Current State of Suspended-Sediment Surrogate Technology

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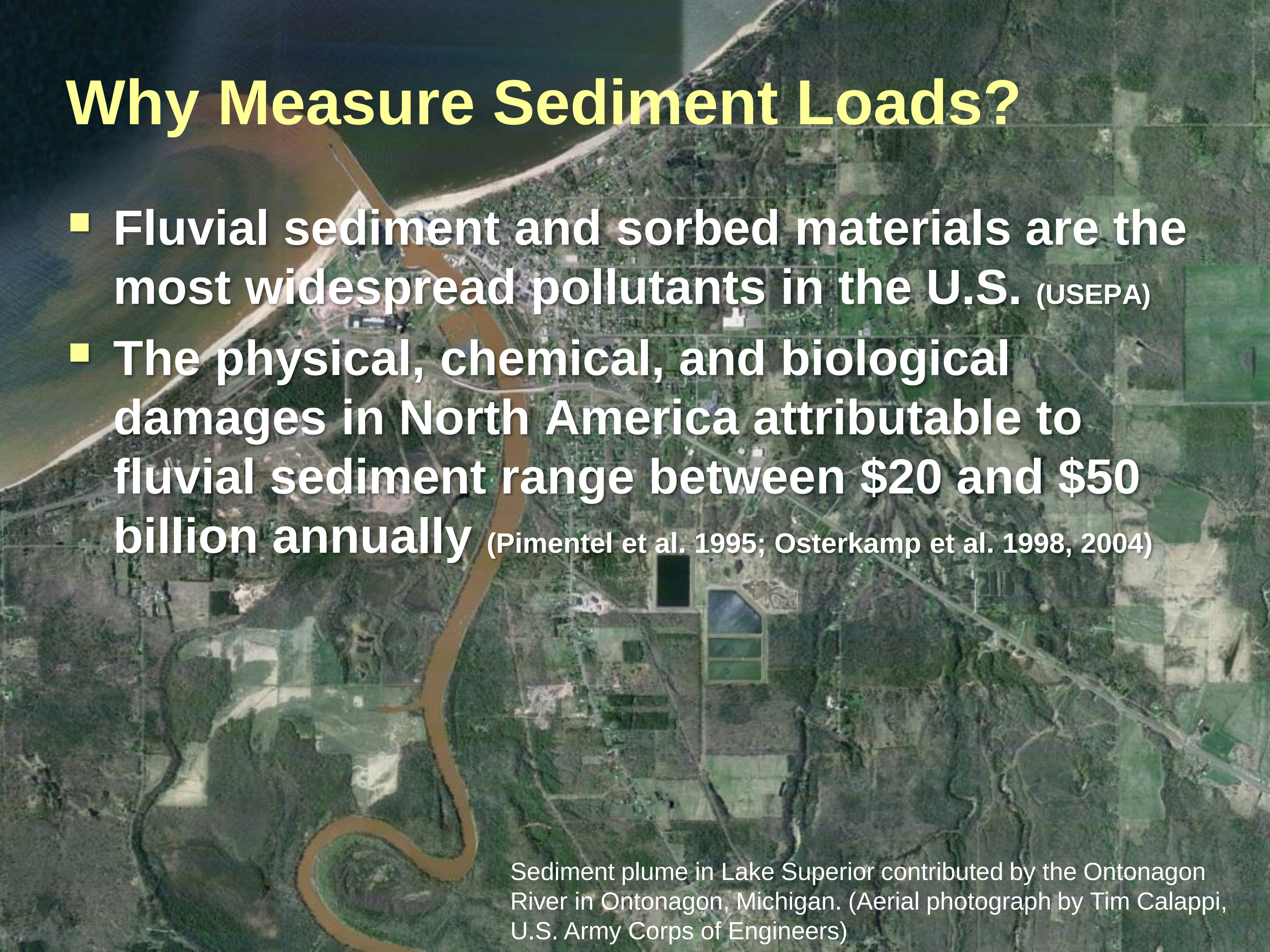
(we are reaching pretty deep in the bullpin)

U.S. Department of the Interior
U.S. Geological Survey

Why Measure Sediment Loads?

- **Fluvial sediment and sorbed materials are the most widespread pollutants in the U.S.** **(USEPA)**
- **The physical, chemical, and biological damages in North America attributable to fluvial sediment range between $20 and $50 billion annually** **(Pimentel et al. 1995; Osterkamp et al. 1998, 2004)**



Sediment plume in Lake Superior contributed by the Ontonagon River in Ontonagon, Michigan. (Aerial photograph by Tim Calappi, U.S. Army Corps of Engineers)

Greater Demand, Fewer Gages

- **The need for reliable, accurate, and cost-effective sediment data in the U.S. has never been greater**
- **However, *between 1981 and 2006 the number of USGS streamgages that collected sediment data decreased by 75%* (i.e. 3 of every 4 sediment sites were discontinued)**
- **The principle reason for the decrease in sediment gages is cost**

Photo by Paul Jenkin

Matilija Dam Delta (California)

- 5.9 million yd^3 of trapped sediment
- < 500 acre feet capacity remain
- USBR Ecosystem restoration project

USGS

Traditional Suspended Sediment Monitoring

Gray and Gartner 2009

- Gravimetric analyses on samples collected manually or by automatic samplers
- Such methods are:
    - Expensive
    - Difficult
    - Labor intensive
    - Hazardous
- Limited samples may result in inadequate resolution of variability over storm event and require temporal interpolations

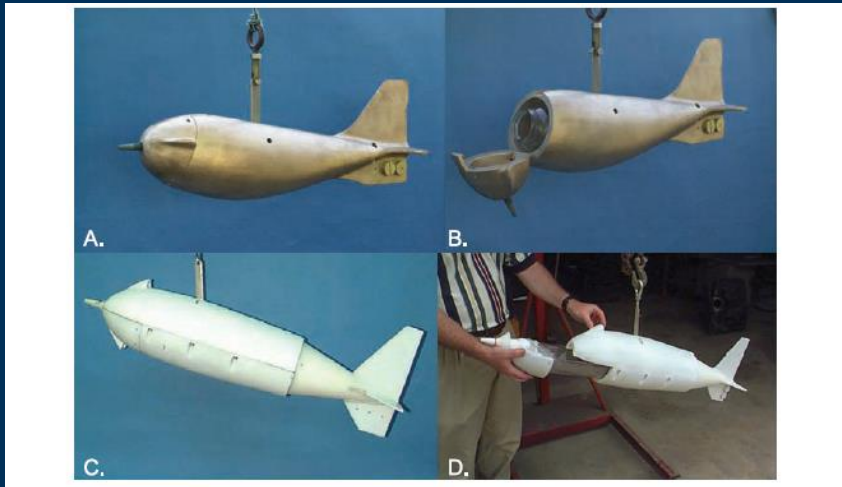
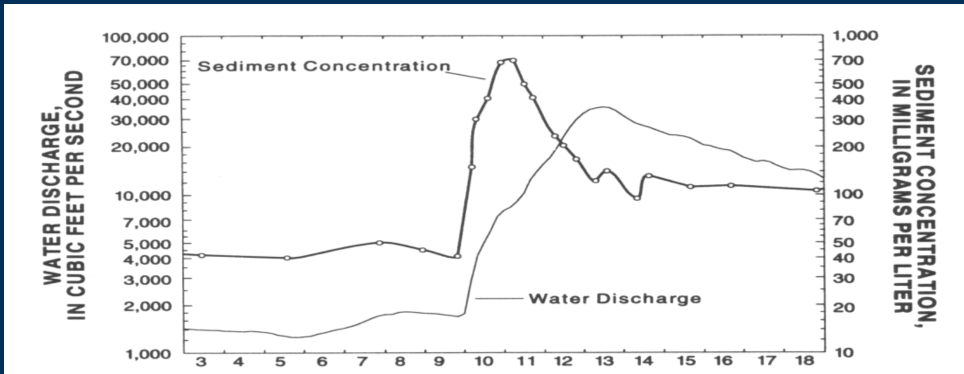


Figure 2. Two Federal Interagency Sedimentation Project suspended-sediment samplers: A U.S. D-74 suspended-sediment rigid bottle sampler (a) closed and (b) open; a U.S. D-96 flexible-bag suspended-sediment sampler (c) closed and (d) with tray containing flexible bag partially open.



