A study on the estimating of sediment concentration with turbidity and acoustic backscatter signal for different sediment sizes

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ABSTRACT

Turbidity and acoustic measurement are alternative indirect methods to determine sediment concentration. Acoustic Doppler velocimetry can be used to estimate suspended sediment concentration (SSC) with the signal-to-noise ratio (SNR) in the water. In this study, particles size affecting turbidity and SNR values was investigated using four different sediment size groups (0–50, 50–100, 100–200, and 200–250 micron). The highest turbidity values were determined for small-sized sediment, and they decreased for bigger sediment size. Clay content decreased the relationship between sediment and turbidity and caused a reading error for high concentrations (>4 g.l^{-1}). However, R^2 values greater than 0.900 were obtained for all treatments (R^2: 0.952, 0.992, 0.987, and 0.977, respectively, from small size to large size group). SNR values had good relationships with SSC values for less than 40 dB and 1 g.l^{-1} sediment concentrations (R^2: 0.990, 0.998, 0.994, and 0.973, respectively, from small size to large size group). SNR values were strongly affected by small changes in sediment concentration but this property can be accepted as advantageous for sensitive measurement. As a result of this study, it could be concluded that turbidity and SNR values can be used for continuous sediment monitoring.

Key words | sediment, signal-to-noise ratio, turbidity, water pollution

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INTRODUCTION

Suspended sediment transport is an important parameter in hydrological studies, and it shows temporal changes depending on many factors, such as discharge flow and basin and climatic characteristics. Continuous sediment measurement has many difficulties due to these fluctuations. The sampling and filtering method is generally used for direct measurement. This gravimetric measurement represents the standard methodology to obtain and quantify suspended sediment and consists of physically separating sediment materials from a water sample. The main disadvantage of this method is its labor-intensive and time-consuming process (Gray *et al.* 2002). Furthermore, many studies have shown that the sensitivity of this method is influenced by sampling and laboratory procedures (Wren *et al.* 2000; Schoellhamer & Wright 2003). Also, this method is restrictive in providing detailed spatial and temporal suspended sediment concentration (SSC) (Thorne & Hanes 2002).

Continuous sediment monitoring requirements have led to new devices, especially those based on sound or light waves in water and developed with technological advances in recent years. Among many other different methodologies, the use of optical turbidimeters with their easy and economical usage is quite common in sediment monitoring (Schoellhamer & Wright 2003).

Turbidity is an optical property of water and is mainly related to the amount of light absorbed and scattered by particles rather than transmitted in water (APHA 1999). Scattering and absorption of light depends on suspended mineral and organic particles, colloids and plankton units,

doi: 10.2166/nh.2015.109

and air bubbles in the water sample (Gippel 1995; Lewis & Eads 2001).

The strong relation between turbidity and SSC has led to the development of turbidimetry being used for continuous monitoring of sediment transportation (Uncles & Stephens 2010). The use of turbidity values for SSC is an indirect method based on obtaining a statistical relationship between these two parameters, such as linear, non-linear, or polynomial functions (Sun *et al.* 2001). The effects of grain size, color, and mineral composition on turbidity are the main limitations for this method and need to be defined for different conditions. These factors should be considered to obtain accurate estimation of sediment concentration with using turbidity values. For this reason calibration is required for each measurement condition (Ziegler 2002). A simultaneous statistical relationship between SSC and turbidity values should be obtained for the calibration process (Gray *et al.* 2002). Gippel (1989) suggested that the turbidity and sediment relationship is required for temporal and spatial monitoring. Chanson *et al.* (2008) conducted a laboratory study to investigate the relationship between sediment concentration and nephelometric turbidity units for low concentrations less than 0.8 g.l^{-1}. The results showed that there was a high correlation ($R^2 = 0.992$ and 0.992) for silt and sand sediment materials. A similar study was conducted by Mitchell *et al.* (2003) for river conditions, and they reported water quality and sediment properties were strongly affected, which led to some errors in the turbidity measurement, especially during the spring season.

The other alternative method, the acoustic backscattering system (ABS), is being developed for sediment monitoring studies because it is capable of simultaneously measuring with high spatial-temporal resolution (Pedocchi & Garcia 2012), and providing information on flow profiles and bedforms (Guerrero *et al.* 2011; Thorne & Hurther 2014). Current acoustic Doppler meters can provide information about the SSC in water, although they are designed for flow-velocity measurements using ABS (Aydın 2009).

