

TURBIDITY THRESHOLD SAMPLING FOR SUSPENDED SEDIMENT LOAD ESTIMATION

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Abstract: The paper discusses an automated procedure for measuring turbidity and sampling suspended sediment. The basic equipment consists of a programmable data logger, an in situ turbidimeter, a pumping sampler, and a stage-measuring device. The data logger program employs turbidity to govern sample collection during each transport event. Mounting configurations and housings for the turbidimeters have been prototyped and tested or deployed at 16 gaging sites in northwestern California. Operational data are presented with examples illustrating storm load estimation.

INTRODUCTION

The utility of information about suspended sediment transport is dependent on the timing and frequency of data collection. Even in seasonally snow-dominated watersheds, most of the annual suspended sediment is usually transported during a few, large rainstorm events. Automated data collection is essential to effectively capture such events. Although it is possible to rely solely on manual measurements, important storm flows are infrequent and difficult to predict, and when they do occur, trained personnel may not be available to collect the required information.

As of yet, there is no reliable method to directly measure total suspended sediment concentration (SSC) in the field. Pumped or manual samples must be transported to a laboratory for analysis. However, a number of manufacturers now offer turbidity sensors that can be deployed on a continuous basis in streams. While turbidity cannot replace SSC, it can be a tremendous asset as an auxiliary measurement. Turbidity can be used, along with discharge, in an automated system to make real-time sampling decisions linking turbidity to concentration. And the continuous turbidity record can reveal sediment pulses unrelated to discharge, providing information about the timing and magnitude of landslides or stream bank failures upstream.

METHODS

Sampling: The turbidity threshold sampling (TTS) method distributes sample collection over the range of rising and falling turbidity values and attempts to sample all significant turbidity peaks. A data logger records discharge and turbidity at frequent time intervals (10 or 15 minutes at current installations) and activates a pumping sampler when specified turbidity conditions are met. Discharge information is used to disable sampling when either the turbidity sensor or pumping sampler intake is not adequately submerged. The resulting set of TTS samples can be used to accurately determine suspended sediment loads by establishing a relation between sediment concentration and turbidity for any sampled period with significant sediment transport. The relation is then applied to the nearly continuous turbidity data.

Turbidity thresholds for sampling are based on the expected turbidity range for a given stream and the number of desired physical samples. The TTS method is designed to permit estimation of sediment loads for individual storm events that vary greatly in size. Thresholds are chosen such that their square-roots are evenly spaced (Lewis, 1996) to ensure the collection of samples during small events while holding the number of samples collected in large events within practical limits. Different sets of thresholds are used when turbidity is rising and falling, with more thresholds required during the lengthier falling period. To avoid oversampling due to transient turbidity spikes, each threshold condition must be met for two intervals before sampling is initiated and a minimum user-specified period of time must elapse before a sampled threshold can be re-utilized.

Reversals in turbidity are detected when the turbidity falls 20% below the previous maximum or 10% above the previous minimum, as long as the change is at least 5 NTU (nephelometric turbidity units). To avoid sampling during ephemeral turbidity reversals, the new direction must be maintained for at least two intervals. Upon reversal detection, a sample is collected if a threshold was passed between the actual time of the reversal and its detection. A pumped sample is collected when sampling is first enabled if the lowest turbidity threshold is exceeded, and pumped

samples are collected at fixed intervals when the turbidity exceeds the upper limit of the turbidity sensor. In addition, field personnel can collect pumped samples, under program control, to pair with depth-integrated samples or to augment the number of threshold samples at any desired interval. A program is available from the authors to implement the sampling logic on Campbell data loggers. (The use of trade names is for information only and does not constitute endorsement by the U.S Department of Agriculture.) All of the numeric values in the algorithm are parameters that the user can easily change.

