Inferring Suspended Sediment Carbon Content and Particle Size at High Frequency From the Optical Response of a Submerged Spectrometer

Dhruv Sehgal1,2,*, Núria Martínez-Carreras1 ♦, Christophe Hissler1 ♦, Victor F. Bense2 ♦, and A. J. F. (Ton) Hoitink2 ♦

1Catchment and Eco-Hydrology Research Group, Environmental Research and Innovation Department, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg, 2Hydrology and Quantitative Water Management Group, Wageningen University and Research, Wageningen, The Netherlands

Abstract Real time monitoring of suspended sediment (SS) carbon content and particle size information is essential to understand SS transport mechanisms and processes. However, limited in situ methods are available, and manual and unattended sampling makes high frequency observation challenging. Based on evidence that optical measurements of SS concentration are dependent on particle size and composition, we hypothesize that SS carbon content and mean particle size \( \bar{D} \) can simultaneously be inferred from the absorbance data measured with a submerged spectrometer at high frequency. With the aim to predict both parameters, we investigate if global calibrations can be obtained and used instead of site-dependent local calibrations. To test this, we created a laboratory data set using a tank setup, and an in situ field data set. Sediment samples varying in composition were collected and used in a tank setup to obtain global (all sites grouped together) calibrations between absorbance, particle size and carbon content. Two sites were instrumented to collect in situ field data, to generate local (site-specific) calibrations and to validate the global calibrations obtained in the laboratory. A procedure to account for the effect of SS concentration when using the global calibration to predict \( \bar{D} \) is also presented. Our findings indicate that global calibrations can accurately predict \( \bar{D} \) from in situ absorbance readings, with a median absolute error of 17.3 \( \mu \)m, versus 10.5 \( \mu \)m for a local calibration. Local calibrations are indispensable to reliably predict carbon content, with a median absolute error of 1.3%.

Plain Language Summary Transport of suspended sediments (SSs) within a river is a temporally dynamic process that can best be monitored with in situ sensors. Turbidity meters are optical sensors that measure the amount of light scattered by the SS in water and are normally used to estimate SS concentrations. However, they are known to be sensitive to SS properties, such as carbon content and particle size, requiring local calibrations at each new measurement site. This study uses a submerged spectrometer, an optical sensor, measuring absorbance in the UV-Visible range to quantify SS carbon content and mean particle size in situ and at high frequency, in a quest to obtain global instead of site-specific local calibrations. To test the proposed method, we performed laboratory experiments with sediment samples from six sites and used the in situ data measured at two instrumented sites. We conclude that a global calibration is obtained to predict mean particle size from absorbance, whereas local calibrations are still needed to predict SS carbon content. This knowledge on SS carbon content, a major organic SS component, and particle size is needed to improve SS transport modeling and eventually better understand SS transport mechanisms.

1. Introduction

Riverine suspended sediments (SSs) are a complex composite of mineral particles (clay, silt, and fine sand), living organisms, natural organic matter (humic substances, extracellular polymers) and contaminants (Droppo, 2001; Paterson, 2001; Tao et al., 2018; Walling & Moorehead, 1989). The physical, chemical and biological interaction among SS components changes the structure (dis-/aggregation) and properties of SS such as particle size, density and composition (Maggi & Tang, 2015), and might result in flocculation (Spearman et al., 2011). These interactions are also influenced by meteorological, hydrological, ecological and anthropogenic pressures (Aleixo et al., 2020; Ankers et al., 2003). Recent studies showed that information on SS size and composition, also considered as primary floc characteristics, is important in physics-based modeling studies (e.g., Grangeon et al., 2012; Lepesqueur et al., 2019; Manning et al., 2011). Both particle size (Williams et al., 2008) and organic...
matter content (Lee et al., 2019) influence SS settling velocities (Manning & Schoellhamer, 2013) and eventually SS transport (Manning et al., 2010). High-frequency information on SS properties may thus allow to improve the accuracy of SS transport models and increase our understanding on SS transport mechanisms.

Traditionally, SS carbon content, a major organic SS component, and particle size are measured in the laboratory after manual or automatic water sampling in the field. These sampling techniques are time-consuming, which make high frequency measurements impractical (Druine et al., 2018). Limited accessibility to stream sampling locations during turbulent conditions or high flows, when the largest amount of sediment is transported downstream, also introduces measurement uncertainty (Aleixo et al., 2020). Furthermore, transformation or breaking of SS flocs might occur during refrigeration and transportation to the laboratory for ex situ analysis (Galuszka et al., 2015). To avoid some of these problems, remote sensing data have been used to map SS properties and SS fluxes in surface water (Maciel et al., 2019). However, remote sensing techniques mostly inform to a depth of a few optical attenuation lengths into the water column, what can be a limitation when trying to understand SS transport mechanisms that may depend on SS composition and particle size distribution throughout the water column (Pavelsky & Smith, 2009). Here, in situ data allow to capture SS-related processes at the micro-scale that ex situ measurements may not reliably represent (Druine et al., 2018).

Methods to measure SS carbon content in situ and at high frequency are not well established. Contrarily, particle size distributions can be retrieved in situ and at high frequency based on laser-diffraction using particle size analysers such as the LISST 100X and 200X (Agrawal et al., 2008; Agrawal & Pottsmith, 2000), video-based systems including the INSSCF-LF (Fennessey et al., 1994; Milly et al., 2008), floc cameras such as DFC (Mikkelsen et al., 2005) and particle imaging camera systems (Smith & Friedrichs, 2011). These techniques have their own advantages and limitations. For instance, imaging methods generally combine the use of an underwater camera and a settling column to capture images. Dyer et al. (1996) mentioned that this may cause floc breakup during sample capture or as a result of fluid motions inside the settling column. The commonly used LISST-100X assumes particles to be spherical in shape as it is based on Mie Theory (Manning & Schoellhamer, 2013), whereas non-spherical shaped particles/flocs are prevalent in nature (Fettweis & Lee, 2017). This problem is partially addressed by LISST-200X sensors, which provide the possibility to use a random shape model. Agrawal et al. (2008) reported some differences between the response of spherical and random shape models. Limitations on the use of the random shape model still remain unreported in the literature.

Contrarily to scattering characteristics, which experience limited influence of particle composition (Agrawal & Pottsmith, 2000), absorption strongly responds to the composition of particles in suspension (Kirk, 1994; Mobley et al., 2007). The basic principles of light optics explain particle absorption theory. When light interacts with suspended matter and the medium itself, two types of processes can take place. Light can vanish when its energy is transferred to another form, such as heat or the energy contained in a chemical bond (chemical reactions). This is known as absorption. Optical waves can also change direction and/or their spectral properties. Both of these processes are governed by scattering. The inherent optical properties of a water body determine its absorption and scattering capabilities (Mobley et al., 2007). Composition, morphology, and concentration are some of the parameters that influence these inherent optical properties (Kirk, 1994). Mie theory is often used to model the fundamental physics of light scattering, yet it applies only to non-absorbing and homogeneous spherical particles. In natural conditions, this prerequisite is generally not met, due to distinct organic and mineral sediment compositions.

