Feasibility of Using Acoustic Velocity Meters for Estimating Highly Organic Suspended-Solids Concentrations in Streams

By Eduardo Patino

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Abstract

A field experiment was conducted at the Levee 4 canal site below control structure G-88 in the Everglades agricultural area in northwestern Broward County, Florida, to study the relation of acoustic attenuation to suspended-solids concentrations. Acoustic velocity meter and temperature data were obtained with concurrent water samples analyzed for suspended-solids concentrations. Two separate acoustic velocity meter frequencies were used, 200 and 500 kilohertz, to determine the sensitivity of acoustic attenuation to frequency for the measured suspended-solids concentration range. Suspended-solids concentrations for water samples collected at the Levee 4 canal site from July 1993 to September 1994 ranged from 22 to 1,058 milligrams per liter, and organic content ranged from about 30 to 93 percent.

Regression analyses showed that attenuation data from the acoustic velocity meter (automatic gain control) and temperature data alone do not provide enough information to adequately describe the concentrations of suspended solids. However, if velocity is also included as one of the independent variables in the regression model, a satisfactory correlation can be obtained. Thus, it is feasible to use acoustic velocity meter instrumentation to estimate suspended-solids concentrations in streams, even when suspended solids are primarily composed of organic material. Using the most comprehensive data set available for the study (500 kilohertz data), the best fit regression model produces a standard error of 69.7 milligrams per liter, with actual errors ranging from 2 to 128 milligrams per liter. Both acoustic velocity meter transmission frequencies of 200 and 500 kilohertz produced similar results, suggesting that transducers of either frequency could be used to collect attenuation data at the study site. Results indicate that calibration will be required for each acoustic velocity meter system to the unique suspended-solids regime existing at each site. More robust solutions may be defined in streams with suspended solids having lower percentages of organic composition.

INTRODUCTION

The transport of suspended material in streams or open channels plays an important role in contaminant transport, aquatic reproduction, and channel stability. Suspended-solids concentrations are directly related to the transport of contaminants, especially those that attach to fine solid particles. Suspended solid particles can reduce light penetration through the water column, thus having a detrimental effect on the natural processes of aquatic life.

Improved measuring techniques are needed to understand the mechanics of suspended-solids (sediment) transport in order to address various environmental concerns. Conventional methods of sediment record computation involve collecting sediment samples during different flow conditions in order to develop a sediment discharge to water discharge calibration curve. Since up to 80 percent of the sediment load can be carried by a single storm, and, in most instances, it is difficult and sometimes impossible to collect samples of suspended solids during the rising period or at the peak of a flood wave, record estimation of sediment loading becomes highly subjective. An instrument capable of accurately measuring the velocity of water in streams and producing a continuous index of suspended-solids concentrations during ambient and flood conditions would greatly aid in the calculation of suspended-solids loadings. As a result, the U.S. Geological Survey, in cooperation with the South Florida Water Management District, began a study in 1992 to determine the feasibility of using acoustic velocity meter (AVM) systems to estimate concentrations of highly organic suspended solids in southern Florida canal waters.

Purpose and Scope

The purpose of this report is to document the feasibility of using AVM systems to estimate concentrations of highly organic suspended solids in streams by using relations developed between AVM recorded data, temperature, and measured suspended solids. AVM frequencies of 200 and 500 kHz (kilohertz) were used to determine the sensitivity of different manufactured frequency transducers to changes in the concentrations of suspended material. Temperature and specific conductance profiles were also recorded to determine any effects on the attenuation of the acoustic signal from temperature or density stratification.

Description of Study Site

The Levee 4 canal below control structure G-88 in northwestern Broward County, Florida, was selected as the study site. This canal is typical of many canals that comprise the southern Florida canal system (fig. 1). The manmade canal, dredged in limestone bedrock, has a trapezoidal cross section; the canal is about 40 ft (feet) wide and has an average depth of between 7 and 8 ft. Flows are well mixed through the channel section and primarily represent runoff from farmlands in the Everglades agricultural area. These flows are sometimes reversed depending on activity at the control structures and agricultural pumping. Velocities ranged from -0.5 to 2.5 ft/s (feet per second). Concentrations of suspended solids vary depending on velocity and the extent of water contribution from farmland runoff to the total flow in the canal.

Previous Studies

Flammer and others (1969) successfully experimented with the response of an ultrasonic plane wave to changing sediment properties and with the ultrasonic measurement of sediment-size distribution and concentration. Meister and St. Laurent (1960) studied the ultrasonic absorption and velocity in water containing algae in suspension, and Watson and Meister (1963) performed experiments with ultrasonic absorption in water containing plankton in suspension. Recent field applications include the experiments made with Acoustic Doppler Current Profiler instrumentation where suspended-sediment concentrations in estuaries are correlated to the back scatter intensity of received acoustic beams (Thevenot and Kraus, 1993).

METHODS OF INVESTIGATION

AVM systems have proven to be accurate and reliable instruments for measuring velocities of water in channels or streams (Laenen and Curtis, 1989). At the same time, these systems could be used to estimate suspended-solids concentrations in open channels. The next two sections of this report describe the instrumentation of the AVM systems and the various methods of data collection that were performed at the Levee 4 canal study site for analysis. Data were collected from July 1993 through September 1994. The AVM, suspended-solids, and temperature data collected during sampling periods are presented in table 1.

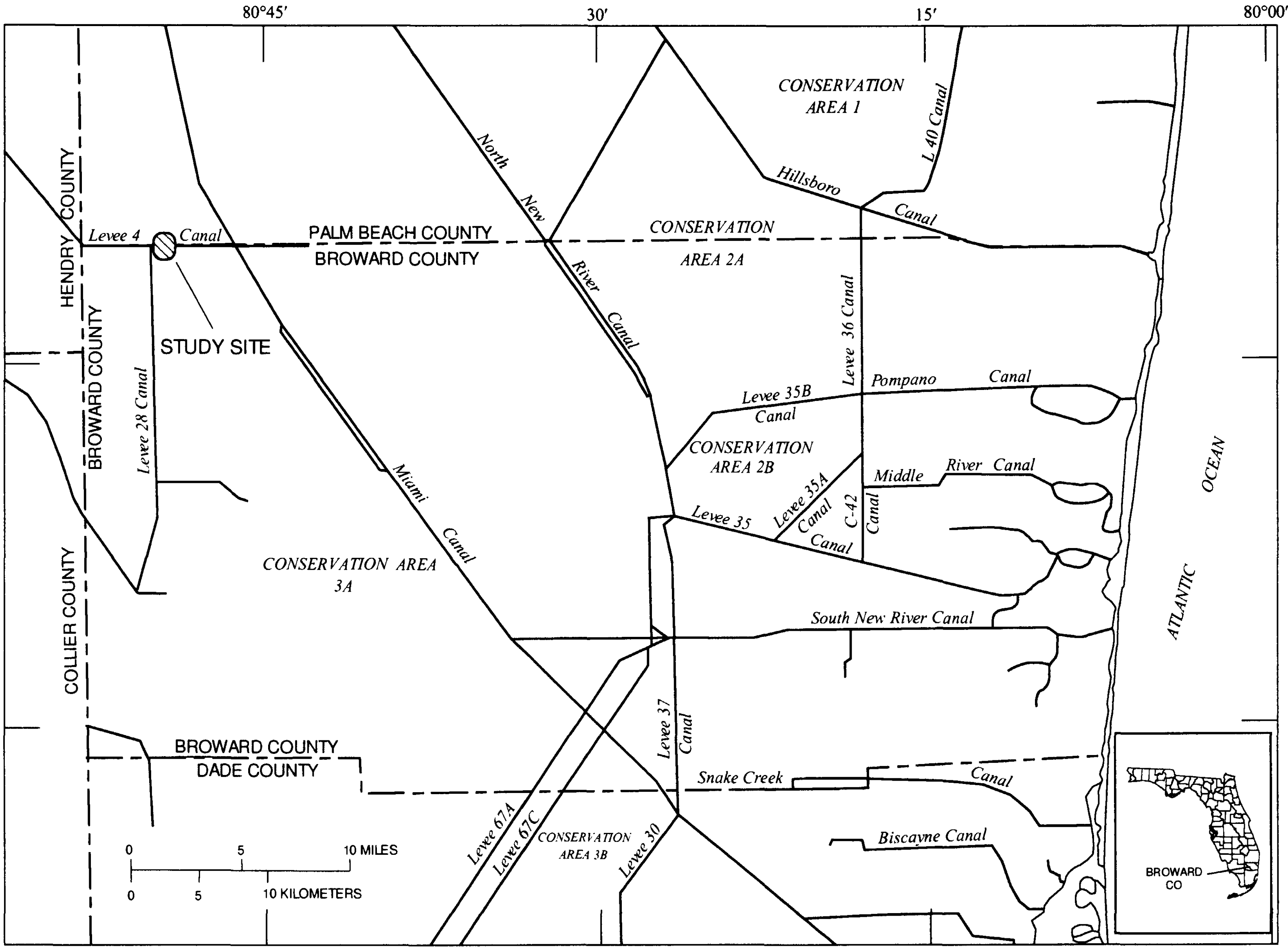


Figure 1. Location of the Levee 4 canal study site in northwestern Broward County, Florida.