Several researchers have investigated acoustic Doppler velocimeters' performance to estimate SSC using the relationship between signal-to-noise ratio (SNR) and measured SSC values. SNR is a measure of the strength of the reflected acoustic signal relative by sediment particles to the ambient noise level (Aydın 2009). Hosseini *et al.* (2006) observed a strong relationship between the concentration of the sediment and the SNR of the instrument. The sediment concentration was measured conventionally from the siphon sampling to calibrate acoustic Doppler velocimetry (ADV) devices and produced a calibration curve relating backscattering intensity and sediment concentration. They obtained a linear calibration curve with 0.02–0.1 mm coefficients.

Salehi & Strom (2011) examined the relationship between SSC and the SNR with a 6-MHz velocimeter in laboratory water. They used four different synthetic and natural mud mixtures and different combinations. For all sediment types less than 1,500 mg.l^{-1} in concentration, calibration equations were obtained from the obtained log (SSC) $= C_1$. SNR $+ C_2$; and R^2 values for all calibrated equations were greater than 0.980.

Ha *et al.* (2009) conducted a laboratory experiment to reveal the relationship between acoustic backscatter strength and SSC. They used three different ADVs with alternative frequencies (5, 10, and 16 MHz). Results showed none of the devices had a good linear relationship; however, within a limited range of SSC, the backscatter signal can be well correlated with the SSC. They suggested an ADV could be a useful instrument to estimate suspended cohesive sediment concentration with two linear segments in calibration slope.

The known relationship between sediment particle size and turbidity or SNR can be used for continuous monitoring of sediment transport in rivers for different sediment property conditions. This study was conducted in the laboratory with similar river sediment material conditions, including different particle sizes and concentrations. The interactions of SSC with turbidity and SNR were investigated, and calibration equations were obtained to estimate SSC.

MATERIAL AND METHODS

A sediment tower (50 liters) was used to prepare suspended sediment, which was mixed with a propeller operated by an electric motor to create homogeneity throughout the tower. Natural sediment materials were used in 0–50 μm (clay + silt), 50–100 μm, 100–200 μm, and 200–250 μm size groups (Figure 1). Nearly 50 different concentrations were prepared between 0.0 and 7.0 g.l^{-1} for all sediment size groups.

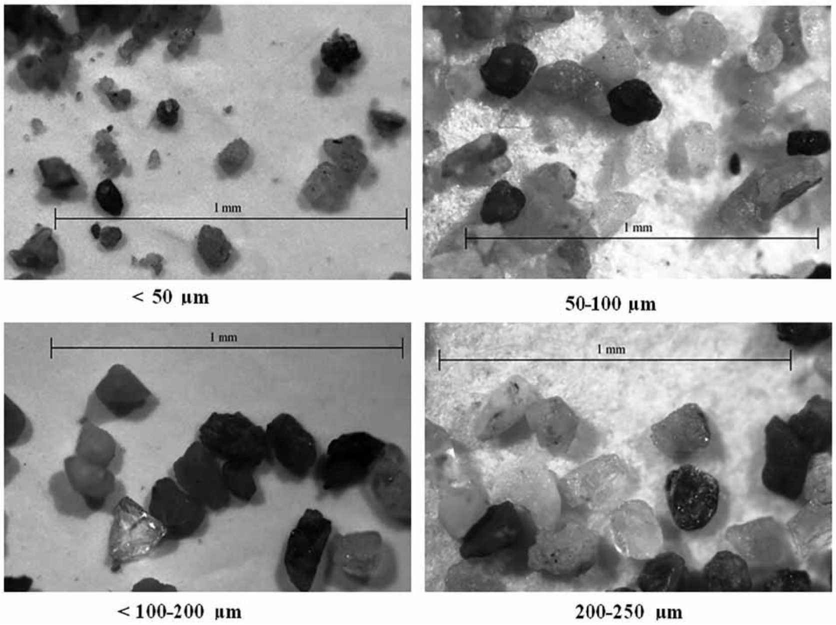

Figure 1 | Microscopic view of different experimental sediment size groups.

Turbidity

Turbidity measurements were made with a Seapoint Turbidity Meter (Figure 2). This device detects light scattered by particles suspended in water, generating an output voltage proportional to turbidity or suspended solids. The output voltage is calibrated to turbidity in formazin turbidity units (FTU). The relationship is linear with a relative error of less than 2% in the range of 0 to 750 FTU, but it becomes nonlinear for turbidity higher than 750 FTU. The unique optical design confines the sensing volume to within 5 cm of the sensor, allowing near-bottom measurements and minimizing errant reflections in restricted spaces. Measured data were saved by an external data logger.

The turbidity sensor read 60 values per minute, and a total of 120 turbidity values were taken over 2 minutes for each concentration. In addition, tree-water sampling was taken to determine real sediment concentration with the gravimetric method.

