which defines the process step by step from the video recording until getting the 3D point cloud of the studied area.

Dykes or levees are elongated structures built parallel to the river, which protect the floodplains against floods. Accurate information about the geometry of these structures is essential when investigating e.g. flood situations, effect of dyke breaches, geotechnical behavior of dykes, or planning flood localization. In order to reveal the feasibility of SFM based reconstruction of dyke geometry, the video-based surveying of a dyke was performed. A raw image of the dyke extracted from the video is shown in Figure 4.8. The resulting dense point cloud of the dyke in VisualSFM is shown in Figure 4.9. The 3D model is built up from 356 images and consists of 674420 points. The image processing required app. 3 hours of computational time in VisualSFM.

Considering the possible utilization of the built 3D objects (e.g. inserting them into existing DTMs, applying them for CFD modeling), the cleaning of the point clouds is a crucial step in the post-processing procedure. This means that points representing bushes, trees, even people on the images have to be removed before creating the 3D model. This can only be done manually, which makes the procedure slower, however, the deleting of the clearly not ground points quite is straightforward. Figure 4.10 presents the visualization of a cleaned point cloud in the post-processing software tool Tecplot. These additional modifications usually take another 10–20 minutes, depending on the amount of corrupted points.

Figure 4.8: Raw image of the dyke from the UAV



Figure 4.9: Raw point cloud of the dyke from different views in VisualSFM

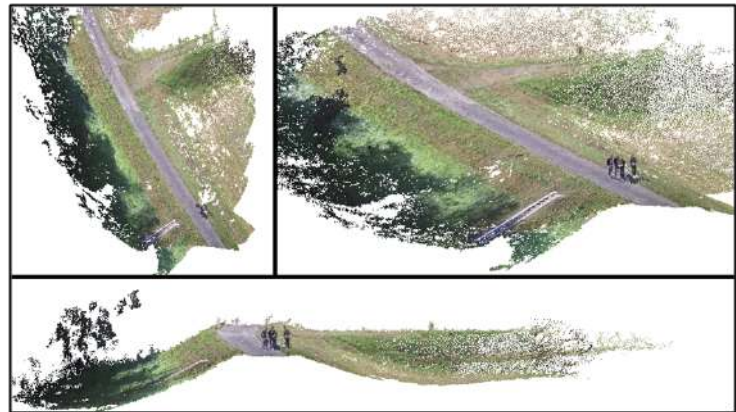
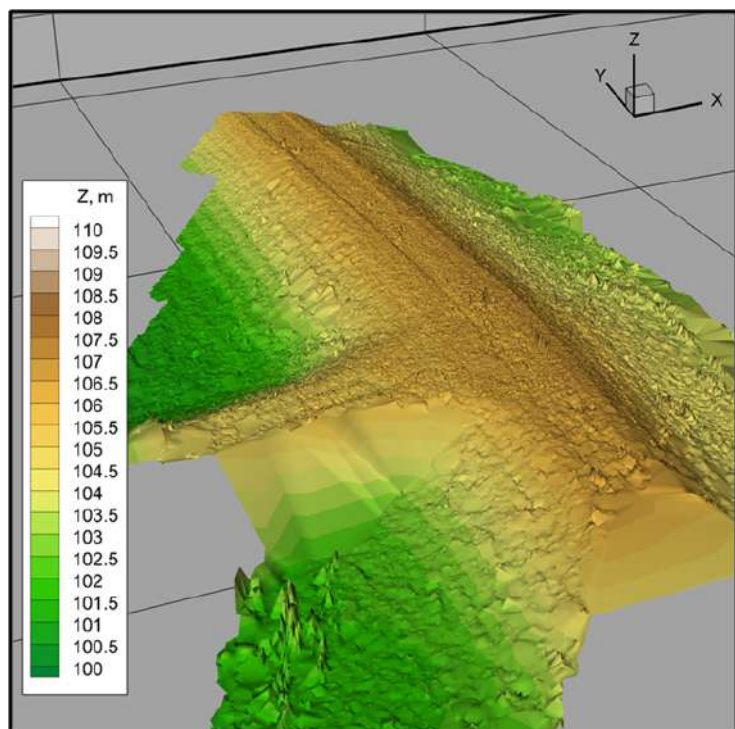


Figure 4.10: Cleaned and georeferenced surface of the dyke visualized in Tecplot



4.4 *River channel geometry – data processing*

In order to perform any kind of hydromorphological investigation in a river, it is mandatory to have clear data about the river bed geometry. Methods have been presented in the previous sections to obtain adequate data for such elevation maps. However, the measured raw data is not sufficient to generate digital elevation models (except for the multibeam device), specific software are to be used to further post processing (e.g. AutoCAD, Tecplot, SMS, ParaView). It is expected that a DTM is an accurate and reasonably simplified model of the actual topology, but since field measurements usually provide unequally distributed discrete coordinates of the terrain of an investigated area, further data processing is to be performed. In order to get a continuous elevation model, different interpolation techniques are to be applied on the measured data.

4.4.1 *Interpolation methods*

It is essential to choose the proper interpolation method for creating a DTM from the measured points of the original terrain. Several adequate techniques are described in the relevant literature. The most commonly used ones are the following:

- Linear interpolation

The basic idea behind linear interpolation is that we estimate the values of a function (in our case, the elevation) between known (measured) points with the assumption that a linear function well represents the changes between these two points.

- Interpolation along streamlines

The process basically seeks the closest measured values to the point where the elevation function is to be evaluated along 2D streamlines both in upstream and downstream direction. Knowing the altitudes of these points the calculation of the examined one can be performed through a distance weighted averaging.

- Inverse distance weighting (IDW)

The altitude of the examined point is calculated by averaging a give number of measured points in its proximity and to all points a weight is assigned based on their distance from the examined point. The further a point is from the examined coordinate, the lower its weight will be, hence the less effect it will have in the averaging.

- Kriging

This base of this methods is basically another weighted averaging, however, the weights are not assigned based on distances but on a statistical basis with the employment of so called variograms.

Detailed description of these methods can be found in the papers of Tritthart and Habersack (2011), or Telbisz et al. (2013). Tritthart and Habersack compared the different interpolation methods through creating DTMs from measured elevation points obtained with a single beam echo sounder. As a reference, they used a DTM created (measured) by a multibeam echo sounder. According to their research, the most adequate method for creating the digital elevation model for the main channel was the streamline-wise interpolation. Szilvia Ádány (Ádány, 2015) performed investigations in a short section of the Hungarian Danube (1692.0–1684.5 rkm) came to the same conclusion.

Considering the fact that the streamline-wise interpolation was repeatedly reported to be the most adequate method for creating DTMs from single beam echo sounder or ADCP measurements, it is advised to employ this method in most of the cases, however, other methods should not be neglected either.

Interpolating the water depth values acquired by moving boat measurements (typically along cross-sections) on triangular or square digital mesh, the continuous horizontal distribution of water depths can be obtained. In conclusion, the generation of a DTM not only requires the proper devices and field measurements, but the employment of adequate post processing methods as well.

4.4.2 *Information provided by DTMs*

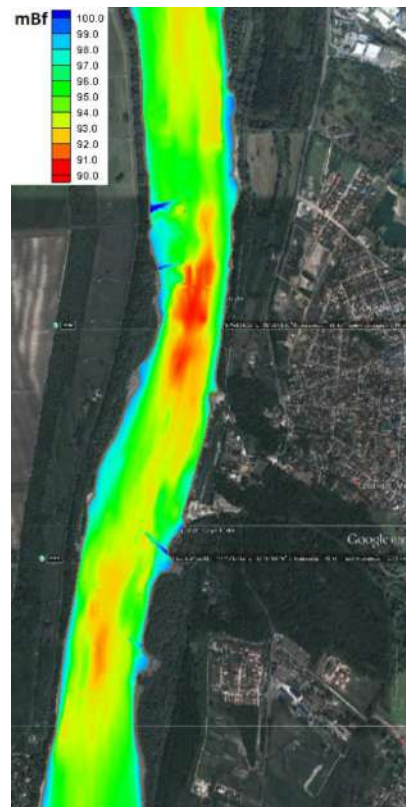
The analysis of digital terrain models provides with the opportunity to investigate important morphological phenomena and processes in an indirect way. This subsection illustrates an example of a DTM generated from field measurements. This process is described according to the report by Gábor Fleit (Fleit, 2013).

Figure 4.11 represents a stretch of the Hungarian Danube (1672–1676 rkm) near the settlement of Sződliget in Hungary. The DTM had been created by interpolating cross-sectional water depth data provided by ADCP measurements. The interpolation was conducted with the streamline-wise interpolation method.

Conducting such surveys with adequate frequency (every few months, or after remarkable flood events) provides with the opportunity to assess temporal changes in the river bed geometry. Figure 4.12 illustrates the change of the riverbed due to a significant flood event. The represented area is located on the northern part of the illustrated stretch of the Danube in Figure 4.11. On the upper right (*b*) part of the figure 4.12, the measured bed elevation differences due to the flood wave have been illustrated. Such difference maps can provide essential information about hydromorphological changes in rivers.

On Figure 4.12 it is observed that these changes can reach even more than a meter in height. It is obvious that the bed altering effect of flood waves is significant which usually manifested as erosion. Figure 4.12 *c* illustrates the changes of two cross-sections

Figure 4.11: Digital elevation model of the riverbed in the area of Sződliget (Fleit, 2013)



of the river: on right on the upstream, one on the downstream side of the northern groin. The continuous line represents the level of the riverbed prior to the flood and the dashed line stands for the changed bed level after the flood wave. The measured cross-sections have been plotted on the satellite maps as well with the according colors. It can be clearly seen that this flood event (hundred-year flood in 2013) resulted in a significant, up to 4 meters deep scour hole at the top of the groin, while notable deposition is observed on the downstream side of the structure. This behavior is however expected in the proximity of such river training works.

According to the analysis, it is clear that the flood in 2013 did not affect the whole reach of the river but only smaller, local areas (e.g. top of the groin). Supposedly the material of the deposition downstream to the groin is originated from upstream eroded parts of the river. According to the measurements, it can be stated, that the erosion of the previously deposited material will not occur, not even in case of such rare flood events.

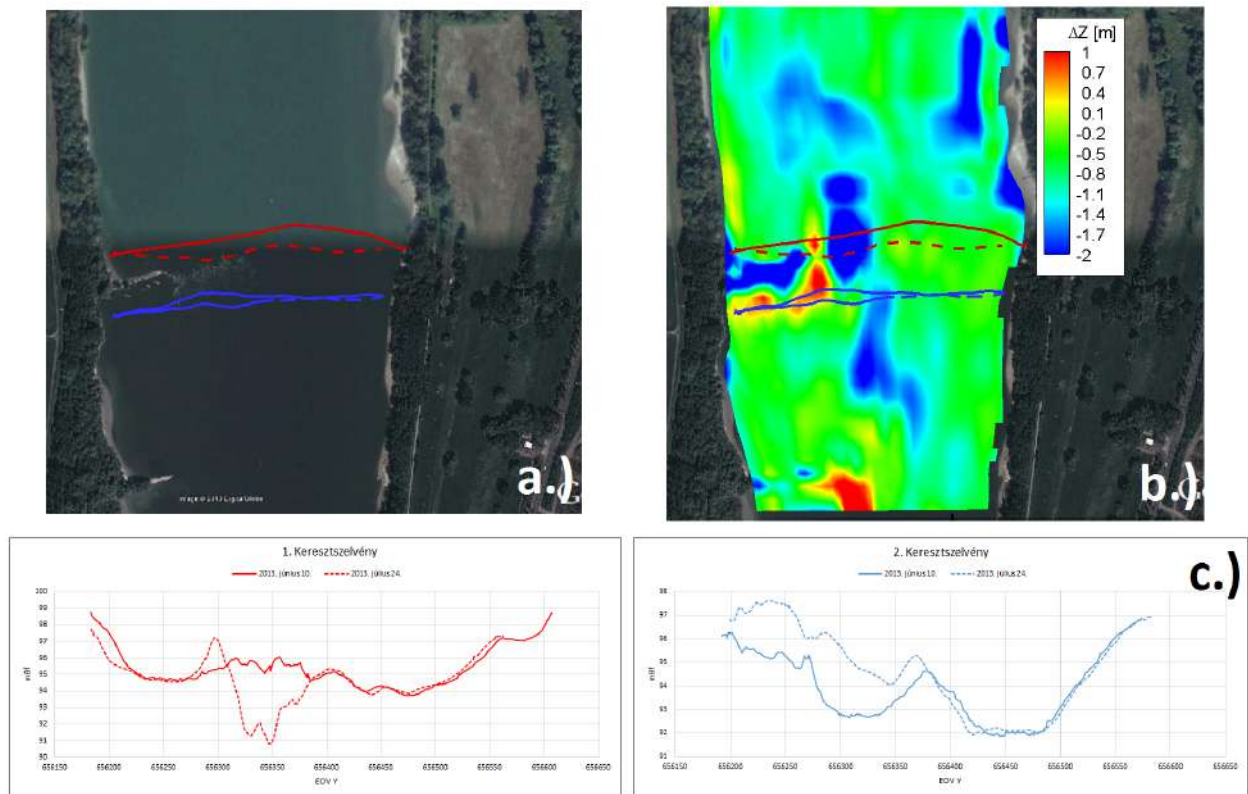


Figure 4.12: Effect of a hundred-year flood on the bed topology in the proximity of groins (Fleit, 2013)

5

Discharge measurement methods for streams

5.1 Introduction

Discharge is the volume of water that flows through a certain cross-section (ΔV) of a stream over a specific period of time (Δt), usually expressed in $[\text{m}^3/\text{s}]$, or $[\text{l}/\text{s}]$. The following expression arises from its definition:

$$Q = \frac{\Delta V}{\Delta t} \quad (5.1)$$

It can also be calculated as the product of the cross-sectional area of the portion of the channel occupied by the flow (A) and the average velocity of the water in that cross-section (v): using : $\Delta V = A \cdot \Delta s$, and

$$\frac{\Delta s}{\Delta t} = v:$$

$$Q = A \cdot v, \quad (5.2)$$

where Δs is the perpendicular extent of the volume of water flowing past under unit time (Δt).

Water discharge measurements can be done in numerous ways. These are the most commonly used methods and devices:

- Acoustic Doppler Current Profiler (ADCP)
- Acoustic Doppler Velocimeter (ADV)
- Volumetric
- Portable measuring weirs and flumes
- Formulas for discharge estimation
- Large-Scale Particle Image Velocimetry (LSPIV)
- Radars
- Induction based velocimeters

5.2 Acoustic Doppler Current Profiler

5.2.1 Conventional ADCP

The Acoustic Doppler Current Profiler¹ (Figure 5.1) is one of the most frequently used devices for discharge measurements. Compared to other methods, this device offers faster, easier and more reliable way to measure the discharge of a river (for Danube-sized rivers the measurement takes only 5 to 10 minutes).

¹ ADCP

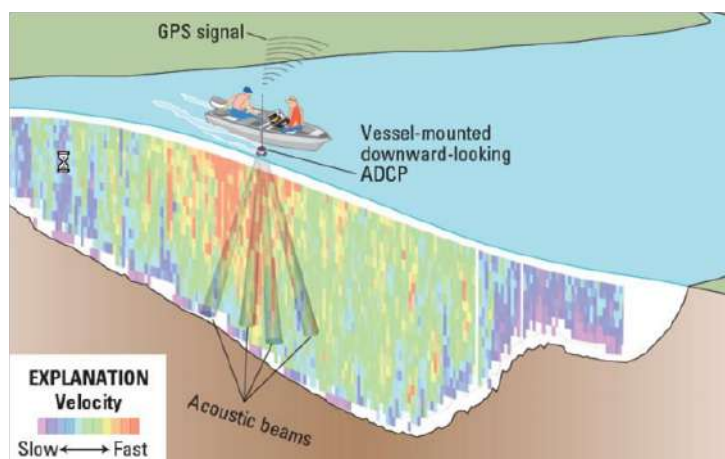
Figure 5.1: Acoustic Doppler Current Profiler

The working principle of the instrument has been described in details in the chapter of 'Acoustic measurements in riverine conditions'.



The ADCP is usually mounted onto a boat for discharge measurements, with its acoustic beams placed below the water surface and looking down to the bottom (Figure 5.2). During discharge measurements the instrument is carried across cross sections of a river, thus partial discharge data can be derived from the velocity and depth measurements. At the end of each cross sectional measurements, these values are summed to give the total discharge. The bottom tracking function of the ADCP or a Global Positioning System (GPS) is used to provide the positioning of the measurements.

Figure 5.2: Moving boat ADCP measurement



The post processing software calculates the area of the subsections (cells) which can be represented by a single, measured velocity vector, according to the GPS data and water depths. Applying the equation of continuity (Equation 5.2) for these individual subsections, partial discharge values can be calculated. The total discharge

in the assessed cross-section is the sum of these sub-discharges:

$$Q = \sum Q_i \quad (5.3)$$

There are other acoustic velocimeters which can be permanently installed such as the Acoustic Doppler Current Meter² and the Acoustic Velocity Meter³. These instruments are capable of acquiring continuous data collection in a fixed position.

² ADCM

³ AVM

Due to the size and the measurement limitations of ADCPs, the field on their practical employment is restricted to larger streams or rivers. For smaller streams with a width of a couple of meters, other methods from the previously presented list are to be applied.

5.2.2 Horizontal ADCP

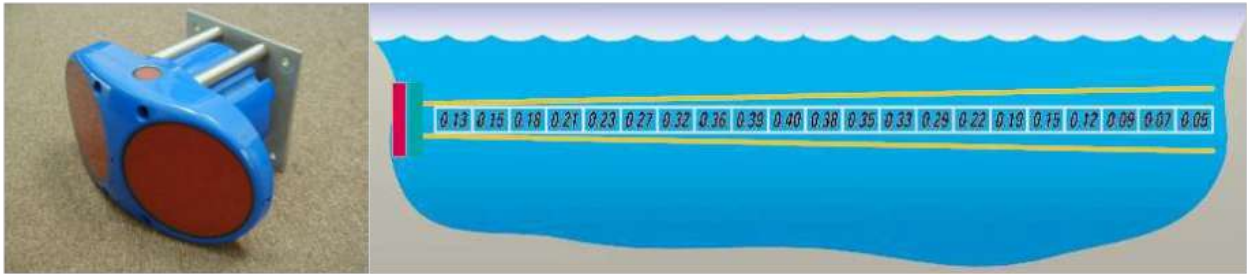


Figure 5.3: H-ADCP (on the left) and its application (on the right)

The horizontal ADCP⁴ (Figure 5.3, left) is fixed on one side of the river channel, and it measures the velocities at a horizontal plate at a cross-section (Figure 5.3, right). There is a high correlation between the discharge which flows past the cross-section and the instantaneous cross-sectional velocity profile at known depth. Calibration is used to establish this relationship. After calibrating the H-ADCP, the discharge can be calculated from the established relationship using the so called index velocity method. So the H-ADCP uses formulas for discharge estimation from the measured water stage and velocity profiles.

The H-ADCP measures the horizontal velocity profiles with two horizontal beams, and also records the water stage with its small beam facing up and built-in pressure gauge.

The idea behind the index velocity method is calculating the mean velocity at the cross section (v) using the index velocity (v_i) and the water stage (H), where v_i is a parameter measured with the H-ADCP. The relationship between the index velocity, water stage and mean velocity can be established using calibration, so v can be estimated indirectly.

$$v = f(v_i, H) \quad (5.4)$$

Finally the discharge (Q) can be calculated from the continuity equation (Equation 5.2). The cross-sectional area of the portion of the channel occupied by the flow (A) is available from the water stage (H) if the geometry of the cross section is known:

$$A = f(H) \quad (5.5)$$

5.3 Single-point velocity measurements

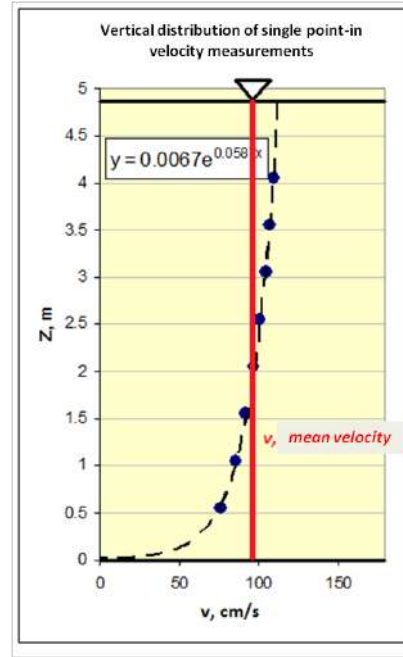
The calculation of the discharge is similar for all single-point velocimeters. The method of calculation is based on the equation of continuity (Equation 5.2). Each subsection's discharge can be evaluated as the product of the area of the subsection and its measured mean velocity.

$$Q_i = v_i \cdot A_i \quad (5.6)$$

The total discharge arises from summing the discharges of all subsections (Equation 5.3).

The width of each subsection is usually measured with a tape measure. If this is not possible directly, the width can be obtained with an optical or electrical rangefinder or with GPS as well. The water depths can be measured with a measuring rod. A subsection's mean velocity can be calculated from the measured single-point velocity values of different depth of the vertical in the middle of the subsection (Figure 5.4).

Figure 5.4: Measured point-in velocities (blue dots) and vertical mean velocity (red)



If the number of measurement points are less than 10, the mean velocity of the subsection can be estimated using the weighted average of the measured velocities (Koris and Winter, 1999):

- Using 5 points:

$$\bar{v} = \frac{v_s + 3 \cdot v_{20} + 3 \cdot v_{60} + 2 \cdot v_{80} + v_b}{10} \quad (5.7)$$

- Using 3 points:

$$\bar{v} = \frac{v_{15} + v_{50} + v_{85}}{3} \quad (5.8)$$

- Using 2 points:

$$\bar{v} = \frac{v_{20} + v_{80}}{2} \quad (5.9)$$

- Using a single point:

$$\bar{v} = v_{60} \quad (5.10)$$

where v_s is the measured velocity 10 cm below the water surface, v_b is the measured velocity directly above the river bottom, and v_{xx} are the measured velocities at $xx\%$ of the total water depth calculated from the surface.

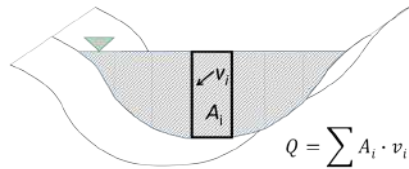


Figure 5.5: Discharge calculation of point-in velocity measurement

Then the discharge of a subsection can be calculated by multiplying the area of the subsection and its mean velocity (Equation 5.6). The total discharge comes from summing the discharge of all subsections (Figure 5.5 and Equation 5.3).

5.3.1 Current meter

In smaller and shallower streams, where the width is generally smaller than 5-10 m and the depth is smaller than 1 m, the previously introduced method with ADCP is generally not applicable. In such cases e.g. the single-point velocity measurement method is recommended. The velocity of the stream flow is measured using a current meter. The most commonly used one in the US is the Price AA current meter while in Hungary it is the OTT current meter (Figure 5.6). The instrument consists of two major parts: the measuring wheel of metal cups that rotate around a vertical axis, and a fin. The fin aims to keep the instrument parallel to the main flow direction. When the instrument is under water the wheel is rotating. An electronic signal is transmitted by the device on each rotation allowing them to be counted. The rate of this rotation is directly related to the flow velocity, hence it can be calculated with a calibration equation based on the number of rotations over a specific amount of time.

The current meter can be attached to a wading rod or suspended from a cable.



Figure 5.6: Price AA current meter

5.3.2 Acoustic Doppler Velocimeter

⁵ ADV

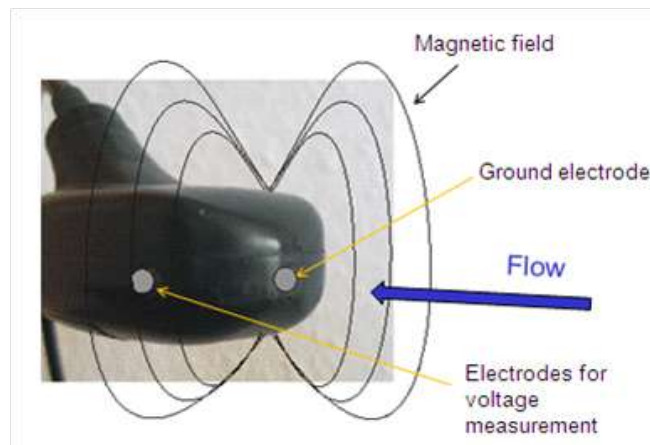
The principle of operation and more was described in section 'Acoustic measurements in riverine conditions'.

Acoustic Doppler Velocimeters⁵ can also be deployed to conduct single-point flow velocity measurements (Voulgaris and Trowbridge (1998)). It is noted, that in contrast with the traditional current meter, the ADV does not only measure the stream-wise component of the flow velocity, but all three components with high temporal resolution, hence turbulence related parameters can be derived from the time series as well. Calculating the discharge from ADV measurements is based on the previously presented method, where the cross section is divided into smaller subsections.

