TECHNICAL DESIGN NOTE

Design and performance assessment of a plastic optical fibre-based sensor for measuring water turbidity

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Abstract

A turbidity sensor based on a plastic optical fibre is presented. The sensor is based on transmission and 90° scattering variations with the total suspended particles in a solution. Transmitted and scattered output signals were characterized and evaluated for different configurations for a large range of clay concentrations. The developed system, in comparison with the OBS-3+ standard system, is more robust, of low cost and has a user-friendly design. A good correlation between the systems was accomplished.

Keywords: turbidity sensor, plastic optical fibres, transmittance, nephelometry, management of sediments, risk assessment

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Turbidity sensors are becoming increasingly used in soil erosion studies and operational water quality monitoring programs for continuous measurement of suspended sediment concentrations. However, the costs of commercially available sensor systems for continuous monitoring of soil losses constitute an important constraining factor. Automatic samplers, for measurements of sediment fluxes at the slope and especially at the catchment's scale, have existed for a couple of decades but can only gather limited numbers of samples, whereas the more recent turbidity sensors continue to be rather costly and, therefore, are generally employed to produce single readings at a fixed height of the water column [1]. However, a low-cost turbidity meter system would allow the employment of multiple sensors across the channel section and with the depth of the water column. Furthermore, as has been proposed by EPA (Environmental Protection Agency) guidance manual, turbidity measurement

systems require complex installation and extensive calibration, and present some durability problems because of the electronic parts involved [2].

Fibre-optic-based sensors are suitable to be used in an environment of a potentially hazardous nature without significant sensor performance deterioration and also in situations where multi-sensor operation and *in situ* and remote monitoring are required and offer a new approach to the measurement problems of conventional sensors [3]. In spite of important advances in the last couple of years, the deployment of fibre-optic-based sensors in field research or operational environmental monitoring programs is a largely unexplored area of research. In the literature, some studies can be found which report turbidity sensors, namely for underwater applications [4] and wine industrial processes [5] but mainly for low concentration of suspended sediments, typically 2–4 g l⁻¹. Campbell *et al* presented a fibre optic in-stream transmissometer for high-concentration measurements; however, the authors did not address the scattering dependence

Figure 1. Schematic design of the sensor.

on the concentration of the suspended particles [6]. More recently, Postolache *et al* obtained very promising results, but the data processing of their multi-beam optical system seems too complex for field monitoring applications and the performance was studied for only four turbidity calibration solutions [7].

The turbidity of a medium is directly dependent on its transparency. Suspended matter in a liquid results in the scattering and absorption of light rays. The attenuation and scattering of a light beam passing through a suspension depends on several parameters, namely particle concentration, particle sizes, size distribution and refractive indices of the particle and medium. Here we report on the first design and performance assessment of a plastic optical fibre (POF) turbidity sensor for different clay particle concentrations and thus make a proof of concept.

2. Description

As can be seen in figure 1, the intensity-based POF system design presented here is used to quantify both the amount of light transmitted through a liquid and the amount scattered at an angle of 90° from the incident beam (nephelometry). The system is based on a LED (IF-E96), with a centre wavelength of 660 nm, connected to the emitter optical fibre (HFBR-RUS100), and on two receiver fibres placed at 90° (scattered light) and 180° (transmitted light), each connected to a photodetector (IF-D91). Both output signals were acquired using a NI DAQ board (USB 6008) with a 2 Hz frequency. Experimental results were obtained through a time average procedure of a 3 min acquisition and error bars refer to their SD. A simple application in LabViewTM was developed as a user interface, allowing (i) the control of USB 6008, (ii) visualization of the collected data and (iii) data storage.

The system performance was evaluated to empirically determine the best configuration with respect to longitudinal separation of two fibres, L , using several single clay

suspensions with a large range of concentrations, up to 10 g l^{-1} , with the particle size distribution between 0.001 and 0.002 mm. Three distances were tested: 2, 5 and 10 mm. Validation of the method was accomplished through the comparison of the selected configuration with a standard commercial system (Campbell OBS-3+) using samples of overland and stream flow collected from the burned study area of Colmeal (Central Portugal). The homogeneity of all suspensions was accomplished by means of a magnetic agitator.

