

# Turbidity Threshold Sampling in Watershed Research

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## Abstract

When monitoring suspended sediment for watershed research, reliable and accurate results may be a higher priority than in other settings. Timing and frequency of data collection are the most important factors influencing the accuracy of suspended sediment load estimates, and, in most watersheds, suspended sediment transport is dominated by a few, large rainstorm events. Automated data collection is essential to effectively capture such infrequent events. Turbidity Threshold Sampling, a method that distributes sample collection over the range of rising and falling turbidity values during each significant turbidity peak, has been used since 1996 at the Caspar Creek Experimental Watershed in northern California.

**Keywords:** suspended sediment, turbidity, automatic sampling, water quality

## Introduction

The Caspar Creek Experimental Watershed is located on the Jackson State Forest, in northwest California, approximately 15 km southeast of the city of Fort Bragg. The 897 ha study area, located about 7 km from the Pacific Ocean, encompasses the North and South Forks of Caspar Creek. The topographic development consists of uplifted marine terraces that are deeply incised by coastal streams (Henry 1998). The Mediterranean climate is typical of low-elevation watersheds on the Pacific coast where the fall and winter seasons are moist with low-intensity rainfall and persistent cloud cover. Snow rarely occurs because of the moderating effect of the nearby Pacific Ocean. The mean annual rainfall from 1962 through 1997 was 1,190 mm. Prior to the 1860s the forest was composed primarily

of old-growth coastal redwood. Current second- and third-growth forest stands are primarily coastal redwood and Douglas-fir, with a small component of hardwoods.

A primary focus of research on the Caspar Creek Experimental Watershed is to evaluate management activities and forest practice regulations on the production of sediment from watersheds. It is difficult to identify the causes of erosion within a watershed because factors such as increased subsurface flow and loss of root strength are difficult to observe (Lewis 1998). In addition, when naturally occurring landslides and erosion from historic land use combine with recent management activities the controlling factors become complex and intertwined. The erosion research in Caspar Creek has relied on the paired-watershed design. The watersheds were chosen because they are physically close together, have similar soil types, and rainfall tends to be spatially uniform in volume and intensity. The studies on suspended sediment in Caspar Creek have relied on comparing data from treated and untreated watersheds that are measured before, during, and after treatment. Gaging structures, either weirs or flumes, are typically installed at the base of the selected watersheds to measure discharge, and suspended sediment samples are collected primarily during storm events.

Suspended sediment data collection is challenging in many environments because most of the annual suspended sediment load is transported during a few large storm events when it may be difficult or impractical to collect an adequate number of samples (Lewis and Eads 2001). Water discharge is often a poor predictor of suspended sediment concentration (SSC) when sediment inputs to the channel are highly episodic. An efficient form of automated sampling is desirable that distributes sample collection based on a suitable real-time surrogate for suspended sediment. The relation between turbidity and SSC is quite good for most streams, particularly when changes in particle size during storm events are minimal. Although turbidity

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cannot replace SSC, it can be a valuable aid in deciding when to collect physical samples. Recent advances in turbidity sensors and mounting configurations now permit reliable and continuous in-stream monitoring of turbidity.

