

QUANTIFICATION OF SEDIMENT CONCENTRATIONS AND FLUXES FROM ADCP MEASUREMENTS

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ABSTRACT

There are numerous reasons to measure sediment concentrations in the water column. It can be because a harbor is located at a tidal river, where sediment transport and deposition are major factors for maintenance of channels and harbors. Or it can be the local authorities that demand a strict control of the environment during dredge operations. The first reason requires constant monitoring of the suspended sediment concentration (*SSC*), at least over tidal periods. For the latter one you must be able to intervene in case of unacceptable disturbances to the surrounding environment occur. For this reason the monitoring results must be available in real time.

In general, both optical and acoustic devices are used for measurements of *SSC*. Optical devices are successfully used for measurements of fine-grained sediments. However, optical measurements have to be regarded as point measurements, which restrict either the temporal or spatial resolution of the *SSC* measurement. Moreover, the intrusive character of optical devices disturb the local flow field and thereby the results of the measurement. Acoustic devices are capable of measuring *SSC* from a distance, at a high temporal and spatial resolution. Several applications of a combined use of optical and acoustic techniques have been described in literature. Starting from the complementary characteristics of optical and acoustic devices we developed a software tool to complete a monitoring system for real time quantification of *SSC* together with fluxes. The software (VISEA-PDT[®]) is based on simultaneous measurements with an Acoustic Doppler Current Profiler (ADCP) and an optical backscatter (OBS) sensor. Additional sensors (e.g. DGPS, RTK, LRK, STD, CTD, LISST, etc.) can be hooked on for supplementary information. It uses OBS and additional other input for real time conversion of ADCP data to *SSC*. This paper presents a case study in which the sediment behavior in the river Weser is monitored during a tidal period.

Keywords: Acoustic Doppler current profiler, suspended solids concentration

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INTRODUCTION

Sediment transport in tidal rivers is a critical component to many coastal and waterway engineering problems: Examples include sedimentation in navigation channels, sand transport in the littoral zone and sediment resuspension during dredging operations or due to natural processes. Effective and powerful sediment management tools are of fundamental importance for harbor and water authorities to reduce the costs for maintenance dredging and waterway building activities. This is underlined by the fact that the further extension of many navigation channels is planned in Europe and worldwide to meet the requirements of new container ship generations. Reliable in situ data of sedimentation rates and suspended sediment concentrations (SSCs) are a precondition to understand the mechanisms that control sediment transport. Regarding the measurement of SSC, both optical and acoustic devices have their pros and cons. In general, optical devices are successfully used for measurements of fine-grained sediments. They feature a nearly linear response to sediment concentrations spanning more than three orders of magnitude, which is advantageous in natural systems where concentrations can vary widely. However, optical measurements have to be regarded as point a measurement, which restricts either the temporal or spatial resolution of the SSC measurement. Moreover, the intrusive character of optical devices disturb the local flow field and thereby the results of the measurement. Acoustic devices are capable of measuring SSC from a distance, at a high temporal and spatial resolution. Disadvantage of using acoustic devices is the dependence on sediment properties such as particle size distribution. The backscattered intensity from a homogeneous sediment suspension ensonified by an acoustic device is proportional to the product $SSC \cdot f^2/a$, where “f” is the particle form factor and “a” is the particle radius (Lynch et al. 1994). For particles that are small compared to the acoustic wavelength, the Rayleigh scattering law applies. Here $ka \ll 1$ (where k is the acoustic wave number) and f^2/a reduces to a^3 (Rayleigh 1945). For increasing particle size in the regime where ka is close to unity or larger, the sensitivity of the backscattered intensity to particle size decreases. Hence, the acoustic response generally grows more rapidly with size for smaller particles. Starting from the complementary characteristics of optical and acoustic devices we developed a software tool to complete a sediment monitoring system for real-time quantification of SSC. The software, VISEA-PDT[®] (PDT stands for ‘Plume Detection Toolbox’), is based on simultaneous ADCP and OBS measurements. Additional sensors can be hooked for additional information (e.g. GPS, STD, CTD, LISST, etc.). VISEA-PDT[®] uses OBS and possible other input for real-time conversion of ADCP data to SSC. During post processing lab results of local samples (SSC and grain size distribution) can be used to validate the real-time calibration. On the basis of a case study in the river Weser the sediment monitoring system is demonstrated here.

ACOUSTIC FORMULATION

ADCP backscatter of sound from suspended sediment can be modeled with the sonar equation (Medwin and Clay 1998). It appoints a balance of the difference between emitted and received energy and the energy lost during the round trip of the acoustic pulse. Absolute calibration requires a complete characterization of the transmit and receive circuit of the instrument. This includes the parameters acoustic transmit power, transmit pulse length, transducer efficiency, acoustic receive sensitivity and temperature sensitivity. To quantify the relationship between these variables affecting the backscatter, a working version of the sonar equation in units of decibel was formulated (Deines 1999):

$$S_v = C + 10 \log_{10} \left[\frac{T_T R^2}{L P_T} \right] + 2\alpha R + K_c (E - E_r) \quad (1)$$

Herein, S_v is acoustic backscatter [dB], C is a constant [dB], T_T is the temperature of the ADCP transducer [$^{\circ}$ C], R is the (slant) range along the beam to the scatterers [m], L is the transmit pulse length [m], P_T is the transmit power [W], α is the attenuation coefficient [dB/m], K_c is a scale factor [dB/count], E is the relative backscatter equal to echo intensity [count] and E_r is the received noise [count]. The values of C , T_T , R , L and P_T are recorded by the ADCP or provided by the factory. E is derived from the Received Signal Strength Indicator (RSSI) of the receivers. Its real-time reference level is denoted E_r , the noise value when there is no signal present. It may be obtained from the RSSI at the end of a profile. A typical value of E_r is 40 counts. The RSSI output is measured in counts that are proportional to the logarithm of power and can be converted to dB units by the scale factor K_c . This factor has values ranging from 0.35 to 0.55 and is typically 0.45 dB/count. The attenuation coefficient α is the sum of water absorption (α_w) and particle attenuation (α_s). Francois and Garrison (1982a, b) summarized the empirical research

on water absorption. The water absorption is the sum of relaxation due to a boric acid component, a magnesium sulphate component and a viscosity component:

$$\alpha_w = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \quad (2)$$

with for the boric acid component:

$$A_1 = \frac{8.68}{c} 10^{0.78pH-5}$$

$$P_1 = 1$$

$$f_1 = 2.8\sqrt{S/35} \cdot 10^{4-1245/(273+T)}$$

for the magnesium sulphate component:

$$A_2 = 21.44 \frac{S}{c} (1 + 0.025T)$$

$$P_2 = 1 - 1.37 \cdot 10^{-4} z + 6.2 \cdot 10^{-9} z^2$$

$$f_2 = \frac{8.17 \cdot 10^{[8-1990/(273+T)]}}{1 + 0.0018(S-35)}$$

and for the viscosity component:

$$A_3 = 4.937 \cdot 10^{-4} - 2.59 \cdot 10^{-5} T + 9.11 \cdot 10^{-7} T^2 - 1.5 \cdot 10^{-8} T^3 \quad \text{if } T \leq 20 \text{ }^\circ\text{C}$$

$$A_3 = 3.964 \cdot 10^{-4} - 1.146 \cdot 10^{-5} T + 1.45 \cdot 10^{-7} T^2 - 6.5 \cdot 10^{-8} T^3 \quad \text{if } T > 20 \text{ }^\circ\text{C}$$

$$P_3 = 1 - 3.83 \cdot 10^{-5} z + 4.9 \cdot 10^{-10} z^2$$

Herein, pH denotes the acid degree [-], S is salinity [psu], z is vertical depth [m] and c is speed of sound [m/s] given by (Urick 1983):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (0.0134T)(S - 35) + 0.016z \quad (3)$$

Particle attenuation is the spreading and absorption of acoustic energy by particles in the water. Urick demonstrated that the attenuation by suspended sediment is given by (Urick 1948):

$$\alpha_s = \left[\frac{k^4 d^3}{96 \rho_s} + \frac{k(\sigma - 1)^2}{2 \rho_s} + \frac{s}{s^2 + (\sigma + \delta)^2} \right] \frac{20}{\ln(10)} SSC \quad (4)$$

where:

$$s = \frac{9}{2\beta d} \left[1 + \frac{2}{\beta d} \right]$$

$$\sigma = \frac{\rho_s}{\rho_w}$$

$$\delta = \frac{1}{2} \left[1 + \frac{9}{\beta d} \right]$$

$$\beta = \sqrt{\frac{\pi f}{\nu}}$$

$$\nu = \frac{40 \cdot 10^{-6}}{20 + T}$$

Herein, F is the acoustic frequency [Hz], ρ_s is the sediment density [kg/m], ρ_w is the water density [kg/m], d is the particle diameter [m] and ν is the kinematic viscosity of water [m²/s] according to van Rijn (1993). ρ_w is calculated based on salinity, temperature and depth according the well-known international equation of state of sea water (UNESCO 1981). All described parameters can be imported into VISEA-PDT[®], either as a profile or fixed value. Fixed values can be used when no profile of CTD data is available. In this case temperature, salinity and speed of sound are calculated from the ADCP data. When CTD data are available these profile data can be used for more accurate range normalization. VISEA-PDT[®] is able to process data from any external device. The result of the range and instrument normalization is S_v that is converted to SSC by means of reference measurements of SSC. Figures 1 to 6 exhibit the processing steps from relative backscatter to SSC.

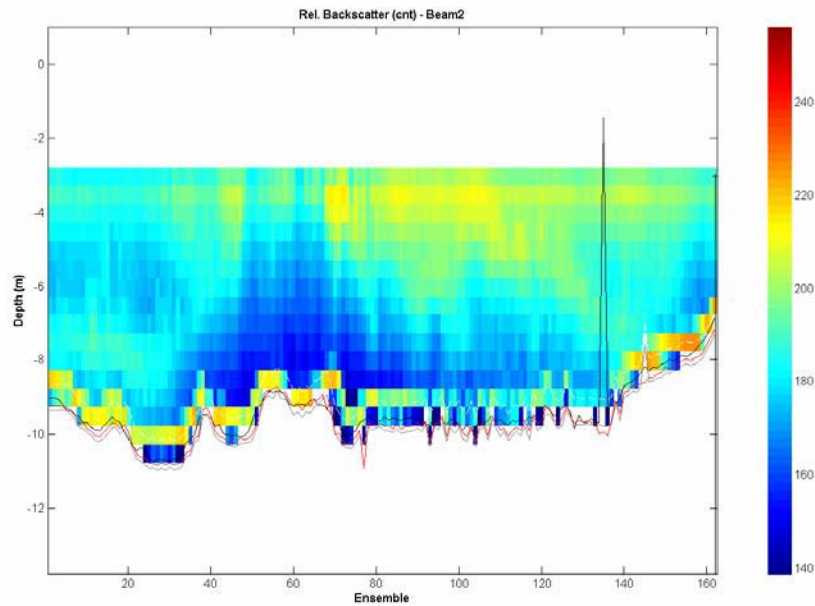


Figure 1. Measured relative backscatter expressed in counts, equal to E in equation (1). Although E reflects SSC in a certain way it cannot be straightforwardly transformed towards SSC.

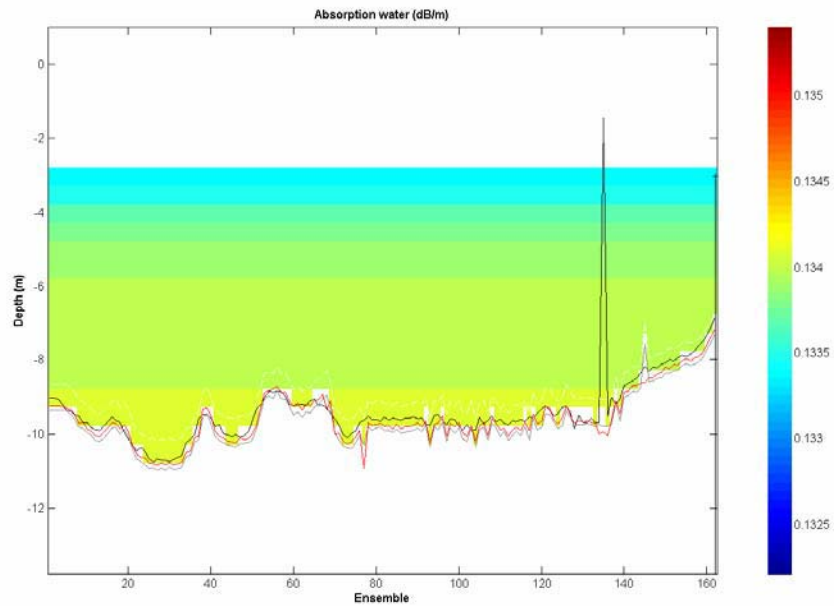


Figure 2. Water absorption, equal to α_w in equation (2). Used for compensating acoustic energy losses due to molecular transfer of acoustic energy to heat.