Suspended Sediment Load Estimation: Suspended sediment loads are ideally estimated for each storm using a turbidity sediment rating curve or *TTS rating curve*, which is a simple linear regression of SSC versus turbidity, based on the samples collected during the event being estimated. In a series of simulations (Lewis, 1996), the best or near-optimal results were obtained without data transformations or polynomial terms. The simulations were based on 10-minute records of turbidity and SSC that had been collected from five storm events at Caspar Creek in northwestern California. In some cases, more accurate estimates were obtained using quadratic regression, or separate regressions for periods of rising and falling turbidity. But the advantages were not large, and complex fitting procedures are best avoided, particularly with small samples, to limit extrapolation errors. Applying simple linear regressions resulted in root mean square errors between 1.9 and 7.7% for the five storms, with mean sample sizes between 4 and 11. These are very small errors by conventional standards of sediment load estimation.

The uncertainty of the load estimated from a TTS rating curve can be quantified using standard theory (Lewis, 1996). However, with small samples, the variance estimates themselves are subject to great uncertainty. In addition, if the model does not fit the population from which the data were sampled (difficult to assess from a small sample), the variance estimates can be very biased as well. In simulations where linear models were applied to nearly linear data with log-linear error distributions (Lewis, 1996), estimated standard errors of the load estimates exhibited root mean square errors from 38 to 72% of their true values, with bias up to 49%. Fortunately, the load estimates themselves exhibited root mean square errors of only 5.6 to 8.3% with a maximum bias of 4.0%.

At some gaging stations, we have found that there are often periods when the recorded turbidity is invalid, typically when the turbidimeter is not fully submerged or because debris or sediment are covering the sensor's optical window. Such conditions typically result in erratic turbidity readings that cause the algorithm to collect extra samples. If that is the case, it is usually not difficult to estimate the sediment load for the period of invalid turbidity using either time-interpolation or a sediment rating curve constructed from the extra samples. However, sometimes the pumping sampler's capacity (usually 24 bottles) is exceeded during a period of optical fouling, resulting in an un-sampled period. In these cases, unless the un-sampled period is very brief, the concentrations must be estimated using a sediment-rating curve constructed from a nearby period of time that covers the appropriate discharge range. The use of multiple estimation methods can result in discontinuities of the estimated concentration versus time. Sometimes discontinuities can be avoided by a judicious choice of methods or transition times between methods. The uncertainty can be judged in part by the amount that the load estimates change when different choices are made.

Equipment: The TTS method requires a data logger, a stage measurement device, a pumping sampler, a turbidimeter, a housing and mounting hardware for the turbidimeter, and a pumping sampler intake.

Data logger: The data logger records the stage and turbidity and signals a pumping sampler to collect a sample based on the TTS algorithm. The lack of a commercially available data logger, programmable in a high-level language, and available with the appropriate hardware interface to connect external devices, has been an impediment to the adoption of the TTS method. During water years 1996-1999, we utilized a TTS program written in TXBASIC, a dialect of the BASIC programming language that runs on ONSET Tattletale data loggers. The practitioner must fabricate these data loggers from a single-board computer, a user-built interface board, and a memory board. Their fabrication and assembly proved to be an obstacle to the transfer of the TTS technology to practicing hydrologists. Therefore, in water year 2000 we converted the TXBASIC code to the widely available Campbell CR510 and CR10X programmable data loggers. The programming language and its capabilities are primitive but adequate and do permit us to distribute code that can immediately be used by hydrologists wanting to employ TTS.

Stage measurement: A device is needed that can provide the data logger with an electronic output linearly related to stage height. We have used pressure transducers at all our installations. The TTS program records the mean of 150 stage readings during each interval to increase the measurement precision.

Turbidimeter: Our first experiments were with the Analite 190 turbidimeter (McVan Instruments, Co.). Subsequently all of our gaging sites have deployed the OBS-3 turbidimeter (D&A Instruments, Co.). Both of these sensors are nephelometers that measure the scattering of infrared light and have a standard operating range of 0-2000 NTU. The TTS program records the median of 61 turbidity readings during a 30-second period to reduce the influence of outlier values.