## Methods

An approach called Turbidity Threshold Sampling (TTS) utilizes a programmable data logger, turbidity sensor, and automatic pumping sampler to collect SSC samples at user-specified turbidity thresholds (Lewis 1996). The resulting set of samples can be used to accurately determine suspended sediment loads by establishing a relationship between sediment concentration and turbidity for any sampled period and applying it to the nearly continuous turbidity data. A distribution of turbidity thresholds that provides adequate sampling for load estimates during small events, but does not over-sample during large events, can be constructed by evenly spacing the square roots of the thresholds to cover the range of the turbidity sensor. Because a larger portion of the sediment discharge occurs during the prolonged recession, more thresholds are required during the falling than the rising portion of the turbidigraph. Although turbidity is a better surrogate for SSC than discharge, errors in turbidity records are more common and can arise from fouling or inadequate flow depth. A set of rules in the TTS algorithm attempts to prevent excessive sample collection by accounting for short-term spikes in turbidity from passing debris, while recognizing valid ephemeral spikes from sediment inputs (Lewis 2002). Spikes in the turbidity record that are a result of fouling, and that are accompanied by a physical sample, can be recognized when the SSC in question is not elevated but in general agreement with surrounding SSC values. Fouling of the turbidity sensor's optics by sediment or organisms can be identified on the turbidity plots as a gradual but unexpected increase in turbidity. In very large storm events, turbidity values may exceed the sensor's range, and in this case, the TTS algorithm will attempt to collect fixed-time samples until the turbidity returns within the sensor's range. Since this condition could exhaust the pumping sampler's available bottles, it is important that a field crew visits the station and exchanges the pumping sampler bottles. On average, we expect to collect about eight samples per storm for each station once the equipment installation is satisfactory and the sampling parameters are correctly set.

The TTS program resides in a programmable data logger, either a Campbell CR10X or CR510, and interrogates a turbidity sensor and pressure transducer at 10-minute intervals (mention of trade names is not an endorsement by the USDA Forest Service). When the sampling rules are satisfied, a signal is sent to the automatic pumping sampler to collect a sample.

## Stage and discharge

Two of the TTS gage sites in Caspar Creek are fitted with a compound 120° V-notch weir, and 19 sites have either a Parshall or Montana flume to measure discharge. The flumes are reasonably efficient at maintaining sediment suspension through the throat, with the exception of coarse bed material that can settle on the flume floor during falling stages, requiring subsequent manual removal. The unimpeded passage of sediment is important when tracking sediment routing in nested watersheds. Ultimately, all of the bed load, and nearly 40% of the suspended load, is deposited in the weir debris basin at the bottom of the watershed. The sediment accumulation is measured annually and the basin sediment is excavated every 5 to 7 years. A flume or weir eliminates the requirement to develop and maintain a discharge rating for each station, and when properly sited, they provide a stable discharge record over time. Flume sizes in Caspar Creek were chosen to accommodate 100-year peak flows. None of the gage site structures, with the exception of the weirs, is grouted to bedrock. Although all flumes have cutoff walls extending into the alluvial bed, an unknown amount of the flow is not captured. Minor discharge errors are acceptable for sediment transport research because most sediment is transported during storm flows, when leakage is proportionally negligible.

Although pressure transducers are deployed at all the Caspar Creek gage sites to measure stage, with minor changes the TTS program could accept other stage measurement technologies. With the exception of the QUE station, all pressure transducers are mounted in stilling wells that are connected to the flume or weir pond. Because the TTS program computes the mean of 150 stage readings in three seconds, the use of a stilling well is not always required to achieve the desired accuracy because fluctuations in water surface elevations are electronically dampened. For example, at station QUE, the pressure transducer is mounted in conduit with the opening at right angles to the direction of

flow. The TTS algorithm uses stage to determine when the flow is deep enough to adequately submerge both the pumping sampler intake and the turbidity sensor. Below this minimum stage, no sample collection is attempted.

## Turbidity sensor

Collecting reliable turbidity information depends on the placement of the turbidity sensor in the stream, its mounting configuration, optical sample volume, and its ability to remove fouling on the optical surface by a mechanical wiper or other automated means. In our experience, mounting the turbidity sensor near the thalweg and approximately mid-depth in the water column, provides the most reliable measurement location. Mounting the sensor near the bed can increase noise in the record when bed material becomes mobilized at higher flows. Mounting the sensor close to the water surface can produce unacceptable records because of air entrainment, floating debris, sunlight, or emergence of the sensor from the water (Eads and Lewis 2002). An articulated sampling boom, mounted on the bank, bridge, or cableway (Figure 1), can limit the amount of debris that is trapped near the turbidity sensor.



Figure 1. Montana flume with turbidity sensor housing suspended downstream on cable-mounted boom at station Porter in the South Fork of Caspar Creek.

