Title
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transmissometer

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3 **High Concentration Suspended Sediment Measurements Using a Continuous Fiber Optic**

4 **In-Stream Transmissometer**

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1   ABSTRACT

2   Suspended sediment loads mobilized during high flow periods in rivers and streams are

3   largely uncharacterized. In smaller and intermittent streams, a large storm may transport a

4   majority of the annual sediment budget. Therefore monitoring techniques that can measure high

5   suspended sediment concentrations at semi-continuous time intervals are needed. A Fiber optic

6   In-stream Transmissometer (FIT) is presented for continuous measurement of high concentration

7   suspended sediment in storm runoff. FIT performance and precision were demonstrated to be

8   reasonably good for suspended sediment concentrations up to 10g/L. The FIT was compared to

9   two commercially available turbidity devices and provided better precision and accuracy at both

10   high and low concentrations. Both turbidity devices were unable to collect measurements at

11   concentrations greater than 4 g/L. The FIT and turbidity measurements were sensitive to

12   sediment particle size. Particle size dependence of transmittance and turbidity measurement

13   poses the greatest problem for calibration to suspended sediment concentration. While the FIT

14   was demonstrated to provide acceptable measurements of high suspended sediment

15   concentrations, approaches to real-time suspended sediment detection need to address the

16   particle size dependence in concentration measurements.

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18   **Key Words:** suspended sediment, sediment transport, turbidity, optical sensors

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| 1 | INTRODUCTION |

2   Suspended sediment loads mobilized during storm and high flow periods in urban and

3   agricultural streams have largely not been characterized. This is due in part to the difficulty in

4   obtaining regular measurements with adequate temporal resolution during high flow periods.

5   Suspended sediments may be a water quality problem for light penetration in relation to algal

6   primary productivity, as well as, for gill clogging of aquatic organisms (Vondracek, et al., 2003;

7   Kirk, 1994). In addition to being a water quality problem itself, sediments facilitate transport of

8   many pollutants including heavy metals (Hatje et al., 2001; Rhoads and Cahill, 1999) and

9   organic compounds like polychlorinated biphenyls (PCBs), dioxins, and pesticides (Borah et al,

10   2003; Milburn and Prowse, 1998; Götz et al, 1994; Walters et al., 1989).

11   While relationships between storm hydrographs and suspended sediment concentration

12   have been developed, these relationships may not be consistent as found in a detailed analysis of

13   seven separate flood events in northern Italy (Menzi and Marchi, 2000). Changes in runoff

14   source water, the sediment source, and storm characteristics may all significantly change the

15   distribution of transported sediment within a storm. In urban intermittent streams large sediment

16   loading events may be related to bank failure, exposed soils due to development, and washout of

17   previous deposits during lower energy flows. Stream channels and banks are major sources for

18   suspended sediments, contributing as much as 66% of the total annual suspended sediment

19   mobilized in urban streams in southern California, USA (Trimble, 1997).

20   Suspended sediment concentrations in urban runoff during large storms can be in excess

21   of 10 g/L, however, few continuous sensors are designed to measure concentrations higher than

22   2-3 g/L. This is a problem in streams where a majority of the sediment load is mobilized in a

23   few large storms. Yet, without continuous monitoring large storms are unlikely to be monitored.

1 Moreover, if suspended sediment concentrations exceed the range of the continuous

2 measurement device, then information is lost during a critical sampling event. For example, a

3 large flood during a three-day storm in northern California during 1997 was reported to transport

4 seven times greater sediment mass than what was mobilized in total for either 1995 or 1996

5 (Ogston et al., 2000). Suspended sediment concentrations in this large storm were greater than

6 10 g/L even in the large river system in this study (Eel River).

7 Various methods are used to estimate suspended sediments such as flow proportioned

8 samplers, sampling pumps, optical back scattering (OBS), acoustic back scattering (ABS), and

9 laser diffraction (Wren, et al., 2000). While grab samplers can accurately estimate sediment

10 concentration at a point in time, they lack the temporal sampling resolution required to capture

11 rapid intermittent flushes of suspended sediment during storms. ABS methods are promising

12 techniques for distributed non-intrusive sediment sampling (Wren et al., 2000), however,

13 research and development of this technology is still ongoing. The continuous monitoring

14 technologies most readily available as commercial products are turbidity probes based on OBS at

15 90 and 180 degrees and laser diffraction.

16 Turbidity correlations to suspended sediment concentrations have been criticized as being

17 inconsistent, with large variability in the signal caused by constituents other than suspended

18 sediment (Riley, 1998). Turbidity, by definition, is the cloudiness of water or the extent to which

19 light is scattered in the water (Davies-Colley and Smith, 2001). As such, turbidity may depend

20 on many factors in addition to suspended sediment including: organic matter and other floating

21 debris, algae, air bubbles, and even water discoloration (Riley, 1998; Clifford et al., 1995).

22 While some of these issues can be removed in when using OBS or ABS devices, the

23 measurement is still not a true value of suspended sediment in the water column (Davies-Colley

4

1   and Smith, 2001). In addition, correlation relationships between turbidity and suspended

2   sediment concentration often fail at high concentrations, where the calibration relationship

3   between turbidity and light scattering becomes nonlinear. Also, the total sampling volume of

4   OBS probes will change with sediment concentration, which could potentially lead to

5   representative sampling and scaling issues.

6   The commercially available laser diffraction technology, the LISST-100 (Sequoia

7   Scientific, Redmond, WA), has been demonstrated to accurately measure both volumetric

8   sediment concentration and particle size distribution at lower concentrations (>2 g/L) using a

9   single device (Gartner et al. 2001; Agrawal and Pottsmith, 2000). Unfortunately this device is

10 expensive (in excess of $10,000), limiting its application few locations in larger monitoring

11 projects. The utility of the LISST has also not yet been demonstrated for high suspended

12 sediment concentration, however, it is expected that higher concentrations could be captured by

13 adjusting the optic pathlength to less that the standard 5 cm (Pottsmith, *pers. comm.*).

