United States
Department of
Agriculture

Forest Service

Pacific Southwest
Research Station

General Technical Report
PSW-GTR-212
March 2009

Implementation Guide for Turbidity Threshold Sampling: Principles, Procedures, and Analysis

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Abstract

Lewis, Jack; Eads, Rand. 2009. Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 87 p.

Turbidity threshold sampling uses real-time turbidity and river stage information to automatically collect water quality samples for estimating suspended sediment loads. The system uses a programmable data logger in conjunction with a stage measurement device, a turbidity sensor, and a pumping sampler. Specialized software enables the user to control the sampling process, plot and correct the data, and estimate suspended loads. This implementation guide describes the entire process, including instrumentation, installation, field procedures, software usage, data collection, laboratory methods, data interpretation, data reduction, and analysis.

Keywords: Turbidity, suspended sediment, sediment loads, pumping sampler, stream gaging, water quality.

Contents

Overview

Background

How traditional sampling methods for suspended sediment are inadequate— Suspended sediment levels in streams and rivers can fluctuate rapidly, often independent of changes in water discharge. Estimation of suspended sediment loads (SSL) has usually been based on infrequent sampling (typically biweekly to monthly) that is inadequate to characterize the temporal variability in suspended sediment concentration (SSC), and usually misses the periods of greatest concentration. Even daily sampling is inadequate for all but the largest river systems. For example, daily SSC data from the South Fork Eel River poorly represents the actual pattern of SSC, as estimated by turbidity at 10-minute intervals (fig. 1).

Sampling at fixed time intervals is usually very inefficient.

In small rain-dominated watersheds, a dozen or more samples might be required in one day to describe the shape of the plot of SSC versus time. Sampling at fixed time intervals is usually very inefficient. Sampling frequency should be greatest when variability in sediment concentration is greatest. Water discharge and turbidity contain information about variability in sediment concentration and, because they are measurable in real time, they can be incorporated in sampling algorithms. An automated system is required to implement such a sampling protocol, and the sampling algorithms may need to be rather sophisticated.

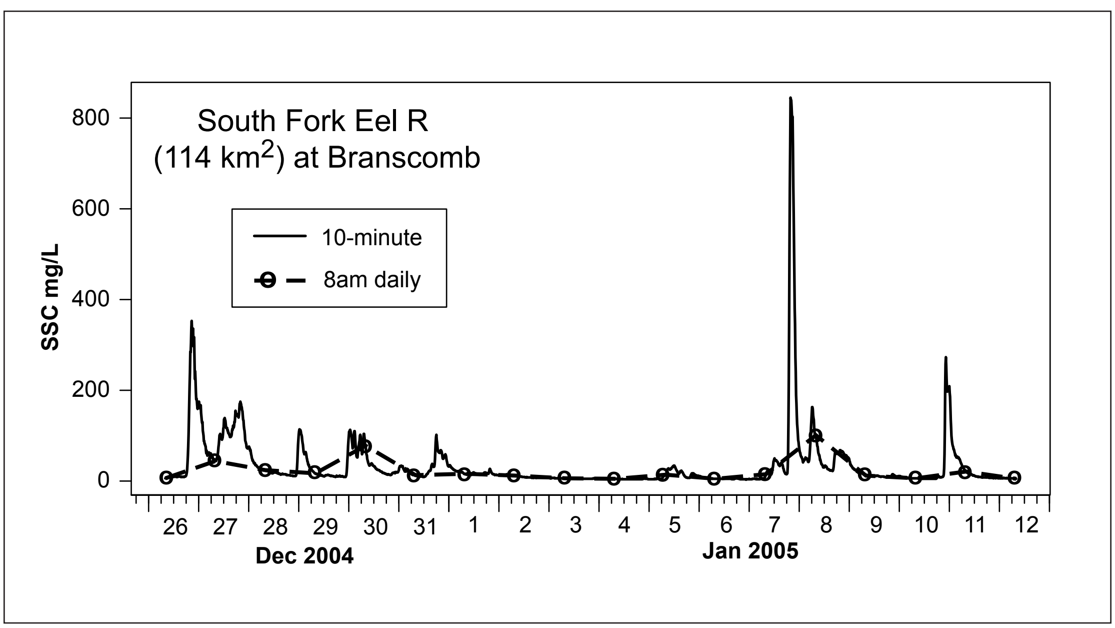

Figure 1—Suspended sediment concentration (SSC) as estimated from turbidity at 10-minute intervals, compared with the subset that would have been observed by sampling once daily at 8 am.

Discharge sediment rating curves and their shortcomings—
Because measurement of SSC requires processing of physical samples in a laboratory, accurate estimation of SSL requires a continuously measurable surrogate variable that is related to SSC. Before the advent of continuous turbidity monitoring, water discharge was the primary surrogate for SSC. Relationships between SSC and discharge, called discharge sediment rating curves, are commonly used to estimate SSC and SSL. These rating curves usually result in very poor estimates of SSL for many reasons (Rieger and Olive 1984, Walling and Webb 1981):

- Suspended sediment concentration is often out of phase with discharge, leading to systematic biases in load estimation.
- Rising and falling limb data may not be appropriately represented.
- High concentrations and discharges are inadequately represented.
- The rating curves change with time.
- The rating curves cannot account for episodic sediment delivery from erosion events, nor differences between rainfall and snowmelt runoff.

Discharge sediment rating curves account only for the energy provided by water discharge and ignore other processes and sources of variability related to sediment supply. However, surrogate measurements other than discharge can be used to derive sediment rating curves.

Turbidity sediment rating curves: a relatively new alternative—
With the advent of commercially available submersible sensors in the 1990s, in situ turbidity can be routinely recorded. A rating curve employing turbidity as the surrogate variable (turbidity sediment rating curve) can be used to estimate SSC much more accurately than a discharge sediment rating curve (Lewis 1996). Turbidity is an optical property of a suspension that is directly related to its particle concentration and composition, as well as the properties of the instrument used to measure it. Although much better than a discharge-based rating, a turbidity rating is only valid for a particular instrument type and range of suspended particle composition. Just as discharge-based ratings can change with time, so can turbidity ratings (although shifts are less pronounced, see fig. 2), because suspended particle composition (e.g., the proportion of fine organic material) can change with time.

Therefore, the best results are obtained by determining a turbidity sediment rating curve for each seasonal or episodic period being estimated. This requires that sampling be undertaken in each estimation period. If the range of sample data spans the range of turbidity recorded, and estimation periods are short (e.g., storm events), there should be little variability in the scatter of the data.

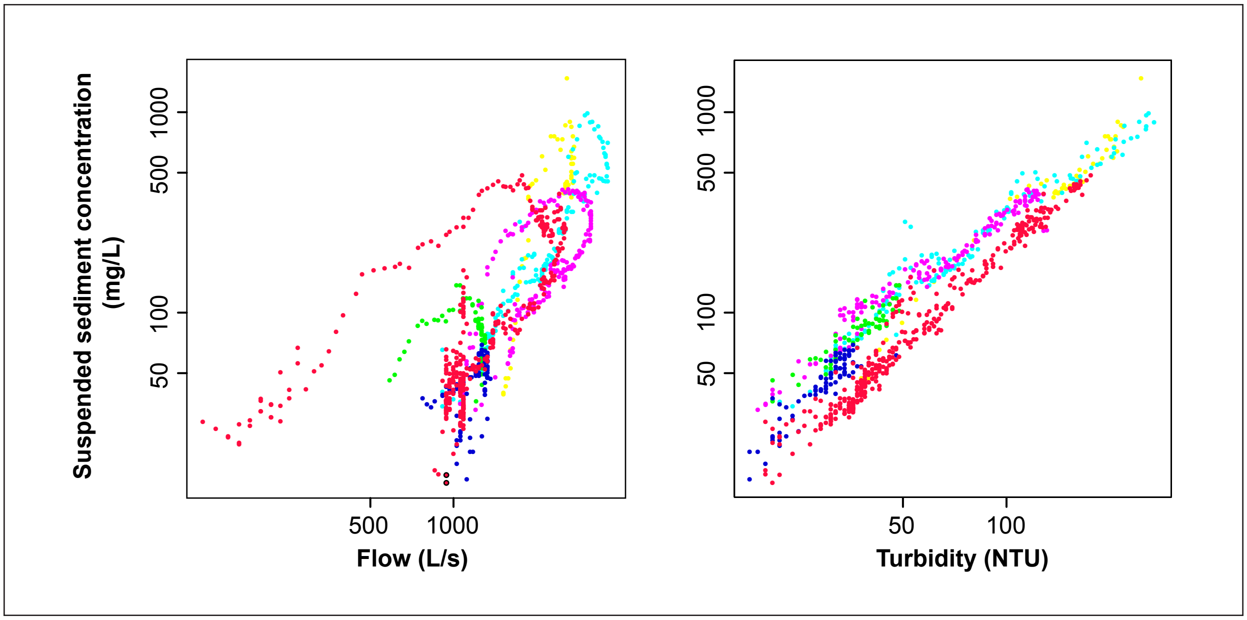

Figure 2—North Fork Caspar Creek, station Arfstein (3.83 km^2), 1995. All data were recorded at 10-minute intervals. Colors represent individual storm hydrographs. NTU = nephelometric turbidity units.

Purpose of Turbidity Threshold Sampling

The Turbidity Threshold Sampling (TTS) method was developed by the U.S. Department of Agriculture, Forest Service to efficiently utilize continuous turbidity measurements in triggering suspended sediment samples from pumping samplers (Lewis 1996, Lewis and Eads 2001). This system provides a practical means to estimate SSC and SSL more accurately than other methods in general use today. A continuous electronic record of turbidity provides details about sediment transport that cannot be obtained manually and can greatly enhance our understanding of sediment dynamics (Kirchner et al. 2004). Short-duration, high-amplitude sediment pulses would not be reliably identified by fixed-interval or discharge-driven sampling schemes (even with automatic sampling) unless deployed at very high sampling frequencies.

The TTS method uses real-time information about stream turbidity to activate a pumping sampler to verify that sediment pulses are real and to provide a set of turbidity and SSC pairs from which to compute a turbidity-sediment rating curve. If a pumping sampler is activated whenever the turbidity reaches one of a specified set of thresholds distributed over the expected turbidity range, then one can be certain that the entire range of conditions will be represented in the sample data (except when the sensor's range is exceeded).

Pumping samplers are best deployed in streams whose sediments are fine-textured and well mixed in the flow. These conditions should be verified at the outset of a sampling program by manually collecting depth-integrated samples at several locations in the cross section where a pumping sampler is to be deployed. If a reliable representation of the mean SSC cannot be obtained with a pumping sampler, the pumped sample SSC can often be adjusted by using a relationship with SSC from simultaneous depth-integrated samples.

A turbidity monitoring program could be established without concomitant pumped samples, but that approach is not recommended unless water clarity is truly the only issue of concern. Even in that case, there is no standard instrument for measuring turbidity, and relationships among instruments vary according to the sediment being measured (Lewis et al. 2007). If suspended sediments or solids are the parameter of concern, then the SSC should be measured.

What Is Turbidity Threshold Sampling and How Does It Work?

Turbidity Threshold Sampling is an automated method for water quality sampling using real-time surrogate data.

Turbidity Threshold Sampling is an automated method for water quality sampling using real-time surrogate data. Turbidity and water depth are measured at short intervals (from 5 to 15 minutes) by using in situ sensors, and a programmable data logger uses these measurements to make real-time determinations of whether a pumping sampler should be activated. Turbidity Threshold Sampling is not limited to sampling suspended sediment. Mercury, phosphorus, and fecal coliform bacteria are often adsorbed on sediment particles; therefore, sampling for these and other constituents could be improved by using TTS. Total dissolved solids or specific chemical salts could also be sampled and estimated by modifying TTS to employ electrical conductivity as the surrogate variable.

Data collection and sampling criteria—

A programmable data logger records water depth and turbidity at frequent, fixed time intervals so that conditions between data points may be considered nearly constant. At each recording interval, the turbidity and the water depth are used to make a decision whether to activate a pumping sampler. The decision criteria are:

- Water depth is adequate to submerge the turbidity sensor.
- Water depth is adequate to submerge the pumping sampler intake.
- A turbidity threshold has been met.

Thresholds are scaled so that their spacing decreases with increasing turbidity. The objective is to optimize sampling efficiency in both small and large events: only enough samples are collected to reliably estimate sediment loads. There are two sets of turbidity thresholds: one for rising turbidity conditions and another for falling turbidity conditions. Because the period of falling turbidity is usually longer than the period of rising turbidity, and it represents the majority of the sediment load, more turbidity thresholds are needed under falling conditions. The criteria for setting thresholds, meeting thresholds, and distinguishing rising from falling conditions are discussed in detail later in the "Turbidity Threshold Sampling Program" section.

Station Visits

When all conditions have been met to activate the pumping sampler, the data logger triggers the pumping sampler to collect a sample from the stream. During a service visit, the full sample bottles are collected from the pumping sampler and are replaced with empty bottles. The latest electronic data are downloaded from the data logger, and the recorded water depth is compared with a manual depth reading from a staff plate in the stream or stilling well. All equipment is checked for proper functioning, and any debris is cleared from the flume or measuring section of the stream as well as from the turbidity sensor and pumping sampler intake. Detailed field notes are recorded, and these are an essential part of the record.

At sites where a flume or weir has not been installed, it is necessary to collect manual discharge measurements over the full range of discharges. This allows a relationship between water depth and discharge to be established.

It will also be necessary to collect simultaneous pumped and depth-integrated suspended sediment pairs to establish a relationship between the pumping sampler SSC and the depth-integrated cross-sectionally averaged SSC. Ideally, this relationship will be one-to-one ($y = x$), but a correction might be needed if the location of the pumping sampler intake is not representative of the average SSC in the cross section.

The flow of information collected in the field can be visualized in figure 3. Field measurements, samples, electronic data, and field notes are processed into various types of information that will ultimately result in estimates of continuous SSC, sediment loads, graphs, and documentation.

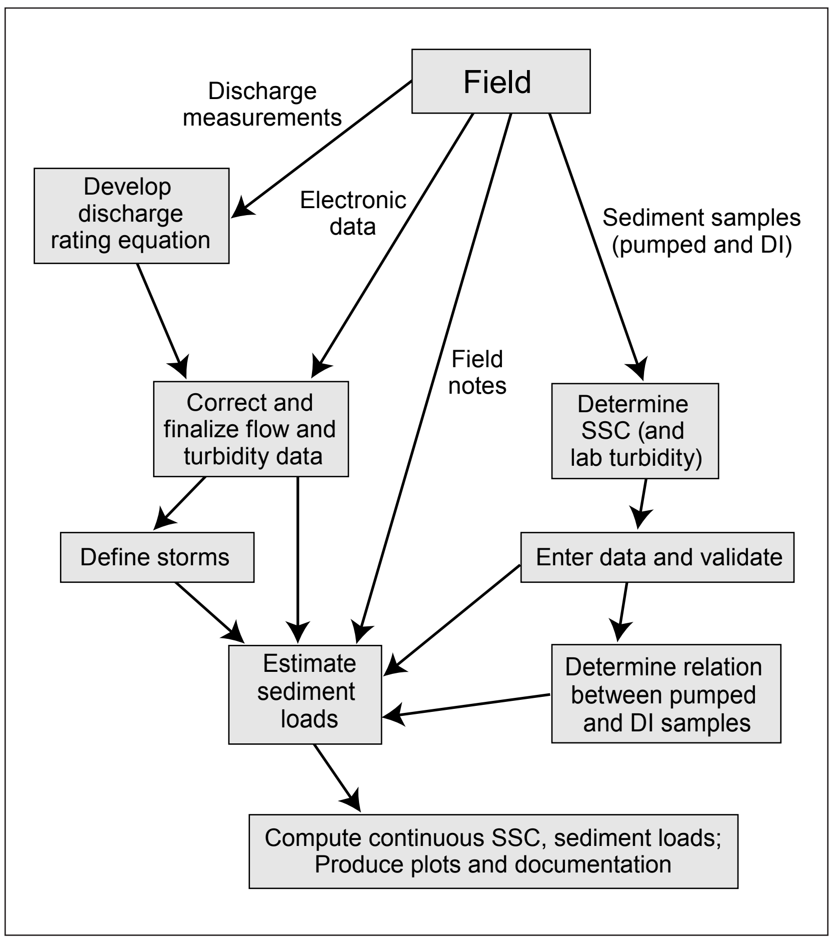

Figure 3—Information types collected in the field and data processing steps required to finalize sediment records. DI = depth integrated.

Equipment Needed

Essential equipment includes:

- Flow measurement device (flume or weir)
- Turbidity sensor
- Stage (water depth) sensor
- Data logger
- Pumping sampler
- Power source (power line or battery)
- Current meter (if rated flume or weir not installed).
- DH-81, D-74, or other manually operated depth-integrating samplers
- Shelter to house equipment

Estimation of the Suspended Sediment Load

Ideally, a linear regression between SSC and turbidity is computed for each period of interest. Turbidity, the predictor variable, is used to estimate the response variable, point SSC (the SSC at the location of the pumping sampler intake), at each measurement interval. The estimated point SSC is corrected, if necessary, to obtain a cross-sectional mean value (applying the regression between the paired point and depth-integrated samples). The SSC and water discharge are then multiplied for each measurement interval and summed over the period of record to obtain an estimate of SSL. It is possible to estimate the variance of the estimated SSL, but the variance estimate can be unreliable for small samples or for data that do not conform well to the regression model (Lewis 1996).

In many cases, an examination of the data reveals periods when the turbidity values are incorrect owing to contamination. During such periods, either (1) discharge can be used in place of turbidity, or (2) if the frequency of pumped samples is adequate, segments can be interpolated between pairs of points on the graph of SSC versus time. The choice between these methods can only be made after examining one or more of the following graphs for each period of estimation:

- Turbidity, SSC, and discharge versus time
- Suspended sediment concentration versus turbidity
- Suspended sediment concentration versus discharge

Limitations to Using Turbidity Threshold Sampling

To date, TTS has been applied most successfully in temperate, rain-dominated watersheds with predominantly fine sediment transport. There are many conditions that can present difficulties for sediment monitoring and automated stream gaging in general.

Freezing temperatures—

In watersheds where freezing conditions persist, several problems are likely to make sediment monitoring more difficult.

- Buildup of ice and snow in the discharge measurement section can invalidate the stage-discharge relationship.
- Ice at the stage sensing location can invalidate stage measurements.
- Ice in the pumping sampler intake tubing can prevent sample collection.
- Low battery voltage caused by temperatures below freezing can cause equipment failure.
- In remote areas where snow is common, gaging sites may be inaccessible for extended periods.

Snowmelt—

Watersheds where runoff is primarily from snowmelt do not necessarily preclude TTS if gaging sites are located at lower elevations where temperatures are moderate. The lengthy hydrographs can be sampled when turbidity threshold conditions are met, just as storm hydrographs would be sampled in rain-dominated watersheds. If turbidity pulses occur daily, it is possible to curtail sampling by modifying parameters in the program.

Fouling—

Algal growth on the turbidity sensor optical surface may corrupt the turbidity record and trigger samples at inappropriate times. Therefore, it is essential that sensors be equipped with an automatic cleaning mechanism, such as a wiper, in watersheds where fouling is expected. It is important to provide access to sensors during high flows (via a pivoting or articulating boom) and to schedule routine site visits to ensure proper equipment functioning.

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Particle size and velocity—

In streams whose suspended load is predominantly sand, it is difficult to obtain representative pumped samples because the pumping samplers we have tested are inefficient at sampling coarse particles. Unless the sampler intake nozzle is oriented directly into the flow (not advisable because it invites plugging of the nozzle), large particles are difficult to sample owing to their relatively high momentum and mass. This is particularly true where stream velocity is high or where the pump is elevated significantly above the sampler intake.

Coarse particles also tend to be nonuniformly distributed in the cross section. In particular, greater concentrations are expected closer to the bed and in areas where velocity or turbulence is greater. Under these conditions, it may be difficult to establish a consistent relationship between the point SSC of pumped samples and the cross-sectionally averaged SSC of depth-integrated samples.

Channel size—

Sediment in large channels with low gradients is less likely to be well-mixed than in small channels with steep gradients. If the sediment is not uniformly distributed in the cross section, it may be difficult to find a sampling location at which the SSC is representative, and it may be difficult to establish a consistent relationship between the SSC of pumped and depth-integrated samples.

Although pumping sampler line velocity varies by manufacturer and model, and depends somewhat on head type, pumping sampler efficiency tends to fall off as the sampler is raised in elevation above the sampling point. It may be impossible to mount the sampler above flood level in larger channels, while maintaining the ability to obtain samples at all flows.

Turbidity range—

All sensors have a maximum turbidity limit. For most sensors, the maximum is under 2,000 turbidity units. Turbidity Threshold Sampling enters a fixed-interval sampling mode when turbidity levels are above the specified sensor limit. The advantages of TTS are lost, however, when conditions require fixed-interval sampling. In streams where turbidity routinely exceeds the sensor limit, TTS will not function optimally. When turbidity exceeds the sensor limit for more than a few hours, it is likely that either all of the bottles in the pumping sampler will be exhausted, or too few samples will be collected to reliably estimate the load.

Site Selection and Equipment Installation

Selection Criteria for Gaging Sites

The general location of a TTS gaging site should be based on the study objectives. Selection criteria often include geographic location, watershed area, proximity of tributaries, soil type, geology, aspect, elevation, forest type, and disturbance history. A discharge measurement section should be located at or near the TTS gaging site. The presence of large unstable trees should be assessed for windfall hazards, and they should be removed before installing the station if they are determined to be unsafe (Butcher and Gregory 2006).

