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Investigation of direct and indirect suspended sediment measuring methods

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Contents

1 Introduction

In the last few decades the importance of monitoring the sediment transport in surface waters increased. It is essential to understand the behaviour of the particles carried by the rivers if we aim to manage the watershed in a sustainable way, utilize the benefits of it and keep it in a good condition. Countries around the world have been preparing their own solutions for such problems for a long time, but nowadays they started to realize that it is necessary to share knowledge, methods with others and learn how to solve the problems together. Dealing with most of the large water basins, large rivers are extremely international tasks, so it is required to help each other with experience, knowledge and tools to reach the common goals. This study aims to demonstrate the up-to-date methods, devices that have just became available in Hungary, provide a brief summary of the experiences with them, and adumbrate the tasks to be carried out in order to use these instruments adequately.

Several projects have started already or being prepared in the EU connected to the sediment transport (sednet.org, 2016). These projects try to solve the problems occurring due to the river regulations, hydropower utilization, dredging, water contamination. It is important to be aware of the impacts of these activities on the sediment transport, such as the hydromorphological changes in the river channels, and reservoir sedimentation. As an EU member, and a country where the Danube flows through, it is Hungary's duty to take part in such projects. Although Hungary has its conventional techniques, this paper intends to introduce a wide range of new possibilities for sediment monitoring methods, thereby help to find an easier and more efficient way to accomplish such tasks.

First of all I will introduce the instruments we used for the measurements. Without going into details, show their working principles and their capabilities. During the measurements we used both in situ and methods that require laboratory examination. The two main types of these instruments were the optical and acoustic devices, supported with auxiliary tools like a water sampler. Measuring suspended sediment concentration (SSC) both acoustic and optical instruments have their advantages and shortcomings so if it there is a possibility it is advisable to use them as complementary methods (Hointink & Hoekstra, 2004). Two of the herein utilized optical instruments' working principle is based on the small angle forward scattering of the laser light (LISST-Portable, LISST 100X), another one is based on the backscattering of infra-red light from suspended sediment (OBS). The other main type of the tools is based on acoustic backscattering (ADCP, ABS). The ABS that is described in this paper is a newly introduced device, measuring suspended sediment in a point like way as the optical tools, but uses the backscattering signal of a very high frequency ultrasonic sound. ADCP uses the so called Doppler-shift to determine velocities primarily, but with a suitable calibration it is able to determine SSC. I will briefly introduce the procedure of the calibration too.

Later on I will introduce results from two case studies which have been carried out in the Danube River, using the devices shown previously. Furthermore, the measurement methods and the calibration of the different instruments will be presented. I will compare the results obtained from the two campaigns and put two and two together. One of them was performed during a dredging campaign on the upstream and downstream of a side branch of the Danube (Ráckevei-Soroksári Duna). In this campaign we investigated the plume of the released sediment. The other one was carried out upstream from Budapest at Göd where the spatial behaviour of the fine sediment transport was studies.

In the end of the paper I will summarize our experiences, introduce the consequences and show some of our ideas for further investigations.

2 Applied instruments

One of the aims of this paper is to introduce some of the recently used suspended sediment measuring devices. Two main groups of these instruments will be introduced in details, the devices based on the acoustic backscattering phenomena and the instruments using optical methods to calculate suspended sediment concentration (SSC) and particle size distribution (PSD). Each group has its pros and cons depending on the actual circumstances, so it is important to use them carefully and utilize the capabilities of them considering the weakness of every instrument. The first introduced devices have a working principle based on optical method.

2.1 Optical tools

The very basic principle for 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, then by the optical laws of physics the light beam scatters, refracts (Hulst, 1957). These optical based devices also can be divided into two groups, the instruments measure the small angled forward scattering of the light and the devices calculate using the backscatter strength of the light. This paper focuses on the experiences from the devices and the probable connected usage of them. Does not go into details during the introduction of these instruments, a more detailed description is available from the producers marked in the references.

The first introduced group is the one that analyses the forward scattering pattern of the laser light. These instruments are the LISST (Laser In-Situ Scattering and Transmissometry) devices produced under the trademark of Sequoia Scientific, Inc. The mathematical solutions for scattering light used by these instruments is the so called Mie's solution (Hulst, 1957), which is the exact solution to Maxwell's equations (Czuba et al, 2015).

"A typical laser-diffraction instrument measures the forward scattering portioned into multiple angle sub-ranges." (Czuba et al, 2015). The scheme of working process of the LISST is shown in the next figure (Figure 1),

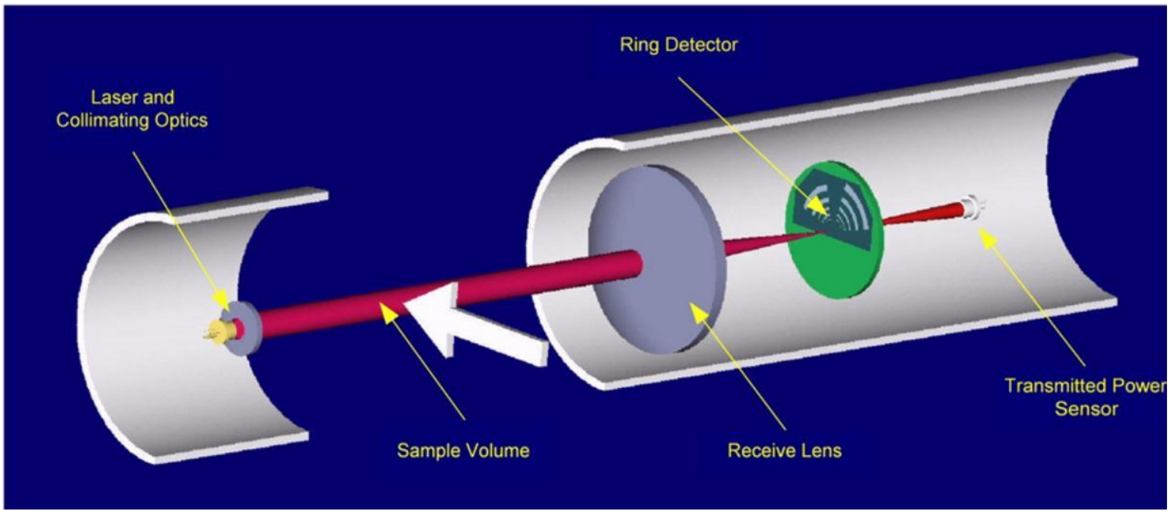

Figure 1 The working method of the LISST (Sequia Scientific Inc.)

The laser beam propagates through the water sample with a known volume containing the particles, than reach the collecting lens that transmit the scattered light onto concentric detector rings. The pattern of the detected light determines the size distribution in the sample, than by the transmitted power the volumetric concentration can be calculated (Figure 1). With a suitable density factor one can easily determine the mass concentration in the sample (Sequia Scientific Inc.). Simpler descriptions of principles are available in the study of Agrawal et al (1991) and a more up to date description of the technology and the application is provided by Agrawal & Pottsmith (2000).

In the following I will briefly introduce the properties of the LISST instruments than I will go on to the backscattering device.

2.1.1 LISST Portable XR

The Portable version of the LISST devices is different in respect of the operation method from the other ones as it cannot be operated without supplementary devices. As it is analyses water samples there is a need for an auxiliary sampler that can provide proper input for the measurements, preferably an isokinetic nonintrusive one.

Figure 2 LISST Portable XR (http://www.sequoiasci.com/product/lisst-portable-xr/)

The working principle of the instrument has been already introduced briefly and the references for detailed descriptions have been provided. In this section I will introduce some of the technical parameters of the LISST-Portable in order to reveal the limitations of it. As it was mentioned before the determination of the PSD is done by the amount of light detected on the different detector rings. The LISST Portable has 44 concentric rings thus it can provide a PSD in 44 logarithmic size classes between 0.34-500 µm (Sequoia Scientific Inc.).

This range is remarkably wide and this property joined with the wide applicability concentration range (30-1,900 mg/l) makes the device very useful. Note that this range is significantly affected by the mean size of the sediment, when measuring finer particles the range drops to 30-170 mg/l. But according to our experiences this shortcoming can be solved by a careful dilution thus samples containing very fine particles in high concentration can also be analysed. Beside the basic equipment LISST-Portable has an auxiliary ultrasonic sensor what used during the measurements the PSD can be obtained more accurately (Sequoia Scientific Inc.).

All in all, the instrument is very handy to obtain SSC and PSD data in a wide range, even though it needs a suitable auxiliary sampler. It has inner batteries so easily can be used during field measurements.

2.1.2 LISST 100X

LISST 100X is a submersible suspended sediment measuring instrument. The working principle is similar to the previously introduced Portable XR, but the difference is that it might be used directly in the water in the investigated area, thus it does not need any supplementary devices. However it also gives a quite good resolution of the sediment structure and the PSD. It must be kept in mind that because of the design and the submersible operation the instrument might disturb the analysed water, so it is an intrusive sediment measuring device.

100X has fewer detector rings than the Portable one thus it can provide PSD only in 32 logarithmic size classes between 1.25 - 250 µm. The sediment concentration range is 1-800 mg/l also significantly depends on the size distribution. This range is valid for the original 50 mm optical path length, but for higher concentrations length decreasing prisms are provided by the producer, thus this range is expandable (Sequia Scientific Inc.). A difference compared to the Portable one, that the 100X does not perform individual sample analysis, it continuously collects data during the measurements. It is really useful to create field type distribution maps or time integrated point measurements but because of these the post processing is more complex.

The instrument has its own inner batteries, but is advised to use an outer power supply because the batteries are not rechargeable. Also important that the 100X has no inner memory, thus a connected computer is required during the measurements to store the collected data (Sequia Scientific Inc.).

Figure 3 LISST 100X (http://www.sequoiasci.com/product/lisst-100x/)

Figure 4 LISST 100X (http://www.sequoiasci.com/product/lisst-100x/)

2.1.3 OBS

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

The working method for any optical backscattering sensors is that the instrument emits infrared (IR) light and measures the strength of the backscattered signal from the suspended material in the sampling volume (Gartner et al, 2001). The detected light is converted to photocurrent by the photo-detectors. The amount of photocurrent mainly depends on the area of the solid particles in the sample, but also affected by their shape, reflectivity and other characteristics. At constant PSD and relatively low concentrations (<5000 mg/l) the measured turbidity by the OBS is proportional to the SSC (Downing, 2006), thus with a suitable calibration it is able to estimate SSC. Because of this dependence on the PSD prior to every measurement the instrument has to be recalibrated according to the actual circumstances (Baranya et al, 2016).

It is also important that the instrument is unaffected by the natural light during the measurements. It is big advantage that the meteorological circumstances do not affect the results whether it is sunny or cloudy.

The parameters introduced in the followings are valid for the Ponsel NTU digital turbidity meter. A photo of the instrument can be seen on the picture below. This is what we used during our measurements. The validated concentration range where the results are reliable is between 1-4500 mg/l. One of the biggest advantages of this instrument is that it has WIFI connection if the necessary software and hardware is available. Thus it does not need wires to communicate with the operator and the duration of the measurement can be set remotely.

Figure 5 Ponsel NTU digital turbidity meter

2.2 Acoustic devices

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

The principle for these instruments is analogous to the previously introduced working method of the optical devices. "A very short pulse of high frequency sound is emitted from a transducer and sediment in suspension scatters some of the acoustic energy back to the transducer." The magnitude of the detected backscattering signal is in relation with the concentration and the size of the sediment and the time delay between the emitting and the receiving linearly proportional to the distance of the location of the scattering (Thorne et al, 1990). A schematic figure of the process can be seen on the next figure (Figure 6).