14   Continuous suspended sediment sensors are needed that can be easily calibrated and

15 deployed to measure high sediment concentrations (Campbell et al., 2003). Therefore, we

16 designed a simple linear Fiber optic In-stream Transmissometer (or the FIT) for continuous total

17 light transmittance measurements of suspended sediment concentration. All the components for

18 the FIT are inexpensive (total system < $1000) and readily available. Our specific objectives

19 were to (1) design and test the FIT to measure suspended sediment concentration, (2) examine

20 influences of sediment color and particle sizes on measurements, and (3) compare FIT

21 performance to commercially available turbidity sensors. In addition, issues of sensor calibration

22 and possible improvements on design will be discussed.

2   ***Theory***

3   Radiant light intensity (I) of a given wavelength (λ) is defined as:

4
$$I = \int_{\lambda} I_{\lambda}\, d\lambda \tag{1}$$

5   Intensity is a traditional term used for radiant power among other radiant fluxes, so the more

6   acceptable term in the sense of this examination is radiant power (P_{λ}) (Braslavsky et al., 1996).

7   The radiant power (P_{λ}) was measured in the FIT using the photodetector and the initial power of

8   transmission from the source to the detector in pure water is defined as P_{λ}^{o}. Then total

9   transmittance (T) can be defined as:

10
$$T = P_{\lambda} \Big/ P_{\lambda}^{o}\,. \tag{2}$$

11   In a practical sense, T is the light reaching a detector from a source, that was not absorbed or

12   back scattered along the way. For the purposes of comparison of the light transmittance results

13   from the FIT with the standard turbidity probes the normalized inverse of transmittance (T_{n}^{-1})

14   was used:

15
$$T_{n}^{-1} = \frac{(P_{\lambda} - P_{\lambda}^{o})}{(P_{\lambda\,\mathrm{max}} - P_{\lambda}^{o})} \tag{3}$$

16   where, $P_{\lambda\,\mathrm{max}}$ was operationally defined as the mean radiant power measured at a suspended

17   sediment concentration of 10 g/L. Therefore, Equation 3 is the inverse of radiant power of

18   transmission relative to the initial power P_{λ}^{o} and normalized by the maximum suspended

19   sediment concentration in the linear range of the transmittance-concentration relationship. For

20   simplicity, the inverse of T_{n} is used so that the output from the FIT will rise with rising sediment

21   concentration so that a single point calibration of the sensor is possible.

1   *Linear FIT Design*

2   Fiber optic transmissometers are based on the total light transmittance between a paired

3   light source and detector. Light emitted from the source will be absorbed or scattered off in

4   different directions, decreasing to total intensity that reaches the detector. A standard

5   relationship described for a specific wavelength of light in photochemistry is the Beer-Lambert

6   Law, which states that there is a logarithmic relationship between the radiant power (P_λ) that will

7   reach a paired detector (*i.e.* light absorbance) and the concentration of a target compound or

8   particle within the pathlength from source to detector (Braslavsky, et al. 1996). When designing

9   a transmissometer, measurements are more easily calibrated to concentration when the basic

10   form of the Beer-Lambert Laws is still linear, where concentrations are still low enough that light

11   absorbance is not approaching the limit (complete absorbance). When the relationship between

12   radiant power and concentration is linear, then a single point of calibration is possible (as in Eq.

13   3).

14   Another design consideration when using fiber optic cables, or waveguides, is the

15   arrangement of the fibers at the sensor end from the fiber bundle in the cable. For example in the

16   schematic in Figure 1, most fiber optic cables are bundled as seen in 1b, however, a linear

17   arrangement of the same optical fibers (as seen in 1a) could be superior for real-time

18   measurement. As illustrated in the schematic figure, if a sharp change in particulate

19   concentration were to flow through a system (common in natural systems), a continuous

20   measurement would be expected to look like those on the right side of the Figure 1. As the sharp

21   concentration change reaches the linear sensor all the fiber encounter the change at the same

22   moment, where as in the bundled arrangement the optical fiber encounter the concentration front

23   a different moments (the sediment front does not reach all fibers at exactly the same time). This

1   leads to the more gradual rise in the combined signal from all the fibers in the graph in 1b than in

2   1a.

3   Given these considerations, paired fiber optic waveguides with the linear optical fiber

4   arrangements on one end were selected. The light source intensity and pathlength between the

5   source and detector were selected to maximize a linear active measurement zone within the Beer-

6   Lambert Law. The resulting simple FIT design is in Figure 2. The light source is a common red

7   light emitting diode (LED) with a with an active bandwidth range from 603 to 672 ηm and a

8   peak at 640 ηm. A red light source was selected as it reduces any interference of color and

9   focuses on the suspended sediment measurement target. A wavelength around 645 ηm is

10 common for suspended sediment measurements (Holdaway et al., 1999). A tunable laser light

11 source (Thor Labs Inc. Newton, NJ, USA) was also tested to determine if there was an advantage

12 of using a higher quality stable source over the inexpensive LED. In this case there was no

13 added advantage so an LED power with a 9 volt battery was selected.

14   Two different detectors were tested, the first a portable USB2000 spectrometer (Ocean

15 Optics Inc., Dunedin, FL, USA) and the second a photodetector connected to a Fluke Co.

16 (Everett, WA USA) multimeter. The photodetectors can be constructed, however in this case the

17 Fluke Company provides a Fiber Optic Meter as an accessory to their multimeter. Both the

18 spectrometer and Fluke setup could communicate directly to a computer to collect

19 measurements. The performance of the two detectors were again, in this case, similar so the

20 Fluke system was used for the following studies.

21 *Laboratory Testing*

22   Once the FIT components were selected and tested, studies were designed to assess the

23 performance of the FIT for high concentration suspended sediment measurement. The precision

1   of the FIT, sensitivity to sediment color, and sensitivity to particle size classes were examined

2   using a laboratory system. In addition, FIT performance was compared to two commercially

3   available turbidity sensors the Global Water WQ710 turbidity probe (Global Water

4   Instrumentation Inc. Gold River, CA, USA) and the LaMotte 2020 grab sample turbidity

5   (LaMotte Co., Chestertown, MD, USA) that is a portable hand held cuvette device.