Different materials absorb light differently at different wavelengths. Understanding how inherent optical properties vary for prevalent constituents in open water is a fundamental problem of underwater optics (Mobley et al., 2007). Equation 1 denotes absorption at a wavelength $a(\lambda)$, as a sum of the absorption of the different constituents in suspension denoted by $a_i(\lambda)$.

$$a(\lambda) = \sum_{i=1}^{N} a_i(\lambda) \tag{1}$$

It is practically impossible to measure absorption properties of each individual absorbing component. Hence, individual components are normally grouped on the basis of similar optical properties and/or analytically based categories, such as phytoplanktons (ph; proxy chlorophyll), non-algal particles (NAP: humic substance, minerals
and bacteria), colored dissolved organic matter (CDOM: proteins, extracellular macro-molecules, etc. interacting with light) and pure water (w; Kirk, 1994; Thomas & Burgess, 2017; Werdell et al., 2018):

\[
a(\lambda) = \sum_{i=1}^{N_{ph}} a_{ph,i}(\lambda) + \sum_{i=1}^{N_{NAP}} a_{NAP,i}(\lambda) + \sum_{i=1}^{N_{CDOM}} a_{CDOM,i}(\lambda) + a_w(\lambda)
\]

where \(N_{ph}, N_{NAP},\) and \(N_{CDOM}\) indicate the number of individual constituents or sub-components of ph, NAP and CDOM, respectively. The magnitude and spectral features depend upon the concentration and composition of the particulate and dissolved constituents, and the medium (water) itself. This suggests that SS total carbon can be inferred from the absorption spectrum readings of a submerged spectrometer.

Submersible UV-Vis spectrometers, which measure the light absorption spectrum of water with dissolved and suspended material between 200 and 750 nm, at sampling intervals as short as 2 min, have recently been used to infer Particulate Organic Carbon (POC) as the difference between total organic carbon (TOC) and dissolved organic carbon (DOC; Bass et al., 2011; Jeong et al., 2012; Waterloo et al., 2006), SS loss-on-ignition (Martínez-Carreras et al., 2016) and to trace SS sources (Lake et al., 2021). Here, Jeong et al. (2012) mentioned the range of 240–280 nm may relate with TOC, Martínez-Carreras et al. (2016) related absorption at 710 and 730 nm to SS loss-on-ignition and Waterloo et al. (2006) used absorption at 255 and 350 nm for estimating DOC. Also in oceanography, in situ spectrometers are used to measure absorption and attenuation properties of absorbing components (Equation 2) at specific wavelengths in the UV-Vis range (Alin et al., 2015; Babin & Stramski, 2004; Berho et al., 2004; Boss et al., 2007; Bowers & Binding, 2006; Tao et al., 2018; Twardowski et al., 2004).

Recently, submersible spectrometers have also been used to assess water quality of streams and rivers by measuring turbidity, DOC, TOC and nitrates (Blaen et al., 2016; Ruhala & Zarnetske, 2017). Generally, it is recommended by manufacturers to make local calibrations before using a spectrometer at a new site. This is because site-specific factors, such as land use, geology, relief and riverine conditions governed by river discharge and sediment input reflect on SS composition, and particle size (Soler et al., 2012), thus influencing local calibrations. Here, we investigated the sensitivity of absorbance at different wavelengths (250–750 nm, with a 2.5 nm interval) to particle size and SS carbon content independently, with the aim of moving from site-specific ”global calibrations” toward ”local calibrations.” Global calibrations would thus allow the retention of near-constant calibrations across sites for predicting both parameters over a wide range of grain-size and carbon content conditions.

Our main working hypothesis is that high frequency and in situ absorbance data can be used to quantify SS carbon content and mean particle size \((\bar{D})\). The hypothesis is framed to address two overarching research questions: (a) How does absorbance, an inherent optical property, respond to SS carbon content and \(\bar{D}\)? (b) Can we use global calibrations instead of local calibrations to infer SS carbon content and \(\bar{D}\) from absorbance? We will address these research questions in four steps. First, we investigate the wavelength best suited to independently predict SS carbon content and \(\bar{D}\) from absorbance in a laboratory setup. Second, we use the laboratory data to obtain global calibrations. Then, we use in situ field data to obtain site-specific local calibrations and finally we compare predictions obtained using local calibrations with those obtained using laboratory-based global calibrations. A tailor-made experimental laboratory setup was designed and constructed. Sediment samples varying in composition were collected, sieved to different fractions and used in the laboratory setup. In situ field data were collected from two sites. The key novelty of this work is the first-ever field application of a submerged spectrometer to simultaneously quantify SS carbon content and \(\bar{D}\).

2. Material and Methods

2.1. Field Site

For the laboratory experiments, bed sediment samples were collected from six sampling sites (S1–S6; Figure 1) within the Alzette River basin (1,078 km²; Luxembourg). Based on previous investigations (Hissler et al., 2016; Martínez-Carreras et al., 2012), we expected sediment from these sites to have contrasting SS compositions. Existing sites of the upper Alzette River at Huncherange and the Attert River at Useldange were temporarily instrumented to perform in situ SS monitoring.
The Alzette River sub-catchment at Hesperange extends over the southern part of Luxembourg and includes parts of France with a total catchment area of 285 km². The catchment geology consists of Lias marls and limestone (Pfister et al., 2003, 2017). This area receives high amounts of industrial effluents, due to past steel production activities, and domestic effluents (Hissler et al., 2016). The Attert River, a tributary of the Alzette River, originates in Belgium and flows from west to east in Luxembourg. It has an area of 250 km². The Attert River at Useldange is representative of a rural basin highly influenced by agriculture. Trias marls and dolomites, Lias sandstone and Devonian shales and phyllites dominate the bedrock geology (Table 1). Precipitation is evenly distributed throughout the year but differs slightly from 895 mm along Attert River basin to 725 mm along the southern region of Luxembourg (Pfister et al., 2017). Therefore, the sampling sites represent different anthropogenic pressures, land use types (i.e., agricultural, industrial, and forested) and bedrock geology (Table 1).

2.2. Field Sampling and Monitoring

For the laboratory experiments, sediment samples were collected manually from the upper layer of the bed at six sampling locations during low flow (Figure 1). They were stored below 5°C before wet sieving into three size classes: <32 μm, 32–63 μm and 63–100 μm. Samples were left to settle for a day and excess water was removed with a pipette. Sieved samples were first oven dried at 60°C for at least 4 days and then gently crushed with a hand mortar to obtain a powder.

Automatic water samplers (Teledyne ISCO, Lincoln, USA) were installed in the upper Alzette River at Huncherange and in the Attert River at Useldange for unattended sampling during storm runoff events. Several consecutive events were sampled for the upper Alzette River during January-February 2020 (n = 69), while only one event was sampled for the Attert River in June 2020 (n = 13).

