Evaluating Methods for Applying Fouling Attenuation Shifts to Acoustic Backscatter Data Used in Suspended-Sediment Computations

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Introduction

The sediment acoustic index method is a standard technique for computing suspended-sediment characteristics from acoustic indices derived from acoustic Doppler velocity meter (ADVM) backscatter data (hereinafter referred to as “backscatter data”) (Landers and others, 2016). The sediment acoustic index method provides advantages over the use of other surrogate measurements such as data obtained from turbidity sensors and traditional streamflow measurements, including reduced hysteresis, better representation of cross-sectional conditions, and a lower risk of data loss caused by biological fouling (the growth of organisms such as barnacles on underwater surfaces, hereinafter referred to as “fouling”) (Glysson, 1987; Rasmussen and others, 2009). Although fouling is a lesser concern with ADVMs when compared to turbidity sensors, heavy fouling has the potential to substantially affect the quality of the backscatter signal, and, consequently, the accuracy of the continuous time-series of computed suspended-sediment concentrations (SSCs). As the sediment acoustic index method gains popularity in the scientific community, the range of aquatic environments in which it is used will likely increase. Developing standard methods for documenting and addressing attenuated backscatter data in environments in which heavy fouling occurs will be essential to maintain accurate, consistent, and comparable suspended-sediment estimates derived from acoustic index equations.

The U.S. Geological Survey (USGS), in cooperation with the Texas Water Development Board and the Galveston Bay Estuary Program, operates a network of streamgages along the Texas coast for the purpose of estimating freshwater inflows and nutrient and sediment loads delivered by streams into Texas bays and estuaries (Figure 1). The network includes streamgages in the lowermost reaches of five major river basins equipped with an ADVM to compute streamflow and estimate SSCs using the sediment acoustic index method (Landers and others, 2016). ADVMs are typically configured to collect and record backscatter data in a series of measurement volumes of equal size referred to as cells (Levesque and Oberg, 2012) (Figure 2). Some attenuation of the backscatter signal (a decrease in the amplitude of acoustic energy along the beam path of the signal) from acoustic absorption due to sediment and water properties is inherent (Landers and others, 2016). However, fouling attenuation (excessive backscatter signal attenuation resulting from sediment deposition, barnacles, or algae growth on the transducers of the ADVM), can also occur (Figure 3). At streamgages along the Texas coast, barnacle growth on the transducers is a common cause of fouling attenuation (Figure 4). Attenuation caused by fouling can affect the accuracy of computed SSCs in the following ways:

The quality of in-situ measurements of backscatter may be affected, resulting in inaccurate continuous time-series SSC estimates.

If attenuation caused by fouling is present when collecting data for a model calibration dataset, the validity of regression equations may be affected, and subsequent estimates of continuous SSCs might be biased.

