COMPARISON OF SUSPENDED-SEDIMENT LOAD ESTIMATES USING A TURBIDITY AND SUSPENDED-SEDIMENT CONCENTRATION REGRESSION AND THE GRAPHICAL CONSTITUENT LOADING ANALYSIS SYSTEM (GCLAS)

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Abstract Water withdrawn from the North Santiam River is treated to provide drinking water to the residents of Salem, Oregon, and surrounding communities. Turbidity testing is done at the water-treatment facility to determine whether the water meets drinking-water standards and to prevent excess sediment in the river water from damaging or clogging the filters. In an attempt to better understand the transport of sediment, a monitoring network was established in 1998 throughout the North Santiam River Basin. A regimen of continuous turbidity monitoring and selective suspended-sediment sampling over the hydrograph was implemented to determine the relation between turbidity and suspended-sediment concentration (SSC) at each of the monitoring stations. Using this relation, continuous turbidity measurements were used to estimate semihourly (every 30 minutes) concentrations of suspended sediment at each site.

Six years of turbidity and suspended-sediment concentration data have been analyzed for one of the network stations, the North Santiam River below Boulder Creek near Detroit, Oregon. The 1999 water year was chosen to illustrate the data, as well as a short period in 2003, as each were well represented by the collection of suspended-sediment samples over varying flow and turbidity conditions. A regression equation was developed between turbidity and SSC to estimate semihourly SSC. The Graphical Constituent Loading Analysis System (GCLAS), developed by the U.S. Geological Survey, was used to further adjust the estimated SSC values. The GCLAS visual interface and coefficient application software adjusted the estimated SSC curve to intersect the measured SSC sample data. Suspended-sediment loads were then calculated using both turbidity/SSC regressions and GCLAS-adjusted SSC estimation methods.

In most years, the highest sediment loads are transported during just a few large storm events. Hence, an accurate estimation of the SSC is critical in determining suspended-sediment loads for the few days during which most of the annual load occurs. Using GCLAS, adjustments were made to the SSC values for two high-turbidity and high-flow events in December 1998, and a summer high-turbidity event in September 2003. Both examples highlight the differences between using turbidity/SSC regressions with and without GCLAS-adjustment methods to compute suspended-sediment loads. The GCLAS adjustments in December 1998 resulted in a combined +35 percent change from the turbidity/SSC regression estimate for the month. The adjustments in September 2003 resulted in a -63 percent change. The December adjustments accounted for a 16 percent increase in annual load, and the September adjustments a 0.8 percent decrease in annual load. GCLAS can enhance turbidity/SSC regression methods during short periods when several measured samples are available during the period of adjustment. For longer time periods, and when fewer samples are collected, the turbidity/SSC regression alone provides a more reliable annual load as the instantaneous estimates are based on several thousand continuous turbidity measurements and the data fit around the regression line incorporates the entire suite of measured samples.

INTRODUCTION

The North Santiam River Basin is located on the western slopes of the Cascade Range in northwestern Oregon, east of Salem. The river flows west from Mount Jefferson to the Willamette River. The basin is 75 percent forested, with timber harvesting and recreation as the dominant land uses. Heavy precipitation is common in the Western Cascades mountain terrain. When rain combines with a melting snowpack, severe erosion can occur on the steep slopes. Geomorphic events, such as landslides, debris flows, and road failures, can supply tremendous volumes of suspended sediment into the river transport network. Slower moving earthflows can also move downslope when they become saturated during wet periods, impinging on streams and supplying fine-grained sediment that can cause persistent high turbidity.

Surface waters of the North Santiam River provide much of the drinking water for the 170,000 residents living in Salem, Oregon and surrounding communities. The City of Salem water-treatment facility is unusual in that it uses a slow-sand filtration system in conjunction with biological activity to treat raw river water. The water settles through an algal mat on the bottom substrate to remove organic contaminants and then through gravel and sand filters to remove inorganic particulates. Excessive sediment can damage these filters; consequently, daily turbidity testing is conducted at the water-treatment facility to assess the condition of the river water.