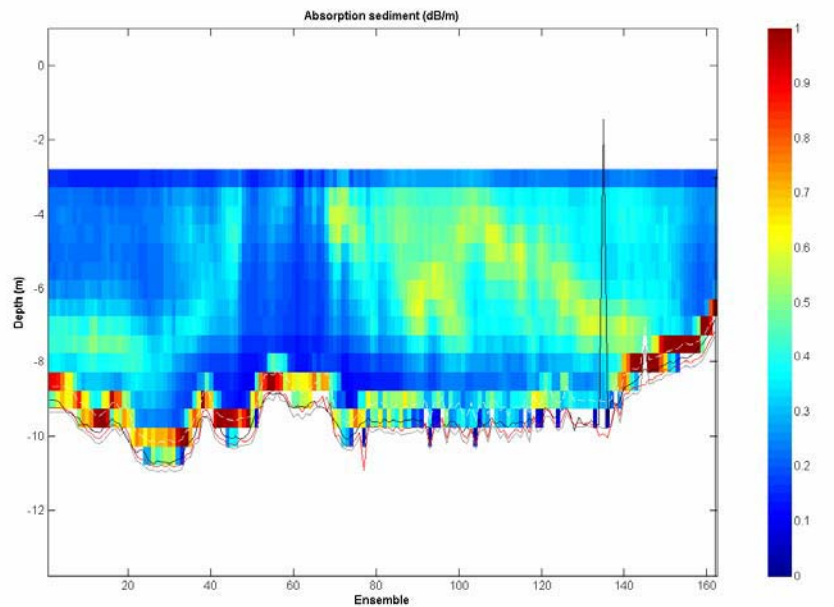


Figure 3. Particle attenuation, equal to α_s in equation (4). This value is used for compensating acoustic energy losses due to the spreading and absorption of acoustic energy by particles in the water.

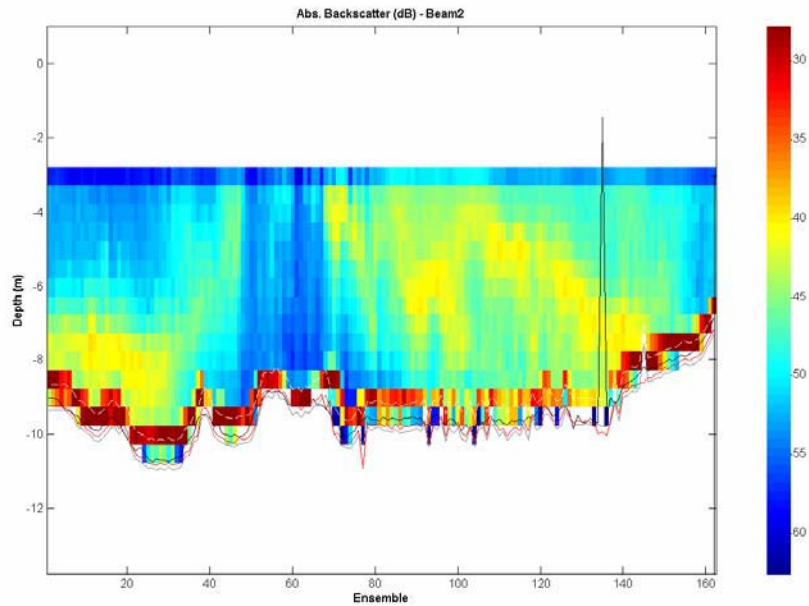


Figure 4. Range and instrument normalized absolute backscatter in dB, equal to S_v in equation (1), derived from signal processing according to the described theory.

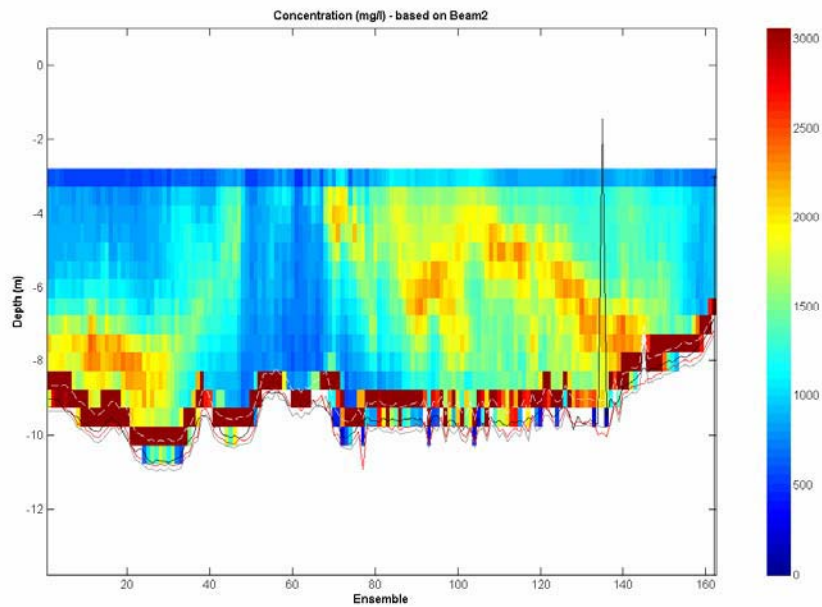


Figure 5. Resulting SSC as converted from S_v in real-time by means of OBS data. Note the difference with the uncorrected relative backscatter in Figure 1.