Site accessibility—

Field crews must have reasonable site access to service equipment and to collect manual measurements during storm events. To acquire storm-based manual measurements at a gaging site, the access time would ideally be less than 1 hour and no longer than about 3 hours. Timely access to the site is particularly important for watersheds that have a rapid hydrograph response. Sites that are difficult to access because of snow accumulation, road failures, or stream crossings should be avoided because data quality is likely to be compromised by infrequent site visits that rarely coincide with storm events. It is difficult to predict when the sampling equipment will require servicing because of unanticipated local conditions. In general, sites are visited just before expected storms, during and after storms, and at a frequency of every 2 or 3 weeks during interstorm periods. The frequency of interstorm visits will largely depend on the likelihood of fouling and the available amount of data logger memory. Because there are only 40 standard work hours out of 168 hours in a week, important storm events more often than not occur at times when it is difficult to mobilize field personnel. Remote telecommunications from the gaging sites (via satellite, cell phone, radio, or land line) can alert personnel of maintenance needs and data collection failures by providing frequent information on the status of the equipment, thereby allowing field personnel to schedule their site visits based on the equipment status.

On large rivers it may be possible to service TTS stations by boat. A boat, fitted with the appropriate sampling equipment, does provide a means to collect manual measurements on rivers when neither a bridge nor a cable way is present. However, this approach presents additional logistic and safety concerns. Boats can also delay the response to storm events because of the additional tasks of fueling, transportation, and launching.

Channel geometry and sediment mixing—
If a tributary enters the main channel close to the selected gaging site (fig. 4), and it is desirable to measure the contribution of the tributary, sediment samples should be collected at an adequate distance downstream to allow complete mixing of the sediment (Guy and Norman 1970). The distance downstream necessary to achieve adequate mixing is determined by the stream velocity and turbulence, sediment particle sizes, and the relative contribution of sediment by the main channel and the tributary. For instance, complete sediment mixing will require a greater distance downstream if the tributary contributes only a small percentage of the total flow and a large percentage of the suspended load. If possible, determine when adequate mixing is achieved by collecting depth-integrated samples at a series of cross sections downstream of the confluence. The samples should be individually analyzed in the laboratory (not combined) to produce SSC for each vertical sample at each cross section. The distribution of SSC values in any downstream cross section may change during storm events because of local hydraulic conditions, but it should still be possible to determine the mixing trend. This sampling process, besides providing information about mixing,

Figure 4—Incomplete sediment mixing during dam removal, McKenzie River, Oregon.

will also determine the most representative sampling location for the turbidity sensor and pumping sampler intake at the selected gaging site.

Under highly turbulent conditions, or in narrow channels, the suspended silt and clay may be fully mixed after only a short distance below a confluence. Once mixed, the fine sediment will remain suspended under moderate flow velocities, whereas sand requires local turbulence or upwelling and high flow velocities to remain suspended for even short distances, owing to its greater ratio of mass to surface area. With stream velocity greater than 3 m/sec and a pumping head of 5 to 7 m, we found that particles larger than 0.5 mm were severely undersampled, and particles larger than 1.0 mm were not represented at all (fig. 5).

Specific site requirements for a TTS station are similar to those used to select a desirable cross section for discharge measurements (Wagner et al. 2006). Channel conditions would include a stable and well-defined control, a straight uniform channel above and below the cross section, and stable channel banks high enough to contain flood flows (Rantz 1982). Careful inspection of the streambanks for deposited woody debris at the proposed gaging site will provide clues about recent high flow events and whether overtopping flows may compromise the sample data. Unfortunately, once the flow spreads across a terrace or flood plain, estimating discharge and sediment loads becomes very problematic.

Once the flow spreads across a terrace or flood plain, estimating discharge and sediment loads becomes very problematic.

Adequate mixing and suspension of sediment in steep-gradient channels dominated by fine-grained particles normally reduces concerns about locating a representative sampling position in the cross section. Large, low-gradient channels, however, may require more careful site selection that could include sampling the cross section at different flows to determine whether a representative turbidity

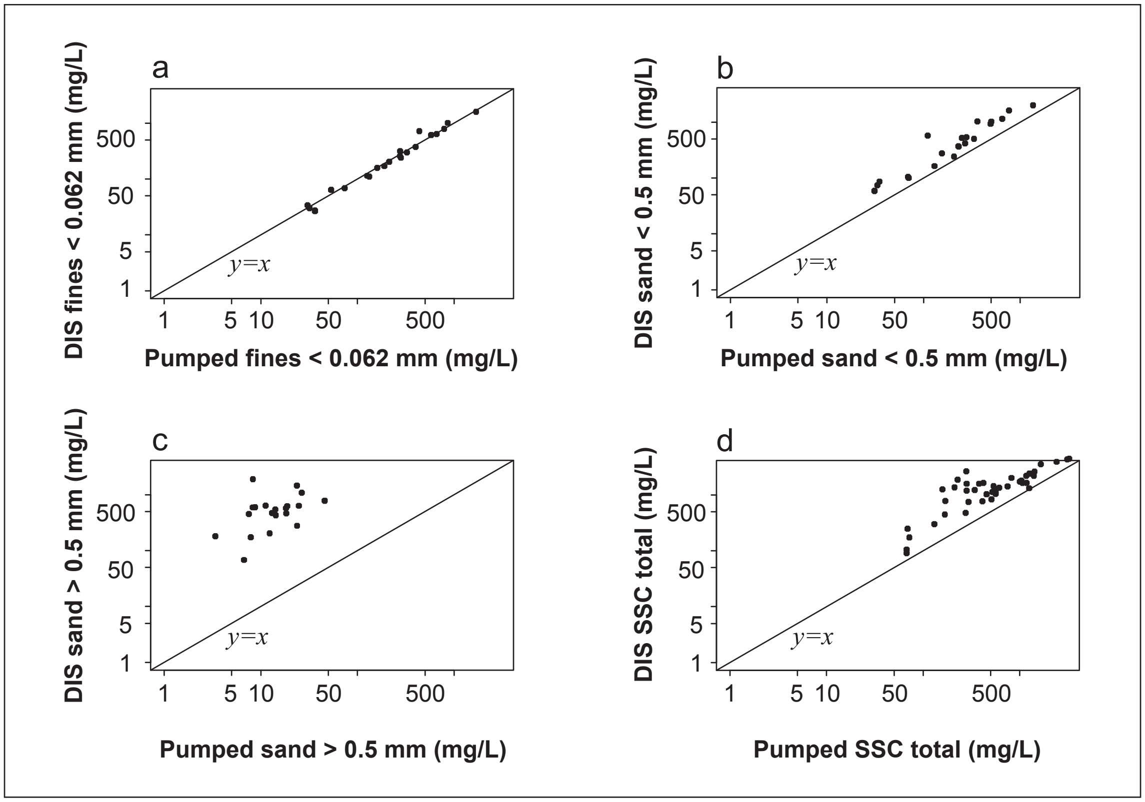

Figure 5—Sand fractions are underrepresented in pumped samples from Grass Valley Creek near Weaverville, California. Comparison of suspended sediment concentration (SSC) from depth-integrated D-49 samples and simultaneous pumped samples for (a) fines < 0.062 mm, (b) fine sand < 0.5 mm, (c) coarse sand > 0.5 mm, and (d) all suspended particles. DIS = depth-integrated samples.

sampling point can be located. Manual suspended sediment samples should always be collected at the same cross section near the gaging site (unless you are determining sediment mixing as explained above) because the ratio of suspended load to total load will vary based on local hydraulic conditions even though total load may be equivalent at different cross sections (Edwards and Glysson 1999). Ideal gage locations are rarely found for this type of channel, and sites are usually selected because of ready access and proximity to a bridge or road.

Depositional reaches are undesirable gage locations because adequate sampling depth is difficult to maintain during low discharge periods, particularly at sites with planar bed surfaces lacking a well-defined and stable thalweg. An aggrading bed can bury the stage sensor and position the turbidity sensor too close to the bed (fig. 6). Depositional reaches may also have highly variable suspended sediment particle sizes, making it difficult to develop relationships between turbidity and SSC. The nearby formation or reworking of gravel bars can alter flow depths across the channel, or cause the local bed elevation to change, making it difficult to develop a stable stage-discharge rating (fig. 7).

Figure 6—Deposition at Freshwater Creek, California, resulted in inadequate sampling depth at sensor location.

Figure 7—A stream reach with easily mobilized alluvial deposits makes a poor gaging site, Decker Creek, Humboldt Redwoods State Park, California.

Small and medium-sized channels with alternating pool-riffle-run sequences often maintain adequate flow depth and mixing of sediment in the reaches between pools (Wagner et al. 2006). Careful onsite inspection and evaluation during storms are desirable for each potential gaging site to eliminate unforeseen sampling complications (such as excess turbulence). New installations may require adjustments, modifications, or relocation of the equipment when site visits or poor-quality data indicate that undesirable sampling conditions are present. Pools or channel depressions may be the only appropriate locations for equipment in small channels to avoid loss of data due to inadequate sampling depth during periods of low flow.

Steep channels that transport mostly bed load during storm events should be avoided. Shallow or wide channels with a coarse substrate and high stream velocities typically have an unstable geometry and are difficult to monitor with TTS (fig. 8).

Figure 8—South Fork Cuneo Creek, Humboldt Redwoods State Park, California. Measuring discharge is difficult in this type of channel because of the turbulence created by the large substrate and unstable channel geometry.

Discharge measurement considerations—

If the gaging site is to be located above a confluence, a site should be selected upstream of stable bedrock or other form of bed elevation control. Below the control, an adequate drop in channel slope is needed to remove potential effects of downstream conditions (backwater) on local velocities (Kennedy 1984). A rated hydraulic structure, such as a flume (fig. 9) or weir, eliminates the need to develop a stage-discharge rating and reduces errors inherent with the velocity-area discharge method (Ackers et al. 1978). Although there is a large capital investment for the purchase and installation of hydraulic structures, they greatly improve long-term data quality and consistency.

Figure 9—Montana Flume with wing walls and sampling bridge (the creek flows from right to left), Xray tributary, Caspar Creek Experimental Watershed, California.

For channels that have unstable beds and lack a well-defined natural control, a permanent hydraulic structure, such as a metal or concrete sill, keyed into the bed and channel banks, can provide a stable section for establishing a discharge rating (figs. 10 and 11). Discharge measurement inaccuracies may, in some circumstances, be the largest source of error when computing sediment loads. Gaging at an unstable cross section requires frequent and repeated current meter measurements, resulting in multiple rating equations that are only valid for brief periods. This greatly increases the cost of fieldwork and data processing, and results in lower quality sediment-load estimates.

For all but the smallest watersheds, either a bridge or a cableway will be required to collect discharge and depth-integrated measurements during high flows (fig. 12). Where the flow is too deep to wade, manual measurements require sampling equipment that is heavy and difficult to transport over steep and uneven terrain, requiring most gaging sites to be located within a reasonable distance to a road. Prefabricated sampling platforms can be used for channel widths up to about 70 ft (21.4 m) in ideal settings, but long spans are normally accommodated by existing bridges or cableways (Martinez and Ryan 2000).

Figure 10— Rated section with steel sill and side walls in North Fork Caspar Creek, California.

Figure 11—Alamitos Creek, near San Jose, California. Gage has a concrete sill, hardened walls, and a traditional stilling well.

Figure 12—Discharge measurement from bridge using a crane, reel, and sounding weight.

Organic loading—

Organic materials, such as logs, branches, and root wads, are normally present in forested watersheds and play an important role in controlling the geometry of alluvial channels (fig. 13). Large woody material is transported during storm events and is often responsible for damaging equipment by direct impact, or by forming debris jams. Debris jams change the local hydraulic conditions and may result in streambank collapse or changes to the channel control feature (from scour and deposition). Selecting a suitable gaging site and the proper sensor mounting will reduce the likelihood of damaged equipment or lost data. Large woody material can exert excessive force on structures and equipment. Therefore the best practice is to choose sites and equipment that do not become debris traps. This would include avoiding channel constrictions, protruding root wads, channel bends, bedrock outcrops, and spanner trees just above the water surface. It is prudent to survey the channel above the proposed gaging site for debris jams. If the debris jams are large and occur with some frequency, expect that mobilized debris rafts will periodically pass through the gaging site.

Figure 13—Debris jam breaking up, North Fork Caspar Creek, California.

Fine organic materials, including ash, can represent a significant portion of the suspended material transported in forested and burned watersheds (Madej 2005). Fine particulate matter (and sediment) can foul turbidity sensors when it is deposited on the sensor's optical surface.

Security—

Gaging site security is a concern that must be addressed during the planning stages and reevaluated during the study if problems occur. Generally avoid locations that are considered public places like swimming or fishing areas. When the gaging site is near homes, try to involve local residents. Explain to them the value of the data and ask them if they will help to keep the site secure. Locate the gaging site some distance behind a locked gate and place an information sign near the site, but not on the equipment, as signs are often used for target practice. Use signage appropriate for groups that might find the site, explaining the purpose of the site and the repercussions of vandalism.

Shelter Design

A shelter provides a dry environment for field personnel to service the equipment and protects the instrumentation from the weather and vandalism (fig. 14). The most useful design is a walk-in painted plywood shelter with adequate work surfaces, several clear fiberglass panels in the roof to allow for natural lighting, and ventilation to prevent condensation. Depending on the distance from the road, sections of

A shelter provides a dry environment for field personnel to service the equipment and protects the instrumentation from the weather and vandalism.

Figure 14—A walk-in shelter provides a dry environment for retrieving data and pumped samples and recording field notes.

the shelter can be prefabricated and transported to the site. Onsite shelter construction is readily accomplishable, however, with the wide array of battery-operated hand tools that are now available.

A shelter with a footprint of 2 by 3 m is adequate for a two-person field crew (fig. 15). Use standard construction and framing techniques for stud walls, floor joists, and rafters, and paint the shelter to match the background colors. For security, omit windows from the design and install a prehung steel entry door with a high-quality deadbolt lock. A simple shed roof is standard except when snow loads are expected. Roofs are a common point of entry for vandals, however, and, if the roof is composed of fiberglass panels, expanded wire can be stapled to the ceiling joists to prevent unwanted access. Expanded wire can also be stapled to the outside of a wooden shelter to prevent entry with a chainsaw. Eliminating all gaps in structural joints and screening entry holes for conduit prevents mice, rats, and wasps from infesting the shelter. Locate the floor of the shelter above the highest expected flow, but place the shelter as close as possible to the stream to reduce cable and tubing runs. Lanterns, headlamps, and fiberglass light panels in the ceiling will provide the background and task lighting required for site visits. Place shelves at a comfortable work height, and plan enough shelf area to accommodate a laptop, pumping sampler, notebook, two batteries, and a minimum of 24 to 48 sample bottles. Place the

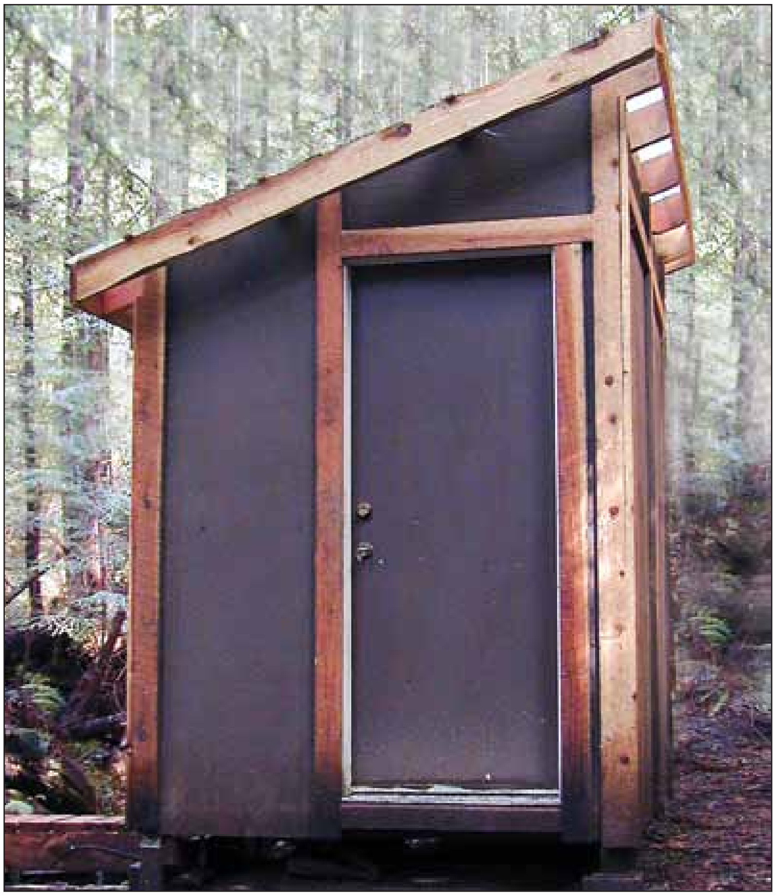

Figure 15—Walk-in shelter, Caspar Creek Experimental Watershed, California.

pumping sampler on a lower shelf to facilitate lifting the mid-section of the sampler during bottle replacement. Providing an area for rain gear storage prevents water from dripping on the laptop and field notes during station visits.

In areas prone to vandalism, consider the entry methods and tools that vandals would be likely to use. During shelter construction use secure bolt-nut-screw combinations and over-sized hardware (hasps, hinges, and bolts), and protect hinges with carriage bolts. Use combination locks or padlocks that have unique keys and use multiple locks or a locking bar on doors. Adding internal lock boxes and locking straps can deter theft if the shelter is entered. The U.S. Geological Survey (USGS) uses a walk-in metal shelter, but its weight requires a road to the site, a forklift, and a concrete foundation pad.

An alternative shelter design uses a standard construction lock box of the type often used to secure tools at construction sites (fig. 16). Several brands are available, and they use similar techniques to prevent entry. The boxes are practical because no construction is necessary, but they lack protection from rain while the box is open during servicing.

Arizona Department of Environmental Quality

Figure 16—Lock box equipment shelter, Beaver Creek, Arizona.

It is essential that equipment be serviceable while it is raining. A temporary tarp system may provide adequate cover during site visits when it is raining as long as high winds are not present. A carport-style shelter (four posts and roof) with sides (fig. 17) is a better solution than a tarp. This type of shelter lacks the shelf space of a conventional shelter, but an overhead cover could allow for shelving attached to the posts. The shelters can be secured by attaching them to a poured concrete block or to bedrock, or by chaining them to a nearby object. The securing method should prevent the entire box from being stolen, for example by cutting a chain with bolt cutters. The shelters are somewhat heavy and awkward, but four persons can carry one over moderate terrain for a reasonable distance. Although they are not airtight, they tend to condense moisture on the inside. Adding several louvered-screened vents to the sides (low and high) will increase the airflow and reduce condensation. Rigid insulation foam can be glued to the inside to further eliminate condensation and moderate interior temperatures. The shelter can be camouflaged by painting it in several colors that blend with the natural background.

Figure 17—
Carport-style shelter,
Little Jones Creek,
California.

Selection of Instrumentation

Data logger—

There are currently three Campbell Scientific[1] data loggers (the CR800, CR850, and CR1000) capable of using the CRBasic version of TTS software that was developed at Redwood Sciences Laboratory (RSL). Two Campbell Scientific data loggers that are no longer in production (the CR10X and the CR510) run the older mixed-array TTS software. Campbell data loggers were selected because the programming language permitted the coding of complex algorithms and control loops that were required by the TTS software logic. The design philosophy for a public version of TTS uses commercially available data loggers and sensors. This allows the end user to receive technical advice and repairs from the various manufacturers. The difference between the CR800 series and CR1000 is the number of available sensor connections. The CR800, when all the TTS sensors are connected, has a more limited capacity to connect additional sensors.

[1] The use of trade or firm names in this publicaiton is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Running TTS at 10-minute intervals, the CR800, CR850, or CR1000 can record data for about 400 days before memory is exhausted. Under most circumstances, the amount of memory that comes standard in the CR10X and CR510 data loggers is also adequate; without additional sensors connected to the data logger, the memory in these models will last about 3 weeks (recording at 10-minute intervals). When memory has been filled, new data will be written over the existing data, starting at the beginning of the file. Because gaging sites should be visited at regular intervals, the limitation of about 3 weeks is reasonable. If more than the 3 weeks between site visits is anticipated or many additional sensors will be connected, the user may wish to order additional flash memory when purchasing the data logger.

Pumping sampler—

Method of operation—Automatic pumping samplers, or wastewater samplers, are battery-powered devices that pump a predetermined volume to a sample bottle from a water source. The samplers use one of two pump types: peristaltic and vacuum compressor. Both types of pumps draw the sample up the intake tube by removing air from the line, creating a partial vacuum in the tube. The sample is then delivered to a bottle in the base of the sampler via a distributor arm.

Peristaltic devices are more common and operate by rapidly moving a set of rollers over flexible tubing inside of the pump housing, thus squeezing the tube to remove air and move the liquid towards the bottle. Peristaltic pumps have more moving parts and the pump tubing must be replaced at regular intervals (about 500,000 revolutions). The silicon pump tubing loses its elasticity over time and may become abraded or cracked from the rollers and sand particles. Peristaltic samplers generally have lower line velocities than vacuum pump samplers.

Vacuum pump samplers pull the sample into a measuring chamber, and the controller pushes the sample, via the distributor arm, into the sample bottle. By closing and opening valves, and reversing the direction of the compressor, the sampler can move fluid towards the sample bottle or towards the stream to purge the line.

Sample bottles—

Sample bottles are available in several shapes and volumes and are made of several types of materials. It is important to choose the sampler brand and bottle type carefully so that bottles are interchangeable across samplers. Sample bottles can be conveniently stored and transported in plastic milk crates.