Table 1. Acoustic velocity meter data, suspended-solids concentrations, and temperature data at the Levee 4 canal site

[All data collected with AVM systems represent averaged values for part of the stream width at a certain location in the vertical. AGC, automatic gain control; AVM acoustic velocity meter; TSS, total suspended solids; kHz, kilohertz, mg/L, milligrams per liter; ABS, absolute value; ft/s, feet per second. Asterisk indicates "bad" measurement (a different method was used); double asterisk indicates measurements during negative flow; dashes (--) indicate AVM not operational]

Measurement number	Date	AGC 200 kHz, AVM 1 (decibels)	AGC 500 kHz, AVM 2 (decibels)	AGC 200 kHz, AVM 2 (decibels)	TSS (mg/L)	Organic suspended solids (mg/L)	Inorganic suspended solids (mg/L)	Percent organic suspended solids	Stage (feet)	AVM 1 velocity ABS 200 kHz (ft/s)	AVM 2 velocity ABS 500 kHz (ft/s)	AVM 2 velocity ABS 200 kHz (ft/s)	Channel mean velocity (ft/s)	Temperature 1 (degrees Celsius)	Temperature 2 (degrees Celsius)
1	08-03-93	28.3	38.3	--	60	44	16	73	11.48	0.65	0.56	--	0.51	28.7	28.7
2	09-03-93	--	40.4	--	224	172	52	77	--	--	.76	--	--	27.3	27.3
3	09-15-93	37.0	41.7	--	1,058	635	423	60	13.02	2.41	2.05	--	1.91	27.0	27.0
4	12-15-93	33.1	41.8	--	246	228	18	93	11.47	.29	.27	--	.23	18.7	18.7
5*	12-15-93	34.2	42.4	--	30	15	15	50	11.46	.28	.26	--	.22	18.8	18.8
6	02-03-94	34.1	--	--	90	60	30	67	10.22	1.27	1.12	--	1.01	16.9	16.9
7	02-03-94	34.5	--	--	136	92	44	68	10.41	1.33	1.16	--	1.05	17.2	17.2
8**	04-04-94	34.6	--	27.6	77	55	22	71	10.36	.33	--	0.20	.26	24.3	24.3
9**	04-04-94	34.1	--	27.8	78	61	17	78	10.41	.27	--	.12	.21	24.5	24.5
10**	04-04-94	31.8	--	27.8	108	91	17	84	10.42	.20	--	.10	.16	24.6	24.6
11	04-22-94	33.5	37.3	25.7	46	20	26	43	10.83	.36	.27	.29	.29	26.3	26.1
12	04-22-94	34.0	37.4	26.0	22	11	11	50	10.80	.36	.25	.27	.28	26.3	26.1
13**	05-17-94	34.0	37.3	26.0	96	29	67	30	11.48	.50	.49	.47	.40	29.5	29.5
14**	05-17-94	34.2	37.5	26.1	35	15	20	43	11.50	.55	.49	.50	.44	29.7	29.6
15	06-24-94	34.1	39.0	26.4	181	154	27	85	9.66	.55	.46	.43	.44	28.3	28.2
16	06-24-94	34.6	39.3	267	72	50	22	69	9.74	.43	.36	.33	.34	28.3	28.2
17	07-01-94	34.0	39.3	26.5	78	49	29	63	11.39	.32	.23	.22	.25	28.9	28.8
18	07-01-94	34.0	39.3	26.5	80	60	20	75	11.39	.32	.23	.22	.25	28.9	28.8
19	07-07-94	--	40.4	30.0	546	317	229	58	12.72	2.27	2.02	1.96	1.80	27.1	27.1
20	07-07-94	--	402	30.4	514	294	220	57	12.70	2.24	2.04	2.05	1.77	27.1	27.1
21	07-07-94	--	40.5	30.3	528	303	225	57	12.68	2.25	2.03	2.11	1.78	27.1	27.1
22	07-07-94	--	42.9	30.3	512	294	218	57	12.65	2.35	2.01	2.10	1.86	27.1	27.1
23	07-07-94	--	40.8	30.2	533	310	223	58	12.57	2.41	2.11	2.17	1.91	27.1	27.1
24	07-08-94	--	38.8	29.4	321	183	138	57	12.74	2.19	1.85	1.97	1.73	28.1	28.1
25	07-08-94	--	39.5	29.3	318	178	140	56	12.66	2.26	1.99	2.05	1.79	28.1	28.1
26	07-08-94	--	39.2	29.4	304	167	137	55	12.55	2.39	2.00	2.06	1.89	28.1	28.1
27	07-08-94	--	39.4	29.8	298	165	133	55	12.52	2.44	2.11	2.10	1.93	28.1	28.1
28	07-12-94	--	38.7	29.1	351	198	153	56	12.44	1.77	1.52	1.54	1.40	29.2	29.2
29	07-12-94	--	39.0	29.5	262	134	128	51	12.44	1.86	1.51	1.59	1.47	29.2	29.2
30	07-12-94	--	39.6	30.1	246	130	116	53	12.08	2.15	1.90	1.93	1.70	29.2	29.2

Acoustic Velocity Meter Instrumentation

AVM systems obtain timed information across the stream from bank to bank at a fixed elevation in the stream by means of ultrasonic pulses sent diagonally from one transducer (transmitter/receiver) to the other and back. Velocity calculations are performed using time differences between the signal traveling with the flow and the signal traveling against the flow and also path angle and path length information.

The AVM systems also provide data pertinent to the quality and strength of the acoustic signal as it is received across the stream. The automatic gain control (AGC) output value can be used as an index of overall acoustic signal attenuation, part of which is due to the presence of suspended particles in the water. The AGC value represents the adjustment in receiver sensitivity needed to increase or decrease the received signal to an amplitude acceptable for recognition. The AGC value is reported in decibels and can be used to quantify the loss of signal strength (attenuation) as the pulses travel through the water across the stream.

AVM data were collected for this study at two different elevations in an attempt to obtain acoustic information through media of different composition. A preexisting 200-kHz (AVM 1) system was in operation at 9.0 ft above sea level and was calibrated to make flow computations. A second system (AVM 2) was installed at 7.0 ft above sea level and was used to collect data at 200 and 500 kHz for this study. Vertical and horizontal views of the AVM instrumentation are shown in figure 2.

Data Collection

Data collected by AVM systems primarily include line velocity and AGC values. All AVM data represent averaged information at an elevation in the stream cross section. Line velocity can be related to the mean velocity of the channel cross section by means of regression analyses. The AGC, as previously indicated, is used to adjust the ultrasonic pulse amplitude, making it acceptable for signal recognition. Resulting AGC values, even though not a true measure of signal attenuation, can be used as an index to represent the total attenuation of the pulse. Changes in AGC values represent comparative corresponding physical or chemical changes in water, provided that electronic components remain unchanged (or that the effects of changes in components are insignificant) and that transducer direction, location, and cleanliness also remain unchanged.

Water samples for measurement of total suspended solids were collected using a DH-59 model sediment sampler with glass bottles in accordance with U.S. Geological Survey prescribed methods (Edwards and Glysson, 1988). Three samples were collected for each measurement at three equal flow subsections, with each bottle representing an integrated vertical sample. A diagram of the spacing between each subsection of equal flow and the sampling locations at midpoint of each subsection is shown in figure 3. Selection of equal flow sections was based on previous discharge measurements at the site. The three samples were combined into one composite sample to obtain an average total suspended-solids concentration for the entire channel section. Point samples were obtained at several depths along the center of the channel to define the vertical distribution of suspended material.

In the laboratory, each composite sample was dried at 105°C (degrees Celsius) to obtain the total suspended-solids concentration and then baked at 500°C to obtain inorganic residue concentration. Measured total suspended-solids concentrations at the study site ranged from 22 to 1,058 mg/L (milligrams per liter) and organic content ranged from about 30 to 93 percent (table 1).

Finally, temperature and specific conductance data were collected to determine possible detrimental effects on the acoustic signal from temperature and density stratification. Water-surface elevation data were also collected to determine water cross-sectional area and discharge and to identify possible multipath interference on the acoustic signal caused by the proximity of the water surface for the acoustic path. These influential factors are discussed in the next section.

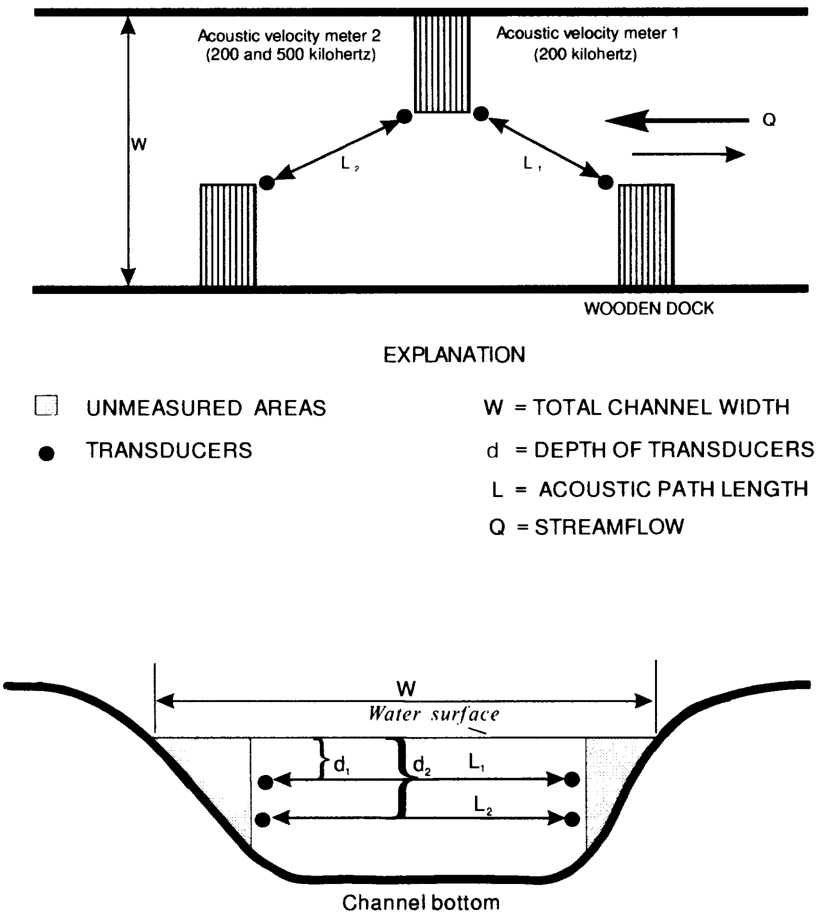


Figure 2. Vertical and horizontal views of acoustic velocity meter transducer (transmitter/receiver) locations.

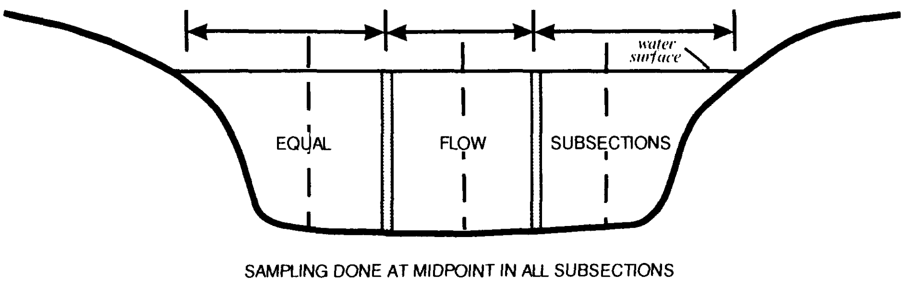


Figure 3. Equal flow subsections used in sample collection. Depth-integrated samples were taken in the center (dashed line) of each subsection and composited.