In 1998, the U.S. Geological Survey, in conjunction with City of Salem, established three sites in the upper North Santiam River Basin to measure water quality (specific conductance, pH, water temperature and turbidity) and streamflow. In 2005, the network expanded to nine continuously operating sites with telemetry, located throughout the basin. Eight additional non-telemetry sites are in operation to monitor turbidity downstream of suspected sediment sources. The monitoring network serves as an early-warning system to the Salem water-treatment personnel by providing near real-time river conditions upstream of the facility. The data allow plant operators to better regulate and control incoming surface waters, which might require application of costly particle settling chemicals during periods of high turbidity or closing intake gates to avoid damage to the sand filters. In addition, the monitoring network can be used to track the progress of high-flow and high-turbidity events from the subbasins in which they originated. This information also assists the appropriate land owners and regulatory agencies in managing their lands in such a way as to minimize or eliminate these high-turbidity occurrences by identifying potential sediment-source areas and activities.

Hence, turbidity monitoring provides useful water-quality data to both water-supply and land-management agencies within the North Santiam River Basin. Collection of streamflow data and suspended-sediment samples also can translate into useful quantitative data. In a previously-published report, Uhrich and Bragg (2003) demonstrated that turbidity is a better surrogate for suspended-sediment concentration than streamflow in the basin and outlined a procedure for estimating suspended-sediment loads. The use of GCLAS can enhance the usability and accuracy of the load data by matching these estimates to the measured field data, but the period of adjustment and number of samples available for analysis must be closely evaluated. The best application of GCLAS is when several samples are collected over a storm hydrograph; otherwise when fewer samples are collected, the turbidity/SSC regression may provide the best annual suspended-sediment load estimate.

METHODS

Suspended-sediment loads were calculated for the gaging station at North Santiam River above Boulder Creek near Detroit, Oregon (14178000) for the 1999 water year (October 1, 1998, to September 30, 1999) and also for September 2003. The 216-square-mile basin upstream of this site is primarily forested and drains a mountainous terrain originating from glaciated volcanic peaks of the Cascade Range that top 10,000 feet elevation. Water year 1999 produced significantly high annual and peak flows in the North Santiam River Basin. The 1999 mean annual streamflow for the North Santiam site was near the 90^{th} percentile for 80 years of record. The highest daily mean streamflow for this station was also above average, near the 70^{th} percentile. There were several high turbidity events in water year 1999, yet only 4 percent of the 30-minute turbidity readings were at or above 10 FNU (formazin nephelometric units). Nonetheless, this short duration of increased turbidity accounted for almost 70 percent of the annual suspended-sediment load.

<u>Estimating Suspended-Sediment Concentrations and Loads</u> Instantaneous suspended-sediment concentrations were estimated for the North Santiam site by developing a regression relation between the instream turbidity recorded at the site (the explanatory variable) and the suspended-sediment sample concentrations (the response variable). The regression analysis used the entire suite of samples collected since the project inception. Regression equations are periodically revised as more samples are collected. The estimated suspended-sediment concentrations, along with their corresponding streamflow, are used to calculate suspended-sediment loads.

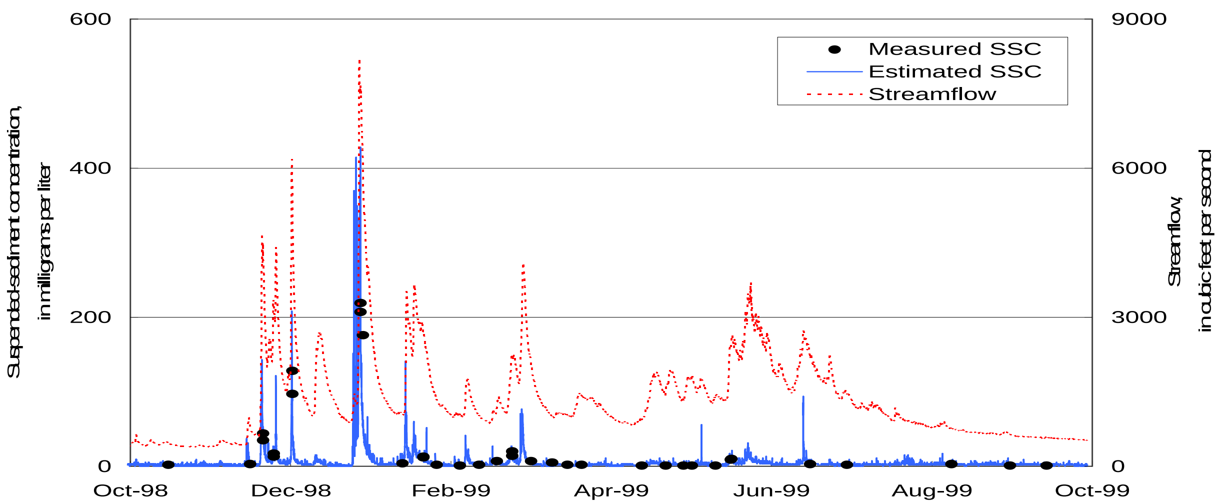

Figure 1 Instantaneous streamflow, measured SSC and estimated SSC, North Santiam River above Boulder Creek, 1999 water year