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Sediment Surrogate Technologies

Performance Criteria: (Gray and Gartner, 2009)

1. Capital, operational, and analytical costs must be **affordable**
2. Technology must be able to measure SSC and PSD (in some cases) throughout the **range of interest**
3. Instrument must be **robust, reliable**, and not drift
4. **Simple** to deploy and operate with sufficient training
5. Data processing should be relatively simple or be accompanied by computational routines

USGS

Technological Advances in Suspended Sediment Surrogate Monitoring

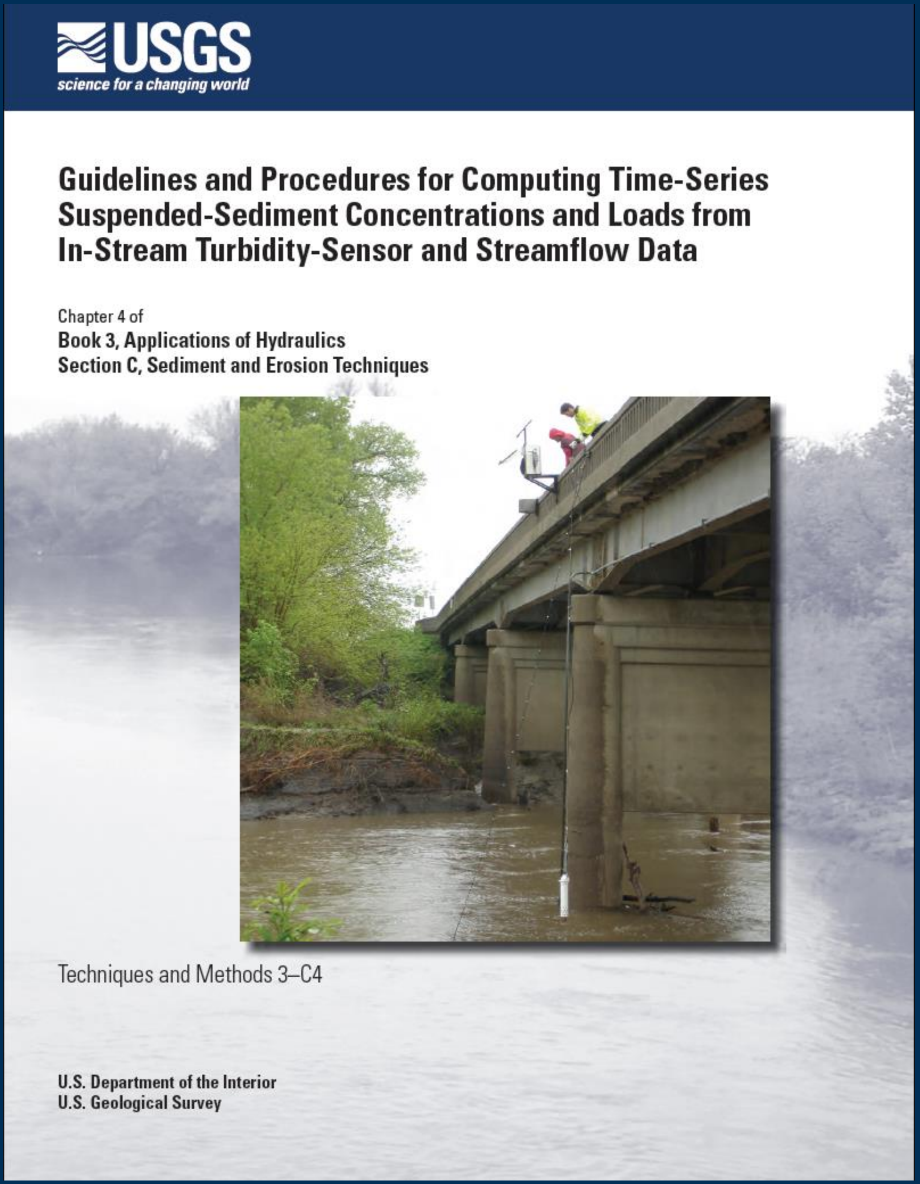
Primary Surrogate Technologies

- Bulk optics (Turbidity)
- Laser Diffraction
- Pressure Difference
- Digital Photo-Optics
- Acoustic Backscatter
  - USGS Sediment Acoustic Leadership Team (SALT)

USGS

Bulk Optics (Turbidity)

- **New chapter in suspended sediment monitoring**
- **USGS T&M 3-C4**
- **With an acceptable regression model, suspended-sediment concentration *can be computed beyond the period of record* used in model development**
  - **Requires ongoing collection and analysis of calibration samples**



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Bulk Optics (Turbidity)

- Most common surrogate for SSC in the U.S.
- Can produce reliable results (< 320 g/L OBS)
- First surrogate to be sanctioned by USGS
- Relatively low cost (~$5k)

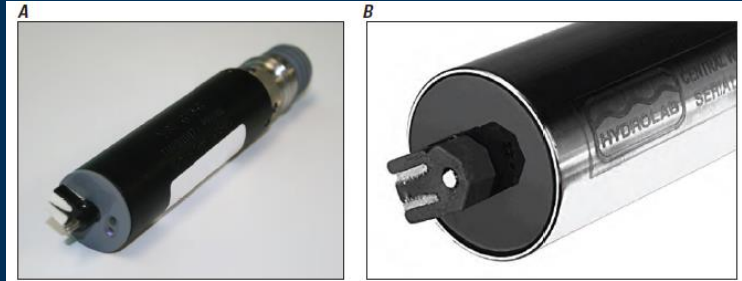


Figure 1. Three self-cleaning nephelometric turbidity sensors—*A*, YSI Incorporated (Yellow Springs, Ohio) model 6136 turbidity sensor, *B*, Hydrolab (Loveland, Colorado) self-cleaning turbidity sensor, and *C*, Forest Technology Systems (Blaine, Washington) model DTS-12 turbidity sensor.

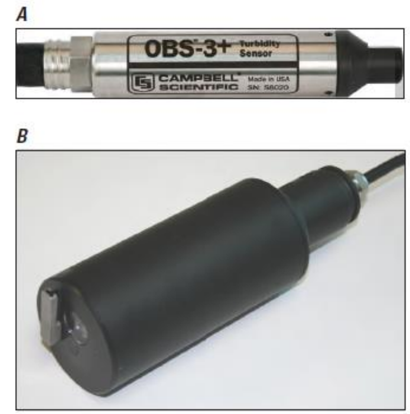


Figure 2. Optical backscatter sensors—*A*, OBS 3+ (Campbell Scientific Inc., Logan, Utah) and *B*, Hach (Loveland, Colorado) Solitax.

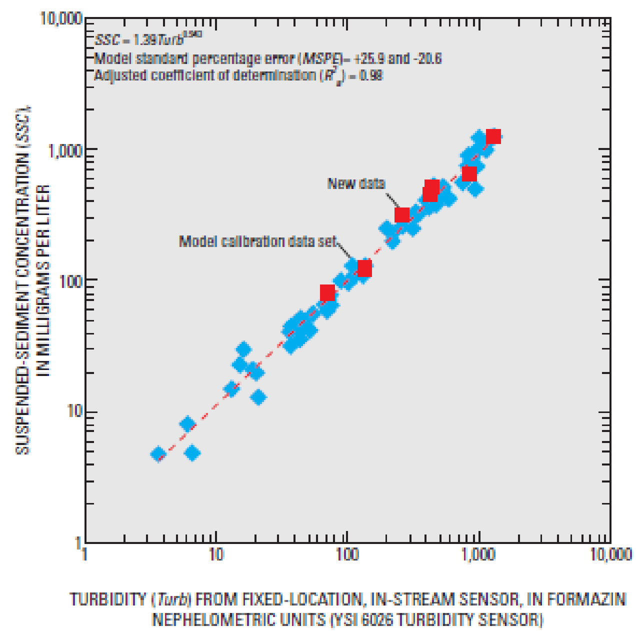


Figure 16. Model-calibration data set (water years 1999–2005) and new (water year 2006) turbidity and suspended-sediment concentration data for U.S. Geological Survey streamgage on Little Arkansas River near Sedgwick, Kansas.

USGS T&M 3-C4

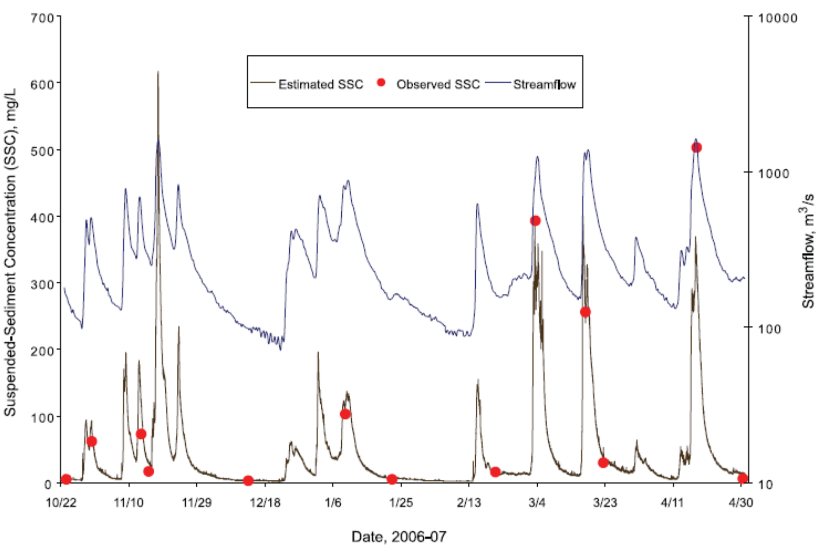


Figure 5. Time series plot of continuous suspended-sediment concentrations (computed by multiple linear regression from square root-transformed time series of turbidity, streamflow, and water temperature data), sampled SSCs in milligrams per liter, and streamflow in cubic meters per second for the James River at Cartersville, Virginia, 22 October 2006 to 30 April 2007. From Jastram et al. (submitted manuscript, 2009).