ACOUSTIC ATTENUATION AND INFLUENTIAL FACTORS

Attenuation of an ultrasonic pulse (acoustic attenuation) as the pulse travels from one point to another through a given medium is usually attributed to spreading, absorption, and scattering (fig. 4). An equation by Urick (1983), which shows that spreading losses are proportional to the distance traveled by an acoustic signal, suggests that these losses are not significant for the acoustic path length (less than 40 ft) at the study site. For changes in acoustic attenuation to be attributed primarily to the absorption and scattering properties of the water and suspended materials, it is necessary to avoid boundary reflections or ray bending. No attempt is made herein to separate the sources of signal loss because the focus of this study is on changes in total attenuation in relation to changes in total suspended-solids concentration. The most significant factors that directly influence acoustic attenuation are water temperature and density stratification, acoustic path length, minimum boundary clearance (for example, water surface or bottom distance from acoustic path), and concentration and composition of suspended material.

Effects of Temperature and Temperature-Density Gradients on Attenuation

Temperature data were recorded on a continuous basis at three elevations at a location near one of the banks (fig. 5). The three temperature sensors were installed at 9.5, 7.5, and 6.0 ft above sea level, covering a depth range that included both acoustic paths. Three vertical temperature and specific conductance profiles were also taken at the same time and at the same locations as the suspended-solids measurements (fig. 3).

Temperature and specific conductance profile data were collected to determine possible path-length changes due to ray bending and to account for attenuation dependency on temperature. The data suggest that no temperature or density gradients exist and, therefore, no adjustments need to be made to acoustic attenuation from these sources.

Ray bending is defined as a change in travel direction of the pulse due to horizontal/vertical temperature or density gradients. If ray-bending conditions exist (fig. 6), the listening transducer will receive an acoustic signal away from its center of power, or no signal at all. Also, because of ray bending, the signal will travel a longer path between transducers and will be at a different location in the vertical—factors that will change the total attenuation of the signal. At the Levee 4 canal site, there were no significant gradients observed in the horizontal and the vertical planes because the system is well mixed at times of flow.

Meister and St. Laurent (1960) have shown in laboratory studies that total absorption (water and suspended material) are inversely related to temperature for all concentrations of algae. Because water samples collected at the study site contain high concentrations of organic material, temperature is considered to be one measurable property that needs to be considered in the total suspended-solids estimation process.

Effects of Path Length and Vertical Location on Attenuation

The distance that the acoustic pulse has to travel across the medium is directly related to the spreading loss. The acoustic path length at the Levee 4 canal site was less than 40 ft and remained constant because no temperature or density gradients were present. Thus, path length is not a factor to be considered in the total suspended-solids estimation process for this location. Because long acoustic paths are more sensitive to temperature and density gradients, the selection of sites in future studies should consider acoustic path length and ray bending.

Continuous water-surface elevation (or stage) data were collected at the study site to calculate time-dependent cross-sectional area and discharge. Water-surface elevation data were also used to monitor the relative location of the acoustic path to the water-surface boundary. The stage measured during the period of study ranged from 9.66 to 13.02 ft above sea level.

Water-surface and streambed elevations constitute the upper and lower travel boundaries of the acoustic signal and need special consideration to avoid multipath interference. Multipath interference (fig. 7) is

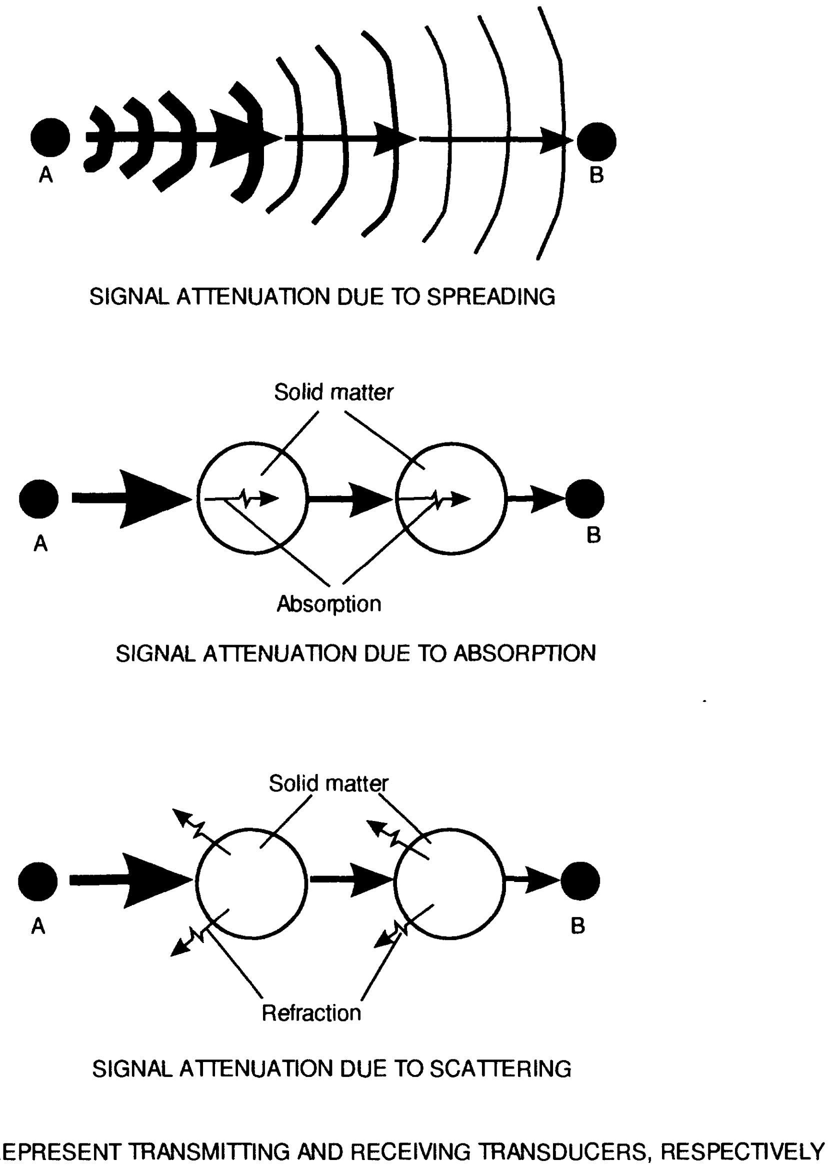


Figure 4. Main causes of ultrasonic signal attenuation (spreading, absorption, and scattering).

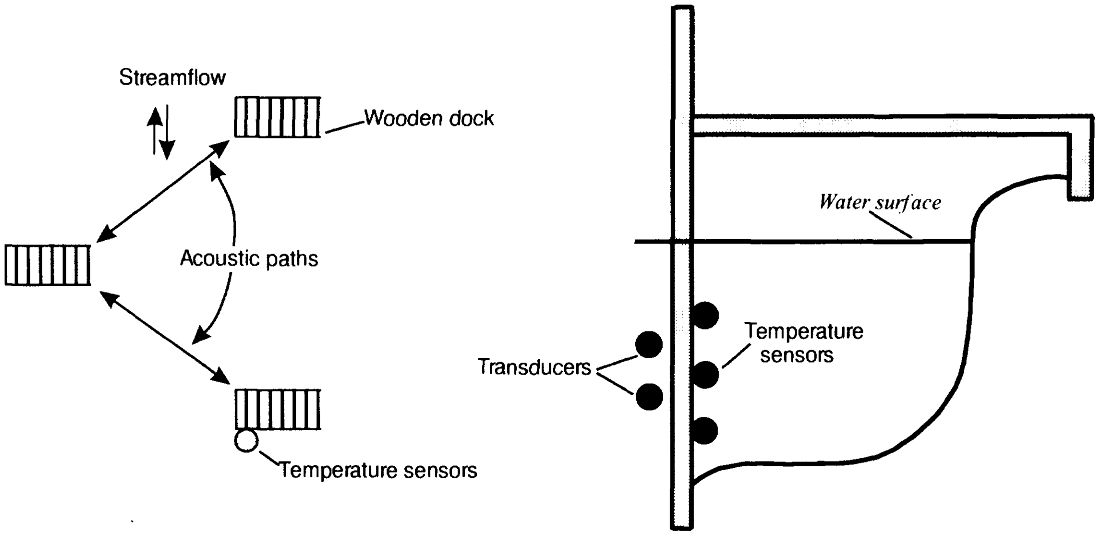
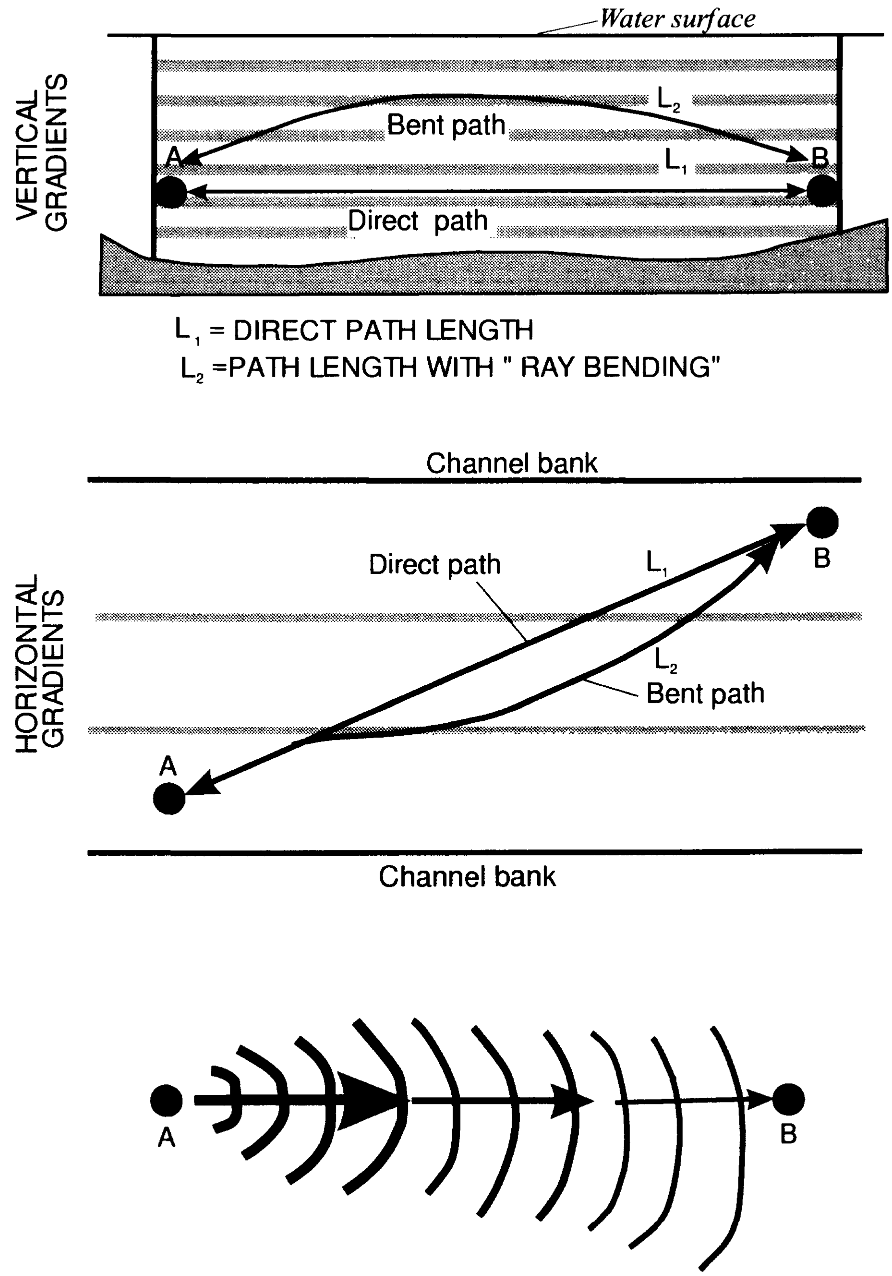