The articulated boom is self-cleaning when large debris accumulates on the leading edge causing it to rise towards the water surface and release the debris. When the sensor is mounted on an articulated sampling boom, field personnel can raise the boom

and access the sensor for inspection or cleaning at any flow. In most streams, the turbidity record is improved when the sensor automatically cleans the optical surface to remove fine sediment or macroinvertebrates before each measurement.

We have experimented with a number of turbidity sensor housing designs and have found that mounting the sensor on the downstream edge of the boom, aligned with the direction of flow, produces the most reliable records. The sensor's optics are aimed across the flow and clear of any obstructions. Maintaining a housing length of 30 cm, or more, from the boom reduces the likelihood that debris on the boom will be viewed by the sensor.

## Automatic pumping sampler

For watersheds that have a rapid hydrologic response, automatic pumping samplers provide a way to collect unattended samples during important events. Their application is limited to streams and rivers that transport mostly fine sediments, where the height from the water surface to the sampler is less than about 6 m, and where the intake line can be routed so that there are no dips or horizontal runs. Reducing the length of the intake line improves sampling efficiency and decreases power consumption. At Caspar Creek, the sampler intake is mounted in the downward sloping floor of the flume throat and projects horizontally into the flow. At other Caspar Creek installations, the intake is fixed at 9.14 cm above the bed, or mounted on the weir wall at the base of the V-notch, or on the sampling boom. Since samples collected in this manner are point samples they may not be representative of the instantaneous cross-sectional average SSC in cases where the sediment is not adequately mixed. We collect a suite of simultaneous depth-integrated and point samples to correct for bias in SSC data.

## Example

The utility of TTS is illustrated by an example (Figure 2) from station Ogilvie on a South Fork tributary draining about 19 ha. The peak flow of  $0.133 \text{ m}^3\text{s}^{-1}$  has a recurrence interval of between once and twice per year. The turbidity spiked sharply several times during the 9-hour rising limb of the event, triggering seven pumped samples. In the 39 hours following the peak, there were a few small turbidity spikes, including a jump of 100 NTU just before 11:40 pm on Feb. 20. Recession limb spikes such as this are often indicative of bank

failures, and sometimes can be tracked at downstream stations.

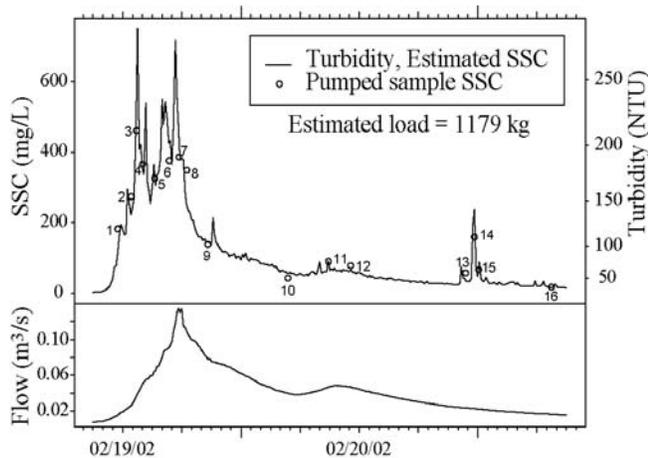


Figure 2. Turbidity, pumped sample SSC, and flow for a storm event at station Ogilvie in the South Fork of Caspar Creek.

In a log-log plot of SSC versus turbidity (Figure 3), samples 2-4 confirm the first spike, samples 13-15 confirm the last spike, and the overall low scatter ( $r^2=0.94$ ) suggests that the sensor was functioning normally throughout the event.