To match the average volume of a depth-integrated sample, pumped sample volume is usually set to 350 ml. Larger volumes reduce variability but add to the laboratory processing cost. Select a sample bottle volume that is larger than the sample size you expect to collect. A 350-ml sample in a 500-ml bottle leaves spare capacity if the programmed volume is exceeded.

Plastic bottles are lighter than glass and are more resilient, although cracks may occur along the seams, resulting in leakage. If other constituents besides sediment are to be measured, it may be necessary to use a Teflon intake line and glass sample bottles with Teflon caps. Disposable sample bags are appealing because they do not require washing (they are discarded after use) and they take up little room, but our experience has shown that it is difficult to remove all of the sediment from a container that is not rigid.

Head height and line length—The length of the intake tube and height of the pumping sampler above the stream limit the placement of the pumping sampler. The maximum head height (from the water surface to the pump) depends on the sampler manufacturer and model. Frictional and gravitational reductions in the transport velocity of water in the intake line may cause starvation of sediment in the sample, particularly when sediment particles are coarse. To maintain the highest line velocity, place the sampler so that it is just above the highest expected flow. The intake line must be free of dips, and it should have a continuous downward slope to the stream. Samplers with peristaltic pumps do not develop sufficient pressure on the air purge cycle to remove plugs of water left in dips in the line. Placing the intake line inside of polyvinyl chloride (PVC) conduit, or a similar design, prevents dips from forming in the intake line. Route the intake line as directly as possible from the pumping sampler to the stream. Excessive head heights and long line lengths require longer pump cycles and place higher power demands on the station's battery.

Intake mounting—At most sites, it is best to place both the automatic pumping sampler intake and the turbidity sensor on an articulating boom that positions the equipment close to the thalweg (see "Sampling boom" below), at about mid-depth in the flow during non-storm periods, and above the bed-load transport zone during storms (Lewis and Eads 2001). Interstorm periods or extended low-flow periods may require positioning the sensor and intake closer to the bed, or in a channel depression, to maintain adequate sampling depth. Although the sensor and intake rise in the water column with increasing velocity and move closer to the bed with decreasing velocity, care is required when setting the depth to achieve the best position for all measurable flow conditions. Position the opening of the intake facing downstream and parallel to the flow lines. The ideal orientation would be facing upstream, but debris fouling and the inability of the sampler to purge the intake line against the force of the current eliminates this as a possible orientation (Winterstein 1986). A rigid intake nozzle is not required, but if it is installed, ensure

At most sites, it is best to place both the automatic pumping sampler intake and the turbidity sensor on an articulating boom that positions the equipment close to the thalweg at about mid-depth in the flow during non-storm periods, and above the bed-load transport zone during storms.

that the inside diameter is the same as that of the intake line and that it is not drilled with radial holes.

In small streams with Montana or Parshall flumes, the pumping sampler intake can be mounted to the floor in the throat section of the flume. Convergence of flow in the flume ensures that the intake will be submerged at nearly all flows and will rarely be buried by sediment. Although pumping samplers are inefficient at sampling bed-load material, flume-mounted intakes may, at times, inadvertently collect a portion of the bed load. This should be avoided if the objective is to sample suspended sediment exclusively. The pumping sampler intake can be mounted in a fixed or adjustable position. We recommend, however, that the intake be mounted on an articulating boom in proximity to the turbidity sensor at about mid-depth in the water column.

***Cross-contamination and sampling sequence*—**Cross-contamination occurs when material left in the intake tubing from a prior sample or drawn by pressure gradients into the intake nozzle between samples is deposited into subsequent sample bottles (fig. 18). Cross-contamination is likely to occur when the wetted surface of the delivery system is not adequately flushed between samples. Higher

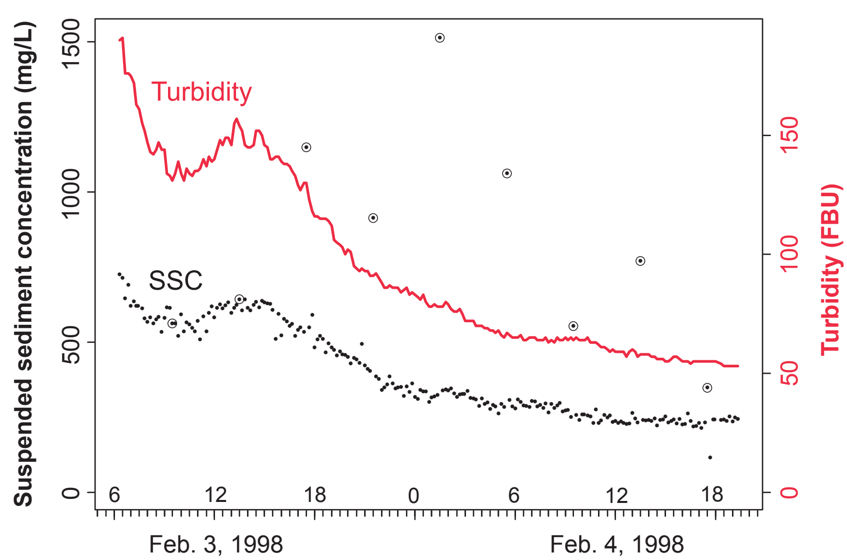

Figure 18—High-frequency (10-minute) record of suspended sediment concentration (SSC) from three pumping samplers operated in series at Grass Valley Creek near Weaverville, California. One rotation consisted of 24 bottles collected sequentially by each sampler. The ISCO 2700 sampler at the site had no water purge cycle; as a result, bottle 1 of each sampler in each rotation (shown as a circled point) was usually contaminated with sediment that had been drawn by pressure gradients into the intake nozzle during the 490 minutes elapsed since the last sample collected by the same sampler. Turbidity was measured by an in situ OBS-3 sensor. FBU = formazin backscatter unit.

line velocities, reduced wetted surface area, and the absence of dips in the intake line reduce the possibility of cross-contamination.

Modern samplers have several options to purge (flush) the intake line. Before a sample is collected, the line is purged with air. In theory this removes debris from the intake orifice and flushes the remaining water and sediment from the line. In practice, peristaltic pumps have inefficient air purges because they cannot develop adequate back pressure. More importantly, after the air purge, stream water is drawn into the intake line until it reaches a sensor located on the stream side of the pump, then reverses the flow direction and expels the water from the intake line back into the stream. Some samplers allow up to three water purges, but we find that a single water purge is a good compromise between energy use and intake line normalization. Following the purges the sample is drawn into the intake line and deposited into the bottle. To ensure accurate sample volumes as head height varies, modern samplers electronically measure the volume. After the sample is collected, the sampler attempts to purge all of the water from the intake line back into the stream, completing the sampling cycle.

***Sediment particle size considerations*—**Silt and clay particles (< 63 µ) dominate the suspended load in many river systems. Local hydraulic conditions can suspend sand-size material for brief periods under favorable conditions, but sand is mostly transported as bed load. Placement of the intake nozzle should normally be located above the bed-load transport zone. In rivers that transport a high proportion of sand, where the pumping sampler has a lift greater than 4.5 m, where flow velocities are very high, or where the length of the intake is long, it is likely that the sand fraction will be underrepresented in the sample. If the momentum of large particles is greater than the suction force at the intake orifice, the particles will not be drawn into the intake. Once inside the intake line, gravity will act on the mass of larger particles to overcome low transport velocities, allowing the large particles to drop out of suspension and fall towards the stream. Comparison between simultaneous depth-integrated and point samples will determine if larger particles are underrepresented (fig. 5). We recommend routinely performing sand fraction analysis in the laboratory on the sample pairs.

***Point and isokinetic samples*—**Samples collected with a pumping sampler are point samples. Regardless of the intake mounting method, the sample is collected from a single vertical point in the cross section and is not integrated across the channel. As discussed previously, a lack of adequate sediment mixing may produce a bias in the sample (the sample may not be representative of the flow-weighted average cross-sectional concentration). Depth-integrated sampling (fig. 19) is the standard method to collect a representative sediment sample that is integrated both vertically and horizontally within the cross section (Federal Interagency River Basin Committee 1952).

Isokinetic, depth-integrated samples represent each sampled point of the cross section in proportion to its flow velocity, hence they are flow-weighted.

The design of depth-integrated samplers allows sediment and water to enter the sample bottle isokinetically, i.e., at the same velocity as the stream. Isokinetic, depth-integrated samples represent each sampled point of the cross section in proportion to its flow velocity, hence they are flow-weighted. These samplers prevent enrichment or starvation of the sampled sediment by evacuating air from the sample bottle at the same rate as the water enters the nozzle. In contrast, pumping samplers maintain nearly a constant transport velocity in the intake line that is rarely the same velocity as the stream. This concern has limited the widespread use of pumping samplers for suspended sediment sampling because of the uncertainty of collecting representative samples. Although the Environmental Protection Agency (EPA) recommends a line transport velocity of 2 to 10 ft/s (0.6 to 3.0 m/s), we suspect that many sampler installations are unable to achieve even the minimum recommended velocity. Sampler transport velocities rarely exceed 6 ft/s (1.8 m/s) under ideal settings. Collecting simultaneous pumped samples and depth-integrated samples over a range of flow conditions is recommended to develop a relationship for correcting biases in the point samples. In our experience with well-mixed streams, there is normally little or no bias in the point sample concentrations; but a bias model should be developed, the point samples should be corrected if a difference exists, and the correction should be stated in reports or publications.

Figure 19—Collecting a suspended sediment sample using a US DH-48 wading type sampler.

Turbidity sensor—

***Turbidity concepts and instrument design*—**There is a wide variety of optical instruments available today that are suitable for measuring turbidity. Section 6.7 of the *National Field Manual for the Collection of Water Quality Data* (Anderson 2004) describes many of these instruments, discusses comparability of measured values, and sets forth standard reporting units. The optical design has a strong influence on the reported turbidity value. Different turbidity values can therefore be reported when the same water sample is measured by different instruments (Downing 2005, Lewis et al. 2007). The polymer formazin has been recognized as a turbidity standard for many years, and instruments of different designs will report approximately equivalent units when measuring a standard in which both instruments were calibrated. Variability in surface water measurements is caused by particle size, color and shape, fine organic material, incident light, and air bubbles. Sensor characteristics that influence readings include optical geometry (e.g., forward or backward scatter), wavelength of the emitted light, sampled volume, and internal signal filtering.

For surface water applications with moderate to high levels of turbidity, we recommend nephelometric or backscatter sensors. They have a wide linear range, with some sensors reading up to 4,000 turbidity units (in formazin). Most applications will require a self-cleaning sensor with a mechanism such as a wiper to remove sediment and organics that collect on the optical surface. Sensors that use the SDI-12 protocol retain their calibration constants internally, so moving the sensor from one location to another does not require modifying the data logger program. Digital output is more robust at rejecting electronic noise than low-level analog signals, and it permits long cable lengths without signal degradation. It is very important to use the same brand and model of sensor for comparisons both within and across watersheds to eliminate differences due to sensor design (Lewis et al. 2007).

Sampling recommendation**—**To avoid stray readings, record the median of a rapid series of turbidity measurements rather than the result of a single instantaneous measurement. The median is preferred to a mean average because it is less sensitive to outlier values. Some digital sensors permit the recording of multiple statistics, including mean, median, range, and variance.

Sensor connections**—**The TTS software, at the time of this writing, will accept three types of wiring connections from a turbidity sensor: single-ended analog (0 to 2.5 V), differential analog (0 to 2.5 V), or SDI-12 digital. For analog sensors, differential wiring is preferred. Although other types of wiring connections are possible, the software would first require modifications.

Sensor deployment**—**Along with the pumping sampler intake, we recommend mounting the turbidity sensor on an articulated boom that positions the equipment close to the thalweg at about mid-depth in the flow during non-storm periods and above the bed load transport zone during storm flows (Lewis and Eads 2001). Direct sunlight on water above the sensor may produce erratic readings during low turbidity conditions. When possible, place the sensor in a location with permanent overhead shade.

Avoid locating the turbidity sensor and sampler intake in high-velocity or turbulent sections of the channel. At high flows, obstructions or large scour holes in the channel can cause local entrainment of air bubbles and coarse sediment that may result in a poor relationship between turbidity and SSC. Clay and silt materials scatter light more efficiently than sand because scattering is primarily a function of number of particles and their shape; clay particles return a turbidity signal that is several orders of magnitude higher than sand particles at an equivalent concentration. Locally induced energy conditions may cause large fluctuations in the suspended load particle makeup. For instance, if silt and clay normally dominate the suspended load composition, but sand becomes periodically suspended during high flows, the result would likely be a relatively small change in turbidity associated with a large increase in SSC.

Sampling boom—

Sampling booms position the turbidity sensor and sampler intake within the sampling cross section at the desired depth, while effectively deflecting large organic debris during storm events (see "Intake mounting" above). The design should allow the field personnel to retrieve the boom at any flow without entering the stream. We have developed four sampling boom applications: bank-mounted, bridge-mounted, cable-mounted, and bed-mounted. Besides the photographs below (fig. 20), detailed drawings and photographs for three of these applications can be viewed on the TTS Web page (http://www.fs.fed.us/psw/topics/water/tts/). A protective and streamlined housing for the turbidity sensor can reduce the impact of organic debris collisions and reduce bubble generation near the optics. The housing may include sun protection and should be custom designed for each sensor model (fig. 21).

The design should allow the field personnel to retrieve the boom at any flow without entering the stream.

The placement of the sampling boom must be carefully considered. The outside bend of a stream receives the brunt of the impacts from large woody debris transported during high flows. Articulating sampling booms are designed to shed a moderate amount of large debris, but positioning the boom close to the bank, where the thalweg is likely to be located, can cause problems when debris is retained on nearby objects such as protruding roots, trapped logs, or overhanging tree limbs. The flow direction in a channel bend may shift at different flows, imposing lateral stresses on the boom, resulting in misalignment of the turbidity sensor housing, thereby raising the likelihood of increased local turbulence and fouling from debris.

Figure 20—(A) Bank-mounted articulating boom holds pumping sampler intake and turbidity sensor at Upper Jacoby Creek in Humboldt County, California. (B) Bridge-mounted boom supports turbidity sensor at Prairie Creek, Humboldt County, California. (C) Cable-mounted boom supports turbidity sensor at Arfstein station on North Fork Caspar Creek, Mendocino County, California. Sensor housing is fitted with sun shield. (D) Bottom-mounted boom with float in Nissouri Creek, Ontario, Canada. Boom positions turbidity sensor and sampler intake at a fixed proportion of the depth of flow.

Figure 21—This housing for a DTS-12 sensor was constructed from square aluminum tubing, cut off diagonally at the optical end, which is oriented downstream.

Stage measurement—

Stage and gage height definition—Stage is the height of the water above a datum elevation such as the channel bed (Langbein and Iseri 1972). Gage height is generally synonymous with stage, although gage height is more appropriate when used with a reading on a gage or staff plate.

Measurement accuracy—

The USGS stage measurement accuracy guideline states that:

> Stage data are to be collected with sufficient accuracy to support computation of discharge from a stage-discharge relation and that procedures and equipment used are to be capable of sensing and recording stage with an uncertainty of no more than 0.01 ft (0.3 cm) or 0.20 percent of indicated reading, whichever is larger [Yorke 1996].
>
> The ISO standard 4373-1979(E), clause 7, states that:
>
> For the measurement of stage, in certain installations an uncertainty of ±10 mm may be satisfactory; in others [depending on site instrumentation] an uncertainty of ±3 mm or better may be required; however, in no case should the uncertainty be worse than ±10 mm or 0.1 percent of the range, whichever is greater (Maidment 1993).

***Stilling wells*—**Stilling wells were once the primary device used to reduce the effects of surface waves on stage sensing devices. Stage can be measured inside the stilling well by means of a float and counterweight that is mechanically linked to a stage-sensing device. The stilling well gained wide acceptance because it effectively dampened water-surface fluctuations by allowing the water to enter the large-diameter well through several small-diameter pipes. Stilling wells located in rivers that transport large sediment loads require a flushing device to remove accumulated sediment from the intake pipes. Clogged and buried intake pipes result in the loss of data. Large-diameter stilling wells are now considered hazardous because personnel must climb down a ladder on the inside of the stilling well to read the staff plate and service equipment. These are no longer recommended because of the risk from falls (requiring the use of fall protection equipment) and from the possible accumulation of toxic fumes or the lack of oxygen (requiring an oxygen source). Small-diameter stilling wells are still commonly attached outside flume walls to improve stage readings from pressure transducers.

***Staff plates*—**Staff plates are installed upstream of, but close to, the natural or engineered channel control (flumes and weirs have required mounting locations). In open channel conditions, the staff plate is mounted with its face parallel to the streamflow lines, facing the bank from which it will be read. It should be mounted in an area of low turbulence that is protected from debris accumulation. The zero point of the staff plate is mounted below the lowest stage of interest. Staff plates are available in 3.3-ft, or 1.0-m lengths. Bridge abutments allow for vertical stacking of staff plates while reducing the chance of debris accumulation. For accurate water height measurement, the best staff plate location is often in the middle of the side face of the abutment. When more than one staff plate is required to cover the range of expected flows, each staff section is separately mounted and surveyed so the top of the lower staff is at the same elevation as the bottom of the upper staff. The staff plates are surveyed to a stable and permanent benchmark to allow for their reinstallation at the original elevations if they are lost during a flood. Steep viewing angles between the observer and staff plate should be avoided to reduce the reading error. Wide channels will require the use of binoculars to achieve the necessary magnification for an accurate reading. Two styles of staff plates are available: those with numeric markings every 0.02 ft (0.6 cm), and those marked like a survey rod, with a pattern of black and white lines and numeric values spaced some distance apart. Our experience indicates that fewer reading errors are made with staff plates that have frequent numeric markings. The stage sensor's electronic offset is adjusted to agree with the staff plate at the time of installation, and

Under most conditions, the staff plate reading is considered to be the most accurate stage; however, because it is less precise than stage sensor measurements, particularly during turbulent flow conditions, sensor data should not be automatically adjusted to match all staff plate readings.

periodically thereafter. Under most conditions, the staff plate reading is considered to be the most accurate stage; however, because it is less precise than stage sensor measurements, particularly during turbulent flow conditions, sensor data should not be automatically adjusted to match all staff plate readings (see “Stage adjustment philosophy” under “Data Processing”).

Stage sensing devices—

There are many modern stage-sensing devices available today. There are four general categories: noncontact, float and counterweight, submersible pressure transducer, and nonsubmersible pressure transducer.

***Noncontact stage sensor*—**Ultrasonic noncontact sensors work by broadcasting a cone-shaped sound wave perpendicular to the water’s surface and converting the bidirectional travel time (at the speed of sound) to a distance after compensating for the ambient air temperature. The sensor is mounted in a fixed location over the stream channel, often on a bridge, and above the highest expected maximum stage. Increasing the height of the sensor and rough water surface conditions reduce the stage precision. Noncontact sensors are used in channels with highly mobile beds that undergo frequent scour and fill, and where other methods are not reliable. The accuracy of the sensor may not be adequate for some applications.

***Shaft encoder with a float and counterweight*—**A shaft encoder connected to a float and counterweight mounted inside a stilling well can produce accurate stage readings, provided the intakes remain free from sediment and the float tape or beaded line does not slip on the shaft’s pulley. The encoder produces a digital pulse proportional to the shaft rotation with a precision of about 0.01 ft (0.3 cm).

***Submersible pressure transducer*—**Submersible pressure transducers can be mounted in a length of pipe and secured at right angles to the flow below the lowest stage of interest. They operate by sensing changes in the water pressure and return a voltage proportional to the stage. The sensor depth rating should be slightly larger than that for the maximum expected stage at the gage location. A calibration coefficient (slope or multiplier) is usually supplied by the manufacturer or it can be determined empirically by calibration. Differential pressure transducers have a tube inside the cable that is vented to the atmosphere to compensate for changes in barometric pressure. The vent tube must terminate in a dry atmosphere to prevent failure due to condensation forming in the vent tube. The pressure transducer is connected to a data logger, and its output can be adjusted by changing the offset (y-intercept) in the data logger program to agree with the current staff plate reading.

A stage averaging routine in the data logger program can electronically dampen wave oscillations from the stream, thereby eliminating the need for a stilling well.

A stage averaging routine in the data logger program can electronically dampen wave oscillations from the stream, thereby eliminating the need for a stilling well.

Nonsubmersible pressure transducer (bubbler)—Bubblers are pressure-sensing devices that detect pressure changes at the orifice of a small tube mounted in the stream. The pressure sensor and other hardware are located in the gage shelter. More specifically, modern bubblers use a small battery-powered compressor to supply the necessary air pressure to maintain a constant bubble rate at the terminus of the orifice tube. As the stage in the river rises, more air pressure is required from the compressor to maintain a constant bubble rate to overcome the increased water pressure. The pressure changes are measured by a transducer that is connected to the orifice line. Unlike the submersible pressure transducer that can be lost in high flows or damaged by debris, the orifice tube and protective conduit are inexpensive and easy to replace. Bubblers are normally used on larger rivers because they can measure water depths of 30 m or more.

Sensor connections—

There are four common types of output signals available from stage sensors. An analog signal can be either a differential signal output (two data wires, high and low) or an amplified single-ended connection (one data wire). In the case of a differential signal, the data logger is responsible for signal conditioning and processing. Because the output voltage has a low magnitude, it is susceptible to interference from stray electrical signals and from changes in temperature. Single-ended sensors are more expensive because of the additional circuitry, but they provide for on-board signal conditioning and amplification with output voltages between zero and 5 V. Sensors can also operate in a current loop, normally between 4 and 20 mA. The current changes in proportion to the stage, and it is immune to external conditions (this type of sensor is a good choice for use in electrically noisy environments). There are two types of digital sensors. Some sensors output a digital data stream that must be captured by the data logger and controlled with handshaking. These devices are losing favor because the data logger programming is more demanding. Finally, a digital sensor can use the SDI-12 protocol. This allows multiple sensors to be connected to a single digital port because each sensor has a digital address. The SDI-12 sensors have an additional benefit of retaining their calibration information internally and can therefore be moved between data loggers without altering the sensors' parameters in the data logger program. Programming statements are straightforward, and handshaking between the data logger and sensor is handled automatically.