5.3.3 Induction based velocimeter

This measurement method is based on Faraday's principle (electromagnetic induction) which states that a moving conductor in a magnetic field will generate a voltage proportional to the velocity of the conductor. The sensor of the meter generates a vertical magnetic field near the center of the probe using an electromagnet. This magnetic field is strongest near the sensor body and diminishes approximately $1/D^2$ moving away from the sensor, where D is the diameter of the sensor. In this case, water is the moving conductor and when velocity vectors point straight to the sensor the flow direction is perpendicular to the generated magnetic field. Based on the velocity of the water, a proportionally high voltage is generated in the magnetic field. The sensor electrodes measure this voltage and the instrument calculates the velocity of the water flow (Figure 5.7).

Figure 5.7: Induction based velocimeter and the illustration of its principle of operation.



In most of the cases, it is not a problem to place the velocity sensor below the water surface (fully submerged), which is required to successfully conduct measurements. This means that the minimum water depth is approximately 3 cm. The flow signals are the strongest near the sensor body and diminishes as they move away from it.

A good rule of thumb is to keep the sensor 4 to 8 cm away from any physical boundaries, such as obstructions. The streamlines

should be parallel to the direction of the device and the flow should move straight in the direction of the the sensor (Figure 5.8).

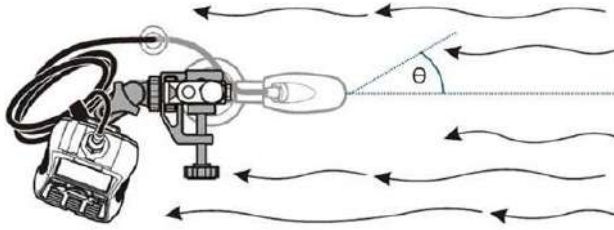


Figure 5.8: Streamlines moving straight in the direction of the sensor.

Electromagnetic velocimeters can be used in water with very low conductivity such as springs or streams fed by snow melt, however, there may be a trade-off with velocity errors if the conductivity of the water is less than $200 \mu\text{S}/\text{cm}$.

Devices coming with a pressure sensor also offer to measure the maximal depth at each vertical.

5.4 Volumetric method

The volumetric method is a very simple way to measure discharge (Hajnal and Koris, 2014). The total flux of the flow is directed into a container of known volume (Figure 5.9), and the time required to fill the container is measured with a stopwatch.



Figure 5.9: Volumetric discharge measurement method

However, there are a couple of simple rules to take note of

- the filling should take longer than ten seconds,
- the container has to be calibrated,
- at least ten separate measures have to be conducted,
- the discharge is calculated using Equation 5.1.
- multiple measurements have to be averaged for the final discharge result.

5.5 Portable measuring weirs and flumes

5.5.1 Measuring weirs (Koris and Winter, 1999)

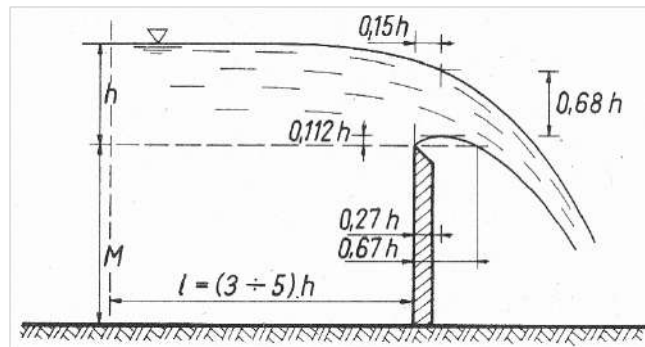
– Bazin-weir

The Bazin-weir (Figure 5.10) is a sharp-crested weir without side contraction. The discharge can be calculated:

$$Q = m \cdot B \cdot \sqrt{2g} h^{\frac{3}{2}} \quad (5.11)$$

where m is the discharge coefficient, B is the width of the weir width and h stands for the upstream head measured from the crest of the weir.

Figure 5.10: Bazin-weir

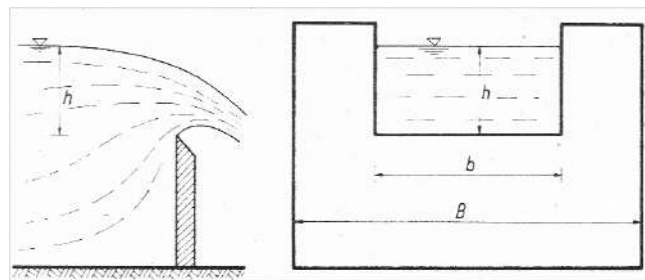


– Poncelet-weir

The Poncelet-weir (Figure 5.11) is a rectangle shaped, sharp-crested weir with side contraction. The calculation of the discharge is similar to the previous one, but the m discharge coefficient has different values:

$$Q = m \cdot B \cdot \sqrt{2g} h^{\frac{3}{2}} \quad (5.12)$$

Figure 5.11: Poncelet-weir



– Thomson-weir

The Thomson-weir (Figure 5.12) is isosceles triangle shaped weir. The discharge can be calculated:

$$Q = C \cdot h^{\frac{5}{2}} \quad (5.13)$$

where C is the discharge coefficient.

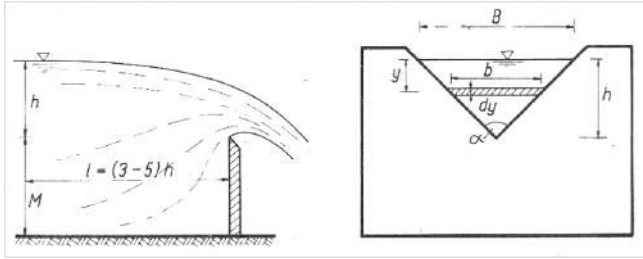


Figure 5.12: Thomson-weir

– Cipoletti-weir

The Cipoletti-weir (Figure 5.13) is a trapezoid shaped weir, where the discharge coefficient is constant due to its geometry. The discharge can be calculated:

$$Q = 1,86 \cdot b \cdot h^{\frac{3}{2}} \quad (5.14)$$

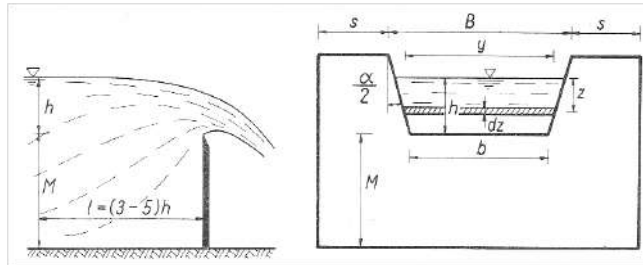


Figure 5.13: Cipoletti-weir

5.5.2 Measuring flumes

The most frequently used portable flumes is the so called Parshall flume (Figure 5.14). It forces the flow into its well specified contracted geometry which provides with the opportunity to conduct fast discharge measurements in smaller streams. There is a specific relationship between the upstream water level and flow rate in the contraction.



Figure 5.14: Discharge measurement with a portable Parshall Flume

5.6 Formulas for discharge estimation

Apart from the presented field measurement techniques, simpler mathematical formulas are also available to calculate to discharge. However, these methods cannot provide the same level of accuracy, still, they are very practical when it is not possible to conduct field measurements, or when only an plausible approximation is required. The so called “Slope-Area method” uses the Manning equation. The mean velocity in a cross section is related to the slope of the channel and to the roughness of the bed material.

$$Q = A \cdot v \quad (5.15)$$

and

$$v = k \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \quad (5.16)$$

where A is the cross-sectional area of the portion of the channel occupied by the flow, v is the cross-section averaged velocity, k is the Manning-smoothness, R is the hydraulic radius and S is the slope of the bed.

In case the water levels are monitored along the studied river reach and the cross-section geometry is known at the gauges, R and S can be calculated, while k can be estimated based on the bed material and vegetation properties.

Another indirect method is the “Contracted-Opening” method which uses the contraction of a stream channel due to a bridge which creates an abrupt drop in the water surface elevation between an approach section and the contracted section under the bridge. This contracted section frames by the bridge abutments and the channel bed can be used to estimate flood flows. High water marks and the geometry of the bridge and the channel are used in this method.

5.7 Large-Scale Particle Image Velocimetry

The main idea behind LSPIV is to record the free-surface of the stream using high quality calibrated video camera(s) (Muste et al., 2008). The main steps of the algorithm are the following: i) transform the images to an orthogonal coordinate system; ii) detect the movement of tracers and patches on the surface using a suitable cross-correlation method; iii) calculation of instantaneous flow velocity vectors for image pairs; iv) estimating a so called index-velocity based on the spatio-temporal averaging of the vector fields. A relationship between the index-velocity and the actual discharge should be set up by performing calibration discharge measurements parallel. Then the method of discharge estimation is rather similar to the one presented for the H-ADCP. This indirect technique offers quick discharge measurements in cases where the conventional methods face difficulties, such as flash floods.

The determination of the free-surface velocity distribution is needed to make estimations on the flow discharge in this proce-

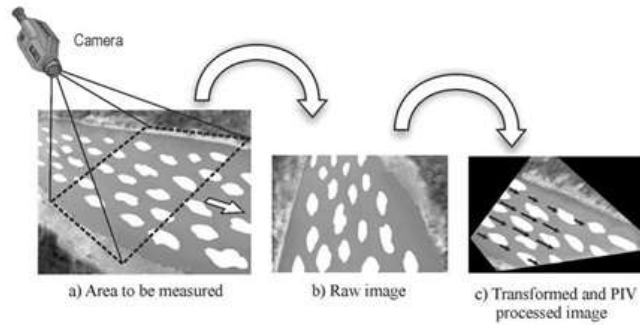


Figure 5.15: LSPIV measurement sequence (Muste, 2008)

ture. A calibrated video camera is needed with a fixed mounting to record a certain area of the stream surface. If possible, the video camera should be right above the stream or in an oblique angle from the river bank (bridge or high building). Even hundreds of square meters can be recorded. As one of the most crucial application criteria, some sort of tracer is necessary for the video processing method which it can track and follow. It may come from a natural source e.g. sediments, foams, bubbles created by turbulence, but it can also be artificial such as plastic particles, candles, etc. As Figure 5.15 shows, once the video has been recorded the raw images need to be transformed onto a truly 2D system (this step is called “orthorectification”) and then the Particle Image Velocimetry procedure can be performed to reveal the surface velocity distribution.

Videos are usually recorded from the river bank or from a bridge. In order to derive accurate flow data from the recorded images, they have to be orthorectified by an appropriate image transformation scheme. A minimum of six GCPs⁶ are required (Figure 5.16) to perform this transformation. The control point selection is often dictated by accessible objects in the field (e.g., trees, power line poles, building corners).

⁶ Georeferenced Control Points

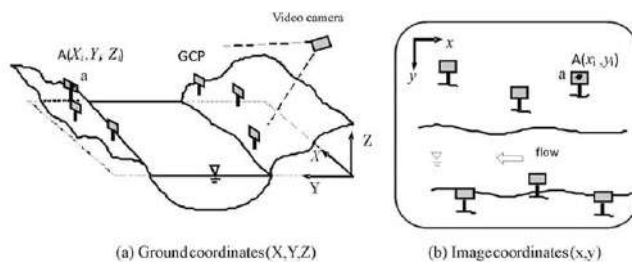
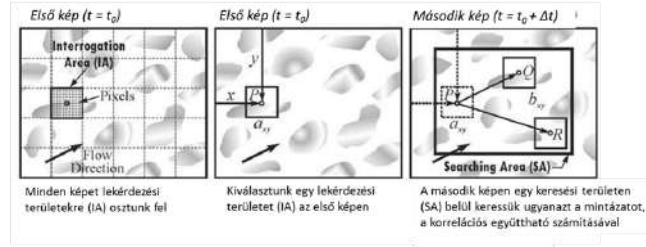


Figure 5.16: Relationship between camera and field coordinates (Muste, 2008)

The LSPIV algorithm uses a pattern matching technique based on image intensity distribution in a series of images as illustrated in Figure 5.17. The similarity index enclosed in a small interrogation area (IA) fixed in the first image is calculated for the same-sized window within a larger searching area (SA) selected in the second image. The window pair with the maximum value for the similarity index is assumed to be the pattern’s most probable displacement between two consecutive images. Once the distance between the

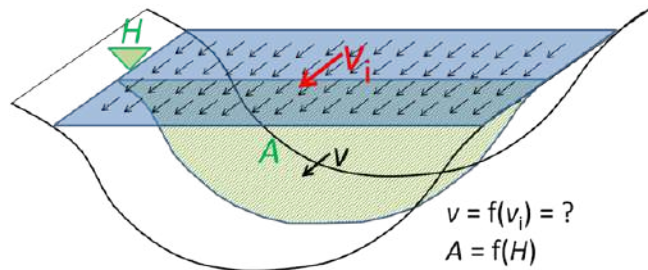
centers of the respective small window is obtained, velocity can be calculated by dividing it with the time difference (dt) between consecutive images. This searching process is applied to all interrogation area in each image.

Figure 5.17: Interrogation Area and Searching Area



The raw LSPIV measurement outcomes are instantaneous velocity vector fields. During the post-processing, it is essential to calculate the time-averaged velocity vector distribution. The principle of the index-velocity method is to establish an equation for the relationship between the channel mean velocity (v) and index-velocity (v_i). Water level (H) may be also a parameter for the rating curve as it determines the wet cross-sectional area (A). Discharge is calculated from Equation 5.2 (Figure 5.18). After the proper calibration, only index-velocity and water level measurements are required to estimate the actual discharge in a cross section using the LSPIV method.

Figure 5.18: Index-velocity



5.8 Radars

This method uses radars to measure the river flow without any direct contact with the water. The radar uses the principle of Bragg scatter from roughness elements of the water surface, such things as rain or wind effects. Radars can be: continuous wave microwave radars (with 24 Ghz center frequency), monostatic UHF Doppler radars (350 Mhz), pulsed Doppler microwave radars (9.36 Ghz), and groundpenetrating radars.

Radars can directly measure the parameters necessary to compute flow: surface velocity (converted to mean velocity) and cross-sectional area, thereby avoiding the uncertainty, complexity, and cost of maintaining rating curves. River channel cross sections were measured by groundpenetrating radar (GPR) suspended above the

river (Figure 5.19). The surface water velocity can be obtained by UHF Doppler radars, and the surface velocity data are converted to mean velocity on the basis of detailed velocity profiles measured by current meters and hydroacoustic instruments. Both the cross-section area and the mean velocity values are reliable compared to acoustic and mechanical current meters.



Figure 5.19: Radar of a noncontact discharge measurement system

Conductivity is however, a significant problem to be faced during experiments. Between some conductivity value ranges (for some tested rivers 300-600 $\mu\text{S}/\text{cm}$) the GPR interpretations of the cross-section area can fail. This method is recommended when other conventional methods are costly, time-consuming, and/or if the stream or river is not accessible.

6

Sediment measurements

6.1 Introduction

The following chapters deal with an other important phenomenon of the rivers, the so called sediment transport. At first, the origin of the river sediment will be introduced, alongside with some of the most important parameters of it. Later in this chapter the way of measuring and investigating of these properties will be shown. This chapter, besides being a general introduction, focuses on the investigation of suspended and bedload sediment, while the next one aims to present the laboratory examination of the different sediment properties. Basically sediment is the material that some kind of media carries away using its own kinetic energy. This media can be for example the air (wind), the ice (glaciers) and from our perspective the most important one: water (rivers, lakes or ocean streams) (Langland and Cronin, 2003)). This term is often used to describe soil-based mineral matter¹ because most of the time these materials are responsible for the changes in river morphology. It must be taken into account that not only these, but organic substances and inorganic, biogenic materials are considered as river sediment as well (Fondriest Environmental, 2014). Sediment transport is the movement of the sum of these materials due to the flow of water. The lecture note is dealing with the origin and investigation of the soil-based sediment, though at some points it is necessary to take notice of the other two groups and examine them collectively.

¹ gravel, sand, silt,...

The emergence of the river sediment is graded by both spatial and formation aspects. By formation generally three different impacts can be distinguished. These are the geomorphological, geological and the organic impacts. The sum of these processes determines the quality, quantity and size of the sediment particles get into the river. By spatial perspective, the sediment comes from the surrounding area of the river, and the sediment that is originally from the material of the riverbed can be separated (Czuba et al., 2011).

Speaking of geomorphological effects we refer to the quality of the surrounding terrain and the surface altering effect of the wind, ice and water, the so called erosion. During the process the exist-

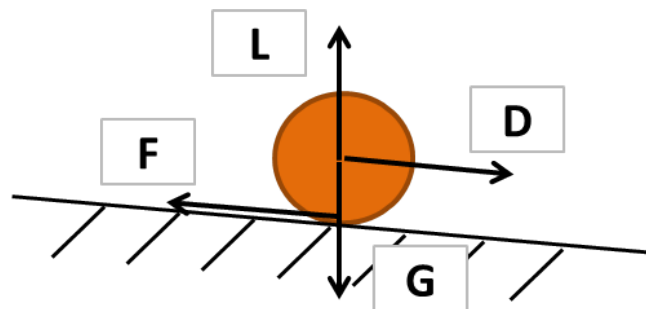
ing rock or soil breaks down and becomes movable by the water flow. Depending on the kinetic energy and the mass of these small particles, they get carried away. It is easy to understand that in mountainous regions where the gradient of the riverbed is higher, the velocity of the water, thus the kinetic energy of it is also significantly increased. Those areas where erosion is dominant, and the flowing water has higher energy, are called upper-river typed, while the declivous ones where the flow velocity is slower and the energy is lower are called down-river typed sections. Erosion is highly dependent on the geological properties as well. In general, the softer rocks are eroded easier while the hard ones are more resistant to water, ice and wind. It must be kept in mind that vegetation, and human activities can affect the scale of erosion significantly (Czuba et al., 2011). The sediment formation due to organic impacts will not be detailed in this lecture note.

² thus on the turbulence occurring in the water, and on the bed sheer velocity

As it has been introduced before, sediment transport is highly dependent on the kinetic energy of the water ². If the kinetic energy is high, the flowing water might mobilize bigger particles such as small rocks and gravels, while if this energy is low then only really small grains can be displaced like sand or silt. By the movement of the particles in the stream, the river sediment can be separated into three different groups (Southard, 2006). It is important to mention that the particle size boundaries between two of these groups (suspended, bedload sediment) might change depending on the energy of the carrying water flow.

Bedload is the part of the carried material in rivers that has such great mass or has such strong cohesion between the particles that the flowing water cannot keep them in continuous suspension and unable to carry away them as suspended sediment. The movement of these particles is neither uniform nor moderate. The motion of a single particle is determined by its own underwater weight, the dragging force of the flow, and the frictional and supporting forces. The velocity of the bedload material is not the same as the velocity of the flow, although the direction is identical. This motion can be rolling, gliding and bouncing (Garcia, 2008). Figure 6.1 shows a scheme of the forces acting on a single particle: gravitational force (G), uplifting force (L), friction (F) and dragging forces (D).

Figure 6.1: Scheme of forces acting on a single bedload particle



Deduced from the parallel components to the riverbed of the

introduced forces on the previous figure, together with the frictional force and the underwater weight of the particle the following equation can be written:

$$d = \frac{\tau_c}{g(\rho_s - \rho_w)\tau^*}, \quad (6.1)$$

where d is the diameter of the particle, g is the acceleration due to gravity, τ^* dimensionless shear stress (dimensionless Shields stress), τ_c is the critical shear stress, ρ_s is the density of the particle and ρ_w is the density of the water (Shields, 1936). In order to determine the critical stress, Shields performed experiments and created the following curve (Figure 6.2). This method is one of the most frequently used techniques to define the movement of the bedload materials.

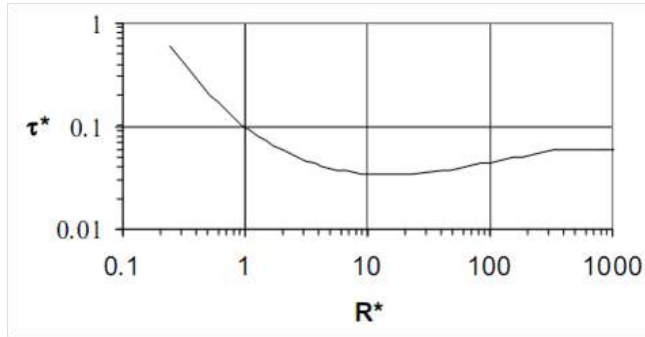


Figure 6.2: Shields-curve

On the x -axis the so called particle Reynolds number is presented, what can be calculated as follows:

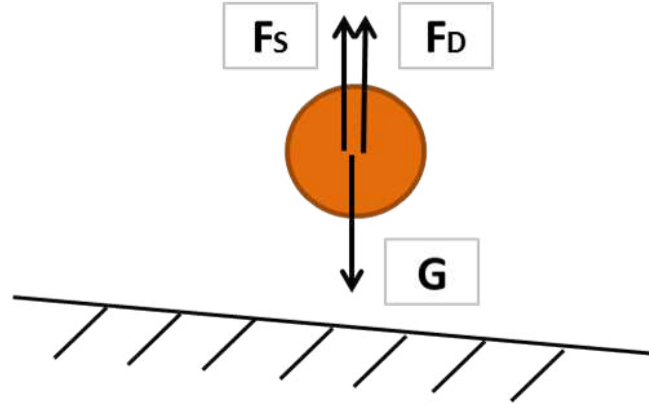
$$R^* = \frac{u_* \cdot d}{\nu} = \frac{d \cdot \sqrt{\frac{\tau}{\rho}}}{\nu}, \quad (6.2)$$

where ν is the kinematic viscosity of water.

The equation illustrates that for a specific sized particle the decisive factor that determines the bedload movement is the bed-shear stress. The current causes a friction on the boundary between the water and the riverbed. Whenever this stress overcomes the forces stabilizing the particle, the sediment will get into motion. The critical shear stress actually represents the exact value of the shear stress which keeps the stabilizing forces in balance. That is the reason why the particles creating the bed surface stay in position, and the particles coming from upstream get into rest if the current generates shear-stress lower than the critical value. Otherwise, the particles on the surface of the riverbed will be dragged by the flow and the sediment coming from upstream moves towards. Based on this, if the shear stress exceeds the critical value and the sediment coming from upstream is less than the dragged quantity of the bedload, the erosion of the riverbed will occur. Contrary to this process, if the shear stress is below the critical one, yet there is sediment coming from upstream, there will be sediment deposition which causes the elevation of the riverbed.

Suspended sediment is the part of the carried particles in a river, which size and weight is small enough to be kept in continuous suspension by the turbulent vortices emerging in the flow. The forces causing the vertical movement of the suspended particle in the water are the gravitational (G), the hydrostatical uplift force (F_S), and the hydrodynamic uplift forces (F_D).

Figure 6.3: Scheme of the forces acting on a suspended sediment particle



If the resultant force of the previously introduced ones equals zero, the particle is in perfect suspension. There is neither sediment deposition nor sediment resuspension. The gravitational and the hydrostatical uplift forces can be practically considered to be constant over space and time. Thus the vertical motion of the suspended sediment particles is completely due to the ever changing hydrodynamic uplift force which occurs due to turbulent vortices between the different layers of the flowing water. The continuous shoving of these vortices keeps the particles in suspension in the flow. The energy of these tiny turbulent currents depends on the velocity of the main flow, so in general if the flow velocity of the river is high, then more particles can be kept in suspension, and the size of these grains are bigger, compared to that condition when the velocity is lower. The approximate settling velocity of a single particle (v_s) can be calculated using the so called Stokes equation:

$$v_s = \frac{g \cdot d^2 \cdot (\rho_s - \rho_w)}{18 \cdot \nu \cdot \rho_w}, \quad (6.3)$$

Where g is the acceleration due to gravity, d is the diameter of the particle, ρ_s is the density of the sediment particle, ρ_w is the density of water and ν is the kinematic viscosity of water. It is easy to see that by increasing the size of the particle the settling velocity also increases, however if the viscosity is higher the settling velocity drops off. In general the Stokes-law might be applied reliably for particles with diameter between 0.01 – 0.1 mm. Smaller particles do not tend to settle at all, the group of these sediment will be discussed later (Török, 2011). As no other horizontal forces affect the suspended sediment particles apart from the kinetic energy of the main water flow, the velocity magnitude and direction of these sediment can be assumed to consistent with the flow field.

Consequently, particles transported through suspension, has a more uniform and smoother motion than the bedload ones. The particles can be transported either suspended or as bedload depending on the properties of the main flow, so the physical parameters of sediments does not determine the way of transport on their own, it is always a function of the flow field. Whenever the velocity in the river drops, the effect of turbulent vortices weakens, the bigger particles will settle down and move towards as bedload material. Of course the inverse process can take place when the sediment mobilizing potential of the flow increases and particles from the bed material can be dragged and carried away as suspended sediment.