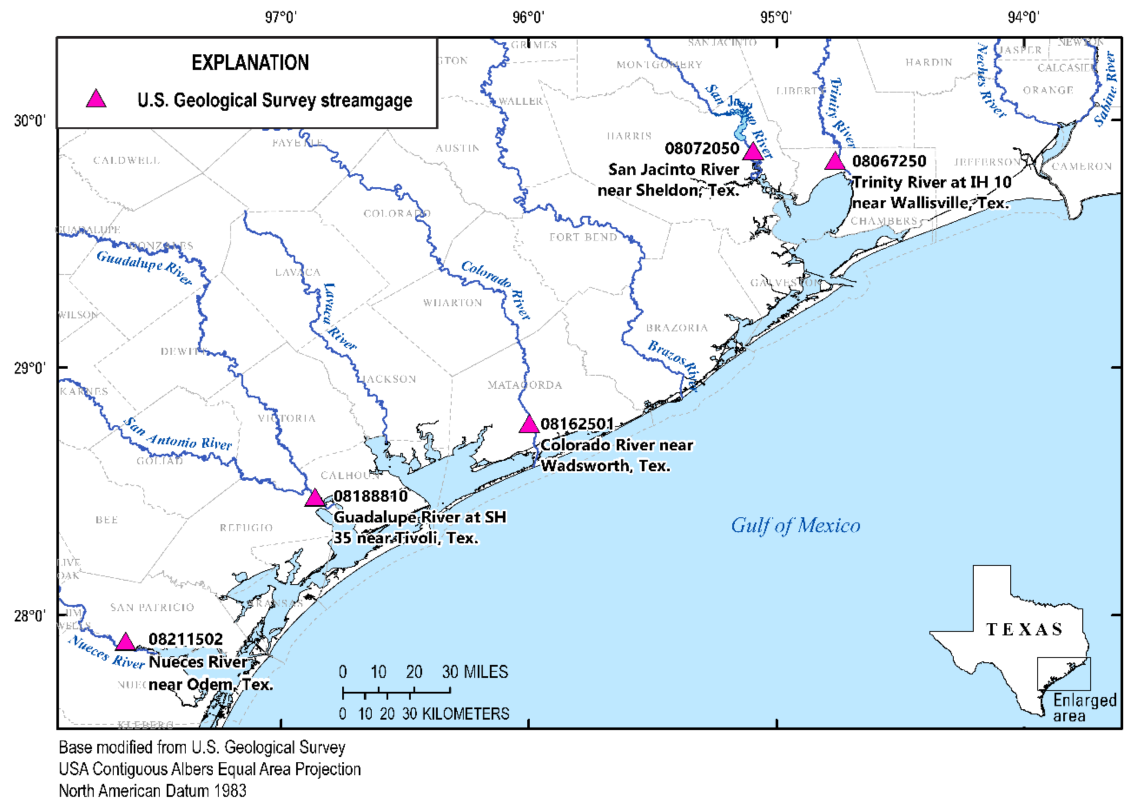

Figure 1. Map showing locations of U.S. Geological Survey streamgages along the Texas coast used for estimating freshwater inflows and nutrient and sediment loads delivered by streams into Texas bays and estuaries

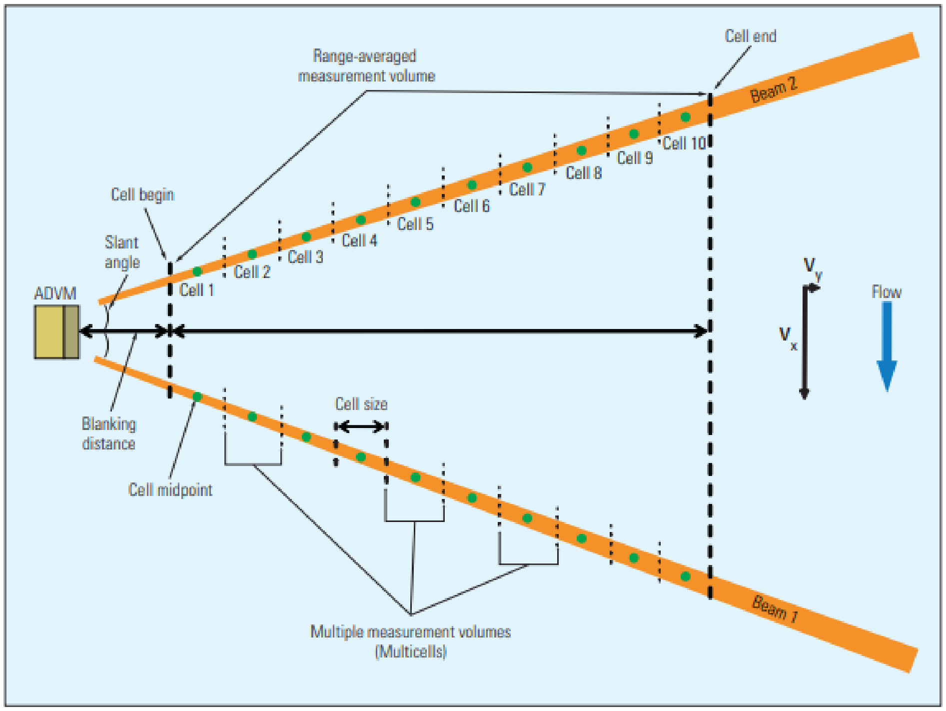

Figure 2. Generalized measurement volumes for a side-looker acoustic Doppler velocity meter (reprinted from Levesque and Oberg, 2012 [fig. 8])

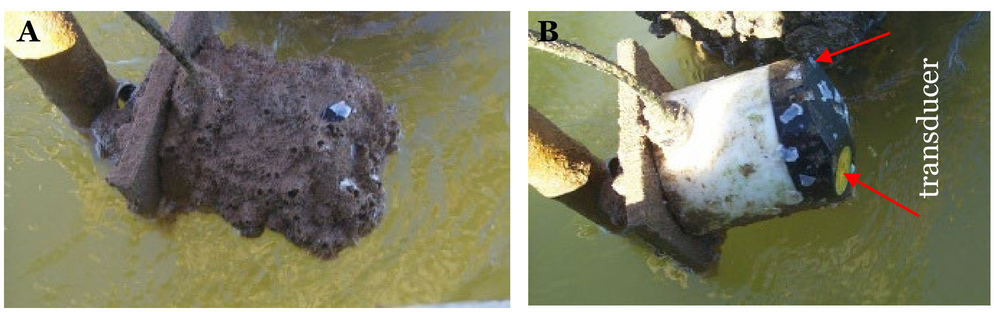

Figure 3. Photographs of an acoustic Doppler velocity meter *A*, before cleaning and *B*, after cleaning the instrument for barnacles; the transducers used to measure the acoustic backscatter signal are identified in panel B (photographs taken by U.S. Geological Survey)

