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Continuous measurement of suspended sediment concentration: Discussion of four techniques

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ABSTRACT

Continuous measurements of suspended sediment mass concentration (SSC) and particle size distribution (PSD) in surface waters and hydraulic schemes are of prime importance for the investigation and management of many fine-sediment related processes. In this paper, the performance of selected techniques and instruments for continuous SSC measurements is discussed based on results of a field study and a recent literature-review paper. SSCs measured with Laser In Situ-Scattering and Transmissometry (LISST) or vibrating tube densimetry were confirmed to be not or less biased by temporary PSD variations than SSCs obtained from turbidimeters or a single-frequency acoustic attenuation method. Vibrating tube densimetry allowed measurements of higher SSCs (e.g. 10 g/l) compared to the other investigated instruments. For the conversion of the instruments' outputs to SSC, i.e. calibration, and for validation, gravimetric analysis of bottle samples is recommended as reference.

1. Introduction

Measurements of SSC and PSD with high temporal resolution are important for a better understanding and management of fine-sediment related processes in rivers, reservoirs and hydraulic schemes. Therefore, there is a need for practical measuring systems, which cover relevant SSC and PSD ranges with an acceptable uncertainty and provide data preferably in real-time. An overview on measurement techniques for suspended sediment monitoring (SSM) is provided in [1], and more detailed descriptions and references to recent studies have been given in [2].

In the scope of an interdisciplinary research project on turbine abrasion [3], four indirect measuring techniques for continuous real-time measurements of SSC were experimentally investigated at the waterway of the hydroelectric power plant (HPP) Fieschertal in the Swiss Alps: turbidity measurement, single-frequency acoustic attenuation, LISST, and vibrating tube densimetry. Gravimetric analysis of bottle samples taken in parallel served as reference. These techniques were also partly treated in [1,2]. In the present contribution, complementary information on vibrating tube densimetry and the acoustic attenuation method are given, the setup and method of the field study are briefly described and the measuring performance of the instruments is discussed based on exemplary field data. Finally, the option of combining measuring techniques is highlighted and the conclusions drawn in [2] are discussed.

2. Measuring techniques and instruments

Turbidimetry and LISST have been reviewed in [2], and gravimetric analysis of bottle samples is well known. However, the literature contains only little information on vibrating-tube densimetry in the context of SSM, and the type of acoustic method used in this study is not widely known. Therefore, complementary information on the latter two techniques are given in the following.

2.1. Vibrating-tube densimetry

This measuring technique is used in 'Vibrating Tube Density Meters' (VTDMs, also called 'oscillating U-tubes') and in 'Coriolis Flow- and Density Meters' (CFDMs). The operation principles of these two types of instruments are e.g. described in [4,5], respectively. The density of a fluid flowing through a VTDM or a CFDM is measured based on the natural frequency of the measuring tubes, which drops as the mass in the tubes increases. VTDMs and especially CFDMs are common in the process industry, whereas they have been rarely used for in-situ SSM so far [6]. CFDMs are commercially available at roughly US$ 15 000. In many CFDM models, the temperature is also measured and thermal dilatation is compensated.

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The density measurements of VTDMs or CFDMs may be biased due to deposits, biofilm growth or abrasion inside the measuring tubes. With particulate fluids, i.e. fluids containing particles, CFDMs may underestimate the mixture density due to 'phase decoupling' [7] if the particles are large. The accuracy of the density measurement of the CFDM used in the authors' field study [3] is ±0.5 g/l according to the manufacturer, which is a common specification [5]. SSC is determined from the measured mixture density, the clear water density and the particle density which is assumed to be constant. Particle density can be determined from the dried residues of a few bottle samples using a pycnometer. The clear water density is calculated as a function of the measured temperature.

2.2. Single-frequency acoustic attenuation method

Ultrasonic signals are mostly used for SSM in connection with Acoustic Doppler Current Profilers (ADCPs), e.g. [8]. The use of ADCPs offers the advantage of obtaining spatially distributed SSCs in cross sections of water bodies. SSCs are inferred from backscattered signals and their correlation with gravimetrical SSCs from bottle samples. In the present study, a single-frequency acoustic method based on attenuation (forward scattering) was used. This method lends itself particularly well for SSM in rivers, canals and waterways where installations for acoustic discharge measurement (ADM) already exist. Like this, SSC can be monitored without additional sensors. ADM installations comprise acoustic transducers installed on both sides of acoustic paths crossing the flow section. For the determination of the flow velocity and the discharge, ultrasonic pulses are sent through the water. If the water contains sediment particles, the received signal is weaker due to attenuation [9]. Similarly to certain turbidimeters, this attenuation is correlated to SSC.