Instream turbidity and streamflow data were collected at 30-minute intervals, resulting in 17,520 values for water year 1999. Suspended-sediment samples have been collected at the North Santiam site over a range of hydrologic conditions from 1998 to 2004, resulting in 121 stream-width/depth-integrated samples. For each sediment sample, the 30-minute turbidity values were averaged over the duration of sample collection, providing a single turbidity value, in FNU. Each sample also was analyzed for suspended-sediment concentration, in milligrams per liter (mg/L). As a result, each suspended-sediment sample has two data values associated with it: turbidity and suspended-sediment concentration (SSC).

The paired data were used to develop a regression equation. The turbidity and SSC values were transformed to base-10 logarithmic values. The log values were then used to calculate a linear least-squares regression. The North Santiam site equation, converted to power form is:

$$SSC = 1.54\ (\text{turbidity})^{1.04} \qquad (1)$$

Transforming the data values to logarithmic values and back introduced a bias into the regression. This bias was corrected with a “smearing” estimator described by Helsel and Hirsch (1992). The final North Santiam regression equation including the bias correction factor is (figure 2):

$$SSC = 1.75\ (\text{turbidity})^{1.04} \quad (R^2 = 0.893) \qquad (2)$$

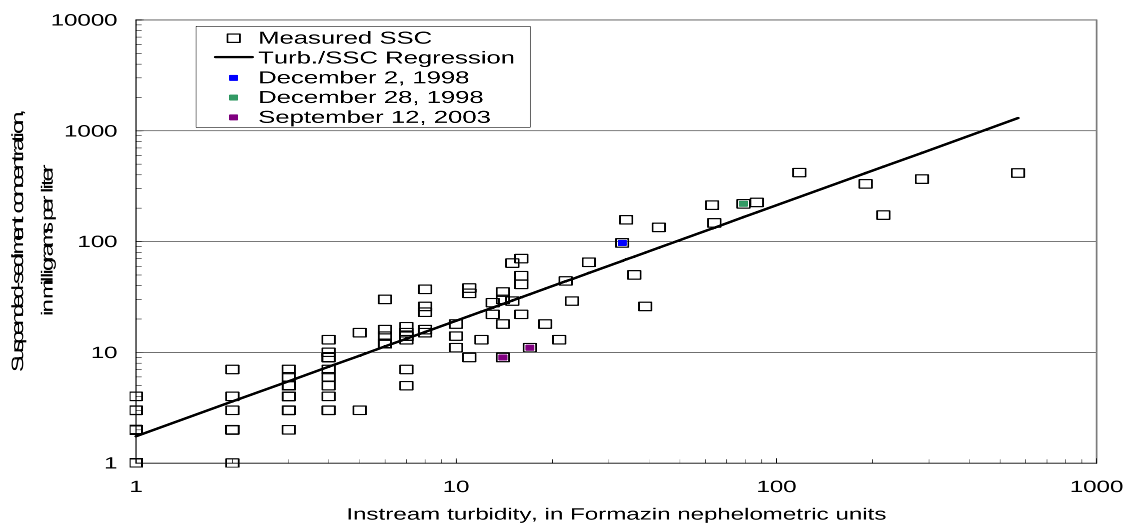

Figure 2 Turbidity and suspended-sediment concentration regression line

The SSC regression equation for the North Santiam site was used to calculate estimated suspended-sediment concentration for each 30-minute turbidity value logged for water year 1999 (figure 1). The instantaneous suspended-sediment load (SSL) values were then calculated using the corresponding streamflow with the following equation (Porterfield, 1972):

$$SSL\ (\text{tons/day}) = SSC\ (\text{mg/L}) \times Q\ (\text{cfs}) \times c \qquad (3)$$

where Q is instantaneous streamflow in cubic feet per second (cfs) and *c* = 0.00270, which converts the units to tons per day. The 48 SSD values calculated per day were averaged to provide a daily mean SSL (SSL is used here to represent Suspended-Sediment Discharge, although load is technically defined as a mass only and discharge as a mass per unit of time).