Figure 2 | Seapoint Turbidity Meter sensor and data logger.

Acoustic Doppler velocimeter

The SNR was obtained by an ADV device; Sontek FlowTracker Handheld 10 Mhz ADV (Figure 3). FlowTracker uses acoustic Doppler technology to measure two dimensions in a small sampling volume located a fixed distance from the probe. Sound generated by the transmitter bounces off suspended particles in the water. This reflected sound returns to the receivers, is averaged together by a processor, and results in water velocity measurements that are recorded at a rate of one per second. The signal is a function of the amount and type of suspended sediments present in the sampling volume; as a result, this ADV could be used to measure SSC if the acoustic response to sediment is known. The

Figure 3 | Acoustic Doppler velocimeter, Sontek FlowTracker.

calibration equations were derived with relation to the SNR measured by an acoustic Doppler velocimeter and known SSC of the water.

Similar measurement procedures with turbidity were conducted, but the first experiment's results indicated ADV was not capable of measuring high-sediment concentration. Therefore, nearly 25 different concentrations were used between 0.0 and 1.5 g.l^{-1} for all sediment size groups. The ADV read 60 values per minute, and a total of 120 SNR values were taken over 2 minutes for each concentration.

Regression models were carried out to determine the relationship between known sediment concentration with measured turbidity and SNR values. These relationships were evaluated using determination coefficient (R^2).

RESULTS AND DISCUSSION

Turbidity and SSC

The turbidity measurements were made for selected concentrations and different size groups. The results and regression analyses with equation and R^2 values are presented in Figure 4. Generally, really good relationships were obtained between SSC and turbidity values (R^2: 0.952, 0.992, 0.987, and 0.977, respectively, from small size to large size group). However, this relationship was not good for the clay + silt sediment group with higher than 4 g.l^{1} concentration and 900 FTU turbidity values. This situation can be explained by the negative effects of clay on turbidity values. However, a reasonable R^2 value (0.952) was obtained under the clay condition, and it was clear that a better R^2 value could be produced considering a

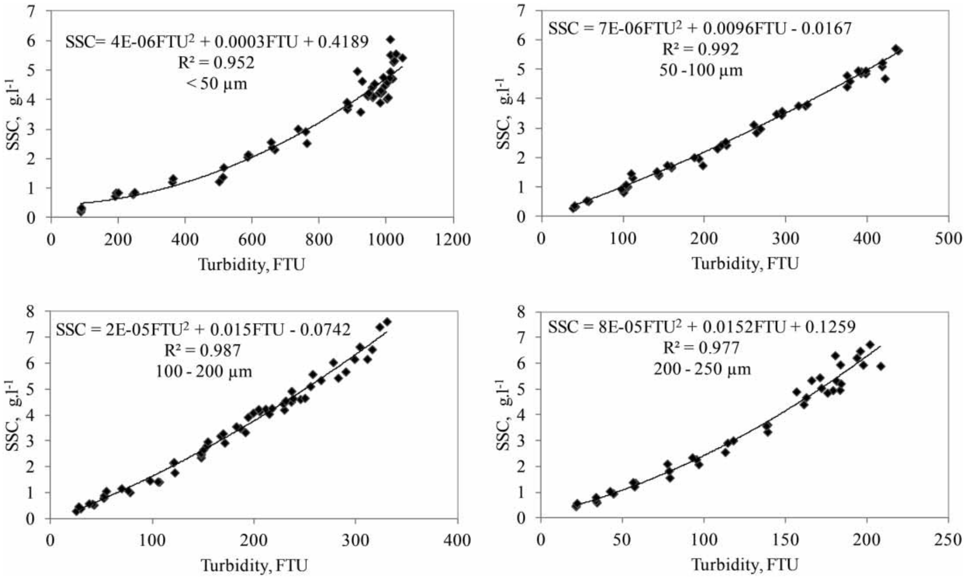

Figure 4 | The relationship between sediment concentration and turbidity.

concentration less than 4 g.l^{-1} for the clay + silt sediment group. Wang *et al.* (2014) reported that values up to 600 FTU had a good relation with SSC. The other result was that the decrease of the turbidity values depended on the increase of the sediment size. The obtained regression equation and R^2 values were really good for the selected size and SSC, but it should be mentioned that a calibration equation should be produced for each river condition. Similar results were obtained by Foster *et al.* (1992) and Pavanelli & Bigi (2005). The researchers reported that large deviation in sediment size led to serious error in estimating SSC. Pavanelli & Bigi (2005) prepared sediment sample groups with narrow intervals (19–31, 58–81, and 124–149 μm) and they obtained a good relationship. They concluded sediment size problems can be eliminated with sensitive calibration, but studies should consider flow regime and water color.