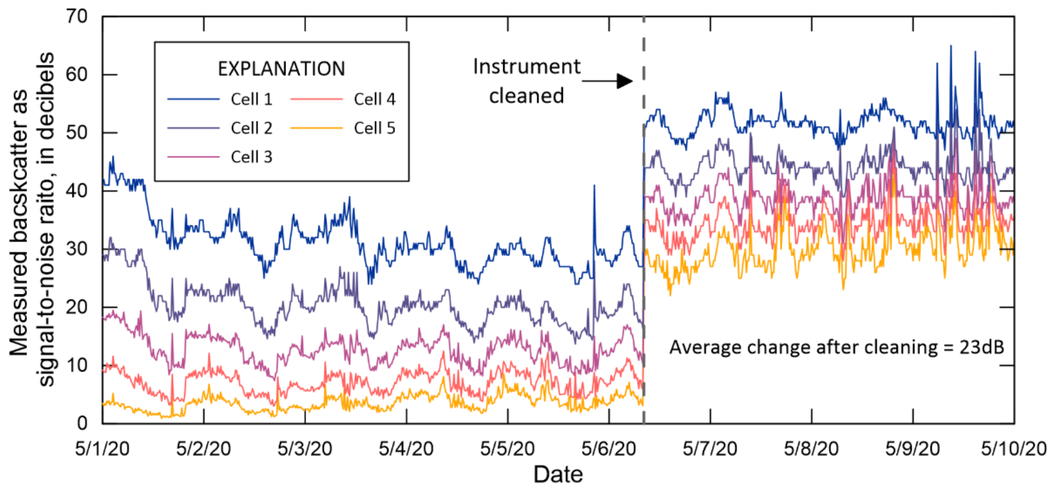

Figure 4. Time series of measured signal-to-noise ratio in decibels (dB) showing before and after cleaning readings at USGS streamgage 08162501 Colorado River near Wadsworth, Texas. After cleaning the acoustic Doppler velocity meter, the signal-to-noise ratio increased by an average of 23 decibels

The USGS applies corrections to raw-water datasets collected at streamgages on the basis of field observations or calibration checks by following a systematic approach (Rantz and others, 1982; Kennedy, 1983; Wagner and others, 2006). Corrections to raw-water datasets are hereinafter referred to as “shifts.” Shifts are applied by (1) determining the difference between in-situ readings from an instrument, (2) comparing the in-situ reading to a more accurate value from a measurement that is not affected by calibration drift or fouling, and (3) adjusting the raw data values by an appropriate value over a range of conditions (Rantz and others, 1982; Kennedy, 1983; Wagner and others, 2006). Landers and others (2016) suggested the use of shifts to address backscatter signal attenuation caused by fouling. To date, the feasibility of applying shifts has not yet been rigorously tested, and guidelines on methods and best practices for correcting backscatter signal attenuation caused by fouling have not been developed. Because the standard practice is to correct backscatter data for water and sediment attenuation at the individual cell level and then combine the individual datasets to compute a mean sediment corrected backscatter (Landers and others, 2016), backscatter-data shifts to account for fouling may not be as straightforward as shifts typically applied to water-quality data following guidelines in Wagner and others (2006). Factors to consider for backscatter-data shifts include the magnitude of attenuation at the cell level and determining when to apply a shift in the process of correcting specific backscatter data.

Different methods were evaluated for applying shifts to backscatter data to compensate for the effects of fouling on SSC computations made using ADVMs. Available data from an existing USGS streamgage were used to assess multiple methods for defining and applying shifts to backscatter data. The results of this study may be useful for developing a method for applying fouling shifts at sediment acoustic index streamgages. Points of consideration for the implementation of shifts in the current (2023) Aquarius Time-Series database platform (Aquatic Informatics, 2022) also were addressed.

