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High Concentration Suspended Sediment Measurements Using a Continuous Fiber Optic In-Stream Transmissometer

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ABSTRACT

Suspended sediment loads mobilized during high flow periods in rivers and streams are largely uncharacterized. In smaller and intermittent streams, a large storm may transport a majority of the annual sediment budget. Therefore monitoring techniques that can measure high suspended sediment concentrations at semi-continuous time intervals are needed. A Fiber optic In-stream Transmissometer (FIT) is presented for continuous measurement of high concentration suspended sediment in storm runoff. FIT performance and precision were demonstrated to be reasonably good for suspended sediment concentrations up to 10g/L. The FIT was compared to two commercially available turbidity devices and provided better precision and accuracy at both high and low concentrations. Both turbidity devices were unable to collect measurements at concentrations greater than 4 g/L. The FIT and turbidity measurements were sensitive to sediment particle size. Particle size dependence of transmittance and turbidity measurement poses the greatest problem for calibration to suspended sediment concentration. While the FIT was demonstrated to provide acceptable measurements of high suspended sediment concentrations, approaches to real-time suspended sediment detection need to address the particle size dependence in concentration measurements.

Key Words: suspended sediment, sediment transport, turbidity, optical sensors
INTRODUCTION

Suspended sediment loads mobilized during storm and high flow periods in urban and agricultural streams have largely not been characterized. This is due in part to the difficulty in obtaining regular measurements with adequate temporal resolution during high flow periods. Suspended sediments may be a water quality problem for light penetration in relation to algal primary productivity, as well as, for gill clogging of aquatic organisms (Vondracek, et al., 2003; Kirk, 1994). In addition to being a water quality problem itself, sediments facilitate transport of many pollutants including heavy metals (Hatje et al., 2001; Rhoads and Cahill, 1999) and organic compounds like polychlorinated biphenyls (PCBs), dioxins, and pesticides (Borah et al., 2003; Milburn and Prowse, 1998; Götz et al, 1994; Walters et al., 1989).

While relationships between storm hydrographs and suspended sediment concentration have been developed, these relationships may not be consistent as found in a detailed analysis of seven separate flood events in northern Italy (Menzi and Marchi, 2000). Changes in runoff source water, the sediment source, and storm characteristics may all significantly change the distribution of transported sediment within a storm. In urban intermittent streams large sediment loading events may be related to bank failure, exposed soils due to development, and washout of previous deposits during lower energy flows. Stream channels and banks are major sources for suspended sediments, contributing as much as 66% of the total annual suspended sediment mobilized in urban streams in southern California, USA (Trimble, 1997).

Suspended sediment concentrations in urban runoff during large storms can be in excess of 10 g/L, however, few continuous sensors are designed to measure concentrations higher than 2-3 g/L. This is a problem in streams where a majority of the sediment load is mobilized in a few large storms. Yet, without continuous monitoring large storms are unlikely to be monitored.
Moreover, if suspended sediment concentrations exceed the range of the continuous measurement device, then information is lost during a critical sampling event. For example, a large flood during a three-day storm in northern California during 1997 was reported to transport seven times greater sediment mass than what was mobilized in total for either 1995 or 1996 (Ogston et al., 2000). Suspended sediment concentrations in this large storm were greater than 10 g/L even in the large river system in this study (Eel River).

Various methods are used to estimate suspended sediments such as flow proportioned samplers, sampling pumps, optical back scattering (OBS), acoustic back scattering (ABS), and laser diffraction (Wren et al., 2000). While grab samplers can accurately estimate sediment concentration at a point in time, they lack the temporal sampling resolution required to capture rapid intermittent flushes of suspended sediment during storms. ABS methods are promising techniques for distributed non-intrusive sediment sampling (Wren et al., 2000), however, research and development of this technology is still ongoing. The continuous monitoring technologies most readily available as commercial products are turbidity probes based on OBS at 90 and 180 degrees and laser diffraction.