Graphical Constituent Loading Analysis System (GCLAS) The U.S. Geological Survey software program GCLAS (Graphical Constituent Loading Analysis System) can also be used to compute suspended-sediment loads, McKallip et al. (2001). The program is designed to use measured sample and streamflow data, along with estimated constituent concentrations to compute loads. The user normally selects a combination of measured and estimated SSC input values to compute loads. GCLAS provides a visual and interactive means to inspect and interpret the concentration data as it relates to the samples collected. The graphical interface of GCLAS can be used to portray the data at varying time and concentration scales, permitting a hands-on approach to adjusting the concentration data in relation to time or streamflow. On-the-fly computations of loads can be accomplished in GCLAS after each manipulation of the concentration curve. The changes can be compared numerically and visually to determine if adjustments are appropriate.

The instantaneous SSC estimated from the turbidity/SSC regression were imported into GCLAS. These estimated SSC values far outnumbered the measured values and therefore were selected instead of the measured SSC values to compute the suspended-sediment loads. The concentration and streamflow values of the measured sediment samples also were imported into GCLAS under a different classification and later used to make adjustments to the estimated SSC values. The suspended-sediment load for the North Santiam gaging station was calculated for two periods of record (table 1). Visual inspection of the estimated SSC curve was conducted by zooming in on the working graph and scrolling through the duration of each water year. In several instances, significant differences were noted between the estimated SSC (from the turbidity/SSC regression) and the measured SSC (from the sediment sample). GCLAS was used to apply coefficients to selected estimated SSC values to better correspond to measured values. Coefficients are multiplication factors applied to the estimated SSC values that adjust the SSC curve to intersect the measured SSC samples, along the sampled timeline. The examples shown in this report used both constant and time- or streamflow-varying coefficients. Suspended-sediment loads were calculated before and after each GCLAS adjustment for comparison.

RESULTS AND DISCUSSION

SSC estimates were evaluated for the 1999 water year at the North Santiam monitoring station. Analysis of the turbidity/SSC regression estimated SSC values and the measured SSC samples identified two periods requiring coefficient adjustments. The estimated SSC values during storm events on December 2, 1998, and December 27-29, 1998, were lower than the values of the stream width-/depth-integrated samples (figures 3 and 4). The GCLAS adjustment coefficients were calculated and applied over the selected time range. A total of 72 hours of SSC data was adjusted for December 2 and December 27-29. These adjustments resulted in an increase of nearly 2,500 tons in the December suspended-sediment load, or a 16 percent increase in the annual turbidity/SSC regression estimated load (table 1).

The entire adjustment period for each event was shifted to a single measured stream width-/depth-integrated SSC occurring on the declining portion of the hydrograph. Single vertical samples are shown, but were used only to verify the cross-sectional samples. GCLAS was used to recalculate the monthly and annual suspended-sediment load after each adjustment. Values for all other 1999 water year turbidity/SSC regression estimated periods were within 5 percent of the measured sample data and were not adjusted. An example of a nonadjustment period is shown in figure 3 for November 25-26, 1998. GCLAS adjustments to turbidity/SSC regression estimates work best for short time periods or for specific high-flow, high-sediment events when several samples are collected to define the changing load conditions. In addition, the measured samples collected during both December 1998 storm events were within the 95 percent confidence interval of the regression, and therefore would not normally be adjusted

Table 1 Adjusted Suspended-Sediment Loads (SSL).

Adjusted Dates	Estimated SSL	Adjusted SSL	Adjustment and percent change
December 2, 1998	940 tons	1360 tons	+ 420 tons (45%)
December 27-29, 1998	6240 tons	8300 tons	+ 2060 tons (33%)
Annual Suspended-Sediment Load Adjustments			+ 2,480 tons (16%)

