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Research article

Measurement differences between turbidity instruments, and their implications for suspended sediment concentration and load calculations: A sensor inter-comparison study

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ABSTRACT

The use of turbidity for indicating environmentally detrimental levels of suspended and colloidal matter in freshwater systems, and for defining acceptable water quality standards in national and European drinking water regulations, is well established. Turbidity is therefore frequently adopted as a surrogate for suspended sediment concentrations (SSC), or as a relative and objective measure of water clarity in monitoring programmes. Through systematic, controlled experimentation, we tested the response of 12 commercially available turbidity sensors, of various designs, to gauge their measurement consistency when benchmarked against pre-prepared sediment suspensions of known SSC. Results showed that despite calibration to a Formazin standard, sensor responses to identical SSC solutions (in the range of 20–1000 mg L^{-1}) varied considerably. For a given SSC, up to five-fold differences in recorded turbidity were recorded across the tested instruments. Furthermore, inconsistent measurements were identified across instruments, regardless of whether they operated using backscatter or side-scatter optical principles. While the findings may have implications for compliance with turbidity-based water quality standards, they are less likely to be an issue when turbidity is being used as a surrogate for SSC, provided that instrument use remains constant and that instrument drift is not an issue. In this study, a field comparison of a subset of four study sensors showed that despite very different absolute turbidity readings for a given SSC, well correlated and reliable turbidity - SSC ratings were established (as evidenced by r^2 coefficients from 0.92 to 0.98). This led to reasonably consistent suspended sediment load estimates of between 64.7 and 70.8 tonnes for a rainfall event analysed. This study highlights the potential for issues to arise when interpreting water turbidity datasets that are often assumed to be comparable, in that measurement inconsistency of the type reported here may remain unknown to water resource decision-makers and practitioners.

1. Introduction

Regardless of their source, elevated levels of suspended and colloidal matter in river systems can have detrimental impacts on aquatic life (Conroy et al., 2016). These impacts have been well reviewed (Bilotta and Brazier, 2008; Collins et al., 2011; Jones et al., 2012b; Kemp et al., 2011) and present significant issues for water quality managers and policy makers. These potentially extend to downstream lakes, estuaries and coastal waters (Mitchell et al., 2003) where eutrophication from nutrient enrichment or diminished bathing water quality are commonly problematic. High levels of sediment can also have economic consequences and increase the treatment costs of potable water abstracted from watercourses and, in navigable waters, can require increased dredging and impose

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other maintenance costs (Hansen et al., 2002; Paarlberg et al., 2015; Telles et al., 2011). Given these wide-ranging issues and their potential for adverse and costly impacts, reliable methods for monitoring the suspended sediment concentrations (SSC), and the sediment loads, within freshwater systems are necessary. These are central to understanding critical sediment erosion, transport and delivery processes in these systems and underpin appropriate and effective decision making regarding the cost-effective management of these resources.

High frequency field measurements of sediment concentrations are however, time consuming and costly. Consequently, techniques that use surrogate data for estimating suspended sediment concentrations are more practical and are widely adopted to inform water resources management. Notwithstanding uncertainties resulting from variations in suspended sediment concentrations arising from different hydrological conditions and variations in catchment characteristics, surrogate methods utilising acoustic, focused beam reflectance, laser diffraction, nuclear, optical backscatter, optical transmission, spectral reflectance, differential pressure and video microscopy principles are reported in the scientific literature (Gray and Gartner, 2009; Wren et al., 2000). However, the use of bulk optical technologies (as used in nephelometers and transmissometers) in measuring water turbidity as a proxy for suspended sediment concentrations in freshwater systems is particularly well established (see for example, Harrington and Harrington, 2013; Jones et al., 2011; Lewis, 1996; Perks et al., 2015; Ruzycki et al., 2014; Sherriff et al., 2015; Thompson et al., 2014; Yeshaneh et al., 2014). The apparent simplicity and cost-effectiveness of these optical measurements has led to their frequent use as an indicator for environmental change and as valuable sediment metrics for assessing the general health of freshwater systems. Turbidity (quantified in Nephelometric Turbidity Units, NTU) is an index of water clarity or opacity, measured by the degree of light scattering by all suspended material (e.g. clays, silt, organic matter, soluble coloured organic compounds, plankton and other micro-organisms) in a water sample. High turbidity, therefore, can be associated with elevated suspended matter content in the water column and highlights the potential for a physical change in system water quality.

