EVALUATING TURBIDITY AND SUSPENDED-SEDIMENT CONCENTRATION RELATIONS FROM THE NORTH FORK TOUTLE RIVER BASIN NEAR MOUNT ST. HELENS, WASHINGTON: ANNUAL, SEASONAL, EVENT, AND PARTICLE SIZE VARIATIONS - A PRELIMINARY ANALYSIS

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INTRODUCTION

Regression of in-stream turbidity with concurrent sample-based suspended-sediment concentration (SSC) has become an accepted method for producing unit-value time series of inferred SSC (Rasmussen et al., 2009). Turbidity-SSC regression models are increasingly used to generate suspended-sediment records for Pacific Northwest rivers (e.g., Curran et al., 2014; Schenk and Bragg, 2014; Uhrich and Bragg, 2003). Recent work developing turbidity-SSC models for the North Fork Toutle River in southwestern Washington (Uhrich et al., 2014), as well as other studies (Landers and Sturm, 2013; Merten et al., 2014), suggests that models derived from annual or greater datasets may not adequately reflect shorter term changes in turbidity-SSC relations, warranting closer inspection of such relations.

In-stream turbidity measurements and suspended-sediment samples have been collected from the North Fork Toutle River since 2010. The study site, U.S. Geological Survey (USGS) streamgage 14240525 near Kid Valley, Washington, is 13 river km downstream of the debris avalanche emplaced by the 1980 eruption of Mount St. Helens (Lipman and Mullineaux, 1981), and 2 river km downstream of the large sediment retention structure (SRS) built from 1987–1989 to mitigate the associated sediment hazard. The debris avalanche extends roughly 25 km down valley from the edifice of the volcano and is the primary source of suspended sediment moving past the streamgage (NF Toutle-SRS). Other significant sources are debris flow events and sand deposits upstream of the SRS, which are periodically remobilized and transported downstream. Also, finer material often is derived from the clay-rich original debris avalanche deposit, while coarser material can derive from areas such as fluvially reworked terraces.

Data Collection, Sampling, and Processing: Unit value (15-minute interval) turbidity values were collected and processed according to established USGS procedures (Wagner et al., 2006), using a Forest Technology Systems DTS-12 sensor oriented vertically in a standpipe on the left bank of the river. Sensors were calibrated in standards (i.e., solutions of known turbidity) before and after deployment periods. Data corrections were applied based on the calibration results. All turbidity sensors have a maximum threshold recording level. For the DTS-12 the threshold is approximately 2,500 Formazin Nephelometric Units (FNU). Turbidity values above the DTS-12 maximum in water year (October to September) 2013 were estimated from a Hach Solitax sensor located adjacent to the DTS-12. Solitax sensor values are measured in Formazin Backscatter Ratio Units (FBRU) up to a maximum value of about 20,000 FBRU; observed values were reasonably consistent with DTS-12 values below about 2,500 FNU. Turbidity data from sensors reporting in different units should not be used interchangeably (Anderson, 2005). Solitax FBRU data in water year 2013 were used only as a visual guide to estimate discrete values of DTS-12 turbidity in FNU for the SSC samples collected above the DTS-12 threshold. Also for water year 2012, some turbidity values above the sensor threshold were estimated by extending the slope of the DTS-12 rise and fall graph line and interpolating the appropriate turbidity value at the time of the sample.

Manual cross-sectional depth-integrated and bankside automated-pumping samples were collected using standard USGS samplers and methods. The manual method used was the Equal Discharge Increment method or EDI, in which a separate sample of the same volume is collected from each centroid in the cross-section. Each centroid has a calculated percentage of flow whose locations are determined by a discharge measurement (Edwards and Glysson, 1999). Samples were analyzed for SSC and many for particle size distribution (Guy, 1977). Sediment particle size is defined by the diameter, such that a diameter smaller than 0.062 millimeters (mm) is considered fine-grained sediment. Coefficients, calculated from a concentration ratio, were applied to correct pump samples to the manual cross-section mean SSC. For example, if an SSC from a manual sample was 120 milligrams per liter (mg/L) and the pump samples collected directly before and after the manual sample were each 100 mg/L, the pump SSCs would be multiplied by 1.2 to obtain a corrected value.