At the Attert sampling site, a V2 submersible UV-visible spectrometer (s::can GmbH, Vienna, Austria), a LISST-200X submersible laser-diffraction based particle size analyzer (Sequoia Scientific, Inc., Bellevue, USA) and a YSI EXO2 multi-parameter sensor measuring turbidity and conductivity (YSI Inc./Xylem Inc., Yellow springs, USA) were mounted horizontally onto a stepladder that was immersed near the riverbank. The sensors were always submerged, positioned parallel to the stream channel and placed around 20 cm above the streambed. This minimized sedimentation and adhesion of particles in the measuring cells. The spectrometer with an optical path length of 15 mm measured absorbance at 15-min intervals. An externally connected datalogger (Con::cube; s::can GmbH, Vienna, Austria) stored the raw absorbance data (200–750 nm, 2.5 nm intervals). A cleaning brush (s::can GmbH, Vienna, Austria) was attached to the spectrometer and programmed to mechanically remove fouling from the lens before every measurement. In situ particle size distributions were measured by the LISST-200X at 5 min intervals. All the instruments were cleaned and calibrated regularly to maintain optimal data quality. A similar setup was used in the Alzette River, where the spectrometer and YSI-EXO2 sensors were installed.

2.3. Laboratory Analysis for Unattended Event Sampling

The collected water samples were filtered through 1.2 μm Whatman filter papers to measure SS concentration (SSC) by gravimetric filtration after placing them inside an oven maintained at 105°C for a minimum of 2 hr. These filters were further used to measure the carbon contents with a CHNS/O vario MACRO cube Elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The protocol is described in Text S1 in Supporting Information S1).
Particle size distributions were measured from the water samples collected in the Alzette River in the laboratory using a LISST-200X coupled with a test chamber provided by the manufacturer. Measurements were recorded at 2-s intervals for 10 min. A magnetic stirrer kept the sample homogeneous and sediments in suspension within the measuring chamber. Raw data generated by the LISST-200X adopting a random shape algorithm (Agrawal et al., 2008) was used for the statistical analysis.

The sampling of flood events covered various flow stages in the upper Alzette (Figure 2a) and the Attert (Figure 2b) Rivers. The SSC at Alzette ranged between 7.4 and 352 mg/l. The maximum SSC lagged the maximum discharge of 29.9 m³/s by 2 hr. During every flood event, two peaks were observed for the \( \overline{D} \). The first peak occurred a few hours before the maximum SSC and the second peak occurred approximately after 3 days. A similar behavior was observed for the SS carbon content.

In the Attert River, the peaks of SSC were smaller than those in the Alzette River. SSC varied between 7.4 and 54.6 mg/l (Figure 2b). The \( \overline{D} \) (35 μm) and the carbon content (6.8%) were close to the minimum when the SSC peak occurred. The last four \( \overline{D} \) values were omitted from the analysis for reasons of bio-fouling. The highest \( \overline{D} \) was measured during the recession limb (110 μm), which we consider to be an outlier.

2.4. Laboratory Tank Setup to Generate Data From Laboratory Experiments

The laboratory tank setup consisted of a cylindrical tank (48 cm diameter) with an open top and a drainage hole at the bottom (Figure 3). An axial stirrer, fixed at a height of 13 cm from the bottom of the tank (approximately one-third of water level; Figure 3a), maintained most of the particles in suspension and attenuated the concentration gradient inside the tank that could appear because of different particle settling velocities. A scan spectrometer, a LISST-200X and a YSI EXO turbidity meter were installed to measure the properties of the particles in

| Sampling site | Area (km²) | Geology (%) | Land use (%) | Size classes (μm) | Weight distribution (%) | Carbon content (%) |
|---------------|------------|-------------|--------------|-------------------|------------------------|-------------------|
| S1: Bibeschbach | 10.4 | Sc:0; M:95 | A:15; U:4 | 32–63 | 98.3 | 2.7 |
|               |           |             |             | 63–100            | 0.8 | 4.9 |
| S2: Upper Alzette | 110.3 | Sc:0; M:64 | A:19; U:37 | 32–63 | 61.7 | 3.5 |
|               |           |             |             | 63–100            | 25.5 | 2.6 |
| S3: Kaylbach   | 80.2      | Sc:0; M:13 | A:47; U:12 | 32–63 | 60.9 | 8.6 |
|               |           |             |             | 63–100            | 15.8 | 3.3 |
| S4: Attert     | 249.6     | Sc:24; M:46| A:29; U:4  | 32–63 | 23.3 | 2.9 |
|               |           |             |             | 63–100            | 22.8 | 4.6 |
| S5: Weierbach  | 0.45      | Sc:100; M:0| A:0; U:0   | 32–63 | 26.6 | 0.6 |
|               |           |             |             | 63–100            | 27.9 | 9.0 |
| S6: Colpach    | 19.2      | Sc:81; M:10| A:23; U:2  | 32–63 | 63 | 10.8 |
|               |           |             |             | 63–100            | 72.0 | 2.5 |

Note. Simplified geology: sandstone (S), limestone (L), schists (Sc) and marls (M). Land use: forest (F), grassland (G), agriculture (A) and urban (U).
A path reduction module for the LISST-200X was used as recommended in the LISST-200X manual to reduce the errors caused by multiple scattering observed at higher SSC_t of the finest size class (<32 μm).

Preliminary tests were conducted to optimize the mixing speed of the stirrer, to check the concentration gradient inside the tank and to decide about the location and depth to collect grab samples during the experiments (see Text S3 and Figure S1–S4 in Supporting Information S1). The cleaned tank was filled with 40 l of demineralized water. To avoid formation of clumps, the powdered sediments were first weighed and added into a beaker containing a small volume of water (50 ml). After setting a mixing speed of 350 rpm, the sediments from the beaker were added into the tank. The concentration of added sediments will be hereafter referred to as “theoretical SSC (SSC_t).” After 10 min, grab samples were taken using a pipette extended with a hose from four diametrically opposite locations at a fixed depth of 20 cm from the water surface (Figure 3b). The grab samples were transferred into aluminum containers and placed inside an oven at 105°C for a minimum of 2 hr. The average concentration measured from these grab samples will be hereafter referred to as “measured SSC (SSC_m).”

Laboratory experiments were performed starting from a SSC_t of 100 mg/l up to 1,000 mg/l, increasing concentrations at a step of 100 mg/l for each size class and sampling site. Due to the limited quantity of sediment in the coarse size fraction of the samples collected at the Bibeschbach (S1; 32–63 μm) and Weierbach (S5; 63–100 μm) sampling sites, the experiments were only possible up to a SSC_t of 300 and 200 mg/l, respectively. Similarly, no experiments were carried out using the coarsest size fraction of the Bibeschbach samples (S1; 63–100 μm).

Figure 4a shows the difference between SSC_m and SSC_t inside the laboratory tank setup. For values of SSC_t below 300 mg/l, the observations show large deviation in SSC_m, which is different for higher SSC_t. In the range between 500 and 1,000 mg/l, SSC_m is observed to be 10%–30% less than SSC_t except for the coarsest fraction (63–100 μm) from Kaylbach (S3) and upper Alzette (S5). This consistent decrease was associated with settling of suspension.

Figure 2. River discharge (Q), suspended sediment concentration (SSC), carbon content and mean particle size (D) measured in (a) the upper Alzette River (n = 69) and (b) the Attert River (n = 13).
particles (Figure S3 and S4 in Supporting Information S1). Additionally, the accuracy of the evaporation method used to measure $SSC_m$ decreases at low concentration (Dramais et al., 2018).