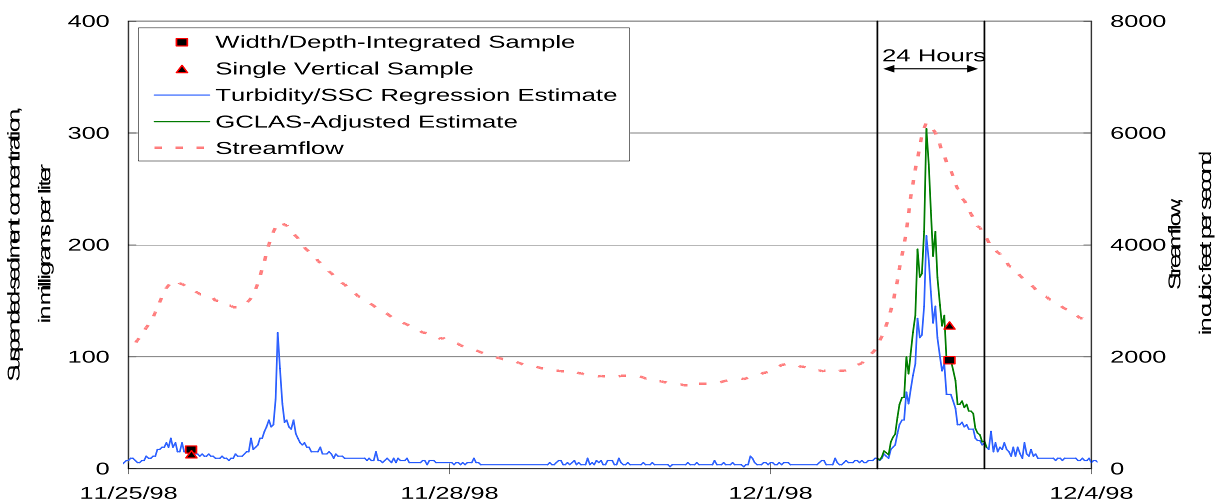

Figure 3 Adjustment of estimated suspended-sediment concentrations for December 2, 1998.

An example of a specific high-sediment event that fell outside the 95 percent confidence interval (figure 2) during which several samples were collected occurred in September 2003 and is shown in figure 5. In this case, two stream width-/depth-integrated samples were collected during this high-turbidity and low-flow period. At that time, an automatic pumping sampler was programmed to collect point samples based on the instream turbidity values. Fourteen point samples were collected before, during and after the collection of the two width-/depth-integrated samples. The turbidity/SSC regression produced estimated SSC values higher than the samples collected. Such events can be common for the late summer season at the North Santiam site, and likely relate to a glacial or wilderness area disturbance in the basin headwaters.

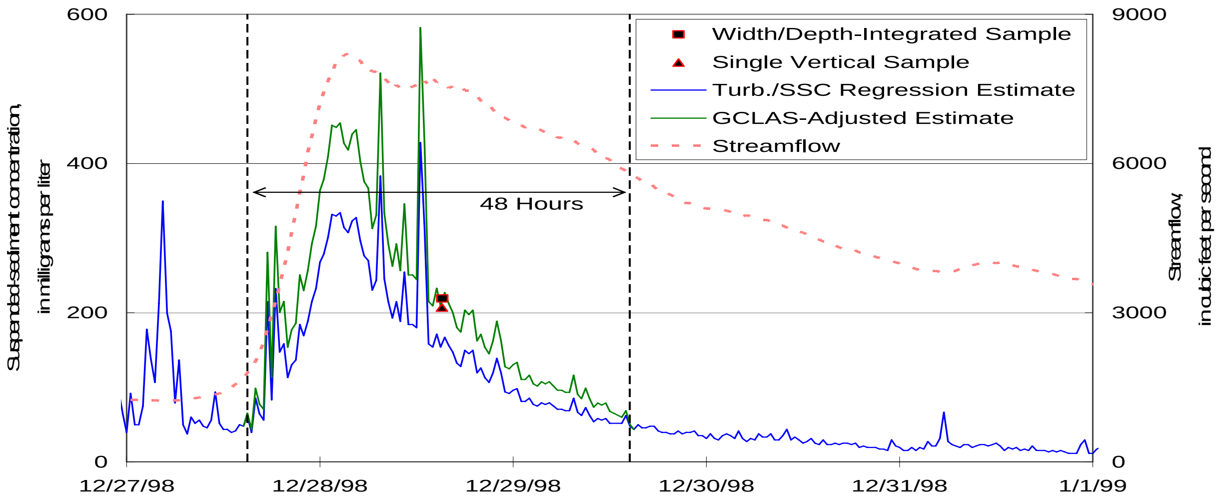

Figure 4 Adjustment of estimated suspended-sediment concentrations for December 27-29, 1998.