REGRESSION ANALYSIS

Datasets of the sample SSC, concurrent in-stream turbidity, and percentage of fine sediment were compiled for 2010–2013 water years. Datasets were then divided by year, season, and specific high-turbidity events. Regression models were developed from these subsets and results were compared from year-to-year and season-to-season, along with evaluations for groups of high-turbidity events. Models were also developed by categorizing the data by specific groups of particle size distribution, or percentage of fine-grained sediment. Samples were categorized in two groups: less than or greater than 60 percent fines. Regression equations and model results were evaluated for each category.

The regression analysis used the power equation form, such that SSC is equal to $a \times \text{Turbidity}^{b}$, where a is the y-intercept and b is the slope. The coefficient of determination (R^2) and sum of squares error of prediction (SSE) values, shown on most figures, are statistical and comparative diagnostics used in regression modeling to evaluate accuracy (Helsel and Hirsch, 2002; Uhrich et al., 2014). In general, the higher the R^2 the better the model fits the data, although there are exceptions and the R^2 should be evaluated with other model statistics and plots of the residual values. The SSE is a measure of variation in the model or its deviation from the mean, hence the lower the SSE the less the variation and tighter fit of the model.

Annual Regressions: Annual turbidity-SSC models can provide adequate results for most Pacific Northwest streams (Bragg et al., 2007) but might not be suitable for the North Fork Toutle basin near Mount St. Helens due to its variable sediment sources and erosional conditions. The analysis of North Fork Toutle River turbidity and SSC data, under varying time scales, reveals how a single turbidity value can have varying SSC and/or sediment-size fraction values associated with it.

Annual data were grouped by water year. The 2010 dataset, a partial year from May to September, was combined with the 2011 water year. The number of samples collected for the 2010–2011, 2012, and 2013 datasets were 653, 509, 408, respectively, totaling 1,570 turbidity-SSC pairs available for analysis (figure 1). Ordinary least-squares regression models, developed for each water year, yielded an equation to estimate SSC from turbidity (Helsel and Hirsch, 2002; Uhrich et al. 2014). SSC was first computed using the 2010–2011 regression equation, for a range in turbidity values from 100 to 2,000 FNU. This turbidity range was the most common amongst all years in matched turbidity with sample SSC, although in 2013 the paired turbidity with SSC was higher, due to the use of the Solitax sensor. The 2010–2011 computed SSC, for the selected turbidity range values, had a percent difference of 5 to 32 percent higher than the 2012 equation estimates, for the same range of turbidity values, with a 54 to 65 percent difference higher than the 2013 equation estimates. For example, a turbidity value of 100 FNU equated to 835 mg/L for the 2010–2011 model. The same turbidity value equated to 795 mg/L and 385 mg/L for the 2012 and 2013 models, respectively. A turbidity value of 1,600 FNU equated to 7,360 mg/L for 2010–2011. The same value equated to 5,150 and 2,630 for 2012 and 2013, respectively. Turbidity values above 2,000 FNU, which were associated with the SSC samples, occurred in 2013 and exhibited slightly greater differences in SSC.

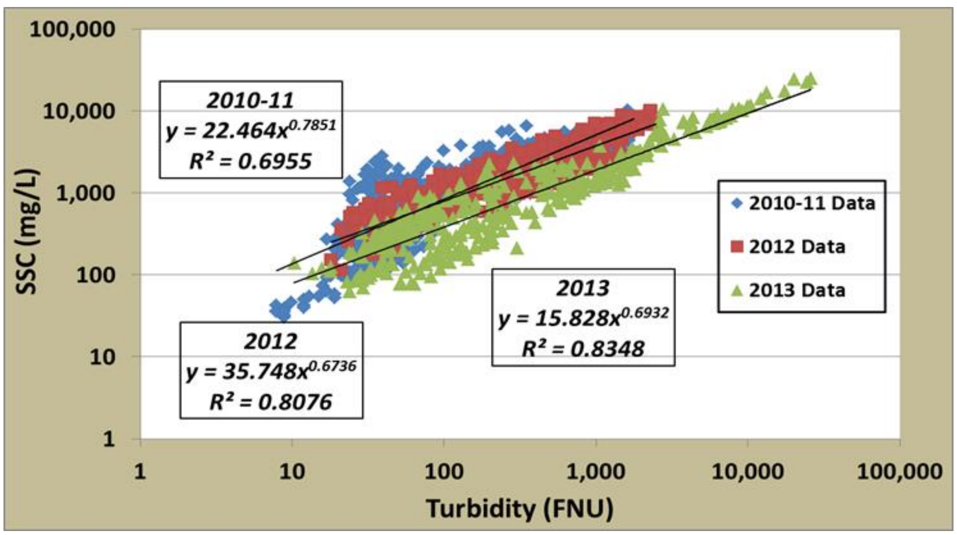

Figure 1 Ordinary least-squares regressions of turbidity and SSC for the USGS streamgage 14240525 North Fork Toutle River below SRS near Kid Valley, Washington, using 2010–2013 turbidity and SSC data pairs.