Housing: Erroneous (usually inflated) turbidity readings can be caused by organics trapped on or near the sensor, entrainment of air bubbles, fine sediment or biological colonization of the optical window, or the proximity of the sensor to the water surface or channel bottom. Some turbidity sensors have been designed with electronically activated mechanical wipers or other devices to keep the optical window clean, but these have not gained wide acceptance due to reliability issues. In our experience, the most effective control of biofouling is through regular cleaning of the optical window, especially during periods of elevated stream temperature and solar input. But a properly designed sensor housing can limit most of the problems listed above as well as protecting the sensor from physical damage from large organic debris.

The sensor housing design is naturally dependent on the device being used. The OBS-3 that we have used at our gaging stations is cylindrically shaped and its optical window is positioned near the end and at a right angle to the probe's axis. We have found that enclosing the sensor in black ABS pipe, screened on the upstream end, created problems by reducing the velocity through the pipe, leading to regular coating of the optical window and pipe wall with a film of fine sediment during storm recessions. The most effective design we have tried to date encloses the sensor in a section of aluminum square tubing that is cut at a shallow angle on the downstream end to expose the optical window to the flow (Plate 1a). The sensor is oriented parallel to the flow with the optical window aimed sideways. In shallow streams, a solar visor is added above the optical window to reduce infrared saturation. This design effectively limits trapped organics and exposure of the detector to sun or water surface. And we have not experienced problems with fine sediment or air bubbles with this housing.

Mounting hardware: It is essential to mount the turbidity sensor and housing in such a way that it can be accessed at any time for cleaning. The mounting hardware should shed debris and keep the sensor above the bed load transport zone and below the water surface. In forested watersheds, it needs to protect the sensor from the impacts of large woody debris. Mounting configurations are very site specific. In the smallest channels, where flow depths rarely exceed 30 cm, we have mounted the turbidimeters on fixed brackets that are bolted to a plywood base staked into the channel. Brackets are drilled to mount the sensors at one of three heights. In channels that can be waded with flow depths up to 60 cm, we have mounted the turbidimeters on bottom-mounted floating booms (Plate 1b) or overhead suspension booms. On bottom-mounted booms the upstream end is hinged to the bed and the downstream end is fitted with a float, thus maintaining the turbidimeter at a depth proportional to the stage (Eads and Thomas, 1983). In larger channels, we have utilized bridge- or bank-mounted overhead booms (Plates 1c and 1d) that allow access to the sensor at any flow. Overhead booms are suspended vertically from a pivoting horizontal arm and typically are positioned and retrieved with a cable and winch system. The vertical arm is jointed to swing both downstream and sideways to shed large woody debris and to reduce stresses from changing flow lines.

Each of the boom configurations has advantages and disadvantages. Booms on fixed brackets are the simplest to build, but are suitable only for very small channels, where it may be impossible to keep the sensor submerged at all times. If the sensor is mounted too close to the bottom, bed load can bury the sensor or otherwise interfere with measurements during high flows. In small channels, the most promising approach seems to be overhead mounting in natural or artificially created pools. Booms hinged on the streambed have the advantage of keeping the sampling point at a constant proportion of the depth, but it is usually difficult to access the sensor for cleaning during high flows. In addition, bottom-mounted equipment is much more vulnerable than overhead-mounted equipment to damage by bed load. Overhead-mounted booms are the most difficult to build and install, but they allow access to the sensor at any flow. Their main disadvantage is that it is difficult to control the sampling depth. As flow increases the boom and sensor rise in the water column. Counter-weights are added to keep the sensor submerged at high flows, but the sensor's exact depth depends on frictional forces and is thus difficult to control.