6   All these studies were performed using a rapid water circulation system constructed out

7   of clear acrylic (Figure 3). The benchtop setup, called the storm water simulator (SWS) is large

8   enough to install the FIT and Global Water turbidity probe and yet not so large that the

9   circulation pump could not keep sediments suspended. Sediments were kept suspended by

10   baffles and water jets that maintained a high flow velocity and also promoted mixing. There

11   were a total of 4 water jets and 4 baffles, that suspended sediments for concentrations up to 10

12   g/L, determined by visual inspection for sediment deposition in the SWS.

13   In order to assess the precision of the FIT, replicate runs of increasing sediment

14   concentration were initiated in the SWS and measured by the FIT. The SWS was started with no

15   sediment and then a mass of sediment equivalent to 1 g/L was added and allowed to mix before

16   measurements were taken. This process was repeated at 1g/L increments up to 10g/L, which is

17   approaching both the expected upper limit of stormwater sediment concentrations and also where

18   the FIT signal begins to become nonlinear.

19   For the color assessment, three different sediment types were collected respectively from

20   the channel of an intermittent stream (Arroyo Las Positas) at the Lawrence Livermore National

21   Laboratory in Livermore, CA, bore hole core samples near the stream channel, and standard

22   commercially available sand. Each sediment sample was ground using a mortar and pestle to

23   break down soil aggregates and classified using a Munsell Color names, as well as, hue,

1   lightness, and chroma (Munsell Soil Color Charts, 2000). This is a qualitative method to

2   compare different soil and sediment coloration. The stream channel sample was a Light Olive

3   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

4   first number indicates the different hue for each sediment sample, but all have a yellow or

5   yellow-red hue base. The lightness and chroma numbers have to do with the intensity of the hue.

6   Measurement sensitivity to different particle size classes was assessed for both the FIT

7   and the two turbidity devices. Ground sediment samples (the stream channel Light Olive

8   Brown) were sieved through standard ASTM Testing Sieves to isolate specific particle size

9   classes. Five particle classes were separated, limited by the available sieves, including > 45 μm,

10 75-150 μm, 150-250 μm, 250-300 μm, and 710-1000 μm. Studies were performed for sediment

11 in each of these particle size classes in the SWS as described above, increasing suspended

12 sediment concentration by 1 g/L increments up to 10 g/L.

13

14   **RESULTS AND DISCUSSION**

15   These tests suggest that the FIT is a reasonable design for real-time measurement of

16 suspended sediment. The components are relatively inexpensive and the entire device is simple

17 to construct. The FIT precision within a replicate run is good and increases slightly between

18 runs (Figure 4). This variability likely has to do with slight changes in the connection of the

19 fiber optic waveguides to the source and detector. Fitting a straight trend line to these data as a

20 calibration produces slopes of 0.1049, 0.1047, and 0.1095 for replicates 1, 2, and 3 respectively.

21 The R^2-values for these trend line calibrations ranged from 0.977 to 0.995. The data in this

22 figure demonstrate the linearity in FIT response and potential for a single point calibration.

23 Using these data, the FIT precision is around 1 to 2 % at lower concentrations and up to about

10

1   4% at 10 g/L suspended sediment. Reported precision for filtered grab sampled, turbidity, and

2   visual clarity techniques are 10%, 10%, and 4%, respectively (Davies-Colley and Smith, 2001).

3   ***Sediment Color***

4   Response variability in tests using the different color sediments was greater than the 1 to

5   4% precision, however the effect was still not greater than 14% at 10g/L (Figure 5). There does

6   appear to be an influence of sediment color in the FIT. At the same time, the measured response

7   was still linear with R^2-values for the trend line of 0.973, 0.988, 0.994 for the Pale Yellow sand,

8   Brown core sample, and Light Olive Brown channel sediment, respectively. Slopes for the trend

9   lines ranged from 0.0858 to 0.0968, which is in reasonable agreement with the slopes observed

10   in Figure 4.

11   Sediment color is an often neglected factor that may influence transmittance and

12   absorbance measurements. In this case, it is possible that differences observed are in part caused

13   by difference geometries of the particles, not just the difference in color. This color comparison

14   was made on particles from the same size class (150-200 μm), however, clays and sands tend to

15   differ in particle geometry. Clay particles made up of illite, montmorillonite, kaolinite,

16   halloysite, tend to be shaped as plates, disks, and fibers, while quartz sands are more spherical

17   with greater width (Jury et al., 1991; Sparks, 1995). As our testing did not account for light

18   scattering by different particle geometries, we can not be sure if the variability observed in

19   Figure 5 results from color or particle geometry. As such, the influence of sediment color on FIT

20   measurement may need further examination.

21   ***Particle Size & Comparison to Turbidity Probes***

22   The particle size dependence of transmittance measurements is clearly the dominant

23   source of variability. Measurement results for the FIT, the Global Water turbidity probe, and the

1   hand held LaMotte turbidity device are presented in Figure 6. The two turbidity devices reach a

2   maximum at 1 to 4 g/L, depending on particle sizes. These maximums are built into the turbidity

3   probe design and calibration. Turbidity signal becomes non-linear beyond a certain

4   concentration, just like the FIT, due to light source intensity and the optical pathlength (Beer-

5   Lambert Law). This is the advantage of constructing a transmissometer for specific applications

6   so that the active measurement range fits those in the system of interest.

7   Particle size dependence in transmittance and optical back scattering measurements have

8   been examined in many studies, however, a systematic relationship between particle size

9   distribution and these measurements has not been defined (Baker, et al. 2001; Clifford et al.,

10   1995; Baker and Lavelle, 1984). Calibrations have included empirical relationships (Baker et al.