Grey and Gartner, 2009

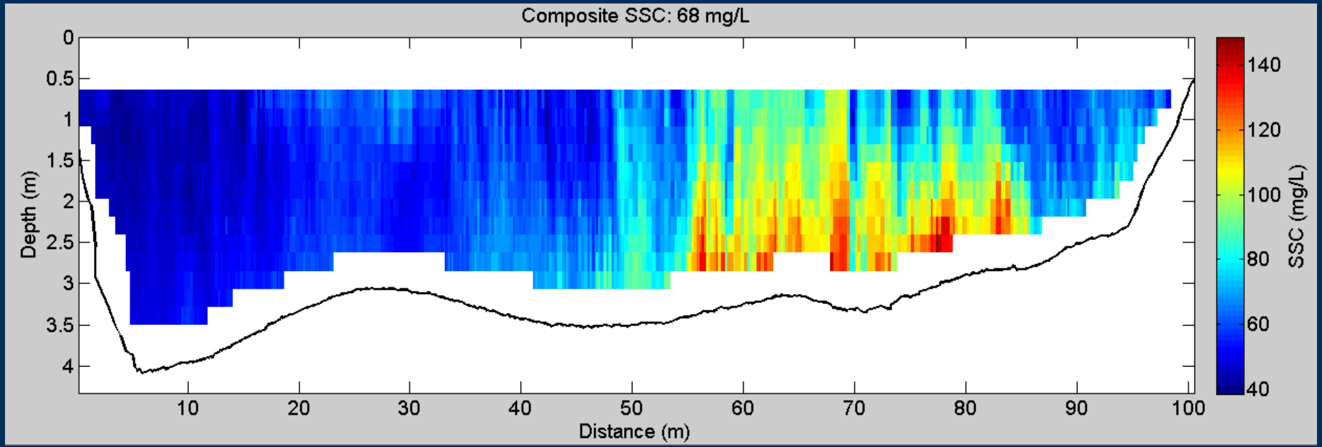
Bulk Optics (Turbidity)

Advantages

- Ample data for evaluation
- Mature, reliable, low-cost technology
- Established calibration techniques

Limitations

- Point measurements
- Consistency amongst sensors
- Variable response to sediment grain size, composition, and shape (best for stable PSD site)
- Subject to saturation, fouling and damage
- Hysteresis can occur (due to change in PSD, see Landers and Sturm, 2013)



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Laser Diffraction

- Exploit the Mie scattering theory
  - At small forward scattering angles, laser diffraction by spherical particles is identical to diffraction by an aperture of equal size (Agrawal and Pottsmith, 1994)
- Originally designed for the lab
- Returns the PSD
- Computes volumetric SSC from PSD
- Insitu and pump-through systems are available

Sequoia Scientific, Inc.

LISST-StreamSide

USGS

Laser Diffraction Application

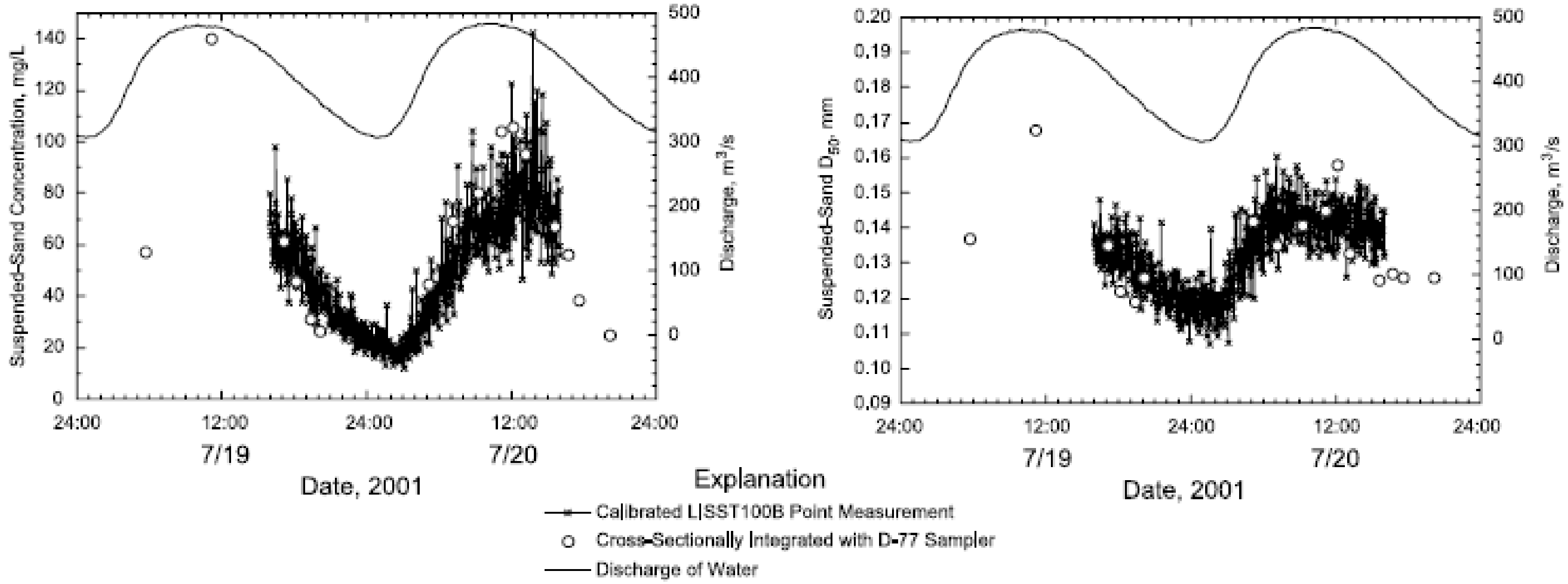

Figure 7. Comparison of sand concentrations in milligrams per liter and median grain sizes in millimeters measured at the USGS streamgage at the Colorado River near Grand Canyon, Arizona, using a LISST-100B and a U.S. D-77 bag sampler. From *Melis et al.* [2003].

USGS

Laser Diffraction

Advantages

- Insitu or real-time PSD in 32 classes
- Calculated volumetric SSC is not affected by changes in PSD
- Isokinetic sampler is available
- Pump-through systems are available

Limitations

- Point measurements
- Deviation of particle shape from spherical may result in bias
- Saturation of the laser sensors occur at about half that of a turbidity sensor
- Biofouling may be an issue
- Costs up to 6 times that of a fully equipped turbidity sensor

USGS

Pressure Difference

- **Exploits the pressure difference between to points in the water column to compute water density**
- **SSC can be inferred after correcting for water temperature and dissolved solids**

Assumes:

1. **The water surface measured by both sensors is equal**
2. **The density of the water column above the lowest sensor is constant**

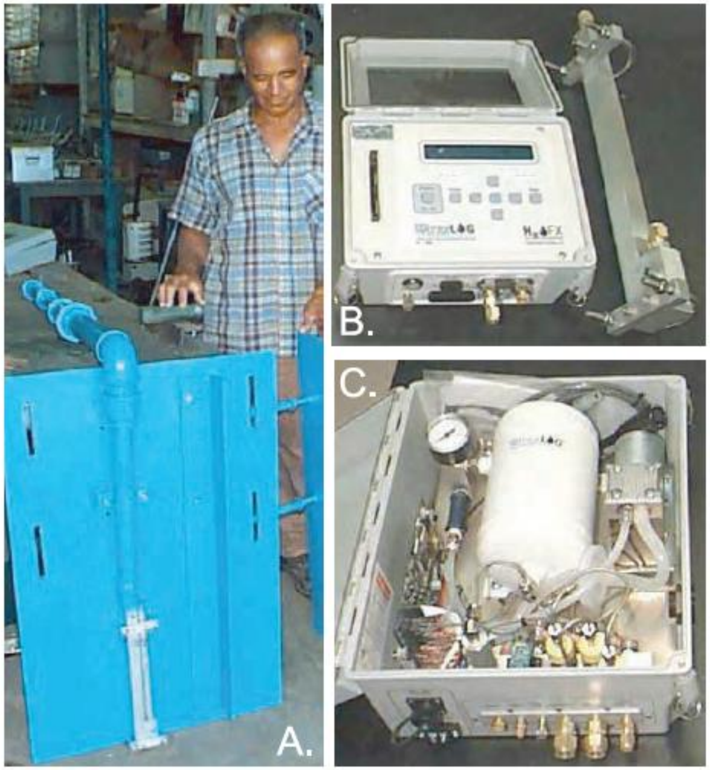

Figure 8. Double Bubbler Pressure Differential Instrument (a) in-stream components before installation, (b) controller and orifice bar, and (c) air compressor and tank assembly. Figures 8b and 8c courtesy of Design Analysis Associates, Inc.