6.2 Suspended sediment measurement methods

Before introducing the methods in detail, a brief overview comes on the most important parameters of suspended sediments. These properties of the sediment are necessary to quantify in order to describe the behavior of the sediment (Haimann et al., 2014):

- Concentration
- Sediment discharge
- Particle size distribution
- Spatial and temporal variety
- Characteristic particle sizes

Suspended sediment concentration³ refers to the amount of particles in water. It can be calculated by dividing the mass of the sediment with the containing volume of water. The mass of the solid particles is often determined by drying the water sample out, than measure the mass of the remaining matter.

³ SSC

$$SSC = \frac{m_s}{V}, \quad (6.4)$$

where, SSC is the suspended sediment concentration in the water, m_s is the mass of the sediment, V is the volume of the sample. Concentration values are usually given in the following units [mg/l], [g/m^3]. The specific discharge of the suspended material shows the amount of sediment passing through a river cross-section under unit time⁴. The specific amount of this value can be calculated as follows:

⁴ e.g. annual, hour, min,...

$$q_s = v \cdot SSC, \quad (6.5)$$

where, q_s is the amount of sediment passes through at a certain point in a unit time, v is the flow velocity at the same point, SSC is the sediment concentration. The amount of sediment flowing through a cross-section can be calculated by double integrating the specific value along the cross section (A):

$$Q_s = \int \int q_s \cdot dh \cdot dB, \quad (6.6)$$

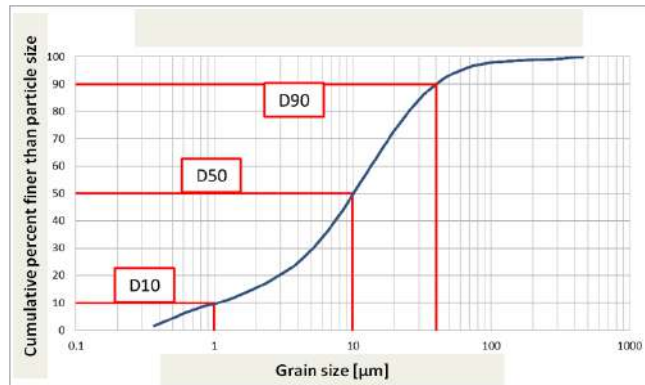
The sediment discharge may change not only in space but in time as well. Integrating the sediment discharge for a given period (e.g. one year) the total amount of passed sediment can be

calculated. The fluctuation of suspended sediment transport can be quite significant not only spatially, but temporarily (annually) as well. These fluctuations might have remarkable effects on river morphology, thus investigating the long term variety of sediment transport is also very important.

The composition of the sediment is determined by its particle size distribution⁵. There are characteristic values (e.g. d_{90} , d_{50} , d_{10}) that typify the quality of sediment.

⁵ PSD

Figure 6.4: Typical particle size distribution curve with some of the characteristic values (d_{10} , d_{50} , d_{90})



In the following sections different methods for the investigation of the previously introduced parameters will be described. These techniques can be divided into two main groups:

- Direct sediment measuring methods
- Indirect sediment measuring methods

6.3 Direct sediment measurement methods

In direct sediment measuring method we refer to a procedure that requires a previously taken water sample, which is later used to directly quantify the properties of its sediment content. During the process it is essential to take nonintrusive samples from the original media if it is possible, thus do not disturb the parameters of the sediment in the water during sampling. On this purpose the so called isokinetic samplers have been developed. On the next few pages the most frequently used sampling techniques will be introduced briefly, as they are fundamental for the direct measurement of sediments. The laboratory analysis will be discussed in details in the next chapter.

At first, the easiest technique will be introduced in a few words. This is the bailing method. During the process only a simple bucket is needed, with which water samples can be collected simply from the surface of the water. It must be kept in mind that this method is neither standardized nor nonintrusive. It might be useful in such circumstances when only approximate values are required or there is no other measuring option. Results coming from such a method always have to be taken with a grain of salt.

6.3.1 Isokinetic samplers

Isokinetic sampler means a device that 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, than the taken sample will have higher SSC value, on the contrary if the sampling velocity is higher, than the SSC is lower than the one in the original flow (Kutai, 2014). This effect is schematically presented in Figure 6.5.

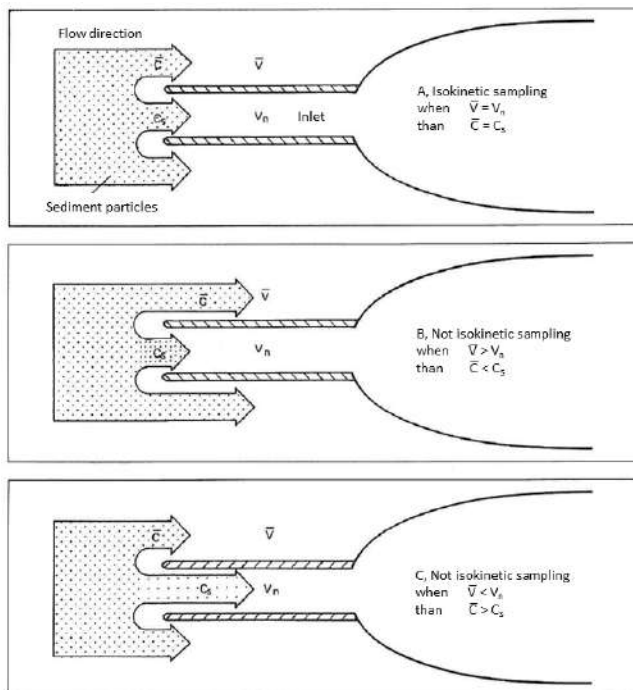
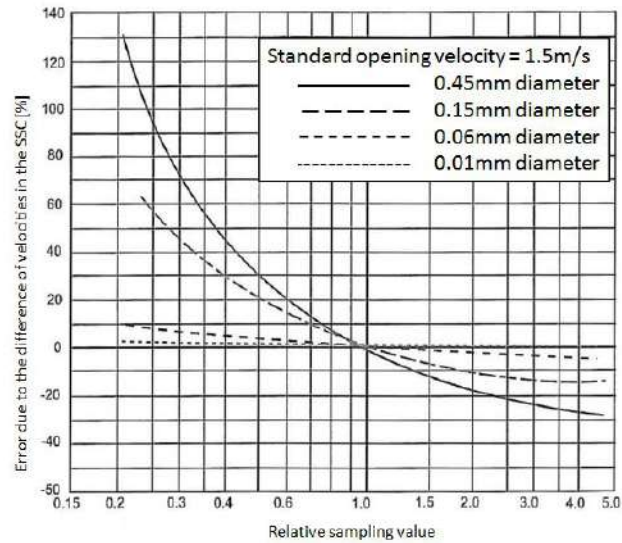


Figure 6.5: The effect of the difference between the sampling and flow velocities (Garcia, 2008)

The error due to the differences between velocities can be seen in the Figure 6.6 depending on the mean particle sizes. On the horizontal axis the relative sampling value is presented – i.e. the ratio of the velocities of the inflowing water and the original media, while on the vertical axis the changes in the SSC values can be seen (Kutai, 2014).

The instrument introduced in the followings is the so called 'quick sampler' (Nagy, 2013). The device is connected to a hoist and it can be released into the water from both a measuring boat or from the deck of a bridge. The instrument has a streamlined design, thus it does not disturb the surrounding flow. Owing to its fins it sets in a position parallel to the flow when it is submerged, and the head faces upstream hereby the water can flow into the tool. On the inside there is small cylindrical holder, whereon the water might flow through undisturbed until the ball pivots at both ends of the container gets closed by the operator from the surface. This can be done in a mechanical way (pulling a string). The closing of the

Figure 6.6: Error in the measured SSC due to the difference in the sampling and main flow velocities. (Garcia, 2008)



pivots due to the previously tensed springs is instantaneous from practical point of view, thus the water sample collected this way is considered to be nonintrusive. A disadvantage of this method is that the inside of the container has a limited volume (0.2 l) and the mechanical closing of the pivots can be cumbersome from the measuring boat.

Figure 6.7: 'Quick' sampler (Nagy, 2013)



A more sophisticated way to obtain water samples is deploying the US P-61-A1 isokinetic sampler that has been developed by the US Army Corps of Engineers. The instrument has the nickname 'the fish' that refers to its streamlined body and fins. Inside its body this device also has a sample container that can be taken out and changed by opening the head part. On this head part there is an opening with an electric valve, which can control the inflowing water. Due to its shape, when it is submerged the device sets parallel to the flow, facing upstream, thus proper water samples can be collected. The operation of the electric valve can be done from the surface by the special hoist system that can transmit electric

signals to the submerged tool. The disadvantages of this method are that the electric system is quite sensitive, requires extremely careful handling and that as it has been developed according to US standards it is not easy to get spare parts for the instrument in the EU (Baranya et al., 2016).



Figure 6.8: US P-61-A1 sampler (Csiti, 2016)

Another isokinetic sampling method is the so called *pump sampler*. This device consists of a simple pump and a hose connected to it. The stability and the proper facing of the end of the hose have to be ensured by a joined weight with fins. Operating such a sampler requires careful attention, the power of the pump has to be adjusted at every sampling in order to obtain the adequate sampling speed, hereby provide an isokinetic condition. An advantage of this method is that the volume of the sample is not limited, as much water can be collected from a measurement point as desired. A disadvantage beside the cumbersome deployment of the device is, if the exact time of sampling is needed to be set together with results from other instruments, the velocity thus the time the sample travels through the hose has to be considered.

Another, rather rarely used samplers are the *bottle samplers*. The principle of these instruments is based on the balance of the hydrostatic and water pressure. The instrument behaves as the previous ones when submerged, facing upstream, parallel to the main flow. The water flows into the container inside the device through an opening on the head. Such instruments are the ones from the US DH series (Kutai, 2014).

After the sampling has been made it is essential to store the samples in a proper way, carry them with care and perform the laboratory tests as soon as possible. If the samples are stored for

Figure 6.9: Bottle Sampler (Kutai, 2014)



a long time, the organic matter may change depending on the quantity of light. Examining samples containing a such additional biological elements due to the inappropriate storing might lead to mistakes in the SSC determination, hence can corrupt the measured data in general.

6.4 *Indirect measurement methods*

Speaking of indirect measuring methods, we refer to a process where the properties of the sediment is determined without taking water samples. Indirect devices measure different properties of water, or emit different signals into the water and investigate the properties of the reflected signals. Using empirical or semi-empirical correlations, the obtained data can be calibrated and the SSC or the PSD can be derived. The fundamental part of these methods is the calibration that might be done through using results from direct measuring methods as reference values. The indirect instruments can be divided into two large groups based on their principle of operation. The two groups are the optical and the acoustic (Csiti, 2016) devices.

It has been reported, that both the acoustic and the optical instruments have their own shortcomings. Depending on the mean particle size of the suspended sediment to be investigated, these techniques provide different levels reliability. The reason of this is the fact that light and sound have wavelengths in different orders of magnitudes, thus they have different response to different sized particles. Acoustic devices tend to operate more reliably when the mean particles are coarser and optical devices are more reliable when the mean particles are in the finer region. This phenomenon is illustrated in Figure 6.10. Additional information on this effect can be found in the original paper ((Agrawal, 2016)).

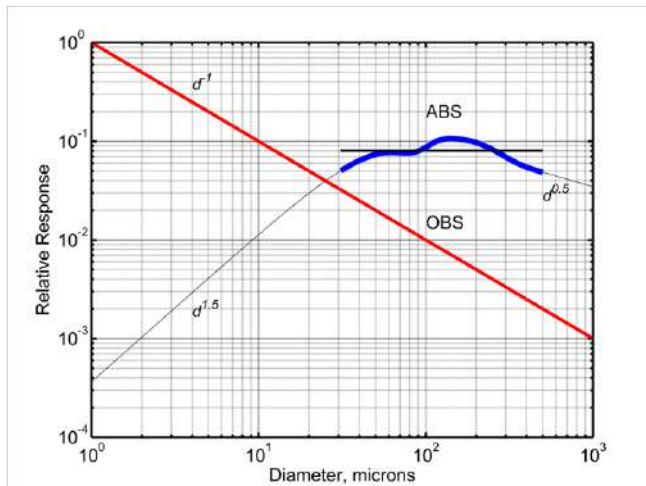


Figure 6.10: Comparison of the relative response of the acoustic and optical devices at different particle diameters (Agrawal, 2016)

6.4.1 Optical devices

The very basic principle behind the 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, the light beam scatters and refracts (Hulst, 1957). These changes in the parameters of light are measured and analysed by the devices. The optical based devices can be divided into two further groups, the instruments either measure the small angled forward scattering of the light or they exploit the backscatter strength of the light for measurements.

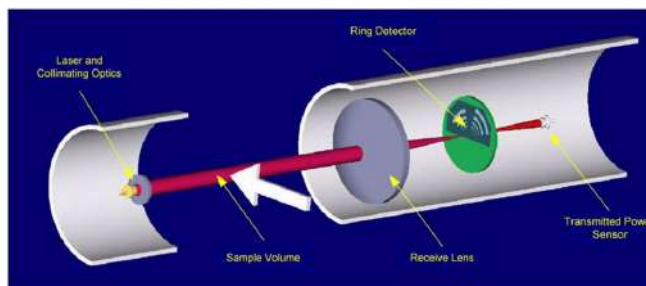


Figure 6.11: Principle of operation of the LISST-100X device (Sequia Scientific Inc.)

– Forward scattering laser light analysing

The group of instruments introduced first analyse the small angled forward scattering pattern of the emitted laser beam. The operation of these instruments is the following: they emit a laser beam with a known wavelength into the examined water then the light scatters on the particles. This scattered light is collected, and focused by a receiver lens onto concentric detector rings. The scattering is dependent on the size of the particle⁶, hereby the amount of light reaching the different rings will deviate. Each detector ring corresponds to different size group of particles, so by the amount of light detected by each ring the proportion of the size groups in the sample can be calculated. The SSC value is estimated by the difference in the emitted

⁶ Mie's theory

and received intensity of light. If the concentration is higher, more light is absorbed in the water. Knowing the volume of the sampled water (length of laser beam through water) the results can be converted into SI units such as $[g/m^3]$ or $[mg/l]$. This is the working principle of the introduced LISST-100X and LISST-Portable Xr devices (Csiti, 2016).



Figure 6.12: The LISST100X



Figure 6.13: The LISST Portable Xr

The first introduced indirect optical tool is the LISST-100X. This device can perform measurement on the spot, directly underwater. Originally it has been developed to investigate sea currents, does not have streamlined body, so this must be considered when using it in rivers. It performs a measurement in every 3 seconds so it is unable to follow rapid changes in the sediment structure suitably. Because of its shape it might disturb the local currents, so it is not advised to use it where the flow velocity is high.

The LISST-Portable exploits the same principle as the 100X, but it is not a submergable instrument. It is the laboratory version of the previously introduced device. It requires water samples that have been taken in advance. The measuring range of the device is larger than the 100X's, the measurement is more precise, thus the results are more reliable. This tool is capable to provide proper reference values for calibration of other indirect methods. It is mounted with inner batteries so it can be directly used during field campaigns as well.

– Optical backscattering sensors

The operation of these instruments is based on measuring the backscattering of the emitted infrared signals from the sediment particles in the water. There is a relation between the SSC and the strength of the backscattered signals. The exact correlation function has to be set up by calibration for every field measurement campaign. As this calibration is highly dependent on the mean particle size it is essential to do the calibration whenever the sediment properties change significantly (Csiti, 2016).

⁷ Optical Backscatter Sensor



Figure 6.14: Ponsel NTU digital turbidity meter

The process of the OBS⁷ measurement is the following: It emits infrared light, using the transmitter located in its head, then this light scatters back from the suspended material and this backscattered signal is detected by photodetectors. The instrument does not measure SSC directly but turbidity and these results can be converted to concentration values through proper calibration.

An advantage of these OBS devices is that they have a relatively low cost yet they can provide quality data. It is also very handy that not only single-point measurements can be conducted, but in case the devices is mounted to a measuring boat, than the horizontal distribution of the SSC can also be derived.

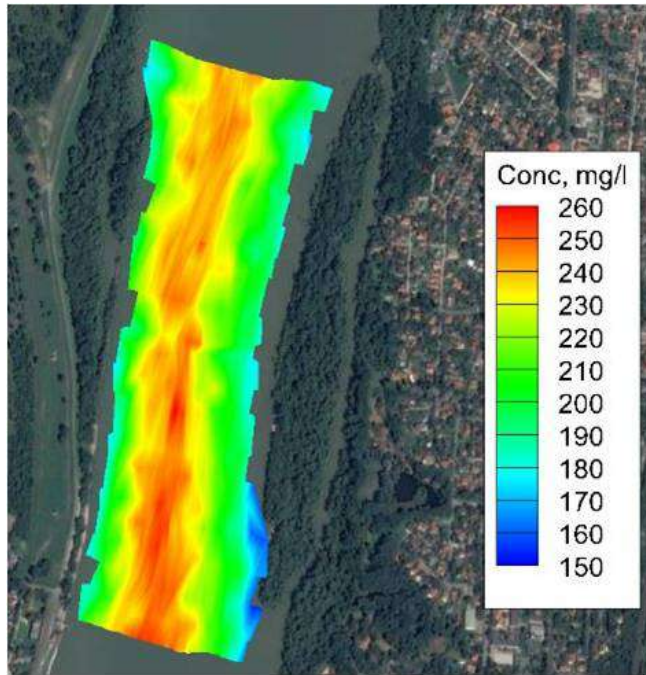


Figure 6.15: SSC distribution generated from moving boat OBS data

6.4.2 Acoustic devices

The principle of operation of acoustic instruments is analogous to the previously introduced optical devices. A very short pulse of high frequency sound is emitted from a transducer and the suspended sediment particles scatter 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 is linearly proportional to the distance of the location of the scattering (Thorne et al, 1990). A schematic figure of the process can be seen in the Figure 6.16.

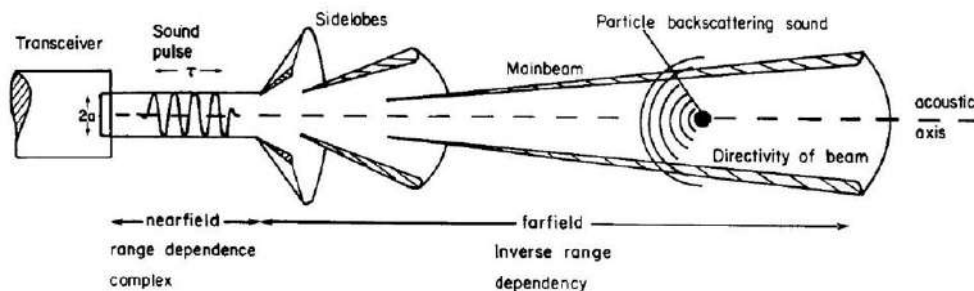


Figure 6.16: Schematic figure of the working principle of acoustic devices

The first introduced acoustic instrument is the LISST-ABS⁸. The basic idea behind the operation of the device is the same as it was for the OBS, however, it uses very high frequency sound pulses instead of infrared light. This device also provides the opportunity to conduct single-point measurements, but mounting the device to a moving boat may also result in horizontal SSC distributions. The analyzed (sampled) volume of water is approximately 5 cm

⁸ Acoustic Backscatter Sensor



Figure 6.17: LISST-ABS



Figure 6.18: LISST-ABS sensor face

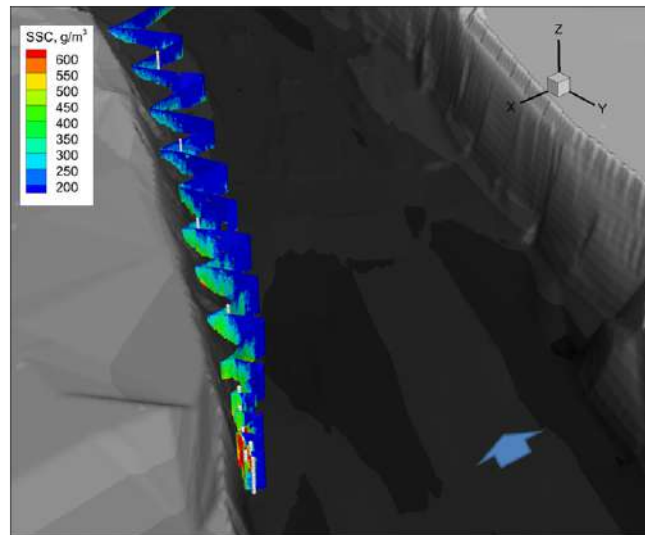
away from the head of the ABS so the absorption of the sound waves does not need to be taken into account. The big advantage of the instrument is that it can be also used reliably when the concentration is extremely high, and its operation is quite simple.

Although the original objective of the previously introduced ADCP was to measure flow velocities and discharge, recent studies have shown that it can be quite effectively and reliably used for SSC estimations as well. The instrument detects the backscattered sound waves from different depths, and as the strength of the detected signal is proportional to the SSC, a concentration profile can be calculated using the echo intensity values. This method also requires an adequate calibration, but in this case the calibration process is more complicated than for the ABS, as the absorption of the sound waves has to be taken into account as well. Calibrating the ADCP is done using the so called Sonar equation (Equation 6.7) (Baranya and Józsa, 2013):

$$SSC = 10^{A+B \cdot (K_c(E-E_r)+2 \cdot (10 \cdot \log(R)+\alpha \cdot R))} \quad (6.7)$$

After the echo intensity values are converted to SSC values, the raw ADCP data can be used to investigate the spatial distribution of suspended sediment. A big advantage of this method is that the ADCP can provide a cross-sectional SSC profile unlike the previously introduced instruments. Performing moving boat measurements the 3D nature of the river suspended sediment load can be investigated.

Figure 6.19: 3D distribution of a suspended sediment plume obtained by ADCP measurements



6.4.3 Other instruments

As it has been previously mentioned, that the indirect methods are sensitive to the changes in the PSD and that in general, the size of the investigated sediment might influence the reliability of the provided results. In order to overcome these shortcomings it is advised to use both acoustic and optical methods simultaneously.

It is noted, that experiments are already in the progress to create devices which utilize the advantages of both the acoustic and optical tools. Such an instrument is for example is the LISST-AOBS. The rather clear idea behind creating such an instrument is to have an ultimate tool that can be deployed for quality SSC measurements regardless of the actual characteristics of the suspended sediment particles (Agrawal, 2016).

6.5 *Field measurements*

In this section, the typical field measurement plan will be briefly introduced. Prior to the actual measurement, the most important thing is to select the most adequate methods and instruments considering the purpose of the measurement. The measurement can be done either *from the deck of a bridge* or as a more practical way using a *measuring boat*. The latter one makes it possible not only to investigate a fix cross-section of the river but even measuring a whole area. Whenever using a measuring boat, there are two alternatives.

The first one is the *fixed boat measurement*, where the investigation is done at given verticals. These measurements reveal the vertical variability of the sediment parameters through taking and then analyzing samples from different depths along the vertical or through performing indirect measurements the same way. Since representative samples are always required for the calibration of indirect measuring devices, fixed boat measurements always have to be conducted when such methods are to be applied. The other way of boat measurements, as it had been already mentioned earlier, is *moving boat measurements*. The idea behind this technique is to conduct different measurements continuously through cross-sections or along any desired path, in order to get the distribution of sediment related parameters along a horizontal plane (e.g. with OBS or ABS) or even in 3D (with ADCP).

It is essential to record the location and the movement of the boat during the procedure with a GPS device which is necessary for the georeferencing of the measurements. The importance of measurement logs during field trips are also underlined.

6.6 *Measurement methods of bedload sediments*

The main goal of bedload sediment measurements is to determine the grain size distribution of the bedload and the to get a reasonable estimation on the cross-sectional bedload rate. Several methods and measurement configurations have been developed for this cause. These techniques can be again categorized in two classes: direct and indirect methods.

6.6.1 Direct bedload measurement methods

The direct bedload measurement methods are basically the physical sampling of the bedload. During the procedure, the bedload is trapped in a given point of the bed surface by a selected sampling method. The trapped sample is then analyzed in laboratory conditions, so one can derive quantitative properties of the bedload, e.g. its grain size distribution. These direct methods are generally more expensive and more circumstantial than the indirect methods. On the other hand, direct methods are considered more reliable compared to indirect methods which are still under continuous development. Furthermore, the validation of indirect methods always needs directly measurement values as well (similarly to suspended sediment measuring methods).

– Basket-type bedload samplers

The most widely used indirect bedload measurement tools are the basket-type devices. The main operating principle is the trapping of the bedload for a given time in a given point of the bed surface. The basket has to be lowered to the bed surface. Because of the basket wings, the flow turns the device gap always towards the main flow direction. Thus, the water and the bedload flows through the gap, the latter gets trapped in the basket. The free water flow through the basket is insured by the perforated basket sides. Internationally, the best known type is the *Helley-Smith sampler* (Figure 6.20., right). A similar, but a Hungarian development version is the *Károlyi bedload sampler*, which was designed by Károlyi Zoltán (Figure 6.20, left). The instruments are usually lowered by a winch and crane, from a bridge or a larger measuring vessel.