Dataset Description

Backscatter data from USGS streamgage 08162501 Colorado River near Wadsworth, Tex. (hereinafter referred to as the “Wadsworth gage”) were used to evaluate methods for applying fouling shifts. The Wadsworth gage is approximately 17.1 river miles upstream from Matagorda Bay, and tides affect the daily streamflow records. Because of its location in an intertidal zone with saline and brackish water, barnacles grow on the surfaces of instruments placed underwater at the Wadsworth gage, resulting in fouling-induced backscatter signal attenuation. The Wadsworth gage was installed on September 28, 2016, and equipped with a SonTek SL 1500 3G ADVM used for computing streamflow and measuring acoustic backscatter signals. The ADVM was configured to collect and record backscatter data in a series of 10 cells, but because of sediment attenuation at the cells farthest from the transducers during periods of high SSCs, only cells one through five were used in the analysis. ADVM configuration properties are included in Table 1. Levesque and Oberg (2012) provide additional information about configuration of ADVMs and discussion of backscatter and other output data. Backscatter data were processed following methods described in Landers and others (2016) and corrected for water absorption and sediment attenuation in Aquarius Time-Series.

Table 1. Acoustic Doppler velocity meter (ADVM) configuration settings

Blanking distance (feet)	Number of cells	Cell size (feet)	Measurement averaging period (seconds)	Measurement interval (seconds)
7.22	5	6.56	300	900

Suspended-sediment samples were collected at the Wadsworth gage following methods described in Edwards and Glysson (1999). Samples were collected at streamflows ranging from 110 to 28,200 cubic feet per second (ft^3/s) (Figure 5). A limitation of this dataset is that SSCs corresponding to streamflows ranging from 4,970 to 21,600 ft^3/s are not represented because of the small number of events of this magnitude since the installation of the Wadsworth gage and the short duration of high-flow events. A total of 18 suspended-sediment samples were collected during October 2016—April 2022. SSCs ranged from 17 to 1,320 milligrams per liter (mg/L).

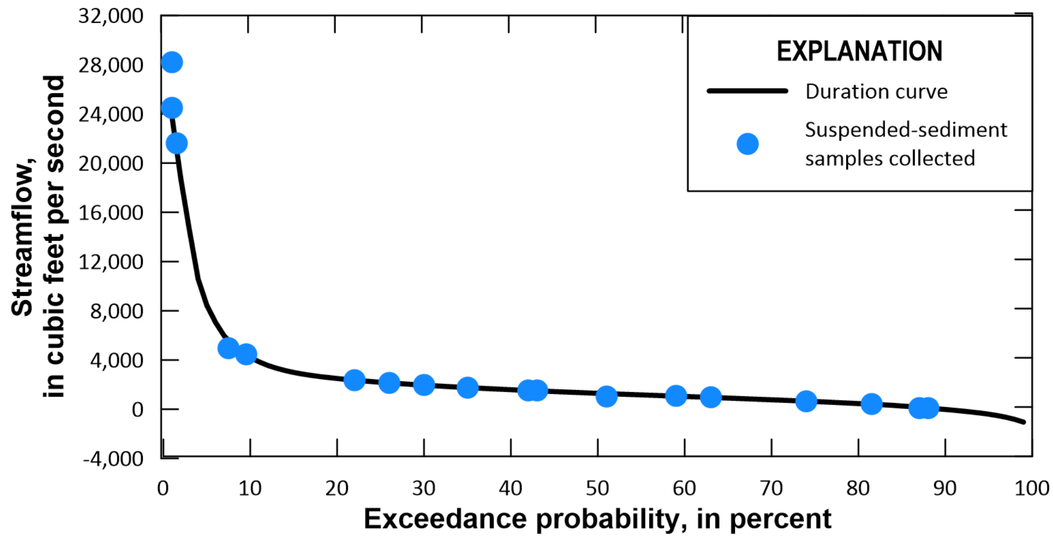

Figure 5. Flow duration curve for U.S. Geological Survey streamgage 08162501 Colorado River near Wadsworth, Texas, 2016–22.

Field Procedures

To determine the effect of fouling on backscatter data, the difference between the backscatter measurement before and after cleaning the instrument is computed. This value is typically referred to as the fouling error and is used to determine the magnitude of the shift to be applied to a time-series of data values (Wagner and others, 2006). For data comparability purposes, the ADVM is typically configured to use same averaging periods for recording backscatter values before and after cleaning. Documentation of the time and date the instrument was cleaned is also needed to establish when to apply the shift. The occurrence and timing of the cleaning of the ADVM and its transducers during a site visit was not always documented prior to 2018 because the USGS field software used for site-visit documentation did not include a section for ADVM inspections. Because some of the data used for this study were obtained prior to 2018, notes from site visits were used to determine when the instrument was cleaned. In some cases, it was assumed that the instrument had been cleaned in the absence of any cleaning documentation if an abrupt change in backscatter data-was evident in the data record corresponding with the time of a site visit. Because there is not a standard procedure for computing fouling shifts, backscatter data-from before and after cleaning were typically not recorded in the field and were thus obtained from the times-series data stored in the USGS National Water Information System (NWIS) (USGS, 2022) corresponding to the time when the streamgage was serviced.