Figure 5. Horizontal and vertical locations of water temperature sensors.



A AND B REPRESENT TRANSMITTING AND RECEIVING TRANSDUCERS, RESPECTIVELY

Figure 6. Ray-bending effects on path length and received signal strength.

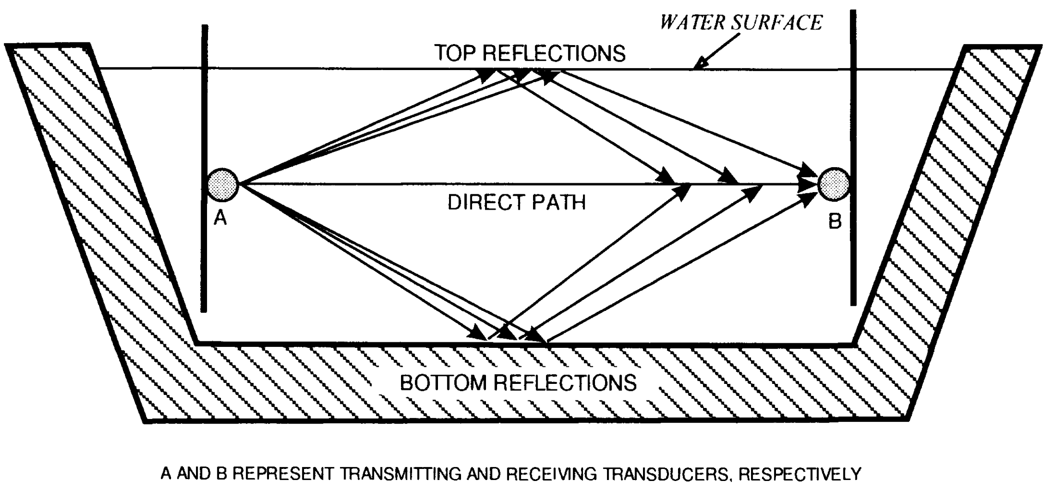


Figure 7. Multipath interference as a result of signal reflections from the water surface and channel bottom.

defined as the deterioration of the main signal due to reflections at the boundaries. The reflected signal is inverted and, when arriving at nearly the same time as the main signal, it tends to cancel or attenuate the main signal. Multipath interference can occur when the water-surface elevation approaches the transducer elevation, weakening the signal received directly across the channel. Additionally, dramatic changes in air temperature would likely cause temperature gradients within the top layer of the water column and bend acoustic paths within this layer, thus biasing AGC values. Several AGC values from AVM 1 are suspected of being biased as the result of multipath interference at low stages ranging from 9.66 to 10.42 ft above sea level (table 1).

Effects of Concentration and Composition of Suspended Material on Attenuation

The attenuation of an acoustic signal by suspended material in water depends on the concentration and composition of the solid particles (different materials will have different absorption and scattering properties). Discharge at the Levee 4 canal site presents a dynamic mixture of organic and inorganic material in suspension which does not remain constant in concentration nor composition. At this site, the nature and concentration of the suspension depend on the source of the flow (such as farm runoff) and the water velocity. Due to the complex nature of the suspension, laboratory analysis was limited to determining concentrations for total suspended solids and inorganic content. Organic concentration was the result of subtracting the results of the two analyses. Meister and St. Laurent (1960) experimented with samples of live and dead algae in suspension, and no detectable difference in absorption could be observed. Even though the mixture of suspended material and frequencies used for this study are different than the algae and frequency used in their laboratory experiment, it is assumed that live and dead organic particles in samples taken at the Levee 4 canal site behave in a similar manner. Therefore, no attempt was made to separate live from dead organic material for this study.

ESTIMATING SUSPENDED-SOLIDS CONCENTRATIONS

Previous studies, including one conducted by Flammer and others (1969), show a direct relation between acoustic signal attenuation and concentrations of suspended material and temperature. Suspended material affects the extent of acoustic attenuation by means of the absorption and scattering properties of the particles, and temperature affects attenuation by changing these properties. These variables must be considered as part of any suspended-solids estimation process.

Water velocity has a great effect on the concentration and vertical distribution of the suspended material in a stream channel. Traditionally, suspended-sediment loads are computed by relating measured water discharges to suspended-sediment discharges; however, for heavily regulated streams, such as the southern Florida canal system where not only the water quantity but also its source is regulated, this relation is poor. At the Levee 4 canal site, it is possible to have large differences in suspended-solids concentrations for similar flow conditions depending on the source and timing of water releases. To develop calibration curves for suspended-solids concentrations based on AVM data, one must first understand the relation of acoustic attenuation to suspended-solids concentration and the relation of acoustic line velocity to suspended-solids concentration (including mean channel velocity to acoustic line velocity and mean channel velocity to vertical distribution of suspended-solids concentrations).

Acoustic Attenuation and Suspended-Solids Concentration

During the last four decades, acoustic technology has been successfully used in laboratory experiments to study acoustic attenuation and its relation to suspended-solids size distribution and concentrations. For this study, water samples collected at the Levee 4 canal site had high levels of organic content that directly affected the manner in which the acoustic signal traveling across the stream was attenuated by the suspended material. Low correlation between AGC and total suspended-solids concentrations (where

$R^2 = 0.662$ and standard error (SE) = 0.2616 with temperature corrections and where $R^2 = 0.592$ and SE = 0.2876 without temperature corrections), indicates that AGC and temperature data alone do not accurately describe the concentrations of total suspended solids measured at this particular site. Graphs showing the relation between AGC and total suspended solids and the effect of temperature on this relation are shown in figure 8.

Total suspended-solids concentrations in figure 8 are shown in logarithmic scale to linearize their relation to AGC, which is reported in decibels (log scale). AGC values are reported as the difference between all measured values (dAGC) and a reference value (lowest measured value). To illustrate the effects of temperature, dAGC values are multiplied by the temperature and replotted against total suspended-solids concentrations. Note the "new" location of the total suspended-solids measurement at 18.7°C. Even though the data set is deficient in the number of total suspended-solids measurements below 20°C, figure 8 clearly shows the importance of temperature as a measurable variable that needs to be considered as a factor in the total suspended-solids estimation process.

Acoustic Line Velocity and Suspended-Solids Concentration

The relation between water velocity and suspended-solids discharge is not clearly defined nor stable in time at the Levee 4 canal site. However, the line velocity measured by the AVM does show some correlation with total suspended-solids concentrations. A graph showing the relation of acoustic line velocity to total suspended-solids concentration for AVM 2 at 500 kHz, is shown in figure 9. Here, the data value corresponding to 1,058 mg/L would seem to be an outlier when, in fact, it represents different suspended-solids concentrations than other measurements at similar water velocities. This condition is not uncommon for the heavily regulated canal system in southern Florida. Large differences in suspended-solids concentrations for similar water velocities can occur as the result of changes in the source of water, or due to a "first flush" situation in which a stagnant system is disturbed or "flushed" by a sudden increase in water velocity as the result of structure operations (for example, gates, pumps, and other control structures). The data from this "outlier" are not used here to illustrate the relation, nor are the data included in the statistics. The velocity to total suspended-solids relation is then described by the equation: $TSS = V_L \times 203.16$, $R^2 = 0.728$, and SE = 90.7 mg/L (TSS represents total suspended solids and V_L represents AVM line velocity).

Mean Channel Velocity to Acoustic Line Velocity Relation

The AVM line velocity is used to compute mean channel velocity and water discharge by establishing a rating curve based on field measurements. Such relations can also be affected by stage or other factors that change the relative position of the line velocity with respect to the vertical velocity distribution in the stream. Measured stage data for the Levee 4 canal site were included in a regression analysis to define mean velocity but found to be insignificant. Only the AVM line velocity was determined to be significant for describing the relation between mean and line velocities. This relation for AVM 1 is shown in figure 10 and is defined by the equation: $V = 0.767\ V_L + 0.0514$, $R^2 = 0.993$, and SE = 0.072 ft/s (V represents mean channel velocity). The curve infers that there is a stable linear relation between mean and line velocities throughout the entire velocity range observed at the study site including negative flows.

Vertical Distribution of Suspended-Solids Concentrations

In any given stream, sediment is generally transported in suspension, as bedload, or both. A large percentage of coarse material and a small percentage of fine material will be carried as bedload, with a continuous exchange of particles between the bedload and the material in suspension. For this study, only the portion in suspension is analyzed.