LISST-200X raw data from the laboratory experiments was used to calculate $\bar{D}$ after calculating the total cumulative volumetric concentration of each sample. The first and last half-minute readings measured by LISST-200X in the laboratory were not considered during data analysis. Figure 4b shows the variation of $\bar{D}$ at increasing $SSC_t$. $\bar{D}$ values of the coarsest size classes (63–100 μm) showed an increase from 700 mg/l $SSC_t$, except S3: Kaylbach. This led to a decrease in the presence of finer particles. A sudden increase was observed for middle fraction particles (32–63 μm) from 400 to 800 mg/l. Figure S5 in Supporting Information S1 shows change between other size distribution parameters ($D_{10}$, $D_{50}$ and $D_{90}$) and $SSC_t$.

### 2.5. Statistical Analysis

Pearson correlations ($r$) were calculated between the absorbance values at all wavelengths (200–735 nm) and (a) $\bar{D}$ (μm), and (b) carbon content (%) for all laboratory samples at $SSC_t$, ranging from 100 to 1,000 mg/l (100 mg/l increments). When grouping all samples from all sites, the correlation was referred to as a "global correlation," whereas when grouped according to location, it was referred to as a "local correlation." In addition, specific absorbance indices ($A_{254}/A_{202}$ and $\ln(A_{350})$) previously used to quantify natural organic matter in water quality monitoring (Byrne et al., 2011) were correlated with SS carbon content. Figure 5 presents a schematic flow chart to illustrate the followed methodology in this study.

Least Square Regression (LSR) and Limited Trimmed Square Robust Regression (LTSRR) models were used to compare and validate laboratory measurements with in situ field measurements. LSR is found to be sensitive toward unusual data points or outliers that are points not following the main
body of the data. On the contrary, LTSRR downweights the data points far away from the linear trend indicated by the main body of the data (Reimann et al., 2008). Therefore, LTSRR was used instead of LSR whenever the data had outliers. After using the LSR and LTSRR for calibration, median absolute deviations (MAD) were computed to quantify differences between predicted and measured values along the median of the differences between predicted and measured values. These differences between measured and predicted values were used to compare both global (derived from the laboratory data) and local (derived from field data) calibrations.

3. Results

3.1. Effect of Particle Size and Carbon Content on Absorption Spectrum in the Laboratory

A maximum global Pearson correlation of −0.73 between absorbance and $A_{730}$ was calculated at a wavelength of 730 nm (Figure S6 in Supporting Information S1). The Pearson correlation between absorbance and carbon content depicted a positive correlation in the range between 200 and 450 nm, with similar values across the wavelength range (Figure S6 in Supporting Information S1).

The effect of SSC on the correlations between absorbance and $A_{730}$, and between absorbance and carbon content was shown by normalizing the absorbance readings with both $SSC_t$ and $SSC_m$. Figure 6a shows calculated correlation coefficients between $A_{730}$ and (a) the Napierian logarithm of absorbance at 730 nm ($\ln A_{730}$), (b) absorbance at 730 nm normalised by theoretical concentrations ($A_{730}/SSC_t$), and (c) normalised by measured concentrations ($A_{730}/SSC_m$). The small differences between the mean correlation coefficients calculated for $A_{730}/SSC_t$ and $A_{730}/SSC_m$ could be related to the larger differences between $SSC_t$ and $SSC_m$ at lower concentrations (i.e., 100 to 300 mg/l; Figure 4a). A higher negative correlation was observed when absorbance data was normalised by neither $SSC_t$ nor $SSC_m$, suggesting that the SSC did not affect the correlation between particle size and absorbance at 730 nm in the laboratory.

Pearson correlations were calculated between SS carbon content and the absorbance indices $A_{254}/A_{202}$ and $\ln A_{350}$ (Figure 6b). The results showed that calculated correlations of all measured samples gave approximately similar values (0.65 for $A_{254}/A_{202}$ and 0.66 for $\ln A_{350}$). The correlations were found to be slightly higher for $A_{350}/SSC_t$ and $A_{350}/SSC_m$ than for

![Figure 5](image_url)  
Figure 5. Flow chart illustrating the methodology followed to address the research questions.

![Figure 6](image_url)  
Figure 6. (a) Box plot of the correlation coefficients ($r$) between mean particle size ($\overline{D}$) and (a) the Napierian logarithm of absorbance at 730 nm ($\ln A_{730}$), (b) absorbance at 730 nm normalised by theoretical concentrations ($A_{730}/SSC_t$), and (c) normalised by measured concentrations ($A_{730}/SSC_m$), when considering all laboratory samples (S1-S6) and all measured concentrations (100–1,000 mg/l at 100 mg/l increments; $n = 10$). (b) Box plot of correlation coefficients ($r$) between carbon content and absorption indices (a) $A_{254}/A_{202}$, (b) $\ln A_{350}$, (c) $A_{350}/SSC_t$, (d) $A_{350}/SSC_m$, and (e) $A_{350}/\overline{D}$ normalised $A_{350}$ values ($A_{350}/\overline{D}$) for the same samples.
ln A

350

, whereas a larger range of correlation values were observed for A

350

/ A

D

𝐴𝐴

𝐴𝐴 𝐷𝐷

A

D

after normalizing the absorbance at 350 nm with A

D

A

D

. This deviation could be related to a larger deviation in A

D

values from 400 to 700 mg/l (Figure 4b).

3.2. Obtaining Global Calibrations Using Laboratory Data

For any value of SSC

, the LSR model between ln A

730

and mean particle size (D) reads as:

ln A

730

= m

Lab,1

∗ D + i

Lab,1

(3)

where m

Lab,1

is the slope, i

Lab,1

is the intercept. Equation 3 can be rearranged as:

D = [ln A

730

− i

Lab,1

]/m

Lab,1

(4)

We observed that an increase in SSC

(100–1,000 mg/l at 100 mg/l increments; color gradient in Figure 7a) only affects the intercept (rather than the slope) of the linear regression lines between ln A

730

and D. To account for this, the intercepts (i

Lab,1

) of the 10 regression lines from Figure 7a were plotted against SSC

m

(Figure 7b). The high correlation (R

2

= 0.98) between i

Lab,1

and SSC

m

justifies a linear model that reads as:

i

Lab,1

= 0.81 ∗ ln SSC

m

− 0.55

(5)

Figure 7. (a) Least square regression (LSR) between the Napierian logarithm of the absorbance at 730 nm (ln A

730

) and the mean particle size (D) for the samples (S1-S6) measured under laboratory conditions (n = 153) categorised by their SSC

, (100 to 1,000 mg/l at 100 mg/l increments). (b) Relationship between the intercept values from subplot (a) (i

Lab,1

) and the Napierian logarithm of measured SSC (SSC

m

). (c) LSR between the Napierian logarithm of the absorbance at 350 nm (ln A

350

) and the carbon content for the samples (S1-S6) measured under laboratory conditions (n = 131) categorised by corresponding SSC

(100 to 1,000 mg/l at 100 mg/l increments). (d) Relationship between the intercept values from subplot (c) (i

Lab,2

) and SSC

m

.
Using Equation 3, we propose the following expression to predict \( \bar{D} \) from absorbance (\( \ln A_{730} \)), by substituting \( t_{\text{Lab},1} \) from Equation 5, to account for SSC in:

\[
\bar{D} = [\ln A_{730} - 0.81 \times \ln \text{SSC}_{\text{in}} + 0.55] / m_{\text{Lab},1}
\]  

(6)

Here, \( m_{\text{Lab},1} \) was calculated as the average of all the slopes in the 10 regressions represented in Figure 7a. For carbon content, a global calibration can be derived at 350 nm in a similar fashion, as a high correlation (\( R^2 = 0.98 \)) can be observed between intercepts as seen in Figure 7c and SSC (Figure 7d).