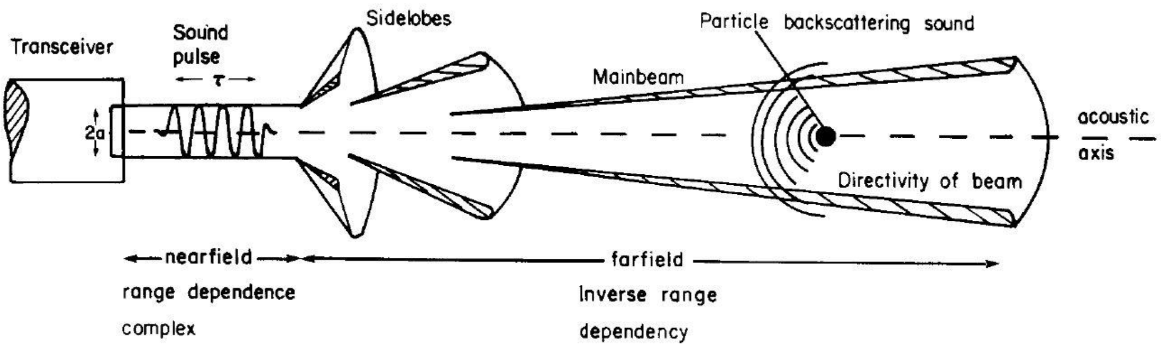

Figure 6 Scheme of the working principle of acoustic devices (Thorne et al, 1990)

In the next sections I will introduce two acoustic devices that had been used during our measurements. The first one is the LISST-ABS than a not originally SSC measuring device follows.

2.2.1 LISST-ABS

The Acoustic Backscattering Sensor (ABS) produced by Sequoia Scientific Inc. has been designed to carry out point like suspended sediment measurements. In this manner this device is more like the optical backscattering ones, but tries to overcome some of the optical tool's shortcomings. Unlike the OBS it sees coarser particles very well (Sequoia Scientific Inc., 2016). The next figure illustrates the comparison of the relative responses against the sediment mean diameter of the two measuring approach (Figure 7).

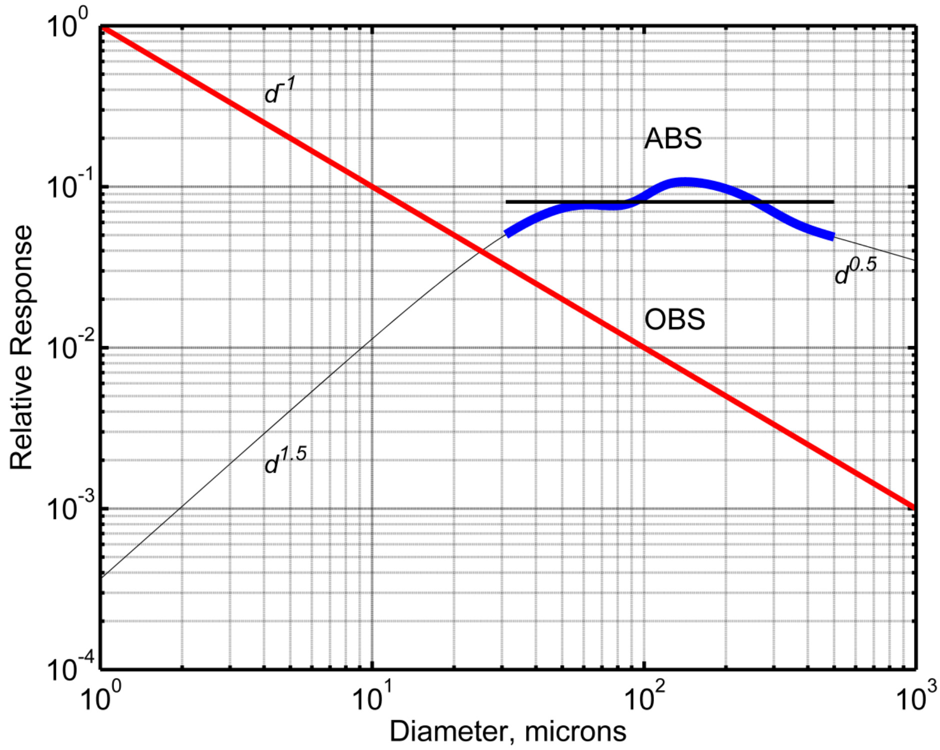

Figure 7 Comparison between OBS and ABS responses (Agrawal et al, 2016)

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

As any other acoustic device ABS also emits sound pulse into the water. The difference is, that the frequency of this sound is very high (8MHz) compare to the other devices, and the analysed point is very close to the transducer (approx. 5cm) thus the attenuation in the water is insignificant, thus the properties of water such as the temperature does not affect the calibration of the ABS. Another advantage is that due to the short path of the signal the attenuation due to the sediment is also not significant, thereby the device may be used in very high concentration as well (Sequoia Scientific Inc., 2016).

Figure 8 LISST-ABS (http://www.sequoiasci.com/product/lisst-abs/)

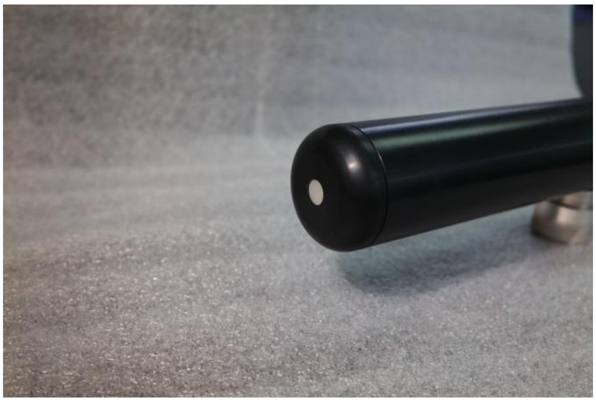

Figure 9 LISST-ABS sensor face (http://www.sequoiasci.com/product/lisst-abs/)

2.2.2 ADCP

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

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

2.3 Water sampling

Figure 10 US P-61-A1 sampler and its setup

The next introduced instrument is not a sediment measuring device itself, but as the most important auxiliary tool during our measurements it must be taken into account. It is the US P-61-A1 point integrating sampler.

This device provided the input samples for the LISST-Portable thus indirectly affects the later calibration of the optical and acoustic instruments. Due to the streamlined designed and the sampling method it can provide undisturbed water samples. The small valve on the headrace where the water flows into the sampler can be operated from the surface, than after the sampling chamber inside the tool is full the instrument can be easily put out from the water by a hoist, than prepare it for the next sampling (Baranya et al, 2016).

3 Case studies

3.1 Hydrocourse

The case study what is introduced first was a cooperative measurement campaign with the Norwegian University of Science and Technology (NTNU). The main purpose of the project was to investigate the behaviour of the suspended sediment in a short section of the river Danube.

The measurement site is located north to Budapest, near the settlement named Göd (Figure 11). During the measurement period there was no extreme flood, nor low water situation, so the circumstances were suitable for analysing a typical sediment structure in the river. We used both acoustic and optical devices and these methods will be introduced in this section.

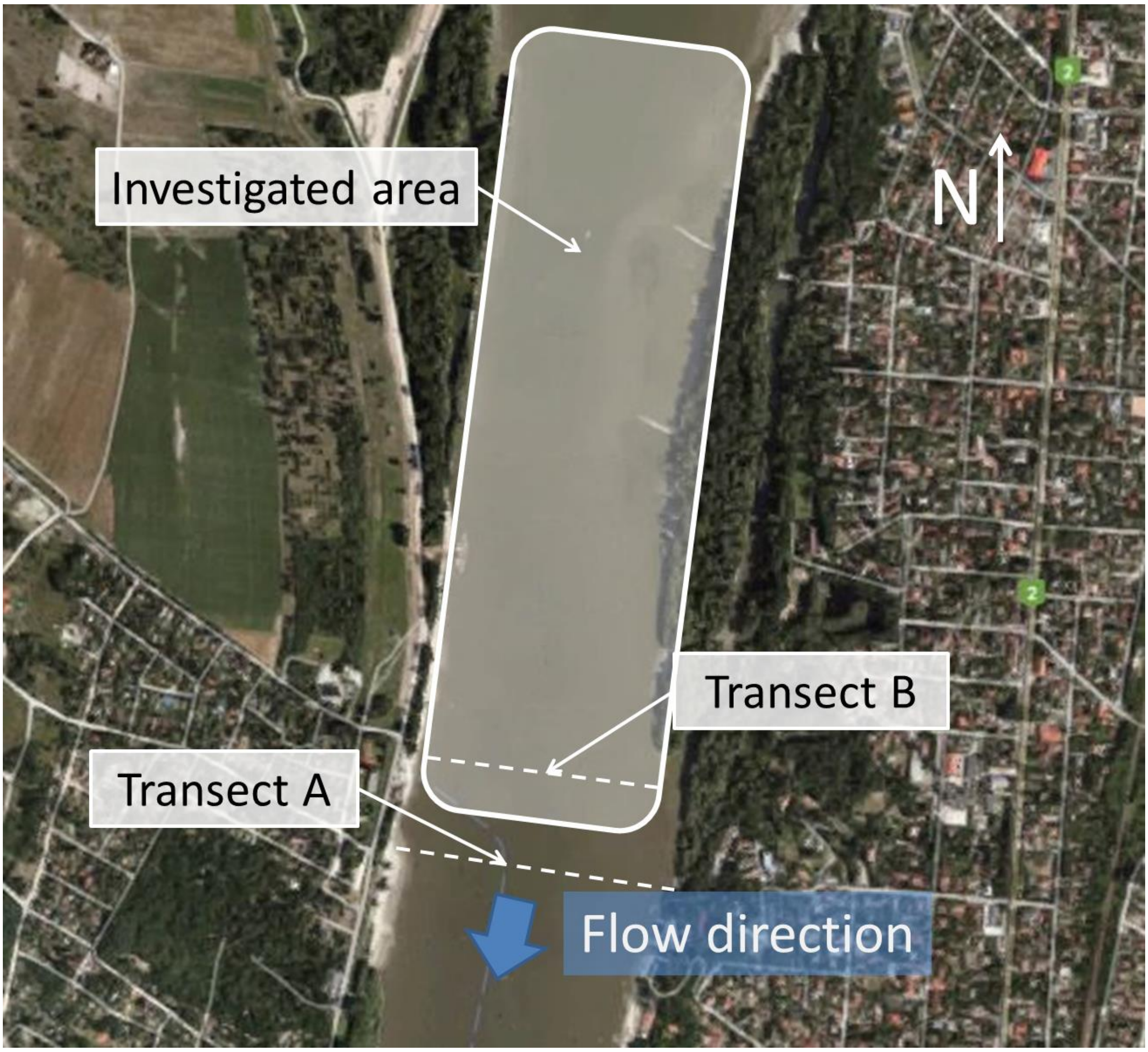

Figure 11 The measurement site near Göd

Two main different types of measurements were carried out. One of our objectives was to obtain field type distribution of the sediment for this section of the river. In order to gain these results we performed moving boat cross sectional measurements along the whole section of the river, using optical (OBS) and acoustic (ABS) backscatter devices, then reconstructed the field distribution from the obtained data. Using this kind of method we managed to generate the field distribution for the investigated area, but only in one depth. To analyse the vertical structure of the sediment it was necessary to prepare fixed boat measurements as well, thus we managed to create profiles for allotted points across a typical cross section of the Danube. For the fixed boat measurements we also used both OBS and ABS, but in the hopes of more accurate concentration values we took samples from the water as well, than later analysed them with the LISST-Portable XR what was previously introduced. As one of our most used device I will introduce the procedure and the gained experiences a bit more detailed. Later on this section I will focus on the results gained from the moving boat measurements (ABS, OBS) and I will both introduce and compare them.

3.1.1 LISST Portable analysis

Prior to the analysis, during the fixed boat measurement we took water samples at four different verticals across the river. We divided the profiles into ten sections in proportion to the depth at these points, taking samples from every one of them thus we were able to create detailed SSC profiles across the river.

Before starting the measurements some preparations had to be done. As the operation of the LISST Portable is based on optical way, it is extremely important to clean the instrument suitably. (This procedure is illustrated by the manufacturer in details in the manual of the device (Sequoia).) The next step is to set the options for the measurements. There are numerous settings that can be adjusted, such as the optical method for the calculations, the duration of the different steps of the measuring process such as the mixing time, the operating time of the auxiliary ultrasonic sensor, the duration of the data collection and so on. During our measurements, we mostly used the automatic settings recommended by the producer. Only a few parameters had been set differently in order to make the instrument more suitable for the river sediment measurements. One of these parameters was the optical method for the calculations. We chose to set the method for randomly shaped particles and beside that we also set the assumed material to the option "Quartz A". (Because of previous experiences we decided to use this one as the most suitable for this kind of environment)

Figure 12 In the middle of a LISST analysis

After the settings had been done the measurements could be started. The procedure begins with the filling of the mixing chamber of the device with the water samples. It is important to shake the samples before filling them into the chamber, thus the possibly deposited sediment will mix into the water again, and a homogenous sample can be placed into the instrument. During the filling the operator must be very careful, not to make any bubbles in the water as they disturb the measurement and cause faults in the results. Also attention has to be paid to the proper amount of the sample. If there is air in the mixing chamber, during the mixing air bubbles will arise causing faulty results again. It is optional but advised to use the auxiliary ultrasonic sensor if the particle size distribution is also important, not just the concentration of the suspended sediment. After the measurement is done, the mixing chamber may be rinsed and prepared for the next sample. The data may be uploaded to a computer for further investigations.