***TTS stage sensor*—**The TTS program currently accepts wiring from a differential pressure transducer, such as a Druck model 1230. Connecting a sensor that has different specifications (such as an SDI-12 interface) will require modifications to the data logger program. In larger river systems where the turbidity sensor and sampler intake are always submerged, water depth is not needed by the TTS program, so stage can be collected by independent equipment and later appended to the TTS file. This situation could arise where an agency such as the USGS is collecting stage and discharge data at the site.

Security—

When installing equipment, it is prudent to take into consideration possible vandalism and to plan accordingly. Paint the equipment to match the background color and place it in a location away from public access, preferably behind vegetation. Engrave all the instrumentation in multiple locations with an electric etching pencil, listing the owner's name and phone number where it would be difficult to deface if the equipment is stolen. Lock all the equipment to prevent tampering and, when possible, store it inside a secure structure. If possible, lock equipment down inside the shelter to further prevent theft if the shelter is broken into. Remove equipment from the gaging site to a secure location when not in use.

Redundancy—

Equipment redundancy permits immediate replacement of lost or damaged equipment with minimal loss of data. Some manufacturers will loan replacement equipment while your device is being repaired, but many will not. If equipment is lost or stolen, it may take between 3 and 6 weeks to replace. Unfortunately these circumstances often occur when data loss is unacceptable. Plan to acquire replacement parts and spare equipment before commencing the monitoring project. Add redundant equipment and parts when affordable.

Calibration—

Follow the manufacturer's recommendation for recalibration of their device. In some settings, more frequent calibration may be necessary to satisfy the requirements of a regulatory agency, or if the sensor is unstable and has excessive drift. Always have an instrument recalibrated if it has been damaged. It is good practice to calibrate instruments at least annually. Pressure transducers are readily calibrated with basic supplies, but other devices, such as turbidity sensors, require the accurate formulation of calibration solutions and, sometimes, a custom calibration container. Turbidity sensors require adjustments to the hardware or to the firmware during the calibration procedure, and this is best left to the manufacturer. The manufacturer will supply a certification of calibration, and this document may be required by a regulatory agency.

Site Operations

Routine Procedures

Visual inspection of the gage site and maintenance—
Physical changes to the site may alter the stage-discharge relation or the sediment-turbidity relation, or both. Upon arriving at the gaging station, make a visual inspection of the channel, sensors, and sampler intake. Check the channel conditions at the gaging site and in the immediate vicinity above and below the gage. Note changes to the streambed composition (e.g., fines covering the armor layer, or the formation of a new scour hole), failure of a streambank, or the accumulation of debris. If the channel has a natural bed control, make a close inspection of the control to determine if any changes have occurred. This may be difficult to detect in gravel or sand bed channels that lack control structures such as bedrock or boulders. If any unusual conditions are identified, make detailed notes on the field form and include a sketch to clarify complex changes. The most common human failure is to write incomplete notes in the field that will later be of marginal use when anomalies in the data are discovered. A good assessment of the note taking detail is to ask if someone unfamiliar with the site could fully understand the notes without a verbal explanation.

The following maintenance steps are not necessarily in the correct sequence for a site visit because some are not required at every site visit.

Sites that have engineered structures, such as a flume, may require sediment removal from the floor of the structure or from the approach to prevent errors in discharge. Read and note all staff plate and wire weight stage readings before removing sediment or debris from the channel or flow structure. Read and note the stage again after the material is removed from these devices and the flow has normalized (this will determine whether the stage has been artificially altered). If a stilling well is in use, check the intakes and flush if necessary after large storm events. Always note each time that personnel enter and exit the channel because both the stage and the turbidity may be altered by disturbance to the bed or flow pattern. Perform in-channel work immediately after a data logger wake-up interval and attempt to complete the work several minutes before the next data logger wake-up.

Both the turbidity sensor and the pumping sampler intake can be adversely affected by debris or sediment accumulation. Depending on the orientation of the pumping sampler nozzle, fine sediment can accumulate inside the intake line near

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Always note each time that personnel enter and exit the channel because both the stage and the turbidity may be altered by disturbance to the bed or flow pattern.

the orifice, particularly if the pumping sampler's purge cycle is inadequate. Debris lodged on a sampling boom that is in proximity to the turbidity sensor or pumping sampler intake can disrupt the flow and generate air bubbles, or it can directly affect the turbidity sensor's optical field. Before removing debris, attempt to determine whether it could have been causing sampling errors. Recording this information in the field notes will help correct data errors and identify samples that can be discarded. For reconstruction of erroneous turbidity data, it may be useful to record laboratory turbidity on those samples, even if they are not processed for SSC.

Again, turbidity sensors with a mechanical means to remove fine sediment and organic matter from the optical surface are preferred, unless prior experience indicates that the turbidity sensor is not prone to fouling. At sites that have high nutrient loads, warm temperatures, and abundant sunlight, fouling can take place rapidly (fig. 22). If filamentous algae grows on the housing near the sensor's optical field, the contamination may be outside the reach of the wiper; but it can cause erroneous readings by waving in front of the sensor and must be manually removed. It is a good practice to remove accumulated material from the end of the sensor and the wiper arm with a toothbrush and a nonabrasive liquid soap. Do not manually move the wiper arm. Always check the optical surface to ensure the wiper has been functioning properly.

Figure 22—Optical contamination resulting from the wiper not being activated, Guadalupe River near San Jose, California.

If the sampler intake has been in place for an extended amount of time, or if it shows signs of biologic growth, rinse the inside of the intake tube with a solution of bleach and water. This can be accomplished without removing the intake tubing if it is mounted on a boom that can be raised above the water surface. Place the intake in the bleach solution and manually run the pumping sampler's pump forward to draw the solution into the tube, but stop the pump before the solution is deposited in a sample bottle. Leave the solution in the tube for 10 minutes. Purge the solution back into the container by reversing the pump, and then rinse the tube with clear water several times in the same manner, being careful to not allow bleach into the stream.

For sites that transport high sediment loads, check the stage-sensing device after each significant storm event. Check bubbler orifices for damage or plugging and examine submersible pressure transducers for sediment accumulation around and, depending on sensor design, inside of the protective cap. Submersible stage sensors will usually continue to function when buried, but changes in stage may be attenuated if the sediment is fine and the sediment layer is deep. Bubblers are more susceptible to burial malfunctions.

Reading the stage—

If the stage is low enough to safely enter the stream, approach the staff plate but maintain enough distance to prevent the wave influence from your legs from affecting the stage. Read the stage while keeping your eyes at a low angle to the water surface. If the water is too deep for wading, use binoculars. Avoid reading the stage from a high location such as a bridge. If the stream velocity is causing the water to build up on the leading edge of the staff plate, take the average reading between the leading and trailing edge of the staff plate. Do this several times and take the average of all the readings.

Field notes—

Field notes are best taken immediately after each specific activity, such as reading the staff plate, rather than waiting until the completion of the site visit. Use a standard form rather than a notebook to prompt field personnel to complete and document all required tasks. Besides specific line item tasks, adequate space should be provided for detailed descriptions and sketches. Care should be taken to provide information about any activity or condition that might affect the data being collected, such as the submergence of the turbidity sensor or flume cleanings. If the original field form is brought back to the office, bring a copy to the field at the next site visit. Maintaining copies of all the field forms for a site from the current hydrologic year in chronological order can provide valuable clues when troubleshooting equipment. Both the date and the field form number can serve as identification. A typical numbering scheme starts at one at the beginning of each hydrologic year.

Checking the current sample status—

Read the "Next Sample" counter on the pumping sampler. This number is one more than the number of samples that have been collected. Between wakeup intervals remove the midsection from the sampler and visually check the bottles containing samples. Ensure that the correct number of samples has been collected and that their volumes are acceptable. We set the pumping sampler controller to collect a sample volume between 330 and 350 ml for 1000-ml bottles, and at 300 ml for 500-ml sample bottles. Samples below 150 ml are considered suspect and overfilled bottles are discarded. A large sample volume reduces the sample variance but increases the laboratory processing cost.

Check the data logger sample counter to make certain that it agrees with the pumping sampler. The data from the data logger are downloaded to a laptop, and sample bottles are replaced when there is a chance that all bottles will be filled before the next visit. This "change out" threshold can differ from site to site, but it is generally when about half the bottles contain samples. Several variables control this number: site access, expected storms, available field personnel, and sampling parameters.

Downloading the data and changing the sample bottles—

The sample bottles and accompanying data are always processed together in the implementation of TTS that runs on Campbell data loggers. The data are downloaded ("dumped") to a laptop computer, any bottles containing samples are replaced with empty bottles, and the data dump number is incremented. If sample bottles do not need to be replaced on a particular site visit, a partial data file is downloaded for plotting but the data dump number is not incremented, and it would not be considered a "data dump." After a data dump, the data should immediately be backed up on a secondary memory device. The data file name contains the three-letter station identification, the start date, and the data dump number. The sample bottles are labeled with the station ID, the data dump number, and the sample number (bottle position).

Plotting the data—

The TTS Data Plotting software, available on the TTS Web page, allows field personnel to view the data file in the field and to check for errors. The plot displays the date and time on the *x*-axis and stage and turbidity on the *y*-axis. Pumped samples are shown on the turbidity trace. The plot can assist in diagnosing equipment problems and provide the field crew with an assessment of whether or not the sampling parameters, such as the turbidity thresholds or the minimum stage, are set correctly.

Depth-Integrated Sampling

Collection of isokinetic, depth-integrated samples involves using either an equal-width-increment (EWI) or equal-discharge-increment (EDI) sampling method. The EWI or EDI methods usually result in a composite sample that represents the discharge-weighted concentrations of the stream cross section being sampled (Wilde et al. 1999). Manually operated isokinetic samplers, such as the DH-81, D-74, or other depth-integrating samplers, are designed to collect composite samples that are automatically weighted by discharge if the sampler is passed through the water column at a constant rate.

The importance of depth-integrated and pumped sample pairs—
Because pumped samples are collected at a single point in the stream, they may not represent the cross-sectional average SSC. Analyses of simultaneous point and depth-integrated samples will determine if a correction to the point sample data is required.

When to collect depth-integrated samples—
The sample pairs should be distributed over the measured range of turbidities recorded at the station. Twenty or more pairs may be needed to detect small biases in pumped samples. After the range of data has been covered, sampling should be periodically repeated to determine if the relationship has changed.

How to collect depth-integrated samples—
Refer to the "Field methods for measurement of fluvial sediment" for a complete description of the procedure (Edwards and Glysson 1999).

Developing a Stage-Discharge Relationship

A rating equation must be developed for gaging sites that don't have a discharge measurement structure such as a weir or flume. Discharge measurements should be collected over the range of possible flows at the site. High flow measurements are very important and the most difficult to collect. If the channel control is stable, it may be possible to develop a good relationship with as few as 20 or 30 stage-discharge pairs. If the channel control is not stable, ongoing measurements will be required to develop a new rating each time the channel control changes. For channels with highly mobile beds, it may not be possible to develop a rating.

How to collect discharge measurements—
Refer to "Discharge Measurements at Gaging Stations" for a complete description of the procedure (Buchanan and Somers 1969).

Equipment Troubleshooting

The most important concept for trouble-shooting instrumentation is to approach the problem systematically.

How to evaluate equipment problems—
The most important concept for troubleshooting instrumentation is to approach the problem systematically. Because the components of a monitoring system are interconnected, a problem with a sensor may be presented as an error message from the data logger. Randomly testing various parts of a system often leads to confusion and rarely identifies the problem. Although a problem can be analyzed from the data logger towards an external component, it is usually more efficient to work in the opposite direction. Recording detailed field notes assists by structuring the troubleshooting and provides a valuable record should the problem arise in the future. Beyond the philosophy of troubleshooting, each component of a monitoring system may have unique attributes that are specific to that particular model. The "TTS Field Manual," available on the TTS Web page (http://www.fs.fed.us/psw/topics/water/tts/), has specific component-level diagnostics to aid field personnel.

Diagnostic tools—
Problem diagnosis requires an understanding of each part of the monitoring system and its correct functioning, diagnostic data logger programs to test specific components, and a multimeter to test voltage levels and circuit continuity.

Field personnel must first understand how a device normally functions before they can correctly identify failures. For instance, is an erratic trace from a turbidity sensor due to suspended sediment, a faulty connection, a failing sensor, or optical fouling?

Component-specific diagnostic programs can test a sensor or pumping sampler by reporting measured values or by triggering a sample. The diagnostic program must account for wiring connections that are specific to data logger and sensor models. For instance, the control port designation that triggers the pumping sampler depends on the data logger model. Use of diagnostic programs is more efficient than troubleshooting during the normal operation of the TTS program because they repeatedly and quickly test a component without waiting for a normal wake-up interval every 10 or 15 minutes.

A multimeter is an electronic instrument that can detect both voltage levels and circuit continuity. In the voltage mode, the multimeter can report supply voltages, for example from the battery to the data logger, and it can measure voltage levels from sensors. The continuity mode is useful for detecting broken or poorly connected wires and for checking relay closures.

Most field personnel can be trained to diagnose failures at the component level and to replace the sensor, data logger, or pumping sampler. If adequate replacement equipment is available, it is more efficient to simply change out a component (e.g., a sensor or sampler controller), than to attempt repairs, unless the field crew is experienced in diagnosing problems. Follow the "TTS Field Manual" or the equipment manual supplied by the manufacturer when replacing components.

Turbidity Threshold Sampling Program

The TTS program has been developed for three different brands of data logger at the time of this writing: Campbell, Forest Technology Systems (FTS), and Onset Tattletale (see footnote 1). The Onset version, written in TXBASIC for Tattletale data loggers, is no longer supported. The Campbell program is freely available from the TTS Web page for model CR510 and CR10X data loggers. The CR510 and CR10X are no longer manufactured. A new TTS version is available for the replacement Campbell data loggers (CR800 and CR1000) that are programmed in Campbell's CRBasic language. The FTS version of TTS can only be obtained from FTS.

Logic

The TTS algorithm attempts to collect physical samples at specific turbidity thresholds. For details, programmers may consult the pseudocode (available from the TTS Web page). Thresholds are usually chosen so that the square roots are evenly spaced to adequately define loads for small storms without oversampling large storms. A programmable data logger, typically recording at 10- or 15-minute intervals, instructs an automatic pumping sampler to collect a sample whenever a threshold is crossed. To avoid recording ephemeral turbidity spikes caused by passing debris, the median of a rapid succession of turbidity measurements is recorded at each interval. To limit sampling of false turbidity fluctuations caused by snagged debris or biofouling, a threshold must be met for two intervals before signaling the sampler. Because most sediment is discharged while turbidity is in recession, a separate, larger set of thresholds is used when turbidity is falling. Reversals are detected when the turbidity drops 10 percent below the preceding peak, or rises 20 percent above the preceding trough. In addition, the change must be at least five turbidity units, and the new course must continue for at least two intervals before declaring a reversal. At the time a reversal is detected, a sample is collected if a threshold has been crossed since the preceding peak or trough, unless that threshold has already been used in a specified number of preceding intervals.

The user can modify the specific thresholds and numerical parameters mentioned here. Specific conditions recognized by the program are described below, with default values of user-specified parameters followed parenthetically by the name of the parameter that controls it in the CRBasic implementation:

1. Base flow. This condition occurs when the stage is less than the "minimum stage" parameter (minimumStage). Minimum stage is usually set to the lowest stage at which both the turbidity sensor and pumping sampler intake are adequately submerged and functional. No sampling takes place in this mode.
2. Rising turbidity. The turbidity condition is defined as rising at the first interval emerging from base flow. For sampling to occur in a rising turbidity condition, the turbidity must be equal to, or greater than, the next rising threshold for two (persistence) intervals that are not necessarily consecutive. When emerging from base flow, a startup sample is immediately collected if the turbidity is above the lowest rising threshold, and no rising thresholds have been sampled within the past 72 (startWait) intervals.
3. Turbidity reversal. A turbidity reversal occurs when the turbidity has changed direction for two (persistence) intervals, and has dropped 10 (peakChange) percent from the prior peak or risen 20 (troughChange) percent from the prior trough, and changed at least five (reversalMinimum) turbidity units in both cases. Upon detection of a reversal, a sample is collected if a threshold has been crossed since the previous peak or trough, unless that threshold was already sampled in the past 18 (waitCount) intervals.
4. Falling turbidity. Sampling occurs during decreasing turbidity when the turbidity is less than or equal to the next falling threshold for two (persistence) intervals.
5. Overflow mode. The overflow condition occurs when the turbidity sensor output exceeds the data logger's millivolt limit setting (mvLimitOBS, OBS-3 sensors) or turbidity limit setting (turbLimit, DTS-12 and NEP395 sensors). In this mode, the sampler begins sampling at fixed time intervals. The number of intervals skipped between samples is specified by the fixedTimeWait variable.

The complete list of parameters that the user can modify is as follows:

CR800/1000	CR510/10X	Description
minimumStage	min_stg	Minimum stage for sampling
turbC1	turb_mult	Calibration slope for turbidity sensor (OBS3 only)
turbC0	turb_off	Calibration offset or intercept for turbidity sensor
stgMultiplier	stg_mult	Calibration slope for pressure transducer
stageOffset	stg_off	Calibration offset for pressure transducer
<eliminated>	logger	Data logger model (CR510 or CR10X)
qCalc	qcalc	Discharge calculation: 0 = not active, 1 = active
qMultiplier	q_mult	Multiplier for discharge calculation (multiply by this value)
qExponent	q_exp	Exponent for discharge calculation (raise stage to this power)
turbDevice	turb_dev	Turbidity device (OBS3, OBS3+, DTS-12, or Analite NEP395)
delayTime	delay	Delay that selected port remains high to trigger a sample
reversalMinimum	rev_val	Minimum absolute change in turbidity to detect a reversal
peakChange	revpct1	Minimum reversal percentage from rising to falling
troughChange	revpct2	Minimum reversal percentage from falling to rising
persistence	stay	Minimum number of intervals before a threshold or new reversal
waitCount	rep_wait	Minimum number of intervals between utilizations of the same threshold
mvLimitOBS	mv_limit	Above this limit, samples are collected at fixed time intervals (for OBS-3, OBS-3+ sensors)
turbLimit	ntu_limit	Above this limit, samples are collected at fixed time intervals (for DTS-12, NEP395 sensors)
fixedTimeWait	lim_skip	Number of intervals skipped between samples when in overflow mode
<eliminated>	obs3poly	Calibration type for OBS3 or OBS3+ sensors (linear or polynomial)
obs3Range	obs3range	Range setting for OBS3+ sensors (1X or 4X)
samplers	samplers	The number of pumping samplers connected (1 or 2)
startWait	startwait	Minimum number of intervals between most recent rising sample and a subsequent startup sample (taken when emerging from base flow)
wipeStage	wipe_stg	Minimum stage for activation of turbidity sensor wiper
waterTempDevice	wtemp_dev	Water temperature device (Campbell T107, DTS-12, or Analite NEP395)

Guidelines for Setting Turbidity Thresholds

General considerations—

The following guidelines are designed to collect a few samples in small storms and more, but not too many, in large storms. The terms "few" and "too many" are subjective, and it is up to each investigator to define the desired range of sample abundance by setting the number of thresholds. The guidelines are based on simulations made with data from the Caspar Creek Experimental Watersheds, and are designed to accurately and economically estimate suspended sediment loads for, on average, the six largest storm events each year (Lewis 1996). At some of

It is up to each investigator to define the desired range of sample abundance by setting the number of thresholds.

the gaging sites with relatively high or low sediment loads, we have had to alter thresholds and other sampling parameters. When an extreme erosion event occurs in a watershed, the sediment regime may be altered drastically for some period of time, and sampling parameters should be adjusted accordingly. In different environments or where objectives differ, parameters will need customizing. For example, if one had a special interest in sampling the first few small events of the wet season, then an extra threshold or two might be temporarily added near the low end of each threshold scale. If relatively more emphasis is to be placed on low flows, then the square root scale might be replaced with a logarithmic scale. However, any alteration that places more emphasis on low turbidity conditions will result in more samples (and higher costs) unless the number of thresholds is reduced at the same time.

Using the threshold calculator applet—

The turbidity threshold calculator on the TTS Web page can be used with any Web browser that has a Java 2 or more recent Java plug-in installed.

- Using the Sensor Maximum slider, set the maximum reading (turbidity units) that your sensor can record. This value can be determined by calibration and may not be the same as the nominal range given by the manufacturer. The manufacturer should be able to provide the necessary calibration information.
- Set *N*, *L*, and *U* on the Rising Threshold sliders, based on the criteria described below under "Rising thresholds."
- Set *N*, *L*, and *U* on the Falling Threshold sliders, based on the criteria described below under "Falling thresholds."
- If desired, test the thresholds as described below under "Simulating TTS."
- Install the thresholds in the TTS Campbell program as described below under "Entering thresholds in the Campbell TTS program."

Rising thresholds—

- Determine the lowest non-zero threshold, *L*. This should be a value that is above typical interstorm turbidity values. In small streams it should also be a value that is expected to occur only after the stage rises enough to submerge both the turbidity sensor and the pumping sampler intake.
- Determine the highest threshold, *U*, within the range of your turbidity sensor.