The large differences between 2013 and the other water years were largely caused by the reconstruction of the SRS spillway, about 2 km upstream from the streamgage. The spillway was raised by over 2 m in October 2012, thereby impounding greater amounts of suspended sediment and limiting downstream transport. Also in 2012, as a precursor to the spillway raise, grade-building structures and diversion channels were placed upstream of the SRS to impede and trap sediment movement. Hence, there was a significant change to turbidity-SSC relations from 2010–2011 and 2012 water years to the 2013 water year. This demonstrates that annual turbidity-SSC models for the North Fork Toutle River must be checked year-to-year as changes are inevitable in this basin due to the ubiquitous and dynamic nature of a natural and managed sediment regime.

Seasonal Regressions: Seasonal differences are also evident. Seasons were differentiated into 4 groups comprising 3 months each: October-December, January-March, April-June, and July-September. These monthly groupings were further simplified to fall, winter, spring and summer, respectively. Regression equations were generated for each season in each year (figure 2).

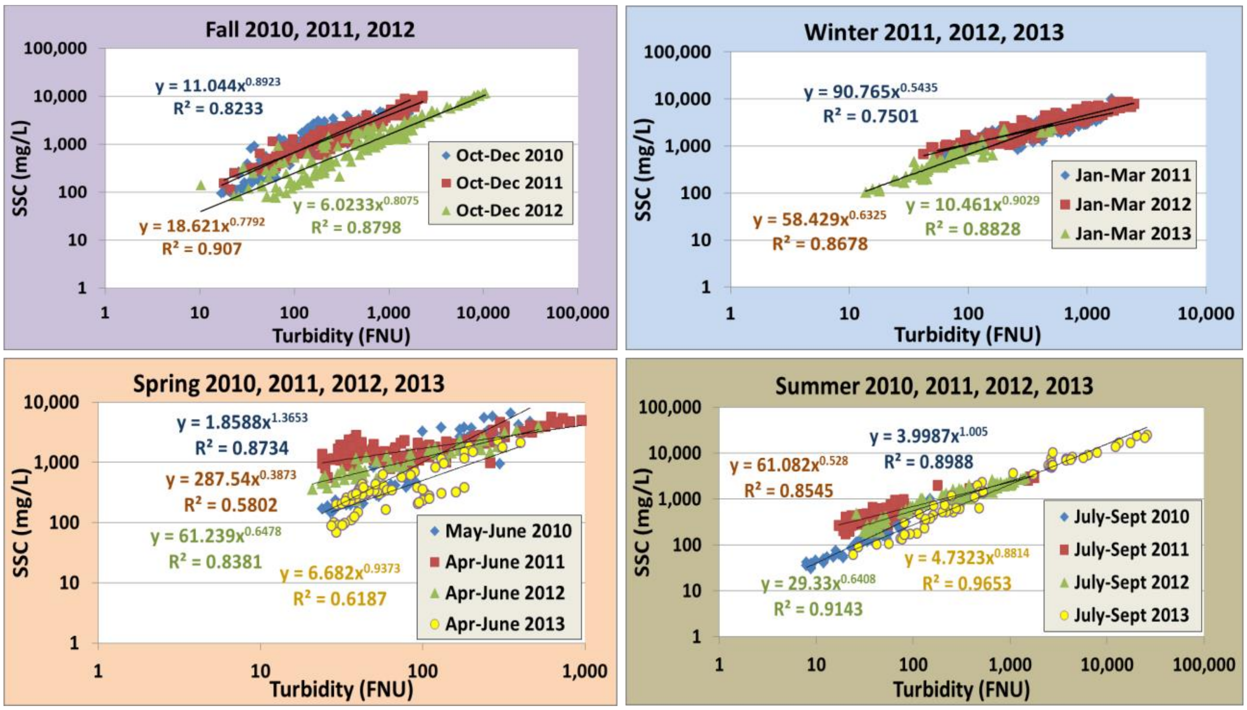

Figure 2 Seasonal regression models for the NF Toutle-SRS streamgage using 2010–2013 data.

