MAXIMIZING THE RELIABILITY AND COST-EFFECTIVENESS OF YOUR SUSPENDED-SEDIMENT DATA

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Abstract An annual record of daily suspended-sediment discharges produced for a U.S. Geological Survey (USGS) streamgage requires suspended-sediment data that are representative of the flow past a river cross section. Depth-integrated isokinetic sampling by a hydrographer at appropriately selected, multiple cross-stream interval centroids by either or both of the Equal-Discharge-Increment (EWI) or Equal-Width-Increment (EDI) methods provide physical samples for subsequent laboratory analyses and use in computation of the daily sediment record. The expertise and attentiveness of the hydrographer, coupled with the sampling scheme used, can have a considerable and consequential influence on the reliability and cost-effectiveness of the derived sediment record.

An evaluation of largely controllable technical and cost factors supports the preferential use of the EDI method, with separate concentration analyses on each sample, for at least one of the two required depth-integrated cross-section sample sets. This conclusion stems from two primary considerations: The value of visually comparing the contents of individual samples to identify and discard bad samples, thus preempting their submission for laboratory analysis; and identifying concentration trends in the cross-section that, in concert with the information from the second sample set, represents a second opportunity to ferret out bad data.

The cost of individual concentration analyses for a single EDI set of six samples is about double that for a six-sample EWI composite-concentration analysis. However, the additional cost of the individually analyzed EDI sample set over that for an EWI composite-concentration analysis – about 1.3 percent – pales in comparison to the annual funding requirements for producing a daily sediment record.

Preventing erroneous sample data from degrading the quality of the sediment record – and permanent storage in the USGS National Water Information System – is desirable for the sake of the accuracy of the records produced, database integrity, and return on investment. The combined cost of composite analyses on two cross-section sample sets as a percentage of total station costs is not substantially less than that for one sample-set composite analysis plus one EDI sample set analyzed to produce concentration values for each sample. Coupled with enhanced data reliability, the added cost of the latter approach is readily justifiable as a cost-effective “sediment-data quality-assurance policy.”

INTRODUCTION

Production of an annual record of daily suspended-sediment discharges by the U.S. Geological Survey (USGS) is a time- and resource-intensive undertaking that requires considerable experience and expertise. Requirements for a demonstrably reliable and accurate sediment record include:

- Collection of suitable suspended-sediment samples using appropriate sampling equipment and methods,
- Analyses of the samples by a certified fluvial-sediment laboratory,
- Derivation of a suspended-sediment concentration (SSC) time-series dataset for each day, with continuity between days, for merging with the concomitant water-discharge time series to compute mean daily suspended-sediment discharges and mean time-weighted SSCs, after the
- Judicious application of correction coefficients relating data collected at a relatively high frequency, such as by an observer (Johnson, 1997), autosampler, or surrogate technology (Gray and Gartner, 2009), to mean SSC values for the river derived from periodic and/or episodic sample sets collected by a hydrographer.

The overall quality of these records is, at best, difficult to quantify. A number of factors and potential sources of error can increase the variance of, or introduce bias in a computed record. These include:

- Failure to adequately account for the temporal and spatial variability inherent in the sediment-transport process (Topping et al., 2011),
- Potential inaccuracies or outright errors introduced by sampler selection, performance, and/or deployment; and sample processing, shipment, and/or storage at the sediment laboratory prior to analysis,
- Potential, albeit rare, sediment laboratory-related errors, and
- The incorrect application of, or failure to apply, the aforementioned correction coefficients.
Production of a reliable daily sediment record at a USGS streamgage presupposes that none of the several links in the sediment data-collection and analysis chain will fail. This evaluation focuses on one of those links: Selection and use of the cross-section sampling method(s) used by the hydrographer, and the laboratory methods requested to process and analyze the sample sets. The evaluation’s objective is to identify demonstrably reliable and cost-effective approaches available to the hydrographer for obtaining the field-calibration data for computing daily suspended-sediment records and permanent storage in the USGS National Water Information System (NWIS). The expertise and attentiveness of the field hydrographer coupled with the selected sampling scheme can have a considerable and consequential influence on the reliability and cost-effectiveness of the derived sediment record.

**COLLECTION AND COMPUTATION OF SUSPENDED-SEDIMENT-DISCHARGE RECORDS**

Numerous methods are available for the computation or estimation of suspended-sediment discharges in open-channel flows (Gray and Simões, 2008). The USGS sanctions two such methods for storage of daily values of suspended-sediment discharge, time-weighted suspended-sediment concentration (SSC), and water discharge in the NWIS:

1. A method that interpolates and, when necessary, extrapolates from SSC data derived from periodic or intermittent physical samples to develop a continuous SSC time series. The SSC time series is merged with a concomitant water-discharge time-series dataset to produce the daily sediment records (Porterfield, 1972; Koltun et al., 2006); and

2. Continuously monitored turbidity as an SSC surrogate (Rasmussen et al., 2009).

Other suspended-sediment surrogate technologies including those based on hydroacoustic, densimetric, and laser technologies have been or are being evaluated (Gray and Gartner, 2009). Some are incorporated in operational programs (Rasmussen et al., 2008; Voichick and Topping, 2014).