- Determine the number of thresholds, N, between L and U (including both L and U).
- Use the threshold calculator applet, or manually calculate thresholds as follows:
- Compute $d = (U^{0.5} - L^{0.5})/(N - 1)$
- The thresholds between L and U are $(L^{0.5} + d)^2, (L^{0.5} + 2d)^2, \ldots, (L^{0.5} + (N-2)d)^2$
- Because of the way the algorithm was written, before TTS Revision 5.0, additional thresholds were needed at zero and above the sensor measurement range, for example, 9999. Starting with Revision 5.0 the extra thresholds are no longer needed.
- The complete set of rising thresholds to be assigned is therefore: $L, (L^{0.5} + d)^2, (L^{0.5} + 2d)^2, \ldots, (L^{0.5} + (N-2)d)^2, U$

Falling thresholds—
The procedure is similar to that for rising thresholds, except guidelines for determining *L*, *U*, and *N* are slightly different, and thresholds are assigned in descending order in the Campbell TTS program.

- *L* should be a value that is at or above typical interstorm turbidity values. In small streams it should be a value that is expected to occur before the stage falls enough to expose either the turbidity sensor or the pumping sampler intake. It is best to choose a different *L* for falling turbidity than for rising turbidity. Otherwise it is likely that, in a small storm event where only the lowest rising and falling thresholds are exceeded, only two samples would be collected, both at nearly the same turbidity.
- *N* should be higher than that chosen for rising thresholds.
- *N* and *U* can be altered in a trial-and-error fashion to minimize redundancy between rising and falling thresholds. However, because samples are not taken precisely at the threshold turbidity, but occur only when the threshold has been passed for two intervals, the risk of resampling the same turbidity is not all that great of a concern. Samples are least likely to occur precisely at thresholds in rising turbidity conditions and at high turbidity levels in general, that is, when turbidity tends to change most rapidly.
- The complete set of falling thresholds to be assigned is:

$$U, (L^{0.5} + (N-2)d)^2, \ldots, (L^{0.5} + 2d)^2, (L^{0.5} + d)^2, L$$

Examples—

- Sensor range 0 to 500
  Rising (L = 10, U = 450, N = 10):
  10 27 51 84 125 174 231 296 369 450
  Falling (L = 15, U = 475, N = 17):
  475 427 382 340 300 262 227 195 165 137 112 90 70 52 37 25 15
- Sensor range 0 to 1000
  Rising (*L* = 15, *U* = 900, *N* = 10):
  15 46 94 158 240 338 453 585 734 900
  Falling (*L* = 20, *U* = 950, *N* = 17):
  950 851 758 670 587 510 439 372 311 256 206 161 122 89 60 37 20
- Sensor range 0 to 2000
  Rising (*L* = 20, *U* = 1850, N = 10):
  20 77 170 300 467 670 910 1187 1500 1850
  Falling (*L* = 30, *U* = 1900, N = 17):
  1900 1698 1507 1328 1160 1004 858 724 602 491 391 302 225 159 105 62 30

Simulating Turbidity Threshold Sampling—
The TTS algorithm can be simulated with any existing Campbell TTS data file and a few functions written in the R programming language. If you have already installed R for making data plots, then it is simple to add the simulation functions. These functions and instructions for installation and usage can be obtained from the TTS Web page. The package provides the capability to read a raw TTS data file and determine when sampling would have occurred for a hypothetical set of thresholds. A plot can be produced that shows the record of stage, turbidity, and simulated pumped samples. Many of the program parameters specified in the TTS program can be altered for the simulation to determine optimal settings.

The package provides the capability to read a raw TTS data file and determine when sampling would have occurred for a hypothetical set of thresholds.

Entering Thresholds in the Campbell TTS Program

Copy the thresholds into Sub 7 of the CR510/10X program or Sub Initialize of the CRBasic program. The rising thresholds are entered from lowest to highest. In older versions before TTS Rev. 5.0, the values 0 and 9999 must be included. The falling thresholds are entered from highest to lowest. In the CR510/10X program, eight thresholds are entered per Bulk Load statement; the ninth parameter is the starting address in memory where the previous eight values will be stored.

The number of thresholds must also be entered in Sub 7 or Sub Initialize, where nfalling (or nFalling) and nrising (or nRising) are assigned. In all of the above examples, the values entered are 10 and 17, respectively. (Before TTS Revision 5.0, the value 9999 would have been included in the counts but 0 would have been excluded).

Laboratory Procedures

Standard Methods

Two standard methods are widely cited in the United States for determining the total amount of suspended material in a water sample. They are:

- Method D 3977-97 (SSC), “Standard Test Methods for Determining Sediment Concentration in Water Samples” of the American Society for Testing and Materials (2000).
- Method 2540 D (TSS), “Total Suspended Solids Dried at 103° to 105°C” (APHA 1998).

The TSS method involves subsampling, whereas the SSC analytical method measures all sediment (above a minimum filter pore size) and the mass of the entire water-sediment mixture. The terms SSC and TSS are often used interchangeably in the literature to describe the concentration of solid-phase material suspended in a water-sediment mixture. However, the analytical procedures for SSC and TSS differ and may produce considerably different results for samples that have a high sand fraction. Gray et al. (2000) compared the SSC and TSS analytical methods and derivative data, and concluded that the SSC method is the more accurate and reliable.

Additional Recommendations

Standard procedures are not generally detailed enough for reliable laboratory implementation, and a detailed laboratory manual is usually required. The manual used at RSL is available upon request. This section discusses procedural details, some of which are specific to the RSL manual. Some of the procedures are nonstandard and, if the methods are adopted, should be noted as such in reports.

Marking water levels on sample bottles—
The water level in each sample bottle is marked in the field to monitor whether any of the sample is lost during transport to the lab. If any water is lost in transport, the error is noted and the bottle is refilled to the field mark with lab-grade or distilled water before processing (see “Lab-grade and distilled water” below).

Storing bottles—
Sample bottles should be stored at a cool temperature, and light should be excluded to inhibit algal growth.

Acidification—

Acidification is a nonstandard procedure applied to most samples processed at RSL. Three drops of 15 percent hydrochloric acid (equal parts muriatic acid and water) are added to samples in the field to reduce algal growth during storage. Acid should not be added to samples in which colloids may be naturally dispersed owing to electrostatic repulsion. Acidification will likely cause flocculation of such samples, altering effective particle sizes and turbidity. In naturally acidic samples from forest streams, however, there is little danger of physical alteration of the sample by acidification.

Gravimetric determination of sample volumes—

Determination of the sample volumes by gravimetric measurements is more precise than volumetric methods because analytical balances can measure to the nearest 0.1 g (0.1 ml H_2O at room temperature) or better, whereas volumes of 300 to 500 ml are measurable with resolution no better than 1 ml using volumetric flasks or cylinders.

Lab-grade and distilled water—

Lab-grade water is tap water that has been filtered for sediment particles. Optimally rinse water will be filtered to the pore size of the filters being used for SSC determination. If samples will be processed using the evaporation method, then distilled or deionized water may be required; otherwise dissolved solids in the tap water could contribute to the final sediment weight.

Filter pore sizes—

Various standards are used at different labs. The EPA typically uses 1.5-µ filters, whereas the USGS often uses 0.45- or 0.70-µ filters. Redwood Sciences Laboratory uses 1.0-µ filters. Sample processing time is directly related to the amount of fine sediment in the sample and the filter pore size. The filter pore size should be chosen with care, taking into account the watershed geology, organic transport, and study objectives. It is important to use the same filter pore size for the duration of the study and report filter pore size in published analyses because results of different studies, even in the same watershed, may not be comparable when methods are different.

Use of multiple filters—

The ASTM Method D 3977-97 (SSC) states “Even though a high-concentration sample may filter slowly, users should not divide the sample and use two or more filters.” Justification is not provided, but one might surmise that the motive has to do with consistency. Very fine particles will not be trapped on filters, but the effective filter pore size decreases during the filtration process. If a single filter is always used, then trap efficiency is only a function of concentration, filter type, and particle size distribution of the sample. Suspended sediment concentration determined with a single filter should therefore be more repeatable than with multiple filters, unless the precise amount of sediment on each filter is specified and controlled. However, complete filtration through a single filter in many cases is impractical or impossible as filter pores become plugged. Therefore, RSL procedures allow for the use of multiple filters.

Handling of prefilters—
Standard Method 2540 D (TSS) requires prerinsing filters with three successive 20-mL aliquots of reagent-grade water with vacuum assistance, then drying, desiccating, and weighing the filter to the nearest 0.0001 g. After recording the initial weight, additional rinsing, drying, and weighing is required until a constant weight of ± 0.0005 g is reached. Washing the filter before use removes small fibers that would otherwise be washed from the filter when the sample is vacuumed through the filter. This step precludes negative filter weights that would result from the loss of loose fibers. Also, glass fiber filters in most environments hold a small amount of ambient water. This water weight can only be removed by drying. In practice, multiple prefiltering steps are not generally needed to achieve a constant weight of glass-fiber filters, and routinely repeating prerinse cycles until a constant weight can be verified is burdensome relative to the benefit. The RSL procedures follow ASTM Method D 3977-97 (SSC) in requiring just one prerinse with vacuum assistance, followed by drying, cooling in a desiccator cabinet, and weighing.

Handling of organic matter and debris—
At RSL, organic matter is considered part of the suspended load and is not dissolved or burned off. Debris is not removed unless some dimension is greater than the diameter of the pumping sampler intake (1/4-in or 3/8-in [0.4-cm or 1.0-cm]). Any debris of a size that potentially could have been excluded by the physical size of the intake is removed during processing.

Any debris of a size that potentially could have been excluded by the physical size of the intake is removed during processing.

Settling and filtering the supernate—
For many samples, processing time can be reduced by settling the sample so that the supernate can be decanted and filtered ahead of the settled portion of the sample. Complete settling followed by suctioning of the supernate is required for efficient filtering of those samples that contain a large proportion of very fine sediment. Complete settling may take a week without disturbing the sample to allow the smallest particles to settle on the bottom of the bottle. Suctioning will speed up the filtering process tremendously, sometimes by hours.

Handling of manual, depth-integrated samples—

At RSL, sand fraction analysis is performed on all depth-integrated and pumped sample pairs to help identify depth-integrated samples that may erroneously include bed material, and to determine if a particle size bias is present in the pumped sample.

Quality coding—

Besides notes that may be recorded on lab sheets, RSL employs two codes that are saved with the data to provide information about the disposition and processing of each sample. The first code is a tracking code that indicates problems that may have occurred before a sample was processed, for example, lost or discarded samples or labeling problems. The second code identifies various sample attributes and processing problems, such as the presence of organics, spillage, and weighing errors. Assigning an appropriate code can be a subjective task. Understanding how the codes will ultimately be used can help lab technicians make better judgments about code assignments.

Evaporation Method

The ASTM Method D 3977-97 (SSC) includes procedures for evaporation as well as filtration. For a given sample, evaporation is the preferred method when filtration would require multiple filters. Evaporation produces higher concentrations than filtration (for the same sample) because results can include very fine particles that pass through filters. If a group of samples is to be processed (the usual situation), it may be preferable for consistency and simplicity to process high-SSC samples with multiple filters. However, when concentrations are very high, it becomes impractical to use the filtration method.

Decanting—

Decanting of samples that are to be processed with the evaporation method is not done by pouring because it will disturb the sediment that has settled on the bottom of the bottle. Using a J-tube on the end of a vacuum hose will remove most of the supernate with very little disturbance of the sediment layer. Removal of supernate is important so that all of the sediment and rinse water will fit into a single dish for evaporating. Using pressurized rinse water reduces rinse water volumes.

Filtering and subsampling the supernate—

Because evaporation leaves dissolved as well as suspended solids, the ASTM procedure requires subsampling the supernate after the sediment has settled to compute a dissolved-solids correction factor. We also filter the supernate before subsampling, in case the supernate contains suspended clays, and include this filtered sediment in the total SSC.

Laboratory Turbidity

Understanding your lab turbidimeter and applying a consistent procedure is important when reading the turbidity of samples in the laboratory. Samples from different locations may behave differently owing to differences in soil composition (especially particle size and shape) and organic matter content. The basic procedure for measuring turbidity in the laboratory at RSL is to:

- Agitate the sample.
- Record the first value displayed (to limit settling time).
- Repeat the above steps two times.
- Compute and record the average of the three individual readings.

Laboratory turbidity can be useful for validating or reconstructing field turbidity measurements (e.g., when turbidity exceeded the field sensor's range). A relation between lab turbidity and SSC can be established from a subset of samples collected at fixed time intervals, then used to estimate SSC for the remaining samples.

Subsampling—
To measure laboratory turbidity, a small volume of the sample must generally be extracted from field samples for placement in the turbidity meter. This is best done before analyzing samples for SSC, but the turbidity subsample must be rinsed back into its original container before SSC is determined. Therefore, it is important to determine the original sample volume before subsampling. Subsampling is an imprecise process, but measures can be taken to maximize the probability of achieving a representative sample. Samples should be swirled, not shaken, to prevent introduction of air bubbles into the subsample. Special pour spouts can aid in transferring samples quickly with minimal spillage, but pouring should always be done over a clean pan, so any spillage can be recovered.

Dilution—
When turbidity exceeds the range of the lab meter, it may be necessary to dilute samples to obtain an estimate of turbidity. A convenient procedure is to split the turbidity subsample into two subsamples of about equal volume, and add water until each diluted subsample is the same volume as the original subsample. The final turbidity will be the average of the turbidity of each diluted subsample, multiplied by the dilution factor: $[(a + b) \div 2] \times 2 = a + b$, which is simply the sum of the two turbidity values.

Dilution should be avoided if an alternate method is available, because it does not always reduce turbidity proportionally to the dilution factor. Uncorrected results from dilution cannot be expected to be accurate without experimental validation. Experimentation at RSL has shown that results of dilutions by the above procedure can result in a value 30 percent too low. Section 6.7 of the "National Field Manual for the Collection of Water Quality Data" recommends that at least three dilutions be made, at about 80, 50, and 20 percent of the original concentration (Anderson 2004). If the turbidity is linearly related and positively correlated to the percentage diluted, then the relation can be used to estimate the concentration at 100 percent. If the response is nonlinear, alternative instrument designs that compensate for interferences should be considered. Turbidity values that are obtained by dilution should be appropriately documented and reported with qualification.

Data Processing

When the data have been collected in the field and uploaded to your computer, the work has only just begun. Stage data are subject to errors because of transducer drift and other calibration problems, debris and obstacles in the channel, and changes in channel form such as deposition, scour, and bank erosion. Turbidity data are subject to errors because of drift and other calibration problems, interference from debris, algae, bugs, bed load, the water surface, nearby objects, bubbles, and sunlight. Problems with batteries, connections, and electrical cables can result in periods of missing data due to loss of power. Occasional failures of sensors are to be expected. Finally, user errors when interacting with the program and hardware often result in lost data. It is essential to carefully document actions and observations taken in the field to understand and cope with data problems later.

Raw Data Plots

It is a very good practice to assemble a binder containing raw data plots, annotated with notes from the field. Annotations should include information such as:

- Turbidity sensor submerged or not submerged
- Turbidity sensor cleaned
- Debris removed from boom or housing
- Work performed in the stream channel
- Sediment removed from flume, stilling well, or cross section
- Sensor offset changed
- Sensor moved
- Equipment changes or problems
- Any data spikes caused by field crew

- Staff plate readings, if the software does not automatically show them
- Data corrections that will be needed, with explanations

Each plot should contain no more than 1 to 2 weeks' data to clearly view details. It is very useful to include both stage and turbidity as well as sample bottles and observer staff plate readings. Additional plots of storm events are also very helpful. Choose a scale that is reasonable for the data. Inappropriate scales can hide important information. Perceptions of the slope of line segments are optimized when absolute values of the orientations are centered on 45 degrees (Cleveland 1993).

Choose a scale that is reasonable for the data. Inappropriate scales can hide important information.

Software for plotting and correcting raw data—
Because of the large number of data plots needed, it is inefficient to create graphs one at a time using a program like Excel or SigmaPlot. A customized script, function, or program can quickly produce plots with a single command or user action. The RSL has developed two methods for creating customized plots, and, at the time of this writing, a commercial system is under development by FTS.

***TTS Data Plotting*—**Developed in R, TTS Data Plotting was designed to quickly read and plot raw data in the field. The program displays raw stage, turbidity, and sample bottles directly from a raw or corrected data file as illustrated in the following example (fig. 23). It can also display corrected stage and turbidity, discharge, rainfall, and water and air temperature from appended and corrected data files. Installation instructions and software can be found on the TTS Web page.

***TTS Adjuster*—**The second program, TTS Adjuster, written in Java, reads and displays raw Campbell data, corrected data, lab sediment concentrations, observer staff plate readings, and electronic field notes. Figure 24 is an example plot showing raw and corrected stage and turbidity data, staff plate readings, and the timing of pumped samples. The TTS Adjuster also appends multiple raw data files and allows the user to adjust and correct errors. The result is one file, in a specific format, for each station and year containing both raw and corrected data, and codes identifying the types of corrections applied. Installation instructions, software, and other documentation can be found on the TTS Web page.

***StreamTrac*—**There is also a processing program called StreamTrac for sale by FTS. The FTS program is a full-featured system, designed to work with TTS data collected by either the Campbell or FTS versions of TTS. The software is designed for maximum flexibility, includes most of the features of TTS Adjuster, and is capable of computing sediment loads.

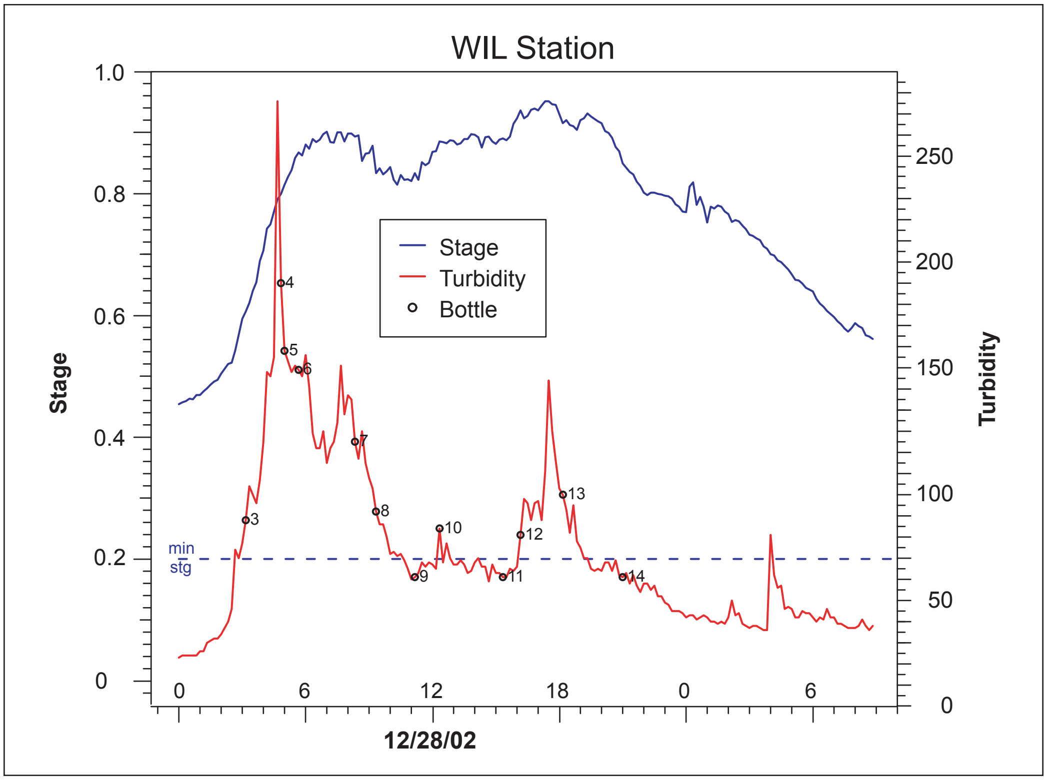

Figure 23—Example of a graph produced by TTS Data Plotting for displaying raw data.

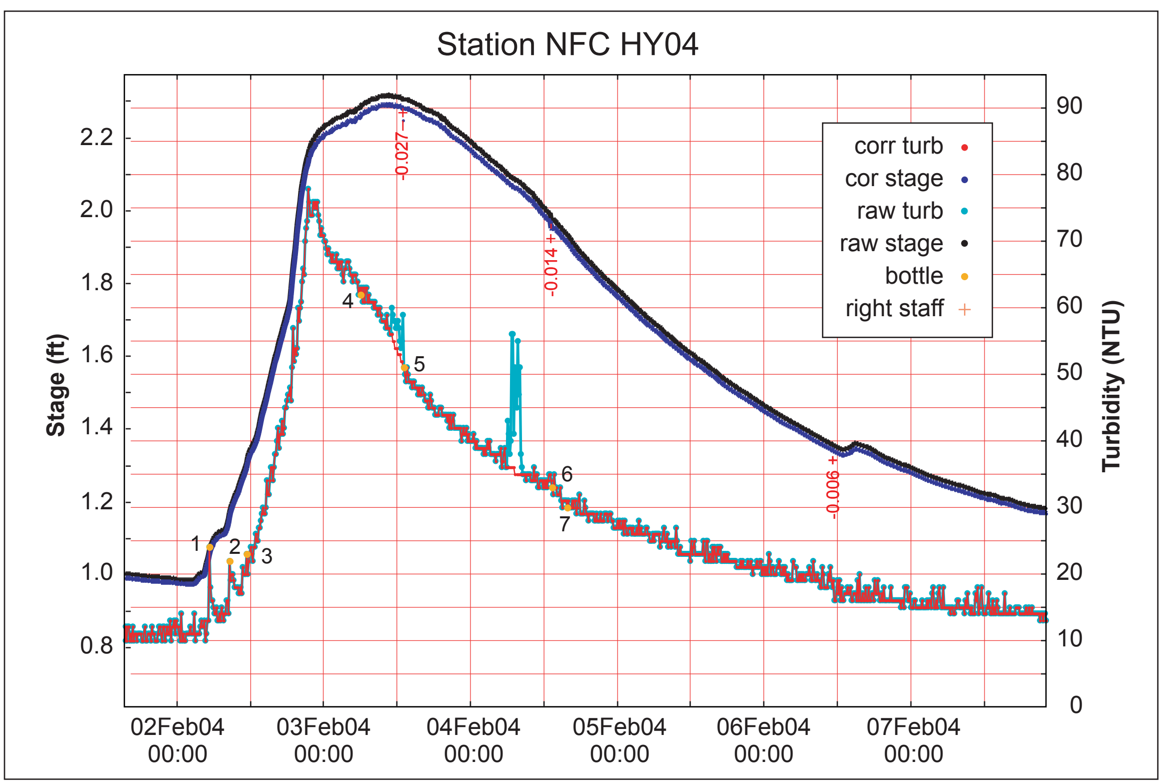

Figure 24—Example of a graph produced by TTS Adjuster for data correction and adjustment.