3.3. Obtaining Local Calibrations Using Field Data

The in situ field measurements were used to obtain local calibrations between absorbance and \( \bar{D} \) (Figure 8a), and between absorbance and carbon content (Figure 8b). The acquired field data from the Alzette River showed higher correlations between \( \ln A_{350} \) and \( \bar{D} \) than the corresponding data from the Attert River (Table 2; Figure 8a).

The correlation coefficients between \( \ln A_{350} \) and carbon content in the upper Alzette River and in the Attert River were 0.69 and 0.20, respectively (Figure 8b). Values of \( \ln A_{350} \) based on in situ measurements in both field sites were negatively correlated with carbon content, which was the opposite for \( \ln A_{350} \) based on laboratory measurements (Figures 8b and 7c, respectively). Therefore, only the global calibration for \( \bar{D} \) is considered valid (Figures 8a and 7a, respectively), whereas the laboratory based calibration for carbon content is not considered further. Table 2 provides the summary of the regression analyses.

3.4. Predicting Mean Particle Size and Carbon Content From In Situ Absorbance

The local and global calibrations (Table 2; Figures 9a and 9b) were used to predict \( \bar{D} \) from in situ absorbance. Median differences between predicted and measured \( \bar{D} \) from local calibrations were similar for both the Attert (\(-2.3 \pm 8.9 \mu m\)) and the Alzette (\(1 \pm 12.1 \mu m\)) sites, whereas those estimated using a global calibration (corrected for SSC), that is, Equation 6, had a difference

| Table 2 | Summary of Regression Analysis Performed Using the Laboratory and Field Data (LSR: Least Square Regression; LTSRR: Limited Trimmed Square Robust Regression) |
| Sediment parameter | Calibration | Data | Location | Regression | (n) | \( R^2 \) | p-Value | SSC corrected |
|---------------------|-------------|------|----------|------------|-----|--------|---------|----------------|
| \( \bar{D} \)       | Local       | Field| Alzette  | LSR        | 67  | 0.23   | <0.001  | –              |
|                     |             |      |          | LTSRR      | 62  | 0.54   | <0.001  | –              |
|                     |             |      |          | Attert     | 7   | 0.05   | 0.55    | –              |
|                     |             |      |          | LTSRR      | 6   | 0.18   | 0.30    | –              |
|                     | Global      | Lab  | S1-S6    | LSR        | 153 | 0.61   | <0.001  | Yes            |
| Carbon content      | Local       | Field| Alzette  | LSR        | 67  | 0.43   | <0.001  | –              |
|                     |             |      |          | LTSRR      | 59  | 0.69   | <0.001  | –              |
|                     |             |      |          | Attert     | 11  | 0.20   | 0.13    | –              |
|                     |             |      |          | LTSRR      | 11  | 0.01   | 0.71    | –              |
|                     | Global      | Lab  | S1-S6    | LSR        | 131 | 0.39   | 0.01    | Yes            |

Note. Local calibrations are site-specific (ALZ: Upper Alzette River and ATT; Attert River) and global calibration represent all sites S1–S6. Values of \( n \) denote the degrees of freedom. \( R^2 \) is the squared correlation coefficient.
of 13.8 μm between the Attert (−3 ± 23.5 μm) and the Alzette (−16.8 ± 11.1 μm). The results obtained using global calibrations were comparable with local calibrations for the Attert River, whereas global calibrations underpredicted $\overline{D}$ for the Alzette River.

The local calibrations (Table 2; Figure 9c) were used to predict carbon content from in situ absorbance. Here, median differences between predicted and measured carbon content were 0.1 ± 1% for the Alzette and 0.1 ± 1.7% for the Attert. All other predictions made for $\overline{D}$ and carbon content from less significant or insignificant calibrations (Table 2) are shown in the Figure S7 in Supporting Information S1.

4. Discussion

4.1. Assessment of Global Calibrations to Predict Mean Particle Size and Carbon Content From Absorbance

Our results lead us to accept the hypothesis that in situ absorbance data from a spectrometer can be used to simultaneously quantify SS carbon content and $\overline{D}$. This becomes manifest from local (site-specific) and global (all sites grouped) calibrations between absorbance at optimized wavelengths, being 350 and 730 nm for carbon content and $\overline{D}$, respectively.
Previously, Martínez-Carreras et al. (2016) related absorbance readings to the SS loss-on-ignition, establishing a local calibration for the Weierbach experimental catchment (SS in this study). Their results indicated a maximum correlation between loss-on-ignition and absorbance at 710 and 730 nm, respectively. In this study, absorbance at 730 nm was better correlated to $D$. Absorbance at specific wavelengths has also been related to other absorbing components in aquatic ecosystems like chlorophyll (Boss et al., 2007; Churilova et al., 2017; Tao et al., 2018), CDOM (Twardowski et al., 2004), and non-algal particles (humic substance, mineral particles, and bacteria). Here, Churilova et al. (2017) proposed an empirical relationship using least squares fitting between chlorophyll ($a$) and $a_{ph} (\lambda)$ at 490 nm, whereas Boss et al. (2007) used multiple wavelengths (650, 676, and 715 nm) to measure chlorophyll concentration. We observed nearly constant correlation coefficients between absorbance and $D$ or carbon content, across all wavelengths in the investigated range. Therefore, multi-parameter calibrations using several wavelengths were not further considered.

Laboratory studies have previously shown that not only the concentration of specific chemical species directly or indirectly affects absorbance (Kim et al., 2016; Shi et al., 2020), but also that particle size of mineral suspensions can have an effect (Alin et al., 2015; Berho et al., 2004; Bowers & Binding, 2006). Similarly, in our study, SSC and particle size influenced absorbance values, which was observed with our laboratory data (Figure 6a). Nevertheless, the influence of SSC on the correlation between absorbance and both $D$ and SS carbon content was used in a reproducible way.

