J Soils Sediments (2014) 14:1235–1241
DOI 10.1007/s11368-013-0813-0

PROGRESS IN EROSION AND SEDIMENTATION IN LATIN AMERICA

Effects of suspended sediment concentration and grain size on three optical turbidity sensors

Gustavo Henrique Merten · Paul D. Capel · Jean P. G. Minella

Received: 30 January 2013 / Accepted: 13 November 2013 / Published online: 3 December 2013

Abstract
Purpose Optical turbidity sensors have been successfully used to determine suspended sediment flux in rivers, assuming the relation between the turbidity signal and suspended sediment concentration (SSC) has been appropriately calibrated. Sediment size, shape and colour affect turbidity and are important to incorporate into the calibration process.
Materials and methods This study evaluates the effect of SSC and particle size (i.e. medium sand, fine sand, very fine sand, and fines (silt + clay)) on the sensitivity of the turbidity signal. Three different turbidity sensors were used, with photo detectors positioned at 90 and 180 degrees relative to the axis of incident light. Five different sediment ratios of sand:fines (0:100, 25:75, 50:50, 75:25 and 100:0) were also evaluated for a single SSC (1000 mg l^{-1}).
Results and discussion The photo detectors positioned at 90 degrees were more sensitive than sensor positioned at 180 degrees in reading a wide variety of grain size particles. On average for the three turbidity sensors, the sensitivity for fines were 170, 40, and 4 times greater than sensitivities for medium sand, fine sand, and very fine sand, respectively. For an SSC of 1000 mg l^{-1} with the treatments composed of different proportions of sand and fines, the presence of sand in the mixture linearly reduced the turbidity signal.
Conclusions The results indicate that calibration of the turbidity signal should be carried out in situ and that the attenuation of the turbidity signal due to sand can be corrected, as long as the proportion of sand in the SSC can be estimated.

Keywords Optical sensor · Scattered light · Sediment flux

Responsible editor: Jorge Enoch Furquim Werneck Lima

G. H. Merten (✉)
Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul (UFRGS), 91501-970 Porto Alegre, Brazil
e-mail: merten@iph.ufrgs.br

P. D. Capel
U.S. Geological Survey (USGS), Minneapolis, MN, USA

J. P. G. Minella
Departamento de Solos, Universidade Federal de Santa Maria, Santa Maria, Brazil

1 Introduction

Estimates of suspended sediment flux in rivers have been put to a wide variety of purposes in water resources management, such as estimating the useful life of the reservoirs (e.g. Morris et al. 2008), identifying land use conditions and management (e.g. Minella et al. 2008), and estimating the flux of pollutants adsorbed to sediments (e.g. Horowitz 1991). The suspended sediment flux (Qss; g s^{-1}) is determined by the product of the suspended sediment concentration (SSC; g m^{-3}) and the water flow rate (Q; m^3 s^{-1}). Whereas the variable Q is usually obtained continuously via equipment that registers the water level that is converted by a stage/discharge relation, SSC is a discrete variable obtained through sporadic manual measurements using appropriate methods and equipment (Nolan et al. 2005). In addition, for many rivers, between 70% and 90% of the suspended sediment flux occurs during high flow events (WMO 2003). Thus, SSC measurements ideally should be collected along with changes in water level, especially during flood events. Therefore, automatic methods of estimating the SSC have been sought to complement traditional measurement methods to reduce the uncertainties associated with estimating suspended sediment flux.

Because turbidity in water correlates well with SSC, turbidity sensors have been used to indirectly estimate SSC in rivers based on automatic, continuous readings of turbidity (Lewis 2002; Schoellhamer and Wright 2002; Rasmussen et al. 2009). Turbidity is an optical property caused by the dispersion of rays of light by suspended material, which may be composed of sand, silt, clay, particulate organic matter, plankton and other microorganisms (ASTM International 2003). The main advantages of indirectly estimating SSC by turbidity are the continuous acquisition of data and low operating cost. On the other hand, there are some limitations to using turbidity sensors, which include low spatial resolution (single point measurement), the accumulation of residues on the lens of the sensor, and the innumerable characteristics of sediments – such as size, shape, and colour – that affect the manner in which light is scattered (Hatcher et al. 2000).

