COMPUTING TIME-SERIES SUSPENDED-SEDIMENT CONCENTRATIONS AND LOADS FROM IN-STREAM TURBIDITY-SENSOR AND STREAMFLOW DATA

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Abstract Over the last decade, use of a method for computing suspended-sediment concentration and loads using turbidity sensors—primarily nephelometry, but also optical backscatter—has proliferated. Because an in-situ turbidity sensor is capable of measuring turbidity instantaneously, a turbidity time series can be recorded and related directly to time-varying suspended-sediment concentrations. Depending on the suspended-sediment characteristics of the measurement site, this method can be more reliable and, in many cases, a more accurate means for computing suspended-sediment concentrations and loads than traditional U.S. Geological Survey computational methods.

Guidelines and procedures for estimating time series of suspended-sediment concentration and loading as a function of turbidity and streamflow data have been published in a U.S. Geological Survey Techniques and Methods Report, Book 3, Chapter C4. This paper is a summary of these guidelines and discusses some of the concepts, statistical procedures, and techniques used to maintain a multiyear suspended sediment time series.

INTRODUCTION

Fluvial sediment and sorbed materials are the most widespread pollutants affecting U.S. rivers and streams (U.S. Environmental Protection Agency, 2008). The need for reliable, comparable, cost-effective, spatially and temporally consistent data to quantify the clarity and sediment content of waters of the U.S. is great. Estimates of the physical, chemical, and biological damages attributable to fluvial sediment in North America alone range from $20 to $50 billion annually (Pimental et al. 1995; Osterkamp et al. 1998, 2004; Gray and Osterkamp 2007). Adequate, consistent, and reliable data describing fluvial-sediment fluxes is needed for the development of technically supportable management and remedial plans.

Historically, suspended-sediment concentration (SSC) data have been collected by methods described by Edwards and Glysson (1999), Nolan et al. (2005), and Gray et al. (2008). Suspended sediment load (SSL) data have been computed from SSC and streamflow data by methods described by Porterfield (1972) and Koltun et al. (1994; 2006). The traditional U.S. Geological Survey (USGS) computation technique presented by Porterfield (1972) is predicated on the availability of continuous streamflow time-series data and a concurrent trace of SSC interpolated from physical samples, and where necessary, SSC estimates. Interpolated and estimated parts of a SSC trace for a stream site can include periods during which a substantial cumulative fraction of the annual SSL occurs. Hence, considerable hydrologic judgment often is required to compute sediment records by Porterfield's (1972) method. This paper summarizes an alternative method, which is described fully in Rasmussen et al. (2009), that uses in-stream turbidity sensor and streamflow data to compare time-series suspended-sediment concentrations.

RELATION OF TURBIDITY TO SUSPENDED-SEDIMENT CONCENTRATION

The magnitude of SSC in streams, lakes, and estuaries is often proportional to in-situ turbidity (fig. 1). Turbidity is an expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample (Anderson, 2005; ASTM International, 2007). Turbid water results from the presence of suspended and dissolved matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids, and dyes (ASTM International, 2007).