Similar to the annual computational method, a range of turbidity values from 100 to 2,000 FNU was used to estimate seasonal SSC. The regression analysis showed that a low turbidity of less than 200 FNU with a relatively low estimated SSC occurred in the seasons of summer 2010 and 2013 and fall 2012. Seasons with high turbidity, greater than 1,200 FNU, having a low estimated SSC also occurred in fall 2012 and summer 2011, 2012, and 2013. The seasons of fall 2012 and summer 2013 had low SSC despite the turbidity level (table 1). Hence, low turbidity in the North Fork Toutle basin with a relative low SSC are indicative of late summer and early fall low flow conditions, where sediment transport is minimal. High turbidity with low SSC can result when the sediment supply is limited and may also occur in conjunction with the low flow, and low turbidity-SSC condition.

A low turbidity less than 200 FNU having a relative high SSC occurred in the two adjoining seasons winter and spring in the years 2011, 2012 (table 1). Also, spring 2010 had low turbidity with a high SSC. There was no data available for winter 2010 to determine if this year followed a similar trend as 2011 and 2012. A season having high turbidity with a high estimated SSC occurred in the 3 adjoining seasons: Spring, summer, and fall 2010. Also, there was a relative high SSC for a high turbidity for fall 2011, and the 2 adjoining seasons of winter and spring in 2012 and 2013.

Table 1 Seasonal regression computed SSC for selected turbidity values.

Turbidity 100 to 2,000 FNU	Low SSC	High SSC
Low Turbidity **(*less than 200 FNU*)**	Summer 2010 Fall 2012 Summer 2013	Spring 2010 Winter 2011 Spring 2011 Winter 2012 Spring 2012
High Turbidity **(*greater than 1200 FNU*)**	Summer 2011 Summer 2012 Fall 2012 Summer 2013	Spring 2010 Summer 2010 Fall 2010 Fall 2011 Winter 2012 Spring 2012 Winter 2013 Spring 2013

Some high SSC conditions may be sediment-transport capacity limited, such that the sediment supply is abundant but the capacity to transport it is restricted. Low turbidity and high relative SSC conditions are indicative of high flow, and/or high sediment-transport conditions and often occur in conjunction with high turbidity-SSC seasons. Overall though, each of the seasonal differences can be attributed to a variety of sediment source, erosion, and streamflow conditions, as well as sediment-particle size, and can shift back-and-forth from a sediment supply limited to sediment-transport capacity limited system.

The seasons with the highest slope and lowest y-intercept were the two adjoining seasons spring 2010 and summer 2010. The seasons with the lowest slope and highest y-intercept were the two adjoining seasons winter 2011 and spring 2011. This shows there was a significant shift in turbidity-SSC relations from 2010 to 2011, although all data from 2010 were not available. These seasonal differences document how suspended-sediment transport can shift within a specific year and how one season can vary from another, and from the same season in different years. Hence, for the highest accuracy, turbidity-SSC model development in the North Fork Toutle basin should follow more seasonal than annual time scales.

Event Regressions: There were several events during the 2010–2011 to 2013 water years that had a distinct turbidity-SSC signature. Twenty-one major events were selected for analysis, which were determined by a rise in streamflow and/or turbidity that increased by at least 100 percent from its previous level, and with an event duration of less than 8 days. There may have been several peaks in streamflow or turbidity during a particular event period. A turbidity-SSC regression model was generated for each of the 21 events. These were categorized into 4 main event groups (A, B, C, D) based on a given turbidity, from a 100 to 2,000 FNU range of values, and a computed SSC from the regression models that was within an average 30 percent difference for all groups. Each event group also had a similar slope and y-intercept within a 30 percent range. A second regression model was then generated for each of the 4 groups (figure 3).