Particles in suspension are supported by water velocity, and their vertical distribution is dependent on the Rouse number (*z*), which is defined as a measure of the relation that exists between the vertical fall velocity of the solid particles and the velocity of water. Vanoni (1977) describes a method of calculating *z* based on measured suspended material concentrations at two depths:

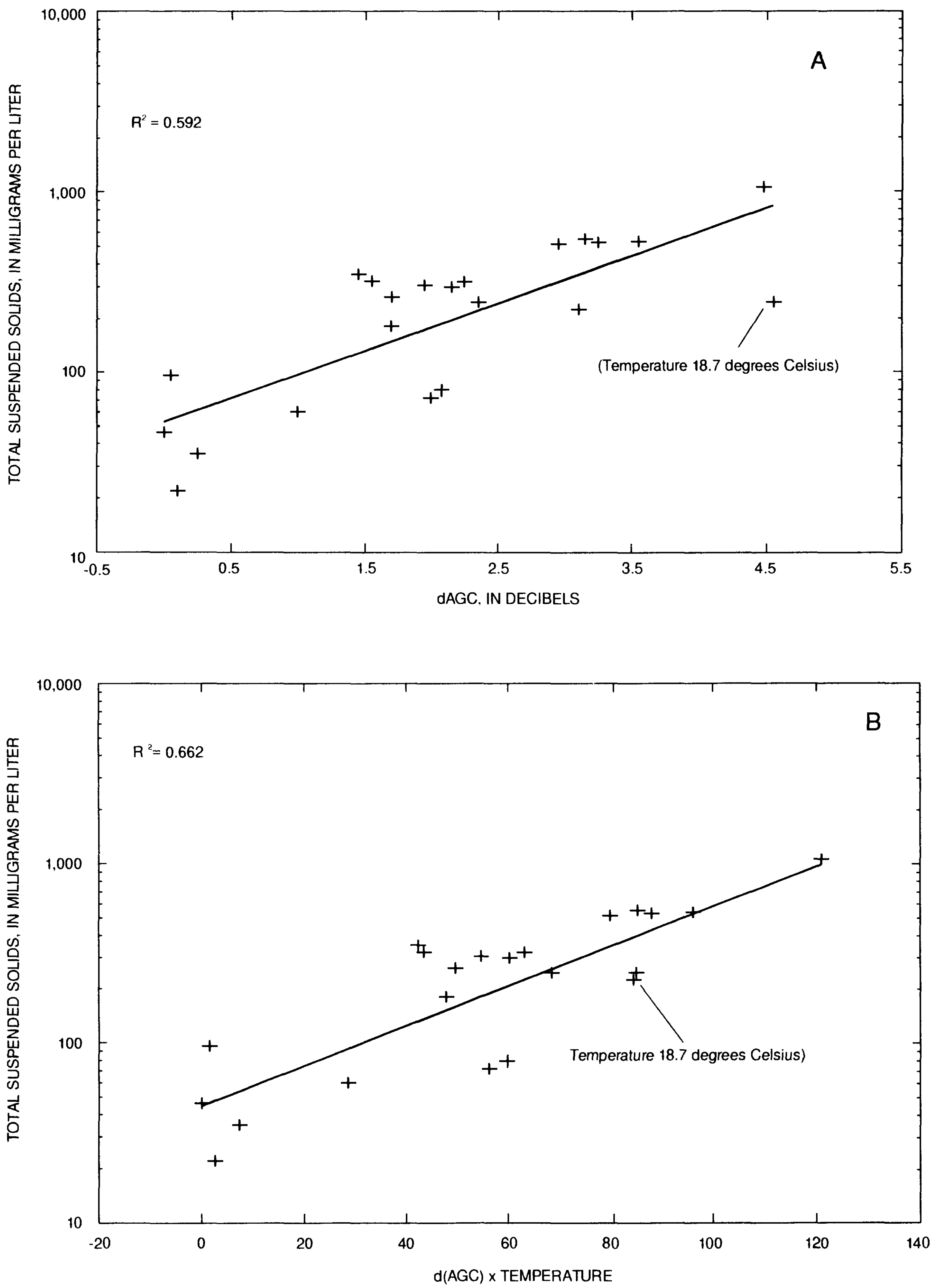


Figure 8. (A) Relation of attenuation (automatic gain control) to total suspended-solids concentrations and (B) the effect of temperature in this relation.

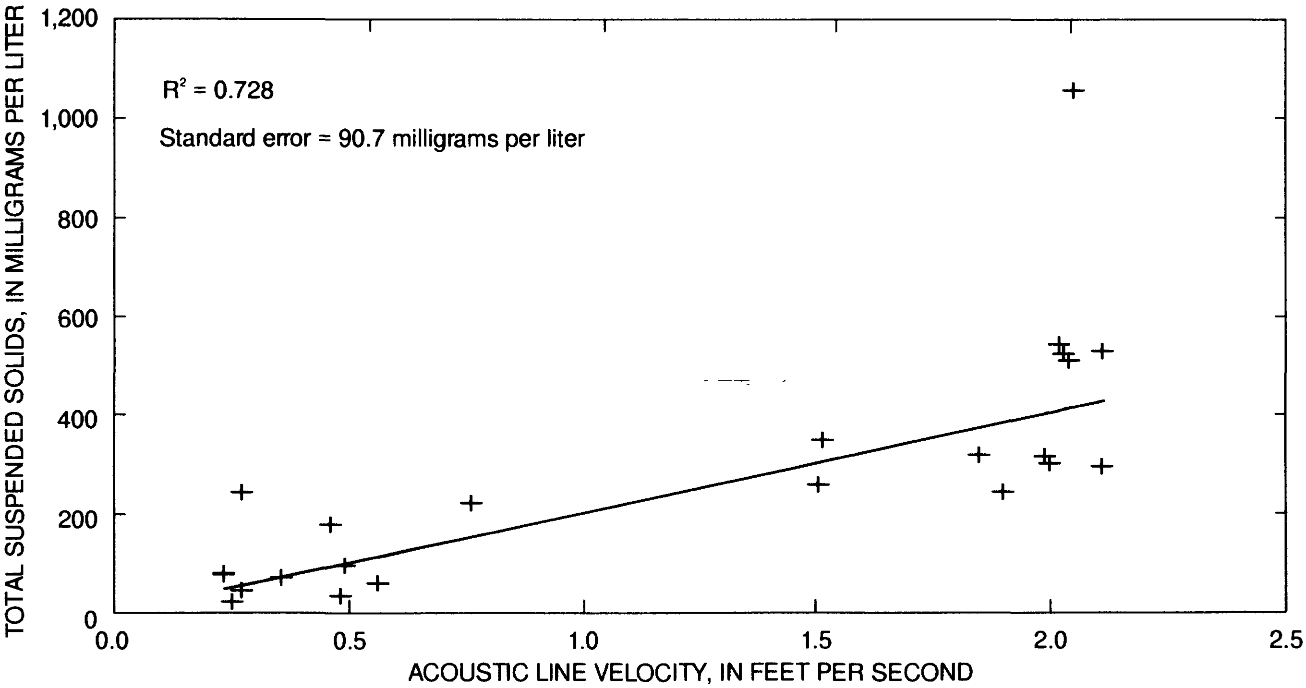


Figure 9. Relation of total suspended-solids concentrations to acoustic line velocity for acoustic velocity meter 2 at 500 kilohertz frequency, as defined by 1993-94 measurements.

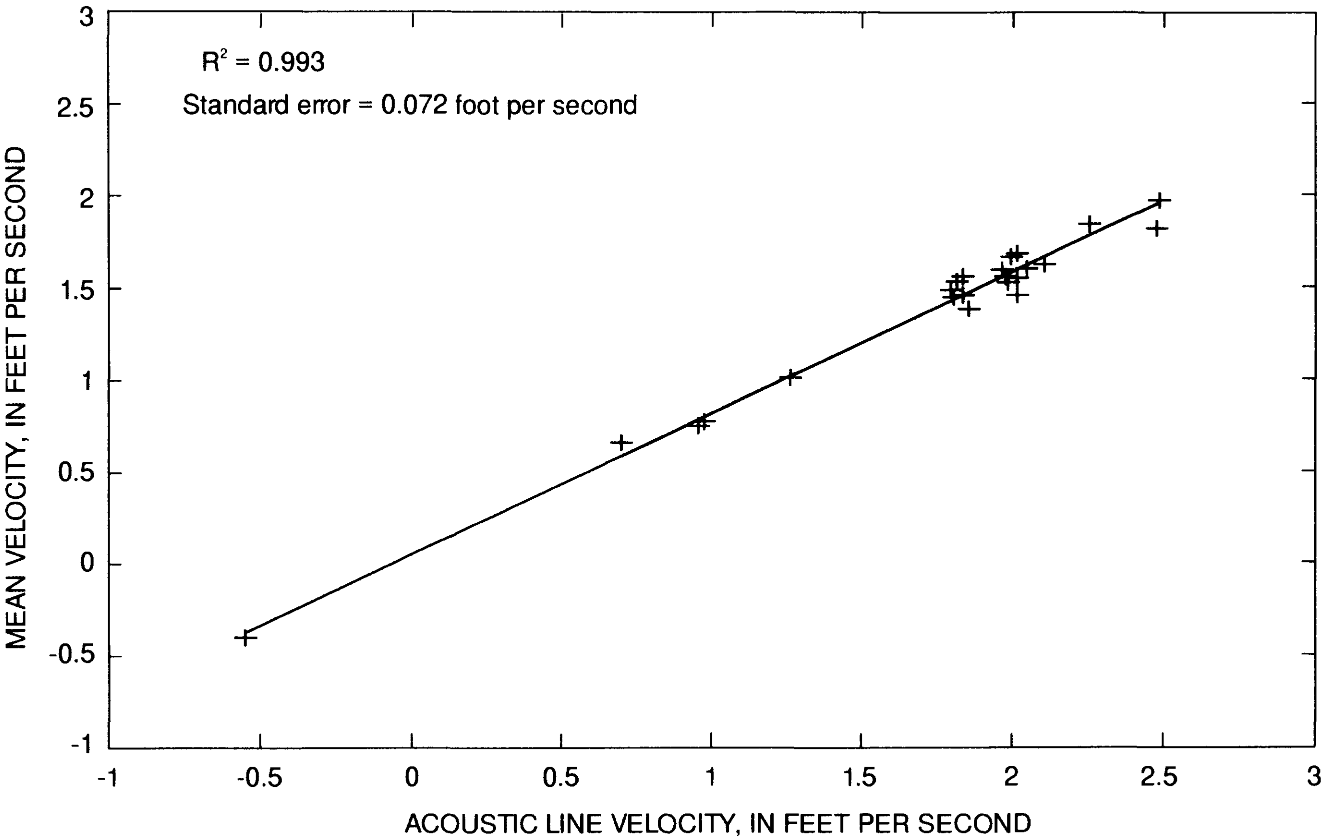


Figure 10. Mean channel velocity versus acoustic line velocity for acoustic velocity meter 1 at 200 kilohertz frequency, as defined by 1993-94 measurements.

$$C/C_a = \left[\frac{D-Y}{Y} \times \frac{Y_a}{D-Y_a}\right]^z \quad (1)$$

where:

C is concentration at depth Y

C_a is Reference concentration at reference depth Y_a,

D is total depth of flow, and

z is Rouse number

The Rouse number assumes standard logarithmic velocity distributions and can be used to calculate an acceptable approximation of the suspended-solids vertical distribution as shown in figure 11. The curve shown in figure 11 was created by using the average z value, 0.028526, for all measured points and using data at 0.5 ft above the streambed as the reference; all data used are presented in table 2.