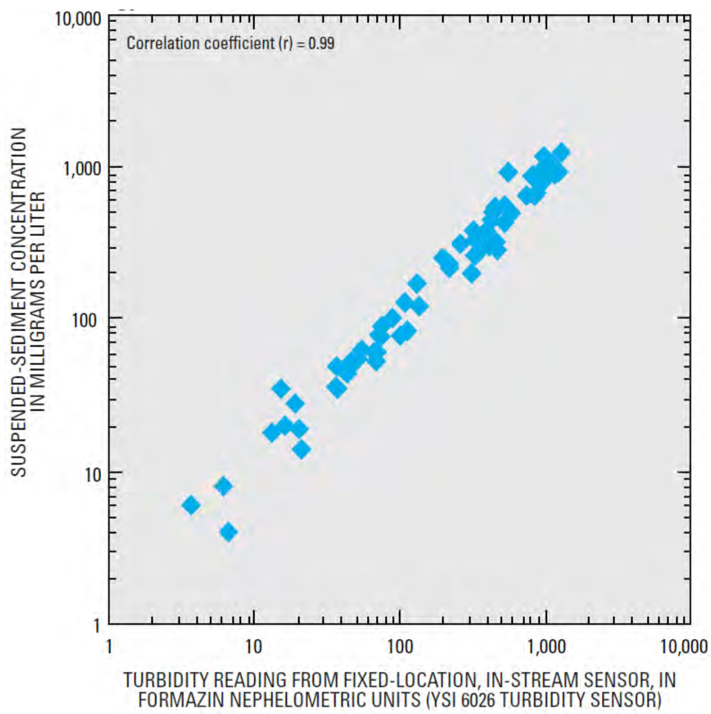

Figure 1 Relation between turbidity and suspended-sediment concentration in $\log_{10}$ space for U.S. Geological Survey streamgage on Little Arkansas River near Sedgwick, Kansas, 1999–2005.

The key characteristics for computing SSC time-series data from periodic instantaneous SSC, turbidity, and streamflow data are the type and goodness-of-fit of the regression model used in the computation. The explanatory variables turbidity and streamflow are generally the most important in SSC regression analysis. A simple linear-regression (SLR) model relating turbidity to SSC is often sufficient for reliable computations of SSC. Criteria are provided in Rasmussen et al. (2009) for determining the sufficiency of a SLR model and for determining when a multiple linear regression (MLR) model relating both turbidity and streamflow to SSC results in a significant improvement. Typically, addition of a streamflow variable is more likely to improve the turbidity-SSC regression as the percentage of the SSC that is sand-size or larger material (coarser than 62 μm median diameter) increases. Regression analysis results are generally site-specific and apply to a single model-calibration data set. Specifically excluded from these guidelines is use of a SLR model for routine computation of SSC solely from streamflow due to varying degrees of hysteresis common in the SSC-streamflow relation. There are three general steps to completing the computation of SCC:

1. Compilation of a model-calibration data set of concurrent turbidity, streamflow, and SSC values;
2. Development of a linear regression model to compute instantaneous values of SSC; and
3. Computation of instantaneous and daily values of SSC and SSL.

When proportional, SSC data from representative water-sediment samples are used in correlations to turbidity. The site-specific turbidity-SSC relation can be quantified through linear regression analysis (fig. 2). The turbidity-SSC regression model, in turn, can be used to compute SSC values from turbidity data within the turbidimeter's measurement range. Continuously monitored in-stream turbidity data enable computation of a SSC time series that can be used with its paired streamflow time series to compute continuous SSL without the routine need for interpolation or estimation.