As to the main experiences during measurements with the LISST Portable, a strange phenomenon occurred during the measurements if we analysed the same water sample continuously. Namely, although we did not rinse and refill the mixing chamber but made the instrument analyse the exact sample multiple times the provided concentration values decreased continuously and the mean diameter of the particles got smaller step by step also. In the next figure this phenomenon has been illustrated (Figure 13). Another issue was that at the first few measuring processes a strange peak occurs in the coarser region (red area on the figure). Sometimes not a peak but a rising tail can be observed in the PSDs. The reason for this might be that small air bubbles arose in the sample despite the careful operation, or deposition inside the instrument despite the continuous mixing, but a third more reasonable answer can be for this problem the so called flocculation and the decomposition of the flocs during the measurements (Fall et al, 2016). As we are dealing with natural sediment that does not contain only sand and this kind of material but small organisms and other organic material that can stick together and form flocs which density and volume is different from the estimated quartz and we should consider using a more complex conception describing the sediment. These flocs might fall apart during the continuous mixing thus the measured PSD can change significantly. The failure caused by this phenomenon in the PSD affects greatly the calculated concentrations.

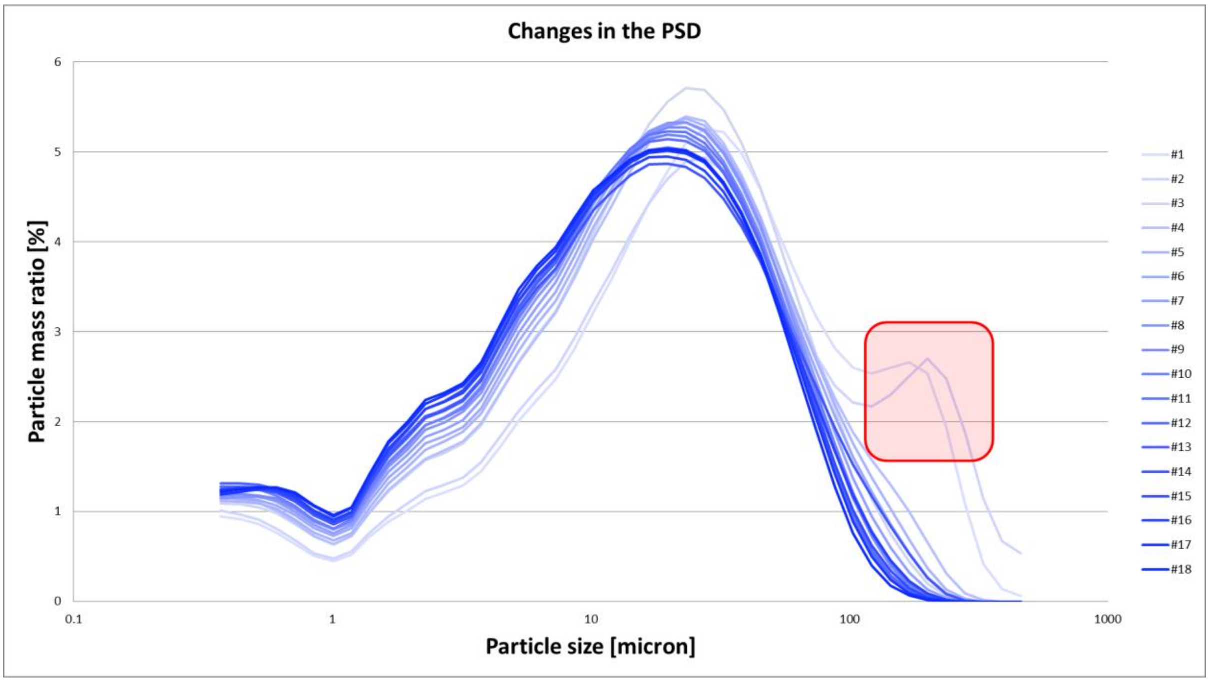

Figure 13 Changing in the PSD during the measurement

In the followings I will introduce the results from our campaign. As it was mentioned before we took water samples during fixed boat measurements, in four points across the river with ten different depths of each one. This resolution for the sediment structure was said to be sufficient to estimate the behaviour of the sediment in the river section and to validate the results gained with other methods.

In the next figure the depth averaged concentrations have been illustrated across a cross section. On the X axis the distance from the left bank had been plotted and on the Y axis the depth averaged concentration values (Figure 14). The results plotted on the figure fulfil our expectations that in the stream-channel (around the navigational channel) the sediment concentration is higher than in the shallow parts close to the banks, due to the higher velocities thus the higher energy of the water.

Unfortunately we were not allowed to do fixed boat measurements in the navigational channel, but even so the trend in the values can be clearly seen.

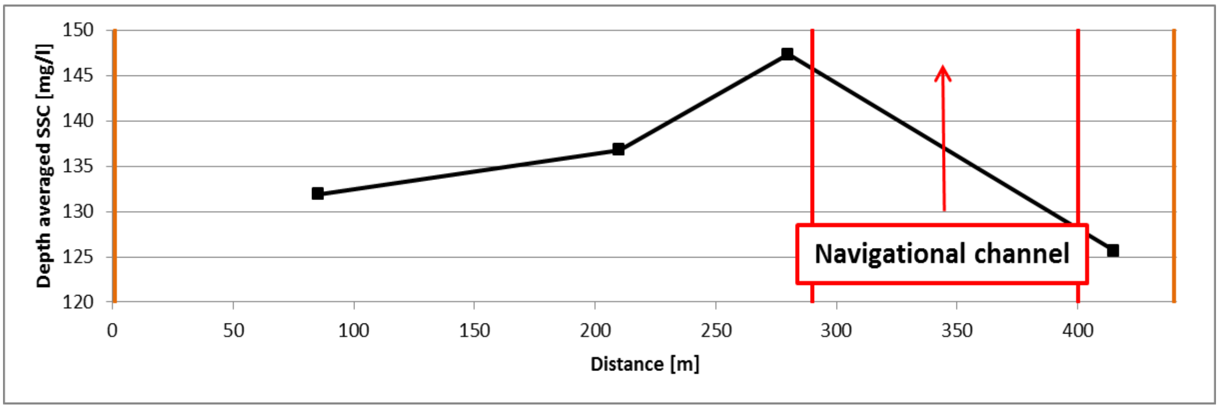

Figure 14 Depth averaged concentration values along Transect A at (Figure 11)

in the next figures two SSC profiles have been plotted, on the X axis there are the concentration values and on the Y axis the depth of the collected samples (Figure 15, Figure 16). The illustrated profiles belong to the measurement points 3rd and 4th from the previous figure about Transect A, on the two sides of the navigational channel. Thus we want to delineate the representative vertical structure of the sediment concentrations during typical hydrological conditions, in deep water with high velocity and in shallow slow water environment.

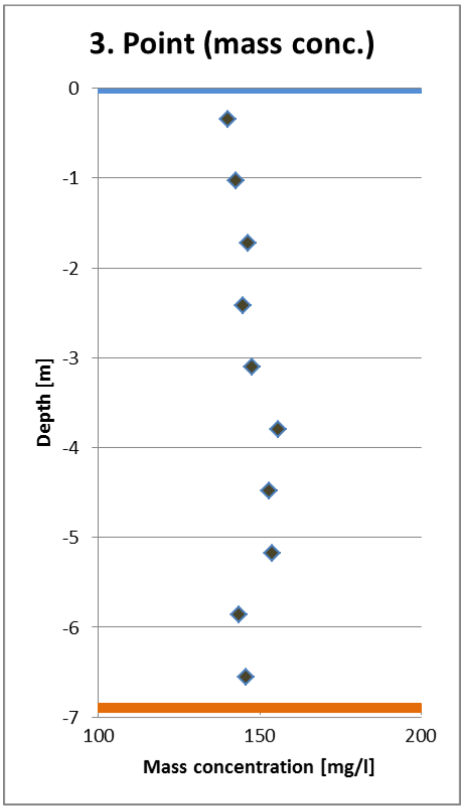

Figure 15 SSC profile at point 3 of Transect A

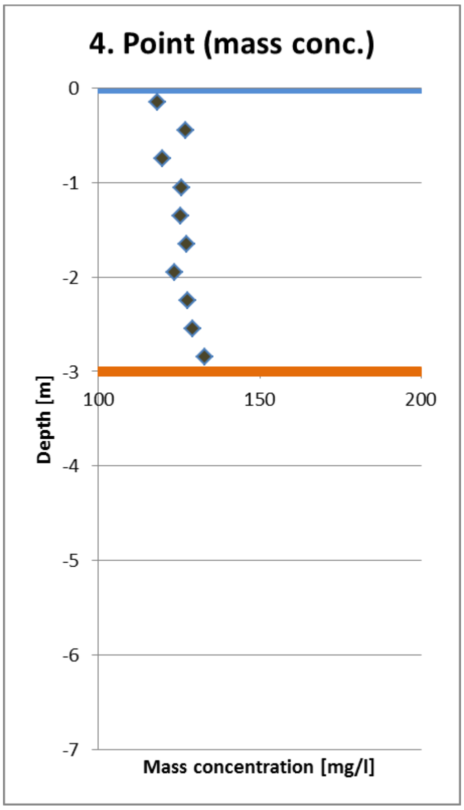

Figure 16 SSC profile at point 4 of Transect A

It is clearly seen again that in the deeper water the SSC values are higher than close to the banks. A theoretical profile would show continuously increasing concentration values as the depth is increasing. This trend can be seen on the profiles created from all the measurements. Close to the riverbed the recorded concentration data is usually the highest sue to the resuspension of the bed sediment, whereas towards to free surface the SSC decreases.

In overall, we found the LISST Portable sufficient for measuring SSC in such a large river like the Danube. The distribution across the river and along the profiles matches the previous expectations according to the theories, and also the measured values were reasonable.

3.1.2 LISST-ABS

During the fixed boat measurements at the previously introduced profiles we also used the ABS and OBS devices (introduced later) alongside the sampling, also performed other fixed boat measurements the day after and a moving boat campaign later on the week. However, the raw data provided by the ABS may not be used immediately, it must be calibrated so it is essential to have a facility to calibrate the ABS. The procedure of the calibration might be read in the paper of Conevski et al. (2016) in details. In the followings a brief introduction will be performed about the applicability of the ABS referred from the mentioned study since all the tests were performed together with the authors of that paper in the frame of the HydroCourse project.

The ABS calibration had been done by the results provided by the LISST-Portable. As it was introduced previously LISST-ABS uses acoustic backscattering signals (BS) to determine the concentration at a known point. This BS has to be adjusted in order to get the correct concentration data. During the campaign (Conevski et al, 2016) used the general form of the sonar equation to calibrate the ABS.

$$(\sigma)^2 = (K_S)^2 * (M_S)$$

Where the σ is the back scattering strength, K_S is the BS coefficient, M_S is the sediment concentration. It is clearly seen that the main task during the procedure is the suitable choosing of K_S value for the current circumstances. The problem with the K_S value is that it seems to be very sensitive to the changes of the particle size distribution (PSD) if the mean diameter of the particles is small. In the next figure the suitable K_S values had been plotted for the 8MHz LISST-ABS, also the recommended LISST-ABS domain (where the K_S is not changing too much due to the PSD changing and can be seen as a constant) had been introduced same as the measured D_{50} range during the campaign (Figure 17). Note that the D_{50} has not been set by the known mass PSD curve but the PSD of the number of the particles (Guerrero et al, 2015).