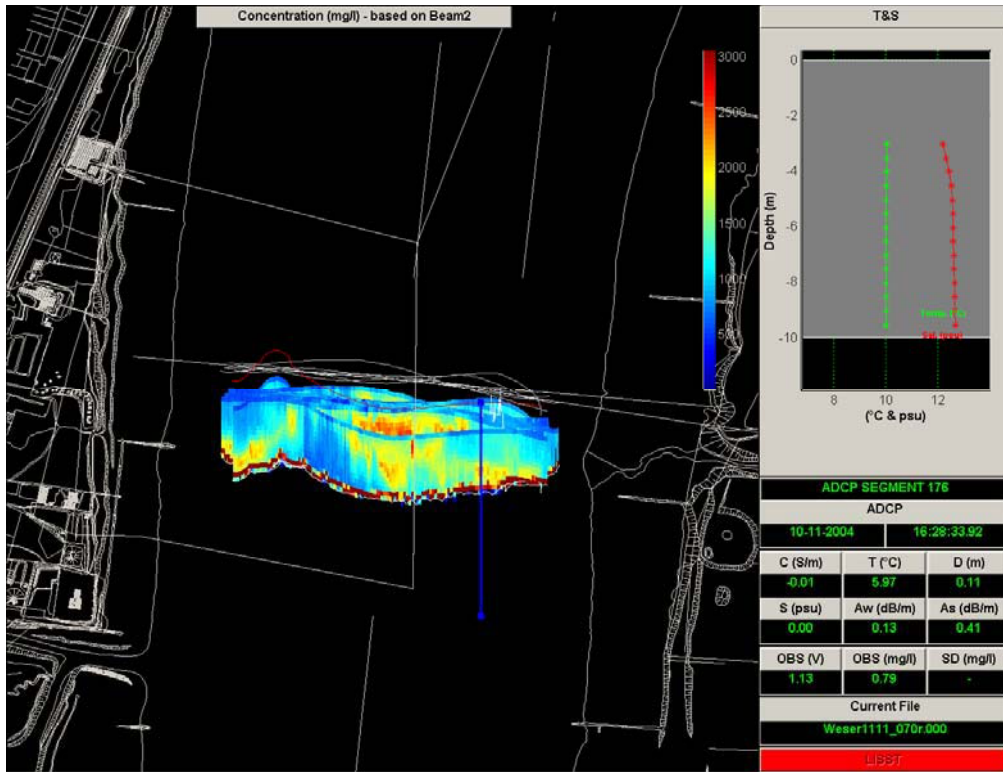


Figure 6. Three-dimensional SSC values in the main window of VISEA-PDT®. The profile plot in the upper right hand corner shows data of T and S. Numerical information of relevant parameters are presented in the lower right corner.

WESER MEASUREMENTS

On 10 November 2004, a 13-hour SSC measurement campaign has been performed in the tidal river Weser near Nordenham. Figure 7 shows an overview of the measurement location in the river Weser near Nordenham. The test was organized by the coastal department of the German 'Bundesanstalt für Wasserbau' (BAW). VISEA-PDT[®] was used for the real-time quantification of sediment concentrations and fluxes. Over a period of 13 hours, SSCs were monitored by moving boat measurements with survey vessel 'TIDE' of the 'Wasser- und Schifffahrtsamt Bremerhaven'. The vessel was equipped with a 600 kHz ADCP of RD Instruments and a pre-calibrated multi-parameter probe for measurement of optical backscatter, conductivity, temperature en depth. Moreover a Laser In-Situ Scattering and Transmissionmetry (LISST) instrument and an automated water-sampling pump were used. A total of 89 water samples were taken and analyzed afterwards in a lab to determine the SSC values and particle size distribution.

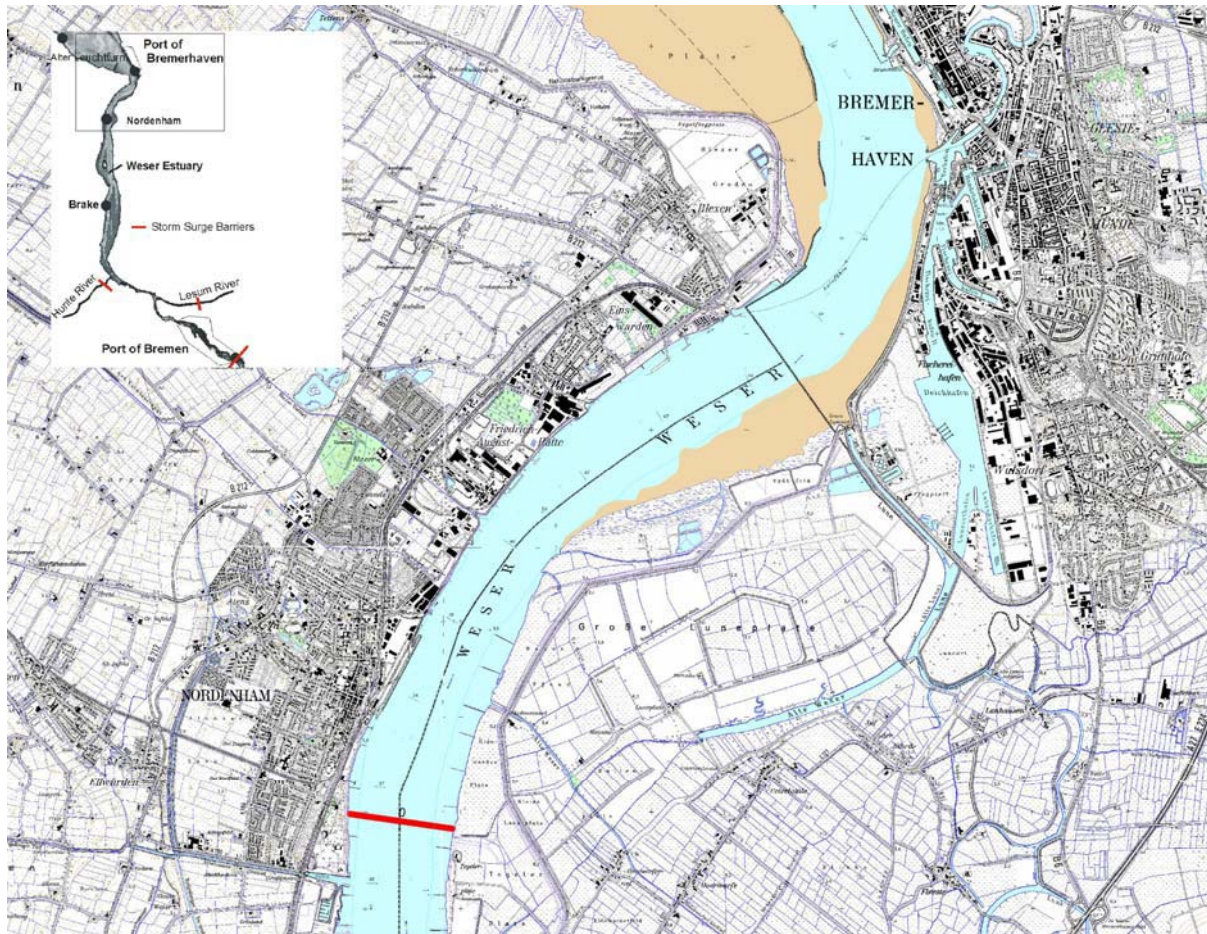


Figure 7. Overview of Weser estuary with measurement location near Nordenham.