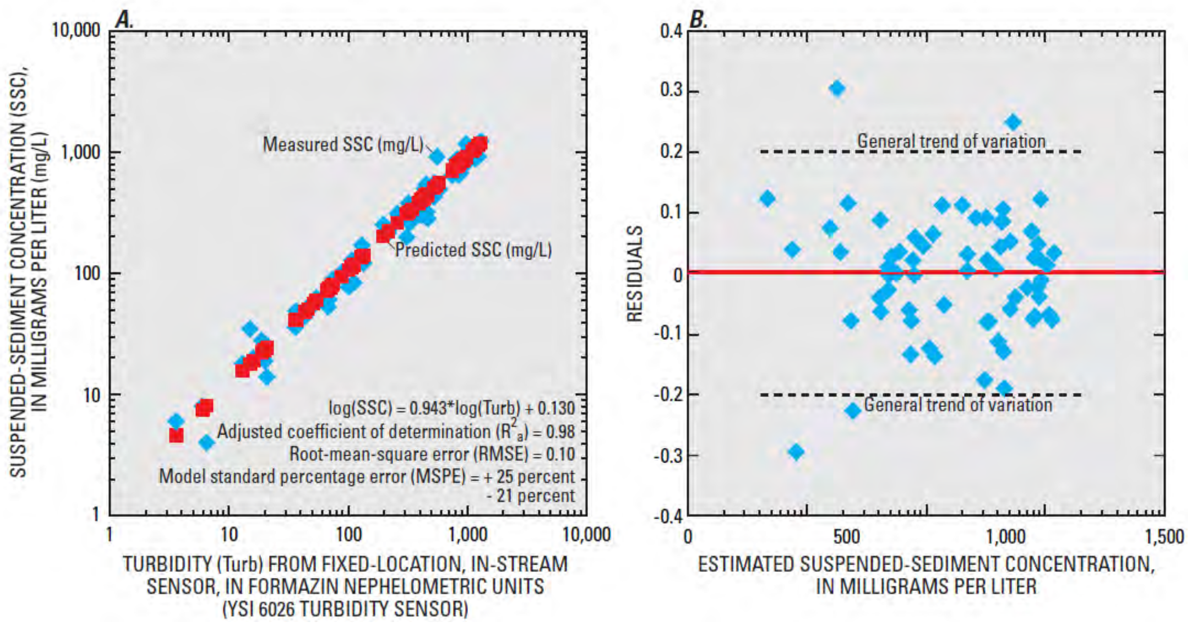

Figure 2 Results of simple linear regression analysis using log-transformed data for *(A)* turbidity and SSC data, and comparison of *(B)* computed $\log_{10}$ SSC concentration and regression residuals.

When the turbidity-SSC model is deemed adequate (fig. 2), a regression-computed SSC can provide a more reliable and reproducible SSC time series with smaller uncertainty values than either a sediment-transport curve using streamflow as the sole independent variable for computations of SSC (Walling, 1977; Lee et al., 2008) or arguably with SSC data produced by Porterfield's (1972) computational method (for which there is no quantitative method for deriving uncertainty). When the turbidity-SSC model is deemed inadequate, the addition of streamflow as a second model variable may result in an acceptable time series of SSC. The turbidity or turbidity-and-streamflow-based computational scheme to produce SSC data has a number of advantages over that of Porterfield's (1972) method, as follows:

1. No subjective interpolation or estimation is required.
2. The computational procedure is precisely reproducible.
3. The scheme takes full advantage of the available database and computational resources; hence, it can substantially reduce the time and effort needed to compute SSL records.
4. Estimates of uncertainty can be computed for the SSC time series.

Adequacy of Model-Calibration Data Set An adequate model-calibration data set consists of an appropriate number of instantaneous manual SSC samples and concurrent turbidity and streamflow measurements collected throughout the observed range of hydrologic conditions for the period of record (Glysson, 1989; Rasmussen et al., 2002; Gray et al., 2008). The number of samples is often cited as the primary criterion for determining if a data set is adequate for computational purposes. Although the sample total is relevant, the distribution of the data over the range of observed turbidity, SSC, and streamflow values for the site is of importance. A regression model developed from 15 samples that are more or less evenly distributed throughout the seasons and range of turbidity and streamflow at a site might result in a more representative model than one developed, for example, using a 50-sample data set where the distribution of values defines only a limited time or range of the sedimentological conditions over which the model will be applied. Defining turbidity-SSC relations during medium- and high-streamflow periods normally takes precedence over more equal spacing of data collection throughout the year, particularly if the purpose is to compute SSL. For example, where the number of site visits to collect manual samples is small, sample collection for SSL computations need to be skewed toward medium and higher flows. Regardless of the range of data values, the data points representing the extremes will have the greatest effect in determining the slope of the relation. For instance, erroneously large turbidity values during low streamflow and low SSC conditions can artificially increase the slope of the regression line.

Another factor to be considered when determining the adequacy of a data set is the amount of variability in the relation between turbidity and SSC. The larger the variability in the relation between turbidity and SSC at a site, the greater the need is to collect more samples. Often, the hydrographer’s challenge is to adequately characterize this variability with the fewest number of site visits and samples.

Duration curves are another tool to evaluate the distribution of SSC data and adapt subsequent sample-collection strategies. Ideally, turbidity and streamflow associated with the SSC samples will span the ranges of the time-series turbidity and streamflow values for the site (Rasmussen et al., 2002). For example, turbidity and streamflow values associated with discrete SSC sample data are plotted on duration curves of turbidity and streamflow (fig. 3A and 3B). The turbidity duration curve in figure 3A was developed from hourly recorded turbidity measurements by the fixed-location turbidity sensor for the study period. The turbidity values associated with the SSC samples were plotted along the duration curve. Sample collection can be determined by closely monitoring the real-time turbidity and streamflow time-series data and optimizing sample-collection times to coincide with duration-curve segments undefined by sample values. As new SSC samples are collected, the hydrographer then adds the corresponding turbidity and streamflow values to the duration-curve plots so that overall temporal distribution of samples can be assessed. Routine use of this tool will maximize the potential that the model-calibration data set optimally represents the range of turbidity and streamflow conditions. Further details on developing and utilizing duration curves, are described in Rasmussen et al. (2009).