Evaluation of Fouling Shifts

Before using backscatter data for computing SSCs, the multi-cell raw backscatter data recorded by an ADVM were corrected for beam spreading, water absorption, and sediment attenuation (Figure 6) (Landers and others, 2016). These corrections result in a variable called sediment corrected backscatter (SCB), which is typically used as an independent variable in linear regression models to predict SSC. Because of the multiple computations required to obtain SCB, applying shifts to backscatter data requires determining the most appropriate backscatter dataset (for example, raw backscatter data from individual cells, SCB data from individual cells, or the mean SCB representing all cells). Each dataset option has advantages and disadvantages and could potentially result in slightly different SCB values. Shifts were applied to data at various steps during the backscatter data-processing procedure (Figure 6) to determine the most appropriate backscatter dataset.

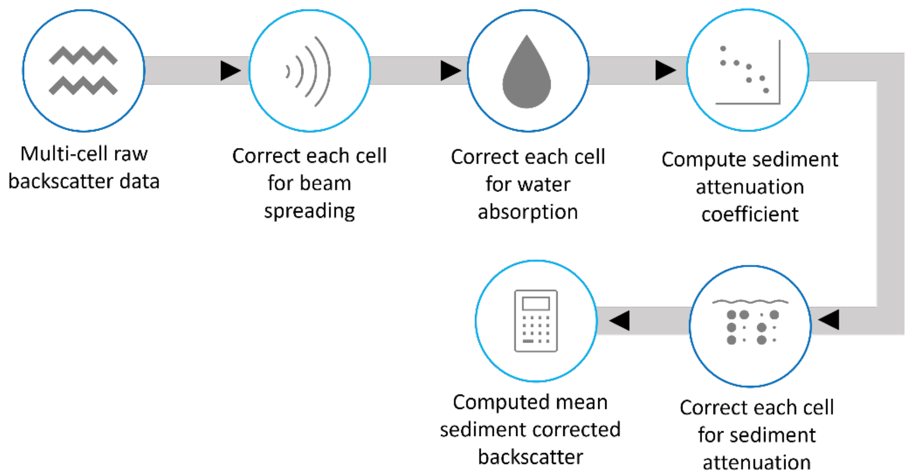

Figure 6. Acoustic backscatter data processing workflow

Multi-Cell Raw Backscatter Shift Evaluation: Possible shifts to raw backscatter data were evaluated for November 17, 2017, to August 13, 2020. The raw acoustic backscatter data (such as the signal-to-noise ratio in decibels) decreases steadily throughout the sampled zone due to water absorption and sediment attenuation (Landers and others, 2016); fouling attenuation typically occurs at a similar rate in each cell, which means the magnitude of the shift that needs to be applied to each cell increases as the cell number increases. The result is the magnitude of the shift is different for each cell. In an example from a site visit on January 30, 2019 (Table 2) the fouling error differs among cells and ranges from 5.86 to 17.7 percent. This variability in fouling error presents various challenges that influence the practicality of applying shifts to raw backscatter data. A minimum fouling error or percent error criterion is used when determining whether to apply a shift to a time-series of data values. Similarly, maximum shift limits are usually established for quality control. Determining minimum criteria and maximum allowable limits for shifts is not feasible for datasets with variable fouling errors. In addition, manually applying shifts to multiple time-series increases the potential for human error and is time consuming. Hence, the raw backscatter data may not constitute the most practical dataset to use when processing backscatter data to correct for fouling attenuation.

Multi-Cell Sediment Corrected Backscatter Shift Evaluation: The feasibility of applying shifts to multi-cell SCB from November 17, 2017 to August 13, 2020 was evaluated. Because multi-cell SCB values are corrected for water absorption and sediment attenuation, there is relatively little variability in fouling errors among cells. An example from a site visit on May 5, 2020, is shown in Table 3. Applying shifts during this step of the process of correcting backscatter data allows for the development of fouling shift minimum criteria and maximum allowable limits. Disadvantages include having to apply a shift to the time-series of data associated with each cell, which increases processing time and potential error introduction by the hydrographer, particularly at streamgages where a large number of cells are used to compute SCB.