Regardless of the monitoring technique or technology selected for operation of a daily sediment station, the reliable measurement and computation of fluvial-sediment loads fundamentally depends on collection and analyses of representative water-sediment samples that integrate variations in the velocities and sediments suspended in the stream cross section. Historically, analytical results from these cross-section discharge-integrated samples were the sole SSC data used to develop the temporal SSC trace (for the most part limited to the Nation’s larger rivers), or to adjust SSCs derived from samples collected on a relatively frequent basis by an observer or autosampler to be representative of the mean SSC value in the cross section (Porterfield, 1972; Johnson, 1997; Koltun et al., 2006). More recently, samples representative of the flow past the cross section are being used to calibrate an SSC surrogate time-series (Rasmussen, et al., 2009; Gray and Gartner, 2009; Voichick and Topping, 2014).

Edwards and Glysson (1999), Nolan et al. (2005), Gray et al. (2008), and Gray and Landers (2014) describe methods approved by the Federal Interagency Sedimentation Project (FISP) and USGS for collecting suspended-sediment samples for subsequent laboratory analyses. For physical sampling in all but the shallowest or most sluggish flows (generally, with cross-section depths less than about 0.3 meter and/or mean flow velocities less than about 0.5 meters/second), two USGS-approved methods for deploying an isokinetic sampler in a single vertical are available: point-integration and depth-integration. Contemporary use of the point-integration method is rare because it is relatively costly and time-intensive, and depth-integrating bag samplers developed since the mid-1990s for use in rivers with depths exceeding about 4.5 meters are available (FISP, 2015; Gray and Landers, 2015). Ergo, the point-integration sampling technique is ignored hereafter. Non-isokinetic sampling techniques are also ignored. However, the potential relevance of these sampling techniques may be inferred by the reader in the ensuing discourse.

Approved USGS sampling techniques rely on the use of an appropriate isokinetic sampler developed by the FISP (2015). A list of FISP isokinetic samplers, their physical characteristics and deployment limitations is available from Davis (2005), Gray et al. (2008), and Gray and Landers (2014; 2015). When a mean value for SSC (or SSC and particle-size distributions, PSDs) representative of the flow-weighted cross section is sought, such as for subsequent use in computation of a daily suspended-sediment record, FISP isokinetic samplers are deployed using either the Equal-Width Increment (EWI) and/or Equal-Discharge Increment (EDI) methods (Edwards and Glysson, 1999; Nolan et al., 2005; Gray et al., 2008; and Gray and Landers, 2014). The data-quality and economic ramifications related to the selection and use of either or both of these sampling methods constitute the focus of the ensuing discourse.
Description and Requirements for Use of the EWI and EDI Methods

Characteristics Common to the EWI and EDI Methods: Both the EWI and EDI methods entail collecting depth-integrated samples in a river cross section. The cross section is computationally segregated into intervals. An isokinetic sampler appropriate for the ambient depth and flow velocities in the cross section is lowered at a constant rate in a water column (vertical) located at the centroid of each interval. After the briefest contact with the bed, the sampler is retrieved at a constant rate. This is repeated at each vertical, changing sample containers as appropriate.

In larger rivers, some hydrographers retrieve the sampler at the 0.90 or 0.95 depth (i.e., without contacting the bed) to minimize the risk of snagging a submerged object, or to preclude the inadvertent collection of bed material by gouging the sampler nozzle into the relatively soft lee face of a dune or infirm bed (Gray and Landers, 2014). This approach can result in an abnormally large unsampled zone between the bed and the nadir of the deployed sampler. If a vertical SSC gradient exists, this partial-depth sampling approach may produce biased samples, usually toward underrepresentation of SSC. Hence the quest for safer sampling and avoidance of sample contamination is potentially countered by the collection of biased data.

During the course of a sampling transect, each sample container (a glass or plastic bottle, or collapsible bag) either must be replaced before overfilling, or the contents decanted to a compositing vessel for subsequent subsampling, such as with a USGS churn splitter, or by pouring through a sub-sampling device, such as a USGS cone splitter (Capel and Larsen, 1996). Subsampling, while more or less a routine step for collecting chemical-quality data, is discouraged for suspended-sediment data collection. This stems from recognition of potential subsampling vagaries that include both a potential for an increase in data variance, and introduction of bias.

At least two sets of cross-section samples are collected per site visit (Nolan et al., 2005; Topping et al., 2011; FISP, 2013; Gray and Landers, 2014). Samples are analyzed to enable comparisons of mean SSCs and PSDs derived for each sample set.

Sampler-transit rates exceeding 0.4 multiplied by the mean stream velocity (“four-tenths rule”) are impermissible. Maximum transit rates for some samplers are less than the four-tenths rule (Edwards and Glysson, 1999).

Overfilling the sample container invalidates a sample. Overfilled samples must be discarded and the sampler re-deployed in the interval(s) that contributed to the overfilled sample.

Each sample should be examined closely for comparisons of the relative estimated SSCs in the sample set (after visually compensating for unequal sample volumes). Of particular interest is the quantity and size of sand-size particles that quickly settle to the bottom of the container. With rare exception, analyses of samples adulterated during the sampling process yield spuriously large SSCs, and inordinately coarse PSDs.

The photograph in figure 1 shows two near-equal volume samples collected from the same vertical on December 11, 2014, as part of a 2-set EDI measurement on the Toutle River at Tower Road near Silver Lake, Washington (USGS station 14242580). The photograph was taken less than a minute after the samples were swirled. Disparities in the quantity, and possibly also the coarseness of the accumulated sediments, are readily apparent. Collecting, examining, and, if needed, analyzing additional samples from this vertical may have been warranted.