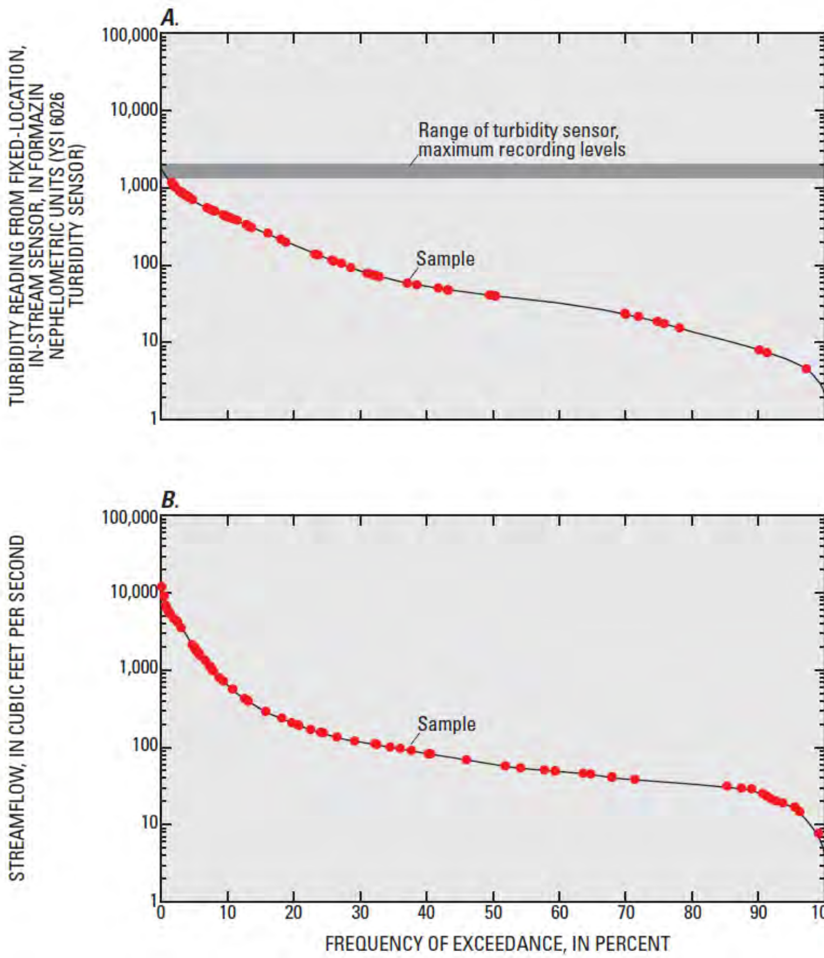

Figure 3 Duration curves for (A) turbidity and (B) streamflow and corresponding values associated with SSC samples collected at USGS streamgage on Little Arkansas River near Sedgwick, Kansas, 1999–2005.

Serial correlation (also called autocorrelation) occurs when data are collected close enough in time that the regression assumption of data independence is violated. For instance, multiple samples may be collected during the rising and falling limb of a single runoff period. The serial correlation between the multiple data points can cause underestimation of the regression uncertainty. Helsel and Hirsch (2002, p. 250-1) present methods for identifying the presence of serial correlation. If serial correlation is detected, the solution is to randomly select a single data point from each group of correlated data. The single point is then used in the model-calibration data set. Alternately, Glysson (1987) describes a procedure by which mean SSC values are computed for each of several contiguous, discrete SSC intervals for the data set. These mean values are used to develop the regression equation.