Laboratory Data

Because lab data entry errors are propagated through all sediment analyses, it is important that all data entry be double-checked. It is a good practice to enter the data twice, each time by different individuals, and then resolve all differences between the two data sets by using the lab sheets to eliminate errors. The following information pertaining to pumped samples should be recorded:

1. Station
2. Water year
3. Dump number (incremented each time bottles are removed from pumping sampler)
4. Bottle number (starting at one within each dump)
5. Initial bottle weight (containing sample)
6. Final bottle weight (tare)
7. Total number of filters used in processing sample
8. Filter number
9. Initial filter weight (tare)
10. Final filter weight (including oven-dried sample)
11. Particle size class (if sample has been sieved)
12. Quality code (denotes conditions such as the presence of organic particles, low volume, spillage, and other lab errors)

The date and time of pumped samples need not be entered, because that information is recorded for each dump and bottle number in the electronic file from the data logger. For depth-integrated samples, all of the above information is needed, as well as the following:

13. Date and time, or matching pumped sample dump and bottle number
14. Location(s) in the cross section (if multiple verticals are sampled)

Several filters are used if a sample contains large quantities of sediment or if information about grain size distribution is needed. In the latter case, the sample would be sieved one or more times to separate it into different size classes, each of which would be separately filtered. Items 7 through 12 in the above list would be entered for each filter that originated from the same bottle. The quality code could include many levels for various types and severity of conditions, or it might be broken into several codes, each denoting the severity of a particular type of condition. The suspended sediment concentration is computed according to the following formula:

$$SSC = \frac{m_s}{V_w + V_s} = \frac{m_s}{\frac{m_w}{\rho_w} + \frac{m_s}{\rho_s}} = \frac{m_s}{\frac{m_{w+s} - m_s}{\rho_w} + \frac{m_s}{\rho_s}} \quad (1)$$

where
m_s = mass of sediment
m_w = mass of water
m_{w+s} = mass of whole sample (water and sediment)
V_w = volume of water
V_s = volume of sediment
ρ_w = density of water
ρ_s = particle density of sediment

If masses are measured in grams and densities in grams per cubic centimeter, multiplying by 10^6 will convert results from grams per cubic centimeter to milligrams per liter. The mass of sediment, m_s, is obtained from the difference between initial and final filter weights, summing over all pertinent filters. The mass of the whole sample, m_{w+s} , is obtained from the difference between final and initial bottle weights. The density of water can be assumed to be 1.00 g/cm^3 and the particle density of the sediment is often assumed to be 2.65 g/cm^3, which is an approximate average for the dominant soil minerals: quartz, feldspars, micas, and clay minerals (Donahue et al. 1977). However, an accurate value of particle density can be determined from a sample's mass and volume by using a pycnometer (Black 1965).

The mean cross-sectional SSC from multivertical depth-integrated samples collected by using the equal transit-rate method can be computed by compositing m_s and m_{w+s} for all the bottles collected before applying equation (1) above (Guy and Norman 1970).

Processing the Stage Data

Before computing the sediment load, it is desirable to have as accurate a record of water discharge as possible. Any errors in water discharge will translate directly into errors of equal magnitude in sediment load. Discharge is computed from the electronic stage record by using the discharge rating equation. The electronic stage record is computed by applying a calibration equation to the output from the stage sensing device. Various sources of error in stage are possible:

Any errors in water discharge will translate directly into errors of equal magnitude in sediment load.

- The slope or intercept of the sensor calibration can be incorrect.
- The stage can be artificially elevated by obstructions such as woody debris, sediment, or sampling devices temporarily placed in the discharge measurement section.
- The stage may be missing (defective sensor or electronic or human failure).

In case 1, the stage record can generally be adjusted to give correct values. In cases 2 and 3, a reconstruction is needed by interpolation or with reference to a nearby gaging site.

Adjustments for stage sensor calibration problems—

***Time-variable shifts*—**Usually, it is the intercept rather than the slope of the calibration that causes incorrect stage readings. The most common causes of intercept errors are incorrect entry of the intercept in the data logger program and change in the vertical placement of the sensor. These errors result in a constant shift in the stage data. If the problem is that the intercept is drifting gradually, a time-variable shift can be applied by prorating the differences between observer and electronic stages over time. In either case, the stage usually can be adjusted to match staff plate readings (observer stages) recorded by field personnel. If the drift is assumed to be linear with time, the corrected stage, E_t', can be computed by using:

$$E_t' = E_t + \frac{(O_1 - E_1)(t_2 - t) + (O_2 - E_2)(t - t_1)}{t_2 - t_1} \tag{2}$$

where

E_t = electronic stage at time t, where $t_1 \leq t \leq t_2$

E_1 = electronic stage at time t_1

E_2= electronic stage at time t_2

O_1 = observer stage at time t_1

O_2 = observer stage at time t_2

If $O_1 \neq E_1$ and $O_2 \neq E_2$, then, in TTS Adjuster, the correction must be done in two steps, by shifting first at one boundary and then the other. Equation 2 is then applied twice. In the first step, we have $O_2 = E_2$, and in the second step, we have $E_1 = O_1$, and E_t is replaced by E_t' from the first step. The effect is equivalent to a single application of the equation as written.

Y-*proportional shifts*—If the slope of the calibration is incorrect, the differences between the observer and electronic stages will be a function of stage height. In this case, a y-proportional shift is required. The corrected stage, E_t', is computed by using:

$$E_t' = E_t + \frac{(O_1 - E_1)(E_2 - E_t) + (O_2 - E_2)(E_t - E_1)}{E_2 - E_1} \tag{3}$$

As with time-variable shifts, if $O_1 \neq E_1$ and $O_2 \neq E_2$, then, in TTS Adjuster, the correction must be done in two steps, by shifting first at one boundary and then the other. Equation 3 is then applied twice. In the first step, we have $O_2 = E_2$, and in the second step, we have $E_1 = O_1$, and E_t is replaced by E_t' from the first step. The effect is equivalent to a single application of the equation as written.

Stage adjustment philosophy—

***Precision considerations*—**The electronic stage data are more precise than manual readings of stage. Therefore, it is to be expected that discrepancies will routinely be found between electronic and manual stages. Staff plate readings are rarely more precise than 0.5 cm, and precision declines with increasing stage owing to wave action and turbulence. Precision can be improved by reading the stage in a stilling well, but precision is still significantly less than that of an electronic device such as a pressure transducer. Therefore, we do not recommend routinely adjusting all electronic data to agree with observer records.

***Accuracy considerations*—**Adjustments should only be made when there is a systematic bias in one direction. If the differences between electronic and manual stage data are as often positive as negative, without a systematic temporal pattern, and if they fall within the precision of the manual stage readings, then it is best not to adjust the data. If the differences are consistent in sign, then an adjustment may be warranted.

***Application of constant and time-variable shifts*—**If there is no trend in the magnitude of the differences, it is probably best to estimate an average difference, and apply that average as a constant shift. If there is a consistent time trend in the magnitude of the differences, then it is appropriate to apply a time-variable shift over the duration of the trend. If there is a nonlinear time trend, then it is appropriate to apply time-variable shifts between consecutive pairs of observer records.

Application of* y*-proportional shifts*—Y*-proportional shifts are only appropriate if it is known that an erroneous calibration slope was applied. If there is no evidence that the slope error changed over time, then it may be best to apply a single *y*-proportional shift over the duration of the erroneous data, rather than applying separate shifts between each consecutive pair of observer records.

***Interpolation of missing data*—**Short periods of missing data can often be adequately filled by linear interpolation. Whether or not linear interpolation will be satisfactory depends on a consideration of hydrologic conditions at the time. If there is a change of direction in the hydrograph, or if the period of missing data is lengthy, then a linear interpolation is not appropriate.

***Reconstruction of missing data*—**Reconstruction of missing data from another hydrograph is usually the best way to repair a record when linear interpolation is inappropriate. The hydrograph may be from another station or, during recession periods, from another time period at the station being repaired. Reconstructions can be reliable and realistic if the missing stage data are strictly increasing or decreasing. The basic method is to rescale another hydrograph segment so that it is continuous with the endpoints of the segment being repaired. Reconstructions can be constrained to agree with intervening observer readings by proceeding in a piecewise fashion between consecutive pairs of observer readings.

***Reconstruction methods employed by TTS Adjuster*—**These methods copy a section of the record from the reference station into the segment being reconstructed. The curve is rescaled to be continuous with the existing data at both segment boundaries. The scaling is based only on the stage or turbidity at each segment boundary and the corresponding values at the reference station. The segment being copied should have approximately the shape that you want to transfer. It need not start at the same stage, turbidity, or time as the start of the segment being reconstructed.

1. Linear relation: This method assumes a linear relationship between the responses at the two stations.
2. Quadratic relation: This method treats the ratio of responses as a linear function of the response at the reference station. It is equivalent to a quadratic relationship (with no intercept) between the responses at the two stations.
3. Time-linear ratio: This method treats the ratio of the responses as a linear function of time.
4. Time-linear difference: This method treats the difference in turbidity or unit-area discharge as a linear function of time.

The choice between these methods is ultimately determined by comparing the results of each to records from similar hydrologic periods, but some generalities can be made. If all the missing discharges are bounded between the starting and ending values, the first method is usually satisfactory. If not, the second method usually produces more reasonable results for lower discharges. The third method sometimes works when the first two fail, because it restricts the discharge ratio to values between the starting and ending ratios. The fourth method is an alternative that will often behave similarly to the third method.

If all four methods fail to produce reasonable results, it is probably because the missing discharges are not between the starting and ending values. In that case, it may be necessary to fit a relationship that includes additional discharge pairs from other hydrographs: pairs that encompass the range of discharges being predicted. However, unless the relationship is forced to pass through the data pairs at either end of the gap, there is no guarantee that the resulting hydrograph will be continuous at the boundaries of the reconstructed period.

To obtain the stage for reconstructed periods, reconstructed discharges must be converted back to stage height by inverting the discharge rating equation. For equations that cannot be algebraically inverted, this might require the use of numerical methods. The Newton-Raphson method (Chapra and Canale 1988) finds the roots of a univariate function and converges very rapidly for smooth discharge rating equations when a starting guess is taken from the nearest known stage on the hydrograph.

When the missing data are not strictly increasing or decreasing, reconstruction by simply rescaling another hydrograph is much less reliable.

Reconstruction of peaks and other nonmonotonic segments—
When the missing data are not strictly increasing or decreasing, reconstruction by simply rescaling another hydrograph is much less reliable. Independent estimates of the missing peaks and other local minima and maxima may be needed to ensure a trustworthy result. Observer readings can be invaluable in this regard. Peaks should be reconstructed from a nearby gaging site by using a method that accounts for the difference in watershed areas (e.g., method 3 or 4 in TTS Adjuster).

Documentation

It is important to document changes to the raw data. Users of the data must be able to distinguish raw data from corrected and adjusted data. The TTS Adjuster produces a data file with both raw and corrected data, so any user can readily observe differences, and it includes a data column identifying the type of correction performed, if any:

- Unedited, good data
- Unedited, questionable data
- Bad data, replaced with missing value
- Constant shift
- Variable shift
- *y*-proportional shift
- Linear interpolation
- Reconstruction from another site
- Freehand reconstruction

It is also a good practice to document corrections and their rationale via handwritten annotations on the raw or corrected data plots, or both. The FTS processing software, StreamTrac, will allow users to place text boxes on plots and either hide or display them for printing.

Converting Stage to Discharge

Development of a rating curve—

The accuracy of computed sediment loads is limited by the accuracy in discharge, so it is important to establish a high-quality stage-discharge rating curve if stage is not measured in an engineered device such as a weir or flume. Development of stage-discharge relations in open channels requires that a range of discharges be measured by using a current meter (Buchanan and Somers 1969). The number of discharge measurements required to achieve any given level of accuracy depends on many factors, including the equipment used, the skill of the hydrographer, flow depth, channel shape, rate of change of flow, and the stability of the cross section. An ongoing program of regular measurements should be undertaken to detect shifts in rating curves in response to changes in channel geometry near the measurement section (Kennedy 1983).

It is important to establish a high-quality stage-discharge rating curve if stage is not measured in an engineered device such as a weir or flume.

Fitting a stage-discharge rating curve—

Curve fitting requires a great deal of judgment and consideration of hydraulic factors that can cause bends and breaks in rating curves (Kennedy 1984). The availability of regression software on every desktop becomes a disadvantage if it promotes the use of oversimplified rating curves. The USGS employs rating tables, not simple equations such as power functions, for calculating discharge (Kennedy 1983). Given the computing power available today, more consideration should be given to nonparametric curve fitting methods, such as locally weighted regression, also known as loess (Cleveland 1979, Cleveland and Devlin 1988, Cleveland et al. 1988). Loess is flexible enough to fit smooth functions of arbitrary shape, and it can be implemented as a table if predictions need to be made in an environment outside that of the curve-fitting software. Loess is available as part of the "modreg" package with R, a free software package for exploratory data analysis, statistical computations, and graphics.

An ongoing program of regular measurements should be undertaken to detect shifts in rating curves in response to changes in channel geometry near the measurement section.

***Complex ratings*—**A simple relation between stage and discharge may not exist at sites where the water-surface slope is variable owing to variable backwater or variable storage caused by a shifting downstream control (Kennedy 1984). In such situations, a plot of stage versus discharge may plot as a loop, and complex ratings are required that involve an additional variable such as change in rate of stage, water surface slope, or index velocity.

***Quality assurance of streamflow records*—**The following standards were adopted by the New Zealand Water Resources, Department of Scientific & Industrial Research, for measurement of discharge and rating curve construction (Maidment 1993):

- Stage-discharge rating curves shall invariably express the stage-discharge relation objectively and shall therefore be tested for absence from bias and goodness-of-fit in periods between shifts of control, and for shifts in control. (ISO standard 1100/2-1982, clause 7.1)
- 95 percent of all flows estimated from a stage record with a rating applied shall be within 8 percent of the actual values.

***Standard procedures*—**Maidment (1993) listed the following sources of standard procedures for streamflow data:

- ISO Handbook 16 (ISO 1983)
- WMO Technical Regulations, vol III (WMO 1988)
- WMO Guide to Hydrological Practices (WMO 1981)
- USGS Water Supply Paper 2175 (Rantz 1982)
- Relevant chapters of *Techniques of Water Resources Investigations of the U.S. Geological Survey*

Processing the Turbidity Data

Adjustments for turbidity sensor calibration problems—
Procedures for solving turbidity sensor calibration problems are exactly analogous to those for stage sensor calibration problems. The only difference is that manual readings for turbidity are not generally available unless a portable turbidimeter is employed at field visits, or unless lab turbidities are recorded on some or all pumped samples. In either case, there are two problems that must be dealt with:

1. It is difficult to extract representative subsamples from pumped samples with high turbidity.
2. Portable and lab turbidimeters cannot be expected to produce equivalent results to field turbidimeters except under low-turbidity conditions (<10 turbidity units).

It may be possible to deal with the second problem by establishing a relationship between turbidimeters. Unfortunately, it is difficult to establish a relationship that can be regarded as unique and unchanging for any given pair of turbidimeters (Lewis et al. 2007). Such relationships depend on the type of suspended material (mineralogy, organic content, particle size, etc.).

***Turbidity adjustment philosophy*—**The difficulty of representative subsampling is probably serious enough that it is not fruitful to attempt minor shifts in the turbidity record based on manual readings of high turbidity in pumped samples. Our recommendation is to apply shifts based only on manual readings of low turbidity samples below about 10 turbidity units, unless it is known that there was a serious calibration error. Keep in mind that calibration errors are unimportant if the only use of the turbidity data is to determine sediment loads. For sediment load calculations, it is only important to know the relationship between measured turbidity, with or without calibration errors, and SSC. Calibration errors are important only if the monitoring objectives require that a consistent and uniform turbidity record be collected, for example, for comparison with other streams.

Calibration errors are unimportant if the only use of the turbidity data is to determine sediment loads. For sediment load calculations, it is only important to know the relationship between measured turbidity, with or without calibration errors, and SSC.

Validating the turbidity record—

There are two primary tools needed to validate the turbidity record: first, a knowledge of typical patterns of turbidity in relation to hydrographs, and second, corroborating SSC or turbidity data from lab measurements, redundant field measurements, or data from upstream and downstream gaging sites. Examining scatterplots of pumped sample SSC versus field turbidity is probably the most typical means of validating questionable turbidity peaks.

***Typical turbidigraphs*—**Recognition of typical and atypical turbidigraphs comes from experience in examining such records from a particular gaging site, but some generalities can be stated (fig. 25).

- Turbidity generally rises more rapidly than it falls (all examples in fig. 25)
- Falling turbidity usually exhibits a smooth exponential decay similar to flow (fig. 25a–c and 25e).
- In most but not all watersheds, turbidity peaks at or before the streamflow peak (all examples).
- When stage and turbidity data are overlaid on similar scales, it is common for turbidity to fall from its peak more steeply than stage (fig. 25a–b and 25e).
- Turbidity often starts to decline during rising hydrographs when the rate of increase in stage declines (fig. 25a–c, 25e, and 25f).
- Corresponding turbidity peaks typically decline for a series of similar discharge peaks (fig. 25c).
- Short-duration turbidity pulses are commonly superimposed on the recession of a turbidigraph, indicating sediment delivery from local streambanks or hillslopes (fig. 25d–e).
- Turbidity can be somewhat erratic, especially during rising and peak conditions (fig. 25e–f). These are the most difficult data to validate. Corroborating data are invaluable during such periods.

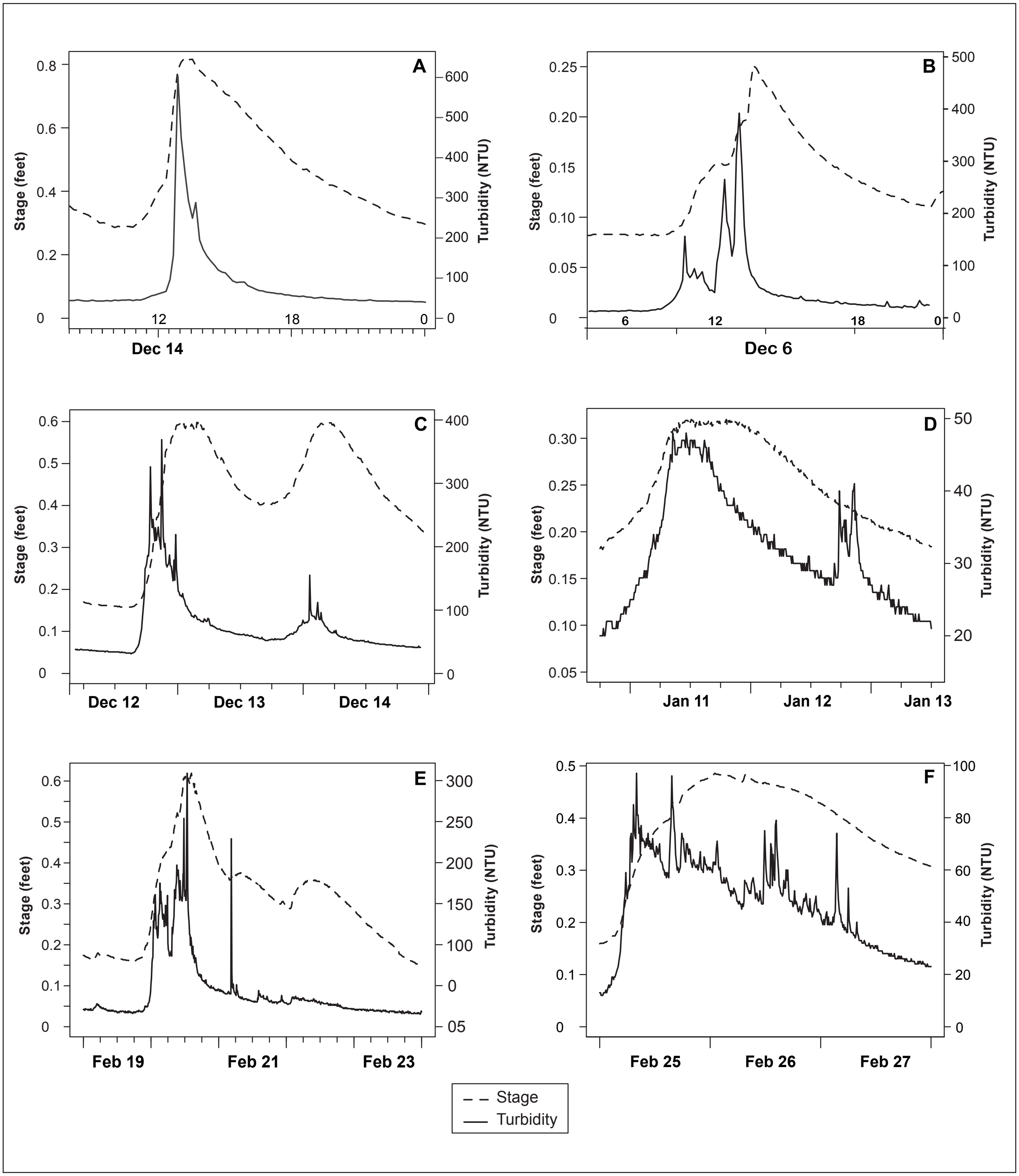

Figure 25—Examples of storms illustrating good-quality turbidity data.