CALIBRATION

The ADCP backscatter is processed and converted to SSC by means of CTD data and reference measurements of SSC. OBS data were used for the real-time calibration of the ADCP backscatter. During post-processing this real-time calibration is optimized by means of the lab results of SSC and particle size distribution analysis of the water samples. The lab results are the ground truth and used for the final calibration here. However, backscatter and therefore SSC is dependent on particle attenuation and particle attenuation is dependent on SSC. For this reason the SSC values have to be optimized using an iterative calculation procedure. VISEA-PDT[®] starts from the absolute backscatter in the first ADCP bin and calculates SSC using a standard calibration relation. For calculation of absolute backscatter in the first ADCP bin, the particle attenuation is not taken into account. Acoustic loss is only based on acoustic spreading and water absorption. The resulting value for SSC is used for calculation of the particle attenuation. This particle attenuation is used to complete the range normalization and obtain a corrected absolute backscatter. This process is repeated until SSC is optimized. This SSC value for the first ADCP bin is used to calculate the sediment attenuation and SSC value in the second ADCP bin. This process is continued downwards for optimizing SSC values for the whole profile. The conversion process takes the influences on sound absorption by variable sediment concentrations in different layers into account. The calibration yields a relation between ADCP backscatter and SSC gained from calibrated OBS. Since the ADCP backscatter is dependent on sediment properties the LISST is used to measure grain size distributions. However, also other sediment properties (e.g. particle form) may influence the backscatter. Therefore a separate backscatter calibration is formulated based on the calibration measurements of 12 subprojects for each hour. The relation between the SSC results from the water samples and the ADCP backscatter (in dB) is presented for one of the subprojects in Figure 8.

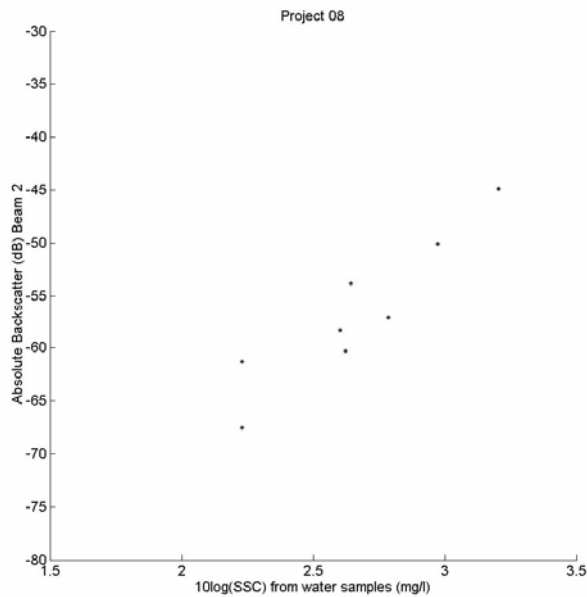


Figure 8. Relation between SSC and the ADCP backscatter for one of the subprojects.

The relation in Figure 8 can be formulated as:

$$10\log(SSC) = A \cdot Backscatter + B \quad (5)$$

Table 1 presents variables A and B, and the correlation coefficient r for each subproject.

Table 1. Correlation variables and statistics.

Project	Period	A	B	r
1	08:00h-09:00h	0.0291	4.1403	0.86
2	09:00h-10:00h	0.0361	4.4753	0.92
3	10:00h-11:00h	0.0241	3.9165	0.82
4	11:00h-12:00h	0.0232	3.6125	0.84
5	12:00h-13:00h	0.0226	3.2687	0.80
6	13:00h-14:00h	0.0281	3.6011	0.92
7	14:00h-15:00h	0.0361	4.3087	0.80
8	15:00h-16:00h	0.0442	5.1650	0.93
9	16:00h-17:00h	0.0340	4.7310	N/A
10	17:00h-18:00h	0.0271	4.3979	0.97
11	18:00h-19:00h	0.0271	4.0732	0.71
12	19:00h-20:00h	0.0220	3.9039	0.97

In general, it can be concluded that A and B vary in time and that relations show a relatively good correlation ($r \geq 0.8$). The correlation coefficient for project 11 is relatively low (0.71) and project 9 has too few points for a statistical analysis. In order to visualize the variation, A and B are presented in Figure 9 together with the measured water levels at the measuring site Nordenham. The figure shows the variation of A and B varies with the tidal phase. During the flood and ebb currents the values of A and B increase as a result of changing sediment properties at the measurement site. This observation justifies the separate calibration calculations for each of the subprojects.

The deviation of A in Eq. 5 with respect to the nominal value of 0.1 (which should be 1 in case the concentration would be expressed in dB instead of the $10\log$) reflects the behavior of mean particle diameter and different concentration values. In general the particle size and mass concentration are correlated, with higher mean particle diameters in high sediment load environment. Since the acoustic response of the ADCP grows proportional with $\langle a^3 \rangle$, there will be a more than linear growth of acoustic backscatter in response to higher concentration values, reflected in a coefficient A value less than 0.1. Because the coefficient A has been obtained by regression between the ADCP data and concentration values derived from water samples this dependency on variation in mean diameter with concentration is taken into account semi-automatically.