Local and global correlations between absorbance and $\overline{D}$ were found to give similar results despite the different SS composition and particle size distributions of the samples considered (Table 1; Figure S6a in Supporting Information S1), whereas local correlations better predicted carbon content than the proposed global correlation (Figure S6b in Supporting Information S1). The differences in accuracy when predicting carbon content using local and global calibrations can be partially explained by the low local correlation between absorbance and carbon content for the Weierbach samples. The Weierbach is a forested catchment (Table 1) and SSs presented high carbon content values in all size classes. This is also true for the coarsest size class (63–100 μm), where the presence of small roots and twigs (from visual inspection) might have increased the carbon content. After discarding the Weierbach samples, the global correlation between absorbance and carbon significantly improved. However, particle size can still affect this correlation (Figure 6b). Wavelengths in the range of 200–450 nm were previously used to relate the absorption spectrum to dissolved organic compounds in water (Bass et al., 2011; Etheridge et al., 2014). Etheridge et al. (2014) used global calibrations ($R^2 = 0.26$) provided by the sensor manufacturer to estimate DOC, whereas Bass et al. (2011) tried to use both, the global calibration provided by the sensor manufacturer and a site-specific local calibration to estimate POC and DOC. Similar to our conclusion for SS carbon content, the authors highlighted that site-specific calibrations were essential to estimate the parameters considered in their respective studies.

4.2. Comparison Between Laboratory and Field Results

Tank setups have been used in previous studies to characterise coastal and estuarine sediment suspensions (Pearson et al., 2021), to calibrate optical backscatter sensors (Sutherland et al., 2000) and to understand the effect of particle shape on LISST-100X particle size measurements (Felix et al., 2013). Comparison between laboratory measurements and in situ field data posed several challenges in our study, which arose from the differences between laboratory samples and field conditions to start with. Another challenge was that laboratory sediments were wet sieved into three size classes (<32 μm, 32–63 μm and 63–100 μm). The wet sieving procedure more likely removed small organics attached to the coarsest primary particles (32–63 μm and 63–100 μm) than to the finest fraction particles (<32 μm), due to multiple washing of the samples with water (Sainju, 2006). We hypothesize that this can result in a considerable difference in the carbon content of the coarsest fraction of the samples used in the experiment. Consequently, carbon content in those fractions might not be comparable with in situ measurements, which consist of a mixture of both primary and aggregated particles. Here, dry sieving was not a better option than wet sieving, because although dry sieving might have preserved the carbon content in between the size fractions, it could have prevented disaggregation of a part of the samples into primary particles (Blaud et al., 2017; Sainju, 2006). Another challenge relates to the effect of changes in SSC, which is different between laboratory and field conditions. On one hand, an SSC increase in the laboratory measurements did not imply a change in the particle size distribution or carbon content of the suspensions. On the other hand, an SSC increase
in the field (e.g., due to an increase in discharge) has an effect on both particle size distribution and carbon content (Figure 2).

4.3. How Accurate Are the Predictions for Mean Particle Size and Carbon Content?

Previous studies that looked at the impact of SS properties on turbidity have shown that the aggregate composition and particle size distribution, both affected by site-specific factors, are two of the major factors influencing optical readings (Boss et al., 2018; Miroslaw & Fournier, 2011; Wozniak et al., 2018). This poses a major challenge in the quest involved in moving from local to global calibrated instruments. In this study, the comparison between local and global models helped to understand the advantages and limitations in the use of absorbance data to predict SS $D$ and carbon content. The laboratory data was not subject to concomitant changes in particle size and SSC. Our results show that a global calibration (corrected for SSC; Equation 6) can accurately predict $D$ (ALZ: $-16.8 \pm 11.1 \mu m$ and ATT: $-3 \pm 23.5 \mu m$). This creates the possibility to use and test the proposed equation at other field sites and further increase the global data set that will eventually improve the accuracy of the proposed global calibration equation. Contrarily, the carbon content showed a different behavior in the laboratory (positive slope in the relation between absorbance and carbon content) than in the field (negative slope). Therefore, a global calibration needs new theory for carbon content, and local calibrations are still needed (Figure 8b). This is despite the fact that it was proven that SS carbon content can be estimated from the readings of a submerged spectrometer. Alternative experiments could be conducted to further explore the relation between absorbance and SS carbon content, for example, at other sites, collecting longer data sets, considering sediment with a larger range of densities and/or implementing other study setups that better conserve the initial SS structure (Manning et al., 2007; Mikkelsen et al., 2005).

Due to the low number of field data points (Figure 2), we opted for not splitting the field data into a calibration and a validation data set. Therefore, local calibrations were both calibrated and validated using in situ field data. Whereas, the global calibration model corrected for SSC was based on the laboratory data set and validated with in situ field data. This highlights three major advantages of the global calibration: (a) it is not site-specific, (b) it was evaluated using different calibration and validation data sets, and (c) data were corrected for SSC. It is also worth noting that the local calibrations for the upper Alzette and the Attert Rivers were influenced by the presence of outliers (both for $D$ and carbon content). Those were measured at low flows and at the beginning of the event, suggesting the presence of aggregates/flocs with distinct properties.

Notwithstanding the utility of the presented models, some limitations are to be considered. The proposed equation to predict $D$ was based on laboratory measurements carried out with SSC values ranging from 0 to 1,000 mg/l. Therefore, the prediction capacity of the model at concentrations above 1,000 mg/l remains unknown. High concentrations are generally seen in locations presenting very specific geological and land cover characteristics (e.g., badlands; Nadal-Romero et al., 2008). The submerged spectrometer used in this study may reach an operation limit with either the finest size classes or/and at high SSC, as specified by the manufacturer. This occurred when conducting the laboratory experiments with the smallest fraction of the Bibeschbach sample (S1; <32 μm; Table 1). In those experiments, the spectrometer was not able to measure absorbance at concentrations larger than 700 mg/l. A different path length of the spectrometer may resolve this. When measuring at high SSCs, a narrower path length can be used, which is likely to occur when the particle size is mostly on the clay range. Although we covered a large range of SS sizes (0–100 μm; Walling & Moorehead, 1989), more tests with wider particle size distributions are needed to further investigate the relation between $D$ and absorbance. Finally, the local calibrations were based on limited data sets. For example, a low number of carbon content measurements were available for the Attert River site, and these presented a narrow range of values (6%–8%), which explains the difficulties to obtain local calibrations at this site. On the contrary, a wider range of carbon content values were measured in the upper Alzette River (2%–15%), which resulted in a better prediction when using local calibrations.

4.4. Implication of Our Findings

To the best of our knowledge, the use of a submerged spectrometer to quantify SS $D$ is here investigated for the first time in a field study. It is well-known that in situ scattering based instruments such as the LISST-200X and recently developed image-analysis based instruments (Manning et al., 2007; Mikkelsen et al., 2005; Smith & Friedrichs, 2011) provide more accurate quantification of the particle size distribution, for a wider range of sizes.
In this study, we do not suggest these instruments can be replaced. We argue that by using absorbance, a single sensor allows the rapid and simultaneous estimation of SS $\bar{D}$ and carbon content, but also the estimation of other parameters such as turbidity, nitrates and DOC (Lepot et al., 2016). Additionally, spectrometers need lower maintenance than other types of sensors including the LISST-200X. Also, even though the laser diffraction method is generally consistent with all particles (Agrawal et al., 2008), additional research with different types of particles is needed to determine how floc composition and density influence $\bar{D}$ predictions from absorbance.