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Pressure Difference Application

Paria River, Lees Ferry, Arizona (July 2004)

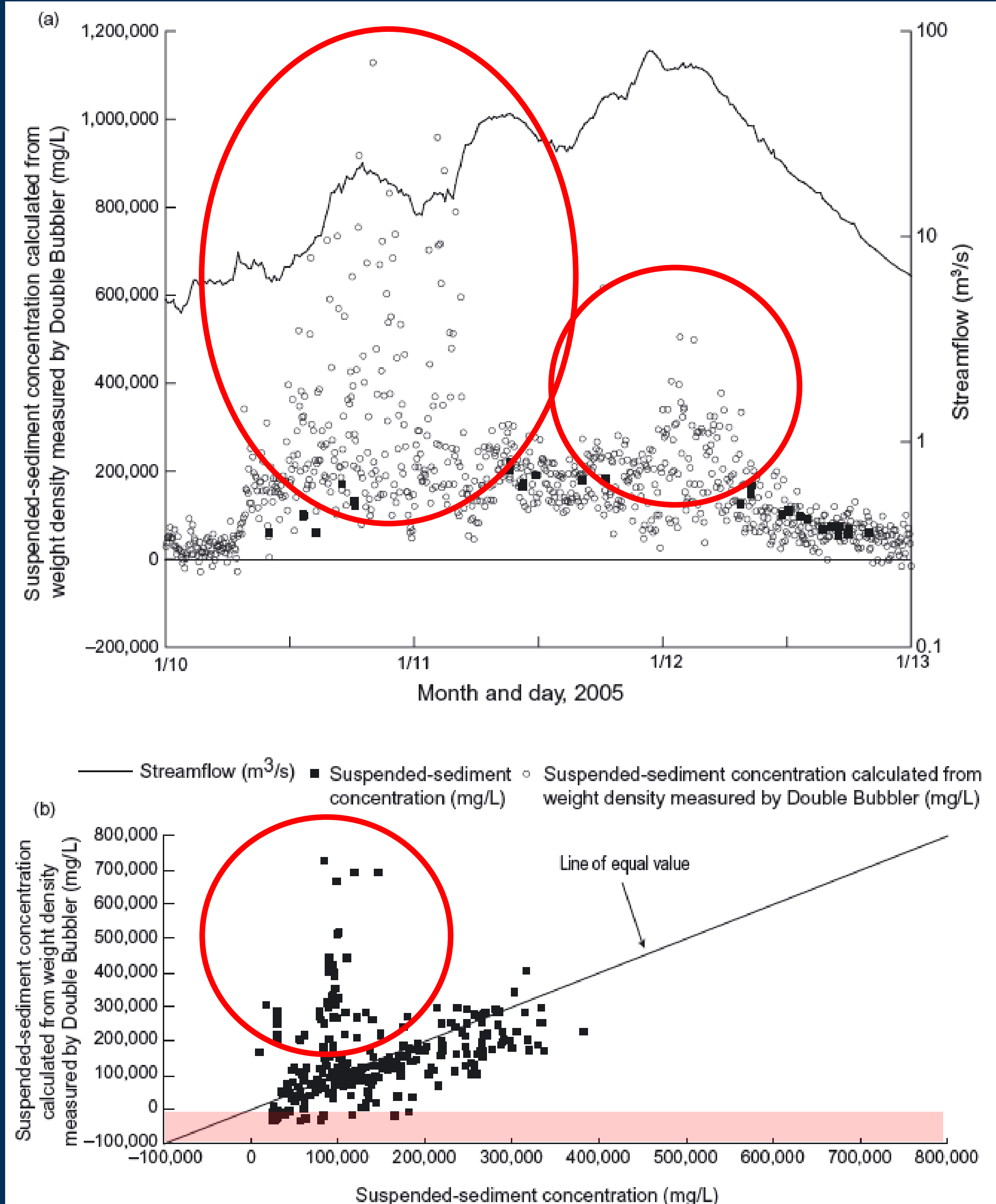

Fig. 1.19 Data for the USGS streamgage on the Paria River at Lees Ferry, Arizona, USA, July 2004 through September 2006. (a) Time series of streamflow, SSCs from samples, and SSCs calculated from weight densities of suspended sediments and dissolved solids measured using the Double Bubbler for a storm in January 2005; (b) scatter plot of measured SSCs from samples and those calculated from the Double Bubbler. Streamflow and sediment data are instantaneous samples, and the Double Bubbler SSC values, calculated from weight densities, are from measurements made at 5-minute intervals.

USGS

Pressure Difference

Advantages

- Infers SSC in a single vertical, rather than point
- Robust technology, resistant to fouling or drift
- Doubles as redundant stage sensor for site
- Accuracy improves with higher SSC (> 10-20 g/L)
- Theory and technology is simple

Limitations

- Point measurement (in XS)
- Assumes constant density above lowest sensor (hard to verify)
- May be incapable of measuring SSC < 10 g/L in turbulent flows (noise)
- Lab results are promising, field performance has been poor
- Both orifices must remain in the water and unburied
- Spurious data are numerous (likely turbulence)
- The manufacturer no longer makes this instrument

USGS

Digital Photo-Optics

- Computes size statistics of particles captured in images in a flow-through cell
- Volumetric SSC is inferred from the size statistics
- High-quality, 2-D images are processed at the pixel level
- Primarily lab-based with field testing
- Accurate up to 10 g/L

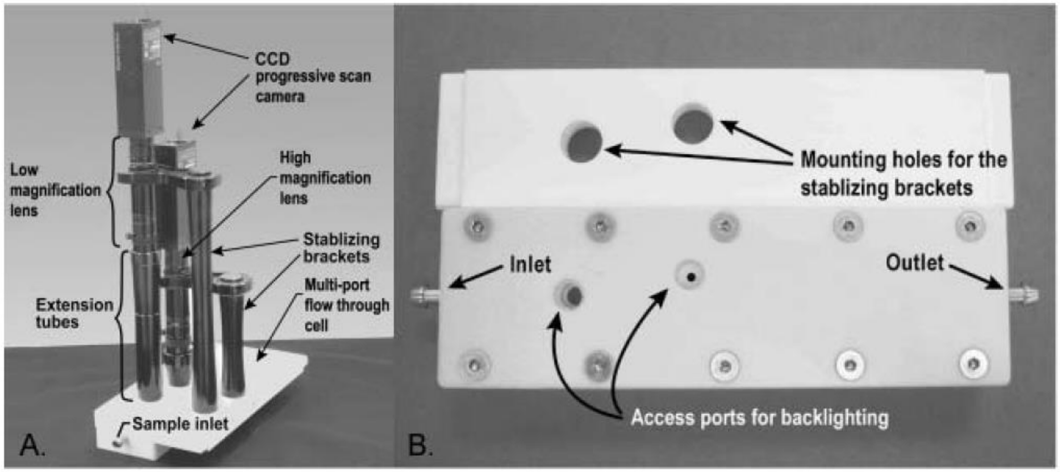

Figure 3 Suspended-sediment digital optic-imaging components: A) Cameras atop encased lenses with extension tubes and encased flow-through cell (fiber optic cable not shown). B) Multi-port flow-through cell (patent pending). From Gooding, 2010.

USGS

Digital Photo-Optics

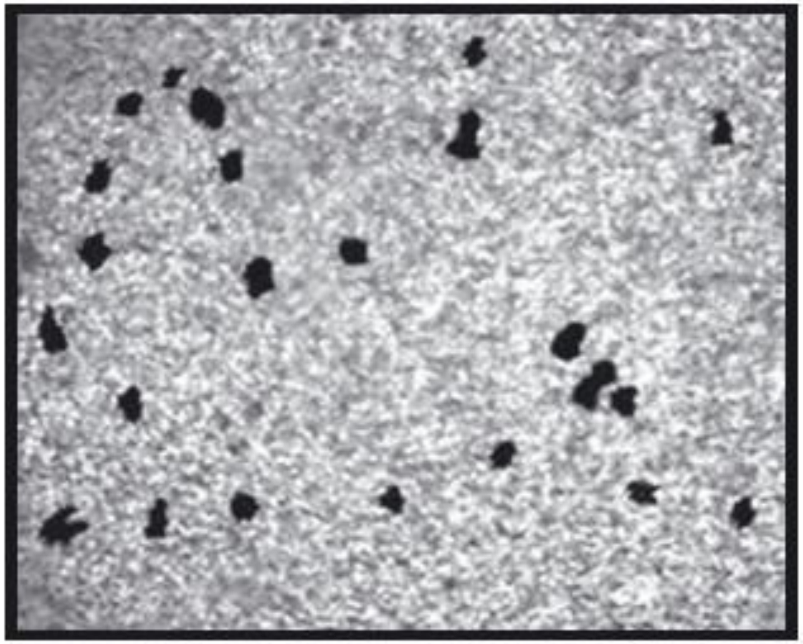

Fig. 1.14 A morphologically transformed image of a water-sediment mixture composed of 10 g/L of material finer than 62 µm, seeded with 125- to 250-µm particles that appear as dark blobs.

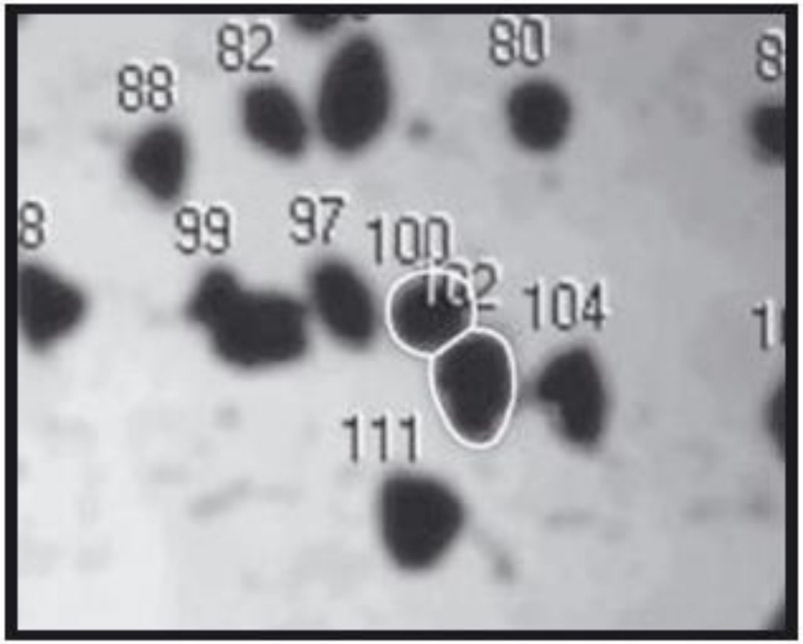

Fig. 1.15 A morphologically transformed image of a water–sediment mixture composed of 62–125 µm particles showing potentially inconsistent interpretation of overlapping or connected particles.