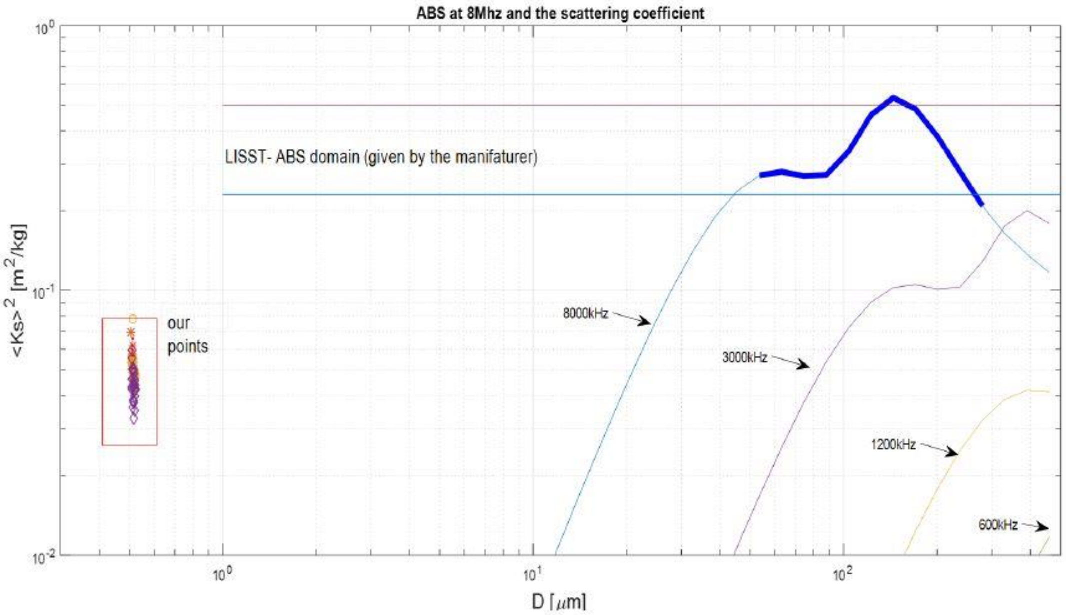

Figure 17 Calibration values for the LISST-ABS (Conevski et al, 2016)

It is obvious that the main particle sizes are way out of the optimal range, thus the calibration for this kind of environment has a lot of uncertainties. Conevski et al. (2016) stated that the uncertainty in this situation could go up to ±70% due to the very small particles and the changing PSD. Although this is huge, they managed to set up a quite acceptable calibration using data from the analysed water samples by the LISST Portable. The correlation had been plotted in the next figure (Figure 18) and the calibration coefficient was found to be 5.7. The results introduced later had been calculated according to this calibration.

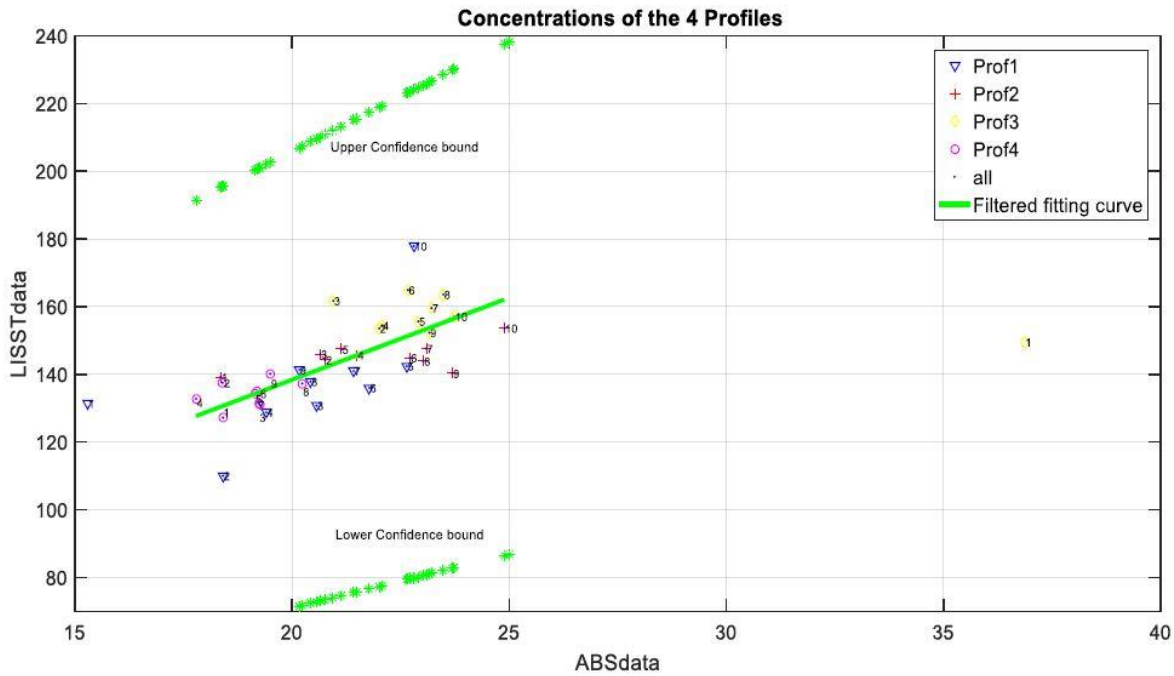

Figure 18 Calibration of the ABS (Conevski et al, 2016) according to the measurements at Transect A

In the next figures I will introduce the SSC profiles recorded by the ABS for the same points where the LISST-Portable results have been analysed (Figure 19). Note that these measurements were running side by side. Because the sampling had certain duration the values plotted below are the averaged ABS data for this sampling interval.

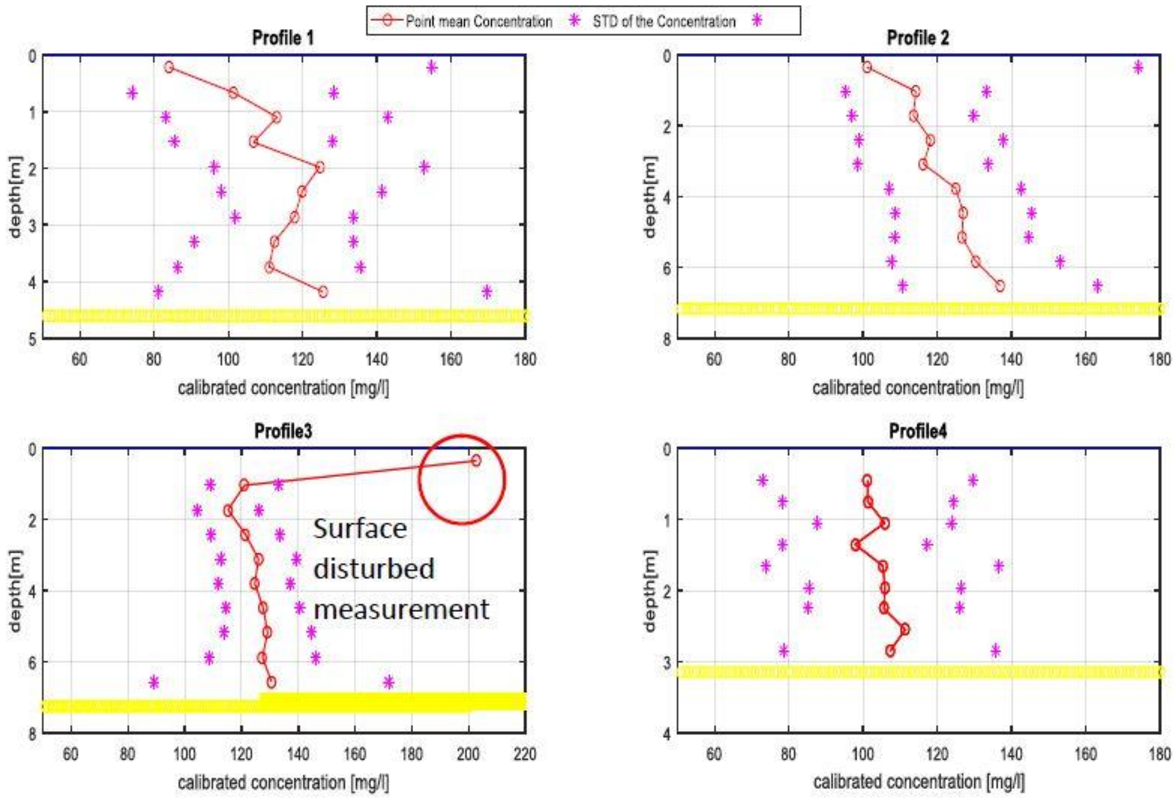

Figure 19 SCC profiles by the ABS (Conevski et al, 2016) at Transect A

The theoretical trend along the profiles also can be observed clearly. Near the bed the measured concentrations are higher and in the deep parts of the river the mean values also higher than in the shallow regions. The purple dots show the STD of the measured concentration that is quite big in the lowest and very first measurements, first due to the higher concentration of sediments in the boundary layer, and second due to the surface flow heterogeneity (Conevski et al, 2016).

Another application of the ABS was creating an SSC field for a short section of the Danube by a moving boat measurement. The depth of the layer where the field had been created was chosen to 1 m below the water surface. The reasons for this depth were mainly operational. Too close to the surface the ABS data can be easily disturbed by the surface, so it is not recommended to use the instrument in the upper regions of the water. However, going too deep is not advised either because than the investigated are becomes too small thus not representative for the section. In order to gain enough data to create the SSC field we performed 21 transects along the river section in every 50-100 m than created the field by interpolating the values. With the results of this campaign we were able to generate an SSC distribution map. In the next figure the created SSC map had been plotted (Figure 20).

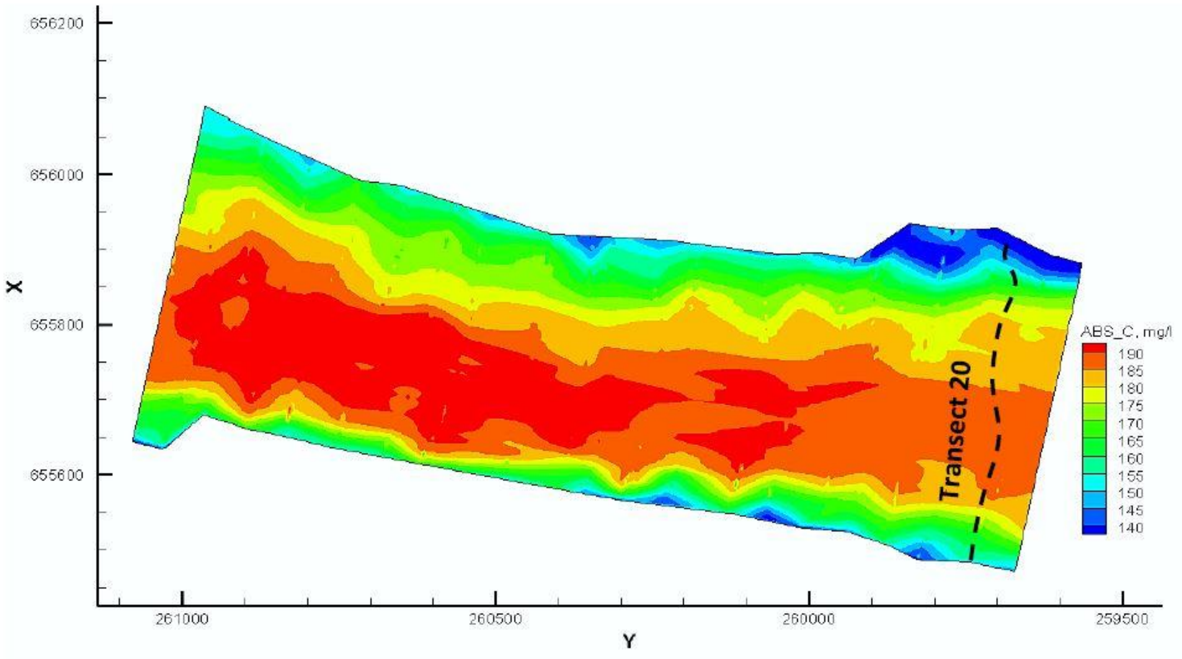

Figure 20 SSC map according to the ABS results (Conevski et al, 2016)

The SSC field at this section seems quite acceptable according to the expectations. Unfortunately this 2D map does not contain the water depths but the highest concentration values did occur in the navigational channel, where the water was the deepest, and along the banks in the shallow parts these values are lower, just as expected. During this campaign the discharge of the river had increased compare to the days when the fixed boat measurements were carried out. This is the reason why the SSC values seem to be higher in general than the values calculated for the fixed boat profiles. The SSC changes between 140-190 mg/l along the section which this also an encouraging result for such a small flood event and such a river like the Danube.