Various styles of optical sensors are used for measuring turbidity in rivers. The differences between them have to do with the wavelength of light emitted and the angle formed between the alignment axis of the light emitted and the position of the photo detector (Sadar 1998). Most turbidity meters use a photo detector of either 90 degrees or greater than 90 degrees (backscatter sensors). Some agencies that monitor water resources in the United States, such as the U. S. Environmental Protection Agency, recommend using optical sensors with 90 degree photo detectors. The justification for this is that these sensors are more sensitive and precise in reading a wide variety of particles (Sadar 1998). On the other hand, the backscatter sensors have been successfully used in oceanography studies of estuary and coastal environments (e.g. Butt et al. 2002; Downing 2006). This article, based on laboratory measurements of natural sediment materials, describes the effects of particle concentration and size on measured turbidity signals of three turbidity sensors with different photo detector positions.

1.1 Operating principles of an optical turbidity sensor

Optical sensors used to measure turbidity in rivers have two main components: a light source and a photo detector that registers the intensity of the light scattered by solid particles suspended in the sample. The light emitted by the source collides with the sediment and is scattered without undergoing any change in its wavelength. The photo detector receives the signal of the scattered light and converts this into an electrical impulse (millivolts) – the more intense the signal of scattered light, the greater the signal registered by the sensor. This linear relation makes it possible to use the scattered light signal to estimate SSC (Bunt et al. 1999).

Most turbidity sensors emit a single wavelength, usually in the infrared range (0.780-0.860 μm). These wavelengths partially compensate for problems with the absorption of light by the colours of the suspended particles in the aqueous medium. The instruments differ, however, in regards to the position of the photo detector relative to the orientation of the beam of light emitted by the source. For sediment particles with diameters greater than the wavelength of the light source, the light scattering actually occurs through optical processes such as reflection, refraction, and diffraction (van de Hulst 1981). Reflection refers to a beam of light colliding with a particle in suspension and changing its direction. In refraction, the ray of light penetrates the particle and undergoes various internal reflections before emerging at a different angle. Diffraction refers to changes in the incident angle that occurs when the light skirts tangent to the particle, but does not actually collide. Some of the light energy can be absorbed by organic-rich particles and dissolved organic matter (Downing 2006).

The direction in which light scatters after collision with a particle depends on the relation between the size of wavelength and the size of the particle. When a particle is much bigger than the wavelength, the light tends to scatter more intensely on the front of the particle (Sadar 1998). Various sediment characteristics affect the intensity of light scattering. The effect of SSC is much greater (by a factor of 1000) than particle size, which is much greater (by a factor of 100) than the shape of the particle, which is greater (by a factor of 10) than the particle color, which in turn is greater (by a factor of 2) than degree of flocculation/disaggregation (Downing 2006).

For backscatter sensors, Downing and Beach (1989) found linear relations for SSCs and turbidity as large as 6000 mg l^{-1} for a mixture of fines (silt + clay). At SSCs greater than this concentration, light absorption becomes the dominant process and the relation becomes non-linear. Ludwing and Hanes (1990) found a linear relation between SSC and turbidity for SSCs as large as 2000 mg l^{-1} for clay and as large as 10,000 mg l^{-1} for sand. Ludwing and Hanes (1990), working with a backscatter sensor using concentrations as large as 10,000 mg l^{-1} and three particle size classes of natural sediment (sand, silt, and clay) collected in an estuary environment, found greater sensitivity for clay and silt than for sand. Foster et al. (1992), working with fines (4 μm to 63 μm) in fluvial sediment and SSC as large as 1000 mg l^{-1}, identified significant variations in sensitivity between particles size fractions. The greatest sensitivity was for clay. The larger the particle size, the less intense the scattering of light. This is because, for a given sediment concentration, the larger the particle sizes, the fewer the number of particles and smaller the ratio of surface area per unit of mass of the suspended particles, and, thus, the lower the probability that the light will be intercepted by a particle in suspension.

2 Material and methods

The experimental set up used is shown in Fig. 1. The sensors tested were installed inside a 19 l, black plastic pail with a diameter of 300 mm and height of 365 mm. The sensor was placed near of the center, 140 mm from the bottom. The sediment was maintained in suspension using a vertical stirring rod that rotated at a constant velocity. Larger particles tended to move toward the walls of the pail due to centrifugal force, which may have reduced the concentration of these particles in the water near the optical sensor.