Figure 6.20: The Károlyi (left) and the Helley-Smith (right) bedload samplers



The samplers are generally designed that the cross-sectional area of the inlet gap is smaller than the outlet. This design results in the decrease of flow velocity inside the sampler, which promotes the trapping of the bedload particles (Helley and Smith, 1971). These kind of basket-type bedload samplers are called pressure-difference samplers. The devices allow the user to measure 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:

$$q_b = \frac{\Delta m}{\Delta t} \frac{1}{s}, \quad (6.8)$$

where q_b is the specific bedload discharge [$\text{kg}/(\text{m} \cdot \text{s})$], Δm [kg]

is the mass of the trapped bedload sample and s [m] is the width of the gap.

However, during the use of the samplers, the following typical symptoms can occur:

- The bed material can be agitated by the sampler at the lowering and can be trapped in the basket (oversampling)
- A gap can develop between the bottom surface and the lower plane of the sampler, or the larger grains can block the part of the basket gap, which reduces the collection efficiency (undersampling)

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 a flexible bottom sampler, steering wings, larger basket as well as underwater cameras (Garcia, 2008). Also, a generally applicable recommendation is the 3-times repetition of the sampling procedure in a given vertical, and the sampling time should be at least 15 minutes.

The Károlyi bedload sampler is recommended to use mainly in case of coarser sediment sampling⁹. The device is relatively large steel instrument and its weight is 35 kg. There is a window on the upper part of the back wall of the sampler. The flow can flow freely out from the device over a deflector, through the window, supporting the trapping of the sediments. The lower part of the back wall is completely closed, thus the sediments cannot leave the basket. The instrument can be equipped with an underwater camera, which can greatly increase the reliability of the sampling. However, the camera can be used only for clean water. The main advantage of using a camera is that the two introduced typical symptoms (over- and undersampling) can be detected. Thus, the sampling period can be corrected (Kulcsár, 2013).

⁹ gravel river bed, e.g. the upper section of the Hungarian Danube

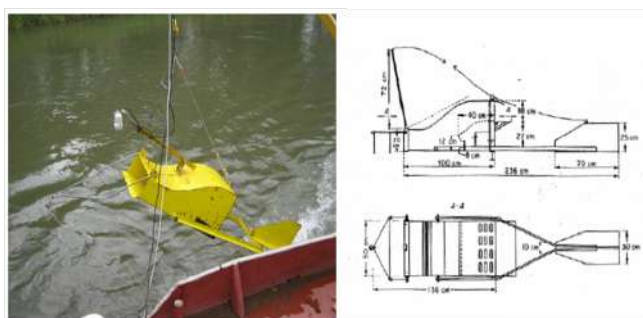


Figure 6.21: The Károlyi-type bedload sampler, which is recommended for gravel river beds

- Trench and trough sampling methods

More expensive methods are the trench- and trough sampling methods which also require major infrastructure (Garcia, 2008). The main operating principle is to evolve a trench on the river bottom surface to capture the bedload. The evolving of the trench can be a simple trapping purpose, but it can be supplemented by measuring and by data recording functions. The

main benefit is the high representativeness of the samples. The disadvantages are that these kind of sampling methods can be evolved mainly on smaller streams and the construction is quite expensive. In Hungary, these bedload sampling methods are not applied.

6.6.2 *Indirect bedload measurement methods*

The indirect methods mean that the applied instrument does not measure directly the required parameter of the bedload (e.g. the mass), but it is estimated based on other, measureable features of a physical process. Thus, the direct sampling can be avoided by the 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, still their not as reliable as the direct ones. One of the advantages of indirect methods is that they provide the opportunity to measure the bedload conditions in larger temporal and spatial resolution than the direct methods.

Nowadays, the combined and complementary use of direct and indirect techniques is the most practical. Reliable single point bedload measurements can be performed by direct measurement methods. Based on these measurements and post processed data, the indirect methods can be calibrated and validated, which provides the opportunity to qualitatively analyze the bedload conditions in a larger surface and over time as well.

– Tracer particles

One of the most widely used indirect method is the use of the trackers. The technique allows the users to track the route of given particles, indirectly. During the last decades, the method has been developing significantly. Einstein used painted particles in laboratory conditions to investigate the bedload motion path (Einstein et al., 1950). Later, the radioactive, fluorescent and finally the magnetic tracer methods were elaborated for purpose of field bedload measurements (Liedermann et al., 2013).

The most up-to-date tracer technique is the high-frequency radiotelemetry equipment. The following figure presents the elements of the system; which are the transmitter, antennas, cables, switching box, receiver, controlling computer and the energy supply. The battery-powered radio transmitters have to be placed into a natural or an artificial gravel. Then, the transmitters emit a signal, which can be perceived by an appropriate receiver, thus the position of the transmitter is determinable. The frequency of the emitted signal can be changed, thus it can be set different frequencies, so the individual gravels can be distinguished. 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.

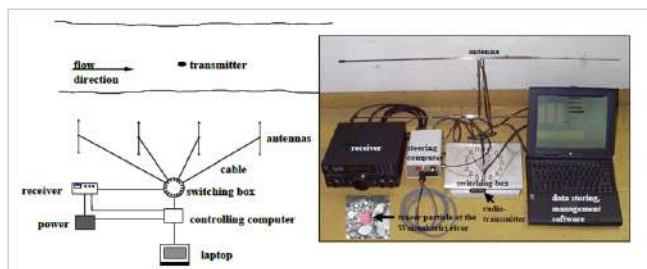


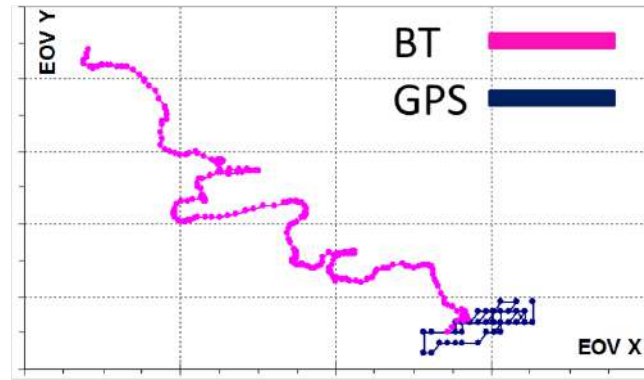
Figure 6.22: Elements of a radio tracer system

- Acoustic-based bedload measurements

The primary areas of application of acoustic devices are the indirect measurement of flow conditions (e.g. ADCP and ADV) and the bed geometry (e.g. Multibeam Echosounder). The instrument operation principle has been introduced in the chapter 'Acoustic measurements in riverine conditions'. Besides the primary functions of the acoustic devices, the application of the ADCP, or Multibeam Echosounder provide 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 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 Track*, 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. However, if the vessel is standing still and is not moving, or the movement of it can be determined independently (e.g. an 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 6.23 shows an example, when the vessel is standing still and there is considerable bedload transport. 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 momentary bedload sediment velocity vector can be calculated by the following formula (Rennie et al. (2002); Rennie

Figure 6.23: 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.



and Villard (2004); Gaeuman and Jacobson (2006); Gaeuman and Rennie (2006)):

$$v_b = v_{GPS} - v_{BT}, \quad (6.9)$$

where v_b [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.

So the ADCP device is capable to estimate the bedload motion indirectly. If the position of the vessel is fixed – e.g. it is anchored –, $v_{GPS} \approx 0$, then the bedload velocity is equal to the opposite vector of the v_{BT} vector. Figure 6.24. shows an example to the calculated bedload vectors based on ADCP measurements, regarding to the Danube reach (1672-1676 rkm) near the settlement of Sződliget in Hungary (Fleit, 2013).

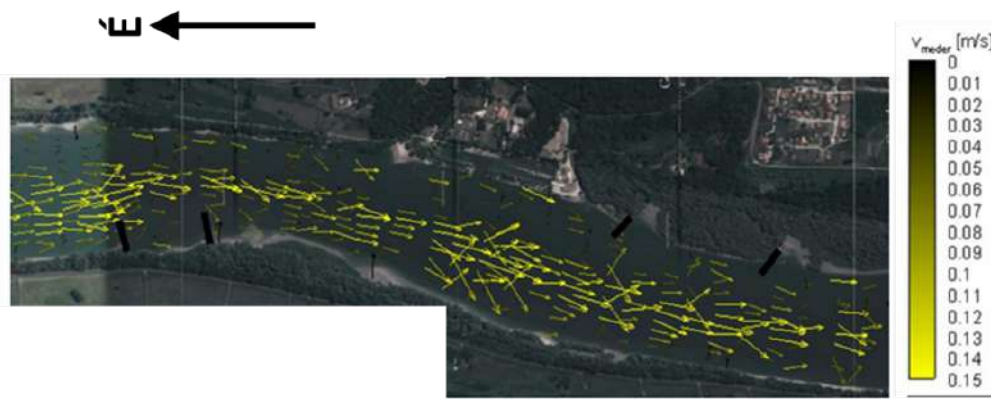


Figure 6.24: Near-bed sediment velocity vectors, calculated from ADCP measurement data (Fleit, 2013)

As it was already introduced in Chapter ‘Acoustic measurements in riverine conditions’, the Multibeam Echosounder device also provides the opportunity to the detection of bedforms (e.g. dunes), because of the high spatial resolution of the instrument. Figure 6.25 shows bed level maps measured by a Multibeam device in laboratory environment. The four maps belong to different moments of a laboratory experiment.

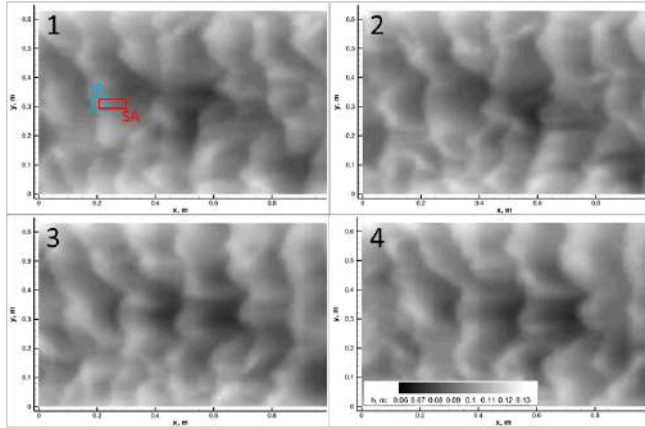


Figure 6.25: Bed level maps taken in different moments, measured by a Multibeam device in laboratory environment (Muste, 2016)

Due to the detection possibility of the dunes based on the Multibeam measurements, the dune velocity vectors can be estimated by the examination of the dune maps taken in different moments (Figure 6.26). The applied method for the velocity calculation is called Large-Scale Particle Image Velocimetry (LSPIV), which was already introduced in Chapter *Discharge measurement methods for streams*.

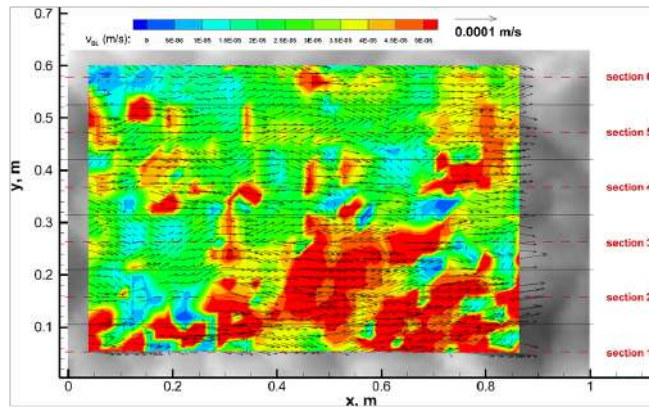


Figure 6.26: Bedload velocity vector-field, calculated with LSPIV (Muste, 2016)

Based on the above introduced methods, both the ADCP and the Multibeam devices provide the opportunity to estimate the bedload velocity. However, there is a major difference between the two calculated values. The velocity vector estimated from the ADCP data describes the motion of a scrolling particle on the bed surface, while the vector derived from the Multibeam data refers to the bedform movement – e.g. the dune velocity, which is much lower, than the particle movement. The specific sediment bedload discharge can be determined according to the following equation, based on the sediment velocity (Muste et al., 2016):

$$q_b = (1 - \alpha_p) v_b d_s \rho_s, \quad (6.10)$$

where q_b is the specific bedload discharge [$\text{kg}/(\text{m} \cdot \text{s})$], α_p [-] is the porosity¹⁰, ρ_s [kg/m^3] is the density of the sediment¹¹, d_s [m] is the thickness of the moving sediment layer and v_b [m/s] is

¹⁰ typical value is 0.3 - 0.4

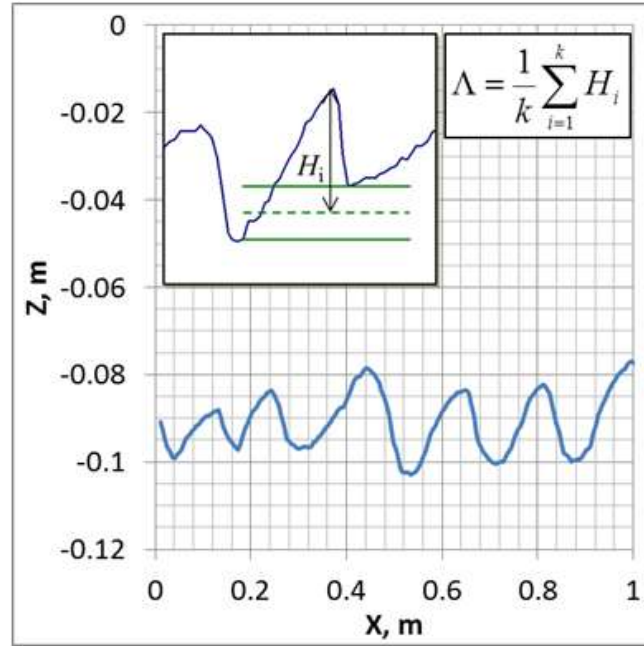
¹¹ typical value is 2650 kg/m^3

the velocity of the near-bed sediment movement. In the practice, neither the thickness nor the porosity are directly measurable, however their approximation can be done with reasonable limits.

Equation 6.10 can be applied for both the ADCP and Multi-beam methods (AMV¹²) as well. In case of the AMV method v_b is the velocity of the dune movement and d_s equals $\Lambda/2$, where Λ is the bed form height, that is the average dune height (see Figure 6.27).

¹² Acoustic Mapping Velocimetry

Figure 6.27: The method for the average dune height calculation, where k is the number of the dunes and H_i is the height of a given dune. (Muste, 2016)



When the ADCP method is used to estimate the bedload rate, v_b is estimated according to Equation 6.9, while d_s is equal to the thickness of the actual moving sediment layer. There are many formulas in the literature for the calculation of this bedload thickness. The most known of them are (Einstein et al., 1950) (6.11.) and (Van Rijn, 1984) (6.12.):

$$d_s = 2D_{50} \quad (6.11)$$

and

$$d_s = f(D_{50}; u_*), \quad (6.12)$$

where D_{50} is the median particle size and u_* is the bedshear velocity.

7

Grain size analysis and shelter frequency measurements

7.1 Introduction

Field measurements were carried out between the 29th of August and the 2nd of September 2016 at River Gaula and Lundesokna, where samples were taken with both bottom probe and freeze probe methods, as well as the the shelter measurements were carried out.

7.2 Measurement methods

When the degree of larger substrate particles buried in fine materials is determined, it is called embeddedness. This feature can be separated to inner and outer embeddedness. The deposition of the fine particles in the pore space of the river bed is called inner, when the deposition is on the river bed it is called outer embeddedness (Schälchli et al., 2002). Inner embeddedness causes the degradation of pore spaces and the uploading of the river bed. The permeability is reduced whereas oxygen flux is habited. Outer embeddedness leads to unstable bed substrate while reduces permeability and oxygen flux of the river bed. Based on the geometrical embeddedness criterion, which defines the particle size that can pass through interstitial spaces or gets wedged there (Noack, 2005). According to Schälchli et al. (2002), a few negative effects on natural habitats appear as fine sediments accumulation appears.

Fine particles are unstable and altering discharge leads to changing living environment. Accumulation of fine sediment leads to reduce infiltration to deeper zones, which provides less oxygen there. Sufficient oxygen is a critical condition for gravel spawning fish species and benthos to ensure survival. The valuable natural habitat for macrozoobenthos is the interstitial spaces which can be uploaded by fine particles easily. Different levels of embeddedness can be seen in Figure 7.1.

As a conclusion, juvenile fish like salmonids prefer interstitial spaces because of different approaches, thereby this study only deals with inner embeddedness, where the increased degree of

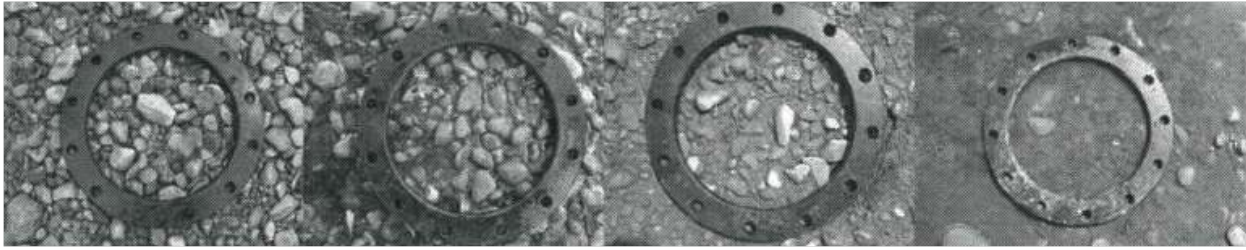


Figure 7.1: Different levels of embedment (Eastman, 2004)

accumulation affects negatively their natural habitat according to Finstad et al. (2007).

7.2.1 The Finstad method

The description and quantifying of embeddedness and substrate quality for juvenile fish is strongly connected with fine sediments accumulation or lack thereof, which has effect on shelter abundance. Keeping this in mind, Finstad et al. developed an easy and fast method to evaluate substrate and embeddedness in regards to measure available interstitial places for young salmonids.

By using a rubber tube shelters can be detected and classified easily. Experiments were carried out in semi-natural channels where hiding places were searched with different tubes with various diameters¹ by Finstad et al. (2007). Using a selected tube they tried to place them into interstitial voids, and if the penetration was deeper than 3.0 cm the shelter has been registered. Each shelter with a single entry is counted, for example a Y shaped void with three enters was counted three times. Substrate must be let undisturbed during the process. Each rubber has different marks to classify shelters. Three classes were determined to sort shelters into different types based on their depth: 3.0, 7.0 and 12.0 cm. Unseen marker determines the class of a shelter during process.

The tube with 13 mm outside diameter served the best variation in fish sheltering and was strongly correlated with juvenile fish of different life stage (newly-emerged fry, fry, parr). Therefore this study uses the results which were provided by a tube diameter of 13 mm. The rubber tube (normal PVC tube) is shown in the next figure (Figure 7.2) with the three markers to identify the category of shelters (3.0, 7.0 and 12.0 cm category I, II. and III.):

Shelter abundance was measured inside a square wooden frame with 50 cm edge length, which was placed on the river-bed. Within this 0.25 m² area the shelter measurement was performed, for instance from one corner to the diagonal one. The placed wooden frame (Figure 7.3) with the plastic tube are shown in use in the Figures 7.4 and 7.5.

During the application of Finstad's method it is not necessary to know the depth of a shelter. However it gives little more information about the habitat. The markers help the analyser to get quick

¹ 5, 10, 13, 16 and 22 mm



Figure 7.2: Rubber tube with the markers and a wooden frame on the background



Figure 7.3: Placed wooden frame in right place to measure

Figure 7.4: Shelter measurement;
Category I



Figure 7.5: Measured shelter, category
II. (left) and category III. (right)



visual information about the approximate depth of an interstitial space, which can be registered. An example of recorded shelters is shown in Table 7.1.

Sample no.	Collector	River	Cathegory I.	Cathegory II.	Cathegory III.
1	Marcell	Gaula	6	4	0

After each shelter measuring, the samples were taken into laboratory of Department of Hydraulic and Environmental Engineering (IVM), NTNU for further analysis.

Table 7.1: Example of shelter recording

7.2.2 Grain size analysis

For the assessment of the sediment status at rivers, it is indispensable to excavate samples and investigate them in laboratory. The composition of the substrate depends on location, gradient, morphology of the river, as well as its range of hydrograph. Grain size analysis is a way to investigate distribution of different sized particles from one or more represented site at the river. In addition, the distribution of particles is a necessary input parameter for sediment transport modelling.

Sampling methods

- Bottom probe method

The basic classification of coarse sediment layers in river bed is presented in the following the Figure 7.6 (Bunte and Abt, 2001):

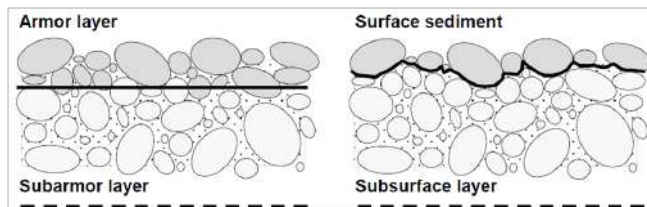


Figure 7.6: Stratigraphy of riverbed with coarser sediment particles (Bunte és Abt, 2001)

The first of all steps is to collect representative samples from the river field. Basically, there are two ways to gather samples correctly, *volumetric sampling* or *surface sampling procedures*.

The volumetric sampling method is determined by a specific layer of interest where the substrate has to be excavated (Figure 7.6, left side). It can be used both in dry and submerged conditions. On the other hand the surface samplings are based on counting the particles along a line, on even spaced grid points or in an exact area (Figure 7.6, right side). The result of the surface sampling is a particle size distribution, calculated by pebble counting, compared to volumetric sampling, where distribution of the particle sizes is calculated by the excavated mass. Following the suggestions of earlier studies (Jocham, 2010), volumetric sampling was applied under dry conditions for this study.

The samples gathered from Gaula and Lundesokna were taken into the laboratory of the Department of Hydraulic and Environmental Engineering for further investigations. The whole process is described step by step below:

- selection of an area where the probability of shelters is significant in the river bank, as close to the current water level of the river as possible
 - random toss of the wooden frame within the selected area
 - taking a photo of the undisturbed substrate composition
 - discovering the shelters from one corner to the diagonal one with the 13 mm OD rubber tube
 - recording the shelters by their class
 - excavating the top layer of the substrate from the same containment area, down to the depth of the largest visible particle, and putting the reclaimed material into one of the marked buckets
 - taking a photo about the excavated area with the frame
 - bringing back the filled buckets to the laboratory
 - drying and sieving individually the samples in the laboratory, and recording the results
- Freeze plate sampling

The freeze panel sampler (FPS) takes completely undisturbed and above all near-surface sediment samples. A common acquirable FPS has a circular metal plate, which functions as nitrogen evaporator, under a carrier plate. A ring of foam material at the edge of the carrier plate compensates the weight, so that the pressure exerted by the evaporation plate on the river bed is limited (Figure 7.7).

Figure 7.7: Freeze plate after sampling at River Lundesokna



Besides, additional weights on the carrier plate compress the foam, to seal the probed volume and decrease cooling energy losses and the washing out of fine particles and organisms. The weights also ease the resistance against the flow during sampling. For a probe, the device is placed carefully on the river

bed and the liquid nitrogen is induced for about 25 minutes, about 35 liters of gas (Figure 7.8). A frozen calotte shaped probe develops beneath the evaporation plate and the system can be taken out of the river bed again. By heating up, the probe can be separated from the evaporation plate. The best way to transport the sampled sediment is to pack it in a film permeable to water and embed it in a dimensionally stable box with filter sand. The defrosting sample will keep its original shape and the water will be drained in the filter sand (Niederreiter and Steiner, 1999).



Figure 7.8: Freeze sampling at River Lundesokna

Particle analysis Although a particle as a three dimensional shape can be described by three mutually perpendicular axes², it is sufficiently accurate to describe the grains with only one variable, for instance with the sieve size where the gravel piece was remained, i.e. *b*-axis. The common procedure for the assessment of larger sediment samples (with larger particles) is generally the mechanical sieving, which is sufficient for further investigations (Krumbein et al., 1938).

Although the categorisation of size classes (hence the size of the sieve hole as well) can be different based on the literature, part of the Wentworth scale was adapted for the study. It is presented in Table 7.2.