11   2001; Clifford et al., 1995), however, these relationships are only applicable in systems where

12   the sediment source constrained (particle size is known) and is reasonably consistent like in low

13   concentration coastal and marine waters. The normalized linear calibration approach for the FIT

14   presented in Equation 3, would account for changes in absolute light absorbance as long as (1)

15   the sediment source is consistent within a storm event, (2) the calibration point is determined

16   from a single grab sample from that storm, and (3) the relationship between T_n^{-1} is linear. The

17   last of these criteria could be a problem for the large (>710 μm) and smaller (<45 μm) particle

18   sizes (Figure 6). Calibration could be adjusted for the proportion of particle sizes beyond these

19   upper and lower bounds. The potential variability introduced by these particle sizes is as large as

20   37% in the 2 to 4 g/L suspended sediment concentration range. While this is an improvement

21   over the comparable variability in the tested turbidity probes, it is still and important limitation of

22   these types of sensors.

23

1   **CONCLUSIONS**

2   We developed a Fiber optic In-stream Transmissometer, or FIT, for continuous

3   measurement of high concentration suspended sediment in storm runoff. The FIT was

4   demonstrated to have good precision for suspended sediment concentration measurements up to

5   10g/L. Performance of the FIT was compared to two commercially available turbidity devices

6   and was shown to provided better measurements at both high and low concentrations. Both

7   turbidity devices reached a maximum measurements at 1 to 4 g/L sediment concentrations. This

8   demonstrates the advantage of constructing a transmissometer for target concentrations by

9   adjusting the optical pathlength and light source intensity as devices like the FIT would be

10   relatively inexpensive to construct. In addition the linear array of coupled optical fibers provided

11   a larger measurement volume and increases the temporal resolution by sampling in only a single

12   spatial dimension.

13   Both the FIT and turbidity probe measurements showed a dependence on sediment particle

14   size. It is clearly the particle size dependence of transmittance and turbidity measurement that

15   causes the greatest problem for calibration to suspended sediment concentration. Despite this

16   large source of variability, it would still be possible to calibrate the FIT for measurements even

17   in particle sized grater than 710 μm and less than 45 μm. The FIT was the only device tested

18   capable of measuring the high suspended sediment concentrations that may be encountered in

19   stormwater runoff. Field testing of the FIT is still necessary to determine long-term performance

20   under harsh filed conditions.

21   Finally, approaches to real-time suspended sediment detection need to address the particle

22   size dependence that exists for optical measurement methods. Research should focus on more

23   sophisticated sensors that can measure and account for sediment particle sizes.

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1   **References:**

2   Agrawal, Y.C. and H.C. Pottsmith. 2000. Instruments for Particle Size and Settling Velocity

3   Observations in Sediment Transport. Marine Geology. 168:89-114.

4   Baker, E.T. and J.W. Lavelle. 1984. The Effect of Particle Size on the Light Attenuation

5   Coefficient of Natural Suspensions. Journal Of Geophysical Research. 89: 8197-8203.

6   Baker E.T., D.A. Tennant, R.A. Feely, G.T. Lebon, S.L. Walker. 2001. Field and Laboratory

7   Studies on the Effect of Particle Size and Composition on Optical Backscattering

8   Measurements in Hydrothermal Plumes. Deep-Sea Research I. 48: 593-604.

9   Borah DK. Bera M. Shaw S. 2003. Water, Sediment, Nutrient, and Pesticide Measurements in an

10   Agricultural Watershed in Illinois During Storm Events. Transactions of the ASAE.

11   46(3):657-674.

12   Braslavsky, S.E., K.N. Houk, J.W. Verhoeven. 1996. Glossary of Terms Used in

13   Photochemistry. Second Ed. Published by the International Union of Pure and Applied

14   Chemistry, Organic Chemistry Division Commission on Photochemistry. 73 pp.

15   Campbell, C.G., J. Richards, M. Zavarin, P. Stratton, J. Coty, D. Laycak. 2003. Novel

16   Application of Fiber Optic Sensor for Characterizing Real-Time Contaminant Transport in

17   Rapid Storm Runoff. LLNL Report UCRL-ID-151580.

18   www.osti.gov/servlets/purl/15004919-YF8PCf/native/

19   Clifford, N.J., K.S. Richards, R.A. Brown, S.N. Lane. 1995. Laboratory and Field Assessment of

20   an Infrared Turbidity Probe and its Response to Particle Size and Variation in Suspended

21   Sediment Concentration. Hydrological Sciences Journal. 40:771-791.

22   Davies-Colley, R.J. and D.G. Smith. 2001. Turbidity, Suspended Sediment, and Water Clarity: A

23   Review. Journal of the American Water Resources Association. 37: 1085-1101.

1 Gartner, J.W., R.T. Cheng, P-F. Wang, K. Richter. 2001. Laboratory and Field Evaluations if the

2   LISST-100 Instrument for Suspended Particle Size Determinations. Marine Geology. 175:

3   199-219.

4 Götz, R. P. Enge, P. Friesel, K. Roch, L-O. Kjeller, S.E. Kulp, C. Rappe. 1994. Sampling and

5   Analysis of Waters and Suspended Particulate Matter of the River Elbe for Polychlorinated

6   Dibenzo-p-Dioxins (PCDDs) and Dibenzofurans (PCDFs). Chemosphere. 28:63-74.

7 Hatje, V., K. Rae, G.F. Birch. 2001. Trace Metal and Total Suspended Solids Concentration I

8   Freshwater: The Importance of Small-Scale Temporal Variability. Journal of Environmental

9   Monitoring. 3: 251-256.

10 Holdaway, G.P., P.D. Thorne, D. Flatt, S.E. Jones, D. Prandle. 1999. Comparison between

11   ADCP and transmissometer measurements of suspended sediment concentration.

12   Continental Shelf research. 19: 421-441.

13 Jury, W.A., W.R. Gardner, W.H. Gardner. 1991. Soil Physics, 5th ed. John Wiley & Sons, Inc.

14   NY, NY. pg. 14-18.

15 Kirk, J.T.O. 1994. Light and Photosynthesis in Aquatic Ecosystems. Second Ed., Cambridge

16   University Press. NY: NY. 509pp.

17 Menzi, M.A., L. Marchi. 2000. Suspended Sediment Load During Floods in a Small Stream of

18   the Dolomites (northern Italy). Cantena. 39:267-282.