Large turbidity values warrant special evaluation. Although the values may be valid, spurious data can occur, especially those recorded when turbidity exceeds the sensor's maximum recording level. Sensor-measurement truncation produces constant-value artifacts when in-stream turbidity levels exceed the maximum recording level of the sensor (1,000–3,000 milligrams per liter (mg/L) for most nephelometric sensors and 4,000-50,000 mg/L for most optical backscatter (OBS) sensors). The maximum recording level is unique for each turbidity sensor and needs to be routinely quantified and documented for each sensor (Anderson, 2005). Because the maximum recording level of the sensor is reported for all turbidity values equal to or larger than the maximum recording level, truncation is manifested as a horizontal line or plateau in the temporal turbidity trace of plotted data (fig. 4). The use of turbidity sensors to compute SSC at a site subject to frequent turbidity truncation may not be appropriate. OBS sensors are used for streams where a substantial proportion of SSL occurs at SSC values exceeding about 3,000 mg/L (fig.4). However, currently (2010) most OBS sensors are not self cleaning and require more frequent routine maintenance.

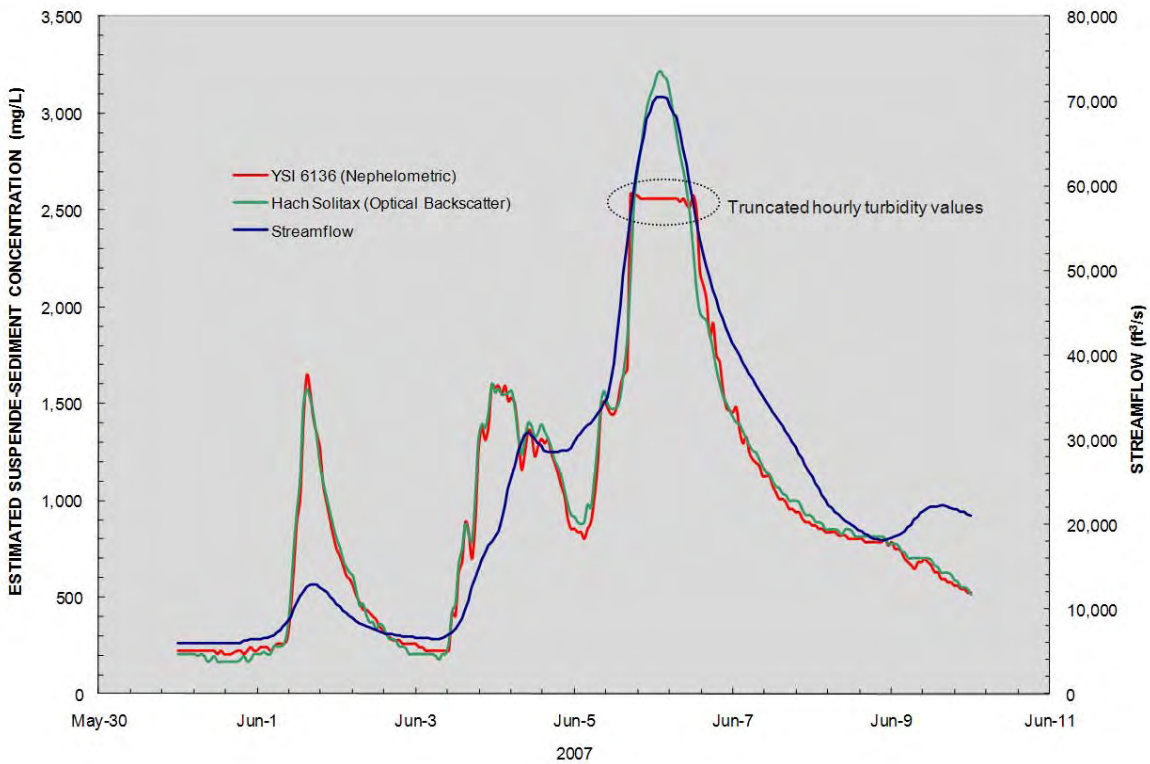

Figure 4 Time-series of computed SSC from hourly nephelometric turbidity (YSI 6136) and optical backscatter turbidity (Hach Solitax), and streamflow data, May 30–June 11, 2007, at the USGS streamgage on Kansas River near DeSoto, Kansas.