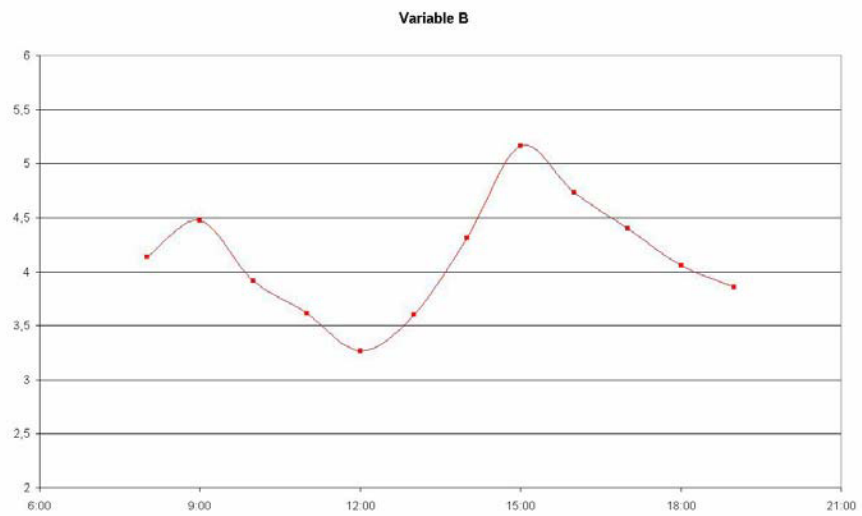
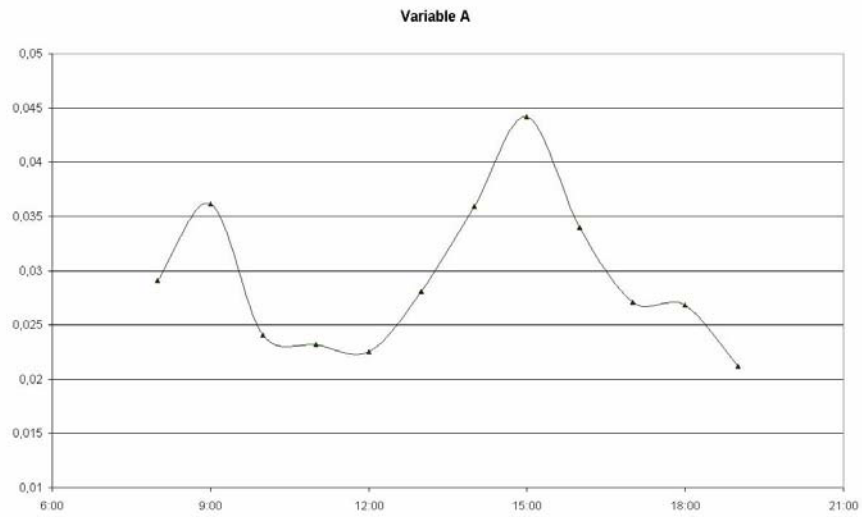
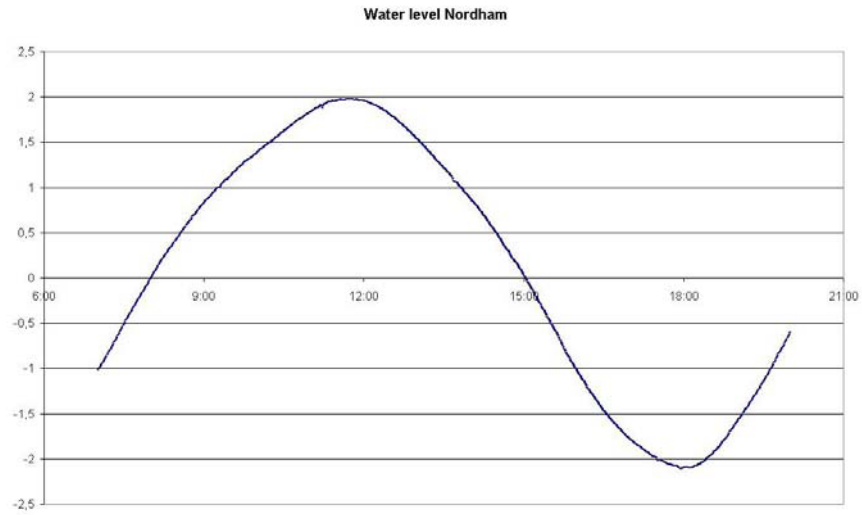


Figure 9. Variables A and B as a function of the tide.

SEDIMENT BEHAVIOR IN THE RIVER WESER

For all transect measurements, SSC is calculated from the backscatter data according the correlation variables of each subproject. Moreover, the concentrations are converted to sediment fluxes by combining the concentration values with the simultaneously measured discharge.

Concentrations

Sediment concentrations of more than 1200 mg/l occur during the maximum flood current. At the end of the flood period the concentrations decrease to below 300 mg/l in the upper part of the water column and 600 mg/l in the lower part of the water column. At the beginning of the ebb period the concentrations decrease to about 50 mg/l near the water surface and 150 mg/l near the riverbed.

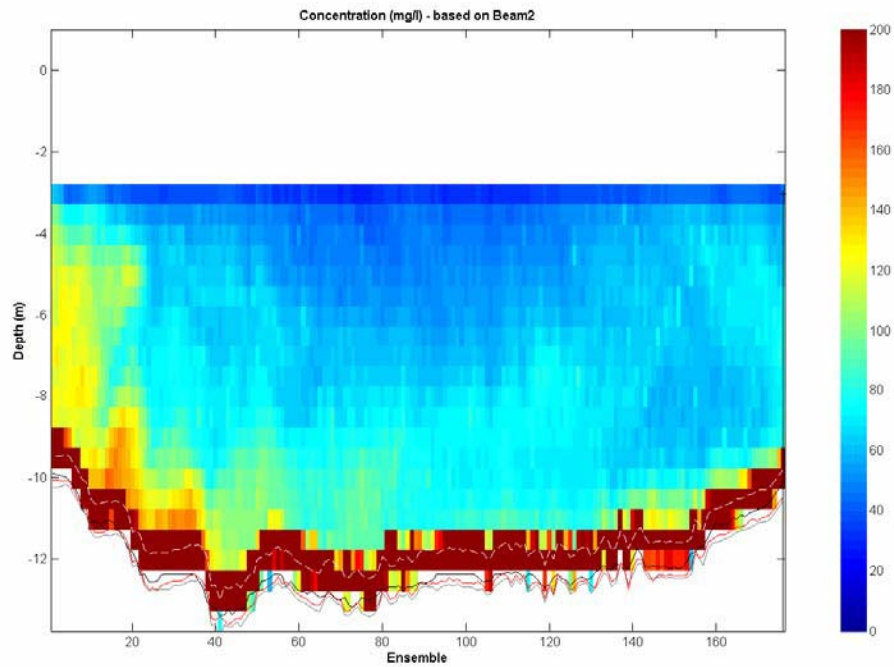


Figure 10. Concentrations at the first part of the ebb period.