19 Milburn, D. and T.D. Prowse. 1998. Sediment Bound Contaminants in a Remote Northern Delta.

20   Nordic Hydrology. 29:397-414.

21 Munsell Soil Color Charts. 2000. GretagMacbeth. New Windsor, NY.

1   Ogston, A.S., D.A. Cacchione, R.W. Sternberg, G.C. Kineke. 2000. Observations of Storm and

2   River Flood-Driven Sediment Transport on the Northern California Continental Shelf.

3   Continental Shelf Research. 20:2141-2162.

4   Rhoads, B.L. and R.A. Cahill.1999. Geomorphological Assessment of Sediment Contamination

5   in an Urban Stream System. Applied Geochemistry. 14:459-483.

6   Riley, S.J. 1998. The Sediment Concentration-Turbidity Relation: Its Value in Monitoring at

7   Ranger Uranium Mine, Northern Territory, Australia. Cantena. 32:1-14.

8   Sparks, D.L. 1995. Environmental Soil Chemistry. Academic Press. San Diego, CA. pg. 28-40

9   Trimble, S.W. 1997. Contribution of Stream Channel Erosion to Sediment Yield from an

10   Urbanizing Watershed. Science, 278: 1442-1444.

11   Vondracek, B., J.K.H. Zimmerman, J.V. Westra. 2003. Setting an effective TMDL: Sediment

12   loading and effects of suspended sediment on fish. Journal of the American Water

13   Resources Association. 39(5):1005-1015.

14   Walters, R.W., S.A. Ostazeski, A. Guiseppi-Elie. 1989. Sorption of 2,3,7,8-Tetrachlorodibenzo-

15   p-dioxin form Water by Surface Soils. Environmental Science and Technology. 23:480-484.
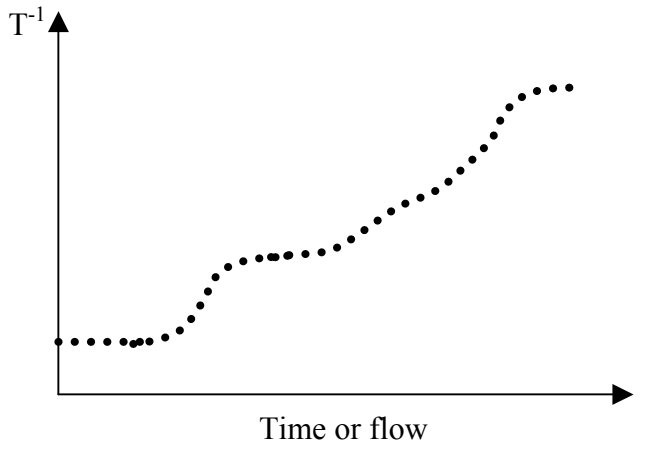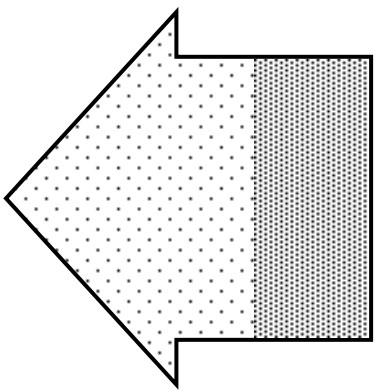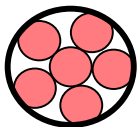
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Figure1: Schematic of the advantage of linear verses fiber bundle design for time-varying sediment mass