The sediment used in this study was collected from the bed of High Island Creek, St. Peter, Minnesota, USA, at a U.S. Geological Survey (USGS) stream gauge (id: 0532700). The bed material was brought to the laboratory of Civil

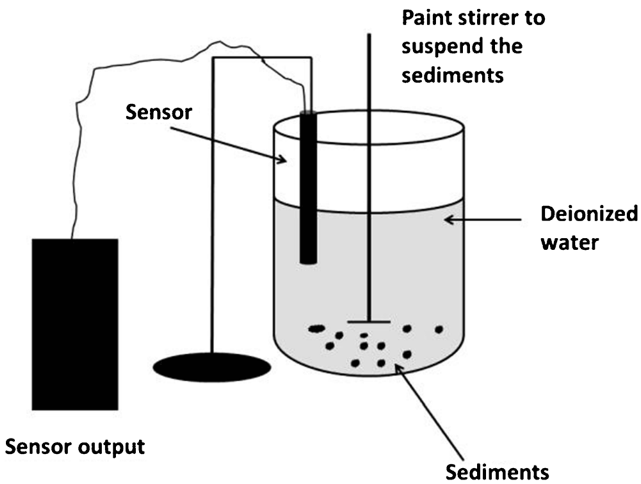

Fig. 1 Experimental set up used for the study

Engineering at the University of Minnesota and dried. Organic matter was removed by heating to 500 °C for 8 hours. Visual observation with a magnifying lens showed that the mineralogy of the sediment was composed largely of quartz, with some less prominent iron and manganese oxides, calcium carbonate, and iron sulfide (pyrite). In addition, the shapes of the particles were observed to be very heterogeneous. The sediment was then sieved to separate it into four classes by particle size: medium sand (D_{50} = 430 μm; range: 500–250 μm), fine sand (D_{50} = 235 μm; range: 250–125 μm), very find sand (D_{50} = 107 μm; range: 125–62 μm) and fines (silt and clay; D_{50} = 40 μm). D_{50} grain size was measured by laser diffraction (for details see Bortoluzzi and Poleto 2006).

Table 1 describes the three turbidity sensors used in the study. The sensors primarily differed in the position of the photo detector. The photo detector was 180 degrees from the beam of light in the SOLAR (Model SL 2000-TS, SOLAR Instruments, Florianópolis, Brazil), 90 degrees in the DTS (Model 12, FTS Instruments, Victoria, Canada), and 90 degrees in the YSI (Model 6136, YSI Instruments, Ohio, USA). The DTS and YSI sensors were initially calibrated with a standardized solution of STABLCAL (Stabilize Formazin Turbidity Standards), and the SOLAR sensor was calibrated with APS Analytical Standards polymers according to manufacturer's recommendations.

Table 1 Description of the three turbidity sensors used in this study

Sensor	Detector angle to incident light (degree)	Light wavelength (μm)
SOLAR	180	0.91
DTS	90	0.78
YSI	90	0.86

2.1 Experiment 1: the effect of concentration and particle size on the turbidity signal

The mixture of water and sediment was prepared in a black plastic bucket with a diameter of 300 mm and height of 365 mm as follows: 10 l of deionized water was mixed with a known amount of dried sediment to make the desired SSC (Table 2). Only three SSCs were evaluated (1000, 3000 and 6000 mg l^{-1}) for medium sand sediments because concentrations for this particle size that are smaller than 1000 mg l^{-1} have a very low turbidity signal. Two small SSC (50 and 100 mg l^{-1}) were added for fines to examine the turbidity signal for low sediment concentrations. When the treatments included silt and clay (<62 μm), a chemical dispersant (5% in mass (sodium metaphosphate + sodium carbonate)) was used in the proportion of 100 ml to 50 g of sediment. To verify the effect of chemical dispersant on the turbidity signal, a mixture of chemical dispersant and deionized water was previously tested, and the results showed that the chemical dispersant did not affect the turbidity signal (zero turbidity). The mixture was soaked overnight prior to mechanical agitation. Before initiating turbidity readings for each sensor and trial (see Table 2), the mixture was pre-agitated for 5 min with a stirring rod. The turbidity (in nephelometric turbidity units; NTU) was read every 30 s over the course of 8.5 min. The final turbidity value for each sensor and grain size class was expressed as a mean. The relation between SSC and turbidity was used to assess the sensitivity (gain) of the sensor (Gippel 1995).