SNR and SSC

Results of the measurements showed SNR values increased depending on the SCC level (Figure 5). Really good relationships were obtained between SNR and SSC values for all sediment size groups (R^2: 0.990, 0.998, 0.994, and 0.973, respectively, from small size to large size group). These relations were observed for lower than 40 dB and 1 g.l^{-1} sediment concentrations. However, for small-sized sediment group (<50 μm) good results were obtained up to 2 g.l^{-1} concentration. In addition, SNR values were strongly affected by small changes in sediment concentration. This property can be accepted as advantageous for sensitive measurement of the mentioned concentration intervals. Aydın (2009) took into account this point and reported SNR values could be used for up to 0.4 g.l^{-1} concentrations for flooding conditions in rivers. Similarly, Ha *et al.* (2009) obtained a good linear relationship between SNR and SSC for 0.9–1.5 g.l^{-1} concentration intervals, and the importance of the measurement device's frequency was emphasized in their study. Salehi & Strom (2011) used experimental data within a similar concentration range to develop calibrated equations of the logarithmic linear form with R^2 values for all calibrated equations greater than 0.980. In addition, they indicated the predicted SSC values were sensitive to changes in the coefficient constants.

The effect of particle size on the calibration equation was observed, especially for the less than 50 μm sediment size group in this study, but a clear effect was not observed between the other size groups. This showed that a single calibration equation can be produced for greater than 50 μm sediment size groups. Rouhnia *et al.* (2014) concluded that the growth of mud flocs influenced the SNR recorded

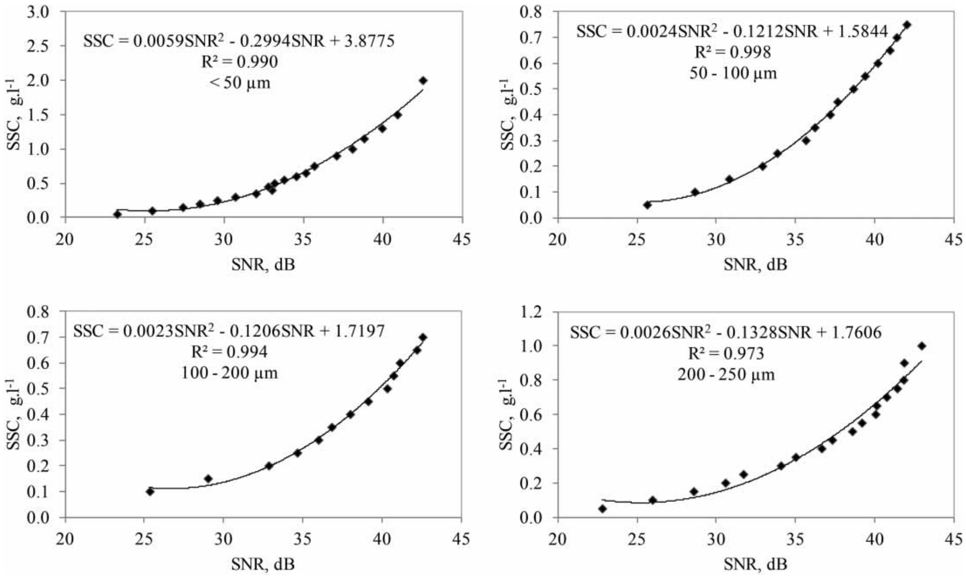

Figure 5 | The relationship between sediment concentration and SNR.

by the ADV and that the sensitivity of the signal to changes in floc size was higher for flocs with diameters less than 80 μm.

CONCLUSION

Turbidity and acoustic methods are promising alternatives for continuous sediment monitoring, but sediment size properties should be considered for each method. The clay content has a negative effect, especially for turbidity measurement; this problem can be solved by obtaining a precise calibration for each condition. In addition, turbidity methods can give reasonable results up to 7.0 $g.l^{-1}$ in concentration, which can allow sediment monitoring in many river conditions. However, color change as a result of water pollution is a problem for turbidity measurements, and it can produce errors when estimating sediment concentrations. ADV can be used to estimate SSC in water, although it is designed for flow-velocity measurements. This study's results showed measured SNR values were strongly related with sediment concentration in water, and an ADV device can be used as a sensitive estimation with a calibration equation. This method has limitations for high concentrations compared with turbidity methods, but it can be used to estimate concentrations, except for flood river conditions, to determine total sediment transportation with flow discharge.

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First received 12 May 2015; accepted in revised form 26 September 2015. Available online 11 November 2015