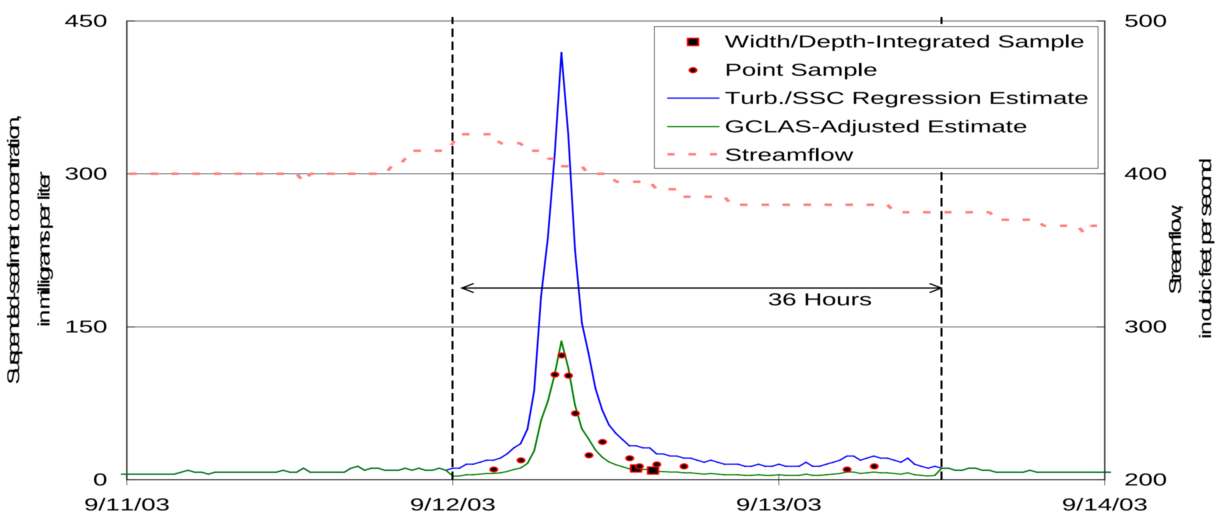

Figure 5 Adjustment of estimated suspended-sediment concentrations for September 2003.

Figure 5 shows the SSC values estimated by the turbidity/SSC regression for September 12-13, 2003. Using the estimated SSC, the suspended-sediment load for these 2 days is 84 tons. GCLAS was used to make adjustments encompassing the duration of the point-sample collection. The coefficients for the width-/depth-integrated samples were calculated and applied over 36 hours. The resulting SSC curve falls much closer to the point samples collected, providing additional support to the adjustment. Using the GCLAS-adjusted SSC values, the suspended-sediment load for these 2 days is 32 tons. Although this represents a 63 percent decrease in these load values, the effect on the annual suspended-sediment load for water year 2003 is only -0.8 percent.

For these high-sediment events at the North Santiam site, the turbidity/SSC regression method appears to underestimate suspended-sediment loads during storm events and overestimate during low-flow periods, but this is entirely basin and event dependent, and may change both temporally and spatially as sediment sources change. Both periods of adjustment were relatively significant (+35 percent combined in December, and -63 percent in September), but the storm events obviously have the greatest impact in sediment transport. The 4 adjusted days in December comprise 47 percent of the annual suspended-sediment loads. The adjustments made with GCLAS can increase the reliability of turbidity/SSC regression derived SSC and load estimates for specific high-flow, high-sediment events when several samples are collected. When few samples are collected during a high-flow event, such as a single sample or samples that do not track the entire hydrograph, using GCLAS may shift the entire load curve, resulting in either an overestimation or underestimation. Use of the turbidity/SSC regression equation to estimate load when measured data are sparse may provide an estimate closer to the true value. When longer time periods are considered, the regression approach at the North Santiam site may better define the overall estimate of suspended-sediment loads under changing scales and degrees of flux.

SUMMARY

GCLAS permits adjustment of concentrations estimated by means of regression relationships developed between instream turbidity and measured suspended-sediment concentrations, which can enhance the use and applicability of the sediment-concentration regression equation. This fine tuning can provide a better estimate of suspended-sediment loads over short time frames or specific events when several samples are collected, since the estimated SSC values can be adjusted to agree with the measured concentration data. Over longer timescales, a turbidity/SSC regression approach, without adjusting with GCLAS, provides a better overall suspended-sediment estimate as it uses all the measured samples collected over several years and flow events, as well as the 17,520 per year readings of continuous turbidity to complete the sediment record. The continuous measurement of turbidity proves invaluable for providing information on concentration trends during periods without measured sediment data by documenting the timing of peak fluvial sediment flux that may not be detectable using streamflow alone.

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