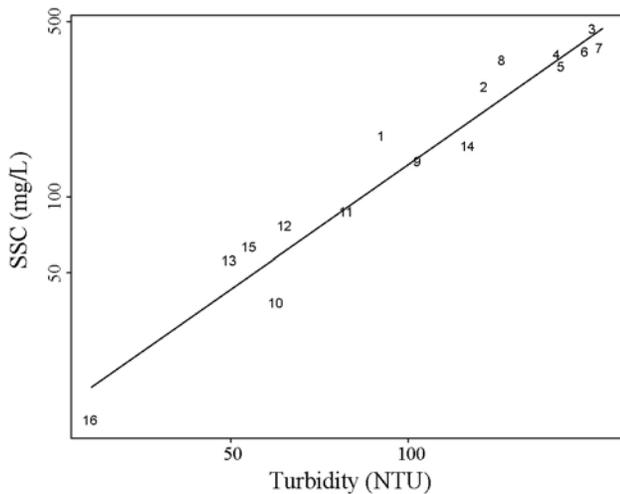


Figure 3. SSC versus turbidity for pumped samples collected at station Ogilvie during event of Figure 2.

Without the physical samples to verify the turbidity fluctuations, it would have been impossible to ascertain that the spiking was not caused by fouling of the sensor. By comparison, a log-log regression of SSC versus discharge (Figure 4) is very poor ( $r^2=0.31$ ). The 95% confidence limits for sediment discharge are 690 and 3078 kg based on the relation

in Figure 4, compared to 1010 and 1349 kg based on the relation in Figure 3. A sampling program based on discharge or fixed-time intervals would likely have missed most of the sediment spikes in this event. In any case, without the continuous turbidity record, little or nothing would have been revealed about the duration or shape of the sediment pulses.

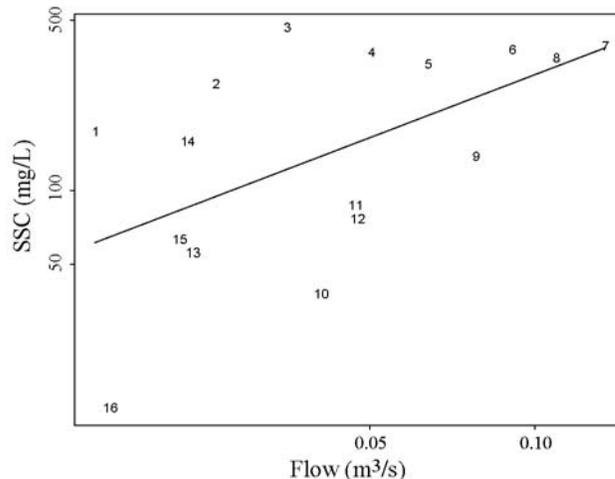


Figure 4. SSC versus flow for pumped samples collected at station Ogilvie during event of Figure 2.

## Conclusions

Turbidity Threshold Sampling is an efficient and proven method for accurately measuring suspended sediment loads in rivers that transport mostly fine sediment. The quality of the continuous turbidity record is dependent on the mounting of the sensor and depth of flow at the measurement location. Very small drainages present a considerable challenge because shallow flow depths, during the start and end of the hydrograph, may be inadequate to submerge both the turbidity sensor and the pumping sampler intake. Small watersheds in the Pacific Northwest have steep channels that produce turbulent flow that can result in unacceptable noise in the turbidity record from air bubbles if suitable measurement locations are not available. As the drainage size increases, the deployment of the instrumentation becomes simpler and the quality of the turbidity data improves. However, very large channels present another set of problems, related to the use of pumping samplers. The sampler must be no more than about 6 m above the water surface. In addition, point samples in large rivers may not be easily correctable to a cross-sectional mean SSC. Using an articulated sampling boom and an appropriate sensor housing can reduce fouling of the turbidity sensor by organic debris. However, fouling

may become chronic if the material on the leading edge of the boom is long enough to wrap around the boom and interfere with sensor's optics, or if the force of the flow is not sufficient to allow the boom to rise to the water surface and allow the debris to pass underneath the boom. Most turbidity records are improved when a turbidity sensor with a self-cleaning mechanism, such a mechanical wiper, is used that reduces fouling of the optics from algae, fine sediment, and macroinvertebrates.

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