Particles below 1 mm were grouped together, marked as fine sediments. The categorisation of the grain sizes according to (Table

² longest as an *a*-axis, intermediate as a *b*-axis and shortest as a *c*-axis

Table 7.2: Wentworth scale – extracted
(Bunte és Abt, 2001)

Description of particle size		Size class [mm]	
Boulder		>256	
Cobble	large	128-256	
	small	64-128	
Gravel	very coarse	pebble	32-64
	coarse		16-32
	medium		8-16
	fine		4-8
	very fine	granule	2-4
Sand	very coarse		1-2
	fine		<1

7.2) is possible and reasonable, as the formation of shelters is highly dependent on the distribution of different sized sediment particles.

The analysis of the sediment samples continues in laboratory environment, where they are measured and then heated in a special oven to obtain they dry weight as well (Figure 7.9, left). This oven is heated to up to 110 °C which results in the evaporation of the moisture from the sample. The average drying time is around 2-4 hours per sample.

Figure 7.9: Drying oven (left) and the sieving machine (right)



The final step in the laboratory to get the required data is to sieve the samples individually. The sieve was operated automatically (Figure 7.9, right). A square hole sieve is shown on the following picture. The sizes of the sieve holes were 64, 32, 16, 8, 4, 2 and 1 mm and an extra compartment at the bottom to catch fine sediment. Every retained material on the different sieves was measured on a scale (Figure 7.10, left) after the sieving, to get the exact mass in stated range.

Figure 7.10: Scale with a few sieving particles (left) and a handmade Wentworth template (right)



Particles larger than 64 mm were measured with a Wentworth template, which was made in the laboratory in 2010 (Figure 7.10,

Size class [mm]	Mass [g]	Mass [%]	Cumulative mass [g]	Cumulative mass [%]
<1	1920	9,7	1920	9,7
1-2	240	1,2	2160	10,9
2-4	380	1,9	2540	12,8
4-8	510	2,6	3050	15,3
8-16	2540	12,8	5590	28,1
16-32	3900	19,6	9490	47,7
32-64	7380	37,1	16870	84,9
64-128	3010	15,1	19880	100,0
128-256	0	0,0	19880	100,0
Summary	19880	100		

Table 7.3: Example for distribution frequency

right). It helped to determine the size of heavier pieces in the sediment samples and to sort them in the classes 64-128 mm and 128-256 mm.

Particle size distributions During the laboratory analysis, the particles were sorted into the determined classes and weighted for statistical assessment. When masses were determined per class fractions, frequencies could be calculated as well. The Table 7.3 shows the recorded masses of a sample in grams and percentages per classes, just as the cumulated masses.

Figure 7.11 presents the grain size distribution with the cumulative curve for the chosen sample presented before.

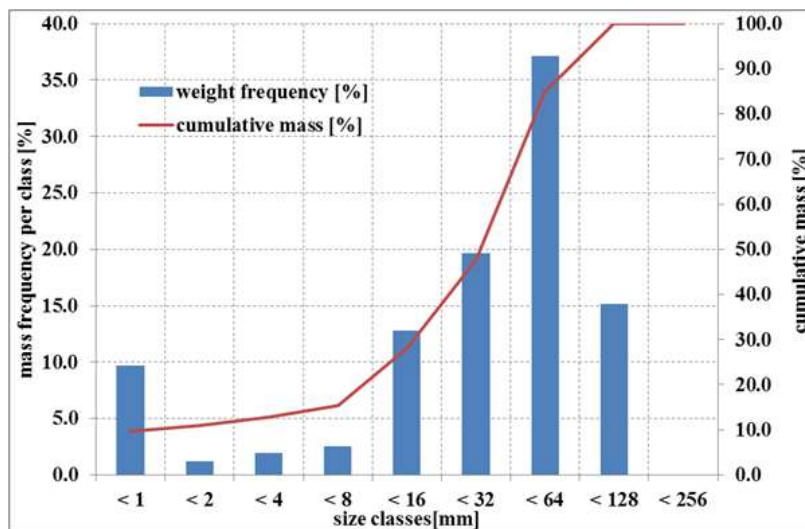


Figure 7.11: Example of a grain size distribution with its cumulative curve

7.3 Results

The samples taken from both River Lundesokna and Gaula have been brought back to the NTNU Laboratory where the grainsize analysis was carried out. The list of samplings is presented in Table 7.4.

Table 7.4: List of samplings at different sites

Activity	Gaula	Lundesokna
Freeze plate	1	1
Finstad method	4	0
Surface sampling	3	0

7.3.1 Results of the Finstad method

Shelter measurements were also carried out in River Gaula and the amount of different category shelters is presented in Table 7.5.

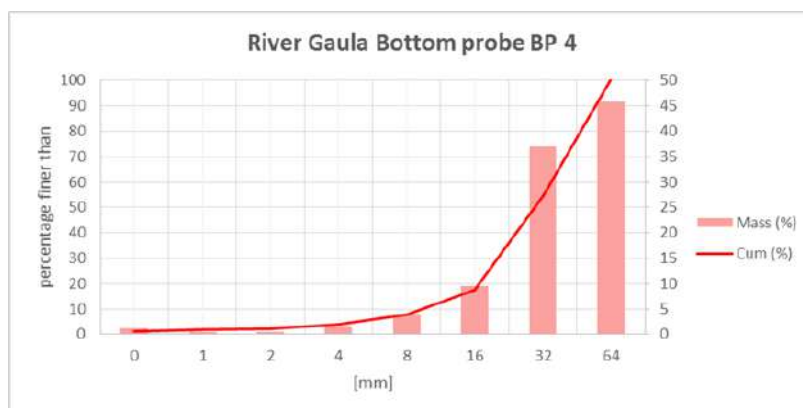
Table 7.5: The number of shelter categories

Sample no.	River	Category I.	Category II.	Category III.
BP1	Gaula	4	1	0
FP1	Gaula	8	0	0
BP4	Gaula	6	1	0
BP5	Gaula	4	0	0

7.3.2 Results of the grain size analysis

Five grain size analysis have been conducted for two different locations, four for Gaula (BP4 and BP5 are shown in Figure 7.12 and Figure 7.13) and one for Lundesokna (Figure 7.14). Corresponding bottom probe and freeze plate measurements were also conducted at sampling point No. 1 called BP1 and FP1, and their grain size distribution is shown on Figure 7.15.

Figure 7.12: Resulting grain size distribution for sample BP 4



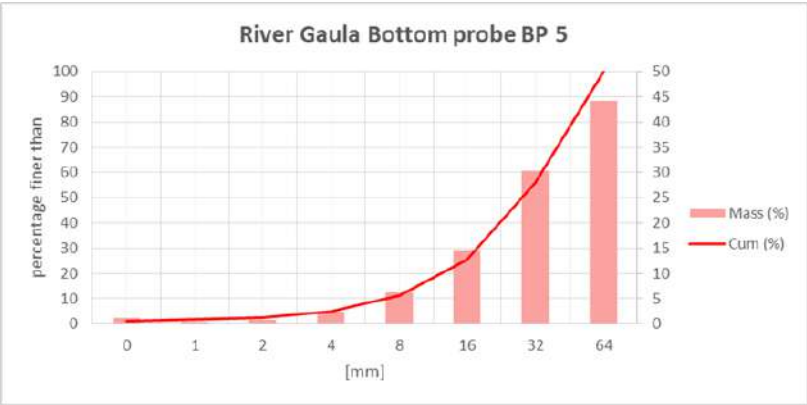


Figure 7.13: Resulting grain size distribution for sample BP 5

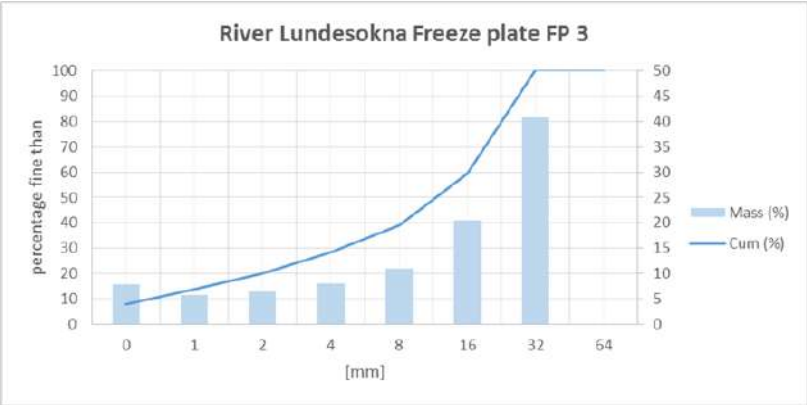


Figure 7.14: Resulting grain size distribution for sample FP 3



Figure 7.15: Resulting grain size distribution for sample FP1 and BP1

8

Sediment analysis

8.1 Introduction

In this chapter the laboratory analysis of the sediment samples will be discussed. The methods that will be introduced here are described according to the handbook that has been created in the international SEDDON (Investigation of the river sediment in the river Danube) project in 2014 (Haimann et al., 2014). This methodology is widely used when analyzing river sediment, was also found to be reliable, thus its introduction is well-founded. The first part of this chapter focuses on the methods of measuring suspended sediment properties, then it moves to the bedload material analysis. The steps of the measurement analyzing procedure will be introduced.

Once again, it is underlined, that the proper storing of the samples has to be ensured until the tests are done, as water samples containing suspended sediment may contain a significant proportion of organic matter. These small biological particles are sensitive to light and other storing circumstances. The sample holders are advised to be kept under the same conditions and in an organized way, thus the effects will be the same on every samples and it is easier to identify the samples and perform the tests.

8.2 Analysis of suspended sediment

Prior to the analysis, the purpose of the tests has to be defined so the most adequate method can be selected accordingly. Since the volume of the samples is often limited, and it may happen that only one test can be performed, the most important analyzed parameter has to be selected carefully. Usually three different parameters are analyzed during these tests. The most important property is usually the suspended sediment concentration¹, the next one is the particle size distribution² and the mean size of the particles³, last but not least is the ratio of the suspended load and the wash load.

The tests described in the followings are found to be adequate to measure such parameters. The SSC and total suspended solids⁴ determination is described according to the „Schwebstoffe im Fließgewässer – Leitfaden zur Erfassung des Schwebstofftransportes“⁵ (Habersack and BfLFÖ, 2008).

¹ SSC

² PSD

³ d_{50}

⁴ TSS

⁵ Suspended sediment in rivers – Guide for analysing suspended sediment transport

8.2.1 Total suspended sediment concentration (SSC)

On the term SSC we refer to the sum of total suspended solids (TSS) and the wash load in the water sample. In order to determine this property of a sample, the so called drying technique is used quite frequently. The simple idea behind this method is to evaporates water from the sample, so the material left over is measurable. Measuring the weight of this matter and knowing the original volume of the sample, the concentration can be calculated. The steps of this process are the following:

- Empty porcelain cups have to be dried for 4 hours at the temperature of 105 °C. (Thus the water from the contamination on the cups evaporates)
- In the next step, using a precision balance, the weight of the cups has to be measured with the accuracy of 0.1 mg.⁶
- After that, the water samples with known volumes (e.g. 40 ml) are poured into the cups.
- The filled cups are dried again for 24 hours in the oven at the temperature of 105 °C.
- After the water evaporated, the cups have to be measured again using the scale with the same accuracy.⁷
- Subtracting the two measured weights from each other, the weight of the left over matter is calculated. Knowing the volume of the original sample, the concentration can be calculated in the preferred units e.g. [mg/l] or [g/m³].

⁶ It must be mentioned that after taking out the cups from the oven, the contamination on them immediately begin to adsorb water from the humidity in the air, so the measurement has to be done as quickly as possible.

⁷ The method is the same as for the empty cups.

Figure 8.1: Total suspended sediment determination using analytical scale (left.: scale, right: water samples in the cups) (Kutai, 2014)



Performing this measurement requires special care, proper tools and a lot of time. Although if the process is done properly, than the result might be suitable for calibrating indirect methods reliably.

8.2.2 *Measuring suspended solids*

During this process the samples are filtered using an extremely fine filtering paper, thus the suspended solids get separated from the wash load. If the SSC value is available for the same sample, than using a proper scaling the proportion of the total suspended solids (TSS) can be calculated. During this procedure only the TSS value is measured, and the steps of this process are the following:

- Filtering papers with the pore size of 450 nm are dried at 105 °C for 2 hours to get rid of the adsorbed water.
- Similarly to the cups, these filters have to be measured with an analytic scale. The accuracy is advised to be the same (0.1 mg) as before.
- A previously defined volume of the samples (e.g. 100 ml) has to be filtered through the papers.
- After the process, the filters needed to be dried in the oven for another four hours at 105 °C.
- The dry filters then have to be measured with the scale again.
- Subtracting the two measured values, the exact TSS value can be calculated. It is advised again to convert the results to SI units.



Figure 8.2: Filters, before and after the procedure (Heimann et al., 2013)

This procedure also requires special care, and takes a long time. However, for calculating TSS, this method is still far the simplest and easiest way.

Figure 8.3: Filtering at the Via Donau Aschach laboratory (Heimann et al., 2013)



8.2.3 Particle size distribution analysis

In order to determine the PSD of a given sample, the previously introduced LISST-Portable XR might be a suitable solution. Its principle of operation has been presented previously. In this section the steps of a measurement with the device will be presented.

The LISST-Portable instrument is a stand-alone tool, mounted with an inner computer and batteries. Due to this reason, it can be used on field measurements as well as in laboratory environment. It can be operated using the built-in touch screen where the results are displayed as well. For further analysis the results from the measurements can be uploaded to a PC. The instrument stores every result with a unique file ID, however the inner memory is limited so it is advised to upload the data to computers every now and then, or delete them if they are not necessary any more. For the analysis, the water sample has to be poured into the mixing chamber of the instrument.

The procedure step by step is the following:

- First and foremost, the right preparations have to be done. The instrument has to be cleaned properly before every single measurement, which means the cleaning of the mixing chamber and the windows where the laser beam enters the sample.
- After the physical preparation had been done, other options must be set. First the desired project file has to be created, then the different properties of this file must be given.
- The most important parameter to set is the optical method. The measurement can be done using either the setting where the instrument assumes spherical particles or the other one where it assumes randomly shaped particles. If the randomly shaped option has been selected a further setting has to be done, namely



Figure 8.4: Use of LISST Portable XR

the presumed material of the particles has to be selected as it alters the optical method. Dealing with samples obtained from rivers the assumed material is usually quartz, as this is the most widespread material in river sediment. In the next step, the assumed density of the particles has to be given. At this part, the organic flocs has to be kept in mind, as the density of these are significantly lower than the soil-based particles, however, their size can be rather similar. The instrument is unable to make difference between them. Other options such as the mixing time and intensity of the samples can also be set, however, if the operator is unsure about these settings it is advised to use the defaults.

- After the preparations, the actual measurement can be started. The first step is the creating of the background file. This means performing a measurement with clear water for reference. Using this background file the instrument adjusts the results obtained from the water samples thus tries to correct the small errors of the instrument.
- In the next step the sample has to be poured into the mixing chamber carefully, minding that no air bubbles arise in the sample. The sample is then ready for the analysis.⁸
- The instrument mixes the sample and perform the measurement automatically. If the concentration is too high i.e. the transparency of the sample is not suitable for the measurement, the sample must be diluted than start the process from the beginning.
- After the results are saved, the procedure can be repeated with the following sample.

An advantage of this method is that the instrument can be mobilized and used during field measurements as well. The procedure

⁸ For more accurate PSD the auxiliary ultrasonic sensor might be used during the process.

is quite quick as well, it takes only a few minutes per sample. The results provided by the LISST Portable seemed reliable so far, these result can be used for calibrating other methods reliably. (Csiti, 2016)

8.2.4 Analysis of bedload sediment

When investigating bedload sediment in rivers, the main property that is being analysed is the PSD of the samples. Usually the procedure is done using a logarithmic sieve series. During the procedure, the sample gets separated into different size ranges, these groups are then measured, then their proportion to the total sample is calculated. Displaying the results the outcome is the PSD curve as it has been already presented previously. The curve provides with characteristic values such as the mean particle size (d_{50}) of the sample or other properties. In the following, the steps of the analysis of bedload material will be introduced according to the Austrian ÖNORM B 4412 standard:

- At first, the sample has to be dried completely.
- The dry sample then has to be sieved manually⁹ or automatically¹⁰ on a chosen series of sieves. The duration of the procedure is dependent on the amount of the sample (Approx. 10 mins). Particles smaller than 0.5 mm, might not fall through the sieves completely so it is advised to use a soft brush to help the process.
- In the next step, the weight of the separated size groups has to be measured including the very fine particles on the collecting tray beneath the sieves.
- At this point of the process a monitoring step has to be done. If the sum of the group weights is differed more than 1% from the weight of the total sample the measurement is false and has to be done again.
- After performing these steps, the size of the biggest particle and other specific particle sizes can be determined (e.g. d_{max} , d_{50} , d_{90}).

⁹ Figure 8.5

¹⁰ Figure 8.6



Figure 8.5: Logarithmic sieves for separating size groups



Figure 8.6: Sieving machine

9

Geophysical survey of rivers and lakes

9.1 Introduction

Mapping of water bottom and sub-bottom morphology of rivers and lakes provide important information for several studies. Water bottom morphology is a basic dataset for hydromorphological studies, while sub-bottom data are key for the understanding of the temporal evolution and physical characterisation of river and lake bed sediments.

Sub-bottom strata can be investigated using surface geophysical techniques. Surface geophysical techniques are based on physical measurements carried out on or very near the surface and provide information on the physical properties and stratigraphy of the sub-surface strata. Different surface geophysical surveys measure different physical properties of the subsurface and therefore are sensitive to varying layer properties.

River and lake surveys are most frequently carried out by seismic profiling using acoustic waves or GPR (Ground Penetrating Radar) measurements using electromagnetic waves for imaging the subsurface layers. Both of these methods are based on the detection and analysis of waves reflected from the subsurface layer boundaries. Main difference is in their sensitivity for different physical properties and limiting factors, therefore they can be effectively combined during the surveys.

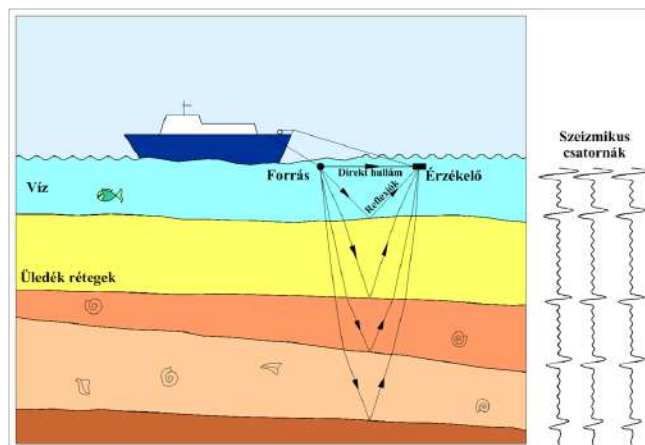
9.2 Seismic surveys

During reflexion seismic surveys compressional waves (P waves) generated on or near the surface are used for imaging subsurface layers, their morphology and the physical parameters of the sediment layers. Compressional waves propagate from the surface down to deeper layers and part of their energy is reflected back to the surface at the layer boundaries. Sources for the seismic waves vary depending on the depth of investigation and survey environment. Off-shore seismic surveys imaging down to multiple kilometres depth use high-pressure air based air-gun or water-gun

sources for high energy, deep penetrating seismic waves. Shallow surveys imaging down to a few hundred or just tens of metres typically use electric sparks (sparker) or induction sources like the boomer. Seismic waves reflected back from the layer boundaries are sensed at the surface by geophones for land and hydrophones for off-shore surveys.

Simplest and quickest to complete are the *single-channel off-shore seismic surveys*. A seismic source and the receiver are towed in fix configuration, the source generating the seismic waves, while the hydrophone sensing the returning reflections. Figure 9.1 shows schematics of the single-channel survey with seismic traces on the right of the figure. The imaged subsurface strata consists of three layer boundaries, hence the seismic record starts with the direct arrival from source to receiver, than continues with the reflection from the water bottom followed by the reflections from the three deeper layer boundaries. Reflected waves are sensed and registered according to their travel time, the so called Two Way Travel time (TWT), which corresponds to the time from source to layer boundary and back to the receiver. Two way travel time can be converted to depth of reflector knowing the acoustic wave velocities in the subsurface strata. A seismic profiler towed next

Figure 9.1: Single channel seismic recording



to or behind the survey vessel can register up to 6-10 seismic traces each second. The source and the receiver in a fixed configuration are continuously moving along the survey profile. Displaying the registered seismic traces one after the other, a seismic profile of the water bottom and the sub-bottom layers develops. Compressional waves generated by the seismic source propagate in the subsurface layers and at each layer boundary, where the acoustic impedance (AI) changes, part of the waves energy gets reflected. ¹ Table 9.1 lists typical compressional wave velocity and density values for materials encountered during river and lake surveys.

Ratio of reflected and transmitted energy on a layer boundary is defined by the acoustic impedance contrast at the layer boundary. Large acoustic impedance contrast results higher energy reflected and less transmitted energy, which is observed on the surface as

¹ Acoustic impedance (AI) is the product of the compressional wave velocity (v) and the density (ρ): $AI = v \cdot \rho$.

Material	Compressional wave velocities [m/s]	Density [kg / m ³]
Air	330 – 350	1,0 – 1,4
Water	1450 – 1500	1000
Dry sand	400 – 1200	1500 – 1700
Water saturated clay, sand	1500 – 2200	2100 – 2400
Sandstone	2000 – 3500	2100 – 2400
Limestone	3500 – 6000	2400 – 2700

Table 9.1: Typical compressional wave velocities and densities

high amplitude seismic reflection. Typically large acoustic contrast is found at the water bottom, bottom of mud and sediment layers, which appear in the seismic profiles as strong reflectors relatively easy to identify based on their amplitude and seismic character. The water surface, the water-air interface is an almost perfect reflector, reflecting most of the energy travelling upwards and generating a second wavefront propagating downwards again. This is the source of the free surface multiple reflectors, which arrive at twice the travel time of the primary reflector and mask the later arriving primary reflectors of deeper layers.

Aim of the seismic survey is to image the subsurface strata and map the layer boundaries with the highest possible accuracy. In order to achieve this good seismic resolution and knowledge of the subsurface velocities is essential.

Seismic resolution is directly related to the frequency spectrum of the source wavelet and modified by the filtering effect of the sediment layers during wave propagation. The inelastic attenuation as a filtering effect during wave propagation is decreasing the resolution by selectively filtering out the higher frequency components. Off-shore seismic surveys have a definite advantage of both the source and the receiver being in water, where acoustic waves propagate almost without attenuation. Frequency content of the seismic waves applied during single-channel seismic recording go up to 20 kHz, providing up to 2 centimetre resolution. Frequency range of the seismic surveys are in the audible frequency range, therefore these survey are often referred to as seismo-acoustic surveys.

Exact knowledge of the acoustic wave velocities is the key to accurate conversion of two way traveltime to depth, calculation of layer boundary depth maps. Acoustic wave velocity in the water is relatively easy to measure, but subsurface layer velocities are more difficult to determine. These velocities are either known from empirical data or derived from the seismic dataset itself.

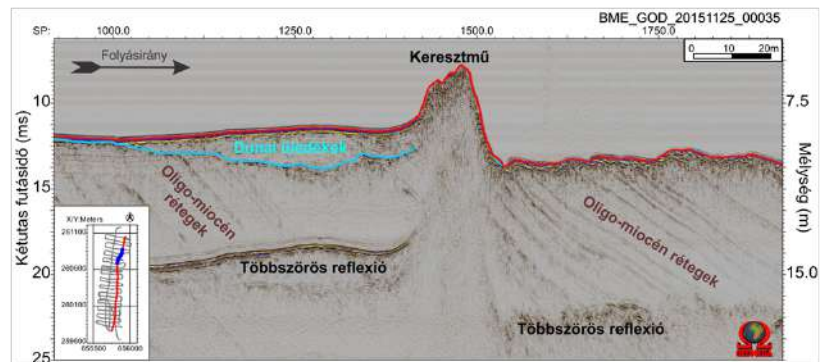
Interpretation of the recorded seismic profiles is typically completed prior to depth conversion. During the interpretation seismic reflections corresponding to the mapped layer boundary are identified and marked on the seismic profiles. Identification of the reflectors is based on the seismic character (seismic facies), in some cases also supported by existing borehole information.

Figure 9.2 shows a seismic profile recorded on river Danube in

the vicinity of Göd-island. The water bottom reflector, marked by red polygon is easy to identify. The boundary separating recent fluvial sediments and older oligo-miocene strata can be drawn based on their different seismic character and dip of strata. This interface is marked by light blue in Figure 9.2. Deeper part of the seismic profile is masked by the multiple reflector generated by the water-air surface. This is not corresponding to a real deeper reflector and has to be treated accordingly during the seismic interpretation.

In the middle of the seismic profile the underwater part of the groyne perpendicular to the profile direction is imaged. Sediment structure above and below the groyne is very clearly imaged on the seismic profile. Up-stream to the groyne a sediment wedge is accumulated, while down-stream no sediment layer is present on the water bottom. The oligo-miocene strata clearly outcrops at the water bottom.