2.2 Experiment 2: the effect of sand in a mixture of sand and fines on the turbidity signal

Five different sediment ratios of sand and fines were evaluated for a single SSC (1000 mg l^{-1}) as follows:

T1 100% silt and clay
T2 75% silt and clay + 25% sand
T3 50% silt and clay + 50% sand
T4 25% silt and clay + 75% sand
T5 100% sand

Table 2 Treatments used in experiment 1 for all three turbidity sensors

Suspended sediment concentration (SSC; mg l^{-1})			
Medium sand	Fine sand	Very fine sand	Fines
	200	200	50
	500	500	100
	1000	1000	200
1000	2000	2000	500
3000	3000	3000	1000
6000	6000	6000	2000

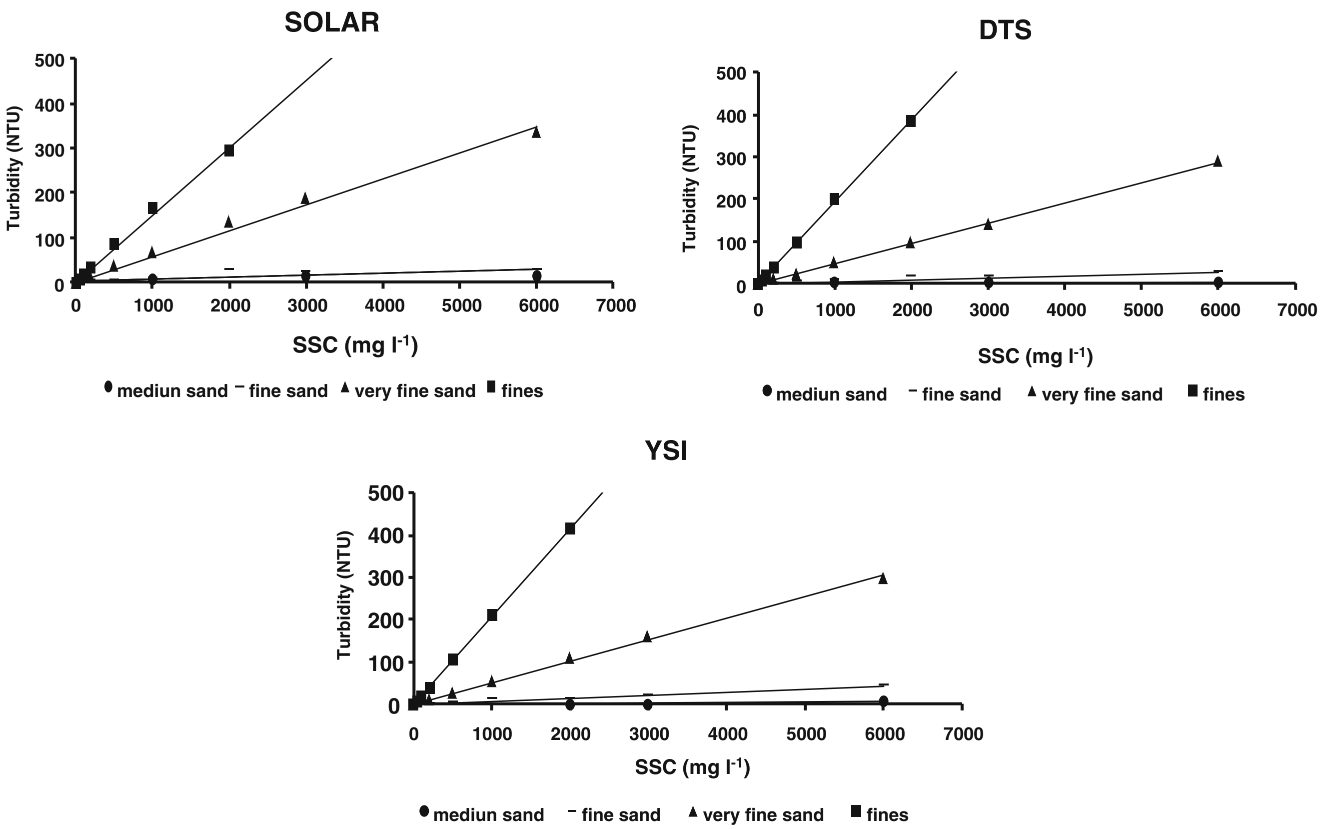

Fig. 2 Relation between turbidity (NTU) and suspended sediment concentration (SSC; mg l^{-1}) for SOLAR, DTS, and YSI turbidity sensors for four classes of particle size: medium sand, fine sand, very fine sand, and fines (silt + clay)

The silt and clay was the same as used in experiment 1. The sand was a composite by mass of 50% very fine sand, 25% fine sand and 25% medium sand. The turbidity reading was determined exactly as described in experiment 1.