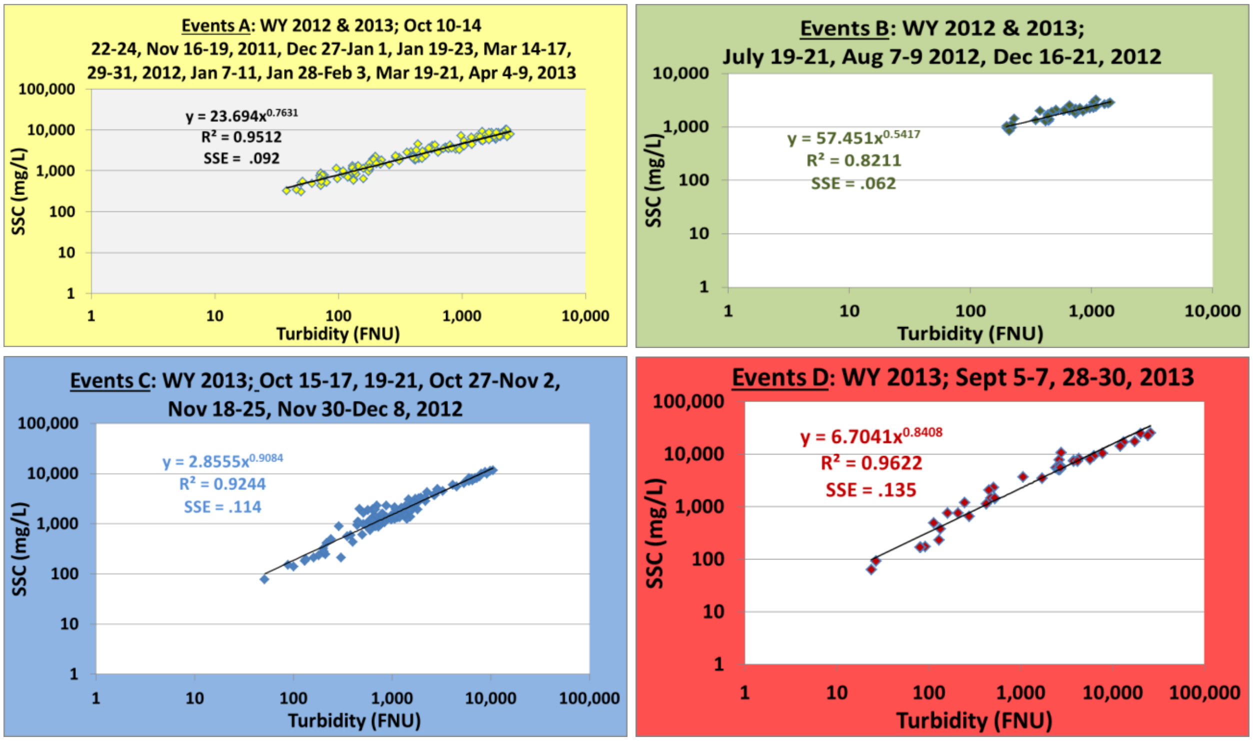

Figure 3 Event regression models for the NF-Toutle-SRS streamgage.

Event group B had the lowest slope and highest y-intercept, which was indicative of low flow, summertime conditions and first-flush autumn events where, in this case, the turbidity peaks precede the streamflow peaks. Event group C had the highest slope and lowest y-intercept, which occurred entirely during the fall of 2012 where the turbidity peaks lagged the streamflow peaks. Event group A was wedged between groups B and C and had a wide-range of events extending through several time spans, occurring primarily from November to March. This is reasonable considering most sediment transport is a combination of both conditions in groups B and C, and in slope and y-intercept. Event group D is comprised of two abnormally large peaks in September, normally the driest month of the year.

Creating separate event models enabled a more accurate SSC estimate for these periods, as compared to the annual and seasonal models, as reflected by the high R^2 and low SSE values in figure 3. Hence, it is possible to fine-tune regression models to smaller time scales for specific events in order to more appropriately approximate an SSC from turbidity for these periods.

Particle-Size Regressions: There were 317 samples available with particle size data for the entire 2010–2011, 2012, and 2013 datasets. As with the previous regression models the turbidity and SSC data with particle-size data were assembled as one dataset. The data points were then separated into two groups by particle size distribution. One group consisted of all samples with 60 percent of total material smaller than sand (<0.062 mm in diameter); the other group had 60 percent of total material larger than sand. Within each group, EDI cross-section samples and pump samples were differentiated.

Similar to the annual and seasonal regressions, a range of different turbidity values from 100 to 2,000 FNU was input to each of the particle-size equations for each year (figure 4). Comparisons were made within each year and from year-to-year for the EDI and pump groups of 60 percent finer than sand. The comparisons between years showed that average particle size decreased from 2010-11 to 2013. The 2010-11 pump sample group greater than 60 percent fines (mostly fine material) showed higher SSC by an average 63 percent difference as compared to 2013 for the turbidity values input to equations.