Figure 9.2: Detail of a single-channel seismic profile measured on river Danube, at Göd-island. Interpretation of the profile is discussed in the text.



Another characteristic feature of the seismic profiles are the diffraction hyperbolas. These are generated by subsurface inhomogeneity, edges, corners, individual objects (e.g. boulders, or even swim bladder of fish) not larger than a few times the seismic wavelength. Diffraction hyperbolas are visible in Figure 9.2 in the middle of the profile inside the groyne structure. Acoustic waves diffract on the boulders inside the groyne thus preventing imaging deeper layers below the groyne.

9.2.1 Single-channel seismic profiler

Traditional tools for mapping the water bottom and the sub-bottom layers are the sonars. They have been in widespread use for more than four decades (Mosher and Simpkin, 1999), primarily for water depth measurements (high-frequency sonars), and for measuring flow velocity using Doppler effect (Evans, 1997). However, they can also be used for sub-bottom profiling. The same piezo crystal can be used as sonar source and detector. When used as source electric signal is converted to mechanical signal, while as a detector it converts pressure waves to electric signal. Sonars can be mounted in the hull of the boat, or towed at a selected depth underwater.

Conventional sonars are based on piezo crystals with different resonant frequencies, typically in the 20 Hz to 20 kHz frequency range. Maximum energy is limited by the cavitation on the sonar head, but this is not preventing usage for deep sea research even at 1500 m water depth. The controlled signature ensures that even with very small amplitude the signal reflected from the water bottom or the sub-bottom layer can be detected with confidence. Advantage of the conventional sonar source is the simple operation, high reliability and deep sea applicability. Disadvantage is the narrow bandwidth around the resonance frequency, the loss of phase information and shallow penetration to the sub-bottom.

To overcome these disadvantages parametric sonars (e.g. Krupp-Atlas Parasound) and Chirp systems were developed. Parametric sonars generate a secondary frequency by using two resonant frequencies. The secondary frequency is the difference of the primary frequencies. This provides good focusing and low frequency signal with good penetration even for a small size equipment. Chirp sonars generate a frequency modulated signal ranging from 400 Hz to 20 kHz. The sweep signal is correlated with a digital filter resulting a zero phase, compressed signature. High frequency sampling and digital filtering are key parameters for Chirp sonars.

An alternative to sonar sources for sub-bottom profiling is the boomer source providing high-energy and high resolution signature. Boomer is an electro-mechanic source (Edgerton and Hayward, 1964; Simpkin and Davis, 1993) consisting of an isolated flat coil and a metal plate placed in the water below the coil. Firing energy is provided by a high-voltage capacitor bank discharged via the coil. At firing the current of the coil generates Eddy current in the metal plate below it, rapidly pushing them apart and accelerating the water column below the metal plate. This initiates a downward travelling pressure wave. Keeping the voltage and capacity of the capacitor bank and the firing depth of the boomer constant, the resulting source wavelet is very stable, highly repetitive with a strong directivity along the axis of the plate. The source depth of the boomer for the IKB-SeistecTM seismic profiler used during the survey at Göd is fixed at 0.45 m (Simpkin and Davis, 1993).

Boomer sources operate with 100-1000 J energy per shot depending on voltage and capacity of the capacitor bank. Source signature and frequency spectrum of the wavelet is shown in Figure 9.3 for four different energy levels.

The boomer sourced IKB-SeistecTM is a novel single-channel seismo-acoustic profiler (Simpkin and Davis, 1993). The boomer source and the hydrophone group in a focusing cone are mounted on a catamaran body (Figure 9.4). The fixed, short distance between the source and the receiver is optimal for shallow water applications in rivers and lakes. The hydrophone group of 7 hydrophones is vertically positioned in the axis of the focusing cone significantly reducing the energy of direct arrival from the boomer, side reflec-

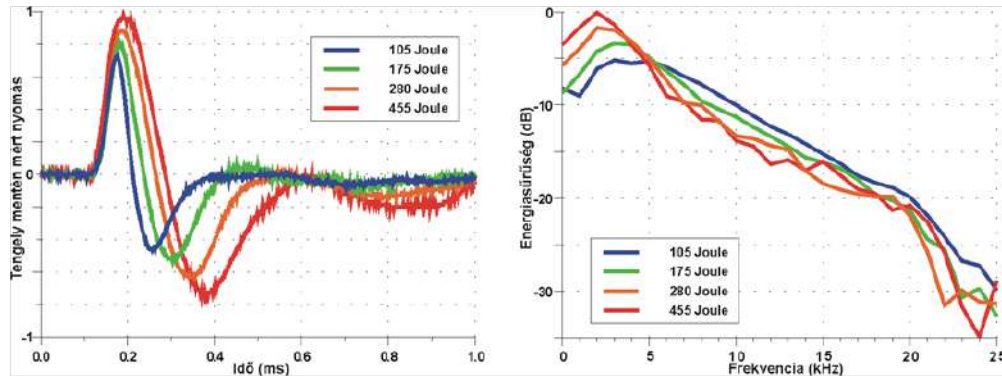


Figure 9.3: Boomer signature at different energy levels (a), and corresponding frequency spectrum (b). Increasing the energy level of the boomer results higher amplitude level and longer wavelet with more low frequency content.

tions or even propeller noise from the survey vessel. The source and the hydrophones shown in Figure 9.4 are in the water during the survey, and the GPS antenna is mounted in the midpoint (CDP) of the source and the receiver. The seismic profiler ready for survey is shown in Figure 9.5 with the survey boat.



Figure 9.4: Bottom view of the IKB-Seistec™ single-channel seismic profiler

The GPS antenna mounted at the midpoint of the seismic profiler provides continuous positioning data during the survey. The resolution of the seismo-acoustic profiler requires sub-decimetres accurate positioning data for both horizontal and vertical positions. Differentially corrected GPS receivers can achieve the required accuracy, therefore whenever possible GPS positioning is used during the surveys. In Hungary real-time RTK-GPS coverage is available almost in the entire country. This centimetre accurate positioning service can be used both for real-time navigation during the survey and positioning of the seismic records. Whenever centimetre accurate GPS data is not available in real-time, the position data have to be post-processed for the required accuracy. This is completed during data processing.



Figure 9.5: IKB-Seistec™ single-channel seismic profiler next to the survey vessel

9.2.2 Survey results

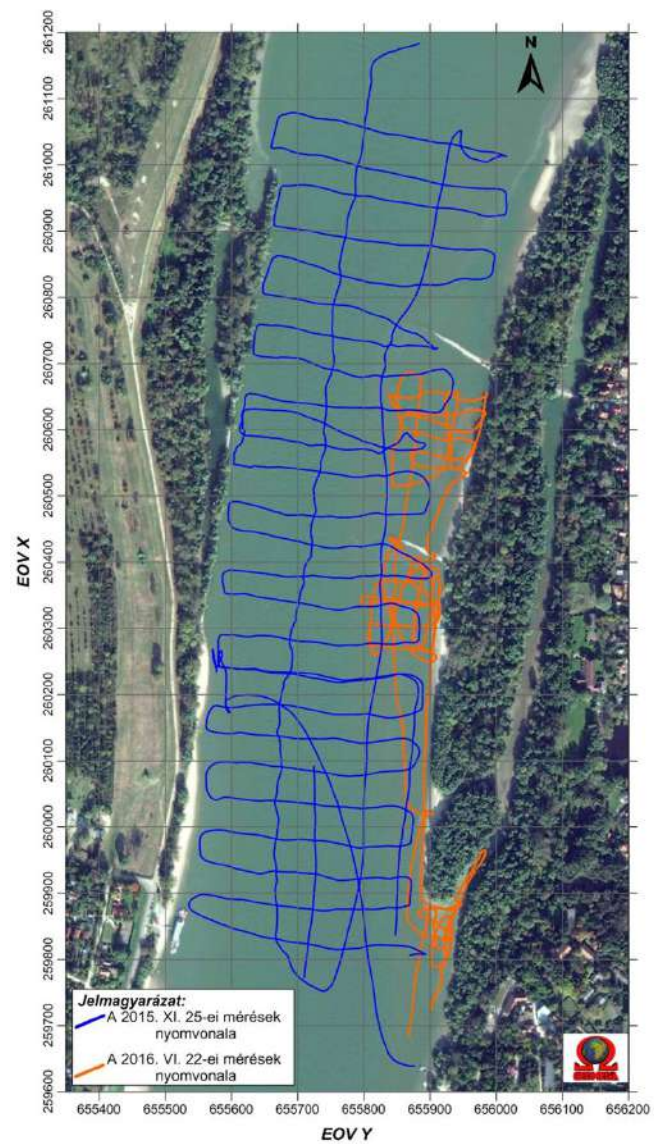
Results of the single-channel seismic surveys are demonstrated using data measured on river Danube at the Göd test site and a seismic profile from Lake Balaton.

Seismic survey on river Danube at Göd-island was completed at two different water level, on 25th November 2015 at 201 cm, while on 22nd June 2016 at 454 cm Budapest Vígadó square water stand. Water level difference was compensated for during the joint interpretation of the two dataset. Survey profiles of the two measurements are shown in Figure 9.6.

During the survey seismic profiles similar to the one shown in Figure 9.2 were recorded. These seismic profiles were processed and interpreted one by one marking the water bottom and the base of fluvial sediments. Following depth conversion of the data map of the water bottom (Figure 9.7) and the base of fluvial sediments morphology (Figure 9.8) was calculated. Both maps are referenced to meter above sea level and shown with the same colour scale. The difference map, thickness of the fluvial sediments is shown in Figure 9.9. The thickness map of recent fluvial sediments clearly shows, that along the Göd-island, in the stream channel very thin, at several location no sediment is present, older oligo-miocene strata is outcropping on the river bed. The outcropping oligo-miocene strata can be directly observed at low water stand along the river bank between Göd and Dunakeszi as shown in the photo of Figure 9.10.

The high energy fluvial sediments of riverbeds are very different in grain size and internal depositional structure from the lacustrine sediments. Good examples of recent lacustrine sediments are imaged in the seismic profiles recorded on Lake Balaton, Hungary. Lake Balaton, in spite of its relatively large size is characterised by an almost completely flat water bottom with 3-4 metres water depth. Below the water bottom approximately 3-4 metres of well layered Holocene mud is deposited. Older Pannonian layers form the base of the Holocene mud layer with a well-defined angular discordance.

Figure 9.6: Basemap of the seismic survey at Göd-island, river Danube



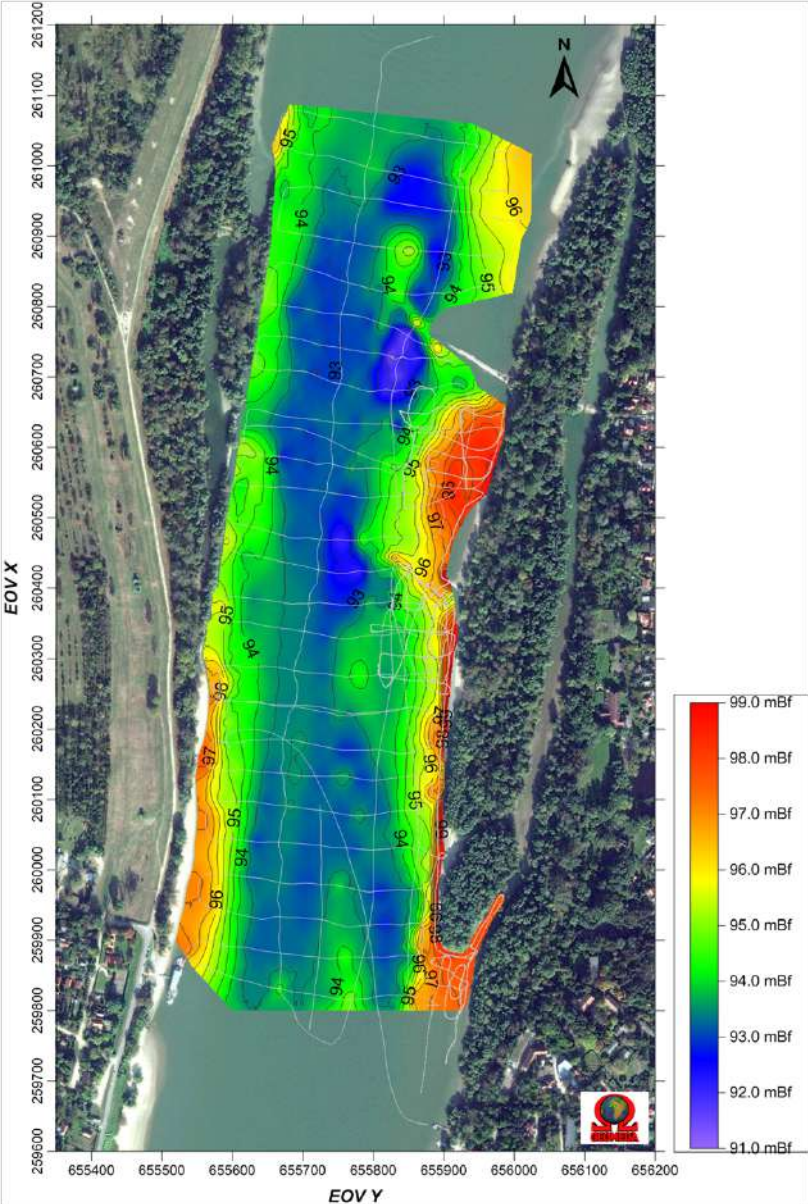
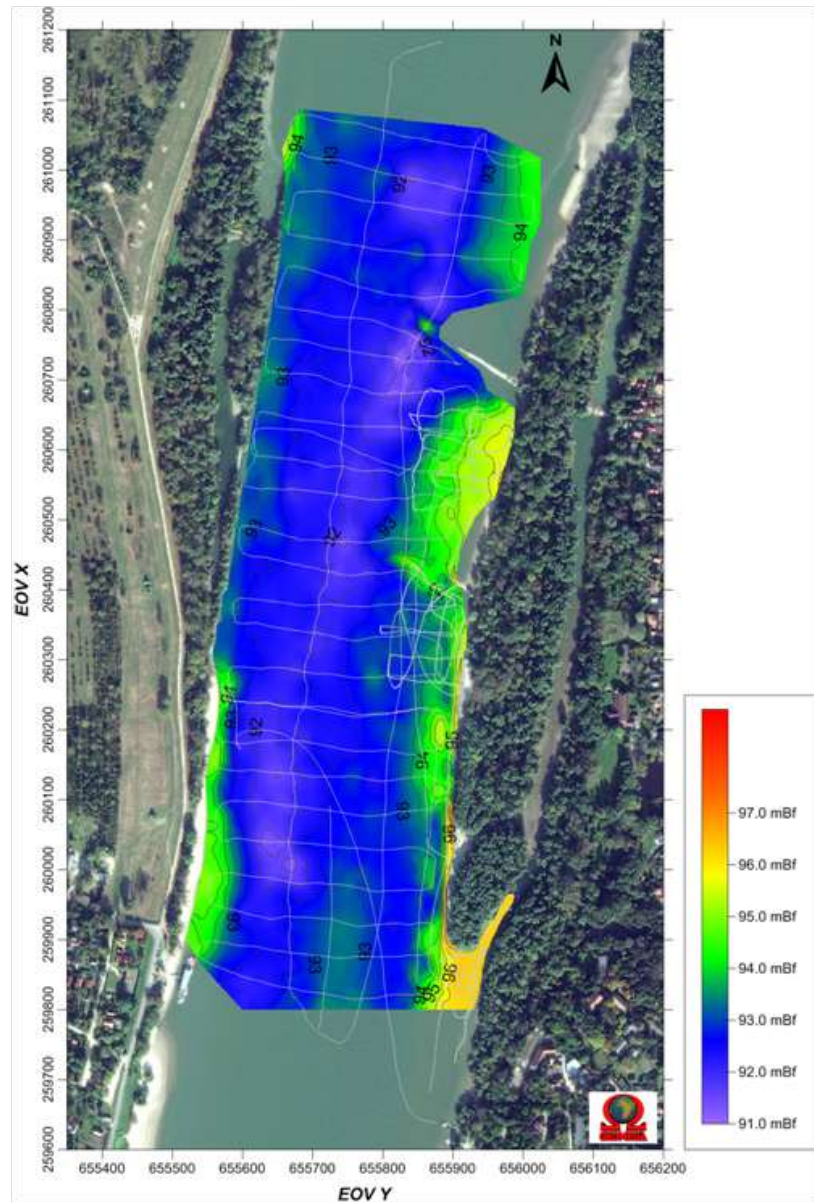


Figure 9.7: Water bottom morphology at Göd-island, river Danube

Figure 9.8: Base of recent fluvial sediments at Göd-island, river Danube



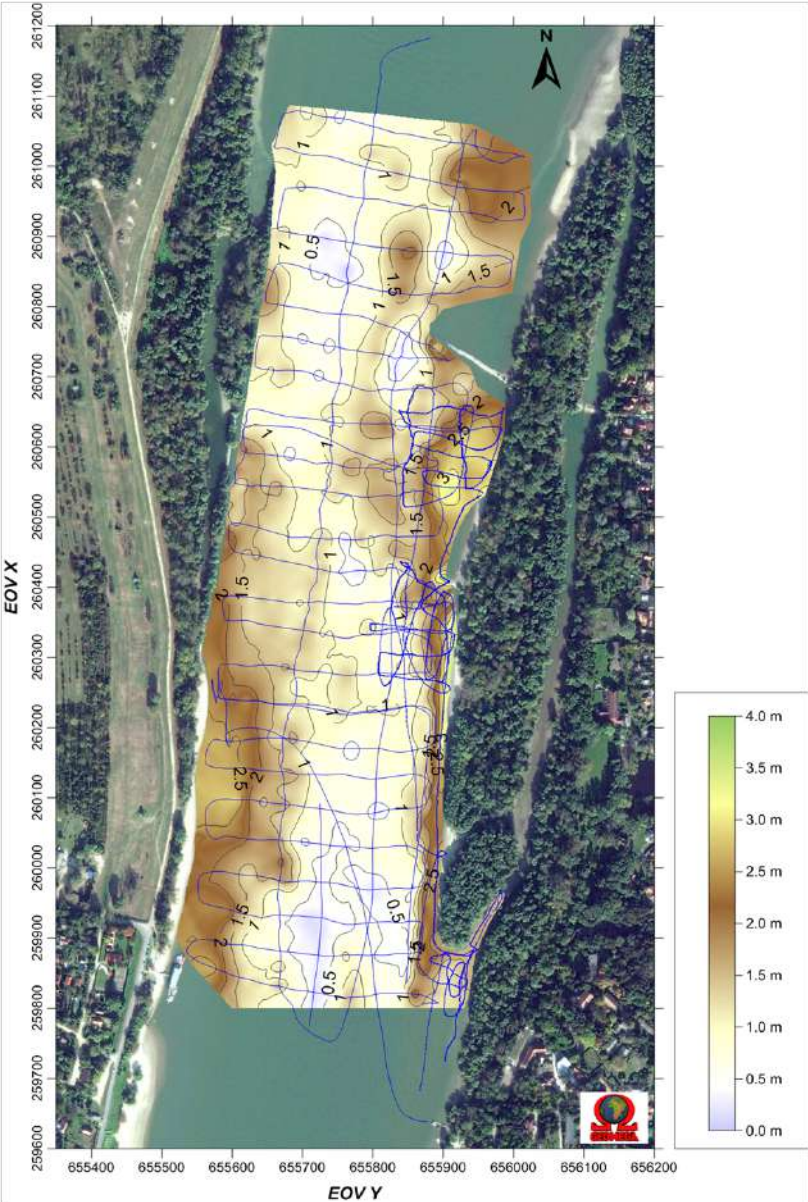


Figure 9.9: Thickness of recent fluvial sediments at Göd-island, river Danube



Figure 9.10: Outcropping oligo-miocene strata along the shore of river Danube between Göd and Dunakeszi

Figure 9.11: Detail of a single-channel seismic profile measured on lake Balatonon. 3-4 metres of well layered Holocene mud is deposited below the water bottom.

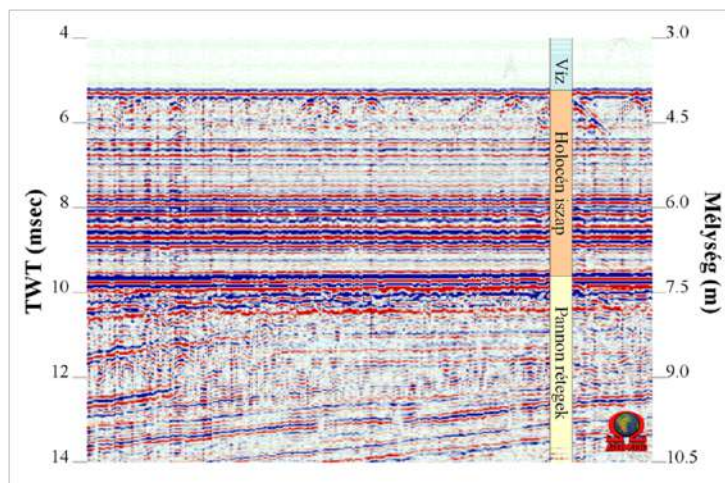
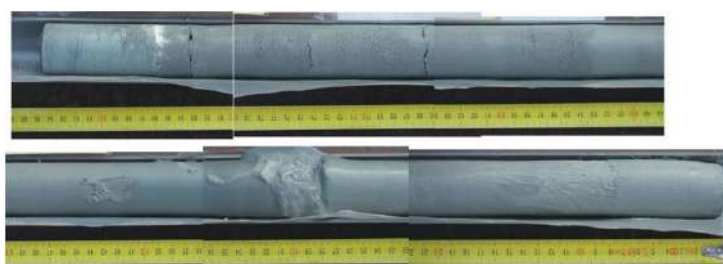


Figure 9.12: Undisturbed core sample taken from the Holocene mud of lake Balaton shows layers of mud with varying physical parameters.



9.3 GPR surveys

One of the strongest limitation of high-frequency single-channel seismic surveys utilizing 1-10 kHz acoustic waves is the biogenic gas accumulating in the topmost mud layers. A few percent of gas saturation in the sediments is enough to “shadow” the deeper layers by attenuating the acoustic waves. This is frequently the case in near shoreline sediments close to vegetation and significant biogenic influx. In these areas the GPR² method may represent an alternative survey tool, imaging the sub-bottom layers with the help of high frequency electro-magnetic (radar) waves. In many survey areas the combined application of seismo-acoustic and GPR surveys provides the most complete solution.

During GPR surveys a transmitter antenna generates focused electromagnetic waves propagating downward in the subsurface, partly reflecting from the layer boundaries and sensed on the surface by the receiver antenna. GPR reflections are generated by layer boundaries where the velocity of electromagnetic waves changes³. Two way travel time and amplitude of the reflected waves is measured. Knowing the wave propagation velocity depth of layer boundaries can be calculated, while the amplitude information provides useful understanding for material properties. High amplitude reflections are generated by interfaces where the electrical properties on the two sides of the layer boundary differ significantly. No reflections are generated by homogeneous sediments.

Performing GPR surveys along a set of 2D profiles or a 3D

² Ground Penetrating Radar

³ e.g. water bottom and mud bottom

survey grid enables mapping the layer boundaries. Reflections for the layer boundary mapping are registered in a time window corresponding to the depth of investigation.

GPR surveys are widely used in engineering-geophysical surveys, archaeological exploration, detecting buried objects, cavities, utility lines, investigating the internal structure of roads, dams and also for mapping geological boundaries or water table.

Propagation of the electromagnetic waves is influenced by three physical parameters; apparent resistivity, dielectric constant and magnetic permeability. In case of off-shore surveys the depth of penetration and the characteristics of the recorded profile is primarily determined by the resistivity (i.e. salt content) of the water and the dielectric constant of the sediments. Water and water saturated unconsolidated sediments are characterised by a dielectric constant close to 81. As a result of this, depth of penetration is a function of electric resistivity. Fresh water enables several metres of penetration for GPR waves, while in salt water or brackish water penetration rapidly drops to practically zero. The shallow penetration can be a strong limit for the GPR applications, but unlike for seismic methods the presence of biogenic gas in the sediments has practically no influence on GPR wave propagation. Therefore combined application of seismic and GPR surveys is often the best solution for surveying a shallow water area. Seismic profiles may provide deeper penetration, while GPR measurements enable imaging of the near shore zone affected by biogenic gas.

9.3.1 *GPR equipment*

As for every GPR survey, that selection of right antenna frequency is key for off-shore applications too. Best combination of resolution and penetration can be achieved by the application of 300-500 MHz antenna frequencies. In order to maximize signal penetration for off-shore GPR surveys, a 500 MHz submergible antenna has been implemented, which can be submerged down to max. 10 m water depth. Instead of towing the antenna on the water surface underwater, or even water bottom tow can significantly increase the signal penetration.