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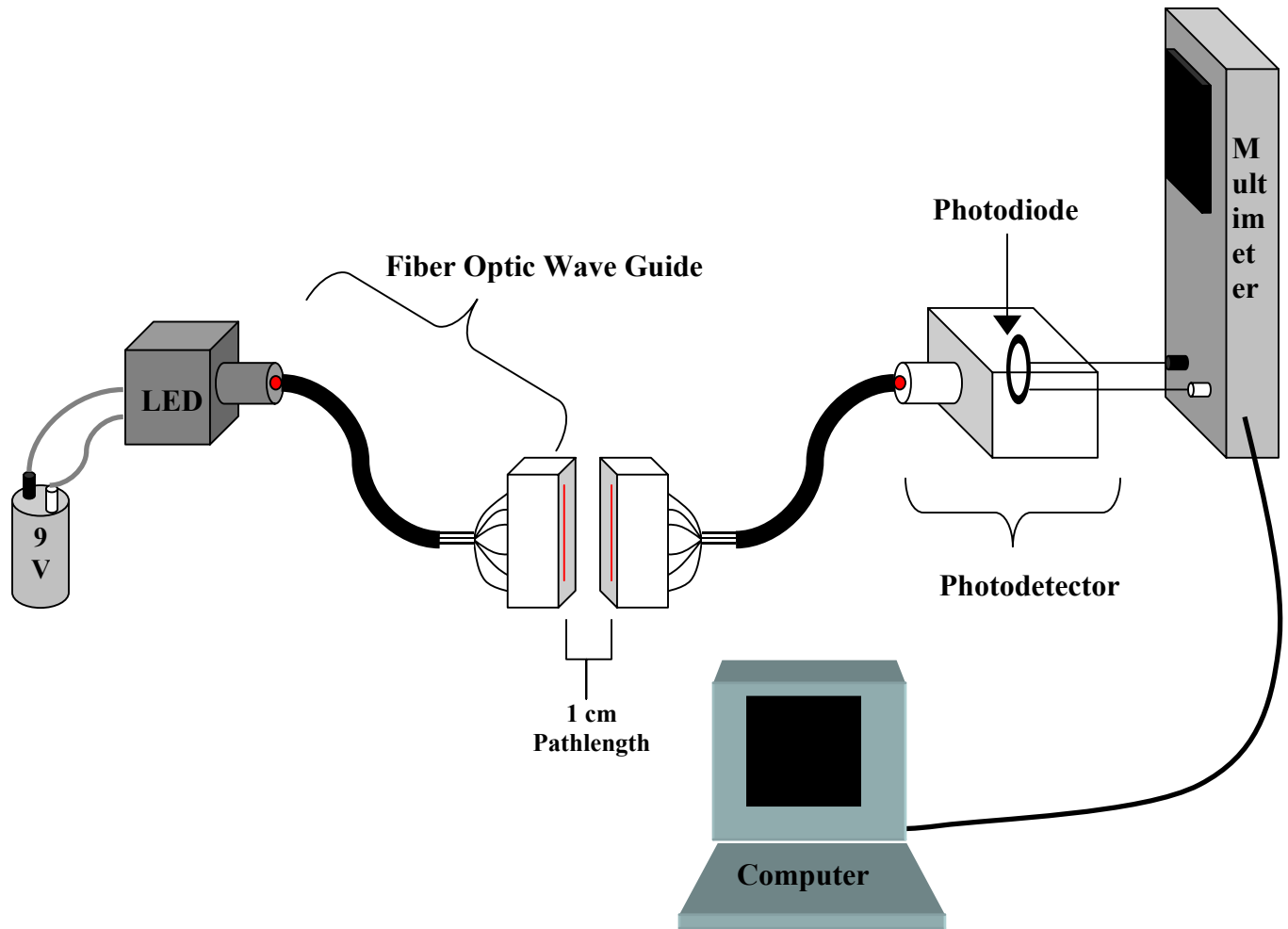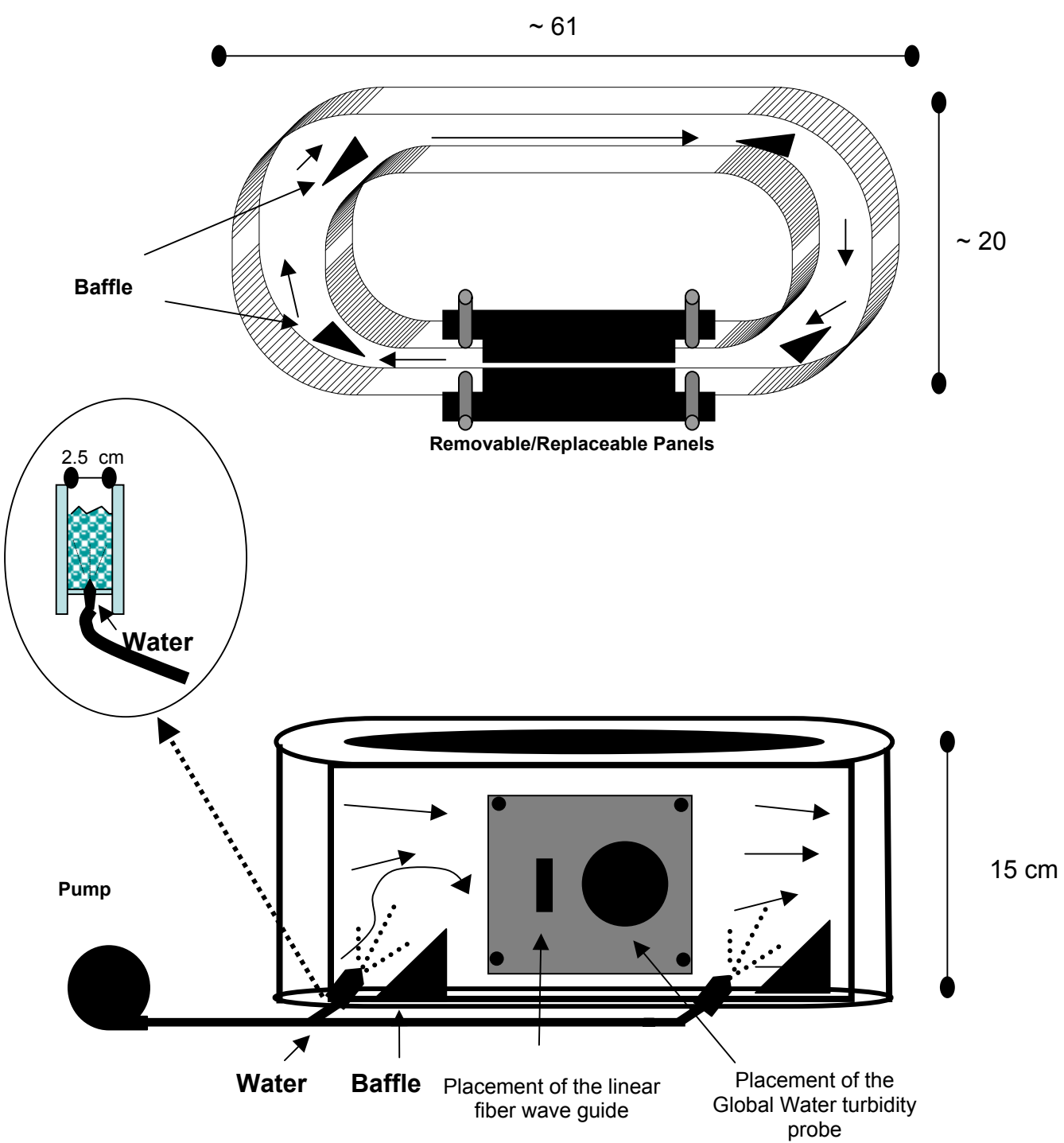10