In that purview, spectrometers can complement the existing instruments and help to better understand SS composition, particle size distributions and carbon fluxes in riverine systems. In fluvial networks, organic carbon is often associated with biological activity (Battin et al., 2008). Microorganisms act as fluvial carbon storage facilities, metabolising it for their energy and growth (Battin et al., 2008). Organic carbon in the form of biofilms and extracellular polymeric substance (EPS) has been observed to cause flocculation in several freshwater rivers (Lamb et al., 2020; Nicholas & Walling, 1996). In situ quantification of SS carbon content (being a proxy for SS organic content) can help to better quantify organic carbon fluxes and to better predict spatial distributions of biological activity required for habitat modeling (Habersack et al., 2014; Parsons et al., 2016).

Recent studies address the joint role of SS particle size and organic content to better understand flocculation (Lee et al., 2019; Maggi & Tang, 2015). These flocculated cohesive sediments, along with traditionally investigated non-cohesive sediments, form an important component of bed sediments, which is a primary contributor to SS fluxes (Mehta, 2014; Schindler et al., 2015; Whitehouse et al., 2000). Here, the height of the deployed sensor above the bed will be critical to capture changes in SS composition. The current study was conducted in rivers that do not have a significant presence of bedforms, which may add complexity to the SS dynamics that merit further study.

5. Conclusion

Our laboratory and field measurements reveal that specific wavelengths of the absorption spectrum measured by a submerged spectrometer show strong correlations with SS $\bar{D}$ and carbon content. This allows for in situ inference of these two major sediment properties at high frequency. A global calibration was defined to predict $\bar{D}$ from absorbance, which results in a similar accuracy as predictions derived using a local calibration. Differences between predicted and measured $\bar{D}$ (Median ± Median absolute deviation) when using the local calibration were $1 \pm 12.1 \, \mu m$ and $-2.3 \pm 8.9 \, \mu m$ for the upper Alzette and the Attert Rivers, respectively, whereas they were $-16.8 \pm 11.1 \, \mu m$ and $-3 \pm 23.5 \, \mu m$ when using the global calibration, derived from laboratory experiments. Hence, the proposed global calibration corrected for SSC can be used and tested at sites with contrasting environmental characteristics. Carbon content can be estimated from absorbance, which requires local calibrations. The difference between predicted and measured carbon content (Median ± Median absolute deviation) when using local calibrations were $0.1 \pm 1\%$ and $0.1 \pm 1.7\%$ in the upper Alzette and the Attert Rivers, respectively.
Data Availability Statement

The data used to generate the results in this study are made available through a public repository https://doi.org/10.5281/zenodo.6509837.

References

Agrawal, Y. C., & Potts, H. C. (2000). Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology*, 168(1-4), 89–114. https://doi.org/10.1016/S0025-3227(00)00024-X

Agrawal, Y. C., Whitimine, A., Mikkelsen, O. A., & Potts, H. C. (2008). Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction. *Journal of Geophysical Research, 11(4),* 1–11. https://doi.org/10.1029/2007JC004403

Alexio, R., Guererro, M., Nones, M., & Ruthier, N. (2020). Applying ADCPs for long-term monitoring of SSC in rivers. *Water Resources Research, 56(1).* https://doi.org/10.1029/2019WR026087

Alin, J., Rubino, M., & Auras, R. (2015). In situ characterization of organo-modified and unmodified montmorillonite aqueous suspensions by UV-visible spectroscopy. *Journal of Colloid and Interface Science, 456, 155–160.* https://doi.org/10.1016/j.jcis.2015.08.011

Ankers, C., Walling, D. E., & Smith, R. P. (2003). The influence of catchment characteristics on suspended sediment properties. *Hydrobiologia, 494(1–3),* 159–167. https://doi.org/10.1023/A:1023558114068

Babin, M., & Stramski, D. (2004). Variations in the mass-specific absorption coefficient of mineral particles suspended in water. *Limnology & Oceanography, 49(3),* 756–767. https://doi.org/10.4319/lo.2004.49.3.0756

Bass, A. M., Bird, M. I., Liddell, M. J., & Nelson, P. N. (2011). Fluvial dynamics of dissolved and particulate organic carbon during periodic discharge events in a steep tropical rainforest catchment. *Limnology & Oceanography, 56(6),* 2282–2292. https://doi.org/10.4319/lo.2011.56.6.2282

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. J., et al. (2008). Biogeochemical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience, 1(2),* 95–100. https://doi.org/10.1038/ngeo101

Berho, C., Pouet, M. F., Bayle, S., Azena, N., & Thomas, O. (2004). Study of UV-vis responses of mineral suspensions in water. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 248(1–3),* 9–16. https://doi.org/10.1016/j.colsurfa.2004.08.046

Blaen, P. J., Khamis, K., Lloyd, C. E., Bradley, C., Hannah, D., & Krause, S. (2016). Real-time monitoring of nutrients and dissolved organic matter in rivers: Capturing event dynamics, technological opportunities and future directions. *The Science of the Total Environment, 569–570,* 647–660. https://doi.org/10.1016/j.scitotenv.2016.06.116

Blau, A., Menon, M., Zaan, B. V. D., Lair, G. J., & Banwart, S. A. (2017). Effects of dry and wet sieving of soil on identification and interpretation of microbial community composition (1st ed., Vol. 142). Elsevier Inc. https://doi.org/10.1016/b.s.agron.2016.10.006

Boss, E., Collier, R., Larson, G., Fennel, K., & Pegau, W. S. (2007). Measurements of spectral optical properties and their relation to biogeochemical variables and processes in Crater Lake. *Crater Lake National Park, OR. Hydrobiologia, 574, (1),* 149–159. https://doi.org/10.1007/s10750-006-2699-3

Boss, E., Sherwood, C., Hill, P., & Milligan, T. (2018). Advantages and limitations to the use of optical measurements to study sediment properties. *Applied Sciences, 8(12),* 2692. Retrieved from http://www.mdpi.com/2076-3417/12/12/2692

Bowers, D. G., & Binding, C. E. (2006). The optical properties of mineral suspended particles: A review and synthesis. *Estuarine, Coastal and Shelf Science, 67(1–2),* 219–230. https://doi.org/10.1016/j.ecss.2005.11.010

Byrne, A. J., Chow, C., Trolio, R., Lethorn, A., Lucas, J., & Korshin, G. V. (2011). Development and validation of online surrogate parameters for water quality monitoring at a conventional water treatment plant using a UV absorbance spectrophotometer. In *2011 Seventh Sensor Networks and Information Processing.* 200–204. https://doi.org/10.1109/ISENSIP.2011.6146515

Churilova, T., Sustin, V., Krivenko, O., Efimova, T., Mukhanov, V., & Smirnova, L. (2017). Light absorption by phytoplankton in the upper mixed layer of the Black Sea: Seasonality and parametrization. *Frontiers in Marine Science, 4(4APR),* 1–14. https://doi.org/10.3389/fmars.2017.00090

Dramais, G., Camenen, B., Coz, J. L., Thollet, F., Bescond, C. L., Lagouy, M., et al. (2018). Comparison of standardized methods for suspended solid concentration measurements in river samples. In *River Flow 2018: 9th International conference on fluvial hydraulics.* https://doi.org/10.1051/e3conf/2018004018

Droppo, I. G. (2001). Rethinking what constitutes suspended sediment. *Hydrological Processes, 15(9),* 1551–1564. https://doi.org/10.1002/hyp.228