It must be mentioned that during the calibration the concentration range was lower than the SSC values during the moving boat measurements in general. The calibration equation was said to be sufficient for this region also, however, the lack of the data from high concentration during the calibration might led to uncertainties as we assuming that the equation stays linear towards the higher concentration range thus we have to extrapolate. Extrapolation always has its uncertainties.

ABS is a very handy tool and the results are very encouraging so it is recommended to deal with this instrument in the future. In the next section the optical backscattering system (OBS) will be introduced as an auxiliary instrument for the ABS.

3.1.3 OBS

Similar to the ABS during our whole measurement campaign we used the OBS device as well. This instrument also requires a suitable calibration before the collected data could be used for estimating SSC. Accepting the LISST-Portable results as reliable information about the SSC, the calibration of the OBS had been done based on those dataset.

The procedure is almost the same as the previous one with the ABS. Because OBS is also a point integrating device that collects data continuously, in order to make the comparison possible with the LISST-Portable results, first we had to extract the relevant data from the data series that covers the period of the sampling. The idea was to average these turbidity results for this period then plot them against the concentration values obtained with the LISST. After this procedure had been done, a relationship could be set up between the data series from the two different devices thus the necessary calibration equation could be calculated. This calibration is also based on the results from Transect A.

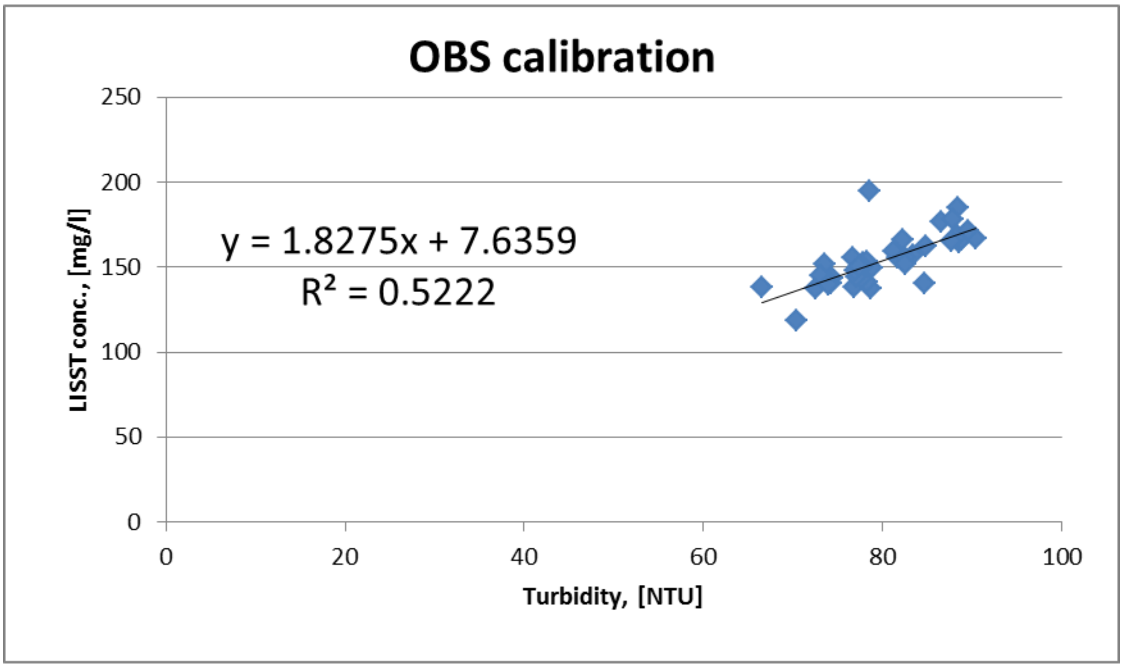

Figure 21 Calibration of the OBS according to the results from Transect A

The relationship is not that strong as it was expected but R^2=0.52 was found to be sufficient for the calibration. These values had been used for the rest of the measurement campaign. Note that the calibration had been done with exactly the same LISST-Portable results that were used for the calibration of the ABS. Because of this, the different response of the instruments for the changed circumstances during the small flood event can be observed, and the differences might be evaluated. At the same time the uncertainties from the small range of the SSC during the calibration also affect the OBS as well.

Creating SSC profiles and field type concentration distributions are also possible with the OBS. Fixed boat measurements were carried out the day after the calibration along a cross-section of the river. At this campaign we measured the SSC at 5 different verticals (along Transect B at Figure 11) and the profiles of these are shown in the next figure (Figure 21). Point 1 and 5 were near the banks and 3 was more or less in the middle of the river. It is clearly seen that the results took shape according to the theory. In the middle, where the water is deep and the velocity is high, the SSC is higher than at the points close to the riverbanks. Also the vertical structure of the sediment concentration had been recorded fairly. Near the riverbed the SSC values are higher than in the near surface regions.

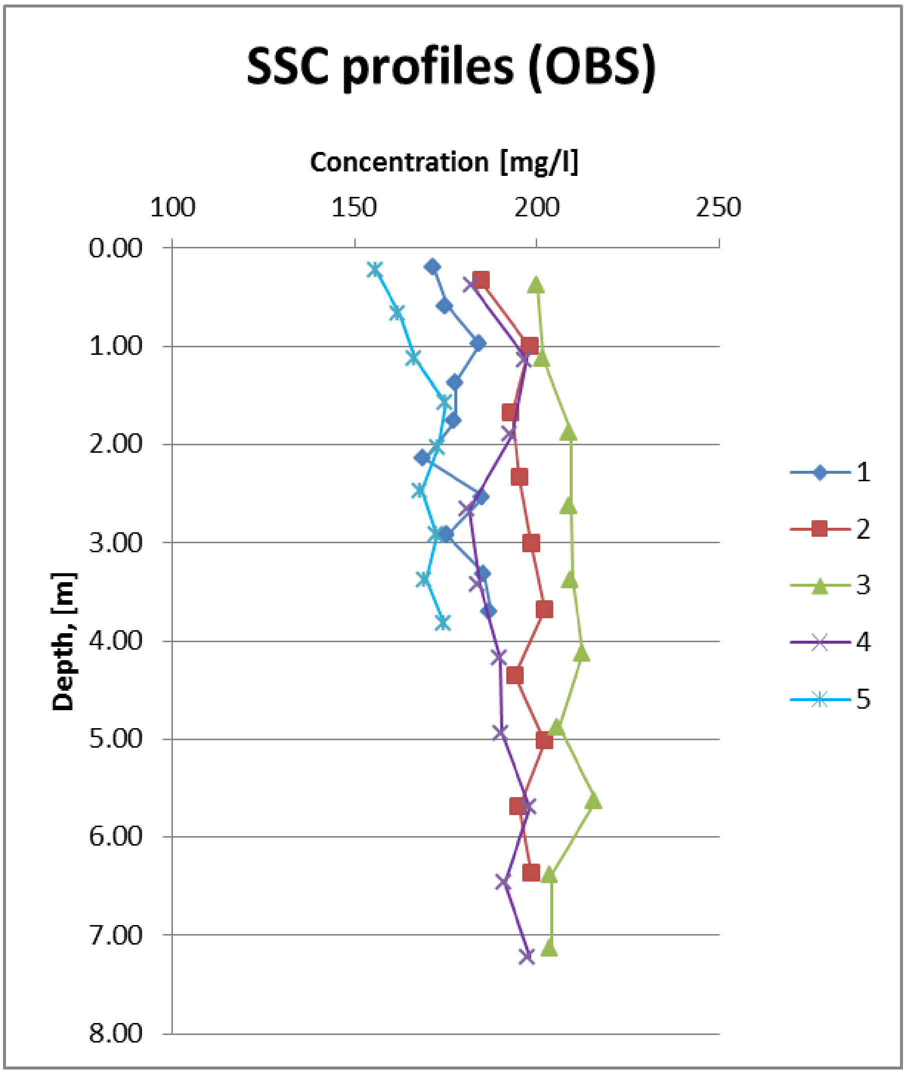

Figure 22 SSC profiles by OBS at Transect B

On the following day of the field measurements, OBS was also operating side by side with the ABS during the moving boat measurement. Thus we aimed to create an SSC field with the OBS too (Figure 23), then compare it with the SSC field obtained by the ABS. Although the concentration pattern seems to be more or less corresponding, it is eye-catching that the SSC range estimated by the OBS is wider than the range from the ABS results. The maximum concentration values reach 250-260 mg/l what is quite a difference compare to the ABS 180-190 mg/l maximum. The reason for this might be the different operation range considering the size and the concentration of the particles thus the response for the higher concentration and probably changed PSD because the flood was dissimilar.

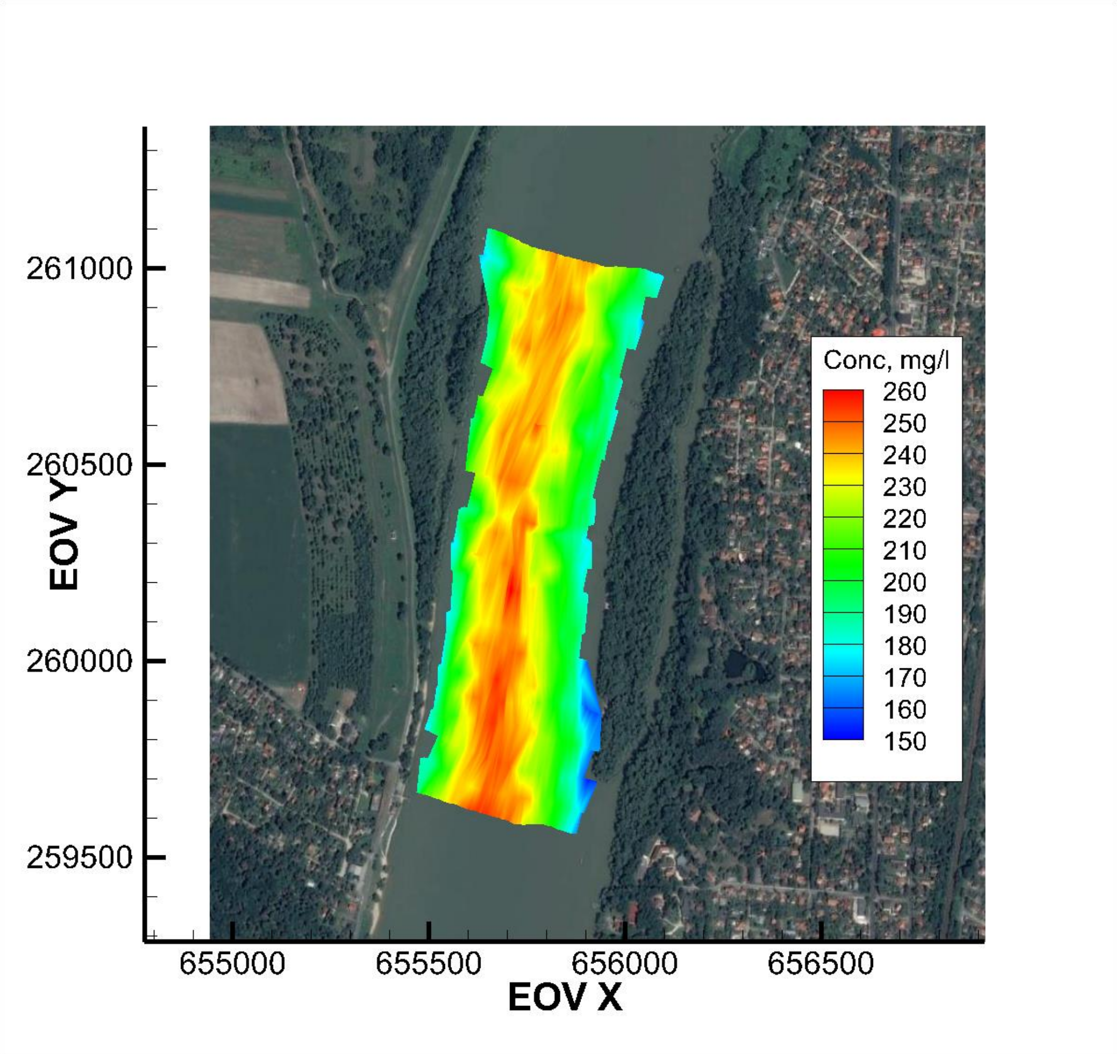

Figure 23 SSC field according to the OBS data

During the one week measurement campaign we focused mainly on the point integrating devices and the calibration of them, although ADCP was also operating alongside the previously introduced instruments. Through the next case study I will focus on the use of the ADCP for SSC measurements and the calibration of the device and some auxiliary instruments also.