![Figure 1 Photograph of two near-equal volume samples collected from the same vertical in the Toutle River at Tower Road near Silver Lake, Washington, on December 11, 2014, showing different accumulations of sediment.](image-url)
The importance of examining each sample upon collection, or at least before departing the site, is hard to overstate. Ignoring this crucial step may result in retaining a sample that provides biased data due to operator error or inadvertent sample adulteration. Unreliable data generated by a hydrographer, as opposed to an observer or by automated means, are particularly counterproductive for at least four reasons:

1. The data are illegitimately ascribed the highest degree of confidence due to the employment status and presumed expertise of the collector(s), and well-documented validity of the sample-collection methods,
2. Hydrographers are correctly admonished to be generally disinclined to discard analytical results of samples, and of hydrographer-collected samples in particular,
3. The results are counterproductive from record-computation, time, and cost-effectiveness perspectives, and
4. If the spurious data represent an influential part of the streamflow hydrograph, they also may deleteriously influence the accuracy of records computed for other periods.

If the hydrographer fails to recognize a potentially bad sample on-site and does not resample the vertical(s), and/or otherwise fails to sleuth the problem – or if a bad sample received by a laboratory is analyzed but the data are neither flagged nor discarded as part of the routine dataset evaluation – the unreliable data will unknowingly compromise the quality of the computed suspended-sediment discharge record. This represents not only a failure to provide the reliable daily-value sediment record expected in return for the allocated funds, but also may compromise the effectiveness of management decisions based on the erroneous record.

Characteristics Specific to the EWI and EDI Methods

**Equal-Width-Increment Method:** An EWI measurement entails division of a river cross-section into equal-width intervals. Typically 10-20 verticals are sampled. The hydrographer deploys an appropriate isokinetic sampler in the centroid of the width of each interval. The sampler transit rate must be constant and equal in both the downward and upward directions – and in all sampling intervals – to ensure collection of a representative sample.

Because of its uniform transit rate, use of the EWI method allows retention of samples collected from multiple verticals into a single container. Although sample containers can be changed after each EWI vertical is sampled, it is seldom done. This is due to the added data-collection effort; extra laboratory expense; and the availability of a generally less-costly but demonstrably superior means for obtaining data describing the cross-section SSC and PSD variability as described in the next sections.

Use of the EWI method requires knowledge of the river width at the sampling cross section. Additionally, before collecting an EWI sample set, a careful hydrographer will identify a vertical at which the product of width and mean velocity likely is at a maxima. Selection of a proper combination of a transit rate and nozzle diameter will preclude overfilling the sample container at this vertical. Absent this precautionary measure, a previously empty container may overfill while sampling in a single vertical, compelling the hydrographer to discard that and all other samples collected as part of the in-progress EWI transect. The next attempt at EWI sample collection either must include a more rapid transit rate and/or use of a smaller-diameter nozzle.

The magnitude of the water discharge is required for subsequent suspended-sediment discharge computations. However, knowledge of the lateral distribution of water discharge is not a prerequisite for EWI sample collection.

An analysis of a laboratory-produced EWI composite sample yields a single mean SSC value, and, if requested, one PSD. The same is true for an appropriately derived aliquot of a composite sample produced by a sample-splitting device, if such subsampling is necessary (Capel and Larsen, 1996).

**Equal-Discharge-Increment Method:** An EDI measurement entails the computational segregation of a river cross-section into intervals of equal discharge. Usually 4-10 verticals are sampled. The hydrographer deploys an appropriate isokinetic sampler in the centroid of each interval of water discharge at a constant downward rate and retrieves it at a constant rate. However, unlike the EWI transit rate which must be uniform in both vertical directions, the downward and upward EDI transit rates for an EDI vertical – and the rates used at each vertical – need not be equal. The contents of an overfilled sample container simply are discarded and that vertical resampled, usually with a briefer time-of-immersion. The vertical can be sampled multiple times to obtain the desired sample volume without changing the sample container.

Use of the EDI method requires knowledge of the distribution of water discharge in the cross section. This can be derived from an antecedent discharge measurement made with a mechanical current meter or acoustic Doppler current profiler (USGS, 2015). Alternately, if the channel is relatively stable, a discharge-width relation based on previous discharge measurements can be developed. This relation delineates the stage-dependent location of each
sampling centroid based on percentages of the total water discharge on each side of a vertical. Figure 2 shows a relation developed for EDI sampling at the Cowlitz River at Castle Rock, Washington (USGS station 14243000).

![Figure 2 Graph depicting a water discharge centroid location versus stage relation developed from discharge measurements for the Cowlitz River at Castle Rock, Washington. The graph was developed to select verticals for collection of 5-vertical EDI sample sets at this site. Regression lines are black. Vertical red lines were hand-derived.]

As each EDI sample is independent and discharge-weighted, the samples can be analyzed individually. Alternately, if all EDI sample volumes are more or less equal (in practice, each sample volume should be within about five percent of the mean sample-set volume), an EDI composite analysis can be performed. Individual-sample analyses as part of at least one EDI cross-section sample set are recommended, as described in the ensuing sections.

If an EDI composite analysis is sought, the extra attention and effort required to obtain a set of near-equal-volume samples is hard to justify compared to use of the EWI sampling method. The same cross-section-averaged data, more or less, are produced by either technique. Hence, the challenge to produce a set of near-equal-volume samples for an EDI composite analysis can be avoided theoretically without change in data quality by using the EWI method.