Table 2. Multi-cell raw backscatter data and fouling drift computations from a site visit on January 30, 2019

Cell number	Signal-to-noise ratio before cleaning, in decibels (dB)	Signal-to-noise ratio after cleaning, in decibels (dB)	Fouling error, in decibels (dB)	Percent fouling error
1	67.72	73.58	5.86	8.7
2	56.98	63.16	6.18	10.8
3	49.16	54.05	4.89	9.9
4	41.02	47.53	6.51	15.9
5	34.51	40.7	6.19	17.9

Table 3. Multi-cell sediment corrected backscatter and fouling drift computations from a site visit on May 5, 2020

Cell number	Signal-to-noise ratio before cleaning, in decibels (dB)	Signal-to-noise ratio after cleaning, in decibels (dB)	Fouling error, in decibels (dB)	Percent fouling error
1	45.69	66.33	20.64	45.2
2	45.15	65.54	20.39	45.2
3	45.69	66.33	20.64	45.2
4	48.37	66.45	18.08	37.4
5	52.02	70.15	18.13	34.9

Mean Sediment Corrected Backscatter Shift Evaluation: The feasibility of applying shifts to the mean SCB time-series was evaluated using data obtained from November 17, 2017, to January 19, 2022. This method only requires applying shifts to one time-series, thus reducing time associated with applying and reviewing shifts to multiple time-series. Because only one time-series is shifted, fouling shift minimum criteria and maximum allowable limits could also be readily developed and applied.

The effect of applying fouling shifts to different time-series on the resulting mean SCB was evaluated by using continuous data from June 14, 2018, to January 30, 2019, a period in which hydrologic and sediment conditions varied appreciably. Multi-cell raw backscatter data and mean SCB data were shifted for this period, and their resulting mean SCBs compared. A time-series plot (Figure 7) shows that the mean SCB resulting from shifting multi-cell raw backscatter data and mean SCB are similar. A linear regression equation between both time series has a slope of 1.0 and an intercept of 0.14 (Figure 8), indicating that mean SCBs from both time series are essentially equal. Hence, there are computational advantages to shifting mean SCB data compared to shifting multi-cell backscatter data, and applying shifts to the mean SCB time-series is preferable compared to applying shifts at the multi-cell level.

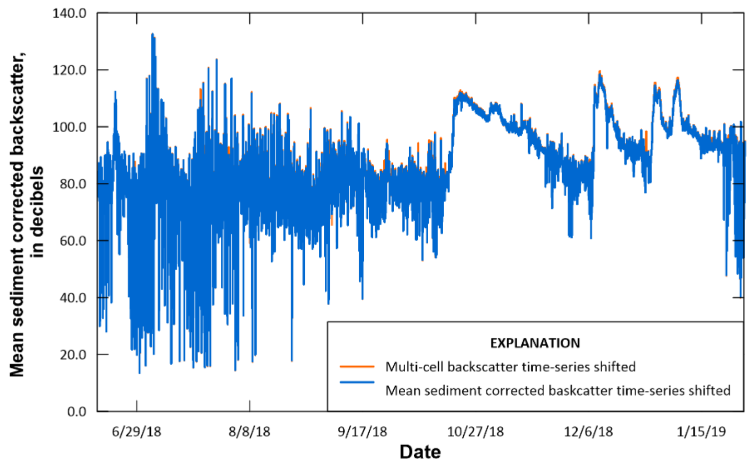

Figure 7. Computed mean sediment corrected backscatter data from June 24, 2018, to January 30, 2019, after shifting multi-cell backscatter data and mean sediment corrected backscatter data from USGS streamgage 08162501 Colorado River near Wadsworth, Texas

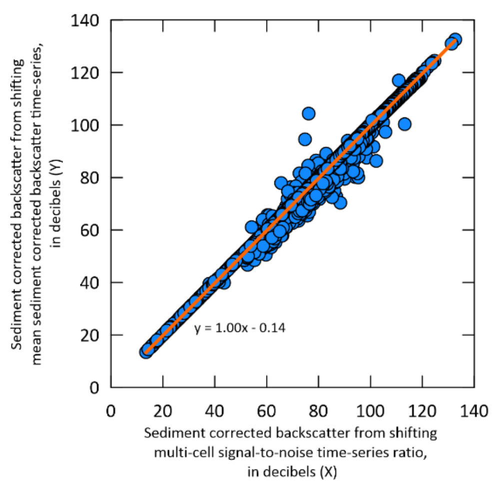

Figure 8. Sediment corrected backscatter data resulting from shifting the multi-cell signal-to-noise ratio time-series and sediment corrected backscatter resulting from shifting the mean sediment corrected backscatter time-series