Turbidity meters for water quality monitoring have two principle modes of operation. Transmissometers are those that determine turbidity from measurements of light attenuation in the water column, and nephelometers determine turbidity from measurements of scattered light from suspended particulates in the water column. Many nephelometers that are approved in standard methods (APHA, 2012; EPA, 1979; ISO, 1999), are side-scatter instruments with the detection angle perpendicular to the light beam, but other angles are also used (Lawler, 2016). Such nephelometers include backscatter instruments and those referred to as 'ratio' instruments that estimate turbidity from a combination of side- and backscatter responses from a single light source. Other commercially available instruments are based on attenuation and scatter detection from multiple light sources. In addition to the differences in the angular range and spectral sensitivity of detectors, nephelometers can have different light source and beam configurations (Downing, 2005; Gray and Gartner, 2006, 2009; Lawler, 2016; Rasmussen et al., 2010; Sadar, 2003). Given these differences in operating principles, together with unpredictable spectral properties of water samples (from variations in colour, shape, size and surface irregularity of suspended particles) in comparison to standard Formazin solutions (Downing, 2005), it is perhaps unsurprising that the response of different turbidity sensors to the same environmental sample can be different (Anderson, 2004; Gray and Glysson, 2003). Despite these differences, there is a tendency to consider water turbidity as an absolute measure of a physical property that is directly comparable across different water bodies, regardless of the sensor used. This is the case for example, in defining acceptable turbidity levels in the provision of drinking water to Irish consumers (EPA, 2009a).

Although the need for research that compares the performance of turbidity sensors is noted in the literature (Gray and Glysson, 2003; Ziegler, 2003), studies to date have tended to focus on laboratory bench-top and portable cuvette style instruments (Austin, 1974; Barter and Deas, 2003; Davies-Colley and Smith, 2001; Dogliotti et al., 2015; Hongve and Åkesson, 1998; Letterman et al., 2004; McCluney, 1975; McGirr, 1974; Murphy et al., 2014; Pavelich, 2003; Sadar, 1999). Very few inter-comparison studies of field sensors exist (Barter, 2014; Lewis et al., 2007) and studies that also present actual field comparisons and their implications for sediment flux estimates have, to our knowledge, not been previously reported. To address this research gap, this paper highlights, quantifies and explains, through a detailed series of rigorous inter-comparison laboratory tests, differences in the performance of 12 commercially available turbidity instruments, four of which were further compared under field conditions. The measured field data were used in combination with continuous river flow data to estimate sediment loads and therefore the study facilitates an instrument inter-comparison for both direct measurements of water turbidity and estimates of sediment flux, derived from turbidity data records. The comparison reported here is based on a greater number of in-situ instruments (from a variety of manufacturers), operating under different principles (backscatter, side-scatter and ratio), than has been previously published and will be of interest to researchers and professionals across numerous disciplines, including hydrology, geomorphology, hydroecology and the estuarine and ocean sciences.

2. Test design and methodology

Twelve commercially available nephelometric turbidity sensors comprising seven in-situ probes, three multi-parameter sondes, one portable submersible probe and one laboratory bench-top instrument were systematically tested under laboratory conditions by simultaneous measurements of their responses to prepared solutions of known suspended sediment concentrations. All the probes are widely used in monitoring programmes where direct measurements of water turbidity are required, or where they record turbidity as a surrogate measurement for establishing suspended sediment concentrations. The manufacturer, sensor type, wavelength and declared technical operating specifications of the sensors are given in Table 1. In addition, four of the 12 instruments were tested in field conditions when continuously recording water turbidity for a storm (high sediment carrying) event. The instruments that were field tested are indicated in Table 1. Although some sensors were pre-calibrated by their respective manufacturers prior to delivery, these were again benchmarked to recognised standards (by the authors) based on dilutions of Formazin stock (4000 NTU) according to the APHA Method 2130B, prior to testing. Sensors that had not previously been calibrated were also standardised to these Formazin dilutions such that consistency of performance across all 12 tested sensors was established at the commencement of the study.

While it is accepted that reporting units for turbidity measurements vary internationally, the European norm is to describe water clarity in terms of either Nephelometric Turbidity Units or Formazin Nephelometric Units (FNU), regardless of the operating principle being adopted in the measurement. NTUs and FNUs are equivalent units and in this paper, all turbidity measurements are reported in NTUs.