Factors Affecting the Relation Between Turbidity and Suspended-Sediment Concentration

The hydrographer needs to be mindful of factors other than SSC that can affect turbidity measurements. Particle size, shape, and color all affect the amount of light scattered (Sutherland et al., 2000). Light is absorbed or scattered as it travels from a light source, to suspended particles, and is reflected back to a detector. As the grain-size distribution of SCC increases beyond about 90 μm (very fine sand), the turbidity-SSC relation will become negatively biased, and that bias will increase as particle sizes increase (Anderson, 2005). Particle shape affects the scatter intensity. Darker or more black-colored (Munsell Color Co., 2000) particles also have been shown to substantially affect turbidity measurements by imparting a negative bias in measurements (Sutherland et al., 2000). Insights as to the potential effects of these and other factors might be gained from having particle-size, organic matter, and color analyses performed on selected water-sediment samples. Other factors affecting the turbidity-SSC relation are measurement error (including SSC sample collection and analysis) and natural variability caused by processes not evaluated in the regression model. Turbidity resulting from the presence of suspended microorganisms–principally phytoplankton–can result in increased uncertainty in the SSC determination. Hence, caution is used when inferring SSC from turbidity or turbidity and streamflow values in water with substantial microbiological activity.

Changes to Turbidity Sensor Model or Type Different sensors can provide different turbidity readings for the same environmental sample (Landers, 2003). The sensor's configuration of detectors and the source of light are important factors to the response of the turbidity instrument. Although comparisons among instruments with differing designs are often robust, their results can also vary according to the character of the sample's matrix and particulates. Results from an interagency workshop held in 2002 demonstrated that turbidity data from different sources and instrumentation can be highly variable and are often in disagreement with each other, even when instrument-calibration methods are similar (Gray and Glysson, 2003). Different detector geometries and light sources do not make equivalent measurements.

A change of sensor model or type most likely will require an adjustment of the historical regression-relation values so that the equivalency of turbidity sensor-response characteristics of historical and newly collected data is maximized. The hydrographer needs to compare turbidity measurements between differing sensors in a range of environmental samples. The difference between sensors cannot be identified in formazin standards (Hach; Loveland, Colo.) and may be reversed in polystyrene bead standards (APS Analytical Standards Inc.; Redwood City, Calif.; fig. 5).

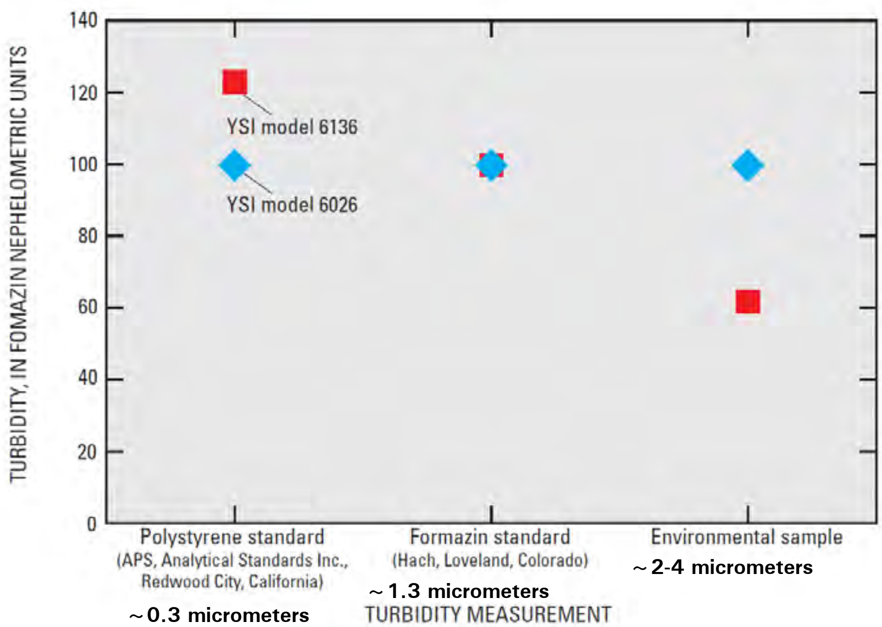

Figure 5 Comparison of turbidity measurements from YSI turbidity models 6026 and 6136 (YSI Incorporated, Yellow Springs, Ohio) in various solutions. Average particle size is shown in micrometers for each solution.