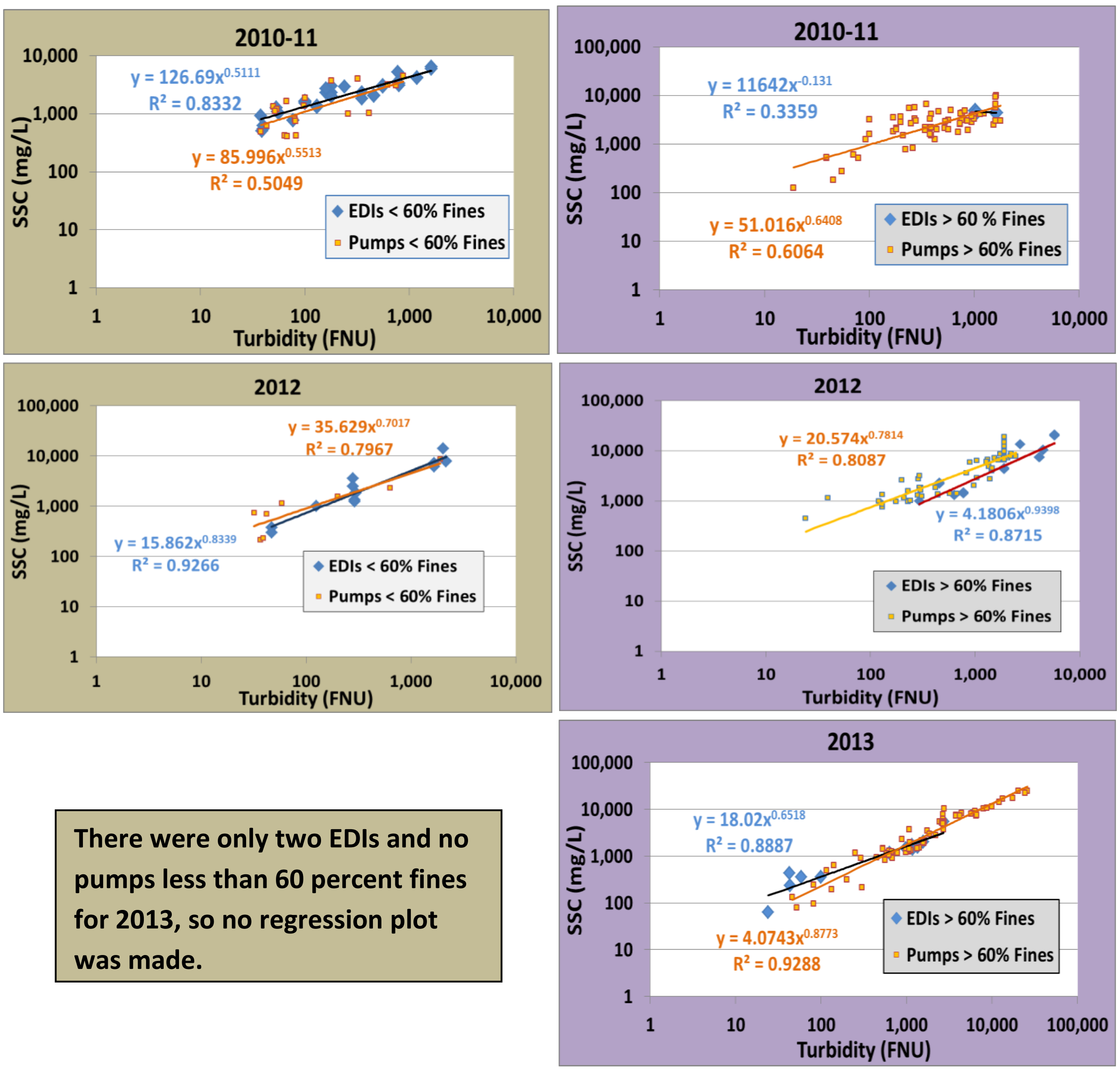

Figure 4 NF Toutle-SRS particle-size regressions for 2010-11, 2012, and 2013.