Digital Photo-Optics

Advantages

- Components cost about the same as a turbidity sensor
- No instrument specific calibrations necessary
- Can be incorporated into isokinetic samplers or stream-side pumped systems

Limitations

- Point measurements
- Accuracy can be affected by
  - Partially hidden particles
  - Aggregates
  - High turbidity levels
  - Bubbles, organics
  - Stagnant material in measurement volume
- Results are expressed as volumetric units and not mass per unit volume (requires assumption about particle density or collection of samples)
- Data can be noisy

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Acoustic Backscatter

- **Relies on the acoustic returns (backscatter) of particles in the water column as SSC surrogate (~analogous to Doppler radar for rain)**

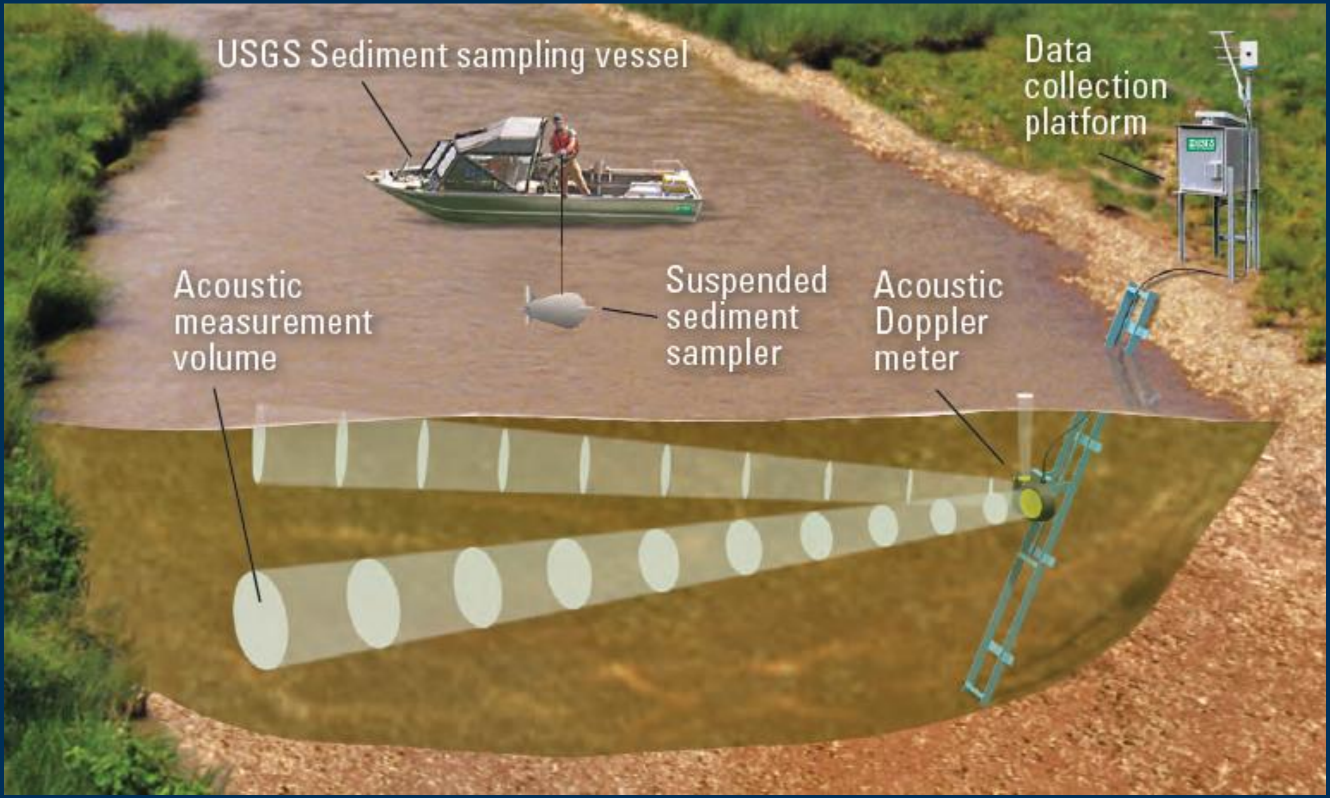
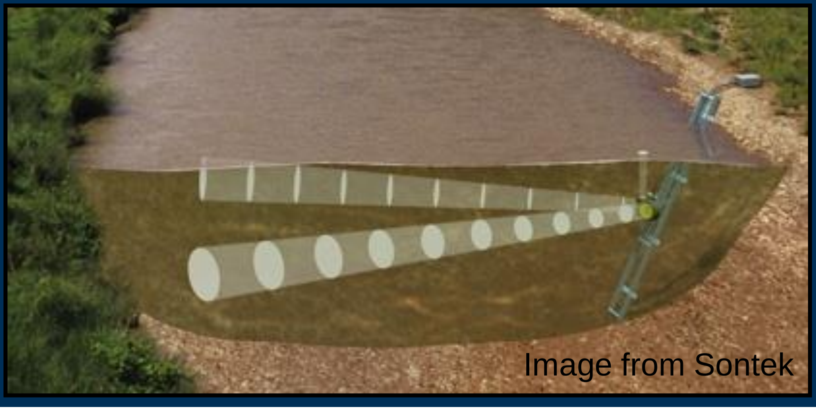
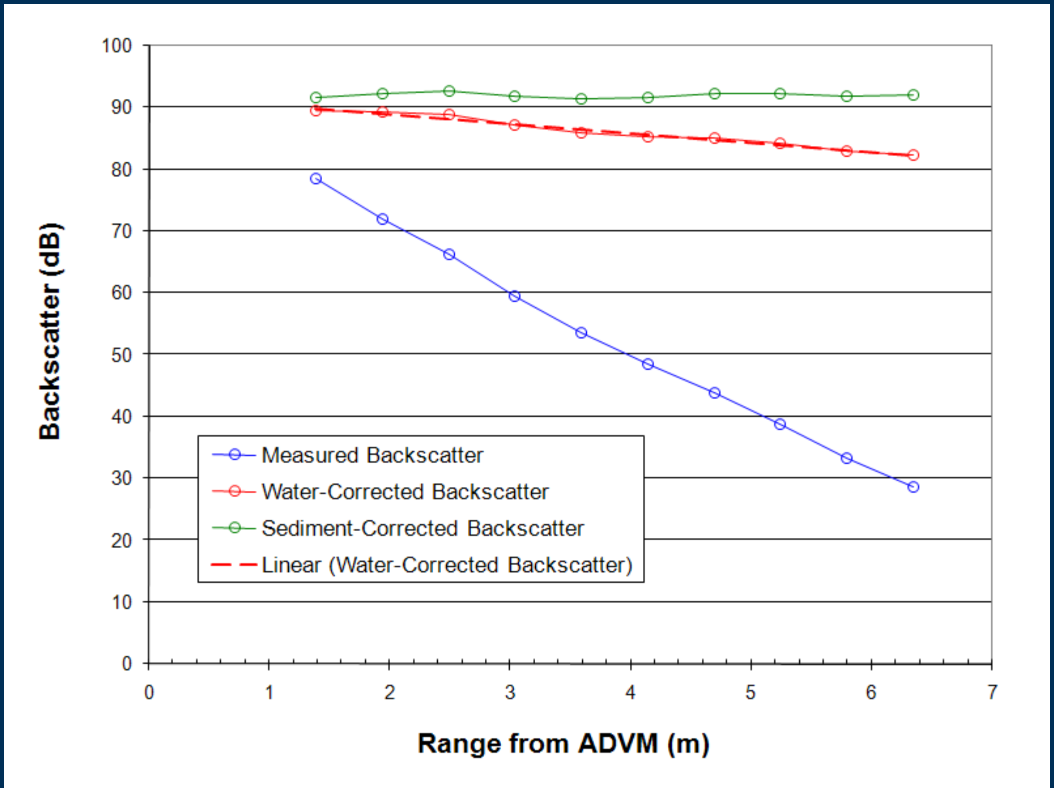


Image from draft Fact Sheet by M. Wood modified from Sontek

Acoustic Backscatter

- Assumes a constant concentration along a beam
- Uses multiple cells along a beam
- Requires multiple steps to formulate a calibration
  - Correction for beam spreading and absorption by water
  - Correction for attenuation by sediment