3 Results and discussion

3.1 Experiment 1: the effect of concentration and particle size on the turbidity signal

The three sensors use light sources with different wavelengths and different positions for their photo detectors (see Table 1). All three demonstrated a linear relation between SSC and turbidity for the suspensions for all four particle size categories (Fig. 2) for the SSC ranges that were tested (see Table 2; 50 to 6000 mg l^{-1}). Based on the slope of the lines in Fig. 2, the sensitivities of the three sensors were calculated (ratio Δturbidity: ΔSSC) (Table 3). All three sensors showed different sensitivities for each particle size tested. The greater the sensitivity, the more responsive the sensor is to changes in concentration. The three sensors were most sensitive to fines (silt and clay particles) with decreasing sensitivity to increasing grain sizes (Table 3). On average for the three sensors, the sensitivities for the fines were 170, 40, and 4 times greater

Table 3 Coefficient of determination (R^2), sensitivity, and standard deviation of the turbidity measurements for different particle-size classes using three turbidity sensors

Sensor	Statistic	Grain size (µm)			
		Medium sand	Fine sand	Very fine sand	Fines
SOLAR	R^2	0.55	0.62	0.99	0.99
	Sensitivity (NTU/SSC)	0.0012	0.0039	0.0550	0.1470
	Standard deviation	10.6	9.8	7.8	2.0
DTS	R^2	0.77	0.88	0.99	0.99
	Sensitivity (NTU/SSC)	0.0004	0.0040	0.0478	0.1940
	Standard deviation	0.9	1.1	2.9	0.8
YSI	R^2	0.85	0.97	0.99	0.99
	Sensitivity (NTU/SSC)	0.0016	0.0071	0.0499	0.2090
	Standard deviation	0.6	1.6	8.1	1.1

than sensitivities for medium sand, fine sand, and very fine sand, respectively. Similar results have been obtained by other authors such as Downing and Beach (1989); Ludwing and Hanes (1990); and Conner and De Visser (1992).

The YSI and DTS showed greatest sensitivity compared to SOLAR. This is consistent with the concept that the photo detector is more sensitive in reading a wide variety of grain size particles when positioned at 90 degrees (Sadar 1998). On the other hand, the SOLAR sensor showed the greatest sensitivity to the very fine sand particles when compared with DTS and YSI.

The shape and colour of the sediment used in this study were heterogeneous. For this reason, it can be assumed that there was some variation in sensitivity due to differences in colour and shape even within the same particle size class, although the effects of these are of a much smaller magnitude than differences in particle size.

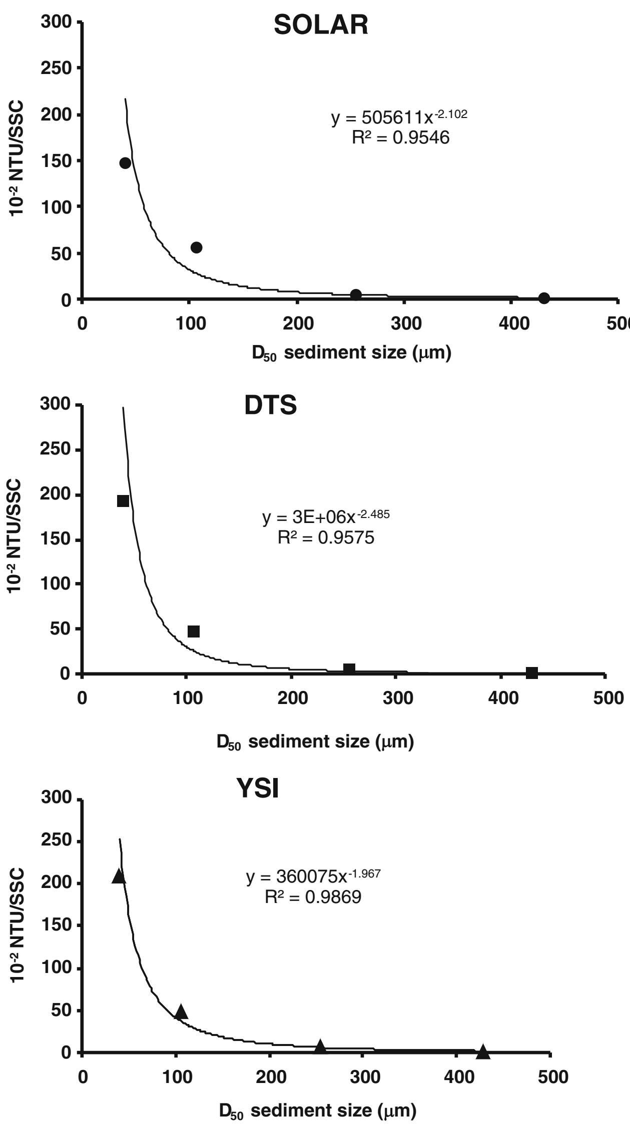

Fig. 3 Relation between sediment class and sensitivity/gain of the SOLAR, DTS, and YSI turbidity sensors