Turbidity correlations to suspended sediment concentrations have been criticized as being inconsistent, with large variability in the signal caused by constituents other than suspended sediment (Riley, 1998). Turbidity, by definition, is the cloudiness of water or the extent to which light is scattered in the water (Davies-Colley and Smith, 2001). As such, turbidity may depend on many factors in addition to suspended sediment including: organic matter and other floating debris, algae, air bubbles, and even water discoloration (Riley, 1998; Clifford et al., 1995). While some of these issues can be removed in when using OBS or ABS devices, the measurement is still not a true value of suspended sediment in the water column (Davies-Colley
and Smith, 2001). In addition, correlation relationships between turbidity and suspended sediment concentration often fail at high concentrations, where the calibration relationship between turbidity and light scattering becomes nonlinear. Also, the total sampling volume of OBS probes will change with sediment concentration, which could potentially lead to representative sampling and scaling issues.

The commercially available laser diffraction technology, the LISST-100 (Sequoia Scientific, Redmond, WA), has been demonstrated to accurately measure both volumetric sediment concentration and particle size distribution at lower concentrations (>2 g/L) using a single device (Gartner et al. 2001; Agrawal and Pottsmith, 2000). Unfortunately this device is expensive (in excess of $10,000), limiting its application few locations in larger monitoring projects. The utility of the LISST has also not yet been demonstrated for high suspended sediment concentration, however, it is expected that higher concentrations could be captured by adjusting the optic pathlength to less that the standard 5 cm (Pottsmith, pers. comm.).

Continuous suspended sediment sensors are needed that can be easily calibrated and deployed to measure high sediment concentrations (Campbell et al., 2003). Therefore, we designed a simple linear Fiber optic In-stream Transmissometer (or the FIT) for continuous total light transmittance measurements of suspended sediment concentration. All the components for the FIT are inexpensive (total system < $1000) and readily available. Our specific objectives were to (1) design and test the FIT to measure suspended sediment concentration, (2) examine influences of sediment color and particle sizes on measurements, and (3) compare FIT performance to commercially available turbidity sensors. In addition, issues of sensor calibration and possible improvements on design will be discussed.
METHODS AND MATERIALS

Theory

Radiant light intensity \((I)\) of a given wavelength \((\lambda)\) is defined as:

\[
I = \int I_{\lambda} \, d\lambda
\]  

(1)

Intensity is a traditional term used for radiant power among other radiant fluxes, so the more acceptable term in the sense of this examination is radiant power \((P_{\lambda})\) (Braslavsky et al., 1996).

The radiant power \((P_{\lambda})\) was measured in the FIT using the photodetector and the initial power of transmission from the source to the detector in pure water is defined as \(P_{\lambda}^o\). Then total transmittance \((T)\) can be defined as:

\[
T = \frac{P_{\lambda}}{P_{\lambda}^o}.
\]  

(2)

In a practical sense, \(T\) is the light reaching a detector from a source, that was not absorbed or back scattered along the way. For the purposes of comparison of the light transmittance results from the FIT with the standard turbidity probes the normalized inverse of transmittance \((T_n^{-1})\) was used:

\[
T_n^{-1} = \frac{(P_{\lambda} - P_{\lambda}^o)}{(P_{\lambda_{\text{max}}} - P_{\lambda}^o)}
\]  

(3)

where, \(P_{\lambda_{\text{max}}}\) was operationally defined as the mean radiant power measured at a suspended sediment concentration of 10 g/L. Therefore, Equation 3 is the inverse of radiant power of transmission relative to the initial power \(P_{\lambda}^o\) and normalized by the maximum suspended sediment concentration in the linear range of the transmittance-concentration relationship. For simplicity, the inverse of \(T_n\) is used so that the output from the FIT will rise with rising sediment concentration so that a single point calibration of the sensor is possible.
**Linear FIT Design**