Fouling Shift Procedures: Fouling shifts for water-quality properties are typically applied to periods between site visits when the equipment is cleaned (Wagner and others, 2006). The assumption is made that fouling-induced drift in the values recorded for water-quality properties occurs at a constant rate; however, if certain environmental or hydrologic events can be identified as distinct fouling events, the event may be used as the start or end date of a given fouling shift. The same assumption would apply to shifting mean SCB data, but additional challenges associated with collecting backscatter data with ADVMs require developing specific operational procedures. One of these challenges is the inability to monitor changing environmental conditions while the instrument is being serviced. Typical fouling-drift computations require deploying a second instrument to monitor any changing environmental conditions at the monitoring location while servicing the streamgage and documenting measurements before and after cleaning the instrument. Backscatter data can vary between instruments because of the variability caused by inherent electrical noise associated with each instrument and because of manufacturing differences. Additionally, because there is no readily available method to calibrate the backscatter data to a known standard, ADVMs are not easily interchangeable for sediment surrogate analysis. Because obtaining comparable data to monitor changing conditions is not possible, scheduling instrument cleaning during periods of relatively stable conditions is critical to minimizing bias.

Another challenge specific to backscatter data is associated with the determination of minimum criteria and maximum allowable limits for data shifts. Minimum criteria are implemented to ensure that data are not shifted beyond the accuracy of the instrument whereas maximum allowable limits are needed to avoid excessive shifts and maintain data quality. For conventional water-quality properties, minimum criteria and maximum allowable limits are based on instrument-calibration criteria; however, backscatter properties are not calibrated, and the range of values observed is dependent on instrument and sediment characteristics. Because ADVMs were developed to primarily measure velocity, not backscatter, there is high variability associated with the backscatter signal and accuracy and precision specifications for backscatter data are not typically published by instrument manufacturers. Measures of statistical variability (such as variance and standard deviation) applied to backscatter time-series data collected at the streamgage would not be appropriate to assess instrument variability because the calculations would also include the variability associated with changes in environmental conditions, such as streamflow and sediment concentrations. Thus, in order to develop minimum criteria and maximum allowable limits for data shifts, a better understanding of the accuracy and variability of backscatter data under stable conditions would be needed.

Although additional data are needed to develop guidelines for minimum criteria and maximum allowable limits, the fouling error was computed for 11 visits to the Wadsworth gage to test the feasibility of applying fouling shifts in the Aquarius time-series platform and evaluate the effects of applying shifts on model calibration data. Fouling error ranged from 0.3 to 172 percent. For purposes of this study, shifts were applied as a prorated percent shift to periods when the fouling error exceeded 6 percent. Without established shifting criteria limits, this value was selected for this dataset because applying shifts based on lower criteria did not considerably improve the derivation of mean SCB in this dataset. Data were shifted up to a maximum of 46.2 percent, the second largest fouling error computed among the 11 visits. During the period with the maximum fouling error of 172 percent, it was determined that excessive fouling occurred after a storm event. Instead of applying an extremely large shift, data were deleted starting from the date excessive fouling likely started.

Model Calibration and Validation Data

Sediment acoustic index ratings were developed by using linear regression equations to model the relation between SSC and acoustic surrogate (mean SCB) data. During the period evaluated for this study, only three out of 17 observations were collected during periods when fouling attenuation was present. To evaluate the effects of processing mean SCB data on model fit, linear regression equations were developed using (1) unshifted data and all 17 observations, (2) unshifted data and the 14 observations not affected by fouling attenuation, and (3) shifted data and 16 observations (one observation was deleted due to excessive fouling) (Table 4). SSC data were log transformed. The model developed with unshifted data and all observations had a coefficient of determination (R^2) of 0.67 and a root-mean-square error (RMSE) of 212.5 percent (Helsel and others, 2020). The R^2 and RMSE improved to 0.75 and 162.6 percent, respectively, when observations affected by fouling attenuation were removed. The model developed using shifted mean SCB data had the highest R^2 (0.81) and lowest RMSE (145.9 percent). Although there are other parameters that should be considered to assess the adequacy of a linear model (such as distribution of residuals and serial correlation) and this evaluation was completed with a limited number of observations, preliminary results indicate that shifting mean SCB data can potentially improve model fit.

Fouling attenuation can be eliminated by cleaning the ADVM prior to collecting SSC samples for model calibration and validation purposes. Thus, following the routine field cleaning practices presented in Levesque and Oberg (2012) before sample collection is advisable. If the ADVM cannot be cleaned prior to collecting an SSC sample and fouling attenuation is observed in the SCB data, either shifting mean SCB data or removing these observations from the calibration dataset should be considered.