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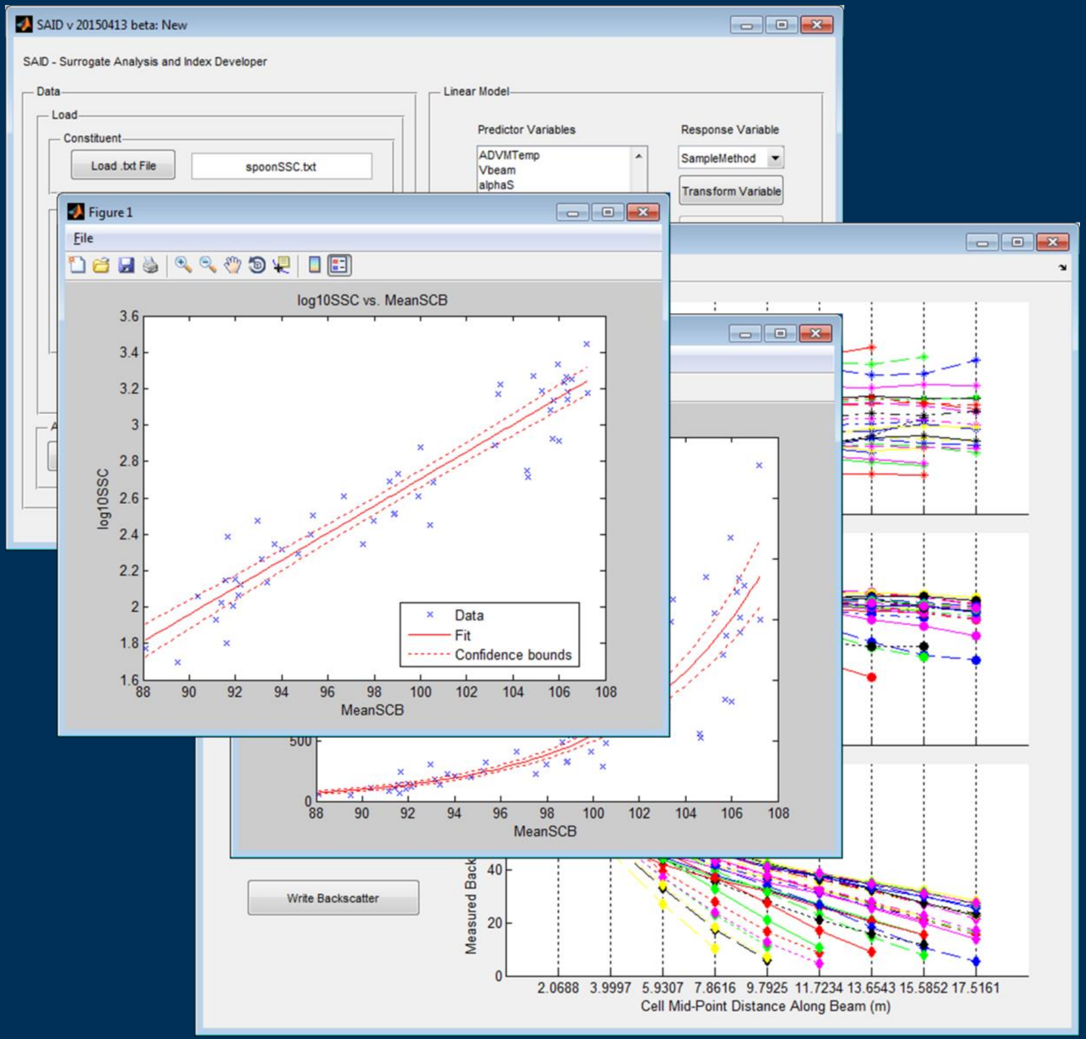
Surrogate Analysis and Index Developer (SAID) Tool

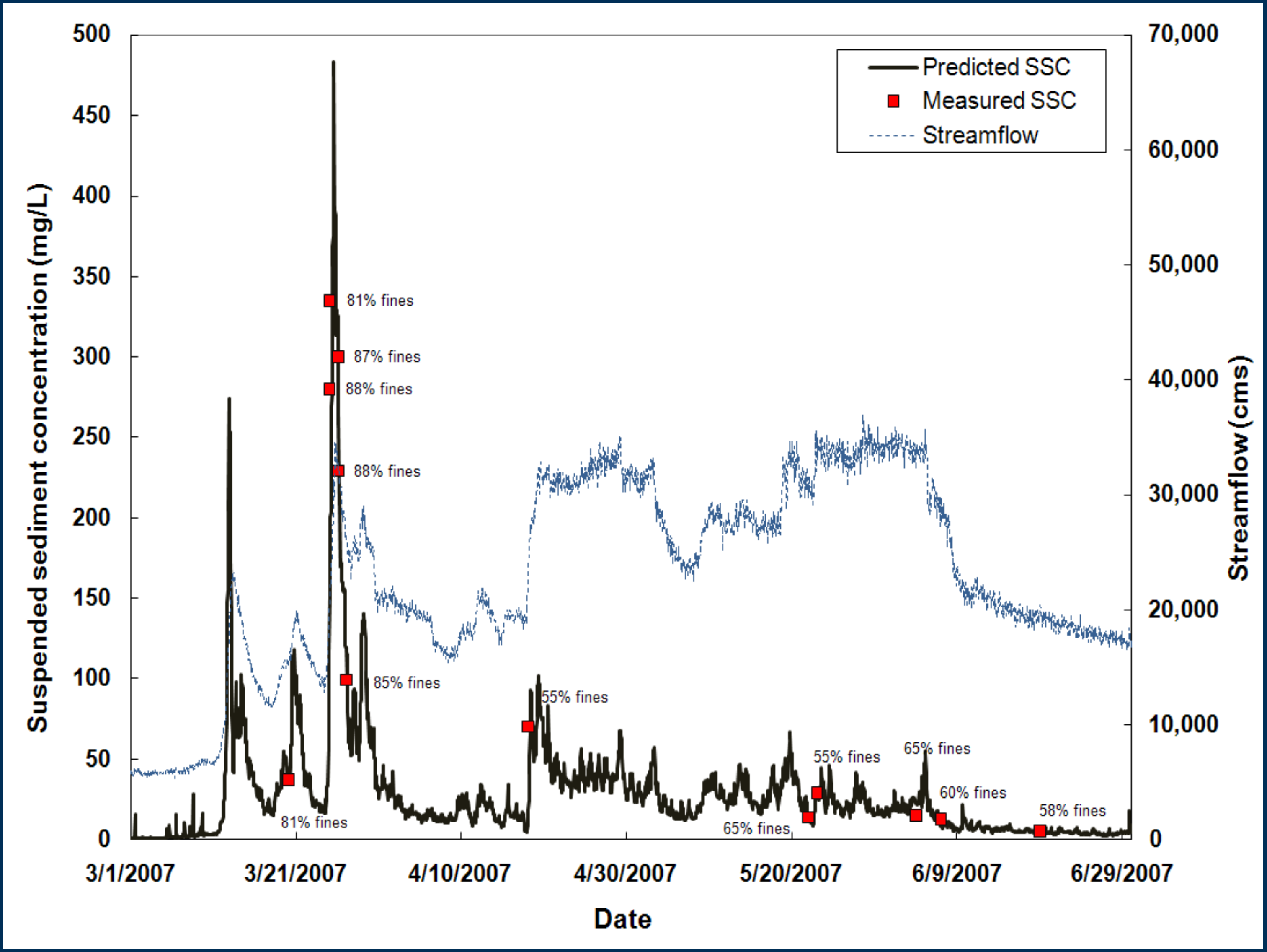
- **Assists in the creation of regression models that relate response and explanatory (surrogate) variables**
- **Supports guidelines**
  - **Multi-agency sediment acoustic methods work**
  - **USGS Techniques & Methods 3-C4 for turbidity and SSC**
  - **OWQ/OSW Surrogate Model Policy Memo**



Acoustic Backscatter Application

Kootenai River (ID)
At Tribal Hatchery

Data from M. Wood, USGS ID WSC

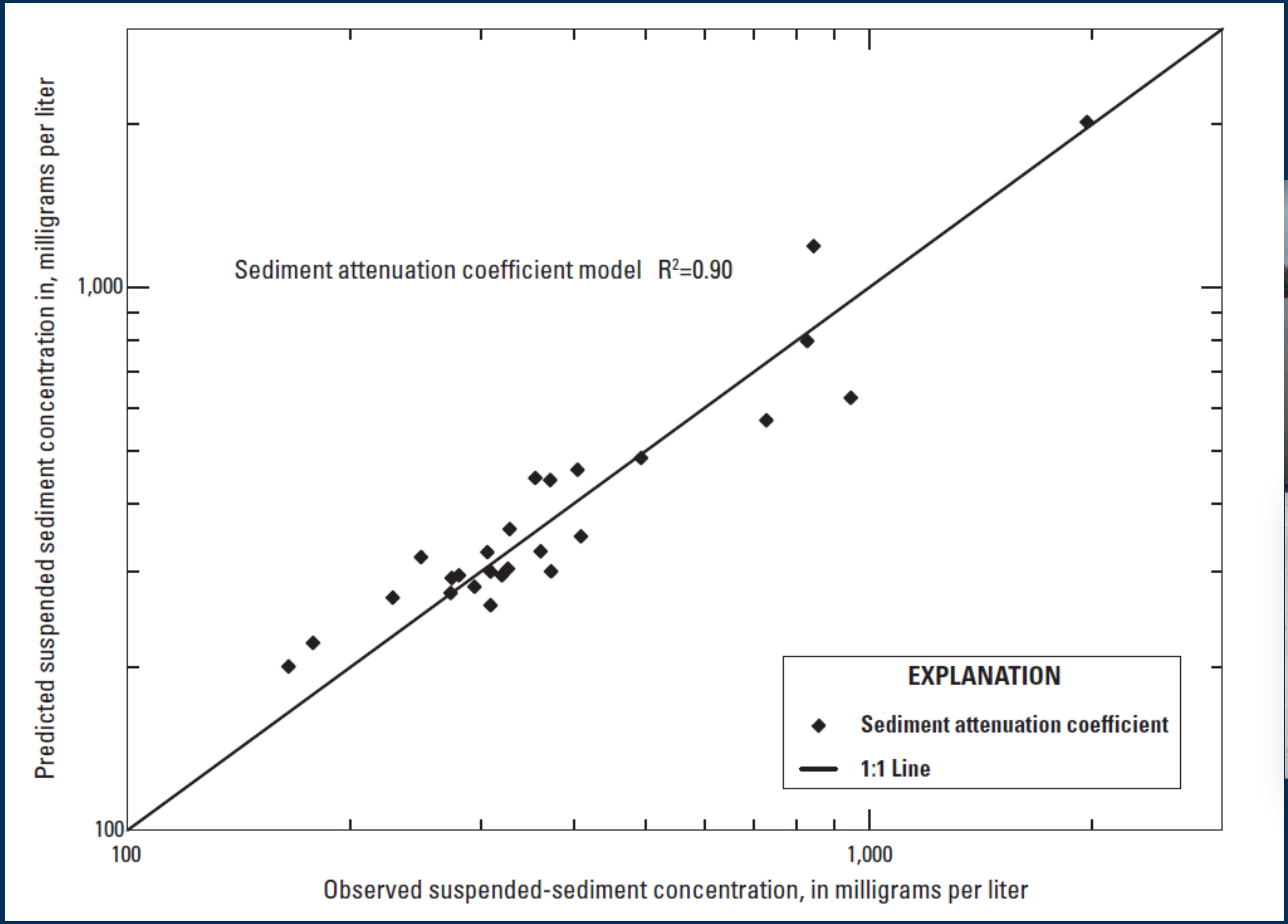


USGS

Acoustic Backscatter Applications

Illinois River at Florence, IL (Spring 2013)