Pumping sampler: At our gaging sites we have deployed ISCO pumping samplers, model 2700 or 3700, operated in a flow mode and activated by a signal from the data logger. The intake line from the sampler to the stream is

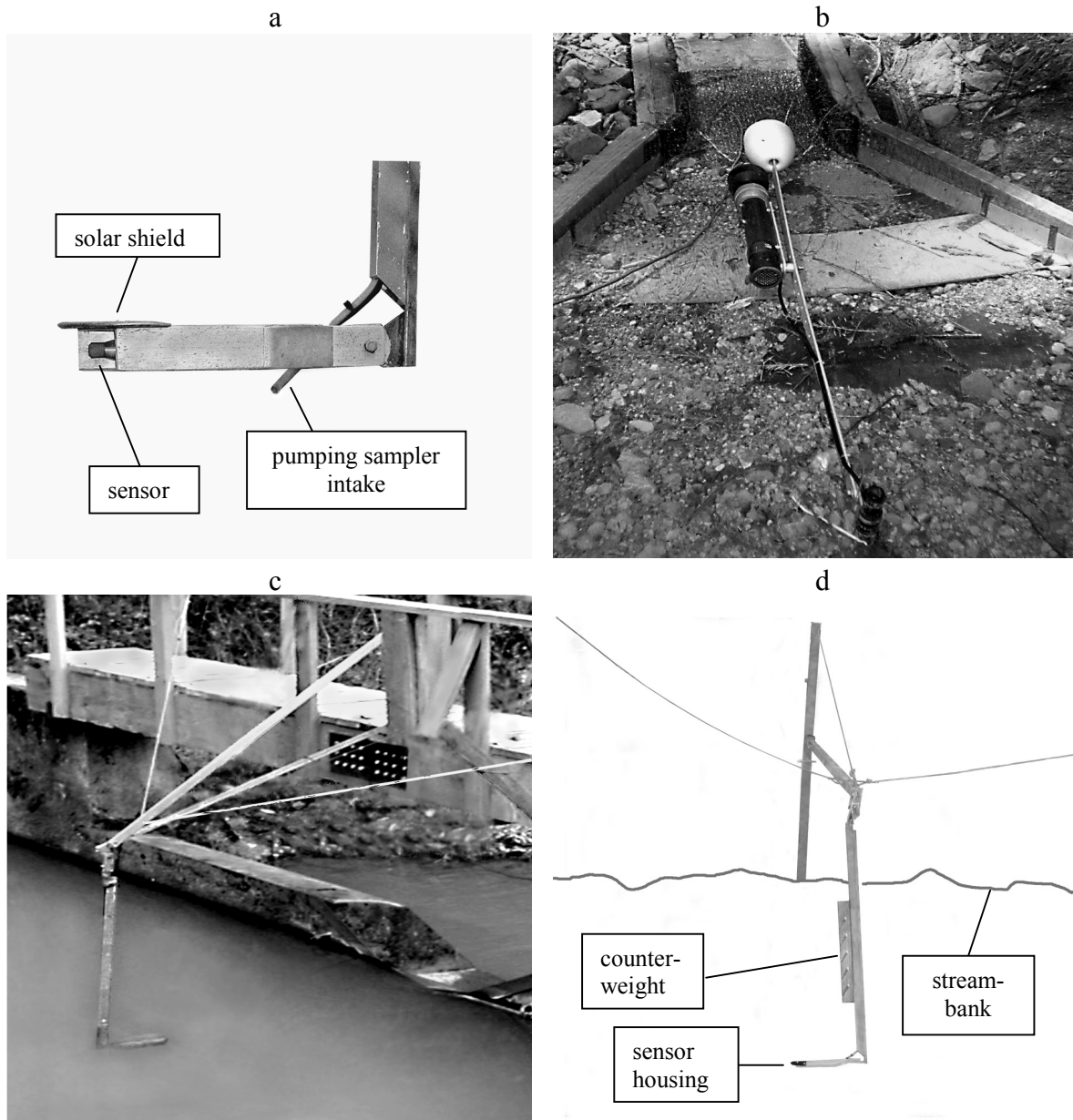


Plate 1. (a) Turbidity sensor in aluminum housing with solar shield, (b) bottom-mounted pivoting boom and sensor in ABS housing, (c) retractable bridge-mounted boom stabilized by lateral cables, and (d) retractable bank-mounted boom.