This situation remains relatively stable for the first half of the ebb period. Then the sediment concentrations increase at both sides of the river to approximately 500 mg/l. Within one hour the concentrations increase to more than 2000 mg/l near the riverbed. During the remaining part of the ebb period the high concentrations spread from the near-bed zone through almost the entire water column. The results consistently show that the concentrations in the middle of the river are lower than at the sides.

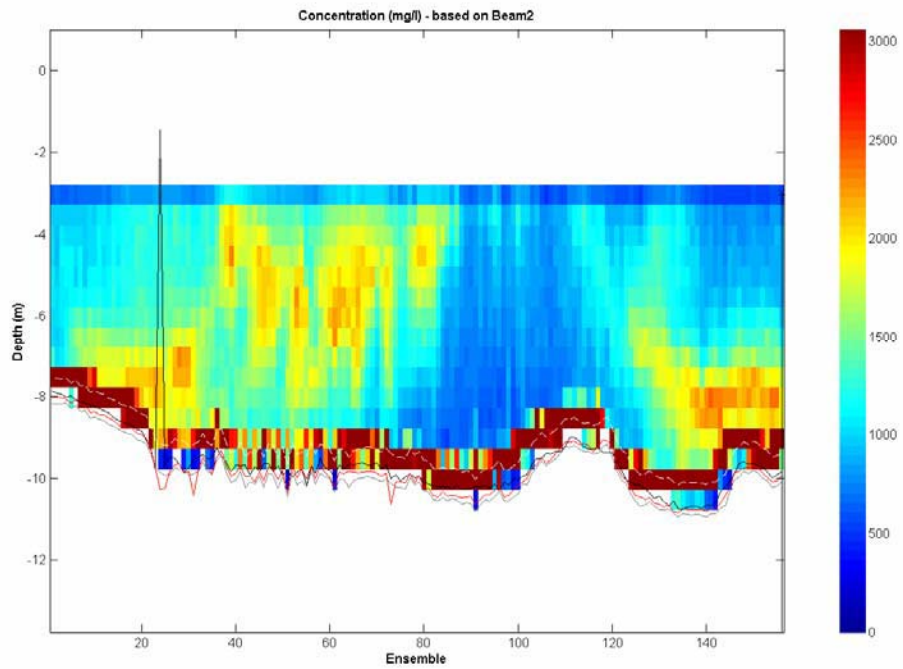


Figure 11. Concentrations at the second part of the ebb period.

This may be the result of the sediment being supplied from the riverbanks. At the end of the ebb period sediment concentrations higher than 2000 mg/l occur in the greater part of the water column. Within a relatively short period of half an hour the concentrations decrease to below 1000 mg/l at the beginning of the flood period.

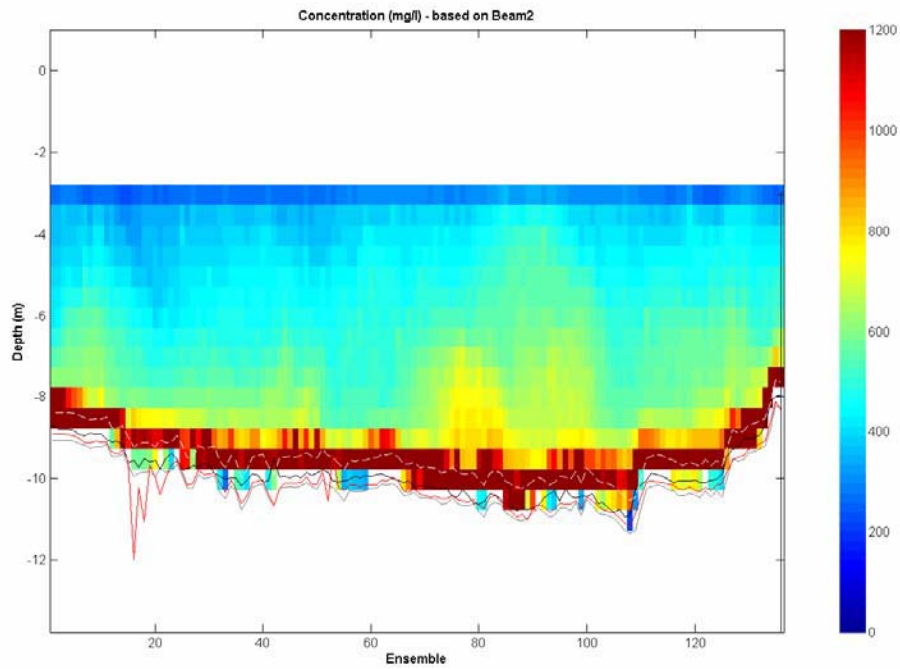


Figure 12. Concentrations at the first part of the flood period.

Fluxes

During the maximum flood current sediment fluxes up to $2000 \text{ g/m}^2/\text{s}$ occur. Towards the end of the flood period the fluxes decrease to lower than $500 \text{ g/m}^2/\text{s}$. After high tide the fluxes remain relatively low ($<500 \text{ g/m}^2/\text{s}$) until halfway the ebb period. As a result of increasing velocities and concentrations fluxes increase up to $4000 \text{ g/m}^2/\text{s}$ occur in a small part at the east side of the river. During the remaining part of the ebb period the high fluxes expand over a greater part of the water column. At the end of the ebb period the fluxes decrease to $500 \text{ g/m}^2/\text{s}$ at low tide. In the first part of the flood period, fluxes of $1500 \text{ g/m}^2/\text{s}$ occur.