Typically, turbidity data collected with an old sensor can be adjusted to an approximately equivalent reading for a new sensor by means of a conversion factor. The conversion factor is computed from a data set consisting of concurrent turbidity measurements collected by the old and new sensors arrayed adjacent to each other in the stream. The hydrographer will take care to ensure that the range of the concurrent measurements spans the known range of turbidity values at the site. One way of achieving this is to operate both sensors in-stream, side-by-side, over a wide range of turbidity conditions. The resulting data set will provide a robust conversion factor for the monitoring site.

MODEL VALIDATION AND MAINTENANCE OF A LONG-TERM SUSPENDED-SEDIMENT CONCENTRATION RECORD

Once an acceptable regression model is developed, it can be used to compute SSC beyond the period of record used in model development with proper sample collection and analysis. Maintenance of a long-term SSC record requires ongoing collection of turbidity and streamflow time-series data and sample collection for reanalysis and verification of the current SSC regression model. The method for validating the regression model is affected by the frequency of calibration-sample collection and the purpose of the study. Regression models can be validated annually (or at some other frequency as needed on the basis of the nature of the monitored hydrologic system and its watershed, and the needs and constraints of the monitoring program) after sufficient applicable new data have been collected or on the basis of other valid criteria. A fundamental characteristic of hydrology is variability, with periods of floods and periods of droughts. A shift in the regression model usually results from a major change in sediment source or transport processes in the watershed, such as those resulting from a substantial change in land use or land cover, construction or removal of an impoundment, wildfire, landslide, or a major flood. Therefore, regression models used to compute SSC at a site are never considered to be static but rather considered to represent a set period in a continually dynamic system in which additional data will help verify any change in SSL, type, and source.

Validation of Suspended-Sediment Concentration Model One approach to updating the regression model is to plot new observations with the original model-calibration data set and recompute the regression coefficient(s) and y-intercept. Typically, at least 4 to 10 SSC samples and associated turbidity and streamflow values representing a wide range of streamflows are collected annually, depending on the site and monitoring program, to validate the existing regression model. The additional data plotted along with the model-calibration data set for comparison will indicate any significant change in the turbidity-SSC relation that would signal the need for a completely revised regression model or additional and more frequent sample collection. A review of the scatter plot for the Little Arkansas River near Sedgwick, Kansas, suggests that there has been no significant change or shift in the turbidity-SSC relation (fig. 6).