Predicted SSC



Sontek
Argonaut
SL500, 1500, 3000

Observed SSC

Acoustic Backscatter

Advantages

- Sample significantly more of the cross section than at-a-point sensors
- Allows computation of unit and daily value sediment fluxes
- Fouling is not a problem
- Applicable to 0.01-20g/L for silt and clay and 0.01- 3 g/L for sand
- ADVMs also measure velocity data

Limitations

- A single frequency unit cannot differentiate between changes in PSD and SSC without calibration
- There is an optimal frequency for a given particle size and a narrow frequency range for a given PSD
- Complex software is required for reduction and analysis of data and rating development
- Higher cost (about 2-3 times a turbidity sensor)
- Calibrations are instrument specific

USGS

Questions?

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Prepared in cooperation with the U.S. Army Corps of Engineers

Use of Surrogate Technologies to Estimate Suspended Sediment in the Clearwater River, Idaho, and Snake River, Washington, 2008–10

Scientific Investigations

U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the Illinois Environmental Protection Agency

Continuous Monitoring of Sediment and Nutrients in the Illinois River at Florence, Illinois, 2012–13

Scientific Investigations Rep

U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the Federal Interagency Sedimentation Project

Estimating Suspended Sediment in Rivers Using Acoustic Doppler Meters

Key Points

- The U.S. Environmental Protection Agency (2009) estimates that excessive sediment is the leading cause of water-quality impairment in water bodies in the United States. The cost of damages attributable to sediment is high, estimated at more than $20 billion annually (Osterkamp and others, 2004).
- Sediment monitoring is essential to informed solutions to sediment-related issues. However, sediment monitoring by the U.S. Geological Survey (USGS) has decreased considerably over the past quarter century.
- New techniques that make use of acoustic backscatter have shown great potential for accurately and cost-effectively estimating suspended-sediment concentrations.

Monitoring sediment is important for the management of water resources. "Sediment monitoring data can be used to determine effectiveness of sediment reduction actions in the watershed and guide adaptive sediment management," states Richard Turner of the U.S. Army Corps of Engineers, Walla Walla District. "Monitoring data helps foster fact-based working relationships with regulators and stakeholders, and contributes to the U.S. Army Corps of Engineers' public safety efforts and flood risk reduction."

Why Is Sediment Important to Measure?

Sediment can be transported as suspended load (moves with the flow of the river) or as bedload (rolls along the riverbed) or can be deposited on the riverbed or bank. The concepts described in this Fact Sheet focus on methods for estimating suspended sediment because it is typically the largest part of total sediment transported in a river (Meade and others, 1990). Sediment is naturally occurring and essential to supporting the ecological function of a water body. High sediment concentrations in rivers and streams, however, can be detrimental (fig. 1).

How Is Suspended Sediment Measured?

For many years, USGS scientists have collected sediment samples from multiple vertical sections in rivers using point or depth-integrating samplers. Sediment samples represent the sediment concentration in a particular river at a given point in time. To continuously estimate sediment concentrations during periods when samples are not collected, scientists develop relations between sediment concentrations and other parameters, most commonly, streamflow measured at a nearby streamgage.

Figure 1. High sediment concentrations can reduce biological productivity of aquatic systems (*A*), impair water quality (*B*), (*C*), (*E*), decrease flood-protection capacity of levees and dams (*D*), decrease reservoir storage capacity (*D*) and affect waterway navigation (*E*).

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U.S. Geological Survey

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APPENDIX

From Concept to Application

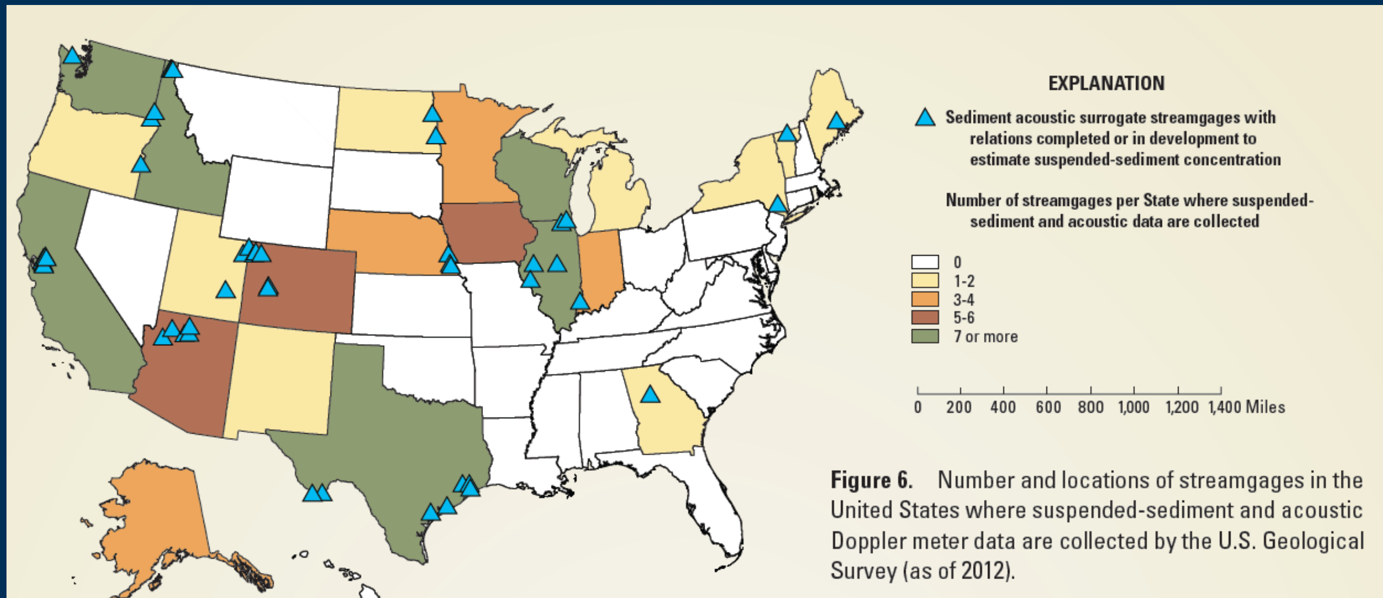
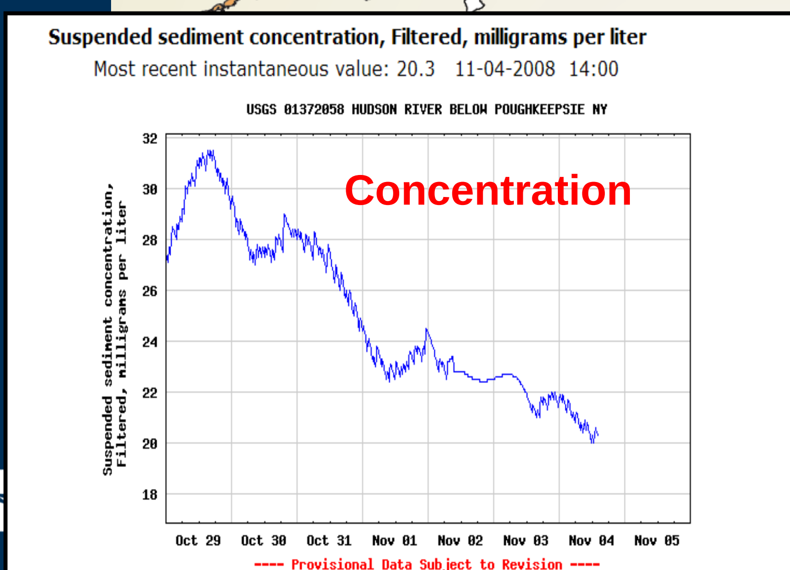
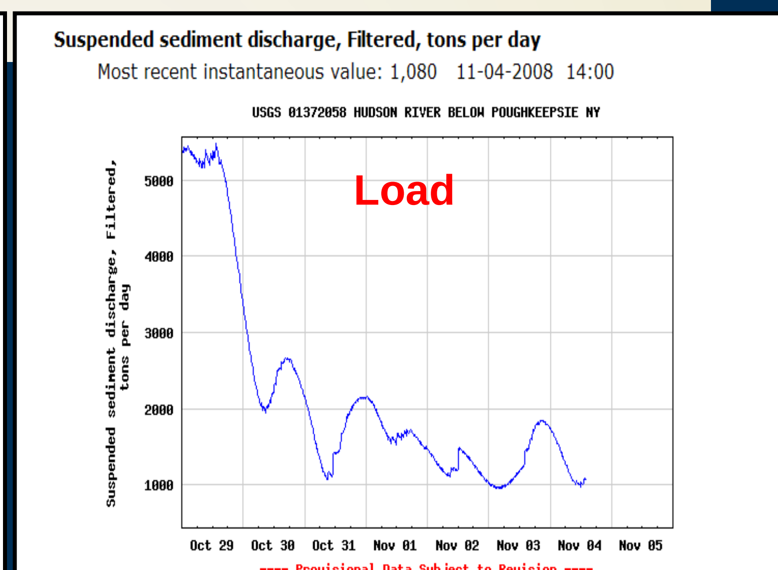