positioned so that it slopes continuously down to the intake nozzle, thus reducing the opportunity for sediment to fall out of suspension and become trapped. We use 0.635 cm inside diameter intake line to increase line velocity while ensuring representative sampling (standard line diameter is 0.953 cm). The intake is a stainless steel tube, of the same diameter as the intake line, and is often mounted on the boom in close proximity to the sensor. At some sites, the intake is mounted in a fixed position in the channel, at a height of 7.6 cm above the bed. In both mounting configurations the intake is positioned in the thalweg, pointing downstream (Winterstein, 1986).

Gaging sites: We have deployed in situ turbidimeters at 16 gaging stations in northwestern California. Some were used temporarily for testing purposes only. At three stations, both turbidity and SSC were collected at 10 or 15-minute intervals for pilot testing. One station was used briefly to test a new mounting configuration. The TTS

program has been used to control sampling for at least one complete winter at 10 gaging stations. Twelve new gaging stations will be operational during the winter of 2000-2001.

Caspar Creek: Pilot testing was conducted in water years 1994 and 1995 at the 3.8-km² Arfstein station in the Caspar Creek Experimental Watershed near Fort Bragg, California. Caspar Creek is a sedimentary basin that produces mostly fine sediments. Turbidity and SSC were collected at 10-min intervals during 7 storm events. The data were subsequently used in sampling simulations to test the accuracy of TTS for estimating sediment loads (Lewis, 1996). Since water year 1996, the TTS method has been running on ONSET data loggers at 8 Caspar Creek gaging stations draining watersheds between 0.2 and 4.7 km². These stations are operated as part of a long-term research project focused on the hydrologic effects of forest practices (USDA Forest Service, 1998).

The two original Caspar Creek gaging stations are compound V-notch weirs. At these sites, the turbidity sensors are suspended in aluminum housings on retractable overhead booms mounted on bridges above the weir faces (Plate 1c). Another site has a bank-mounted overhead boom (Plate 1d) and one site has its boom suspended from a cable running across the channel. There are two sites with bottom-mounted pivoting booms (Plate 1b) and three sites have fixed mounts on the channel bed. In the winter of 2000-01, as part of a new study of third-growth logging, ten new gaging stations will utilize TTS in the 4.2-km² South Fork of Caspar Creek and its tributaries.

Other gaging sites: Turbidity and suspended sediment were collected at 15-minute intervals for two storms on Mill Creek, a boulder-bedded stream draining 63 km² of mostly dioritic terrain in the Hoopa Valley Indian Reservation. The bottom-mounted boom was destroyed and the turbidimeter lost when the streambed was entrained in a moderately high flow.

Our first experiment with an overhead boom (bank-mounted) was at Grass Valley Creek (80 km²), which transports an abundance of coarse sandy material derived from decomposed granitic rocks. This location was a severe test for our equipment because of its coarse load, high velocities, woody debris loading, and freezing temperatures.

Upper Prairie Creek in Prairie Creek Redwoods State Park near Orick was an experimental site where a prototype bridge-mounted boom was deployed for one season. Bank-mounted booms have also been installed at Freshwater Creek (34 km²), Little Jones Creek (71 km²), Godwood Creek (4.4 km²), and Horse Linto Creek (99 km²) in Humboldt and Del Norte Counties. Freshwater Creek was the first site where TTS was implemented on a Campbell data logger. The program has been running for two winters there, and for a partial season at Little Jones Creek. Godwood Creek and Horse Linto Creek have no pumping samplers and are collecting only turbidity data.

RESULTS AND DISCUSSION

The most successful installations have been at sites with overhead booms using the aluminum housing design. At these sites, the sensor is continually submerged, interference from debris is minimized, and the sensor can be accessed at any time for cleaning.