The AVM line velocity has a direct and linear relation to the mean velocity for this stream, and even though the velocity distributions might not present true standard logarithmic shapes, it is assumed (based on data shown in fig. 10) that this relation remains stable for all flow conditions, including reverse flow. Given the relation that exists between water velocity and the vertical distribution of suspended solids and given the stability of the relation of line velocity to mean channel velocity, it can be assumed that there is a stable relation between AVM line velocity and the vertical distribution of suspended-solids concentrations for flow in both directions.

Suspended-Solids Estimation Model

A suspended-solids estimation model was developed using a combination of acoustic attenuation and line velocity principles and the relation to suspended-solids concentrations. Four measurable parameters are identified as the variables included in the model. Because the model is used to estimate concentrations of total suspended solids, measured concentrations are used as the dependent variable; measurements of attenuation (in this case, AGC), line velocity, and temperature are classified as the independent variables in the model. For analysis purposes, the independent variables are subclassified as primary and secondary variables. Primary variables (AGC and line velocity) have a direct relation to suspended-solids concentrations, whereas the secondary variable (temperature) has an indirect effect on the estimate of suspended-solids concentrations by altering one of the primary variables (AGC). Including line velocity as one of the variables in the suspended-solids estimation model will account for changes in the vertical distribution of suspended-solids concentrations for all flow conditions as discussed in the previous section.

The suspended-solids estimation model was constructed to include a transformation of AGC data, the absolute value of line velocity, temperature, and measured concentrations of total suspended solids. The absolute value of velocity is used since flow and suspended-solids transport characteristics are assumed to be the same for flow in both directions. All forms of the model were tested for variable sensitivity, and the mathematical expressions with corresponding SE's are presented in table 3. Attenuation expressed as dAGC in decibels is included in the model as a power of 10 because decibels is an expression of energy flux to the base 10.

Sensitivity Analysis

A test of the significance of variables used can be made from the regression analyses that were performed leading to the selection of the best-fit equation (table 3). Data from AVM 2 (500 kHz) were used for the analyses because this site has the most complete data set and the most comprehensive ranges of suspended-solids concentrations, velocity, and temperature available for the study.

The best results are obtained with option e (which excludes temperature as one of the variables), producing actual residuals that range from 2 to 128 mg/L; however, for data collected at the AVM 2 site, the effects of temperature are overshadowed by the use of water-velocity data. To determine the effects that

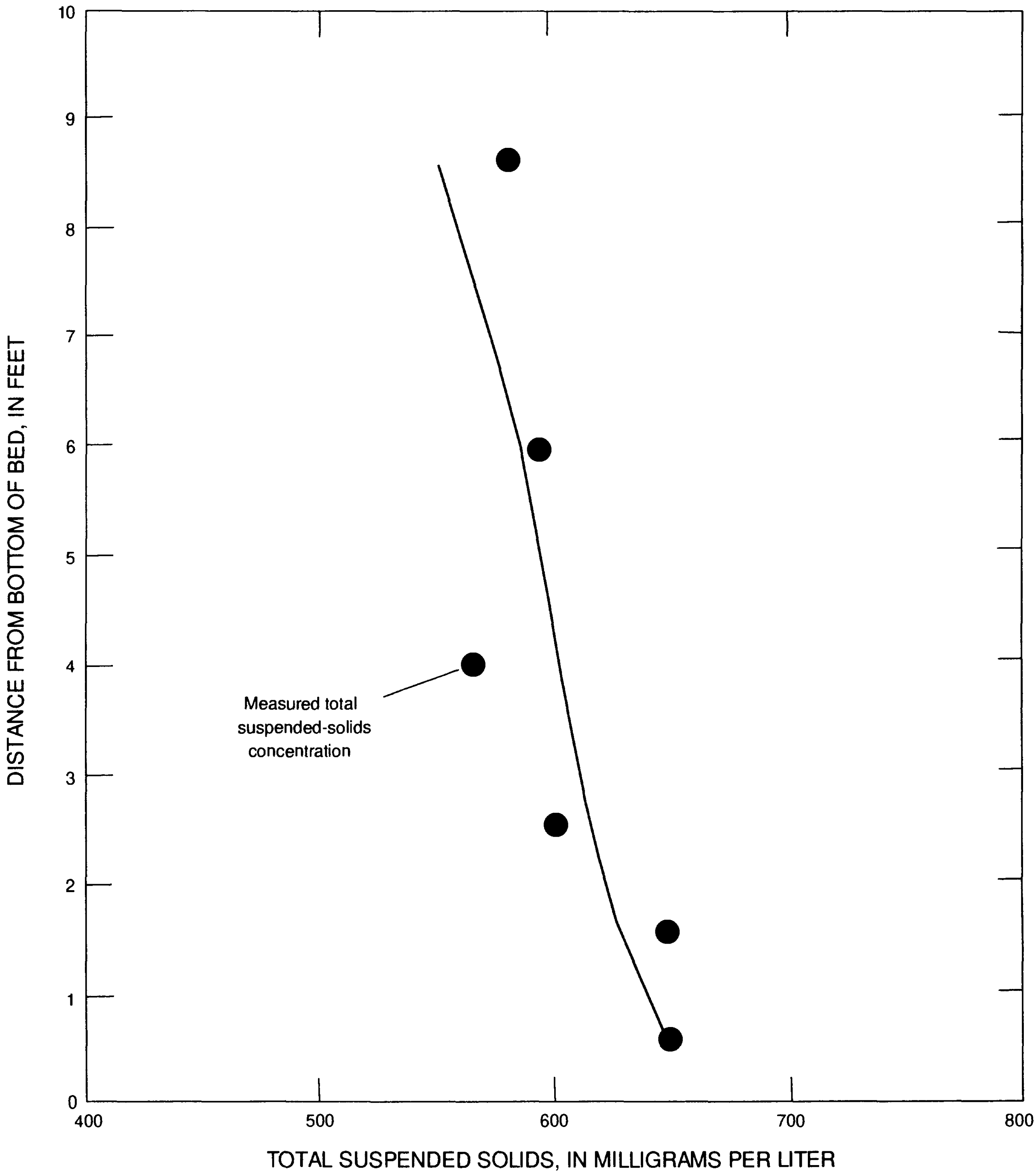


Figure 11. Measured total suspended-solids concentrations and a curve generated from an equation by Vanoni (1977) defining a total suspended-solids concentration profile for mean velocity of 1.90 feet per second.

Table 2. Measured and estimated suspended-solids concentrations at different vertical locations and values for the Rouse number (z)

[Estimated average z = 0.028526; ft, feet; mg/L, milligrams per liter]

Distance from bottom (ft)	Measured total suspended solids (mg/L)	Rouse number	Estimated total suspended solids (mg/L)
0.5	650	--	650
1.5	648	0.002518	628
2.5	601	.041741	616
4.0	566	.053017	603
6.0	594	.025548	588
8.5	581	.019805	553

Table 3. Suspended-solids regression models tested and their respective standard errors

[TSS, total suspended-solids concentrations; dAGC, difference in automatic gain control between measured and reference values (lowest measured value was used); a,b,c, regression coefficients; T°, temperature, in degrees Celsius; vel, acoustic velocity meter line velocity, in feet per second]

Option	Equation	Standard error (milligrams per liter)
a	$TSS = a \cdot 10^{(dAGC)}$	267.7
b	$TSS = a \cdot (10^{(dAGC)} \cdot T°)$	266.7
c	$TSS = a \cdot vel$	157.8
d	$TSS = 10^{(dAGC)} \cdot (a + b \cdot T°)$	273.0
e	$TSS = a \cdot 10^{(dAGC)} + b \cdot vel$	69.7
f	$TSS = a \cdot (10^{(dAGC)} \cdot T°) + b \cdot vel$	70.7
g	$TSS = a \cdot 10^{(dAGC)} \cdot (a + b \cdot T°) + c \cdot vel$	71.4

temperature has on the results of the model, it is necessary to have multiple measurements of high and low total suspended-solids concentrations and water velocities during temperatures covering the entire range encountered at the site (17 to 30°C). There is only one total suspended-solids concentration (246 mg/L) found for AVM 2 (500 kHz) at temperatures below 20°C (18.7°C) that can be used in regression analyses (this low temperature also corresponds to a low water velocity of 0.27 ft/s). Therefore, caution should be observed and temperature should always be considered in any analysis that includes attenuation as a variable and should not be removed from the equation unless proven to have negligible effects on attenuation.

The graphs shown in figures 12, 13, and 14 were developed using option e in table 3 and represent plots of measured and estimated concentrations of total suspended solids, with the dashed line representing a line of equivalence. Figure 12 shows suspended solids estimates using data from AVM 1 as defined by the equation: $TSS = 0.0617 \times 10^{(dAGC)} + 131.42$. This relation, in spite of having a high correlation number (R^2) of 0.915 and SE of 74.8 mg/L, is based on limited data sets, and thus, results are considered unreliable for the determination of regression coefficients. Figures 13 and 14 represent results of analyses performed with data from AVM 2 at 200 and 500 kHz, respectively. The relation for 200 kHz is defined by the equation: $TSS = 0.0081 \times 10^{(dAGC)} + 159.74$ ($R^2 = 0.852$ and SE = 58.4 mg/L). The relation for 500 kHz is defined by the equation: $TSS = 0.0227 \times 10^{(dAGC)} + 191.31$ ($R^2 = 0.919$ and SE = 69.7 mg/L). The regression model produces similar results when using data from AVM 2 at both frequencies (200 and 500 kHz), suggesting that transducers of either frequency could be used to collect attenuation data at this site.