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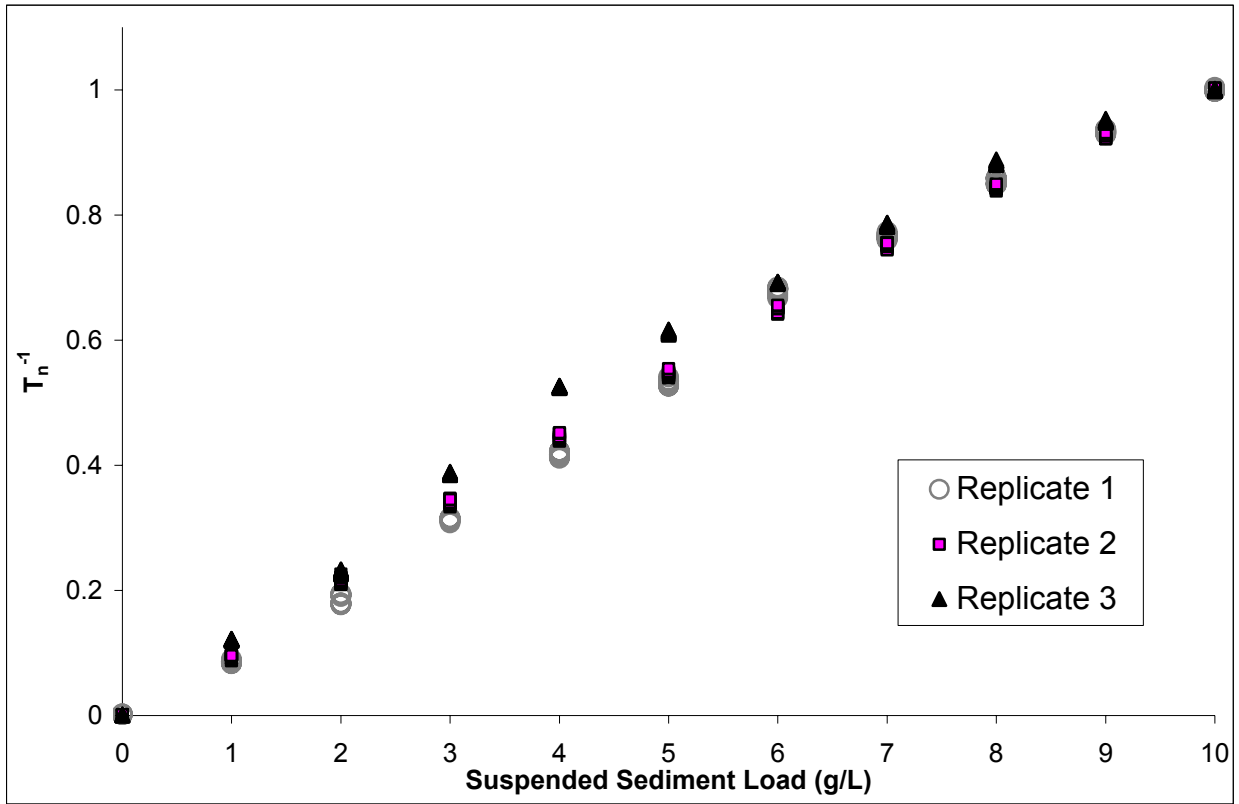23   Figure 2. Schematic diagram of the FIT

Fiber Optic Wave Guide

Photodiode

M ult im et er

LED

9 V

1 cm Pathlength

Photodetector

Computer

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2

~ 61

2

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4

5

~ 20

6

Baffle

7

8

Removable/Replaceable Panels

9

2.5 cm

10

11

12

Water

13

14

15 cm

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16

Pump

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20

Water   **Baffle**   Placement of the linear fiber wave guide   Placement of the Global Water turbidity probe

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1   Figure 3: Design of the storm water simulator (SWS)

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12   Figure 4: Replicate runs of light transmission for different sediment load of the same