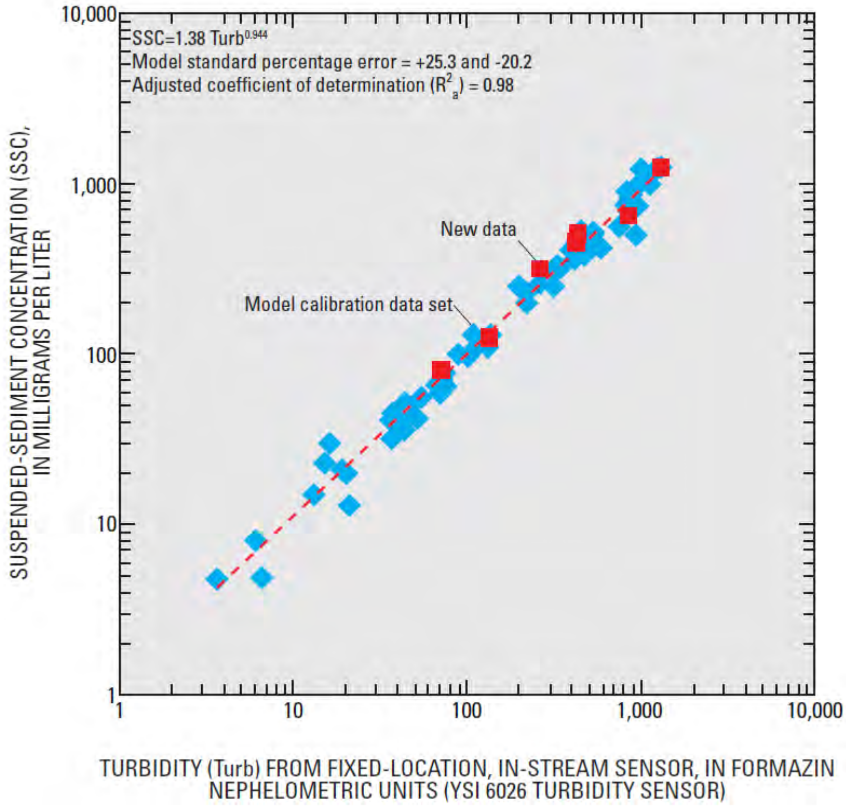

Figure 6 Model--calibration data set (water years 1999–2005) and new (water year 2006) turbidity and suspended-sediment concentration data for USGS streamgage on Little Arkansas River near Sedgwick, Kansas.

A regression model developed from new measurements not used in previous model development needs to be compared to the existing regression model. Analysis of covariance (ANCOVA; Helsel and Hirsch, 2002) can be used to test (1) the regression model on the basis of the original model data and additional data, (2) the original regression model, and (3) the regression model solely on the basis of the additional data. ANCOVA will determine if the slope or y intercept of any of these models is significantly different, indicating a fundamental shift in the turbidity-SSC relation and the possible need to develop a new model. If a shift occurred, the hydrographer also will need to determine when it occurred and when to cease use of the existing model and begin use of a new model. A more likely scenario is a gradual change over years that can be detected only by continued sample collection and analysis.

New data that do not significantly change the original regression are added to the model-calibration data set to refine the regression model. The slope, y intercept, and the computed SSC values from the new model will not be significantly different from the old model, but the improved estimate of root mean square error may reduce the prediction interval (Rasmussen et al. 2009). The hydrographer has to determine when the refined model will take effect. If sample collection and analysis are considered on an annual basis, the new model starts at the beginning of the ensuing water year. An approved computed SSC time series is not recomputed unless there is strong evidence that the turbidity-SSC relation changed during the approved period. The hydrographer in this case has determined that the revised model will take effect at the beginning of water year 2006.

SUMMARY

Collection, computation, and publication of suspended-sediment and related environmental data are a necessary part of investigations to evaluate effects of fluvial sediment and sediment-associated constituents on water resources. In-stream continuous turbidity data, or continuous turbidity and streamflow data, calibrated with measured SSC data, can be used to compute a time series of SSC and SSL. Development of a simple linear regression model between turbidity and measured SSC data is the first step in computing a SSC time series. If the model standard percentage error for the simple linear regression model meets an established minimum criterion, this model can be used to compute a time series of SSC. If the simple regression model does not meet the acceptability criterion, a multiple linear regression model using paired instantaneous turbidity and streamflow data is developed. If the addition of streamflow is statistically significant and the uncertainty associated with the multiple regression model results in an improvement over that for the simple linear model and is ultimately acceptable, it is used as the basis for computing a time series of SSC. The computed SSC time series is subsequently used with its paired streamflow time series to compute a time series of SSL by standard USGS techniques. Time-series SSC and SSL data can be used to better describe variability in suspended-sediment conditions, to evaluate SSC relative to numerical water-quality criteria and management goals, and to make watershed comparisons.

Once an acceptable regression model is developed, it can be used to compute SSC beyond the period of record used in model development with proper sample collection and analysis. Maintenance of a long-term SSC record requires ongoing collection of turbidity and streamflow time-series data and calibration-sample collection for reanalysis and verification of the current SSC regression model. The method for validating the regression model is affected by the frequency of sample collection and the purpose of the study. Regression models can be validated annually (or at some other frequency as needed on the basis of the nature of the monitored hydrologic system and its watershed, and the needs and constraints of the monitoring program) after sufficient new data have been collected or on the basis of other valid criteria. Regression models to compute SSC are generally site specific and are never considered static but rather considered to represent a set period in a continually dynamic system in which additional data will help verify any change in SSL, type, and source.

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