Resolution for GPR surveys is also defined by the minimum layer thickness which result non-interfering reflections from the top and bottom of the layer. This layer thickness depends on the length of the radar impulse. The shorter the impulse is, the better the resulting resolution. If the layer boundaries are closer on the GPR record than half of the radar impulse, than the top and bottom layer reflection will interfere, the layer cannot be resolved. In case of 500 MHz antenna and surveys performed in water 2-3 cm maximum resolution can be achieved.

Positioning of GPR surveys is similar to the positioning of seismo-acoustic surveys. GPS antenna mounted above the geometrical centre of the GPR antenna system is continuously recording the

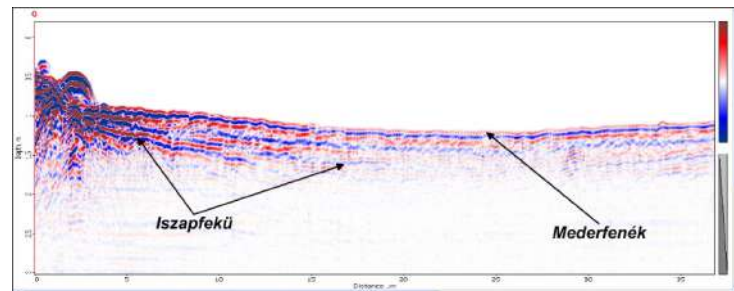
antenna position during the survey. In case of underwater antenna the positioning problem is more complex as only the position of the surface tow point can be exactly measured, the antenna position has to be extrapolated from these measurements. Centimetre accuracy cannot be achieved neither in vertical nor in horizontal position, therefore these GPR surveys are best evaluated together with a parallel run seismic survey.

9.3.2 GPR survey results

Similar to the seismic surveys processing of the GPR profiles is the first step after the field survey. This is followed by the interpretation of the GPR data. The interpreted horizons are mapped and the depth of the surfaces and layer thicknesses are calculated. This can be completed based on GPR data only or a combination of GPR and seismic datasets integrating them respecting the differences in propagation velocities of the seismic and radar waves.

Figure 9.13 shows a GPR profile recorded on the river branch Soroksári-Duna, where nearshore areas are strongly affected by the presence of biogenic gas. In the nearshore section the profile images both the water bottom and the mud bottom. In the deeper part of the profile the limited penetration of the GPR profile becomes evident, the reflection from the water bottom is still easy to identify, however the mud bottom reflection gradually diminishes.

Figure 9.13: GPR profile recorded at near-shore location. The mud layer at the water bottom was filled with biogenic gas.



Another advantage of GPR surveys over the seismic profiling is the sensitivity of radar waves to metal objects. It is hard to differentiate a seismic diffraction generated by a boulder or a metal pipe, but on a GPR profile diffractions generated by metal objects stand out by their strong amplitude response. GPR reflection from a metal object is significantly higher energy than any reflection from the surrounding geological boundaries, therefore their identification is fairly straightforward. A metal pipe crossing under river Tisza is shown in Figure 9.14. The data was recorded with a 500 MHz underwater GPR antenna towed on the water bottom.

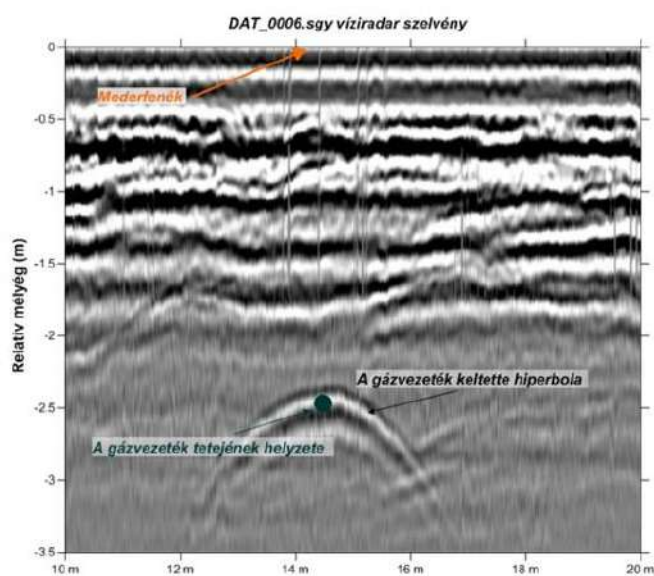


Figure 9.14: GPR profile imaging a gas pipeline crossing below river Tisza. The GPR profile was recorded with an underwater GPR antenna towed at the water bottom.

River planforms

10.1 Introduction

In this chapter, the river planforms (Schumm, 1963) are discussed, as well as the environmental controls on their occurrence. 'River planform' is, as its name indicates, a planar feature, the outline of the stream in a map, not concerning neither its three-dimensional structure nor the spatial distribution of the river depth (Schumm, 1985). According to this, the planform is easily identified from just a map. However, it must not forget that in a map usually the whole channel is indicated by the blue color of the water, at 'upper water mark' situation. On the contrary, in the reality, especially when we walk on the field or analyze a satellite image, we rather see the bars in the channel that are usually visible.

The concept of planforms cannot be applied to all streams. Some rivers are actually cutting, eroding into the basement rocks, are deepening their valleys. Therefore, their map outline refers less to their own hydraulic characteristics but rather to the lithological circumstances of the nearby part of the catchment area. Even in the case when the river flows over a thin sediment layer, its course and map outline is controlled by the bedrock. Therefore these kind of streams, the bed-rock rivers, are skipped from our discussion. In case of most of the streams, the bedrock section(s) ends well before the estuary or confluence and the river deploys its sediment load at the lowland sections or in the estuaries/deltas. When a river flows on its own sediment load, we call them 'alluvial rivers', which is the counterpart of the bed-rock rivers. The planforms are characteristics of the alluvial rivers (Miall, 1996).

In the easiest cases, rivers are bed-rock types at its offspring parts, and later, as their slope decreases, after shorter or longer geological control, they continue their path to the estuary as alluvial rivers. In case of longer rivers, as they cross other mountain ranges than the one of their spring, they can go under geological/lithologic control again and again. The iconic river of Europe, the Danube is clearly controlled by the bedrock at least twice after leaving its own spring area: the crossing of the Bohemian Forest in Upper Austria and the Carpathians at the Iron Gate not only its course but also its channel form is controlled by the rocks. Also, the Danube

River is partially bedrock controlled in the Wachau (Austria), in the Devín-Hainburg gorge (Slovakia/Austria) and in the Danube Bend (Hungary).

The planform of the rivers are in continuous change. Change occurs not only along the river course, as the slope and the sediment control them in different ways. Change can be detected also in time at the very same place/section, as the controlling parameters are also the subjects of change. This might be acknowledge purely an interesting scientific observation, however the quick climate change – and, e.g. the disappearing of the ice floods, important to channel forming – may result it even in some decades.

The planform of the alluvial rivers – besides providing rare information about the geology and vertical crustal movements of the crossed area¹ – has quite an importance in hydraulic engineering. For the river control works, or even for planning and building of unique installations, it is important to know, how the river behaves at the given section – how it wants to behave without any human control. Knowing the planform type, resulted by given slope, water and sediment discharge and sediment composition, is also important when we deliberately change the characteristics of the river and/or its environment by active river control and/or artificial inundation. The natural planform, which is a kind of state of equilibrium, the status of the river, which is naturally reformed by the nature without active river control, can be estimated by the natural hydraulic characteristics.

For the practice of the hydraulic engineering, it is also important to know, how the active engineering, the building of some installations influence the hydraulic characteristics of the downstream section (mainly the sediment characteristics) and through them the planform, thus the operation of already working installations. At the end of the section, we'll see some examples of this.

10.2 Overview of planforms of the alluvial rivers

Because of their importance and frequent occurrence, we acknowledge two planforms (the braided and meandering) as main ones, while the other four can be partially derived from them.

10.2.1 Braided planform

It is the main riverine environment of the sedimentation in mountain ranges. There is no permanent main channel, its branch system is in continuous change. Its water discharge shows extreme low in most time intervals and extreme high in case of snowmelt or precipitation peaks. In most of the time, the water covers only a tiny part of the channel. The sediment load is very high, as well as the characteristic size of the load: gravel, rocks, even boulders, which are mostly dry. We find a lot of islands, gravel bars and small river branches (Fig. 10.1). Vegetation can barely colonize the bars,

¹ cf. Ouchi (1985)

especially not the perennial plants, so the branch system is not stabilized at all (Miall, 1977). It is the 'absolute chaos' at very first sight, and the system is chaotic indeed from the point of view of the physics. However this planform, 'drowning to its own sediment' occurs in relatively short sections, as it is out of this sediment surplus, we find other, more peaceful patterns.



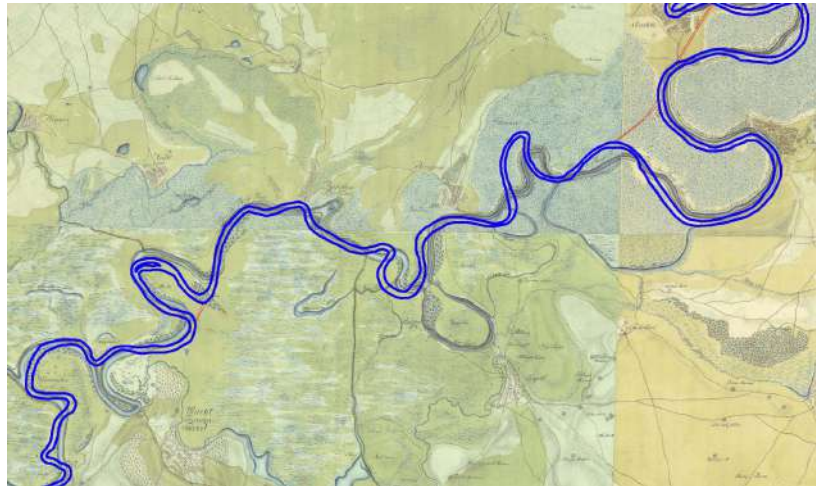
Figure 10.1: The Rakaia River (New Zealand) shows typical braided planform in alluvial environment. Note the generally linear character of the channel, with numerous internal branches (Photo of Andrew Cooper, Wikimedia Commons)

10.2.2 *Meandering planform*

The characteristic, even iconic pattern of rivers flowing on lowlands, far from the mountains. This planform is the antagonist of the braided one practically in all sense. The only channel flows with smaller and larger curves. It barely has islands, and usually only if the external controls are temporarily change. The difference between the high and low water marks (minimum and maximum discharge) is much smaller than in the braided case, because of the big distance from the offspring area and the large catchment area. Its banks are accompanied by riparian forests. However, the curvy, settled pattern does not show full stability. The thalweg moves towards to outer curve banks and the curves slowly move in downstream direction (Fig. 10.2). Sediment load starts from the outer banks of the curves and depositing at the inner ones. The speed of this slow course change is not constant. The floods, reaching the bankfull discharge, can alter the course surprisingly quickly, during some days (Brice, 1974). The cut-off of over-developed meanders happen also during these floods, leaving an oxbow lake in the floodplain.

Even with this geologically constant course change, the meandering river sections have balanced sediment budget. The pattern, recognized in maps and aerial or satellite images is all but not

Figure 10.2: The Tisza River in the Great Hungarian Plain is the archetype of the meandering planform. The base map is the First Military Survey of the Habsburg Empire (1783-86), the blue line pair shows the digitized bank lines from the Second Military Survey, compiled some 70 years later. Note the channel course changes: the meanders are growing, shifting to downstream and cutting off.



chaotic. As it is shown later, it has a refined self-controlling system: the dynamics of the meandering river is working to keep its own channel slope. The sediment surplus that can fill large geological basins, occurs in time of floods. This is fine sediment called 'over-bank fines', thus it can be transferred far from the channel into the wide floodplain.

In this system, there are only two ways to form islands. One is in the inner part of the curves. The sedimentation occurs in stripes, connected to floods (after their similarly to the tree rings, we may call them 'flood-rings'), producing a series of point bars or scroll bars. Between them, the terrain is low at first and frequently inundated (therefore filled up slowly by sediment). Some point bars, which are the closest ones to the stream, might be drawn as islands in the maps, albeit they are functionally not islands at all. The other possibility is at the inflexion point of the stream, between two curves, where the tangent line crosses the thalweg. It is also the riffle-point of the meandering river. In case of external sediment surplus, usually because of a confluence of a smaller river with high sediment load, island can occur at this very point.

Besides of these two main planforms, we discriminate four other ones. The first two ones of them are the intermediate and modified ones. The last two ones are quite rare, occurring only in very flat lowlands, usually in (delta)estuaries of the rivers.

The name of meandering is from the Greek name of Meandros River, now called Menderes in Western Anatolia, Turkey.

10.2.3 Wandering planform

Rivers of this planform tend to migrate laterally, quite quickly in geological scale. Both in geographic position and in morphology, this planform is an intermediate type. Big curves are characteristic of the main channel like in meandering type of rivers. However, from this sinuous main channel, a lot of anabranches flow to the floodplain, filling its width completely and they are also sinuous. Which branch is the main channel? It is quickly changing, provid-

ing a basis of outflow of new side branches if positioned to the side of the floodplain. Therefore the wandering river is sinuous and also has islands and bars. Its sediment is typically gravel, that's why it is sometimes referred to as '*wandering gravel-bed*' planform.



Figure 10.3: As the Tisza River quits the Carpathian Mts. flowing to the Great Hungarian Plain, its slope drops dramatically while still has a lot of sediment. This is the section of the alluvial fan building. The wandering planform makes a true transition between the braided and meandering ones.

It is the main pattern of the rivers of alluvial fans. Its lateral displacement enables to make fluttering moves, similarly to the garden hose. The point where the river valley quits the mountains is fixed while the river is fluttering to one end of the alluvial fan to the other and back, deploying the sediment to all points of it.

10.2.4 *Anabranching pattern*

Its channel is stable, its course barely changes, dominantly straight with mild curves. The obvious main channel is characteristics with the many small anabranches. The type is the home of the biggest river islands, however numerous smaller islands are also occur both in the main and in the inferior channels. Dense vegetation, riparian forest is characteristic at its banks. The islands slowly moves downstream, so the oldest trees are located in the upstream tip of the islands. The banks are covered by the bedload material, usually gravel and fine gravel.



Figure 10.4: The Danube River, section upstream of Budapest, a very nice example of the anabranching planform. The channel has moderate curves and a lot of islands and anabranches can be seen. Vegetation covers the banks, the islands are slowly moving downstream, however the system is quite permanent.

10.2.5 *Anastomosed planform*

It occurs in rivers of the the very flat and horizontal lowlands, dominantly near to the sea estuary or near to local erosion base.

The suspended sediment load is usually high therefore the effect of the meandering is given. Many small, sinuous branches fill the whole floodplain, some of them serve as main channels. It is the dominant type of the estuaries, the river deltas with strong sedimentation (Smith and Smith, 1980).

Figure 10.5: Example of the anastomosed planforms: the Brahmaputra River delta, Bangladesh.



10.2.6 *Straight planform*

It occurs in very-low energy hydraulic environment (low discharge, small slope), it is a quite rare pattern. It is different from the anabranching type as it rarely holds islands. In the sea estuaries it can be formed also by river branches with higher discharge (Fig. 6) if the tidal activity washes the sediment load away. The tidal wave itself has also a straightening effect. It is also characteristic for the final sections of the main channels of anastomosed planform rivers in deltas.

10.3 *Planforms and sediment budget*

The above discussed planform names could lead to some misunderstanding. In the American literature, the terms 'braided', 'meandering' and 'straight' refer not only to these planforms but also to the river sections of sedimentation, sedimentation equilibrium and incision, respectively Leopold and Wolman (1957). This is a different context that we use in the above classification. A river that is classified as 'straight' in the sediment-budget point of view, is practically a bedrock river, which is beyond the scope of the alluvial river classification. A braided planform is also a theater of sedimentation, of course. Similarly, a river with meandering planform is in sediment-equilibrium status. However, if we invert these statements, we might fail. A river that is in sediment-equilibrium

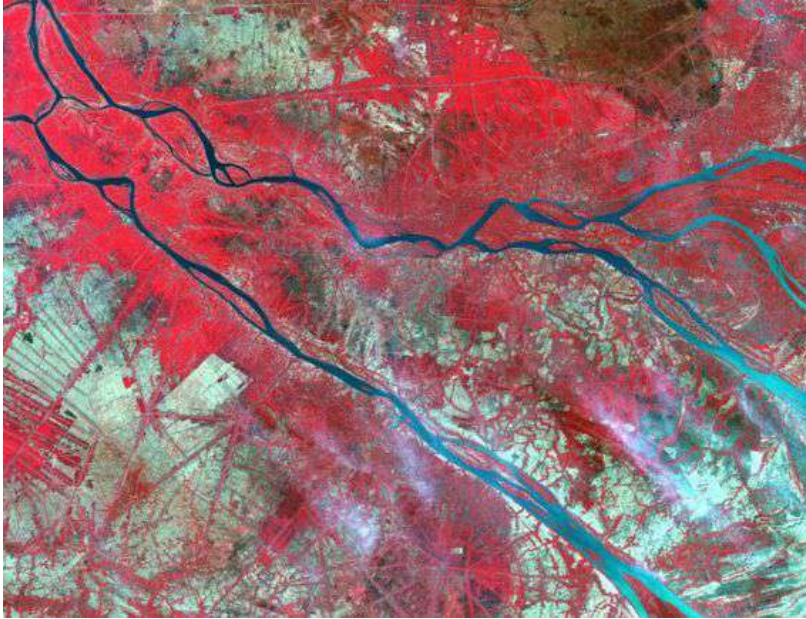


Figure 10.6: A reach of the Mekong Delta (Viet Nam) was straight enough even before water control works. The low slope, thus the low energy does not allow to form large meanders. This is coupled here the straightening effect of the sea tides, near to estuary.

status, is not necessarily has meandering planform; in some circumstances (see below), it may be anabranching as well. Similarly, sediment surplus does not necessarily imply braided planform, wandering pattern may also occur. So, we should using carefully these two different classifications with similar class names. The sediment budget is regular if the upstream section is incising, the middle section is in equilibrium and the river, near to the estuary has sediment surplus. However, this 'regular' type is characteristic only for shorter rivers. Longer river have complex sediment-budget pattern along their course, as they cross more mountain ranges after leaving the upspring region. Moreover, mountain ranges may have clear borders and the river quickly 'finds itself' in a flatland after quitting the hills. It usually coincides a sudden decrease of valley slope, resulting massive sedimentation, practically alluvial fan building. The sediment-equilibrium (meandering/anabranching) section only follows this, switching the 'regular' sedimentation type into a complex one, however we shall recognize it the usual pattern.

10.4 Morphometric parameters of streams

However the planform of the streams can be easily identified almost at first sight, there are some quantitative parameters that make it possible to do this identification even in algorithmical way. The most important ones are the *braiding index* and the *channel sinuosity*.

To introduce the braiding index, we shall understand the concept of pools and riffles. The slope of the rivers is not completely gradual, not even in local scale. The small variations in the water speed is the natural consequence of the small variations of the

slope. In case of any planform type, the repeating system of riffles (decreased depth, quicker flow, local banking up) and the pools (increased depth, slow flow, local basin) appears. In case of meandering and wandering rivers the riffles are in the inflexion points. According to the original definition of the braiding index, it is the number of islands and bars between two riffles. In the practice, it cannot be precisely estimated in some cases. Therefore the method can be replaced by the number of the channels and (ana)branches, crossing a line that is perpendicular to the main channel.

The sinuosity is the river length between two points of it along the thalweg, divided by the Euclidean distance of these two points. Thus the minimum value of the sinuosity is the unity. Its maximum value depends on the river itself, giving by longest curve connected to the shortest neck. As it is already the pre-cutoff situation, similarly we can choose the longest oxbow lake and divide its length by the distance of its endpoints, we get a number, which is close to the maximum sinuosity of the respective river.

In the practice of geomorphology, the sinuosity can be computed between any point pair of the river. However, for numerical analyses it is worth to compute the sinuosity at points with a pre-defined distance from each other. When doing this, and we connect the index not only to a river section but to a point, a so-called 'window size' should be defined. It tells, we compute the sinuosity for how long section of the river around of our investigated point. Then we step along the thalweg with some interval, for each point going up- and downstream by the half of the window size to get the respective endpoints. Dividing their riverine distance (which is the window-size) by the Euclidean distance of these points, we get the sinuosity of each point (Fig. 10.7²). This way the sinuosity changes can be shown quantitatively.

² With the window size A , we shall go from point P by distance of $A/2$ to both up- and downstream. We compute the Euclidean distance D of these two endpoints. Thus, in point P , besides the window size A , the sinuosity is $S=A/D$. We can stop point P to positions P' , P'' , etc. by step of d , thus providing there the sinuosities of S' , S'' , etc. This way, the sinuosity can be computed for a longer section in quantitative form.

To select the proper window size is a bit complex task, because it is a function of the size (discharge) of the river. A creek in a mountain meadow and a big lowland river may meandering the same way, however their meander size is completely different. A selection method is shown by Lancaster and Bras (2002). Meanwhile, Petrovski et al. (2012) propose to compute the sinuosity of a longer river (with often an increasing discharge) not only one but several (even 8-10) different window sizes, to provide a kind of 'sinuosity spectrum', which is capable for scale-independent analyses. A possible improvement is to defining classes for these spectra. The rivers can be classified into the six described planforms according to the values of the braiding index and the sinuosity, according to Table 10.1.

Table 10.1: Classification of the rivers into the six known planform types, according to the braiding index (Br) and the sinuosity (S)

	Br<1	1<Br<3	Br>3
S<1,5	straight	anabranching	braided
S>1,5	meandering	wandering	anastomosed

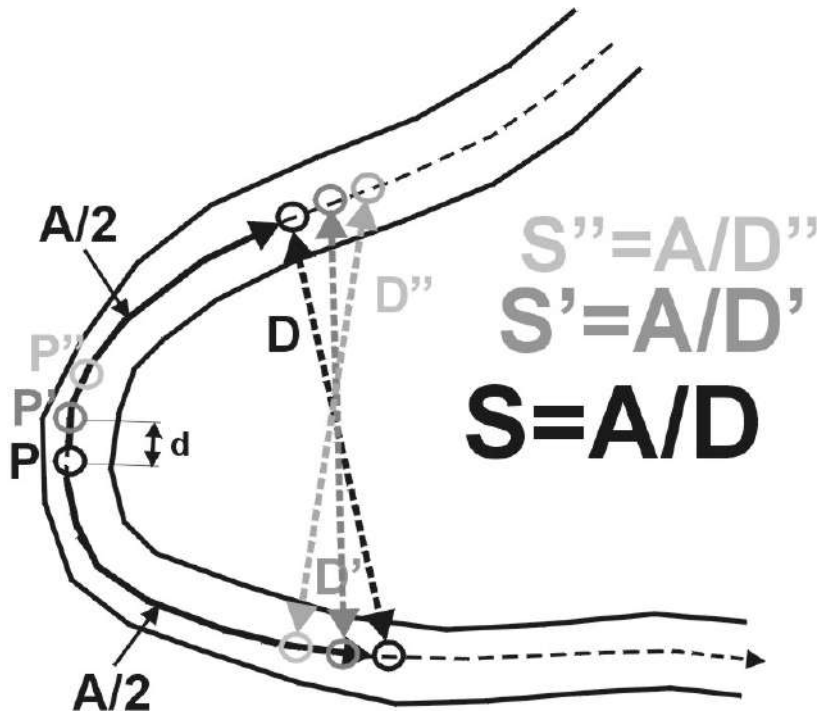


Figure 10.7: Computation of the sinuosity.

10.5 Controls on the river planforms

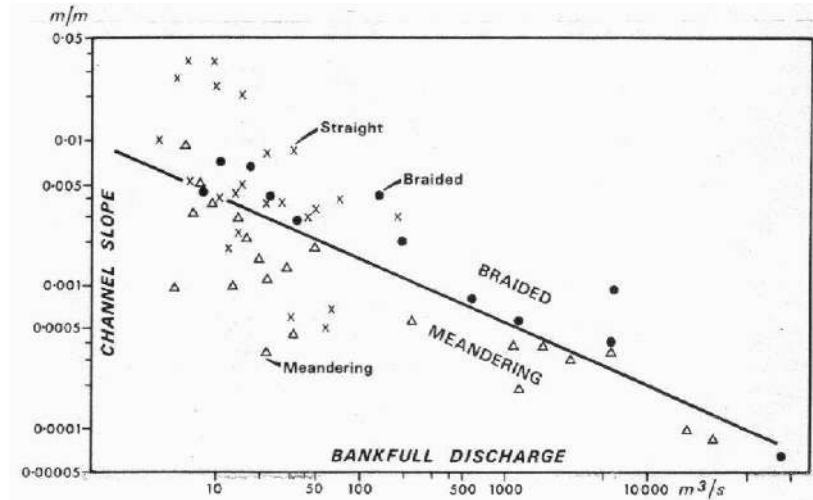
Occurrence of the rivers is not random, however it is not completely deterministic. The planform is controlled by hydrological parameters, of which are – not surprisingly – the most important ones are

- the valley/channel slope
- the water discharge
- the sediment discharge, and
- the size distribution of the sediment.