**TECHNICAL CONSIDERATIONS FOR USE OF THE EWI AND EDI METHODS**

Use of an appropriate sampler deployed by either the EWI or EDI method – with proper on-site and subsequent quality-control steps – will provide representative data for sediments and other constituents in suspension. However, inevitably, some adulterated samples that go unrecognized are received and analyzed by sediment laboratories. These can include bad samples in hydrographer sample sets as well as those collected by observers or autosamplers. Even valid samples can be adulterated as part of the sample handling, shipping, and storage continuum. The authors, who have reviewed scores of daily USGS sediment records from dozens of USGS Water Science Centers, have ample reason to believe that this problem occurs at a frequency worthy of concern.

Without proper screening, analytical results from composite analyses adulterated by a bad sample(s) collected at one or more verticals will be factored into the ensuing computation of the mean SSC value. With rare exception, the resulting composite SSC value is biased toward higher values. The degree of the bias can be a function of a number of factors, but can range up to an order-of-magnitude or so.

Such an outcome is more prevalent in lower-SSC streamflows where even a few grains of bed material inadvertently introduced to a sample can substantially influence the derived SSC value. Acceptance and use of spuriously variant mean-SSC values (and concomitant PSDs) result in the proportional derivation of erroneous instantaneous sediment-discharge data in addition to any subsequently derived statistics that are based on the bad data.

The hydrographer’s challenge is to understand the potential for this problem and to implement procedures to preempt its occurrence. In addition to examining each sample upon collection for the presence of an inordinate
A benefit of having each sample from an EDI cross section analyzed for SSC is exemplified by results of concurrent EDI and EWI sample sets collected on March 24, 2014, as part of field-based instruction for the USGS training course, “Sediment Data-Collection Techniques” (Johnson et al., 2015). The sample sets were collected from the bridge at the aforementioned Cowlitz River streamgage by students under the close supervision of course instructors with some three centuries of cumulative experience in sedimentology (Gary P. Johnson, USGS, written communication, 2015). SSC plots that include percentages of sand-size material are shown for the EWI (figure 3) and EDI (figure 4) cross-section sample sets. For instructional purposes, SSC and sand-fine split analyses were performed on individual EWI samples. Likewise, sand-fine splits in addition to the usual SSC analyses were performed on each EDI sample. Normally a laboratory-derived composite sample would have resulted in production of a single SSC value for the 12-bottle EWI sample set. Instead, the mean EWI SSC value was computed as the cumulative mass of sediment divided by the sum of the sample volumes. A mean EDI SSC value was calculated by the routine method of summing the individual SSC values and dividing by the number of EDI samples – five.

The mean SSC value of 262 mg/L from the EWI 12-sample set exceeds the 71 mg/L value for the concurrently collected EDI 5-sample set by a factor of 3.7. This is an inordinately large mean-SSC differential, and one that should invite skepticism from a competent record analyst.

Examination of the EWI SSC data indicates the presence of at least one outlier. The SSC value for station 140 is about double the SSC average for the other stations excluding that for station 330. The percent fines at station 140 is the maximum for this sample set, ergo, the percentage of sand-size material is at a minimum. Although the reference to “cracked bottle” gives the analyst more ammunition to question the validity of the station 140 SSC value, for present purposes this value was retained and attention directed to the more egregious station 330 outlier.

The SSC value of 2,947 mg/L at station 330 is some 90 times larger than the average SSC of the other 11 EWI samples. The 2-percent fines value for this outlier is at odds with the average value of 43-percent fines determined from the four cross section sample sets, which ranged from about 30-80 percent fines. With little if any doubt, the inconsistent and inordinately influential station 330 SSC and PSD data are bad. Although it is possible that the sampler was incorrectly deployed – perhaps left on the bed for more than an instant before being retrieved – it is more likely that the sampler nozzle gouged the soft lee face of a sand dune at the nadir of the sampler’s deployment, inadvertently adding bed material to the suspended-sediment sample.

![Graph showing SSCs and percent of material finer than 0.062 millimeters for samples collected using a US DH-76 suspended-sediment sampler and the EWI method (the EDI sample set depicted in figure 4 was collected concurrently at the USGS Cowlitz River at Castle Rock, Washington, streamgage on March 24, 2014, as part of the USGS training course, “Sediment Data-Collection Techniques”). References to “Cracked bottle” and “Just bad” were noted by the sample collectors. Sand-fine split and individual-sample SSC analyses were performed on the EWI sample set for instructional purposes.](image-url)
If an inexperienced and/or inattentive hydrographer failed to notice the comparatively large mass of sand in the station 330 EWI sample and submitted it as part of the EWI sample set for a composite analysis, the resulting spuriously large SSC value of 262 mg/L and inordinately small percentage of fine material would become part of the station record as a relatively muted but still substantial composite-sample outlier. If the record analyst failed to identify and discard this composite-sample outlier in the ensuing analysis, suspended-sediment discharges computed for any part of the record influenced by this composite outlier will be inflated, perhaps by a factor of about 3.7. It is worth noting that USGS record analysts are instructed to be reluctant to discard hydrographer-collected data based on the premise, “if our own data cannot be trusted, what data can be trusted?”

Figure 4 Graph showing SSCs and percent finer than 0.062 millimeters values for samples collected using a US DH-95 suspended-sediment sampler and the EDI method (the EWI sample set depicted in figure 3 was collected concurrently at the USGS Cowlitz River at Castle Rock, Washington, streamgage on March 24, 2014, as part of the USGS training course, “Sediment Data-Collection Techniques”).

If, on the other hand, the EWI station 330 sample was inspected, suspected, disrespected, and duly discarded in the field after one or more unbiased duplicate samples were collected, the correct composite SSC value would be derived, assuming that the true station 330 SSC value was consistent with those for adjacent sections. Alternately, if the record analyst, upon receipt of these data, rightly deduced that the concurrent EDI SSC and sand-fine split values were internally reasonable and consistent, as were all individual EWI sample results other than the station 330 outlier (and perhaps also that for station 140), the EWI outlier(s) could and should be discarded.