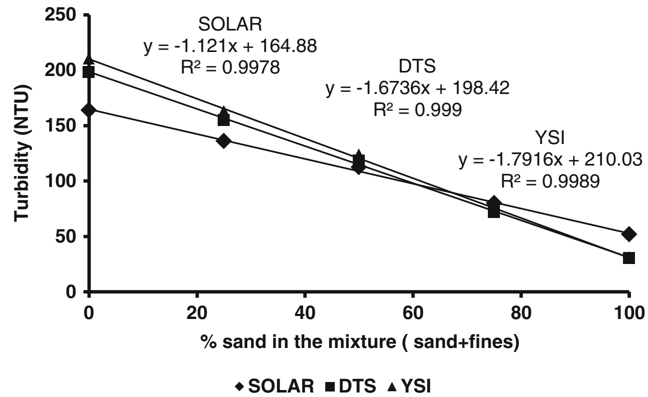

Fig. 4 Turbidity signal relative to the proportion of sand for a single suspended sediment concentration (SSC) as read by the SOLAR, DTS, and YSI turbidity sensors

Figure 3 shows reduction in sensitivity with increasing particle size (D_{50}) for all the sensors. The shapes of the lines in these figures can be described by a power function. Conner and De Visser (1992), working with glass beads of different sizes, also found that a power function described the loss of sensitivity with increased particle size.

3.2 Experiment 2: the effect of sand in a mixture of sand and fines on the turbidity signal

Figure 4 shows the results of turbidity measurements by the three sensors for a single SSC concentration (1000 mg l^{-1}) over a range of sediment ratios of sand and fines. The presence of sand linearly reduced the turbidity signal for the three sensors examined. The size distributions of the suspended sediment probably change over time on an intra- or inter-event basis. Suspended medium sand and fine sand are closely associated with the flow shear stress or hydraulic power at any given moment (Vanoni 1975). Because these larger size fractions are less sensitive to the turbidity signal, they can disproportionately change the SSC compared to the measured

Table 4 Mass of sediment mixture (sand + fines) to form a suspended sediment concentration (SSC) of 1000 mg l^{-1}

	% sand in the mixture				
Grain size	100	75	50	25	0
			mg		
Medium sand	250	187.5	125	62.5	0
Fine sand	250	187.5	125	62.5	0
Very fine sand	500	375	250	125	0
Fines	0	250	500	750	1000

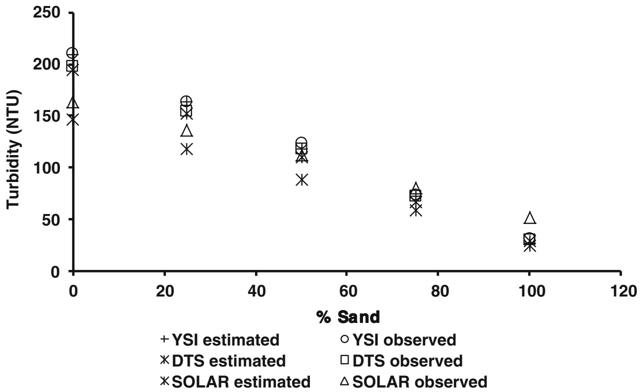

Fig. 5 Estimated and observed turbidity signal attenuated by sand presence in SOLAR, DTS, and YSI sensors to a suspended sediment concentration (SSC) of 1000 mg l^{-1}

turbidity. The reduction in the turbidity signal caused by sand could be corrected for by field measurements or by estimating the concentration of the sand fraction in the suspended sediment mixture based on shear stress or stream power, but must be tested in the field.