Residual Analysis

Sample residuals are defined as the difference between the measured values and predicted (model) values. An analysis was performed to determine if trends are present in the relation of residuals to measured suspended-solids concentrations. The data set used in this analysis (AVM 2 at 500 kHz) lacks sufficient information at the high end of the total suspended-solids concentration range, with only one sample having a concentration in the high range. Because of this deficiency, the data set cannot be subdivided into two groups to test for equal variance for both high and low values. Thus, the only analysis performed is a comparison of residuals obtained with option e and regression coefficients determined with and without the high concentration value. As shown in figure 15, using the high concentration value forces the results toward it but does not significantly affect the results at the lower end where most of the data are present, thus eliminating the possibility that this value represents an outlier. Additionally, residuals for both approaches indicate no trend in the relation to measured concentrations. The regression equation developed without the high value is able to predict this high value within 20 percent, also confirming that the high value is not an outlier.

Data Set Limitations

The error associated with estimates of suspended-solids concentrations is dependent on the accuracy of suspended-solids measurements, the measured range of all variables to be included in the equation, AVM transducer stability and cleanliness, and AVM instrument malfunction. As previously indicated, water samples for measurement of total suspended solids were collected with a DH-59 sediment sampler, which might not be the most appropriate method for sampling of highly organic suspended solids (for example, long algae filaments and roots). Other limitations in the Levee 4 canal data set that could possibly contribute to the error include an insufficient number of measurements for suspended-solids concentrations that range from about 550 to 1,100 mg/L and with temperatures less than 25°C. Additionally, even though it is assumed that sediment transport and flow characteristics are the same for water movement in both directions, only one measurement of mean velocity and two measurements of total suspended solids during negative flow were available for describing relations used.

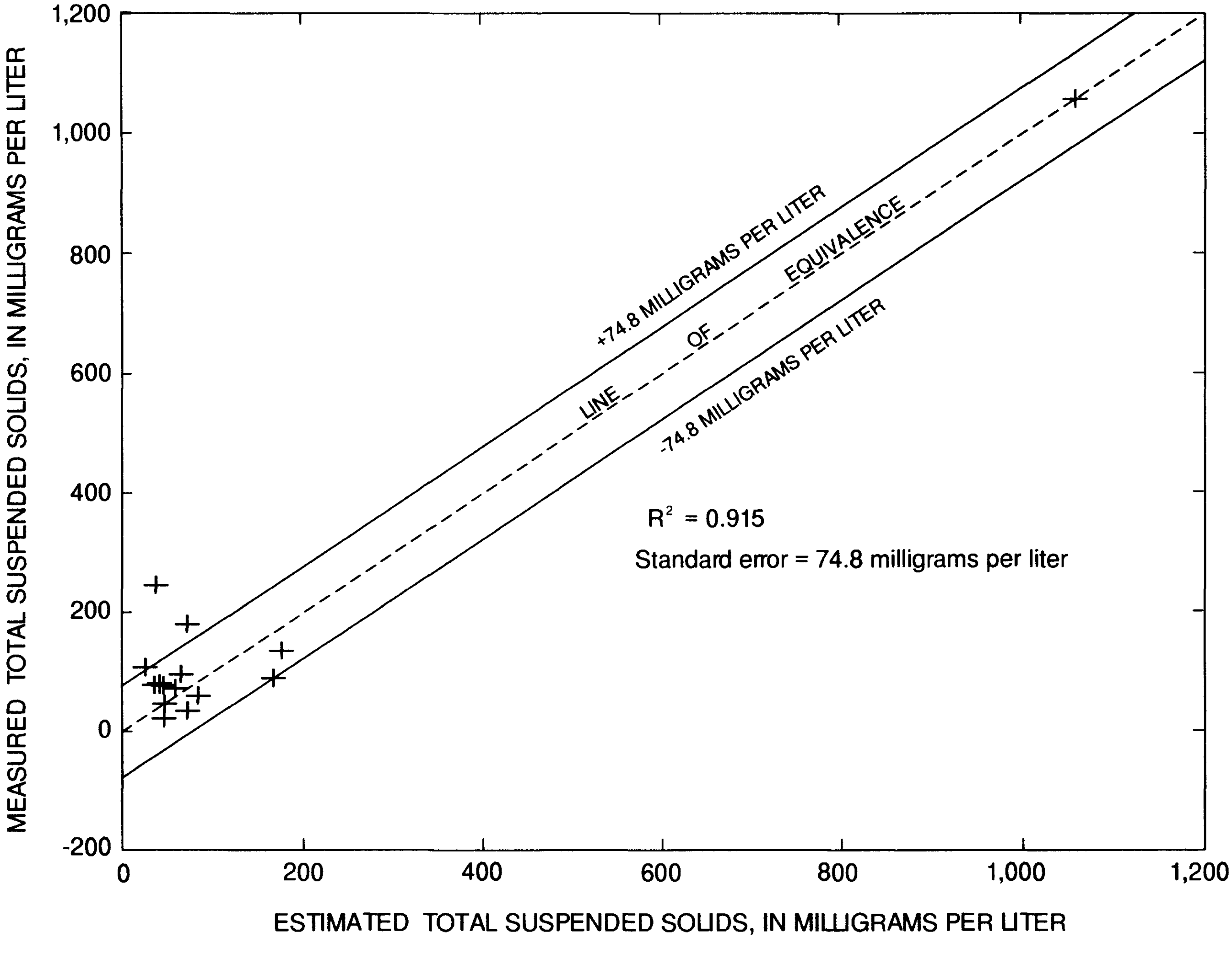


Figure 12. Measured and estimated total suspended-solids concentrations for acoustic velocity meter 1 (excluding all measurements during instrument malfunction) and standard error band widths.

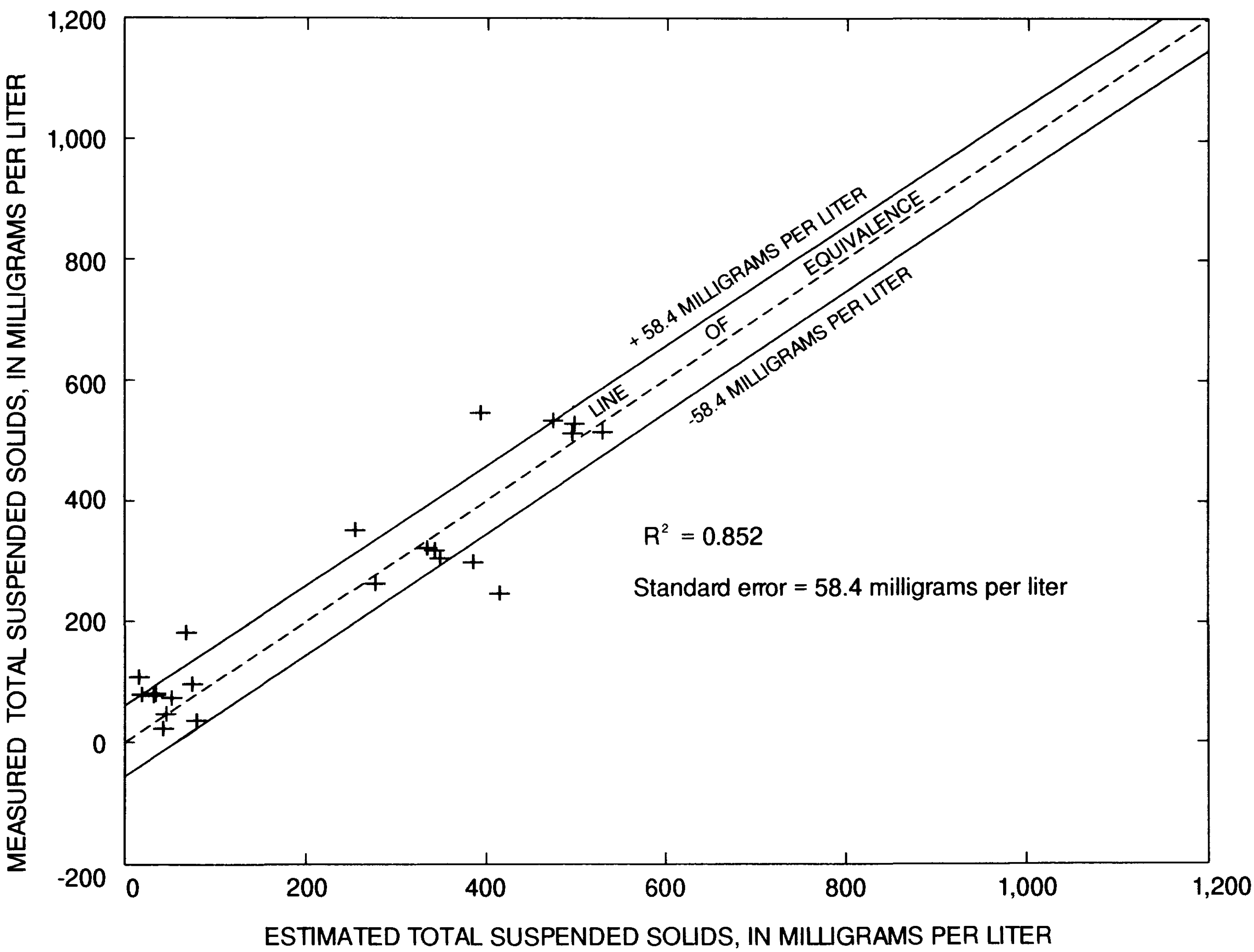


Figure 13. Measured and estimated total suspended-solids concentrations for acoustic velocity meter 2 at 200 kilohertz frequency and standard error band widths.