Druine, F., Verney, R., Deloflire, J., Lemoine, J. P., Chaplain, M., Landemaine, V., & Lafitte, R. (2018). In situ high frequency long term measurements of suspended sediment concentration in turbid estuarine system (Seine Estuary, France): Optical turbidity sensors response to suspended sediment characteristics. *Marine Geology, 400(July),* 24–37. https://doi.org/10.1016/j.margeo.2018.03.003

Dyer, K., Cornelisse, J., Deanayl, M., Fennessy, M., Jones, S., Kappenberg, J., et al. (1996). A comparison of in situ techniques for estuarine floc settling velocity measurements. *Journal of Sea Research, 36(1–2),* 15–29. https://doi.org/10.1016/0924-7349(95)00026-5

Etheridge, J. R., Birgand, F., Osborne, J. A., Oubrun, C. L., Burchell, M. R., & Irving, J. (2014). Using in situ ultraviolet-visible spectroscopy to measure nitrogen, carbon, phosphorus, and suspended solids concentrations at a high frequency in a brackish tidal marsh. *Limnology and Oceanography: Methods, 12(1),* 10–22. https://doi.org/10.4319/lom.2014.12.10

Felix, D., Albayrak, I., & Boes, R. M. (2013). Laboratory investigation on measuring suspended sediment by portable laser diffraction meter (LISST) focusing on particle shape. *Geo-Marine Letters, 33(6),* 485–495. https://doi.org/10.1007/s00367-013-0343-1

Fennessy, M. J., Dyer, K. R., & Huntley, D. A. (1994). MARINE: an instrument to measure the size and settling velocity of flocs in situ. *Marine Geology, 117(1–4),* 107–117. https://doi.org/10.1016/0025-3227(94)90009-4

Fettweis, M., & Lee, B. J. (2017). Spatial and seasonal variation of biomineral suspended particulate matter properties in high-turbid nearshore and low-turbid offshore zones. *Water, 6(9),* 1. https://doi.org/10.3390/w60900694

Galuszka, A., Migaszewski, Z. M., & Namieśnik, J. (2015). Moving your laboratories to the field - advantages and limitations of the use of field portable instruments in environmental sample analysis. *Environmental Research, 140,* 593–603. https://doi.org/10.1016/j.envres.2015.05.017

Grangeon, T., Legout, C., Esteves, M., Graziot, N., & Navratil, O. (2012). Variability of the particle size of suspended sediment during highly concentrated flood events in a small mountainous catchment. *Journal of Soils and Sediments, 12(10),* 1549–1558. https://doi.org/10.1007/s11368-012-0562-5

Habersack, H., Trithart, M., Liedermann, M., & Hauer, C. (2014). Efficiency and uncertainties in micro- and mesoscale habitat modelling in large rivers. *Hydrobiologia, 729(1),* 33–48. https://doi.org/10.1007/s10750-012-1429-x
Sainju, U. M. (2006). Carbon and nitrogen pools in soil aggregates separated by dry and wet sieving methods. *Soil Science, 171*(12), 937–949. https://doi.org/10.1097/01.ss.0000228062.30958.5a

Schindler, R. J., Parsons, D. R., Ye, L., Hope, J. A., Baas, J. H., Peakall, J., et al. (2015). Sticky stuff: Redefining bedform prediction in modern and ancient environments. *Geology, 43*(5), 399–402. https://doi.org/10.1130/g3.6262.1

Shi, Z., Chow, C. W., Fahrs, R., Liu, J., & Jin, B. (2020). Alternative particle compensation techniques for online water quality monitoring using UV–Vis spectrophotometer. *Chemosometrics and Intelligent Laboratory Systems, 204*, 104074. https://doi.org/10.1016/j.chemolab.2020.104074

Smith, S. J., & Friedrichs, C. T. (2011). Size and settling velocities of cohesive flocs and suspended sediment aggregates in a trailing suction hopper dredge plume. *Continental Shelf Research, 31*(10), S50–S63. https://doi.org/10.1016/j.csr.2010.04.002

Soler, M., Nord, G., Catari, G., & Gallart, F. (2012). Assessment of suspended sediment concentration measurement error in relation to particle size, using continuous sensors in a small mountain stream (Vallecebre catchments, Eastern Pyrenees. *Zeitschrift für Geomorphologie, 3*, 099–113. https://doi.org/10.1127/0372-8854/2012/00106

Spearman, J. R., Manning, A. J., & Whitehouse, R. J. (2011). The settling dynamics of flocculating mud and sand mixtures: Part 2-numerical modelling. *Ocean Dynamics, 61*(2–3), 351–370. https://doi.org/10.1007/s10236-011-0385-8

Sutherland, T. F., Lane, P. M., Amos, C. L., & Downing, J. (2000). The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. *Marine Geology, 162*(2–4), 587–597. https://doi.org/10.1016/S0025-3227(99)00080-8

Tao, J., Hill, P. S., Boss, E. S., & Milligan, T. G. (2018). Variability of suspended particle properties using optical measurements within the Columbia River Estuary. *Journal of Geophysical Research: Oceans, 123*(9), 6296–6311. https://doi.org/10.1002/2018JC014093

Twardowski, M. S., Boss, E., Sullivan, J. M., & Donaghy, P. L. (2004). Modeling the spectral shape of absorption by chromophoric dissolved organic matter. *Marine Chemistry, 89*(1–4), 69–88. https://doi.org/10.1016/j.marchem.2004.02.008

Walling, D. E., & Moorehead, P. W. (1989). The particle size characteristics of fluvial suspended sediment: An overview. *Hydrobiologia, 176/177*, 125–149. https://doi.org/10.1007/BF00979894-009-2576-8_12

Waterloo, M. J., Oliveira, S. M., Drucker, D. P., Nobre, A. D., Cuartas, L. A., Hodnett, M. G., et al. (2006). Export of organic carbon in run-off from an Amazonian rainforest blackwater catchment. *Hydrological Processes, 2097*(12), 2581–2597. https://doi.org/10.1002/hyp

Werdell, P. J., Mckinna, L. I. W., Boss, E., Ackleson, S. G., Craig, S. E., Gregg, W. W., et al. (2018). An overview of approaches and challenges for retrieving marine inherent optical properties from ocean color remote sensing. *Progress in Oceanography, 160*, 186–212. https://doi.org/10.1016/j.pocean.2018.01.001

Whitehouse, R. J. S., Soulsby, R., Robert, W., & Mitchener, H. (2000). *Dynamics of estuarine muds: A manual for practical applications*. Thomas Telford.

Williams, N. D., Walling, D. E., & Leeks, G. J. L. (2008). An analysis of the factors contributing to the settling potential of fine fluvial sediment. *Hydrological Processes, 22*(20), 4153–4162. https://doi.org/10.1002/hyp

Wozniak, S. B., Sagan, S., Zablocka, M., Ston-Egiert, J., & Borzychka, K. (2018). Light scattering and backscattering by particles suspended in the Baltic Sea in relation to the mass concentration of particles and the proportions of their organic and inorganic fractions. *Journal of Marine Systems, 182*, 79–96. https://doi.org/10.1016/j.jmarsys.2017.12.005