Fiber optic transmissometers are based on the total light transmittance between a paired light source and detector. Light emitted from the source will be absorbed or scattered off in different directions, decreasing to total intensity that reaches the detector. A standard relationship described for a specific wavelength of light in photochemistry is the Beer-Lambert Law, which states that there is a logarithmic relationship between the radiant power ($P_\lambda$) that will reach a paired detector (i.e. light absorbance) and the concentration of a target compound or particle within the pathlength from source to detector (Braslavsky, et al. 1996). When designing a transmissometer, measurements are more easily calibrated to concentration when the basic form of the Beer-Lambert Laws is still linear, where concentrations are still low enough that light absorbance is not approaching the limit (complete absorbance). When the relationship between radiant power and concentration is linear, then a single point of calibration is possible (as in Eq. 3).

Another design consideration when using fiber optic cables, or waveguides, is the arrangement of the fibers at the sensor end from the fiber bundle in the cable. For example in the schematic in Figure 1, most fiber optic cables are bundled as seen in 1b, however, a linear arrangement of the same optical fibers (as seen in 1a) could be superior for real-time measurement. As illustrated in the schematic figure, if a sharp change in particulate concentration were to flow through a system (common in natural systems), a continuous measurement would be expected to look like those on the right side of the Figure 1. As the sharp concentration change reaches the linear sensor all the fiber encounter the change at the same moment, where as in the bundled arrangement the optical fiber encounter the concentration front a different moments (the sediment front does not reach all fibers at exactly the same time). This
leads to the more gradual rise in the combined signal from all the fibers in the graph in 1b than in 
1a.

Given these considerations, paired fiber optic waveguides with the linear optical fiber 
arrangements on one end were selected. The light source intensity and pathlength between the 
source and detector were selected to maximize a linear active measurement zone within the Beer-
Lambert Law. The resulting simple FIT design is in Figure 2. The light source is a common red 
light emitting diode (LED) with a with an active bandwidth range from 603 to 672 nm and a 
peak at 640 nm. A red light source was selected as it reduces any interference of color and 
focuses on the suspended sediment measurement target. A wavelength around 645 nm is 
common for suspended sediment measurements (Holdaway et al., 1999). A tunable laser light 
source (Thor Labs Inc. Newton, NJ, USA) was also tested to determine if there was an advantage 
of using a higher quality stable source over the inexpensive LED. In this case there was no 
added advantage so an LED power with a 9 volt battery was selected.

Two different detectors were tested, the first a portable USB2000 spectrometer (Ocean 
Optics Inc., Dunedin, FL, USA) and the second a photodetector connected to a Fluke Co. 
(Everett, WA USA) multimeter. The photodetectors can be constructed, however in this case the 
Fluke Company provides a Fiber Optic Meter as an accessory to their multimeter. Both the 
spectrometer and Fluke setup could communicate directly to a computer to collect 
measurements. The performance of the two detectors were again, in this case, similar so the 
Fluke system was used for the following studies.

**Laboratory Testing**

Once the FIT components were selected and tested, studies were designed to assess the 
performance of the FIT for high concentration suspended sediment measurement. The precision
of the FIT, sensitivity to sediment color, and sensitivity to particle size classes were examined using a laboratory system. In addition, FIT performance was compared to two commercially available turbidity sensors: the Global Water WQ710 turbidity probe (Global Water Instrumentation Inc. Gold River, CA, USA) and the LaMotte 2020 grab sample turbidity (LaMotte Co., Chestertown, MD, USA) that is a portable hand held cuvette device.

All these studies were performed using a rapid water circulation system constructed out of clear acrylic (Figure 3). The benchtop setup, called the storm water simulator (SWS) is large enough to install the FIT and Global Water turbidity probe and yet not so large that the circulation pump could not keep sediments suspended. Sediments were kept suspended by baffles and water jets that maintained a high flow velocity and also promoted mixing. There were a total of 4 water jets and 4 baffles, that suspended sediments for concentrations up to 10 g/L, determined by visual inspection for sediment deposition in the SWS.