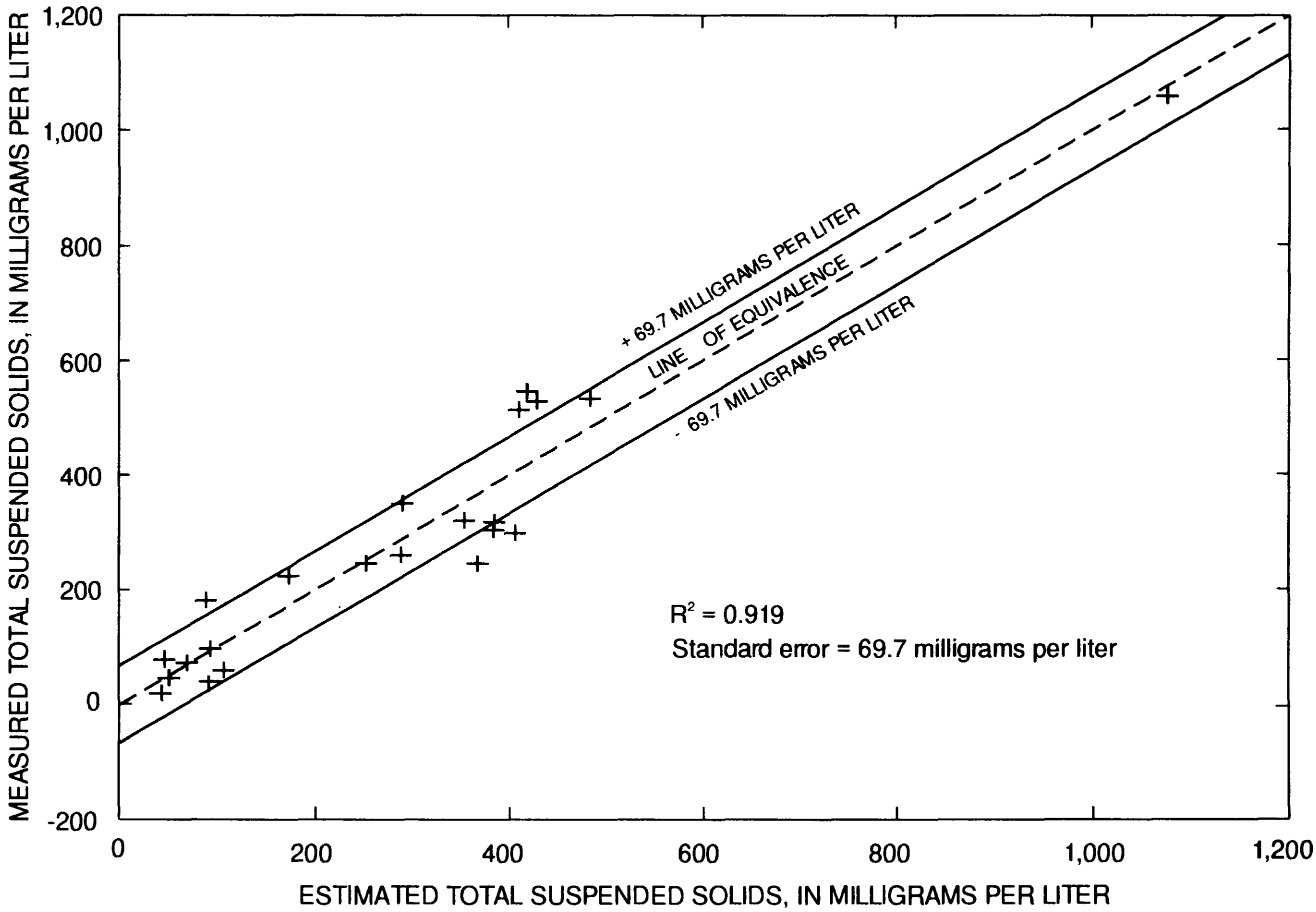


Figure 14. Measured and estimated total suspended-solids concentrations for acoustic velocity meter 2 at 500 kilohertz frequency and standard deviation band widths.

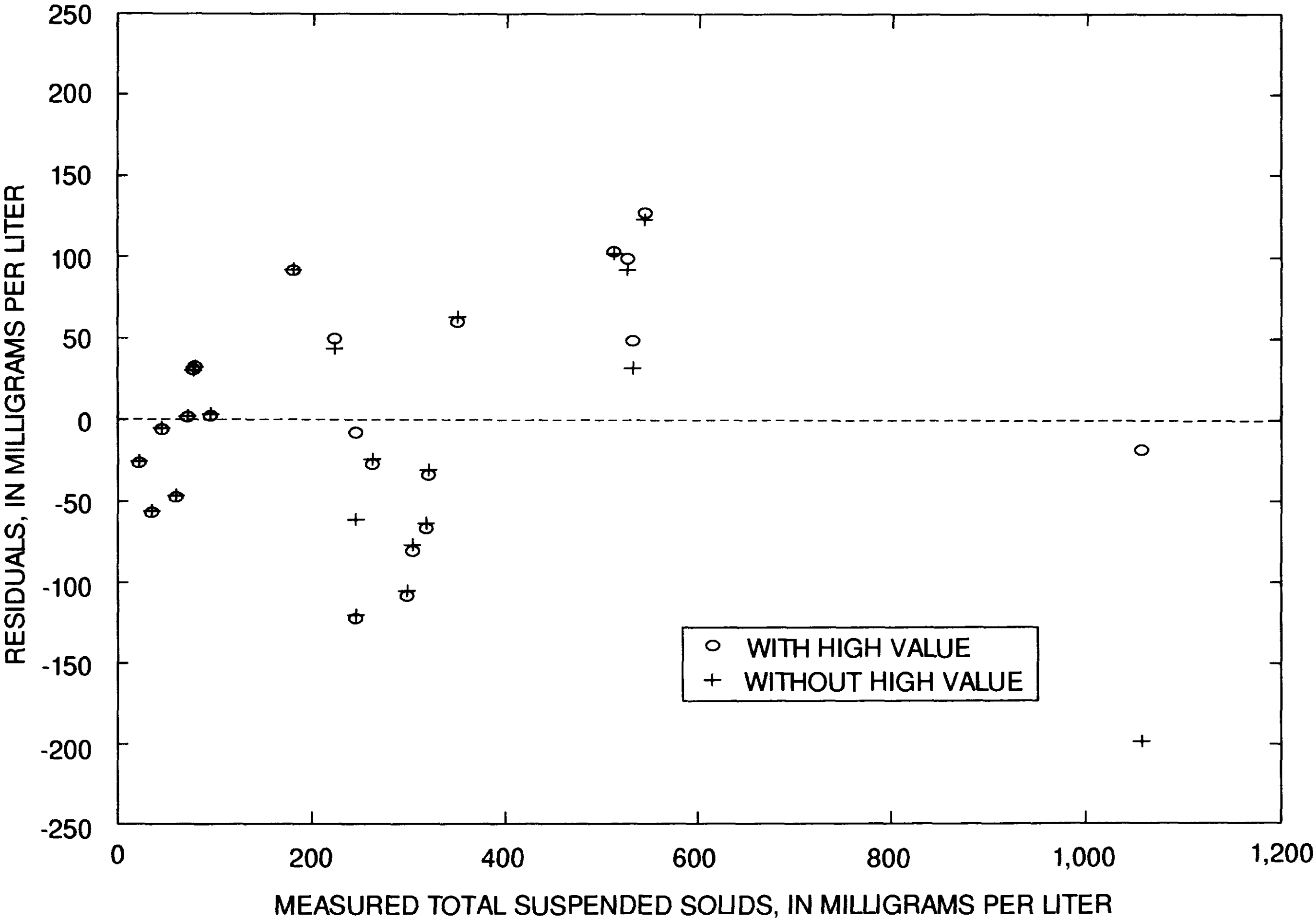


Figure 15. Residuals of total suspended-solids concentrations with and without using the high concentration value for determining regression coefficients (acoustic velocity meter 2 at 500 kilohertz frequency).

SUMMARY AND CONCLUSIONS

Commercially available acoustic velocity meter systems are widely used for discharge computations in streams. Additionally, these systems can provide information pertinent to the quality and strength of the acoustic signal as it is received across the stream. The AGC value is one output from acoustic velocity meters that can be used as an index of total attenuation of the acoustic signal, part of which is due to the presence of suspended particles in the water. The AGC values represent the adjustment in receiver sensitivity needed to increase or decrease the received signal to an amplitude acceptable for recognition and velocity computation.

Acoustic technology for estimating concentrations of suspended solids has been successfully performed in laboratory experiments, but only limited success has been obtained with field measurements. Laboratory experiments have been based on the principles of acoustic attenuation using predetermined concentrations and type (organic or inorganic) and size of suspended particles. In these experiments, acoustic attenuation by organic matter (plankton) has indicated a direct dependency on concentration and an inverse dependency on temperature. Natural environments, however, present a more complex situation where concentrations, type, and size of suspended particles are not known and depend on water velocity, flow duration, and the source of flow.

A study was conducted at Levee 4 canal below structure G-88 in southern Florida to examine the feasibility of using existing AVM systems to estimate highly organic suspended-solids concentrations in streams. Various types of information were gathered including the collection of AVM line velocity and AGC data, water sampling for suspended-solids analysis, measurements of water temperature, and profiles of temperature and specific conductance. Two frequencies (200 and 500 kHz) were used to determine estimation sensitivity to frequency. AVM 1 (200 kHz) was already in place at 9.0 ft above sea level and was calibrated to make discharge computations. AVM 2 was installed as part of the study at 7.0 ft above sea level and used to collect data at 200 and 500 kHz.

A suspended-solids estimation model was developed using a combination of acoustic attenuation and line velocity principles and the relation to suspended-solids concentrations. Regression analyses were performed using different forms of the model by adding one variable (or cross product) at a time until all combinations were used. A test of the significance of variables used can be made from the regression analyses that were performed leading to the best-fit equation. Data from AVM 2 (500 kHz) were used for the analyses because it has the most comprehensive data set available for the study.

The best results from the regression model were obtained with an equation that uses AGC and line velocity data (but does not include temperature as a variable), producing residuals that ranged from 2 to 128 mg/L. These results suggest negligible effects from temperature on acoustic signal attenuation; however, for data collected during the study, the lack of sufficient measurements at low temperature caused the effects of temperature to be overshadowed by water-velocity data. The only low temperature measurement available for the analysis (18.7°C) was during low water velocity (0.27 ft/s).

The equation was used to analyze all data collected with both AVM systems used for the study (AVM 1 and AVM 2). The regression model produced good and similar results with high correlation when using data from AVM 2 at both frequencies (200 and 500 kHz), suggesting that transducers of either frequency could be used to collect attenuation data at this site. For 200 kHz, $R^2 = 0.852$ and SE = 58.4 mg/L; for 500 kHz, $R^2 = 0.919$ and SE = 69.7 mg/L. Although AVM 1 had a high correlation number ($R^2 = 0.915$), data sets were scarce, making determination of regression coefficients unreliable.

Results from the study indicate that it is feasible to use output from AVM systems for the estimation of highly organic suspended-solids concentrations in streams when both attenuation (AGC) and acoustic line velocity data are used. Estimating suspended-solids concentrations with existing AVM systems is a feasible method that could prove to be much more accurate than traditional sediment estimation methods, such as sediment transport curves.

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