13   sediment and particle size class (150-250 μm)
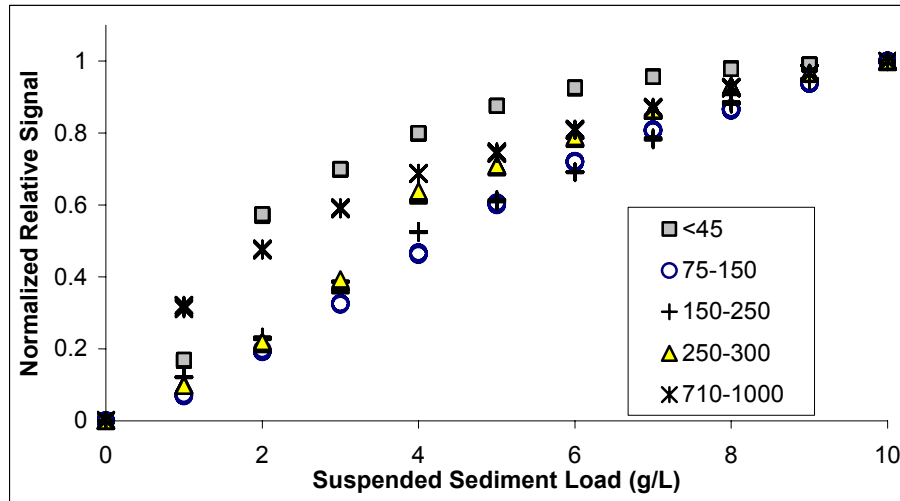
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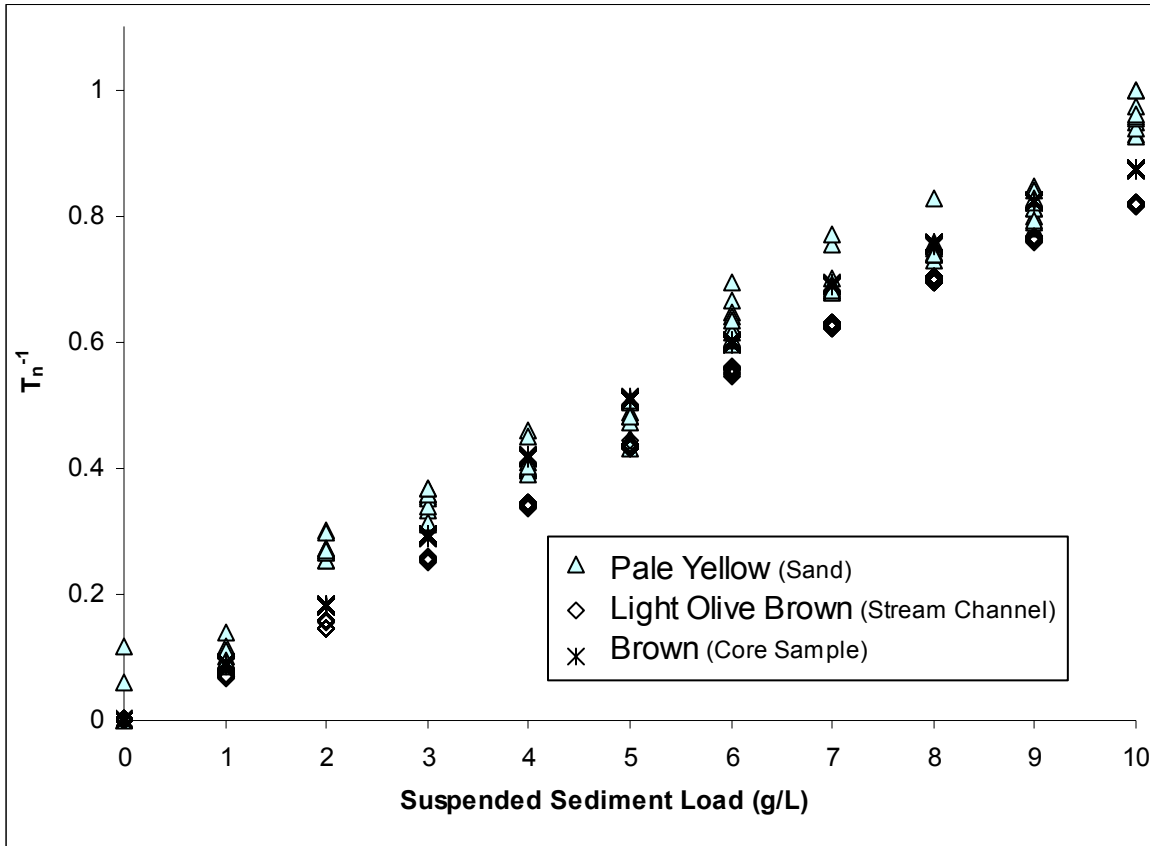
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10   Figure 5: Comparison of sediment of different color for the same particle size (150-250

11   μm)
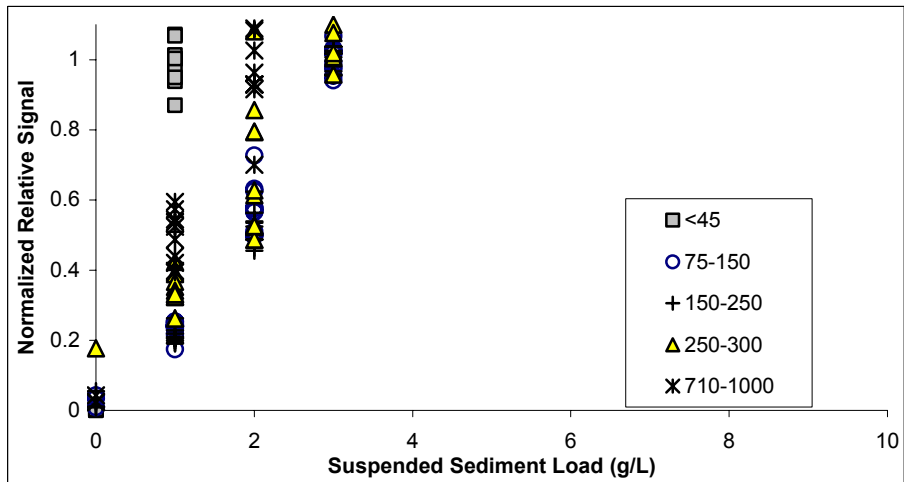
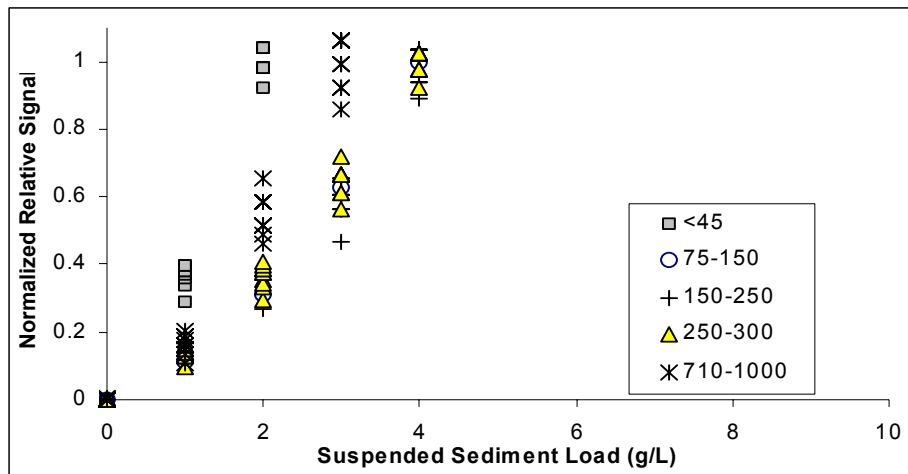12

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1   FIT

2   Global Water WQ710

3   LaMotte 2020

4
5   Figure 6: Normalized relative intensity measurements using the FIT for different loading
6   of specific particle size classes (in μm)