Table 4. Linear regression equations and statistical diagnostics for three different models developed with unshifted or shifted mean sediment corrected backscatter data

[SCB, sediment corrected backscatter; n, number of observations; R^2, coefficient of determination; %, percent; RMSE, root-mean-square error; BCF, bias correction factor]

Data processing	Linear regression equation	n	R^2	RMSE (%)	BCF
Unshifted mean SCB	log10SSC = -0.498 + 0.0306MeanSCB	17	0.67	212.5	2.16
Unshifted mean SCB, removed data points affected by fouling	log10SSC = -1.44 + 0.0405MeanSCB	14	0.75	162.6	1.68
Shifted SCB	log10SSC = -1.61 + 0.0424MeanSCB	16	0.81	145.9	1.63

Data Processing and Documentation

After a sediment acoustic index rating is developed and approved, it can be used to compute SSCs and suspended-sediment loads in real-time (Landers and others, 2016). A typical practice of the USGS is to compute sediment concentration and load data derived from linear-regression equations by using the Aquarius time-series platform and publish these computed data values in the USGS NWIS database (USGS, 2022). These data are subject to USGS policies for processing, approving, auditing, and publishing time-series records for water data (USGS, 2017). In this section, procedures that incorporate current platforms available to the USGS for data processing and documentation are proposed.

Documentation of Field Data: The date and time an instrument is cleaned and backscatter data obtained from measurements before and after cleaning are needed to determine the shifting period and the magnitude of the shift. The current (2023) version of the field software application used by the USGS (Site Visit Mobile Aquarius [SVMAQ]) contains a section for index-velocity inspections that can be used to document the time and date an instrument was cleaned and redeployed. Noting any observations on the type and degree of fouling is good practice as field observations are sometimes useful when processing time-series records.

Obtaining before and after cleaning readings of mean SCB in the field is currently not possible because mean SCB is a computed value resulting from processing and correcting the backscatter data. The most efficient method to obtain mean SCB values associated with a cleaning visit is to set up the computations for processing the backscatter signal in the Aquarius platform and retrieve the before and after cleaning readings corresponding to the time of the visit. This requires either manually loading the ADVM log into Aquarius or using telemetry to transmit ADVM data from the streamgage.

Time-series Processing: After determining the processing period and obtaining the mean SCB values associated with the cleaning visit, the fouling error can be computed and applied to the time series. For conventional water-quality properties, fouling shifts are applied in the Aquarius platform by either applying a percentage correction or a point-value correction. Percentage corrections are applied when the range of values is large over the period and point corrections are applied when the range in environmental values is small (Wagner and others, 2006). Because of the variability of backscatter data and typical ranges observed, percentage corrections tend to be the most appropriate. In the Aquarius platform a prorated percentage correction is available as part of the “Multipoint” edit type. Currently, applying these corrections require the analyst to compute the fouling error and apply the percentage correction manually.

Records Processing Documentation: The USGS uses the Records Management System (RMS) to document the processing of time-series data, including computed time series such as SSC derived from an acoustic index rating. Because mean SCB is typically not a published time-series, fouling shifts applied to the mean SCB time-series can be documented in RMS when analyzing the record for SSC. A limitation of documenting fouling shifts when processing the SSC time-series is that the SSC time-series would not be available until the acoustic index rating is developed and approved.

Data Processing and Documentation Limitations: Because applying shifts to backscatter data is not a standard USGS procedure, the platforms currently available, although functional, are not optimized for processing these data. For example, although SVMAQ has a field to document the time an instrument was cleaned, the information is not imported into Aquarius and can only be retrieved by opening the site visit file. Some improvements in the workflow could include the development of tools that provide the ability to automatically compute or apply fouling errors to the time-series data and allow for the computation of mean SCB from measurements made during cleaning visits.

Limitations and Future Considerations

This paper presents a workflow for applying shifts to backscatter data affected by fouling attenuation and demonstrates the feasibility of applying these shifts while incorporating current platforms available to the USGS for data processing and documentation. Limitations of this study include the lack of complete records on instrument cleanings and the availability of data from only one streamgage (the Wadsworth gage) for testing the proposed procedures. The USGS has already identified another streamgage that is affected by fouling attenuation and is currently collecting data to test the procedures presented in this report to determine if they can successfully be replicated. Additionally, applying these methods at another streamgage will help to improve the documentation and processing guidelines and continue evaluating protocols for minimum criteria and maximum allowable limits for backscatter data.

Disclaimer

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