3. Field study set-up and method

In the study at HPP Fieschertal [3], the instruments No. 1 to 3 and 5 listed in Table 1 were installed in the valve chamber at the head of the penstock. For the acoustic method (No. 4), a pre-existing ADM installation with transducers inside the penstock was employed. The CFDM and the in-line turbidimeter were integrated in a sampling pipe fed with water from the penstock. At the outflow of the pipe, the measuring head of an all-round LISST instrument was accommodated in a bucket with an overfall and a bottom outlet. The partially opened bottom outlet allowed continuous sediment evacuation.

The water in this HPP comes from a highly glaciated catchment area and contains mainly silt particles. At the measuring location, the sediment particles are smaller than 0.3 mm, since coarser particles are removed by upstream gravel and sand traps. No air bubbles were observed in the sampling pipe during the study. Water samples were automatically pumped from the bucket every three days or more frequently in periods of high SSCs (triggered by CFDM density). From these samples, the SSCs were determined in the laboratory by gravimetrical analysis. These SSCs were taken as reference and served for the conversion of the instruments' outputs to SSC time series. These conversion functions can also be called field calibrations. In addition, PSDs were calculated from the LISST data in the range of 3–380 μm based on the assumption of so-called 'random shaped' particles [10].

4. Results and discussion

Out of three years of measurements, exemplary PSD and SSC time series during two summer days are shown in Fig. 1. The particle size d_x stands for the diameter of graded particles, of which x% by mass are smaller. The following comments on the measuring performance of the instruments are made:

1. The SSCs obtained from the instruments were similar if the particles were relatively fine ($d_{50} \approx 15$ μm), as during most of the time. In periods with larger particles transported, however, the turbidimeter and the acoustic method underestimated SSCs, due to effects of PSD variations which are not correlated to SSC. At sites with such highly dynamic sediment transport, SSCs obtained from turbidimeters or single-frequency acoustic methods may contain significant uncertainty. If PSD is constant (e.g. for wash load), or is highly correlated with SSC, these two methods may yield results with a good accuracy. With the LISST technique, changes in PSD are measured and accounted for in the calculation of SSC. With particles mainly in the size range of silt, no effect of PSD variations was observed on the SSC data obtained from the CFDM.
2. The SSCs from LISST and gravimetry are in good agreement because of the field calibration, which accounts for the particle density and compensates particle shape effects on LISST volume concentrations. Without field calibration, the SCCs would be overestimated by 70% on temporal average at this site. Considerable overestimations were also quantified in preliminary laboratory investigations with highly non-spherical particles [11].
3. The SSC sometimes exceeded the measuring range of the LISST instrument used in this study, as also indicated by Rai and Kumar [2] and the manufacturer. The upper limit of the SSC measuring range of a LISST instrument depends on its optical path length, the PSD and particle shapes [11]. The optical path length of the LISST instrument was reduced to 5 mm using the strongest available path reduction module, and a further reduction was not well feasible. Another type of LISST instrument, providing measurements at up to ten times higher SSC using sample dilution with clear water, was not affordable in the authors' study. Turbidimeters and the acoustic method were also not able to cover the whole range of SSCs occurring at the study site, i.e. up to 50 g/l in a major flood event. The CFDM, however, which was installed after that major flood, allowed measuring SSCs up to 13 g/l without reaching the upper limit of its measuring range (Fig. 1).

Table 1
Instruments for SSM in the valve chamber of HPP Fieschertal.

No.	Instrument description	Measuring technique	Instrument model	Instrument manufacturer	Instrument outputs	Derived parameters
1	Coriolis Flow- and Density Meter (CFDM)	Vibrating-tube densimetry	*Promass 83F DN15*	Endress + Hauser	Density, temperature	SSC
2	Standard LISST, with 90% path reduction	Laser diffraction (LISST)	*LISST-100X* (Type C)	Sequoia Scientific	Volume concentrations	SSC, PSD
3	In-line turbidimeter at free falling jet	Turbidity	*AquaScat*	Sigrist Photometer	Turbidity	SSC
4	SSC monitoring using ADM installation	Acoustic attenuation	*Risonic* (1 MHz)	Rittmeyer	Attenuation	SSC
5	Bottle sampler and weighing in laboratory	Gravimetric	*Isco 3700* (24×1 l)	Teledyne Isco	Filled bottles, SSC	–