In order to assess the precision of the FIT, replicate runs of increasing sediment concentration were initiated in the SWS and measured by the FIT. The SWS was started with no sediment and then a mass of sediment equivalent to 1 g/L was added and allowed to mix before measurements were taken. This process was repeated at 1g/L increments up to 10g/L, which is approaching both the expected upper limit of stormwater sediment concentrations and also where the FIT signal begins to become nonlinear.

For the color assessment, three different sediment types were collected respectively from the channel of an intermittent stream (Arroyo Las Positas) at the Lawrence Livermore National Laboratory in Livermore, CA, bore hole core samples near the stream channel, and standard commercially available sand. Each sediment sample was ground using a mortar and pestle to break down soil aggregates and classified using a Munsell Color names, as well as, hue,
lightness, and chroma (Munsell Soil Color Charts, 2000). This is a qualitative method to compare different soil and sediment coloration. The stream channel sample was a Light Olive Brown 2.5Y 5/3, the core sample a Brown 7.5 YR 5/4, and the sand a Pale Yellow 5Y 7/3. The first number indicates the different hue for each sediment sample, but all have a yellow or yellow-red hue base. The lightness and chroma numbers have to do with the intensity of the hue.

Measurement sensitivity to different particle size classes was assessed for both the FIT and the two turbidity devices. Ground sediment samples (the stream channel Light Olive Brown) were sieved through standard ASTM Testing Sieves to isolate specific particle size classes. Five particle classes were separated, limited by the available sieves, including $>45 \mu m$, 75-150 $\mu m$, 150-250 $\mu m$, 250-300 $\mu m$, and 710-1000 $\mu m$. Studies were performed for sediment in each of these particle size classes in the SWS as described above, increasing suspended sediment concentration by 1 g/L increments up to 10 g/L.

**RESULTS AND DISCUSSION**

These tests suggest that the FIT is a reasonable design for real-time measurement of suspended sediment. The components are relatively inexpensive and the entire device is simple to construct. The FIT precision within a replicate run is good and increases slightly between runs (Figure 4). This variability likely has to do with slight changes in the connection of the fiber optic waveguides to the source and detector. Fitting a straight trend line to these data as a calibration produces slopes of 0.1049, 0.1047, and 0.1095 for replicates 1, 2, and 3 respectively. The $R^2$-values for these trend line calibrations ranged from 0.977 to 0.995. The data in this figure demonstrate the linearity in FIT response and potential for a single point calibration.

Using these data, the FIT precision is around 1 to 2 % at lower concentrations and up to about
4% at 10 g/L suspended sediment. Reported precision for filtered grab sampled, turbidity, and visual clarity techniques are 10%, 10%, and 4%, respectively (Davies-Colley and Smith, 2001).

**Sediment Color**

Response variability in tests using the different color sediments was greater than the 1 to 4% precision, however the effect was still not greater than 14% at 10g/L (Figure 5). There does appear to be an influence of sediment color in the FIT. At the same time, the measured response was still linear with $R^2$-values for the trend line of 0.973, 0.988, 0.994 for the Pale Yellow sand, Brown core sample, and Light Olive Brown channel sediment, respectively. Slopes for the trend lines ranged from 0.0858 to 0.0968, which is in reasonable agreement with the slopes observed in Figure 4.

Sediment color is an often neglected factor that may influence transmittance and absorbance measurements. In this case, it is possible that differences observed are in part caused by difference geometries of the particles, not just the difference in color. This color comparison was made on particles from the same size class (150-200 $\mu$m), however, clays and sands tend to differ in particle geometry. Clay particles made up of illite, montmorillonite, kaolinite, halloysite, tend to be shaped as plates, disks, and fibers, while quartz sands are more spherical with greater width (Jury et al., 1991; Sparks, 1995). As our testing did not account for light scattering by different particle geometries, we can not be sure if the variability observed in Figure 5 results from color or particle geometry. As such, the influence of sediment color on FIT measurement may need further examination.