Two examples from Caspar Creek (Figure 1a, b) demonstrate the utility of TTS in situations where discharge-sediment rating curves would have failed to adequately describe supply-limited sediment transport. The first case, from the South Fork weir, was a double-peaked storm in which the second discharge peak was higher than the first, while the relative magnitudes of the turbidity peaks were reversed. The second case, from the Dollard tributary, shows two sediment peaks completely unrelated to discharge. We know the sediment originated from the channel in the 600-meter reach between Dollard and the upstream Eagle gaging station because (1) no turbidity spikes occurred at Eagle, and (2) the only active erosion sources in that reach are the channel banks and bed. In both examples, there was a tidy linear relation between laboratory SSC and field turbidity, dispelling any doubt that might exist about the veracity of the turbidity spikes. The coefficients of variation (standard error divided by estimated suspended load) in these two examples were 2.3% and 10.2%, respectively.

A single TTS rating curve is not always entirely satisfactory for defining the sediment transport during a storm event. The predicted concentrations at low turbidities during the storm recession are commonly too low or even negative. In a typical example from Freshwater Creek (Figure 1c), this was easily remedied by applying a second

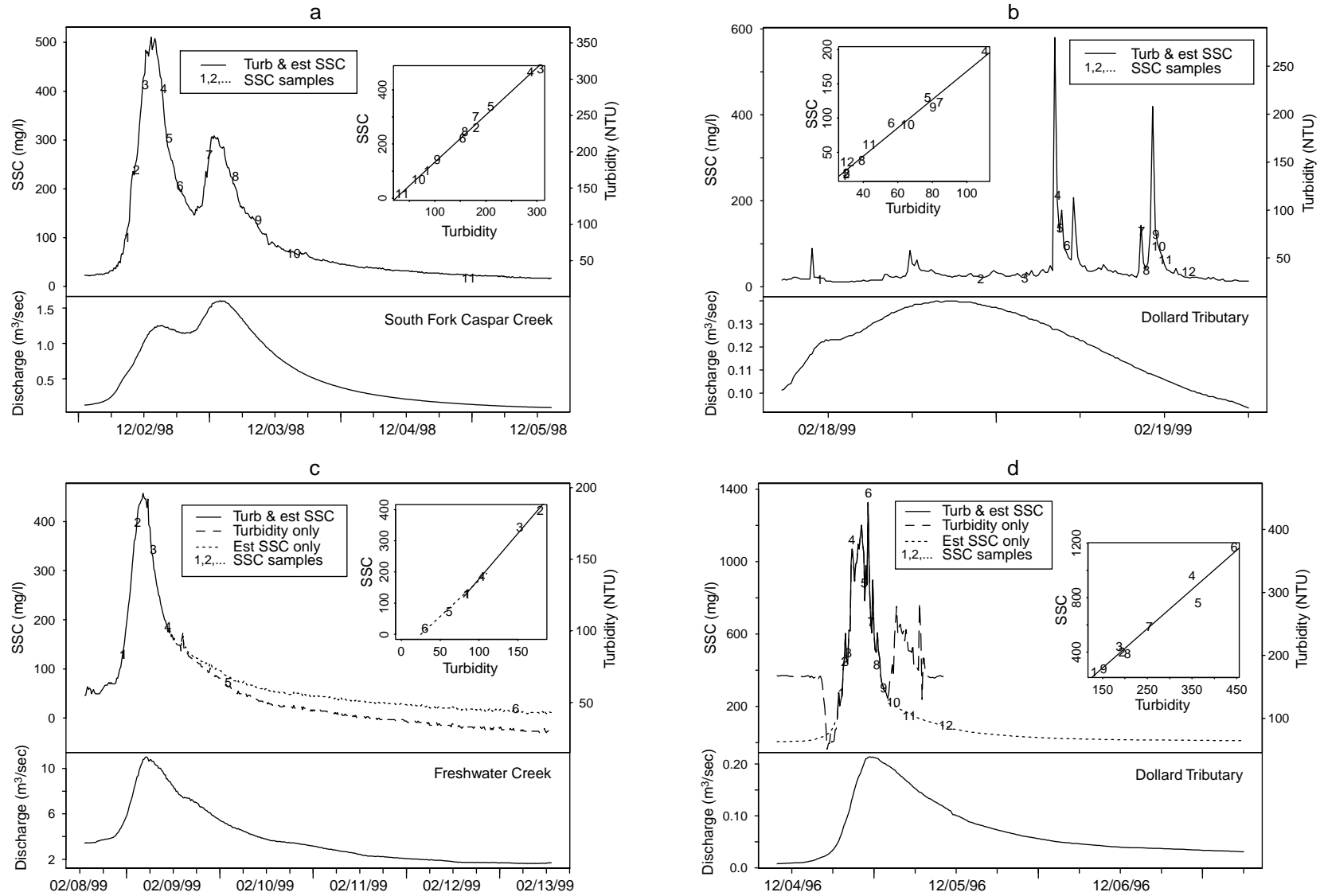


Figure 1. Suspended sediment concentration (SSC), turbidity, and discharge in four storm events. Inset graphs show TTS rating curves used to estimate SSC. Plotted numbers represent measured SSC. Solid lines in upper frames of (a), (b), (c), and (d) represent both turbidity and SSC estimated from TTS rating curve. Left-hand SSC axis is scaled to right-hand turbidity axis through the TTS rating curve. Dashed lines in (c) and (d) represent turbidity only. Dotted lines show SSC estimated from a second TTS rating curve (c) or from discharge-based rating curves (d).

TTS rating curve, based on the last three samples, for the recession period. The load estimated from the two rating curves, each based on three samples, is only 2% greater than that from a single rating curve (replacing negative predictions with zeroes), but the predictions from the second rating curve are clearly more realistic for the recession.