3.2 Dredging projects

The second case study I will introduce is about two dredging campaigns in the Danube. The dredging sites were located at the upstream and downstream end of a side-branch of the Danube, called Ráckevei-Soroksári Duna, located downstream to Budapest. In the next two figures the schematic dredging sites have been illustrated. Near the inlet and outlet sections locks had been built, where due to the locally decreasing flow velocities permanent sedimentation characterizes the bays between the locks and the main river. During the dredging campaigns the deposited silt layer had been removed with hydraulic dredging method, then released back in the Danube immediately via a pipeline.

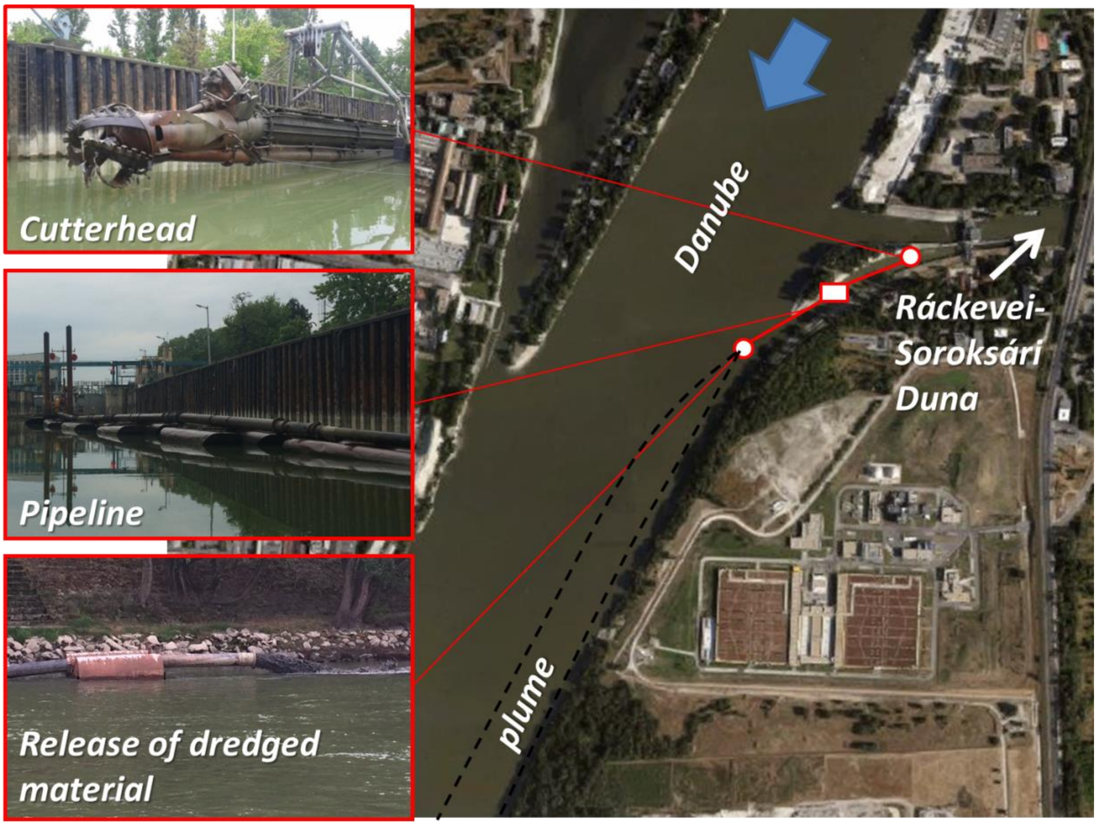

Figure 24 Dredging site at the upstream end of the side-branch of the Danube (Upstream 'Kvassay' lock)

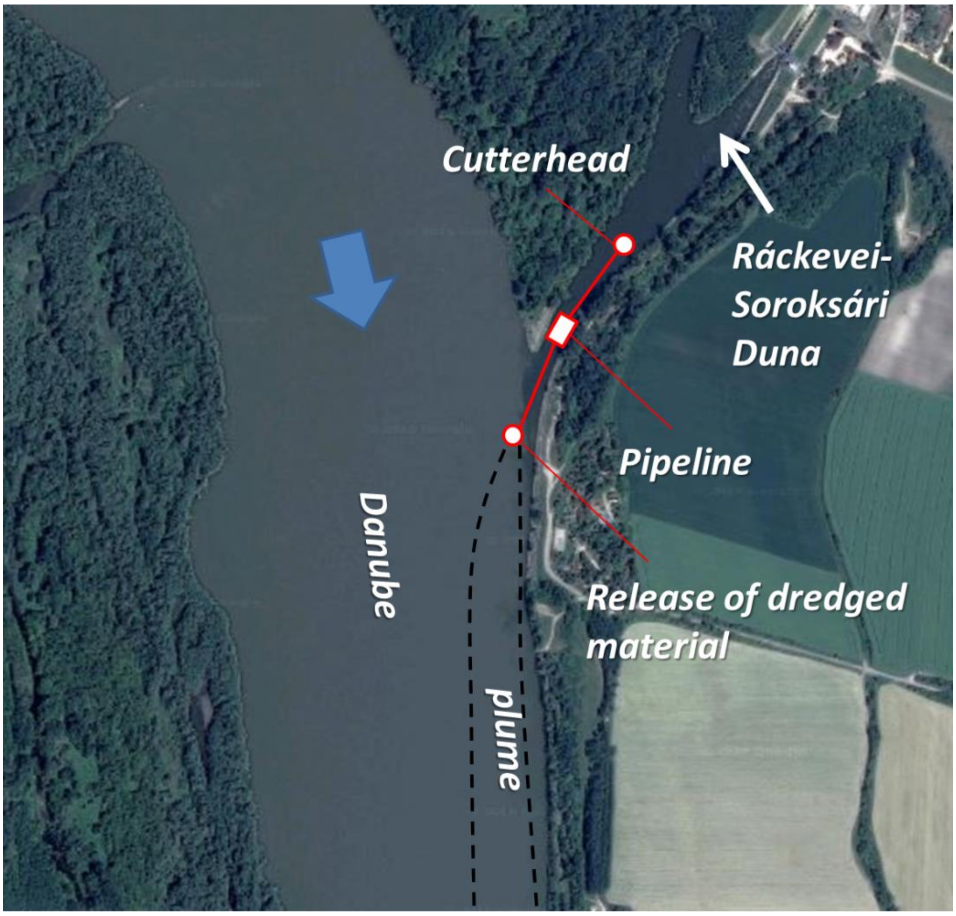

Figure 25 Dredging site at the downstream end of the side-branch of the Danube (Downstream 'Tass' lock)

In the next table the time and location of the different measurements during the dredging projects have been introduced.

Campaign ID	Location	Date
K01	Upstream (Kvassay) lock	25/04/2016
K02	Upstream (Kvassay) lock	02/05/2016
T01	Downstream (Tass) lock	16/03/2016
T02	Downstream (Tass) lock	25/03/2016

The aim at these measurements was to monitor the behaviour of the plume of the released sediment, determine the distance where the mixing is complete and the original concentration is reconditioned. In order to fulfil these claims we needed a reliable method to measure SSC with a high temporal and spatial resolution. Due to the need of the monitoring of the vertical dispersion also we chose to use an Acoustic Doppler Current Profiler. To calibrate and validate the ADCP we took water samples from the plume, then analysed them with the LISST-Portable and a traditional laboratory way. We also made an attempt to use the LISST100X, and gain some experience with it besides validating the ADCP and LISST-Portable results.

Although as it was mentioned before, the ADCP was originally designed to determine the velocity in water current (e.g. Muste et al, 2004), but with a suitable calibration, it is possible to calculate the sediment concentration in the water column from the raw backscatter data (e.g. Guerrero et al, 2014). In order to get the SSC with adequate temporal and spatial resolution, during our measurements we have done this calibration for every campaign. In the followings I will briefly introduce this procedure.

Figure 26 The equipment for the measurements

3.2.1 ADCP

In the last few years the requirement to obtain suspended sediment concentration with high spatial and temporal resolution has led to the development of the acoustic backscattering methods. Although the translation from backscattering data to suspended sediment concentration has some uncertainties, these techniques have been used successfully in the recent years. Up to the present day only semi-empirical approaches have been introduced since the properties of the backscattering signal highly related both to the water and sediment attributes, thus a suitable calibration is required before every measuring campaign (Thorne et al, 1990).

The methodology for calibration of the ADCP can be conducted from the so called sonar equation (Hointink & Hoekstra, 2004). This equation shows the connection between the emitted and received energy during an acoustic pulse, considering the energy loss due to both water and sediment parameters. During our calibration we used the inversion of this equation on the way it had been introduced previously by many authors (Gartner, 2004) (Guerrero, 2012) (Baranya & Józsa, 2013).The inversion of the sonar equation is in the following,

$$SSC = 10^{A+B*(K_c(E-E_r)+2(10*\log(R)+\propto*R))}$$

where A and B are calibration constants, Kc is a conversion factor from instrument counts to echo intensity which is instrument-specific and temperature dependent (DRL Software Ltd, 2003), E is echo strength (in counts), E_r is the reference level for echo intensity (in counts), R is the slant range from transducer head to measured bin, while α is a coefficient describing the absorption of energy by the water (α_w) and attenuation from suspended sediments (α_s). E, E_r and R can be measured with the ADCP, α_w and α_s are estimated, whereas A and B parameters can be calibrated with concurrent sediment concentration data with e.g. least squares fitting. (Baranya et al, 2016) In the study the applied values for the parameters are the followings: K_C = 0.44, E_r = 50, α_w = 0.46 (dB/m), α_s = 0.001 (dB/m per 1 g/m^3 concentration) (Baranya et al, 2016). The last parameter contains the actual concentration of the water, thus implicitly affects the calibration. The SSC values for assuming the αs parameter based on the physical water samples what we took during the measurement. These samples were analysed with the LISST-Portable than the result were implanted into the calibration process. The echo intensity for each sample was obtained from the ADCP time series by averaging the individual EI's for the sampling period from the corresponding cells. The last step was the calibration of the A and B constants. At one campaign we got very good relationship between the measured and the calculated SSC using this calibration but there were also not that successful measurements. Two of these comparisons had been illustrated below (Figure 27, Figure 28).

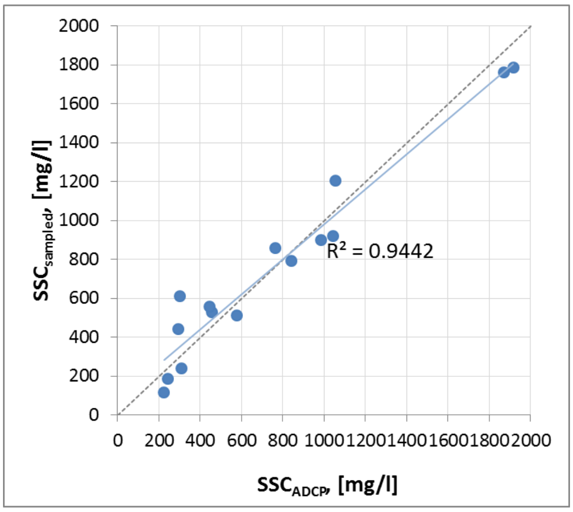

Figure 27 Calibration of the ADCP (Campaign K01)

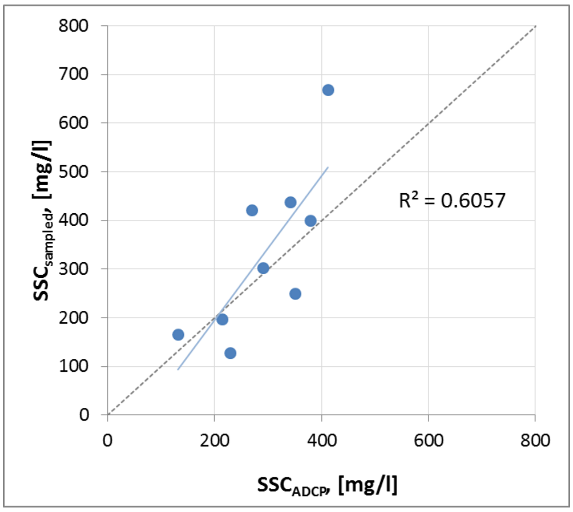

Figure 28 Calibration of the ADCP (Campaign T02)

As it was mentioned before, our main goal was to investigate the behaviour of the released sediment. We aimed to recreate the plume of the dredged material so we performed crisscrossed moving boat measurements along the estimated plume geometry in the hopes of collecting enough suitable and relevant data. The results that will be introduced are the ones what were created by using the data from the measurement with the best fitting comparison (Figure 27) i.e. the results from campaign K01.