Knowing these parameters, not only the planform but – using probabilistic and fuzzy models – also their numerical parameters can be estimated.

The first systematic analysis in this subject was carried out the Leopold and Wolman (1957). They investigated the connection between these parameters and the river planform for numerous North American rivers and creeks. Their most important result is a log-log type two-dimensional cross-plot of discharge and slope values of the streams. The streams are classified into straight, meandering and braided types – however this classification is rather according to sediment budget than to planform (Fig. 10.8). In our planform discussion we can omit all bedrock streams ('straight' type). In the cross-plot of Leopold and Wolman (1957) they draw a discrimination line that divides the meandering and braided stream types.

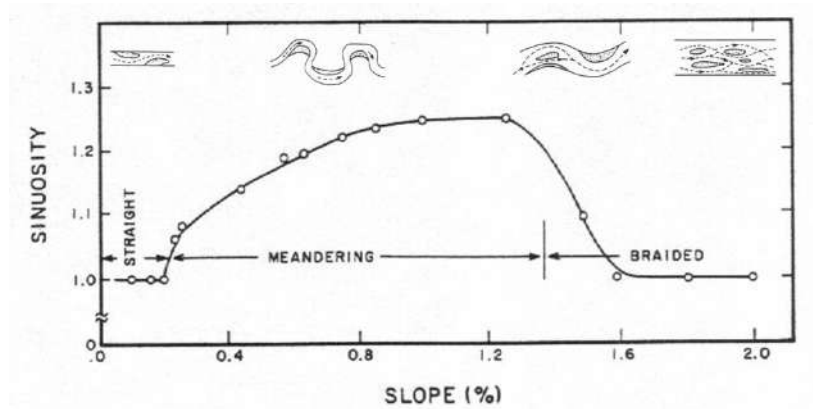
Figure 10.8: The classic chart of Leopold and Wolman (1957) about the connection of the planforms and the most important hydraulic parameters, the slope and the discharge. The small 'x' points in the chart, indicated as 'straight' rivers refer to bedrock-controlled rivers. They can occur anywhere, they do not fit and does not disturb our discussion of alluvial rivers.



The braided type naturally occurs at higher energy (higher slope and discharge) range. The cross-plot was further developed by Ackers and Charlton (1971); they draw another discrimination line at the lowest-energy part of the meandering region, to divide the true meandering and (alluvial) straight rivers.

The experimental research of the sinuosity of meandering rivers pointed out interesting relations to interpret the above discrimination lines. The experiment series carried out by Schumm and Khan (1972) investigated a low-discharge artificial stream flowing on sand-bad with controllable slope, in a tilt laboratory flume. Their results, the slope-sinuosity function and the occurring patterns are shown in Fig. 10.9. According to this, at low slope values there is not enough energy to form meanders, however the alternate bars occurred. At a distinct slope value the meandering starts, the sinuosity increases with the slope, first quickly, later in a slower pace. At another distinct slope value the sinuosity reaches its maximum and further tilt results quick straightening, then appears the braided pattern.

Figure 10.9: Result of the experiment of Schumm and Khan (1972). Planform and sinuosity of a small stream with constant discharge as a function of its slope. In top we see the characteristic patterns and the location of bars. The planforms with the increasing discharge are: straight, meandering, wandering and braided.



After a linear→logarithmic transformation and the valley slope → channel slope recomputation it seems, that this graph shows the sinuosity of the meandering stream along a vertical (slope-dependent) line in the Leopold and Wolman (1957) graph. In fact, this line is not even displayed in the Fig. 10.8, because of the extreme low discharge of the experimental stream, it would be left from its Y (slope)-axis. However, the two phenomena can be explained in a combined model. The transition from the straight to meandering pattern is the crossing of the discrimination line of Ackers and Charlton (1971). Further up, the transition from the meandering to braided stream indicates the crossing with the discrimination line of Leopold and Wolman (1957).

We have to note that in the lower part of the meandering interval the sinuosity responds to the increasing valley slope with increasing, while after a distinct slope value, the further tilt straightens the stream. In the first range, the meandering river shows self-organization, it keeps its own channel slope around a value in case of changing valley slope. In the second range, it is unable to do it. Further investigation shows that this second range coincides with the wandering pattern (Timár, 2003), they have unorganized character. Combining the graphs of Leopold-Wolman and Schumm-Khan, we can assume a – yet theoretical – surface over the slope-discharge plane, showing the most probable sinuosity values for each slope-discharge pair (Figure 10.10., Timár (2003)).

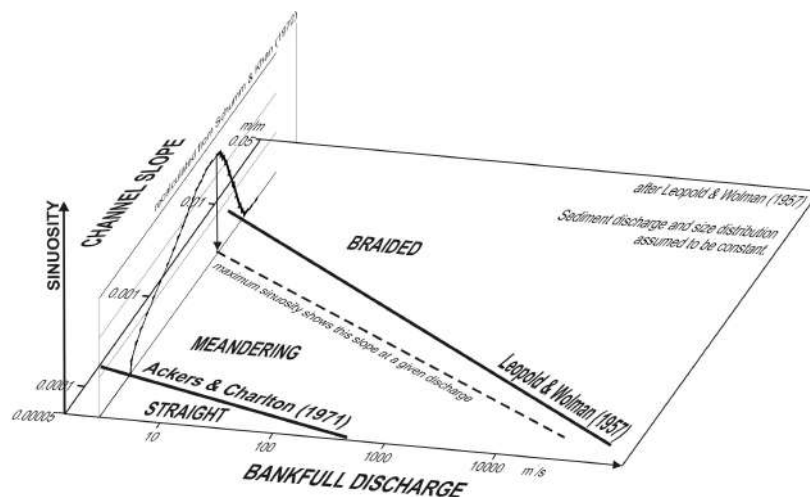
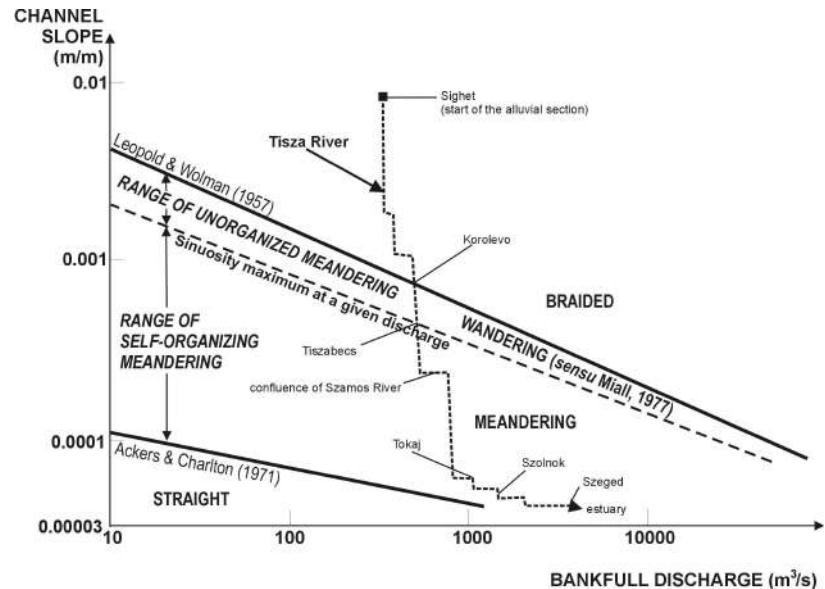


Figure 10.10: A theoretical combination of the charts of the Figs. 10.8 and 10.9: sinuosity as a function of the discharge and slope, with the discrimination lines of Fig. 10.9. Bankfull discharge: the discharge needed to fill the whole channel without inundating the floodplain. The channel formation is the most effective at this discharge (Timár, 2003).

The sections of the Tisza River are shown in this cross-plot in Fig. 10.11. Putting the real, measured sinuosity values of the rivers of the Pannonian Basin into the 3D structure of Fig 10.10, we indeed find some signs of such a saddle surface, probably characterized also by regional settings. The difference between the sinuosity according to this model surface and the real, measures sinuosity might be connected to the sediment parameters, especially to the sediment discharge (Petrovszki et al. (2014)).

Figure 10.11: Alluvial section of the Tisza River in the 'horizontal' chart of Fig. 10.10 (Tímár, 2003).



The experiment of Schumm and Khan (1972) had a similarly important but less discussed result and conclusion. The low-discharge³ experimental stream, flowing on sand bed formed no meanders if it was supplied by clean water. At steeper slope intensive bar formation started, then the almost straight stream became braided. However, when gypsum was added to the water supply, the stream started meandering in the respective slope range.

It is an important observation, which has obvious practical usage, especially the explanation of occurrence of meandering and anabranching planforms. As it is shown by the rivers of the Pannonian basin, these two planforms occur in overlapping slope- and discharge ranges. For example, the Danube River, while its slope and discharge is more or less constant in a 200-kilometer long section around Budapest, in its upstream part forms anabranching, while in the downstream part, originally meandering planform. The explanation is in the result of Schumm and Khan (1972): the difference is in the size distribution of the sediment. A pre-requisition of the meandering is the enough quantity of suspended load! In case of purely or dominantly bed load, the 'erosion in outer curve, sedimentation in inner curve' meandering base-algorithm cannot be working. In the experimental small stream, the sand was bed load, the gypsum acted as suspended load. In case of the Danube, the bed load is the gravel, while the sand (with all finer sediments) is the suspended load. While the river bed is gravel-dominated, there is no meandering, the anabranching pattern with the generally straight river and the islands around Budapest are formed. Where the river is out of gravel, meanders occur immediately. Even the color of the rivers refer to this. The Danube, which is clean with less suspended load at Vienna, obviously gave a hint to Johann Strauss to give the title of 'Blue Danube Waltz', while the mean-

³ a few liters/s

dering Tisza River has a 'permanent' attributive: Blond Tisza. This 'blond' color of the high suspended load is characteristics also to the Danube in southern Hungary.

10.6 *Equilibrium form, importance for engineers*

The above statements about the effects of hydraulic characteristics of the streams to the planform and the morphometric indices are governing the rivers in probabilistic basic. Interesting examples of the connected modern methods can be found in the works e.g. of Di Baldassarre et al. (2009) and McMillan et al. (2010). The self-organizing criticality (Turcotte (1992)) of the meandering phenomena are discussed by Stolum (1996); Stølum (1998). For us, hydraulic engineers and geophysicists, its importance is to give estimations: in a given hydraulic characteristics set, which planform's occurrence is the most probable, how sinuous would it be, where the sediment bars are expected. It's worth to take it into account, if we try to make a different, artificial form of the river by engineering control works. The difference between the aimed and the most probable natural forms gives an estimation of the cost of maintaining the new form and its installations.

Moreover, two things have to be considered. First is, that in some cases the water control work is advised to be made with less installations by changing the hydraulic characteristics and giving time to the river to adopt to them, making the desired form without direct earthworks. An example is given from the control works of the Danube River at Budapest in the late 1800s, early 1900s years. An outflow point of a smaller branch was to be redesigned. Instead of making excessive filling up by earth transport, a levee and a short spur dike were built to alter the water-speed regime of the river. This forced the Danube to fill up the desired channel part in a few decades (Timár et al., 2013).

The other important consideration is that some installations, especially the dams seriously alter the respective river section, especially to downstream direction. Keeping in important part of the sediment, especially the bed load in the reservoir decreases the sediment discharge or alters its composition in the downstream river section. The effect occurs and is investigable in rivers both in Norway and Hungary. Because of the decreased sediment load, a new equilibrium state is formed, realized by a lower channel slope. It causes incision, and its rate is decreasing both in space and time as we go from the dam and as the time passes after its application. So, this incision is not 'infinite', the adaptation to the new equilibrium is completed in some decades, depending on the river size. After that, maintaining the new form requires no further work. Another example is taken from the Vistula River, Poland. During the historical time when water control works usually started in Europe, the river was divided – together with Poland itself – to parts flowing first in the Austro-Hungarian Monarchy, then in Russia and finally

in Germany. The Austrian section of the river, near Cracow, was controlled, making the flow quicker. As the Russian section was not controlled at all, the velocity of the river fell at the border, forcing the stream to deposit the sediment, forming a completely artificial wandering, partially braided planform, which is still detectable in modern satellite images (Starkel, 1983).

A

Historical maps in the practice of hydrology and earth sciences

A.1 Introduction

In the practice of hydrology and hydro-engineering, knowledge of the earlier, natural or near-natural status of a region around a river, is often required. It may be important to know the natural settings of a river prior to the water control works, because

- the hydrological/hydraulic parameters were changed by natural or artificial effects and we aim to restore the original status, or
- we have no data source about the original status of a valley, prior to an artificial inundation.

Besides the above ones, it is also an argument that the earlier status of the landscape keeps more information about the older features, such as about earlier channel patterns and courses. While we plan new installations, levees, dams, it is an important information, whether their position/line was crossed by earlier abandoned stream channels. If so, they can considerably influence the effectiveness of our installation through the hydraulic characteristics of the soil basis. It is important to know that the knowledge about the earlier thalwegs, channel system gives no quantitative information about the changes in soil structure. However, they may point to the location of the necessary geophysical measurement, which can provide numerical contributions to our knowledge in soil mechanics and hydraulic parameters.

To know the earlier status of the geographic environment, our main tool is to analyze the historical maps – if we work in a lucky part of the world that was imaged by them. Luckily enough, both Hungary and Norway is such a region. Moreover, if the historical maps shows the situation of different times in a row – and, luckily enough again, both Norway and Hungary are such pieces of land – we can follow even the dynamics of the rivers prior to their control works.

A.2 *Georeference: the tool of quantitative analysis of the historical maps*

Sometimes it is useful just looking on the historical maps and to trying to imagine the earlier status, picture of the landscape. For quantitative analyses, however, we shall place the information content with respect to the modern locations. The *georeference* is the tool to do this. It means to place all elements, rasters of the map (in its realization, it is practically a scanned image file) in a pre-defined map coordinate system. In Norway, it may be the transverse Mercator projection system used by the NGO¹, while in Hungary, the standard grid, the Unified National Projection², an oblique Mercator-type grid. It is also an interesting application to put our scanned map image to the OpenStreetMap or other map basis (e.g. Google Earth/Maps, Bing Maps, Yahoo Maps) as a layer.

¹ Norsk Geografiske Opmålung

² Egységes Országos Vetület, EOVS

The most obvious solution of this is to find control points in the map, whose modern positions are known, e.g. from modern maps. This method can be easily applied to a sole map section with some constraints³. The method, however, has two theoretical and one practical hindrances.

³ enough number of control points, not too large map extent

If we have not only one single map but a whole series of map sheets, showing a country or a region in a regular network, we usually aim that the frames of the geo-referred result of the sheets are fitting each other. With this simple method it cannot be guaranteed. However if no other solution is available, we shall construct first a real or virtual mosaic of the sheets, thus providing one, yet very big map image and fit that with control points.

If the map is georeferred not in its genuine coordinate system (in its true projection), the distortions between the applied and the real projections are marred the fit. This effect can be neglected only if the map extents is below some 10-15 kilometers. Besides the above theoretical problems, there is a practical one. Both in Hungary and Norway there are a lot of regions, where we cannot find control points in enough number for 150-200 years old maps. The theoretically correct solution is to find the map's genuine coordinate system, namely the geodetic datum and projection. Then, applying the control points, given by their coordinates in the above genuine system, we can make the georeference. The map can be re-projected into a modern coordinate system only after these steps are all done.

A.3 *Basis of the georeference: the coordinate system of the map*

Without discussing the connected GIS considerations (cf. Timár and Molnár (2013)), the coordinate system of the maps consist of two things: the *geodetic datum*⁴ and the *map projection*.

⁴ in older terms: the triangulation network

Geodetic datum means the parameters of the base surface (sphere or rather ellipsoid, given at the map making) and its spatial

position to the solid Earth. In case of base ellipsoid, there are two independent parameters (e.g. the semimajor axis and the flattening) of the figure and at least three other ones of the spatial displacement.

The map projection is defined by the projection type⁵ and its parameter set (position of the projection origin in the geodetic datum, position of the same point in the projected plane, scale factor). In our practice, the map projection is nothing more than a function set that is connecting the ellipsoidal coordinates of the terrain points and their map position. The form of these functions depends on the projection type. The parameters were selected by the map makers, to minimize the distortions in the depicted area.

⁵ e.g. true or artificial; planar, conic or cylindric

As it is discussed above, the georeference can be carried out in the most precise way in the genuine coordinate system of the map. This system can be known from the original documents of the mapping and survey (usually archive data), from the literature or by analyzing the map itself.

A.4 *The georeferencing process and its result*

During the georeferencing process we define ground control points (GCPs) in the scanned map. We give their position in the scanned image, as well as their map coordinates. The minimum number of the GCPs is three, however if we'd like to see the transformation errors, we shall have at least a fourth one, too. The georeferencing software estimates the parameters of the image-to-map linear transformation. The error represents the average distance in pixel units between the computed and given map coordinates at all GCPs. In case of modern maps, we can accept a fit with better than 2-3 pixels of error, however in case of a historical map this error margin can go up to 10-15 pixels. Higher error values indicate any theoretical error (most probably the selection of wrong projection) or a misplaced GCP, with given erroneous coordinates. Sometimes we use map products, consisting of many sheets in a uniform system, covering a whole country or region. Georeferencing such a map system we avoid to use real terrain objects as GCPs, if possible. GCPs are selected at the corners of the map frame or at the crossing or crosshairs of coordinate lines or latitude/longitude lines. The borders of a unique sheet of such a system are usually coordinate lines in some system. If the shape of the sheet is rectangle, then they are north-south and east-west grid lines in the original projection of the sheet⁶. If the shape of the sheet is a degree trapezoid then the frame borders run on latitude and longitude lines⁷.

⁶ in Hungary: second military survey; in Norway: square mile maps, kvadratmil kart and rectangle maps, rektangelkart

⁷ in Hungary: third military survey; in Norway: degree maps, gradteigskart

While georeferencing a rectangle-shaped sheet, we choose practically the four corner points of the sheet. In this case, beyond the definition of the coordinate system, we shall know the location of the sheets in this very system. This location is defined by

- the location of the projection origin in the system of the sheets

(the origin is in which sheet at what position, or it is in a corner of which sheets)

- the terrain extents of the sheets.

If the sheet labels are given systematically, with consequent row and column numbers, the coordinates of the corners can be easily given by simple addition and multiplication based on the above information. In other cases, an overview map is needed or to be created, to give the location of the individual sheets in the projection plane, thus defining the coordinates of its corners. We shall be well aware that most of the historical maps are made before the introduction of the metric system.

In Hungary, the basis of the map coordinates was the Viennese fathom, while in Norway, it was the alen-based old Norwegian mile (gamle norsk mil).

If only the latitude and longitude lines are given in the map, the georeferencing process needs an extra step. In the first step, the corner points or latitude/longitude crossings are defined as GCPs with their ellipsoidal latitudes and longitudes. Don't be surprised, at first it leads to relatively high errors as the map is not in this coordinate system (the latitude and longitude lines form no parallel and perpendicular line sets). In the second step, we re-compute these figures into the genuine projection of the map, using our GIS software applied for the georeferenced. The errors shall be pretty low after this last step.

The result of the georeference is a map with a coordinate system, which is correctly defined. This enables us to draw the scanned map image in all known projection system. For example, it can be shown as a layer in OpenStreetMap database. This way, the old, mapped terrain status can be compared to the modern one, and e.g. precise GPS coordinates can be tagged for the information items of the old map. Moreover, if more historical maps cover the same area from different time, they can be also fit to each other, providing a kind of 'time machine' in our application.

A.5 *Systematic topographic map products and their georeferenced*

A.5.1 *Hungary*

First military survey Scale is one Viennese inch to 400 Viennese fathom; in metric system it is equivalent to 1:28800. Its geodetic basis is still unknown. It was completed for the whole Habsburg Empire. The sheets covering Hungary were surveyed in 1783-86 (Kretschmer et al., 2004). The parameters of the assumed Cassini projection of the maps can be estimated for each region (Timár and Molnár, 2015). However, at the time of this very handout, its georeferenced is based on a virtual mosaic of all sheets of Hungary and a set of terrain GCPs in it. With local corrections, the horizontal errors are below 200 meters (Fig 10.2).

Second military survey

Its scale is identical to the precedent work. The survey has

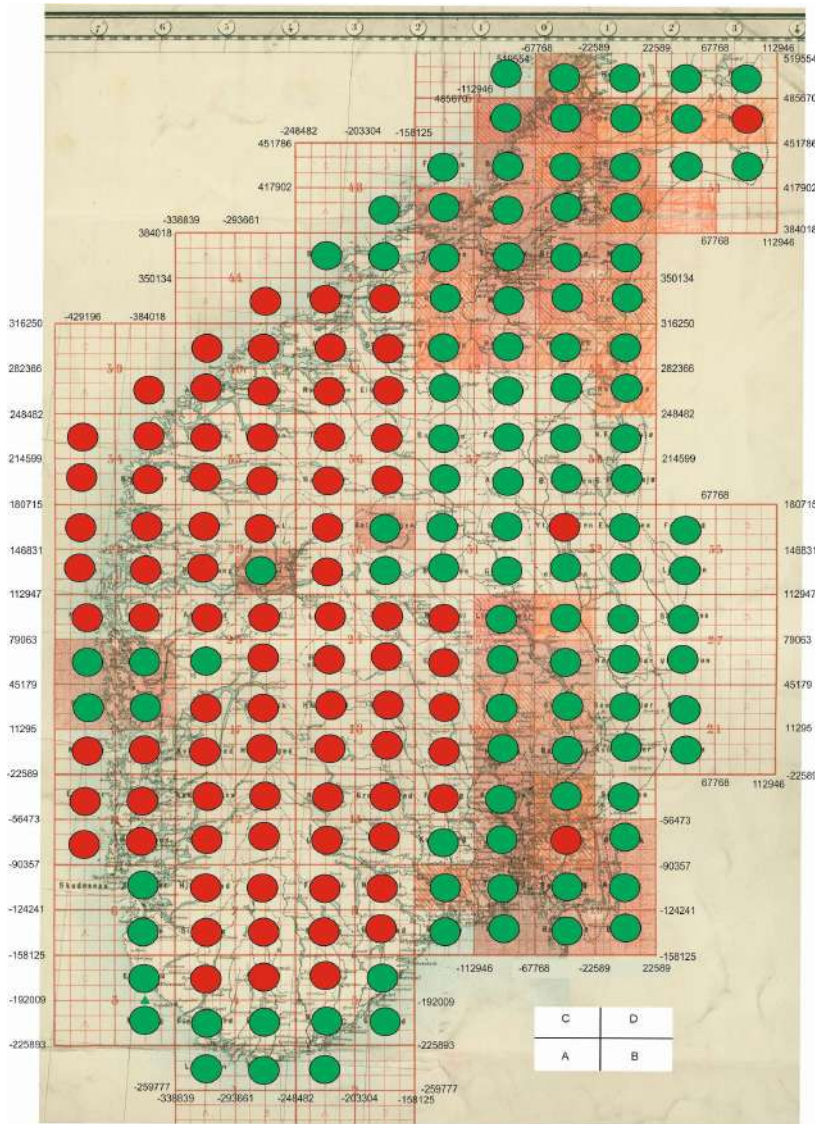


Figure A.4: Overview map of the rectangle map series, with the sheet border coordinates in meters from Kongsvinger. Green circles indicate the available sheets, the red ones only have theoretical sheet labels but never produced (or nor find in the Kartverket archive).

is 2 miles to east and 1 mile to south of the northwestern corner of the containing sheet. Georeference is made based on projection coordinates of the corner GCPs (Fig. A.5).

Larger scale working version of this map product (e.g. in 1:50 000 scale; Fig. A.6) were completed for some parts of the mapped area.

Degree maps (Gradteigskart) In the beginning of the 20th century, the Norwegian mapping authority switched to application of the Gauss-Krüger (transverse Mercator) projection grids. Production of the rectangle maps has been stopped. The still missing, non-mapped parts of the country was covered by the 1:100 000 scale degree map system in Gauss-Krüger zones. Later it was extended to the most parts covered earlier by the rectangular maps, providing an almost full cover of Norway. The terrain extents of the sheets is not uniform: it varies with the geographic latitude. The georeferenced can be made by corner GCPs and their geodetic coordinates



Figure A.5: Georeferenced mosaic of the 1:100,000 scale rectangle map sheets of the Trondheim area.



Figure A.6: The 1:50 000 scale sheet provides the most detailed and the also the oldest (1867) available topographic information about the Lower Gaula River valley, South Trondelag.

(latitude and longitude) in the NGO datum, then re-project them to the respective Gauss-Krüger zone coordinates.

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