If a composite analysis had been performed on the EWI sample set (figure 3), the perceptive record analyst would deduce that “something’s wrong” with the EWI composite SSC and percent finer than sand values. After carefully evaluating all relevant information, the analyst should feel compelled to discard those data. In this case, only the values from the EDI sample set would be reported and used in record computations. This, of course, would achieve the desired technical outcome – production and use of reliable data – even if the time, effort, and funds associated with collection and analysis of the EWI sample set ultimately were wasted.

An EDI sample set can also include one or more samples with spuriously large SSC(s). However – unless, or perhaps even if an egregiously careless job was done at the sampling site – it is typically and imminently clear from results of separately analyzed EDI samples if an SSC value is unreliable. In this case, unlike in the preceding discourse that centered on the EWI composite outlier, all is not lost. An outlier in the EDI sample set simply can be mathematically eliminated from the mean-SCI computation. Alternately, an experienced analyst may discern a lateral SSC trend in the EDI data and, presupposing a high degree of confidence, estimate a replacement SSC. In this case, the estimated value is used only in the computation of the mean EDI SSC, but not stored as a discrete value.

The thrust of the previous discourse can be summarized as follows: For suspended-sediment studies, the EDI method provides both more, and more readily verifiable information than the EWI method. A composite EWI SSC value that contains the water-sediment contribution from one or more undetected anomalous sample(s) cannot be corrected. It is a bad value – the production of which cost time and money – upon being analyzed and forevermore.
On the other hand, the EDI method provides more detailed cross-section information and thus enables a more informed evaluation of the dataset. This in turn enables the analyst to revise the mean SSC value if bad data are identified and discarded.

Thus, routine use of the EDI method with individual SSC analyses as part of suspended-sediment data collection can be considered to be a "sediment-data quality-assurance policy" of sorts. However, as with the benefits accrued from ownership of a health or life insurance policy, use of the EDI method with individual sample analyses comes at a cost. This observation led to the following economic analysis performed to answer the following questions: "What is the magnitude of additional costs of the EDI method with individual sample analyses compared to those for the EWI or EDI composite method," and "Does the additional cost of the EDI method justify its use from data-quality and knowledge-gain perspectives?"

**ECONOMIC CONSIDERATIONS FOR USE OF THE EWI AND EDI METHODS**

With rare exception, program managers seeking cost savings select the least-expensive data-collection and -analysis scheme for operation of a daily sediment station or sediment-monitoring network. The degree to which cost reductions might affect data quality is difficult to determine, and may not be adequately considered when selecting a data-collection scheme. The ensuing analysis was performed to ascertain if the costs associated with the routine use of the EDI method with SSC analyses performed on individual samples – as part of at least one of the two cross-section sample sets collected per site visit – are reasonable as compared to those for the more prevalent dual EWI samples set (or for a single EWI sample set, contrary to USGS policy for collection of suspended-sediment data). The evaluation inevitably mixes subjective and objective factors that include but are not limited to the following considerations, each of which should be addressed in the design and operation of a daily sediment station:

- Factors associated with data production,
- The data-quantity and -quality expectations of the funding organization(s),
- The value of demonstrably good data, and
- The arguably insidious nature of unidentified bad data that degrade the quality of the sediment record, waste relatively and typically limited resources, and may result in incorrect management decisions.

A practical economic analysis was performed primarily to define and compare sediment-laboratory processing costs associated with use of the EDI method; the EWI methods; and as a combination of the two. The evaluation focused on analytical costs of hydrographer cross-section sample sets. Other sediment-related costs, such as for analyses of partial-section samples collected manually or by an autosampler, are largely independent of the hydrographer-collected samples. Likewise, the sampling scheme selected has little if any effect on the capital, travel, and labor costs associated with sediment-station operations.

Ergo, the economic analysis focused on data-analysis costs of cross-section sample sets collected as part of hydrographer station visits. The economic analysis performed was cognizant and appreciative of the perpetual competition between the quest to maximize data quality and the oft-limited resources for production of the record.

A survey of production sediment laboratories located in six USGS Science Centers, all using methods described by Guy (1961), and Knott et al., (1992; 1993), was conducted in 2014 to ascertain the costs to perform the following selected analyses:

- Suspended-sediment concentrations (SSC) analyses only,
- SSC and sand-fine break (S/F; percent finer than 0.062 millimeters in median diameter) analysis, and
- SSC and full size (FS; percentages from 0.002–2.0 millimeters in median diameter).

Table 1 lists the average analytical costs for three types of sediment-laboratory analyses. They are based on cost information from USGS production laboratories in Water Science Centers located in California, Iowa, Missouri, Kentucky-Indiana, New Mexico, and the Cascades Volcano Observatory, Washington.

Table 1 Average costs for laboratory analyses, from information provided by six USGS Science Centers in 2014.