Problem identification—

***Progressive fouling*—**This condition is caused by the gradual buildup of sediment, algae, or fine debris on the optical window of the sensor, or a surface visible to the sensor. The turbidity gradually flattens or increases while streamflow is receding or low, then it suddenly drops when the sensor is cleaned (fig. 26a). Progressive fouling can generally be avoided by deploying sensors that use a mechanical method to remove the contamination.

***Debris fouling*—**Debris fouling from twigs, leaves, and other objects usually causes upward spikes and erratic fluctuations in turbidity until the debris is dislodged. Spikes are often very brief, after which turbidity may drop suddenly to levels present before the problem occurred (fig. 26b). Samples collected during spikes due to debris fouling are located to the right of the general trend on plots of SSC versus turbidity (fig. 26c).

***Direct sunlight*—**Some sensors are affected by direct sunlight. The altered signal is site specific, but a characteristic wave of similar duration and shape is superimposed on successive sunny days. The waveform may include both a spike and a dip (fig. 26d).

***Air bubbles*—**Air bubbles caused by turbulent flow may produce high-frequency noise on the turbidity record. The amplitude of the fluctuations generally increases with increasing flow (fig. 26e).

***Nonsubmergence*—**Nonsubmergence of the sensor often results in a decrease in turbidity. This can be caused when high flow raises an inadequately weighted boom to the water surface. Nonsubmergence can also occur when there is inadequate flow to cover a sensor. This condition creates a temporary rise in turbidity while the sensor is partially submerged, followed by depressed turbidity while the sensor is suspended in the air (fig. 26f–g). The characteristic pattern that appears when a sensor is being exposed may often be seen in reverse when the sensor is again submerged. The rising pattern will often be compressed in time because the stage generally rises faster than it falls.

***Bed load and burial*—**When a sensor is partly buried by bed load or is in the saltation zone, it usually results in a very noisy pattern similar to debris fouling (fig. 26h). Spikes can be equally steep on the rising and falling side. To identify bed load influence, it is helpful to examine scatterplots of SSC versus turbidity (fig. 26i) and particle size distributions of pumped samples. Assuming the pumping sampler intake is also in the bed load zone, scatterplots will show outliers both above and below the general trend, and pumped samples are likely to be enriched in sand. These situations can be challenging to resolve. In the example (fig. 26h), there were no samples collected during the large spike after sample 24 because pumping sampler capacity had been reached. The shape of that spike is plausible, but the weight of evidence points to continued fouling:

- The previous 9 hours' data was apparently disturbed by bed load.
- It is a very large spike for a relatively calm period in the hydrograph.
- After the spike, sample 1 is again an outlier with high SSC.

Interference from channel—
Interference from the channel boundaries or objects such as wood in the channel is not always obvious because the general pattern of turbidity may be quite reasonable. An indication of this problem is when there is a poor relation between turbidity and SSC despite a reasonable turbidigraph that looks valid in other respects (fig. 26j–k).

Interference from water surface—
When the water surface is visible to the sensor, reflected light can cause an elevation in apparent turbidity. This may be partly responsible for characteristic patterns associated with exposure and resubmergence of sensors at low flows, as illustrated in the paragraph on nonsubmergence.

Adjusting Point Suspended Sediment Concentration to the Cross Section Mean

A well-designed study plan will require that paired simultaneous pumped and depth-integrated samples are collected over the full range of flows and turbidities.

Before estimating sediment loads, one must decide whether the point SSC obtained from pumped samples should be adjusted to be more representative of the entire stream cross section. When multiplying SSC by flow, it is assumed that SSC is a discharge-weighted mean concentration. That is, each SSC in the cross section is weighted by the local discharge when computing the mean. A well-designed study plan will require that paired simultaneous pumped and depth-integrated samples are collected over the full range of flows and turbidities. Therefore, when the time comes to compute sediment loads, one can examine the relation between the two types of samples to determine whether an adjustment to the point SSC is needed.

An adjustment to the point SSC is warranted when:

- There is a statistically significant difference between point and depth-integrated concentrations, and
- The prediction error is smaller than the error being corrected.

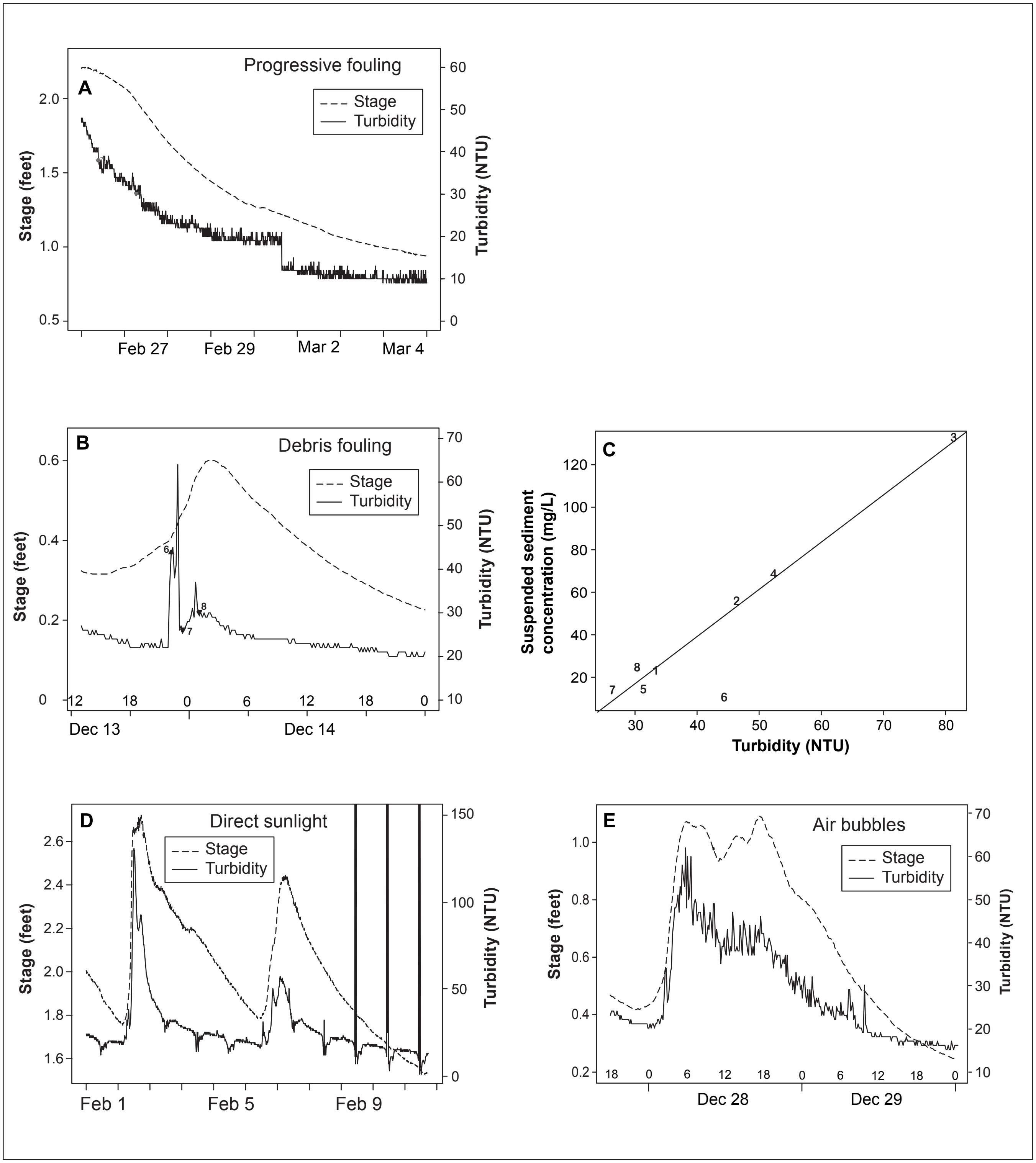

Figure 26—Examples of storms illustrating poor-quality turbidity data.

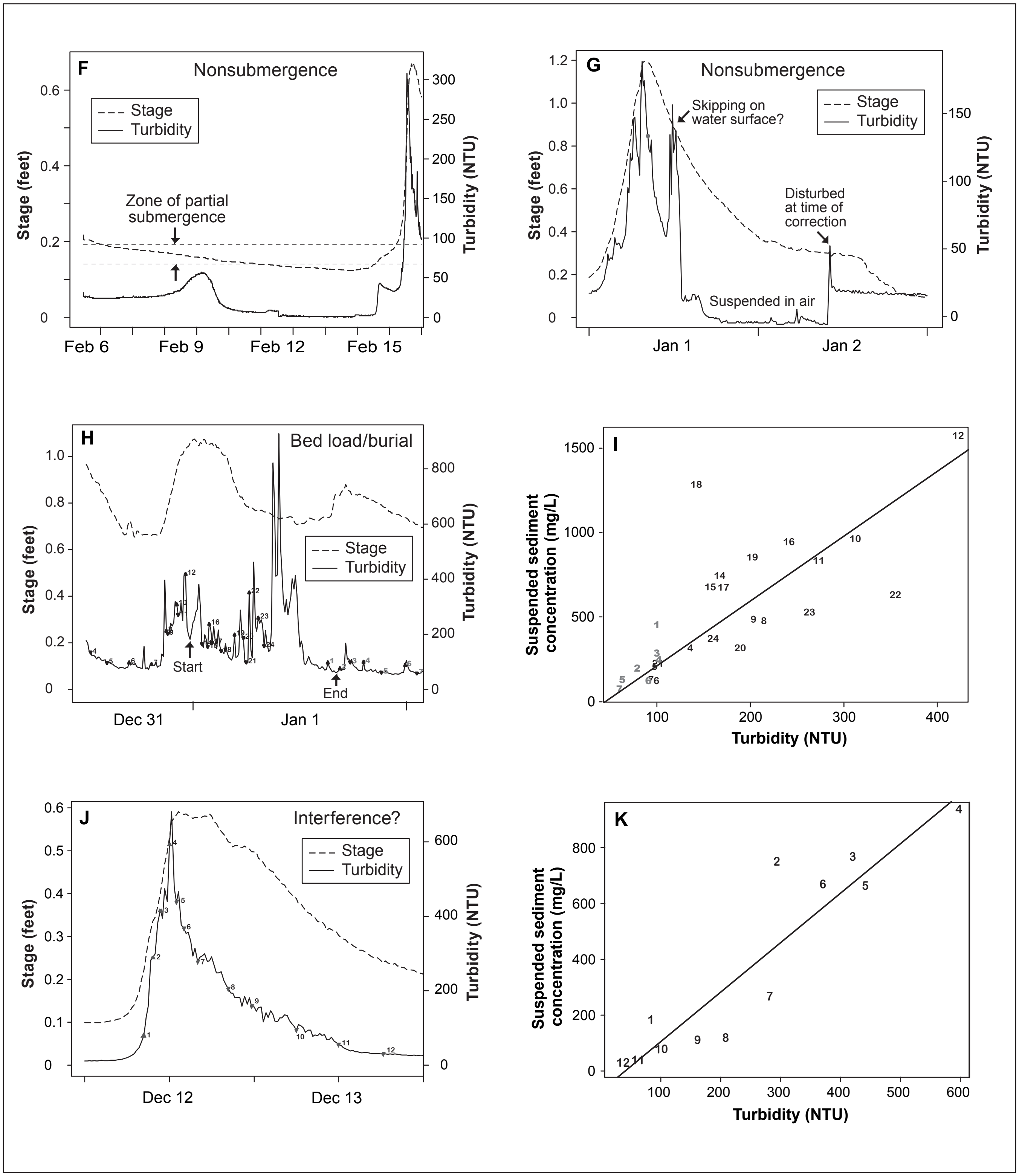

Figure 26—Examples of storms illustrating poor-quality turbidity data (continued).

F-test—
Before testing for a significant difference, egregious outliers should be removed, as they are likely to be the result of operator error in collecting manual samples. A common error, for example, is to enrich the sample by stirring up sediment when the sampler contacts the streambed. Cook's distance is a standard statistic that can help identify outliers with undue influence on the regression coefficients. An F-test can be used to determine whether there is a statistically significant difference between a simple linear regression line and a line of perfect agreement ($y = x$). The appropriate F-statistic is:

$$F = \frac{(\mathrm{SSW} - \mathrm{SSE})/2}{\mathrm{SSE}/(n-2)} \tag{4}$$

where $\mathrm{SSW} = \sum (y_i - x_i)^2$, $\mathrm{SSE} = \sum (y_i - \hat{y}_i)^2$, and $\hat{y}_i$ denotes the fitted (predicted) values. The F-statistic is compared to the $F(2, n - 2)$ distribution.

Transformations—
The F-test requires that the regression have normally distributed residuals with independent errors unrelated to x. If residuals are greater for larger values of x, it may be appropriate to transform both x and y before computing the regression. The most commonly useful transformation is the logarithm. The major drawback of the logarithmic transformation is that it cannot be applied to zero. If a logarithmic transformation is applied to the data, then a correction must be made after making predictions, when retransforming back to the original scale. The simplest method is the Baskerville (1972) correction, also known as the quasi maximum likelihood estimate, which requires multiplying the back-transformed prediction by the factor $\exp(0.5s^2)$, where exp denotes exponentiation to the base e of the natural logarithm, and $s = (\mathrm{SSE}/(n - 2))^{0.5}$ is the residual standard error from the transformed regression.

Prediction error—
If the prediction error is greater than the error of using an unadjusted point concentration, then more error may be introduced by making the adjustment than not. Prediction error, in this context, is that error due to uncertainty in the regression coefficients, and can be assessed by looking at confidence bands around the regression line. If the confidence bands enclose the line $y = x$, then it is better not to introduce further error by adjusting the data. Generally, the confidence bands will not enclose the line if the F-test was significant at the same level of confidence.

Shifting relationships—

It is important to be aware that the relationship between pumped and isokinetic sample concentrations might shift over time. This would likely occur with a change in channel morphology or other factors affecting turbulence at the pumping site. Therefore, it is a good idea to examine the relationship for different periods. If the relationship is shifting, then it may be necessary to use different relationships for different periods. Doing so reliably, however, requires a large number of paired samples. The application of multiple relationships should be done with great caution because, in environmental impact studies, they can confound real changes in SSC. Using multiple relationships within a particular analysis should be avoided unless there is unequivocal evidence that it is necessary.

In an ongoing study, the data set of paired pumped and depth-integrated samples will grow each year. Regressions done on the growing data set will vary slightly from year to year even if there is no real change in the relationship. Therefore it is best not to apply any adjustments until after all the data for a particular analysis have been collected. At that time, a decision can be made whether an adjustment is needed, and if so, then the adjustments can be based upon all the data. In long-term studies, the decision to make an adjustment will constrain and perhaps complicate subsequent analyses of the same data.

Estimating Sediment Concentration and Load

After the complete data set has been corrected, the primary task required for computing sediment flux is to estimate SSC at the same frequency as that of the recorded discharge and turbidity. Once the SSC has been estimated, the sediment load (load, flux, and yield are all synonymous terms) can be simply calculated as

$$L = \sum_i ktq_i c_i \tag{5}$$

where t is the time between measurements, and q_i and c_i are the instantaneous water discharge and estimated SSC for interval i. Generally, the conversion factor k will also be required to express the result in the desired measurement units. Before the advent of computers, it was common to sum average fluxes, weighted by flow duration, over flow classes (i.e., the flow-duration sediment-rating-curve method). However, with today's computing power, there is no longer any reason to use such an approximate method.

Software—

Most of the methods described in this section are available in a set of procedures developed by RSL for use within the R software package. The procedures and instructions for their use and installation can be found on the TTS Web page. The procedures are designed to be used for estimating sediment loads for input files created specifically by TTS Adjuster. The FTS processing system, still under development at this writing, is planned to include many of these methods as well.

Surrogate variables—

Instantaneous SSC is normally estimated by using one of three surrogate variables: turbidity, discharge, or time. Turbidity is the preferred surrogate. If the turbidity data are of high quality and if the range of turbidity is wide enough, the relationship between turbidity and SSC is usually very good and certainly better than the relationship between discharge and SSC. However, when turbidity data are of poor quality or missing, it may be necessary to fall back on discharge as the surrogate. If enough pumped samples were collected during the period of bad turbidity data, then instead of using a relationship between discharge and SSC, a better estimate of SSC can be obtained simply by interpolating SSC over time between samples. In the interpolation scenario, time is effectively the surrogate variable.

Defining the relationship between surrogate and SSC—

The selection of the data and determination of the surrogate relationship(s) are subjective, but must be guided by general principles. The data used to determine a surrogate relationship should ideally

- Be representative of the period whose flux is being estimated.
- Span the range of both variables in the period whose flux is being estimated.
- Include enough samples to reasonably define the relationship.

Annual loads—

For calculating an annual sediment flux, assuming the turbidity data are complete, it may be reasonable to fit a single relationship between turbidity and SSC based on a whole year’s data. Such a relationship is likely to overestimate some storm events and underestimate others, but these errors tend to balance one another and the annual flux may often be estimated accurately enough (often to within 10 percent) by the one relationship.

Replacing the estimated SSC during storm events by using storm-based relationships can result in an even more accurate estimate of annual load, and this can be used to validate or reject the first procedure.

Using a relationship based on samples from the entire year or, worse, from a prior year is likely to severely miscalculate a storm event load.

Storm event loads—

For calculating a storm event load, it is best to use only data from that storm event, assuming enough samples were collected. Using a relationship based on samples from the entire year or, worse, from a prior year is likely to severely miscalculate a storm event load. If an inadequate number of samples were collected to reasonably define the relationship, or if the samples collected do not span the range of turbidity or SSC or both, for the given event, then additional samples should be included from neighboring periods.

Dividing the data—

Just as with annual loads, it may be more accurate to divide a storm event into multiple periods and multiple relationships. This decision should be based on an examination of scatterplots between turbidity or discharge and SSC. If the samples in the scatterplot are numbered, then it is easy to tell if a relationship has shifted during the event. If the relationship clearly shifted, and if enough samples were collected to define both relationships, it usually is best to divide the event into two periods. The drawback to dividing the data is that the individual relationships will be less precise because they are defined by fewer points.

The form of the relationship—

***Linear regression*—**Linear regression is usually the simplest relation considered. If several different models seem to fit the scatterplot adequately, the simplest relationship is usually preferred. However, there are other considerations. When dissolved substances are present that cause turbidity, or when SSC is determined by filtration and the filtrate contains fines that cause turbidity, concentrations near zero will have significantly positive turbidity, and linear relationships between turbidity and SSC will have a negative intercept. The result is usually that predictions of SSC are negative for some range of low turbidity values that have been recorded. The solution is to either set negative predictions to zero, or to adopt a model that never predicts negative SSC, for example, a log-log regression or a power function.

***Transformed linear regression and bias corrections*—**Transformations can be used to produce models that cannot make negative predictions, to develop linear relationships, to normalize residuals, to equalize variance, or a combination of the above. Sometimes a transformation can accomplish more than one of these objectives, but there are no guarantees. Retransformed predictions from log-log regressions are always positive, but they have the drawback that they cannot be evaluated when the predictor is zero. The square root transformation may accomplish the same thing without eliminating predictions at zero.

Transformation of the response (the SSC) has a drawback. The prediction must be retransformed back to the original units, which introduces a bias (Koch and Smillie 1986, Miller 1984). The bias arises because regression predicts the mean of a normal distribution of responses for a given x, and the transformed mean of a normal distribution is not equivalent to the mean of the transformed distribution. To correct for retransformation bias, Duan (1983) introduced the nonparametric "smearing" estimator:

$$\hat{y}_{sm} = \frac{1}{n}\sum_{i=1}^{n} h(\hat{y}_0 + e_i) \qquad (6)$$

where $\hat{y}_{sm}$ is the corrected prediction in original units, h is the inverse transformation, $\hat{y}_0$ is the prediction before retransformation, and e_i are the residuals from the regression. For square root transformations, the smearing estimator takes the form $\hat{y}_{sm} = \hat{y}_0^{\,2} + 2\,\hat{y}_0\,\bar{e} + \sum e_i^2/n$ where $\bar{e}$ is the mean residual.

For transformations by *ln* (logarithm to the base *e*), the bias is always negative, and increases with regression variance. The smearing estimator becomes $\hat{y}_{sm} = \exp(\hat{y}_0)\sum \exp(e_i)/n$. If the *ln* transformed regression has normally distributed residuals, there is an exact minimum variance unbiased estimator, but it is quite complex and computationally demanding (Cohn et al. 1989). A more widely known, approximate correction for *ln* transformations when residuals are normally distributed is

$$\hat{y}_{qmle} = \exp(0.5s^2 + \hat{y}_0) \qquad (7)$$

where s is the residual standard error of the transformed regression. The QMLE subscript stands for quasi-maximum likelihood estimator (Cohn et al. 1989). This estimator has also been called the naive correction, or the Baskerville (1972) correction. More generally, for logarithms to the base b, the QMLE correction factor is $\exp[0.5\,ln(b)^2 s^2]$, which, for base 10 logarithms, yields $\hat{y}_{qmle} = \exp(2.65s^2 + \hat{y}_0)$.