**Particle Size & Comparison to Turbidity Probes**

The particle size dependence of transmittance measurements is clearly the dominant source of variability. Measurement results for the FIT, the Global Water turbidity probe, and the
hand held LaMotte turbidity device are presented in Figure 6. The two turbidity devices reach a maximum at 1 to 4 g/L, depending on particle sizes. These maximums are built into the turbidity probe design and calibration. Turbidity signal becomes non-linear beyond a certain concentration, just like the FIT, due to light source intensity and the optical pathlength (Beer-Lambert Law). This is the advantage of constructing a transmissometer for specific applications so that the active measurement range fits those in the system of interest.

Particle size dependence in transmittance and optical back scattering measurements have been examined in many studies, however, a systematic relationship between particle size distribution and these measurements has not been defined (Baker, et al. 2001; Clifford et al., 1995; Baker and Lavelle, 1984). Calibrations have included empirical relationships (Baker et al. 2001; Clifford et al., 1995), however, these relationships are only applicable in systems where the sediment source constrained (particle size is known) and is reasonably consistent like in low concentration coastal and marine waters. The normalized linear calibration approach for the FIT presented in Equation 3, would account for changes in absolute light absorbance as long as (1) the sediment source is consistent within a storm event, (2) the calibration point is determined from a single grab sample from that storm, and (3) the relationship between $T_n^{-1}$ is linear. The last of these criteria could be a problem for the large (>710 $\mu$m) and smaller (<45 $\mu$m) particle sizes (Figure 6). Calibration could be adjusted for the proportion of particle sizes beyond these upper and lower bounds. The potential variability introduced by these particle sizes is as large as 37% in the 2 to 4 g/L suspended sediment concentration range. While this is an improvement over the comparable variability in the tested turbidity probes, it is still and important limitation of these types of sensors.
CONCLUSIONS

We developed a Fiber optic In-stream Transmissometer, or FIT, for continuous measurement of high concentration suspended sediment in storm runoff. The FIT was demonstrated to have good precision for suspended sediment concentration measurements up to 10g/L. Performance of the FIT was compared to two commercially available turbidity devices and was shown to provided better measurements at both high and low concentrations. Both turbidity devices reached a maximum measurements at 1 to 4 g/L sediment concentrations. This demonstrates the advantage of constructing a transmissometer for target concentrations by adjusting the optical pathlength and light source intensity as devices like the FIT would be relatively inexpensive to construct. In addition the linear array of coupled optical fibers provided a larger measurement volume and increases the temporal resolution by sampling in only a single spatial dimension.

Both the FIT and turbidity probe measurements showed a dependence on sediment particle size. It is clearly the particle size dependence of transmittance and turbidity measurement that causes the greatest problem for calibration to suspended sediment concentration. Despite this large source of variability, it would still be possible to calibrate the FIT for measurements even in particle sized grater than 710 µm and less than 45 µm. The FIT was the only device tested capable of measuring the high suspended sediment concentrations that may be encountered in stormwater runoff. Field testing of the FIT is still necessary to determine long-term performance under harsh field conditions.

Finally, approaches to real-time suspended sediment detection need to address the particle size dependence that exists for optical measurement methods. Research should focus on more sophisticated sensors that can measure and account for sediment particle sizes.
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References:


Figure 1: Schematic of the advantage of linear verses fiber bundle design for time-varying sediment mass
Figure 2. Schematic diagram of the FIT
Baffle

Removable/Replaceable Panels

Placement of the linear fiber wave guide

Baffle

15 cm

Water

Pump

2.5 cm

Water

Placement of the Global Water turbidity probe
Figure 3: Design of the storm water simulator (SWS)

Figure 4: Replicate runs of light transmission for different sediment load of the same sediment and particle size class (150-250 µm)
Figure 5: Comparison of sediment of different color for the same particle size (150-250 µm)
Figure 6: Normalized relative intensity measurements using the FIT for different loading of specific particle size classes (in µm)