<table>
<thead>
<tr>
<th>Sediment Laboratory Analysis Type</th>
<th>Average Cost Per Analysis</th>
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<tbody>
<tr>
<td>Suspended-Sediment Concentration (SSC)</td>
<td>$17.00</td>
</tr>
<tr>
<td>SSC and Sand/Fine (SSC + S/F)</td>
<td>$40.00</td>
</tr>
<tr>
<td>SSC and Full Size (SSC + FS)</td>
<td>$170.00</td>
</tr>
<tr>
<td>Each Additional Container, Composite Analysis</td>
<td>$8.30</td>
</tr>
</tbody>
</table>
A second 2014 survey was conducted to determine the range of costs charged by the USGS for operating a daily sediment station (considered herein to exclude the concurrent collection of streamflow data) in tandem with a continuous-record streamgage for streamflow data (hereafter referred to as a “sediment streamgage”). The cost data in table 2 were provided by all but one first-survey respondent are included in the second survey. The Wyoming-Montana Water Science Center cost data were used in lieu of a second-survey response from Kentucky-Indiana.

Table 2 Average annual costs to operate a USGS Daily Suspended-Sediment Station (without streamflow data) and a Sediment Streamgage (with streamflow data), based on data provided by six USGS Science Centers in 2014.

<table>
<thead>
<tr>
<th>Type of Data Produced by a USGS Gaging Station</th>
<th>Average Annual Cost</th>
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<tbody>
<tr>
<td>Daily-Record Sediment Station (sediment data only)</td>
<td>$32,700</td>
</tr>
<tr>
<td>Daily-Record Streamflow Station (streamflow data only)</td>
<td>$17,500</td>
</tr>
<tr>
<td>Daily-Record Sediment and Streamflow (“Sediment Streamgage”)</td>
<td>$50,200</td>
</tr>
</tbody>
</table>

Operation of a sediment streamgage results in production of three sets of daily values that are computed, reviewed, permanently stored, and available to the public: Suspended-sediment discharge; mean time-weighted SSC; and water discharge; along with selected ancillary data. Table 2 lists the average annual costs for operating a sediment streamgage, and the costs of collection of the sediment records versus those for the combined sediment and the streamflow records. Because production of a daily sediment record requires continuous streamflow data, essentially all USGS sediment stations are operated as sediment streamgages that collect continuous streamflow records selected regardless of the funding source(s).

Cost comparisons for selected EDI and EWI sampling-event options are listed in Table 3. These options include costs for collecting one of the two required cross-section sample sets per site visit (referred to as a “sampling event”); collecting either four, six, or nine bottles in each cross-section set (a range that encompasses the number of bottles routinely collected as part of a sample set); and requesting the desired laboratory analyses (Table 1). In all sample-analysis options proposed other than the minimalist dual-EWI sampling method, individual samples collected as part of an EDI sample set are analyzed to identify SSC values for each vertical sampled.

Particle-size analyses—either sand-fine splits or full-size analyses—can be performed as part of either an EWI or EDI composite sample set. Size analyses performed on an unbiased, composite sample set have the advantages of being based on a demonstrably representative sample while providing a sufficient mass of sediment for a full-size analysis.

Although individual size analyses on samples from an EDI sample set would add information useful for better understanding transport characteristics per sediment-size fraction in the cross section, and for the ensuing sediment-record analysis, the relatively substantial added cost would be prohibitive. Additionally, the mass of sediment in individual EDI samples may be insufficient for a full size analysis. The authors are unaware of routine size analyses being performed on most or all suspended-sediment samples submitted to any USGS Water Mission Area sediment laboratory. At least one other USGS sediment laboratory routinely uses optically based analyses to produce concurrent sand-gradation and SSC data on each suspended-sediment sample. Routine production of particle-size data from each sample is highly desirable from the perspectives of the data analyst and data user, albeit substantially more expensive than if only SSC data are produced. These and perhaps other data produced by technologically advanced means may be sanctioned for storage and public release given compliance with USGS (2004) policy, to wit: “All data stored in publicly accessible USGS databases (the NWIS, and other publicly accessible files) must be collected and analyzed using approved collection and analytical protocols.”

The combination of options listed in Table 3, factoring in sampling and analytical costs, are but some of the many sample-analysis options available. The authors consider these to represent realistic options for many sediment-monitoring planning purposes. They also might be used as a starting point in the quest to optimize the available resources with the data, and data-quality needs for collection of a daily sediment record — a quest that should include contingency plans for adequately characterizing the suspended-sediment SSCs and PSD of floods that may occur during the monitoring period.

A protocol for an annual sediment-station sampling program that presupposes ten sampling events (hydrographer site visits to collect a suite of physical samples for subsequent laboratory analyses plus a measurement of water discharge if required) was selected as a comparison of annual stations costs using the EDI, EWI, and a hybrid combination of the two methods (FISP, 2013). The hybrid composite sample set is collected using either the EWI or
EDI method (table 4). Options for three types of laboratory analyses—SSC, sand-fine split, and a full-size—were included. The actual number of sampling events in a given year might vary due to a number of factors including the frequency, timing, and magnitude of medium and higher flows at the station.

Table 3 USGS laboratory analysis cost comparisons for selected EWI and EDI single cross-section sampling event options. Laboratory costs are average values for each analytical type as shown in table 1.

**Options for analyses of individual EDI subsamples, and for composite EWI or EDI analyses**

<table>
<thead>
<tr>
<th>EWI # of Sample Containers/X-S for Composite Analyses</th>
<th>SSC only Composite Analysis</th>
<th>SSC + Sand/Fine Composite Analysis</th>
<th>SSC + Full Size Composite Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$42</td>
<td>$65</td>
<td>$195</td>
</tr>
<tr>
<td>6</td>
<td>$58</td>
<td>$83</td>
<td>$212</td>
</tr>
<tr>
<td>9</td>
<td>$84</td>
<td>$106</td>
<td>$236</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EDI # of Sample Containers/X-S for Individual Analyses</th>
<th>SSC Individual Analyses</th>
<th>SSC + Sand/Fine Composite analysis</th>
<th>SSC + Full Size Composite Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$68</td>
<td>$65</td>
<td>$195</td>
</tr>
<tr>
<td>6</td>
<td>$102</td>
<td>$83</td>
<td>$212</td>
</tr>
<tr>
<td>9</td>
<td>$153</td>
<td>$106</td>
<td>$236</td>
</tr>
</tbody>
</table>

*The cost of an EDI composite SSC analysis is equal to that for an EWI composite analysis regardless of the number of samples collected and analyzed.