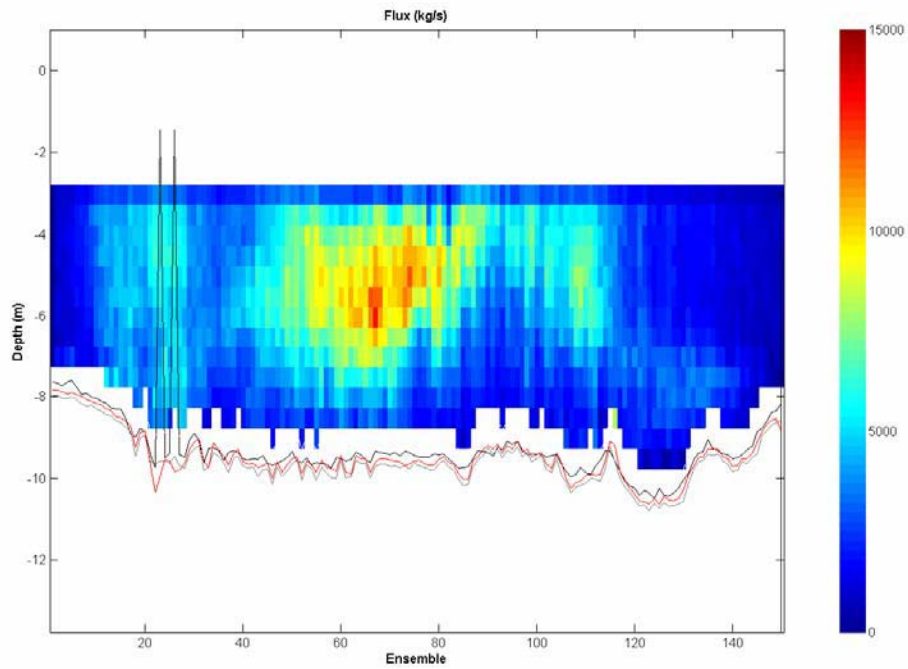


Figure 13. Sediment fluxes at the second part of the ebb period.

DISCUSSION

Although designed for current measurements, ADCPs can accordingly be used for obtaining information on the suspended sediment concentration. The used methods for converting ADCP backscatter to sediment concentrations can only be applied in the Rayleigh regime. The use of a 600 kHz ADCP system limits the Rayleigh regime to grain sizes of 0-800 μm . Figure 14 presents typical grain size distributions of the suspended sediments in the Weser as measured with the LISST system. The grain size distributions show that the monitored sediment in the Weser meets the Rayleigh regime and that the used conversion method is valid.

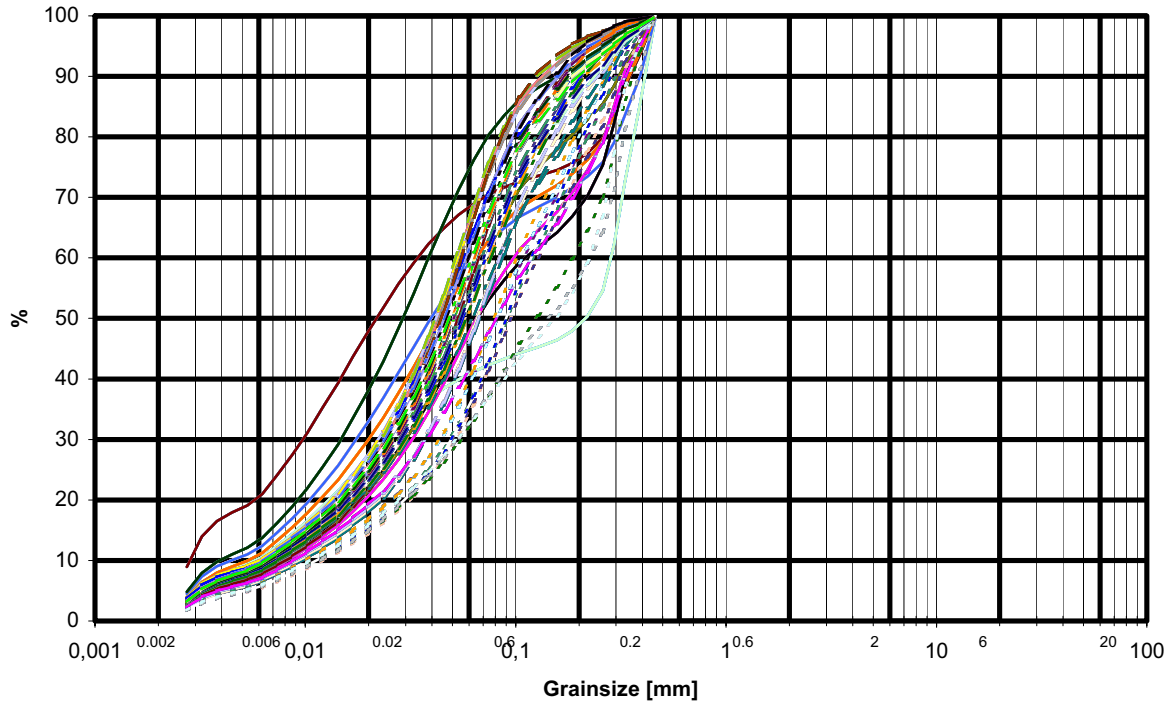


Figure 14. Typical grain size distributions of Weser sediments.

Compared to optical devices, ADCPs have the advantage of yielding SSCs over the depth range that is ensonified, at a high temporal and spatial resolution. ADCPs are non-intrusive as the sediment suspension is being monitored at distance. The disadvantage of the acoustic approach is the dependence on sediment properties. In particular, irregularities of the grain size distribution restrict the accuracy of acoustic sediment measurements. For this reason grain size distributions were measured by the LISST system and used for post-processing the data. Applying the LISST data result in more accurate processing. In comparison with the default grain size distribution the sediment attenuation is lower as a result of the LISST grain size distribution. However, because the sediment absorption is a part of the total absorption, the results are not changed significantly by taking the LISST data into account. The resulting concentrations are slightly lower in comparison with the results based on the default grain size distribution. The correlation between the ADCP backscatter and the water sample results varies with time. From this can be concluded that changing sediment properties are of relevant interest and should be taken into account if possible. However, the used method uses high resolution (both temporal and spatial) calibration data as input and meets the latest standards in the field of SSC monitoring. This study showed, despite the LISST input, a variable relation between the acoustic backscatter and the water samples. Most likely changing sediment shapes cause these variations. Unfortunately, there is not a simple instrument that can measure the sediment shape in real-time. Regarding the results of the Weser measurements the used method has been proven to be a fast and reliable method for SSC monitoring. During the measurement all used sensors showed their value. All the relations between the resulting backscatter and water samples showed a good correlation.

CONCLUSIONS

Because of its high temporal and spatial resolution, an ADCP is a very usable tool for measurements of sediment concentrations and fluxes. The additional input of grain size distributions from the LISST instrument did not change the results significantly. Variable sediment shapes probably cause the variable relation between ADCP backscatter and water sample results. The separate relations between backscatter and water samples have a good correlation.

ACKNOWLEDGEMENTS

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