When comparing the three sensors, the greatest decline in the turbidity reading was for the YSI sensor, followed by the DTS and then the SOLAR sensor. For example, for the same sediment concentration, the mixture of 50% of sand with 50% fines was 30% lower for the SOLAR sensor and 40% lower for the other two sensors as compared to a mixture of 100% silt and clay. Sensor sensitivity to larger sized particles was already shown to be less than sensitivity to smaller sized particles, so for a given SSC, the presence of sand reduced the intensity of scattered light and, thus, registered a lower turbidity than another sample with the same SSC that did not contain sand.

3.3 Consistence analysis between experiments 1 and 2

A simple linear mathematical model was used to compare the results between experiments 1 and 2. This model was adjusted, using sensitivity values observed in experiment 1 (see Table 3) to estimate turbidity signal attenuated by sand particle as observed in experiment 2:

$$\mathrm{Turb_{Total}} = \left(\mathrm{S_{Fines}SSC_{Fines}}\right) + \left(\mathrm{S_{Medium sand}SSC_{Medium\ sand}}\right) + \left(\mathrm{S_{Fine\ sand}SSC_{Fine\ sand}}\right) + \left(\mathrm{S_{Very\ fine\ sand}SSC_{Very\ fine\ sand}}\right) \quad (1)$$

where: $\mathrm{Turb_{Total}}$ represents the turbidity signal (NTU), S is sensitivity (nondimensional) and SSC represents the suspended sediment concentration (mg l^{-1}). Using Eq. (1) and the S factors presented in Table 3, a set of turbidity equations can be written for the SOLAR, DTS and YSI sensors (Eqs. (2), (3) and (4)).

SOLAR:

$$\mathrm{Turb_{Total}} = \left(0.1470\ \mathrm{SSC_{Fines}}\right) + \left(0.0012\ \mathrm{SSC_{Medium\ sand}}\right) + \left(0.0039\ \mathrm{SSC_{Fine\ sand}}\right) + \left(0.0550\ \mathrm{SSC_{Very\ fine\ sand}}\right) \quad (2)$$

DTS:

$$\mathrm{Turb_{Total}} = \left(0.1940\ \mathrm{SSC_{Fines}}\right) + \left(0.0004\ \mathrm{SSC_{Medium\ sand}}\right) + \left(0.0040\ \mathrm{SSC_{Fine\ sand}}\right) + \left(0.0478\ \mathrm{SSC_{Very\ fine\ sand}}\right) \quad (3)$$

YSI:

$$\mathrm{Turb_{Total}} = \left(0.2090\ \mathrm{SSC_{Fines}}\right) + \left(0.0016\ \mathrm{SSC_{Medium\ sand}}\right) + \left(0.0071\ \mathrm{SSC_{Fine\ sand}}\right) + \left(0.0499\ \mathrm{SSC_{Very\ fine\ sand}}\right) \quad (4)$$

The $\mathrm{Turb_{Total}}$ for each sensor was estimated by applying the respective Eqs. (2), (3), and (4) and by using the mass values described in Table 4. These values represent a corresponding sediment mass for the different grain size particles (medium sand, fine sand, very fine sand, and fines) considering the same SSC (1000 mg l^{-1}) and the same grain size distribution for sand (50% very fine sand + 25% medium sand + 25% fine sand) used in experiment 2. The estimated $\mathrm{Turb_{Total}}$ for each sensor was compared with observed turbidity values presented in Fig. 4 (experiment 2). The observed and estimated values are presented in the Fig. 5. The differences between estimated and observed turbidity signal were very small, except for the

SOLAR sensor. In this case, the difference can be explained by high standard deviation observed in the turbidity signal in experiment 1 (Table 3).

4 Conclusions

For medium sand, fine sand, and fines, the YSI sensor (photo detector sensor at 90 degrees) had a higher sensitivity compared to the SOLAR (photo detector sensor at 180^0) and DTS (photo detector sensor at 90 degrees) sensors. The SOLAR sensor had a higher sensitivity to the very fine sand particles when compared with the DTS and YSI sensors. Sediment samples composed of medium sand and fine sand particles had a lower sensitivity when compared with very fine sand and fines. On average for the three sensors, the sensitivities for fines were 170, 40, and 4 times greater than sensitivities for medium sand, fine sand, and very fine sand, respectively.

Regardless of the type of sensor used, the turbidity signal was linearly reduced for an SSC of 1000 mg l^{-1} as the sand fraction increased in a mixture of sand and fines. These results indicate that calibration of turbidity signal should be carried out in situ and should be done for different events to capture a watershed mean particle size distribution.