The program covers a year of sampling over a presumed range of flows: three low-flow site visits where only SSC analyses are requested (in part because a dearth in sediment mass in samples collected during lower flows often precludes accurate size analyses), and seven low-to-high flow site visits where SSC and particle-size analyses (sand-fine or full-size analyses) are sought.

Table 4 uses data from tables 1 and 3 to compare costs of sole use of the EDI method, sole use of the EWI method, or in a hybrid combination of the two. They describe cost scenarios for consistent submitting for analysis four, or six, or nine samples per cross-section, with two sample sets obtained per site visit, and ten hydrographer visits per year. Numerous permutations of these analytical options could be developed; regardless, the authors contend that no operational sampling scheme used by a credible hydrographer—given the analytical costs and frequency of site visits—would result in substantially reduced annual analytical costs than the minimum of $1,261 for dual EWI cross sections with four samples collected per cross section, and composite analyses performed on both sample sets.

The analytical cost for the minimalist dual-EWI sample set is the least costly method evaluated for a given number of samples collected per cross section, ranging from 21-33 percent (for samples sets of four and nine samples, respectively) less expensive than a dual-sample set that includes one EDI individually analyzed sample set. However, as previously noted, sole use of the EWI method tends to increase the risk of inadvertently acquiring unreliable data. For example, if analyses of one or both composite sample sets included bed material gouged from any of the 10-20 EWI verticals typically sampled in a single cross section, the composite value will not be representative of the stream conditions. The two marginally more costly methods, on the other hand, each provide at least one cross-section sample set analyzed individually for SSCs—a substantial advantage over the dual-EWI sample-set approach.
Table 4 Cost comparison for the EDI, EWI, and hybrid methods with an annual protocol of ten sampling events and four, six, or nine samples collected as part of each of two cross sections. All individual EDI samples are analyzed solely for SSC. All EWI and EDI composite sample sets are analyzed for SSCs and in some cases also for PSDs.

<table>
<thead>
<tr>
<th>Sampling-Event Approach with Two Cross Sections/Event</th>
<th>Number of Sampling Events, Types of Laboratory Analyses, and Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling Event Cost Scenarios</strong></td>
<td>3 Low-Flow EDI Individual SSC Analyses</td>
</tr>
<tr>
<td><strong>Four Containers/X-S</strong></td>
<td></td>
</tr>
<tr>
<td>Approach I: EDI Individual + Composite</td>
<td>$330</td>
</tr>
<tr>
<td>Approach II: Two EWI Composites</td>
<td>$252</td>
</tr>
<tr>
<td>Approach III: Hybrid of EDI Individual SSC + EWI or EDI Composite for Size Analysis</td>
<td>$330</td>
</tr>
<tr>
<td><strong>Six Containers/X-S</strong></td>
<td></td>
</tr>
<tr>
<td>Approach I: EDI Individual + Composite</td>
<td>$480</td>
</tr>
<tr>
<td>Approach II: Two EWI Composites</td>
<td>$348</td>
</tr>
<tr>
<td>Approach III: Hybrid of EDI Individual SSC + EWI or EDI Composite for Size Analysis</td>
<td>$480</td>
</tr>
<tr>
<td><strong>Nine Containers/X-S</strong></td>
<td></td>
</tr>
<tr>
<td>Approach I: EDI Individual + Composite</td>
<td>$711</td>
</tr>
<tr>
<td>Approach II: Two EWI Composites</td>
<td>$504</td>
</tr>
<tr>
<td>Approach III: Hybrid of EDI Individual SSC + EWI or EDI Composite for Size Analysis</td>
<td>$711</td>
</tr>
</tbody>
</table>

Table 5 summarizes annual absolute and relative costs for sediment-station operation for each of three sampling approaches: The cost-identical dual-EDI and hybrid approaches (approaches I and II), and the minimalist dual-EWI approach (III).

Table 5 Annual absolute and percent costs for the hydrographer-collected 6-sample set option shown in table 4 in comparison with total costs of a daily sediment station and a sediment streamgage (sediment and streamgage).

<table>
<thead>
<tr>
<th>Station Type</th>
<th>Average Annual Cost (see Table 2)</th>
<th>Approach I (Dual EDI) or Approach II (Hybrid) Cost (see Table 4)</th>
<th>Approach III Dual EWI Composites Cost</th>
<th>Added Annual Station Costs as Percent: Either Dual EDI (I) or Hybrid (II) minus Dual EWI Composites (III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Daily Sediment Station</td>
<td>$32,700</td>
<td>$2,033</td>
<td>$1,593</td>
<td>6.2%</td>
</tr>
<tr>
<td>II: Sediment Streamgage</td>
<td>$50,200</td>
<td>$2,033</td>
<td>$1,593</td>
<td>4.0%</td>
</tr>
</tbody>
</table>
The dual-EDI sampling approach is functionally and economically identical to the FISP (2013) hybrid approach; the only difference is submittal of an EDI sample set instead of one collected by the EWI method for a composite analysis. Their marginally higher cost is more than balanced by the dual benefits of individual EDI SSC values and with the cost savings associated with a single analysis on the composite sample set. If the composite analysis results are deemed unreliable compared to individual EDI sample-set results, discarding the EWI results is unfortunate, but all is not lost; the mathematically averaged EDI SSC results – after a careful evaluation – provide a mean SSC value for subsequent record computations. Additionally, the time spent in record analysis ultimately is reduced.