Negative predictions on storm recessions might in some cases result from using 1-micron filters in the laboratory. In 1-micron filtrate from 65 samples collected at 8 of the Caspar Creek gaging stations, an average of 15.5 mg/l was measured on 0.22-micron membrane filters. Assuming the relation between total SSC and turbidity passes through the origin, the effect of disregarding the finest particles is to shift the TTS rating curve downward, creating a negative y-intercept. Extrapolations at the low end of the regression thus can result in negative predictions of concentration.

Various problems often preclude using a TTS rating curve for much of the storm. Figure 1d shows a storm at the Dollard station in 1996, before the turbidimeter was relocated to a pool. In the first part of the storm, the turbidimeter was not submerged because the water was too shallow. Beginning early on Dec. 5, the sensor became fouled with debris. Several hours later, the field crew removed the debris, but made an error that resulted in no electronic data or samples being collected for the remainder of the storm. The discharge for the missing period was later reconstructed from the Eagle station upstream and SSC was estimated for the start and end of the storm using two sediment rating curves. The relation of SSC to discharge formed a wide hysteresis loop, but the first four samples and final three samples of the loop defined more-or-less linear relationships. Therefore separate sediment rating curves were computed from these two subsamples and applied to the periods of invalid or missing turbidity at each end of the storm.

Sometimes when the sensor is fouled, fluctuations in turbidity are produced that result in collection of enough additional samples to adequately define the temporal trend in SSC without resorting to a sediment-rating curve. In these circumstances, linear interpolation between the measured values of SSC is all that is necessary to reliably estimate the load during the period of missing turbidity.

Sampling at Mill Creek and Grass Valley Creek was conducted in order to investigate the feasibility of the TTS method where suspended particles are mostly sand. In the storms sampled at Mill Creek, about half the load consisted of sand, but most was fine sand less than 0.5mm. The TTS rating curve for the larger of the two storms (Figure 2) suggests that the TTS method should work fine in this stream. Whereas the bottom-mounted boom was destroyed at Mill Creek, the prototype overhead boom at Grass Valley Creek was able to withstand impacts from