Power function—The power function $y = cx^k$ can be obtained by retransforming $\log_b(y) = a_0 + a_1 \log_b(x)$ to obtain $c = b^{a_0}$ and $k = a_1$, but it can also be fitted directly by using nonlinear least squares (NLS) estimation (Bates and Watts 1988). The estimated coefficients will be different from the retransformed linear regression, with or without correction. The log-log regression gives more weight to data with small x. Algorithms for NLS are iterative calculations that are provided in many statistical packages such as S-PLUS and R. Fitting a power function by NLS instead of log-transformed regression has the advantages that no bias-correction is necessary and data with large x are not deemphasized. In Microsoft Excel, power function regressions are computed by retransforming the log-log regression, not by

NLS. Excel ignores the bias correction, so predictions based on Excel power models favor data with small *x* and are negatively biased.

Loess—Locally weighted polynomial regression (loess) is a nonparametric curve-fitting technique that can estimate a wide class of regression functions without distortion (Cleveland 1979, Cleveland and Devlin 1988, Cleveland et al. 1988). It is similar to a moving average. The fitted value at each *x* is the value of a regression fitted to data in a neighborhood near *x* using weighted least squares, with the closest points being weighted most heavily. The degree of smoothing, which affects the number of points in each neighborhood, is determined by the user. The advantage of loess is its flexibility. It nearly always can produce an acceptable fit to the data, but care must be taken not to over-fit the data. With SSC and turbidity, we recommend smoothing until no more than one inflection point (where curvature switches between convex and concave) is present. A statistic that characterizes the amount of smoothing is the equivalent number of parameters, which can be compared to the number of parameters estimated by a polynomial fit. The loess computation seems to require at least two more data points than the equivalent number of parameters, so it cannot generally be applied with less than about five samples.

The advantage of loess is its flexibility. It nearly always can produce an acceptable fit to the data, but care must be taken not to over-fit the data.

At many sites, organic sediment becomes dominant at low values of turbidity, causing a reduction in the slope of the rating curve near zero. The slope change is most apparent in annual plots of turbidity and SSC. Loess is often the most satisfactory modeling method to capture this slope change (fig. 27).

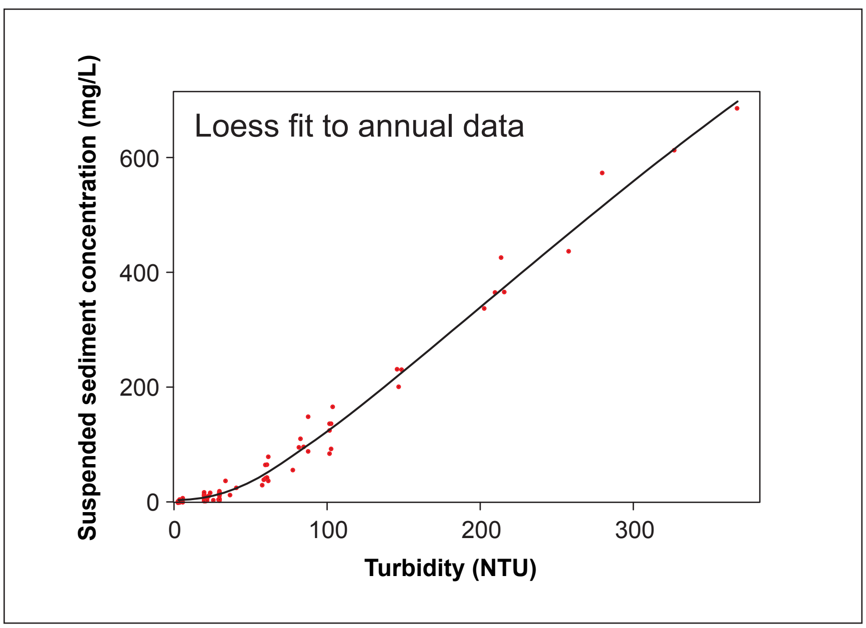

Figure 27—Loess curve fitted to yearly data from South Fork Caspar Creek, California.

Because there is no simple algebraic expression for a loess curve, prediction is usually done within the statistical package that computed the curve. S-PLUS and R have prediction capabilities, but the built-in prediction methods do not permit extrapolation beyond the range of the data used to fit the model. Extrapolation can be done manually by computing regression lines for the last few points of the curve at either end of the range. The RSL procedures for computing sediment loads in R automatically extrapolate linearly when necessary.

***Hysteresis and pairwise fitting*—**It is common for the relationship between surrogate and target variable to shift during an event. The shift is usually near the turbidity or discharge peak and, on a scatterplot, the shift often appears as a loop pattern known as hysteresis. Hysteresis loops for SSC and turbidity are less common and narrower than loops for SSC and discharge. It might be possible to approximate a loop as two curves, in which case the data could be divided into two periods, as discussed above, applying two of the previous methods to estimate the load.

Another approach to hysteresis loops, which is occasionally useful, is to connect each consecutive pair of samples with a line segment, using each segment to predict the period between that pair's sample collection times. The reason this method is only occasionally useful is that, if turbidity or discharge is the surrogate variable, all the line segments must have positive slopes to produce a reasonable result (fig. 28). If any of the segments have negative slope, and some usually do have negative slope near the peak, the surrogate time series for that segment will be inverted, that is, surrogate peaks will be converted to SSC troughs and vice versa.

***Linear time-interpolation*—**The one situation in which pairwise fitting is often useful is when time is the surrogate variable. In that case, pairwise fitting becomes linear interpolation between consecutive sample times (fig. 29). But SSC cannot always move in the same direction as time, so the positive slope restriction, which makes sense when turbidity or discharge is the surrogate, does not apply. As mentioned when surrogate variables were first discussed, if enough pumped samples were collected during a period of bad turbidity data, then instead of using a relationship between discharge and SSC, a better estimate of SSC can often be obtained simply by linear time-interpolation. A smoother curve can be obtained by using cubic spline interpolation, but a spline is not constrained to the y interval defined by each data pair, so the result is often less realistic than linear interpolation.

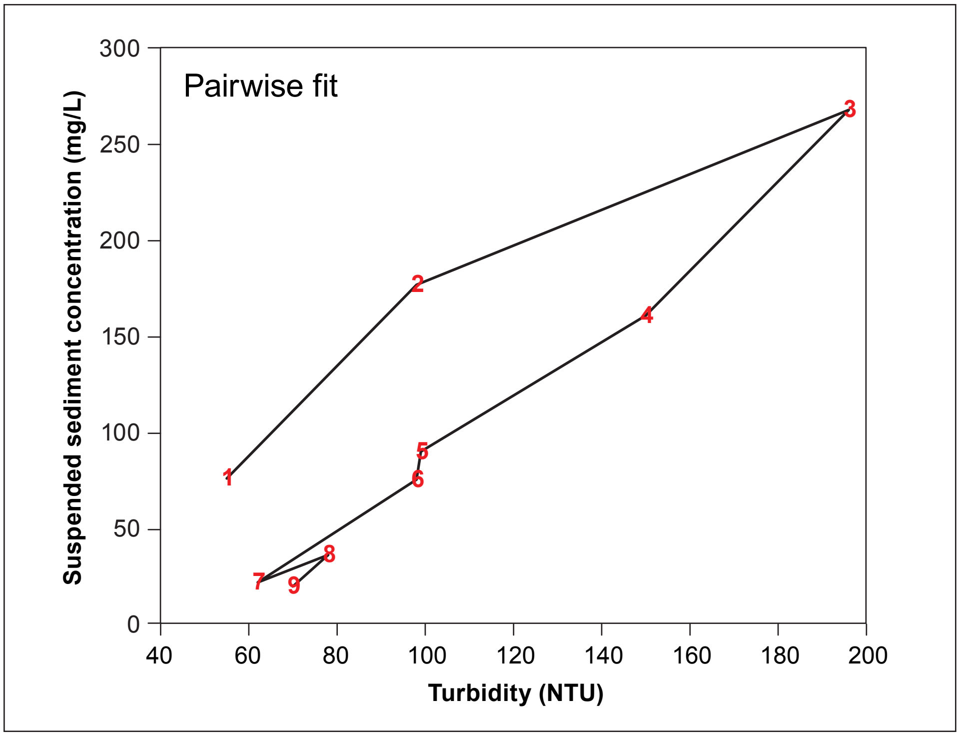

Figure 28—Pairwise fit captures hysteresis in this data from the Xray tributary of Caspar Creek, California.

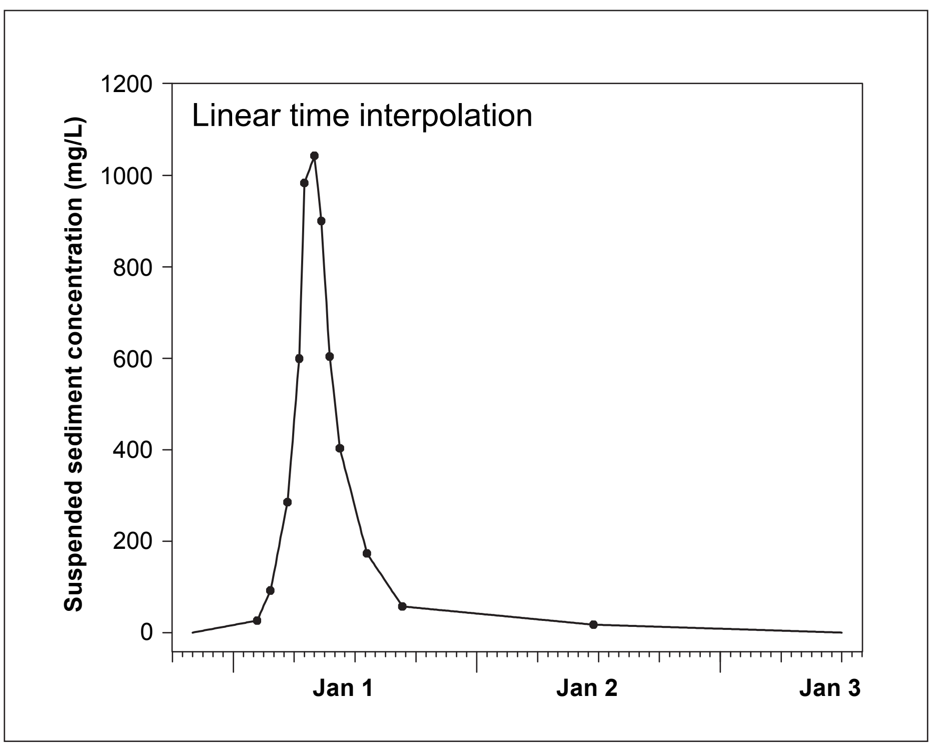

Figure 29—Linear time interpolation of suspended sediment concentration (SSC) for a storm at the Xray tributary of Caspar Creek, California.

Variance of the estimated sediment load—
The variance of the estimated sediment load is the variance of the sum of the estimated fluxes for all the intervals in the period being estimated. The variance of a sum is the sum of the variances and covariances among the items being summed. The covariances cannot be ignored because flux estimates for similar values of turbidity are highly correlated. The covariance matrix of estimated fluxes is derived from the covariance matrix of the regression coefficients, assuming that the surrogate variable for intervals to be predicted is just a set of constants (not random).

***Case of simple linear regression*—**The derivation is not difficult for simple linear regression, but the computation is demanding because the dimension of the covariance matrix of estimated fluxes is $N \times N$, where N is the number of intervals being predicted. The elements of this covariance matrix must be summed to obtain the estimated variance of the load:

$$\boldsymbol{V} = s^2 \boldsymbol{Z}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{Z} \tag{8}$$

where s is the residual standard error of the regression; $\boldsymbol{X}$ is the $n \times 2$ design matrix whose rows are $(1, x_i)$, x_i is the ith sampled turbidity value; and $\boldsymbol{Z}$ is the $N \times 2$ matrix whose rows are $(ktq_j, ktq_j x_j)$, q_j and x_j are the discharge and turbidity for the jth interval to be predicted, t is the length of the interval between instantaneous discharge readings, and k is a units conversion factor that expresses the load in the desired units.

***Log-log regression*—**Variance computation is much more complicated for retransformed predictions from log-log regression (Gilroy et al. 1990).

***Power functions*—**An approximate covariance matrix can be obtained for power functions by using the delta method for vector-valued functions (Rice 1994). If the power function is $b_0 \boldsymbol{X}^{b_1}$, where $\boldsymbol{X}$ is an $N \times 1$ vector of surrogate variables, the $N \times N$ covariance matrix of estimated concentrations is

$$\boldsymbol{C} \cong \left[\boldsymbol{X}^{b_1}, b_0 \ln(b_1)\boldsymbol{X}^{b_1}\right] V(\boldsymbol{B}) \left[\boldsymbol{X}^{b_1}, b_0 \ln(b_1)\boldsymbol{X}^{b_1}\right]' \tag{9}$$

where $\boldsymbol{B} = (b_0, b_1)'$ and $V(\boldsymbol{B})$ is the coefficient covariance matrix estimated by using NLS. The dimension of the first bracketed matrix is $N \times 2$, $V(\boldsymbol{B})$ is 2×2, and the last matrix is $2 \times N$. The covariance matrix of estimated fluxes also includes the discharge, time interval, and units conversion factor:

$$\boldsymbol{V} = (kt)^2 \boldsymbol{QCQ} \tag{10}$$

where $\boldsymbol{Q}$ is an $N \times N$ diagonal matrix containing the discharges for each interval, and k and t are scalars defined as before.

Loess—The author is not aware of any methods that have been developed for estimating the covariance matrix for loess predictions or derived fluxes.

Coefficient of variation—A more intuitive way of expressing the variance of the estimated sediment load is the coefficient of variation, which is the standard error as a proportion or percentage of the estimated load. The standard error is just the square root of the variance, so the coefficient of variation is given by

A more intuitive way of expressing the variance of the estimated sediment load is the coefficient of variation, which is the standard error as a proportion or percentage of the estimated load.

$$CV = 100 \frac{\sqrt{V}}{L} \tag{11}$$

where V is the sum of the elements of the matrix V defined by equation 8 or equations 9 and 10 above and L is the estimated sediment load defined by equation 5 above.

Statistical criteria for selecting among models—
There are several statistical criteria available for selecting between competing models. No statistic should be used as a yardstick, however, without considering the other factors mentioned previously in the sections "Storm event loads" and "The form of the relationship." Models that are based on different data sets (e.g., with or without certain data pairs) should not be ranked based on a statistic. For small sample sizes, statistics are not very reliable. All other things being equal, the model that expresses the relationship in simplest terms should be the model chosen. In particular, models with too many parameters will tend to have greater prediction error.

***Coefficient of determination* (r^2)**—The coefficient of determination, r^2, is an expression of the shape of a scatterplot. It is the squared correlation of predicted and observed values and can be interpreted as the proportion of total variance of y that is explained by x, a value always between zero and 1. Therefore, r^2 depends strongly on the range of the data sampled. If the range of x is very small, on the order of the residual standard error, then r^2 will be close to zero. If the range of x is much larger than the residual standard error, even as a result of one extreme value, then r^2 will be close to 1. In addition, r^2 can be heavily influenced by a few points, so it is best not to use r^2 if the values of x are not evenly distributed. Because r^2 is unitless, it is possible to compare r^2 between transformed and untransformed regressions. It is available from loess as well as linear and nonlinear regression models.

Residual standard error (s)—Residual standard error is an expression of the average deviation of points from the regression line. It is expressed in the same units as the *y* measurement; therefore, it cannot be used to compare regressions on transformed and untransformed data. It is available from loess as well as linear and nonlinear regression models.

Coefficient of variation of the estimated load (CV)—Coefficient of variation (*CV*) is a good yardstick for comparing loads estimated by transformed or untransformed linear regression, or both, but may not be available for models other than linear regression. For small sample sizes, *CV* may be a poor error estimate and is likely to be the least reliable of the criteria mentioned here.

Other statistics—There are other statistical criteria for selecting among competing regression models that are beyond the scope of this report. These include prediction residual sum of squares (PRESS), Mallows' C_p , and Akaike's information criterion (AIC). Unless the models being compared have different numbers of parameters, these criteria will generally give the same ordering of models as the residual standard error.

Quality Evaluation

Many considerations determine the quality of a sediment load estimate derived by using the methods described in this report. The following factors can be used to qualitatively rate a sediment load estimate.

- Sediment sample coverage
  - Were an adequate number of samples collected?
    - For a simple turbidigraph with one peak and no spikes, four or more samples are needed.
    - Extra samples are desirable for complex turbidigraphs with multiple peaks or spikes. We like to have at least two or three samples for each additional extended peak and one sample for each spike.
  - Are there samples covering the full range of turbidity for the storm? If the range of samples is too small, the regression slope will be unreliable, and extrapolation errors are likely. If the range or number of samples is too small, samples from a neighboring storm event should be considered for inclusion.
  - Are samples well-distributed temporally?
    - Were samples collected near the start, peak, and end of the storm?
    - Are there any extended periods with no samples?

   - If there were periods of turbidity data with poor or questionable quality, were samples collected during those times? These are needed to validate the turbidity and to permit time-interpolation if they show that the turbidity measurement was bad.

- Relationship of the SSC to turbidity
   - What is the variance about the regression line? Low variance is meaningless if there are only two data points or if one end of the regression line is based on a single point.
   - What is the CV of the estimated load? This expresses the standard error of the estimate as a percentage. As with regression variance, if the sample coverage is poor, this measure is meaningless.
   - Can the relation be expressed by a single regression? For a given data set, using more relationships divides the data into smaller groups, so there is greater uncertainty about each relationship.
   - Can the relation be expressed as a simple linear regression? Curvilinear fits are more susceptible to extrapolation error and require more data for support.

- Quality of recorded turbidity
   - Refer to the above section "Validating the turbidity record" and figures 25 and 26 for validation guidelines.

- Quality of pumped samples
   - Were the sample volumes too low or too high?
   - Are there known problems in the transport or processing of the samples?
   - Were there any conditions (e.g., particle sizes, stream velocity, freezing conditions, pumping sampler problems) that might have compromised the quality or representativeness of the pumped samples?

Documentation

The database containing annual results should include all of the following:

A. Raw data
B. Field forms
C. Raw data plots, annotated with notes from field forms
D. Corrected plots (optional)
E. A table or file containing at least the following information at the data logger's recording interval (usually 10 or 15 minutes):
   1. Date
   2. Time

3. Dump number (if applicable)
4. Bottle number (for intervals with pumped samples)
5. Raw stage
6. Corrected stage
7. Code for stage quality or type of correction
8. Discharge
9. Raw turbidity
10. Corrected turbidity
11. Turbidity code for quality or type of correction
12. Estimated concentration for periods in which flux was calculated

F. A table or file for each pumped sample that was collected, containing at least
   1. Date
   2. Time
   3. Dump number (if applicable)
   4. Bottle number
   5. Lab concentration
   6. Lab quality code (if available)
   7. Items 5 to 11 merged from section E (optional)

G. Documentation of the procedures used for estimating sediment loads. This should be very detailed so that the whole process could be reproduced from scratch. For each period for which flux was estimated (there may be multiple periods per storm event), at least the following should be recorded:
   1. Start and end times
   2. Surrogate variable used (turbidity, flow, or time)
   3. Type of model used (linear, loess, power, etc.)
   4. Which sediment samples were included in the model for estimating SSC
   5. Scatterplot showing the samples and model that were employed
   6. Whether or not the concentrations were adjusted based on a relation between point and depth-integrated SSC
   7. Explanations of the reasoning behind the above choices
   8. Estimated sediment flux and related statistics
   9. Summary plot showing discharge, turbidity, and estimated concentration against time (one plot per storm event)
   10. If sediment loads were estimated by using RSL's load estimator package for R, some of the above documentation for estimating sediment loads could be recorded simply by saving a list of the R commands that were executed to compute the loads.

Acknowledgments

The authors thank Mark Uhrich, Bob Ziemer, and Mike Furniss for reviewing the report. We also appreciate Elizabeth Lemon's thorough copyediting and Tom Lisle's helpful comments.

Acronyms

ASTM	American Society for Testing and Materials
CV	Coefficient of Variation
EPA	Environmental Protection Agency
FBU [2]	Formazin backscatter units
FTS	Forest Technology Systems, Ltd.
ISO	International Standards Organization
NLS	Nonlinear least squares
NTU [2]	Nephelometric turbidity units
R	Free software for statistical computing and graphics
PSW	Pacific Southwest Research Station, U.S. Forest Service
RSL	Redwood Sciences Laboratory (PSW field office, Arcata, California)
SDI-12	Serial Data Interface at 1200 baud (digital data communications protocol)
S-PLUS	A commercial statistical software package
SSC	Suspended sediment concentration
SSL	Suspended sediment load
TTS	Turbidity Threshold Sampling
TTS Web page	http://www.fs.fed.us/psw/topics/water/tts/
USGS	U.S. Geological Survey

[2] Turbidity data reporting units were established by the U.S. Geological Survey in the *National Field Manual for the Collection of Water Quality Data* (Anderson 2004).

English Equivalents

When you know:	Multiply by:	To find:
Meters (m)	3.2808	Feet (ft)
Centimeters (cm)	.3937	Inches (in)
Millimeters (mm)	.03937	Inches (in)
Microns (µ)	.00003937	Inches (in)
Square kilometers (km^2)	.3861	Square miles (mi^2)
Meters per second (m/s)	2.2369	Miles per hour (mph)
Milliliters (mL)	.06102	Cubic inches (in^3)
Grams (g)	.03527	Ounces (oz)
Grams per cm^3 (g/cm^3)	62.428	Pounds per ft^3 (lb/ft^3)
Degrees Celsius (C)	1.8C + 32	Degrees Fahrenheit (F)

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