There were no EDI samples in 2010-11 that were greater than 60 percent fines, although from 2012 to 2013, in this greater than 60 percent fines category (mostly fine material), the EDI and pump concentrations, estimated from the range of turbidity values, decreased an average 26 and 64 percent difference, respectively. Hence, the concentration of fine material for a given in-stream turbidity, transported downstream past the SRS, was lower in 2013 than 2012. Also in 2012, the EDI particle-size concentrations that were less than 60 percent sand (mostly coarse material), for the 100-2,000 range in turbidity, were all higher than the 2012 greater than 60 percent finer than sand group (mostly fine material) by an average 48 percent difference. Hence, all EDI suspended-sediment concentrations in 2012 were primarily SSCs with coarser-grained sediment than in 2013. The pump samples in 2012 did not have as much or as consistent a difference.

There also were differences between EDI and pump estimates based on particle size. In 2010-11 the EDI concentrations for a given turbidity in the less than 60 percent fines group (coarser material) had an average 12 percent difference higher than the pump concentration for the same group. Yet in 2012 the EDI concentrations were much lower than pump concentrations, especially for samples grouped as greater than 60 percent fine material, which averaged a 56 percent difference lower. For coarse material, less than 60 percent fines, the concentrations of EDIs and pumps varied in 2012, such that at low turbidity pump SSCs were higher and at high turbidity the EDIs SSCs were higher.

The 2013 estimated SSCs, for the range in turbidity values, also varied between the EDIs and pumps, although the reverse occurred in 2013 such that, at low turbidity the EDI SSCs were higher and at high turbidity the pump SSCs were higher. In 2013, there were only values for EDI and pump samples that were greater than 60 percent fines (mostly fine material), with no values for less than 60 percent fines (mostly coarse material), so no comparisons could be made for the coarser material. Hence, the EDI finer-grained SSCs for a given turbidity were usually lower than the pump SSCs, particularly in 2012. The EDI and pump differences may be due to the mechanics of pumping sediment up a stream bank, through a hose to a sampler, as opposed to directly collecting into a sampler by manual cross-sectional methods, through the water column, and at the same velocity as the stream. Auto-pump samplers tend to collect more fine sediment than coarse particles due to these restrictions, so even though the pump concentrations can be corrected to the EDIs the particle size distribution cannot. These discrepancies should be considered in deciding which samples to select for developing turbidity-SSC regression models, especially in any type of particle-size analysis.

DISCUSSION

These analyses are not the final regression equations, but were developed to demonstrate the general turbidity-SSC relations in the North Fork Toutle River basin. Also no bias correction factors were applied to the regression equations, which are used to correct for any shift in converting log values back to linear space (Helsel and Hirsch, 2002; Uhrich et al., 2014). The bias correction factors usually alter the equations only slightly so were not considered in presenting preliminary turbidity and SSC relationships. Also, the Solitax high-end turbidity sensor was used as a guide to fill in missing flat-line DTS-12 threshold periods for the 2013 data.

The estimated data was applied from the start to the stop point of the flat-line DTS-12 threshold period.

The logical next step with this preliminary analysis is to develop final regression equations, incorporating a suite of elements to fine tune the models, such as bias correction factors, and developing a separate Solitax to DTS-12 regression. Also, multiple regression models for the North Fork Toutle basin have been shown to more accurately predict SSC from turbidity by using streamflow and a lag of turbidity as added explanatory variables (Uhrich et al., 2014). The final test would be to compute a sediment record using the regression-model approach and compare the results to the conventional sample-based approach.

Fine- and coarse-grain sediment will have fluctuating turbidity and SSC, based on seasonal and rise/fall periods, which can be grouped into defined categories. Model R^2 and SSE values will usually improve with concentrations having finer particle sizes. Hence, suspended-sediment discharge can be differentiated by particle-size distribution. Defining these hysteresis effects improves resource planners' and stakeholders' understanding of fluvial sediment transport and subsequent deposition in the studied lower basins. In the lower Toutle and Cowlitz River channels, aggradation of coarse-grain sediment has significant effects on flood inundation risk to surrounding communities, and in the Columbia River it affects river navigation and shipping commerce by large deep-draft, commercial ocean-going vessels.