Acknowledgements The authors would like to thank Casey J. Lee of the USGS Kansas Water Science Center, Lawrence, KS, and Christopher A. Ellison and Jason L. Roth of the USGS Minnesota Water Science Center, Mounds View, MN, on the valuable contribution to improving this article. The authors would also to thank Jorge Rosso of Solar SA, Florianópolis, Brazil, for the generous loan of the optical turbidity sensors used in this study and Kimberlie Perkins, USGS, National Research Program, Menlo Park, CA, for the particle size analysis. Financial support was provided by CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico Programa Ciência Sem Fronteiras. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

ASTM International (2003) D1889-00 Standard test method for turbidity of water. In: ASTM International, Annual Book of ASTM standards, Water and Environmental Technology, V. 11.01, West Conshohocken, Pennsylvania, USA

Bortoluzzi EC, Poleto C (2006) Sediment studies methods. In: Poleto C, Merten GH (eds) Sediment Quality. ABRH Publication, Porto Alegre, Brazil, pp 83–144 (in Portuguese)

Bunt JAC, Larcombe P, Jago CF (1999) Quantifying the response of optical backscatter devices and transmissometers to variations in suspended particulate matter. Cont Shelf Res 19:1199–1220

Butt T, Miles J, Gauderton P, Russel P (2002) A simple method for calibration optical backscatter sensor in high concentrations of non-cohesive sediments. Mar Geol 192:419–424

Conner CS, De Visser AM (1992) A laboratory investigation of particle size effects on an optical backscatterance sensor. Mar Geol 108:151–159

Downing J (2006) Twenty-five years with OBS sensors: The good, the bad, and the ugly. Cont Shelf Res 26:2299–2318

Downing J, Beach RA (1989) Laboratory apparatus for calibration optical suspended solids sensors. Mar Geol 86:243–249

Foster IDL, Millington R, Grew RG (1992) The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation. In: Bogen J, Walling DE, Day TJ (eds) Erosion and sediment transport monitoring programs in river basins. IAHS Publ 210, IAHS Press, Wallingford, UK, pp 51–62

Gippel CJ (1995) Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrol Process 9:83–97

Hatcher A, Hill P, Grant J, Macpherson P (2000) Spectral optical backscatter of sand suspension: effects of particle size, composition and color. Mar Geol 168:115–128

Horowitz AJ (1991) A primer on sediment trace element chemistry, 2nd edn. Lewis Publishers, Chelsea, USA

Lewis J (2002) Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations. In: Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, Appendix 2, U.S. Geological Survey. Circular 1258. Reno, Nevada, USA

Ludwing KA, Hanes D (1990) A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. Mar Geol 94:173–179

Minella JPG, Walling DE, Merten GH (2008) Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields. J Hydrol 348:546–563

Morris GL, Annandale G, Hotchkiss R (2008) Reservoir sedimentation. In: Garcia M (ed) Sedimentation engineering process measurements, modeling and practices. Amer Soc Civil Engineer (ASCE), Reston, USA, pp 1–17

Nolan KM, Gray JR, Glysson GD (2005) Introduction to suspended-sediment sampling. U.S. Geological Survey Scientific Investigations Report 2005–5077, 1 CD-ROM, available on Web, accessed January 27, 2013, at http://pubs.usgs.gov/sir/2005/5077/

Rasmussen PP, Gray JR, Glysson GD, Ziegler AC (2009) Guidelines and procedures for computing times-series suspended-sediment concentration and loads from in-stream turbidity-sensor and streamflow data. U.S. Geological Survey Techniques and Methods Book 3, Chapter 4, 53 p., available on Web, accessed January 27, 2013, at http://pubs.usgs.gov/tm/tm3c4/

Sadar MJ (1998) Turbidity science –Technical Information Series- Booklet No.11, 26 p. Available on Web, accessed July 2012, at http://www.hach.com/fmmimghach?CODE%3AL7061549%7C1

Schoellhamer DH, Wright SA (2002) Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors. In: Bogen J, Fergus T, Walling DE (eds) Erosion and sediment transport measurement in rivers. IAHS Publ 283, IAHS Press, Wallingford, UK, pp 28–36

Van de Hulst HC (1981) Light scattering by small particles. Dover Publications, New York, USA

Vanoni, VA (ed) (1975) Nature of sedimentation problems in sedimentation engineering, ASCE Task564 Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Committee of the Hydraulics 565 Division, New York, USA, pp 1–16

WMO (2003) Manual on sediment management and measurement. World Meteorological Organization, Geneva, Switzerland