In order to recreate the spatial pattern of the plume we had to turn the echo intensity time series onto relevant SSC data using the parameters obtained from the calibration. A perspective visualization of the obtained results has been illustrated in Figure 29. The shape of the propagating sediment is represented by red and green areas, i.e. high concentration zones. During the measurement there were no extreme hydrological conditions, the discharge was around the annual mean value thus the mean background concentration was around 150 mg/l, what is represented by the blue areas on the figure. It is well seen that the concentration is very high, a bit downstream to the release of the dredged material it can reach 1500-1600 mg/l. No remarkable horizontal spreading could be observed, but the reasons for this were the local hydrodynamic circumstances. The width of the plume hardly changed along the investigated area, it remained around 20 to 40 m. However the vertical mixing was very efficient due to the sudden settling of the coarser particles. After a few 10 meters the higher concentration values appear in the lower zones of the water column also. The rapid change in the vertical SSC profiles can be seen beside the map of the plume (Figure 29). These profiles were extracted from the SSC time series randomly considering the shape of the plume aiming to follow the central line of it (marked with white vertical lines on Figure 29). It is well seen that on the first profiles the concentration values are extremely high in the upper regions of the water, but it rapidly changes. After a few 10 meters the vertical mixture can be considered complete and the typical structure of the sediment is re-established although the average concentration is still higher than the background values. Later on this chapter the longitudinal mixing will be introduced more detailed.

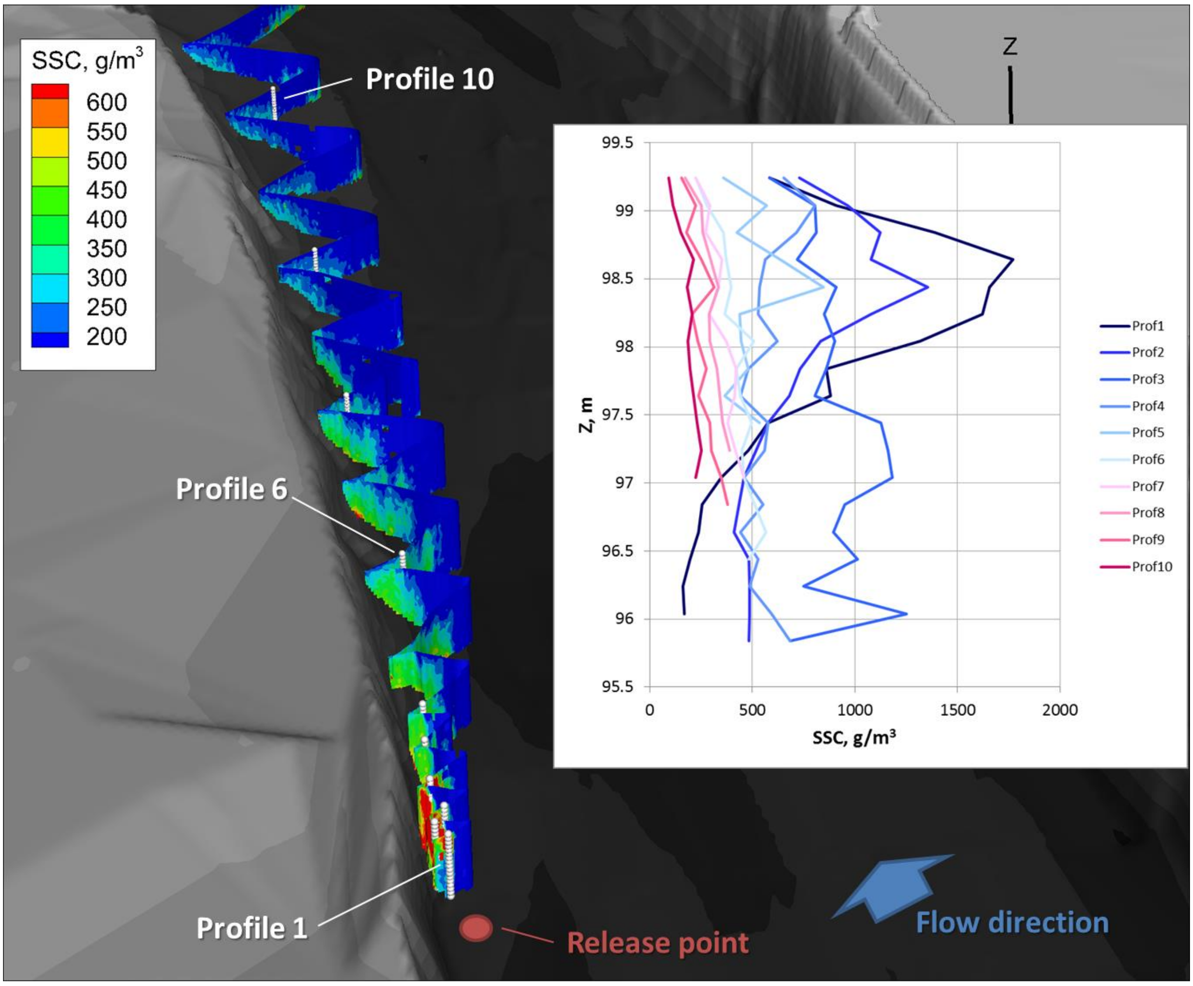

Figure 29 Shape of the plume and SSC profiles by ADCP from campaign K01

In order to assess the applicability of theoretical approaches for studying the longitudinal mixing of the slurry a comparative analysis was performed based on the measured and calculated variation of the sediment concentration along the longitudinal direction. Note that the first measured points are approximately 10-15 m downstream to the point and due to the fast mixing of the slurry the concentration of the original material had to be estimated in order to describe the longitudinal behaviour of the sediment by a theoretical approach. An estimated average value of 10000 mg/l had been set as starting concentration with a discharge 0.4 m^3/s for campaign K01 and K02. During the theoretical description we used the 2D, depth averaged, dispersion equation that can be expressed as (Holly, 1975).

$$C(x,y) = \frac{M}{2h(\pi D_y x v_x)^{1/2}} exp\left(-\frac{v_x}{4D_y x} y^2\right)$$

where C is the concentration, M is the mass of the release, h is the water depth, D_y is the transversal diffusion coefficient, x is the longitudinal distance from the source, v_x is the depth averaged longitudinal velocity and y is the transversal distance from the source. This equation estimates that the source of the contaminated water is point like and permanent. The transversal diffusion coefficient was described according to (Fischer, 1975). Most of the parameters are based on the field measurements, estimated from the relevant data or had been previously described for the investigated Danube reach (Muszkalay, 1980).

Using the described method we managed to estimate the longitudinal profile of the depth averaged SSC for our campaigns. After the theoretical profile had been created we compared it with the values obtained from the other two indirect methods. We needed comparable depth averaged SSC values from the ADCP and the samples also, so for we used the extracted profiles from ADCP surveys, averaged the calculated concentration values for the whole profile, and located the investigated profile from the release point based on the measured GPS data. These values are marked with blue dots in Figure 30. For the samples we used the results provided by the LISST-Portable. At campaign K01 we took water samples from five different depths along every investigated profile, then averaged the obtained values along the profiles in order to gain comparable depth averaged SSC data. These are marked with red dots in Figure 30.

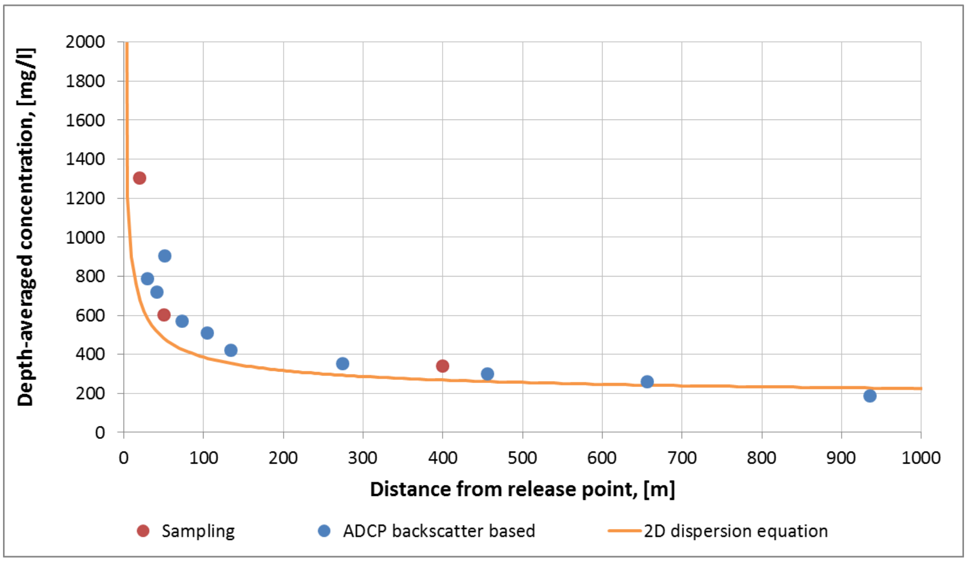

Figure 30 Longitudinal profile of the SSC (Campaign K01)

The significant settling in the first few 10 meters can be clearly observed on the theoretical curve. The results from the measurements show the same behaviour. It is evident that these results have their own uncertainties because of the procedure, yet there is a really good relationship between the ADCP and the theoretical results. This is also valid for the results from the physical samples. It must be noted that the dispersion equation seemed to be very sensitive to the concentration of the released material (i.e. the concentration of the slurry at the end of the pipeline) which was not measured directly, thus the theoretical method have uncertainties as well. In the next figure the same longitudinal distribution has been illustrated from another measuring campaign (T02 in Figure 31 Figure 31).

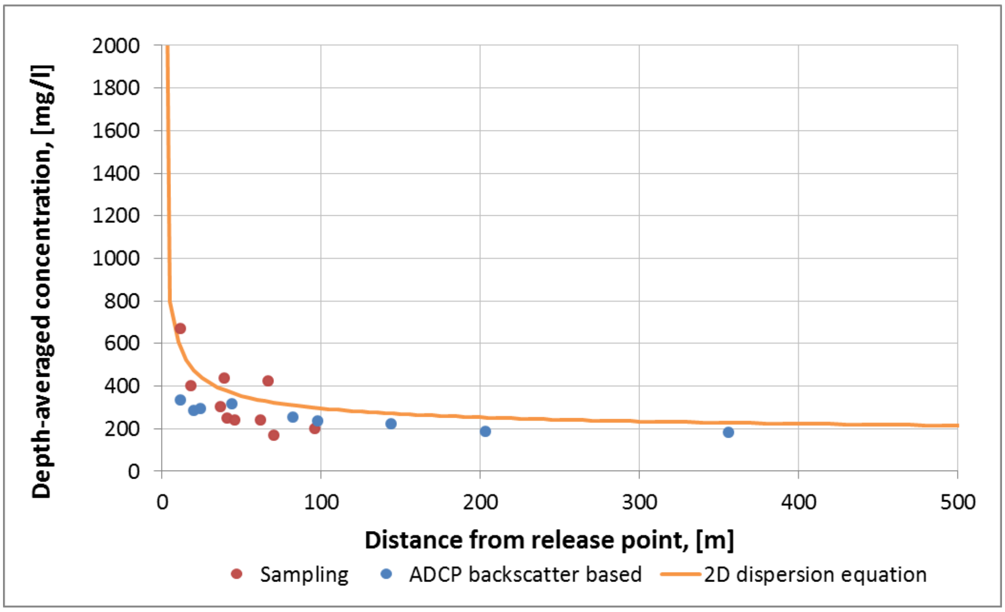

Figure 31 Longitudinal profile of the SSC (Campaign T02)

At campaign we made an assumption that at the sampling profiles the vertical mixture was complete and the concentration gradient was small along the profile, thus the measured value was representative for the whole profile. Using this method we managed to perform measurements at more points. Again the results from the sampling are marked with red dots and the blue dots represent the SSC values from ADCP, obtained with a similar method than at campaign K01.