3. Results

For the three established distances between emitter and receiver fibres, the transmitted output signal decreases with increasing concentration of suspended clay particles (figure 2(a)). Moreover, in accordance with the Beer–Lambert law, exponential models provided an excellent fit to the measurement results for all three materials (all correlation coefficients were 0.999). Comparing the different configurations, it can be seen that a distance of 2 mm provides higher resolution and range of operation when compared with the distances 5 mm and 10 mm. This is due to the dependence of the light coupling on the axial distance of the fibres. The noise level (4.22 mV) is achieved at 5 g l^{-1} and 9 g l^{-1} for 10 mm and 5 mm, respectively, and extrapolating data are expected to be attained 40 g l^{-1} for 2 mm. However, the 5 mm spacing was preferred for being less susceptible to clogging up under field conditions, especially by the coarser ash and plant particles that are commonly eroded from hill slopes during the initial phases after wildfire.

The scattered output signal (figure 2(b)) revealed similar behaviour for all configurations because the scattering receiver was always kept at the same position: as close as possible to the emitting fibre but avoiding direct light. It can be seen that the scattered light only starts to be detected at 1 g l^{-1} . After this threshold, a strong linear correlation ($R^2 = 0.995$) with clay concentration is accomplished, at least up to 10 g l^{-1} (figure 2(b)). Trials to place the scattering receiver at greater distances resulted invariably in the total loss of the scattered signal.

Due to the dependence of both the output signals on other variables than the particle concentration, results shown in figure 2 cannot be understood as global calibration curves of each design, being valid only for the specific conditions of this test: clay particles with a size range of 0.001–0.002 mm suspended in water ($RI \sim 1.33$). However, results suggest that the transmitted and scattered output signals can be used for low and high clay particle concentrations, respectively.

Figure 3 shows the results obtained for 29 runoff samples collected in a Colmeal fire, which were analysed with a commercial backscatter sensor, OBS-3+, and the new developed plastic optical sensor. Scattering results were not used because the concentration of suspended particles in runoff samples was within the threshold. The POF-sensor values (figure 3(a)) agree well with those obtained in the initial test with similar concentrations of clay for 5 mm configuration. However, the runoff sample with the highest

Figure 2. Transmitted (a) and scattered (b) output signal with varying concentrations of clay for three configurations.

Figure 3. (a) Transmitted output signal $\pm$ SD of the 29 runoff samples; (b) correlation between sensors: POF-sensor measurements displayed in light losses (obtained from $1 - V_{\text{trans}}/V_{0 \text{ g l}^{-1}}$) and OBS-3+ measurements in NTU.

sediment concentration (1.09 g l^{-1}) did not follow the same tendency. The higher-than-expected transmitted output signal of this sample was confirmed by OBS-3+ with a comparatively low turbidity. A possible explanation is suggested by the fact that the sample's POF-sensor values are more variable than the values of the other runoff samples. This greater variability could be due to the larger suspended particles, which were detected by visual inspection, suggesting sensitivity of the sensor to the particle size. In fact, particles of larger dimensions can more easily interrupt the coupling of light between the emitter and receiver fibres when passing between them, increasing signal variability. This study will be addressed in further work. With respect to the validation of the proposed method, the POF-sensor values for the runoff samples are closely related to the corresponding OBS-3+ values (figure 3(b)). This relationship can be fitted very well by a linear regression equation.

4. Discussion

A new low-cost and robust POF-based system for turbidity evaluation of suspended particle solutions was presented and showed viability on the determination of sediment concentration. From the three configurations tested, a distance of 5 mm between the emitter and transmitted light receiver was selected because it presented the best balance between the sensitivity of the sensor and its capacity to operate with suspended particles of large dimensions. The proof of concept of our system is accomplished but, for the accurate estimation of particle concentration with the proposed sensor, other variables have to be considered and studied, namely particle size. As indicated by this study, preliminary results on this matter suggest that, not only the average transmitted output signal is dependent on the particle size class, but also the output signals variability.

By comparing OBS-3+ and POF-based system performance, a good correlation was obtained. Nonetheless

the operation mode is easier with the newly developed system since the homogenization of samples is more difficult with OBS-3+ because measurements have to be performed in 3L tanks (sensor output depends on the tank used). The output of the POF does not depend on the tank, support or specific position and it is cost-effective. The small-sized optical systems make it highly mobile for field measurements. It must be emphasized that the developed system is cost-effective, opening new opportunities for soil erosion and operational water quality monitoring studies.

Further investigation will also be focused in the study of the effect on the system performance of several sediment properties, such as reflectivity, sediment colour and optical properties of the medium, in different field conditions.

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