Following are observations gleaned from table 5, which relied on information from the previous four tables:

- One should expect the need to allocate about 5-7 percent of the annual daily sediment station cost toward laboratory analyses of sample sets collected by hydrographers. For the sediment streamgage, that range might fall to about 3-4 percent.
- To attain an a minimally acceptable level of confidence in hydrographer-produced data, one should be reticent to allocate much less than about six percent of the annual cost of a daily sediment station for laboratory analyses, or about four percent of sediment streamgage costs.
- The allocation of an additional 1-2 percent of funding to the total operating costs of a sediment streamgage enables use of the reliable hybrid or dual-EDI methods (table 5, approaches I and II) in lieu of the comparatively risky (from a data-quality perspective) sole use of the dual-EWI method (approach III).
- This cost evaluation does not include de facto increases in the percentage of analytical costs versus total-station costs if any bad data collected by the hydrographer must be discarded.
- Conversely, the added monetary value of enhanced data quality due to the exclusion of bad data may be substantial albeit unquantified and perhaps unquantifiable. Regardless, these de facto cost benefits are quite real and should be recognized as such when considering the cost of the sediment record.

**SUMMARY AND CONCLUSIONS**

The technical and economic consequences of sole use of a dual-EWI as opposed to a dual-EDI, or a hybrid of the two methods – based on practical considerations related to data quality versus the resources to collect and analyze the samples for computation of an annual sediment record – have been described in the previous sections and can be summarized thusly: The expertise and attentiveness of the field hydrographer coupled with the selected sampling scheme can have a considerable and consequential influence on the reliability and cost-effectiveness of the derived sediment record.

Factors germane to this conclusion follow:

1. **HYDROGRAPHER, EXAMINE THY SAMPLES**: At the risk of being pedantic, it is difficult to overstate that the single most important activity available to the hydrographer is to minimize the potential for collecting bad data at a site by routinely examining the volume and quantity of accumulated sediments of each sample upon or soon after collection. Samples with anomalous quantities and/or sizes are the first and foremost tip-off that something may be amiss. The wise and conscientious hydrographer will not depart the site without resampling the vertical(s) that contributed to the potentially anomalous water-sediment mixture. The hydrographer must ascertain if the visual observations are likely to reflect the sedimentary conditions at the sampled verticals, or if results of the sample analyses are likely to contribute to the desk-bound analyst’s headaches when trying to deduce what might have gone awry at the sampling site.

2. **BAD DATA HAPPEN**: Some data that unequivocally are at odds with the preponderance of those used to produce a sediment record appear in the large majority these datasets. Although some of these outliers defy logical explanation, a careful review of field notes, laboratory reports, and other information usually infer with a high degree of confidence that the outliers originated as bad samples. The authors have ample reason to believe that this problem occurs at a frequency worthy of concern to those producing or using the data.

3. **BAD DATA ARE...BAD**: Without proper screening, analytical results from composite analyses adulterated by bad subsamples from one or more verticals will be factored into the computation of the mean SSC value. With rare exception, the resulting composite SSC value is biased toward higher values.

4. **ADDED COST FOR “BEST JOB” IS REASONABLE**: The annual station-operation costs for an increased number of analyses of hydrographer-collected samples listed in (one EDI sample set with individual-sample SSC analyses plus a second sample set composite analysis; table 5, approaches I or II; see FISP, 2013) exceed the minimal dual-composite approach (approach III) by a paltry 1-2 percent.
5. **AND YOU GET A BIGGER BANG-FOR-BUCK:** The hybrid or dual-EDI sample-set options have the added benefit of minimizing the risk of unknowingly including bad data in the permanent record. This is a consequence of the availability of spatially detailed SSC data from the individually analyzed EDI sample set that is both internally (within-set) comparable, and externally comparable to the results from the companion cross-section sample set. Additionally, the time spent in record analysis ultimately is reduced.

6. **A COST-EFFECTIVE QUALITY-ASSURANCE POLICY FOR YOUR SEDIMENT DATA:** To summarize the preceding observations: An EDI sample set with SSC analyses performed on each sample provides useful information on the cross-sectional SSC distribution. Also desirable, albeit rarely produced and generally cost-prohibitive, are size analyses on individual EDI samples. These data provide a “sediment-data quality-assurance policy” of sorts that enables the hydrographer to identify and discard unreliable EDI single-vertical SSC values, and/or to ascertain if the concurrent composite SSC value is consistent and reasonable with that for the EDI SSC value. This, in turn, either substantially increases the likelihood that hydrographer-collected data are demonstrably reliable, or enables the hydrographer to discard unreliable data. Conversely, this benefit is lost when using the dual-EWI composite approach.

7. **ERGO, AN ENDORSEMENT:** The authors unequivocally endorse the FISP (2013) hybrid option — or using that approach but substituting the EWI composite analysis with a composite EDI analysis — for the cost-effective and comparatively reliable derivation of hydrographer-collected SSC and PSD data. This endorsement is particularly germane to sediment-record computations for periods of medium-and-higher flows that are most influential in suspended-sediment transport.

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