These gained results led us to the consequence that the significant part of the mixing is done in the first few 10 meters due to the sudden settling of the coarser particles and due to the turbulent currents in the water. The sediment is mixed completely in the water column in this region. Although the rapid mixing slows down after this part, yet the background concentration is restored only after few hundreds of meters.

3.2.2 LISST 100X

Alongside the sampling and the ADCP measurements we also used the LISST100X. Unfortunately due to the unsteady operation of the dredger we were unable to obtain reliable data to recreate the propagation of the plume with the 100X, however, we performed point integrating measurements during the samplings that resulted useable data series. The SSC series for the sampling period had to be extracted from the whole time series, then averaged in order to be comparable with the results of the sample analysis. It must be mentioned that at this T02 campaign we did not use the isokinetic sampler instead we took the samples with a pump which duration was 30 s per sample. This method might have led to more uncertainties than previously expected. The comparison can be seen on the next figure for campaign T02 (Figure 32). The averaged SSC values that had been recorded by the 100X are marked with the blue dots on Figure 32 and the measured minimum and maximum range is marked with the black lines in the figure. The highlighted point which is marked with red dot and circle will be discussed later in details.

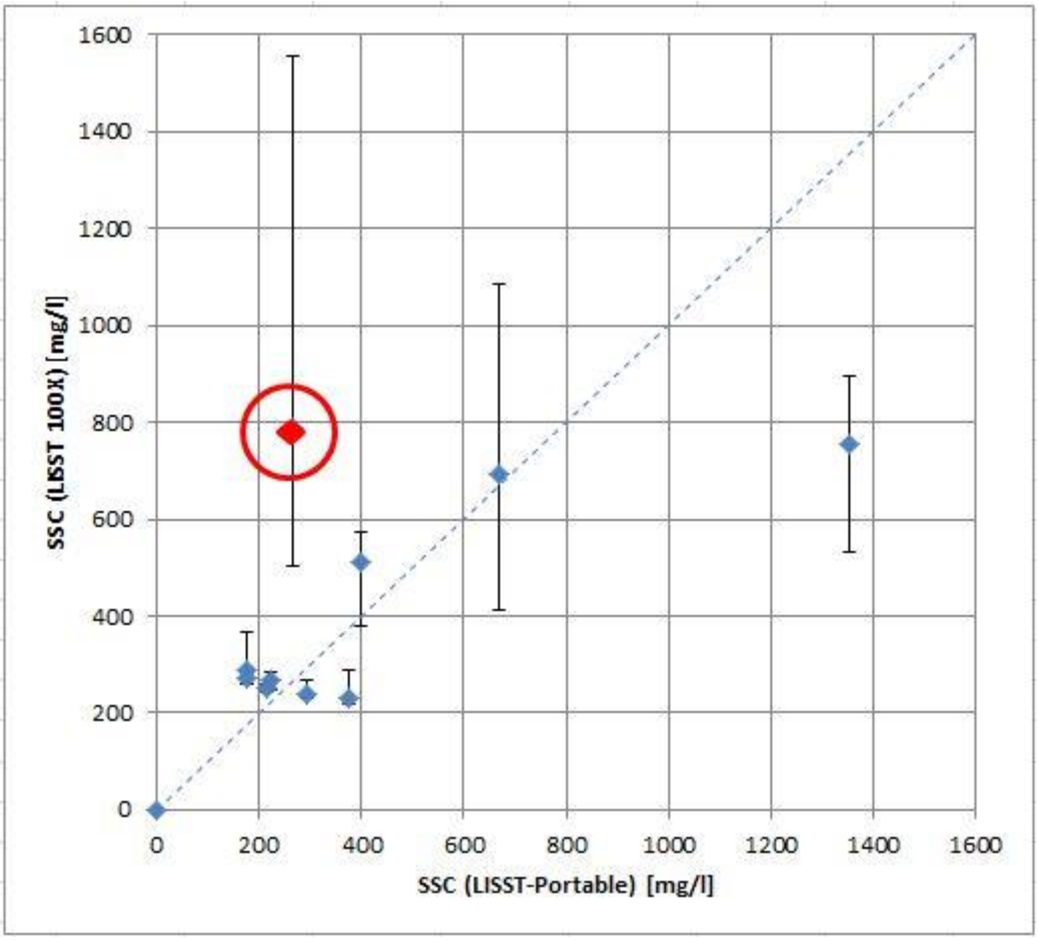

Figure 32 LISST100X values against LISST-Portable results

Although the inlet of the pump and the LISST was side by side in the water, due to the immensely inhomogeneous plume of the sediment, these comparisons have significant uncertainties in the higher concentration regions. The measuring frequency of the 100X is around 0.3Hz i.e. 1 measurement in every 3 seconds, and beside that 10-15% of the recorded data has faults in it thus not usable. Providing data in such a low temporal resolution makes LISST100X unable to record the rapid changes in the plume thus not advised to use under the given circumstances. A sequence of the measured instantaneous data of the highlighted point in Figure 32 is shown on the next figure (Figure 33). The blue dots represent the SSC values from the 100X during the highlighted measurement, and the red patches show the missing data.

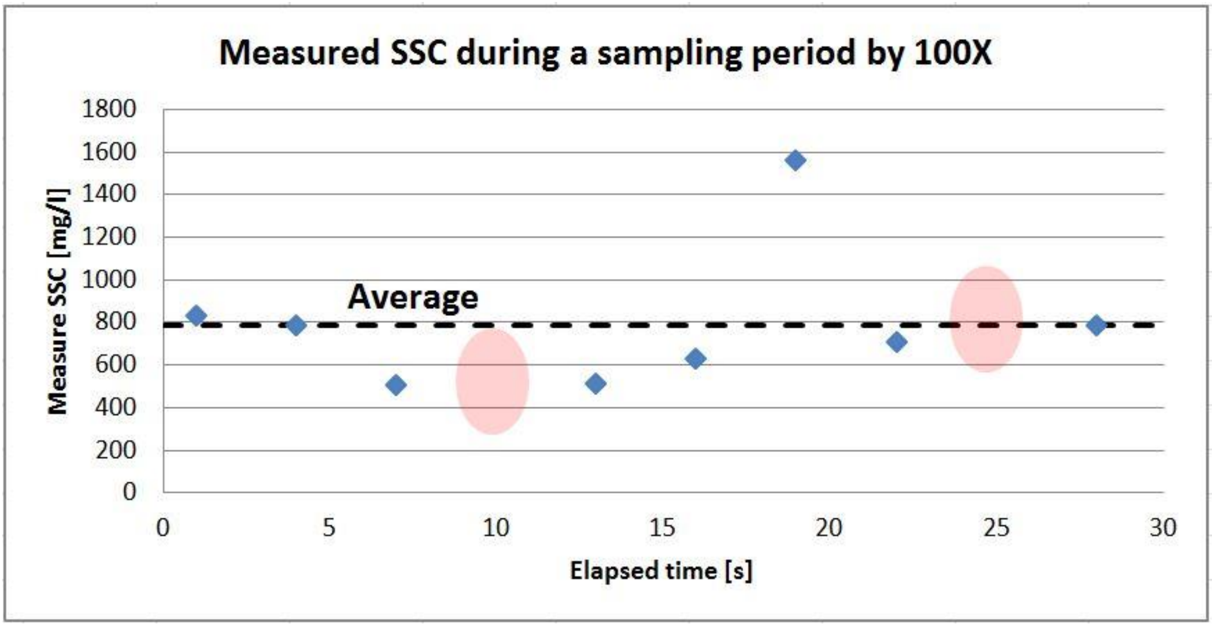

Figure 33 Measured SSC sequence for a sampling period

It must be noted that the very original purpose of developing the LISST100X instrument was not to measure SSC in rivers but to investigate marine environment where the velocities are much lower and the circumstances do not change rapidly. Even the non-isokinetic shape of the device suggests that it is not the most suitable instrument for river environment. However, we gave it a try in such an environment, and despite the shortcomings of it under more stable conditions and for fixed boat point measurements the instrument could be used as a useful device for investigating river sediment behaviour.

4 Summary and Conclusions

In this paper I have introduced the recently used suspended sediment measuring instruments, and methods via two different case studies. I went through both the optical and acoustic based instruments, and briefly described the working principles of them. In this section a relevant study that revealed the essential differences between the optimal operation ranges of the two approaches was also introduced (Agrawal et al, 2016). According to this paper the optical backscattering based devices are more suitable in the fine particle dominated environments, and acoustic devices seem more effective dealing with coarser particles. As a logical consequence, it was assumed that the combined utilization of these instruments may lead to more accurate results in such a natural environment as the Hungarian part of the Danube, where the sediment conditions of this part of the river is dominated by fine particles but also containing solids with larger diameter, not to mention the organic flocs and small organisms. According to the field tests performed in this study, the difficulties to obtain reliable data during the case studies and the problems arose during the calibrating processes, it seems unadvisable to stick to one method and expect reliable results when investigating such a diverse sediment structure. It must be noted that there are current intentions to develop a single device that combines the advantages of the optical and acoustical devices (Agrawal, 2016).

Later on I have introduced two case studies where in order to assess the capabilities of the different instruments we used both acoustic and optical methods. At these studies we have found that both approaches can be suitable to carry out fixed boat point, and profile measurements, and they are also capable to reconstruct instantaneous SSC fields with reasonably high spatial resolution. For investigating the spatial suspended sediment patterns the ADCP seems to be the more adequate solution. However, it requires a very thorough calibration that is quite a complex task. For this calibration and also for the same process for the different instruments we had to obtain reliable concurrent dataset, preferably from direct samplings as introduced in this research. To gain this data we took undisturbed water samples then analysed them with the LISST-Portable device.

The analysis of a very high number of water samples using the LISST-Portable device, the first ones of this kind for the Danube River in Central Europe, provided crucial experiences with this device. During the measurement campaigns it became clear that the appropriate operation of this tool requires a lot of attention. At the same time, after the thorough testing it can be stated that the use of the LISST-Portable becomes straightforward and the tool can become a fundamental part of the sediment monitoring projects. The results provided by the laser based instrument can be used for calibrating other devices. During the measurements the operator must take into account the phenomena of flocculation of the sediment though, as it affects the results significantly and it is important to be fully aware of the properties of the analysed sediment also.

This study also dealt with the ABS and OBS devices, what proved to be very useful in creating SSC profiles or SSC mappings. The disadvantage of these instruments is that they need suitable calibration before every measurement campaign, as they are very sensitive to the PSD of the sediment thus this calibration can be unusable if the circumstances change significantly during a campaign. The advantages are the cost-efficiency of these methods and the relatively easy operation.

The application for SSC detection of the well-known ADCP was also introduced in this study, which was proved to be suitable to carry out SSC mapping with high spatial and temporal resolution. This character of the measurements can be very important in dynamically varying sediment conditions, such as the case at river dredging and releasing of the dredged material. It has to be noted that the calibration of the method is essential here as well (like at the above mentioned methods) which requires concurrent data collection. The obtained results, however, are very encouraging and it is rewarding to make the necessary efforts to make the ADCP suitable for these tasks also.

The last tested instrument was the LISST100X laser based tool. This device was originally designed to observe marine environments thus it was not proved to be very useable under such dynamically changing circumstances like a dredging project in a river. For more stable conditions this tool can be very useful also.

The application of many of the tested methods only recently have been possible in Hungary, which means that before including these techniques in the operative water management activities, thorough tests ought to be carried out in the closer future. The first steps on this way, introduced here, were very beneficial but certainly, more have to be done in order to reveal all the pros and cons of these complex measuring methods, and to set up a proper methodology for measuring such diverse and always changing environment in a proper way.

At the end of this paper I would like to thank to everyone who made it possible for me to work on such an innovative topic. First and foremost I would like thank to my two consultants Dr. Sándor Baranya associate professor of the Budapest University of Technology and Economics and to Gergely Tihamér Török research fellow for their guidance and all-embracing help. Also would like to thank to the staff of the NTNU, especially to Slaven Conevski who let me use his study about the ABS results obtained during the common case study at Göd. I would like to thank to the technical staff of the BME who helped us to carry out all the measurements. The Norway Grants project called EEA Hydro-Course is also acknowledged as a part of this study was supported by this program.

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