SUMMARY

Annual regression models are used for many Pacific Northwest streams to estimate SSC from turbidity. For the North Fork Toutle River an annual time span may not be appropriate, as episodic erosional events and changing sediment sources require shorter time scale models to accurately predict SSC from turbidity. Evaluating sediment transport using seasonal time frames is one method in which this could be achieved, as precipitation patterns in the Pacific Northwest lend themselves to predictable occurrences during certain times of the year. Although seasonal approaches offer improved accuracy over annual models the time scale may not capture shorter-term events that can occur within each season. Shorter-term models for specific events and time scales provide improved accuracy over longer-term turbidity-SSC models. Monitoring of turbidity and sediment transport can vary by particle size. The selection of samples as EDI or auto-pump is important as there can be distinct differences between the collection methods. Once representative samples are selected, it is possible to develop regression models based on sediment-size data from the sample analysis. These particle-size models can be used to predict not only the concentration but also the type of sediment in transport.

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REFERENCES

Anderson, C.W., 2005, Turbidity (ver. 2.1): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6, section 6.7, 64 p., accessed December 18, 2014, at *http://water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html.*

Bragg, H.M., Sobieszczyk, Steven, Uhrich, M.A., and Piatt, D.R., 2007, Suspended-sediment loads and yields in the North Santiam River Basin, Oregon, 1999–2004: U.S. Geological Survey Scientific Investigations Report 2007-5187, 26 p., access December 18, 2014, at *http://pubs.usgs.gov/sir/2007/5187/*

Curran, C.A., Magirl, C.S., and Duda, J.J., 2014, Suspended-sediment concentration during dam decommissioning in the Elwha River, Washington, September 2011 to September 2013: U.S. Geological Survey Data Set, accessed December 18, 2014, at *http://wa.water.usgs.gov/pubs/misc/elwha/ssc/pdf/elwhasscV2_2014.pdf*

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p., accessed December 18, 2014, at *http://pubs.usgs.gov/twri/twri3-c2/*.

Guy, H.P., 1977, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, accessed December 18, 2014, at *http://pubs.usgs.gov/twri/twri5c1/html/pdf.html*.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. C3, p. 221–263, accessed December 18, 2014, at *http://pubs.usgs.gov/twri/twri4a3/*.

Landers, M.N., and Sturm, T.W., 2013, Hysteresis in suspended sediment to turbidity relations due to changing particle size distributions, Water Resources Research, Volume 49, Issue 9, pp. 5487-5500.

Lipman, P.W., and Mullineaux, D.R., 1981, The 1980 eruptions of Mount St. Helens, Washington 1981, U.S. Geological Survey Professional Paper: 1250, p. 844, accessed December 18, 2014, at *http://pubs.er.usgs.gov/publication/pp1250*.

Merten, G.H., Capel, P.D., Minella, J.P.G., 2014, Effects of suspended sediment concentration and grain size on three optical turbidity sensors, Journal of Soils and Sediments, July 2014, Volume 14, Issue 7, pp. 1235-1241.

Rasmussen, P.P., Gray, J.R., Glysson, G.D., and Ziegler, A.C., 2009, Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. 4, 53 p., accessed December 18, 2014, at *http://pubs.usgs.gov/tm/tm3c4/*.

Schenk, L.N., and Bragg, H.M., 2014, Assessment of suspended-sediment transport, bedload, and dissolved oxygen during a short-term drawdown of Fall Creek Lake, Oregon, winter 2012–13: U.S. Geological Survey Open-File Report 2014–1114, 80 p., accessed December 18, 2014 at, *http://dx.doi.org/10.3133/ofr20141114*.

Uhrich, M.A., and Bragg, H.M., 2003, Monitoring instream turbidity to estimate continuous suspended-sediment loads and yields and clay-water volumes in the upper North Santiam River Basin, Oregon, 1998–2000: U.S. Geological Survey Water-Resources Investigations Report 03-4098, accessed December 18, 2014, at, *http://pubs.usgs.gov/wri/WRI03-4098/*.

Uhrich, M.A., Kolasinac, Jasna, Booth, P.L., Fountain, R.L., Spicer, K.R., and Mosbrucker, A.R., 2014, Correlations of turbidity to suspended-sediment concentration in the Toutle River Basin, near Mount St. Helens, Washington, 2010–11: U.S. Geological Survey Open-File Report 2014-1204, 30 p., *http://dx.doi.org/10.3133/ofr20141204*.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedure for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods, book 1, chap. D3, 51 p., plus 8 attachments, accessed December 18, 2014, at http://pubs.usgs.gov/tm/2006/tm1D3/.