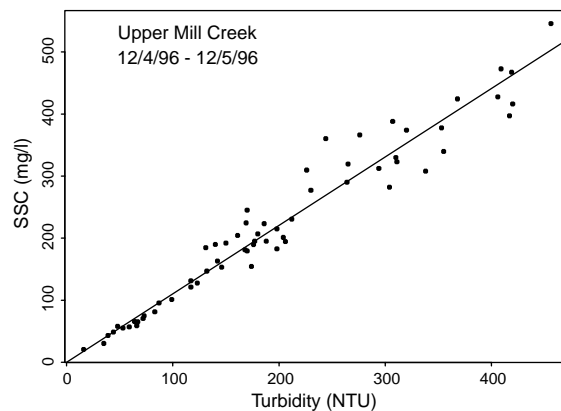


Figure 2. TTS rating curve (regression line) based on a fixed 15-minute sampling interval at Upper Mill Creek

large woody debris transported at velocities as high as 15 ft s^{-1} . However, at Grass Valley Creek, the load was so coarse and the velocities often so great that in one storm the concentration of particles larger than 0.5mm in pumped samples averaged just 4% of that in simultaneous depth-integrated samples ($n=8$). The relations between SSC from pumped and depth-integrated samples (composited from multiple verticals) are shown in Figure 3. These relations indicate that, unless a pumping sampler becomes available that can efficiently sample sand-size particles at both high velocities and moderate head heights, the TTS methodology can be effective at estimating only the finest part

of the load in streams such as Grass Valley Creek. Unless a tight and reliable relationship could be established between pumped and manual SSC, manual samples would be required throughout high transport events to reliably estimate the total suspended load.

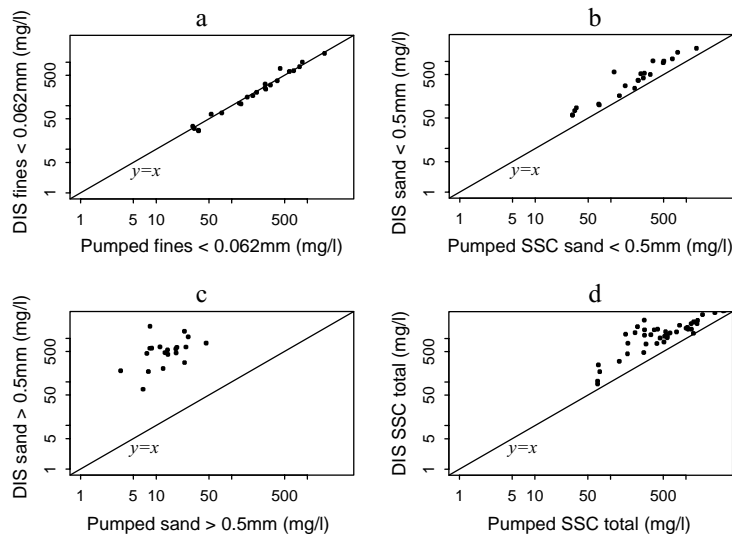


Figure 3. Comparison of SSC in 1998 at Grass Valley Creek from depth-integrated D-49 samples and simultaneous pumped samples for (a) fines < 0.062mm, (b) fine sand < 0.5mm, (c) coarse sand > 0.5mm, and (d) all particles.

The TTS method can also be used to estimate seasonal or annual sediment loads, either by summing storm event loads or by applying seasonal or annual TTS rating curves. However, since TTS samples every significant sediment pulse, it probably collects more samples than necessary for the task. A more suitable approach, when event loads are not of interest, might be random sampling stratified by turbidity. Such a design should be an improvement upon the similar flow-stratified sampling method, which Thomas and Lewis (1995) recommended for estimating seasonal and annual loads.

CONCLUSIONS

Turbidity Threshold Sampling is a proven method for accurately measuring suspended sediment loads at stream gaging stations on a storm event basis. If turbidimeters are properly installed and maintained, the sampling algorithm distributes samples over the entire turbidity range during each transport event. However, in streams with very coarse suspended loads, accuracy is limited by the ability of pumping samplers to collect representative samples.

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