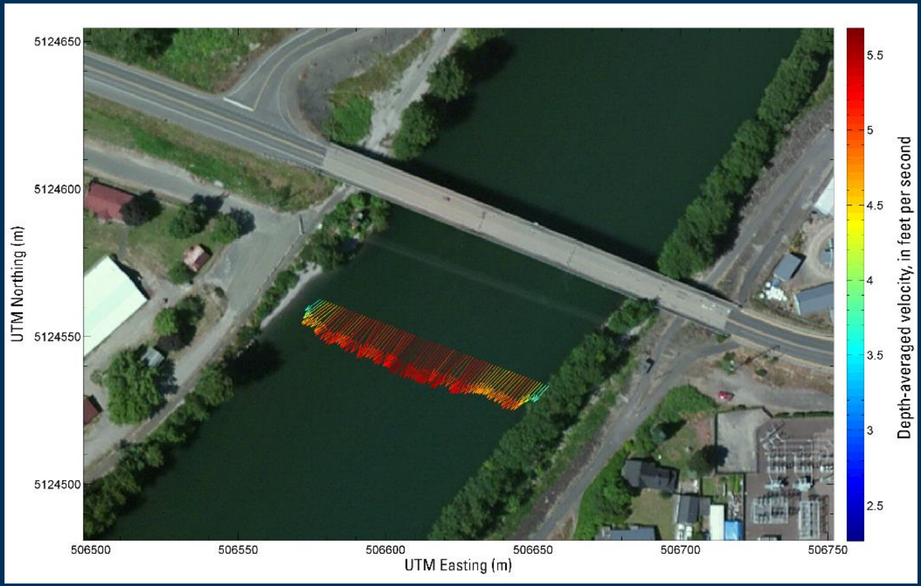
Figure 6. Number and locations of streamgages in the United States where suspended-sediment and acoustic Doppler meter data are collected by the U.S. Geological Survey (as of 2012).

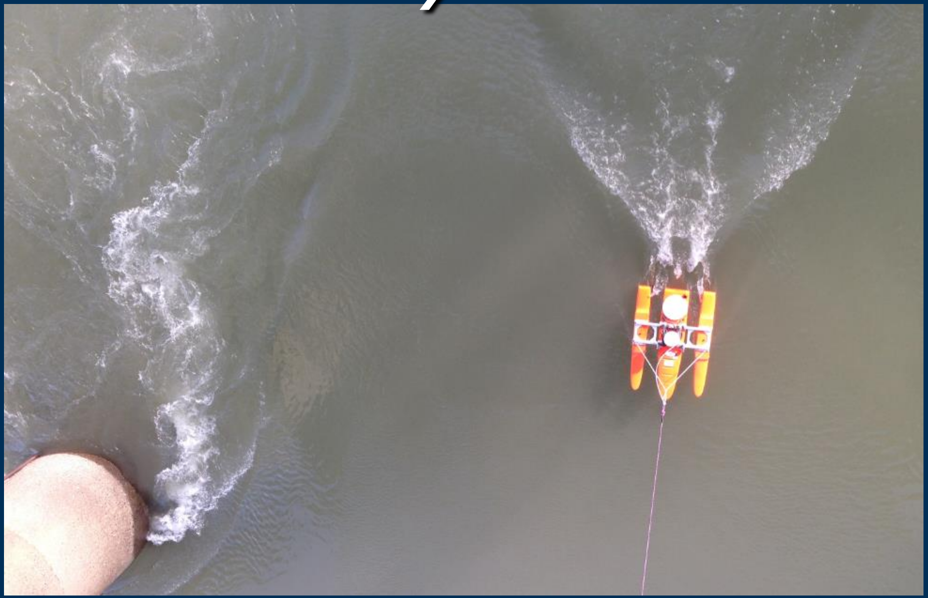


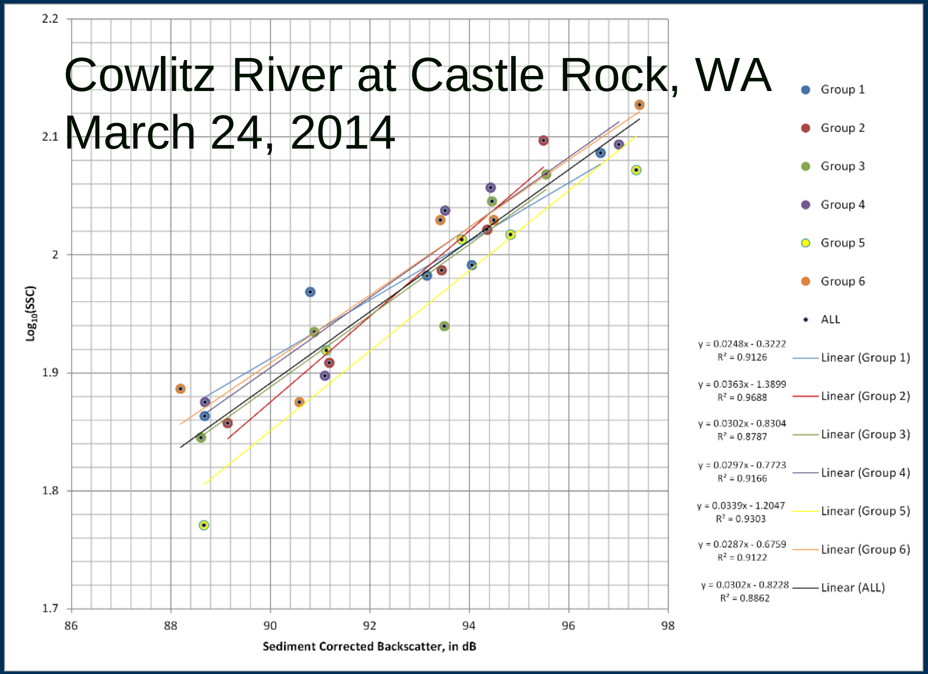


Courtesy: USGS New York, Lower Hudson River Project

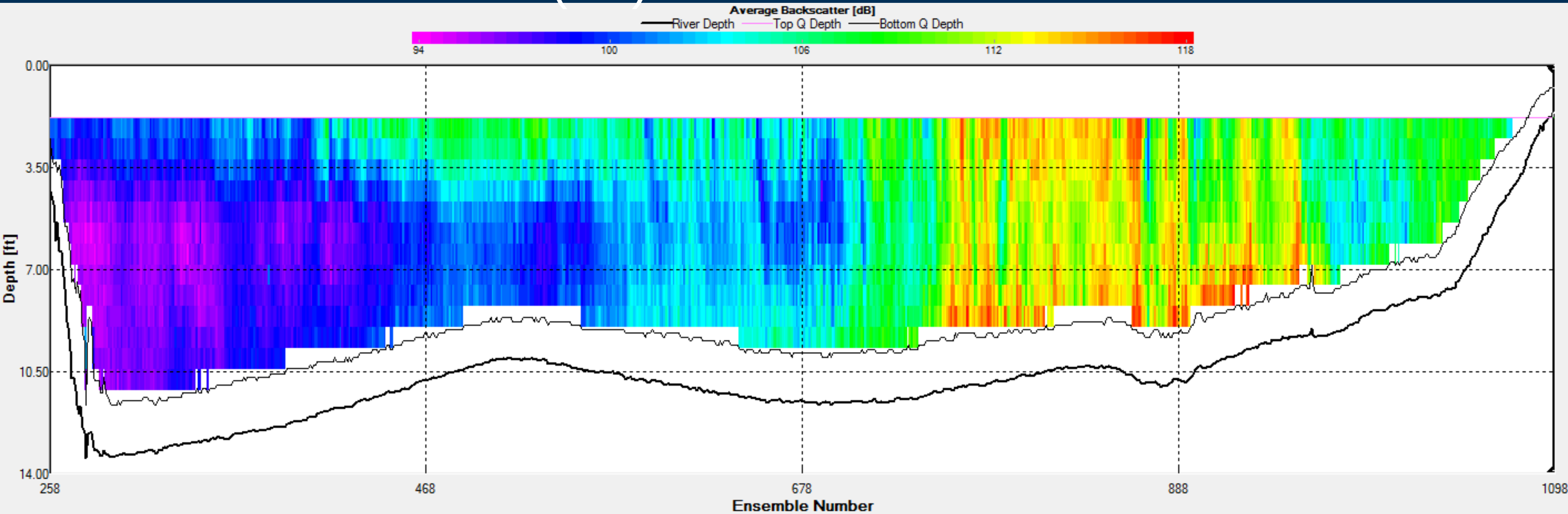
Discrete Measurements of SSC by Acoustics





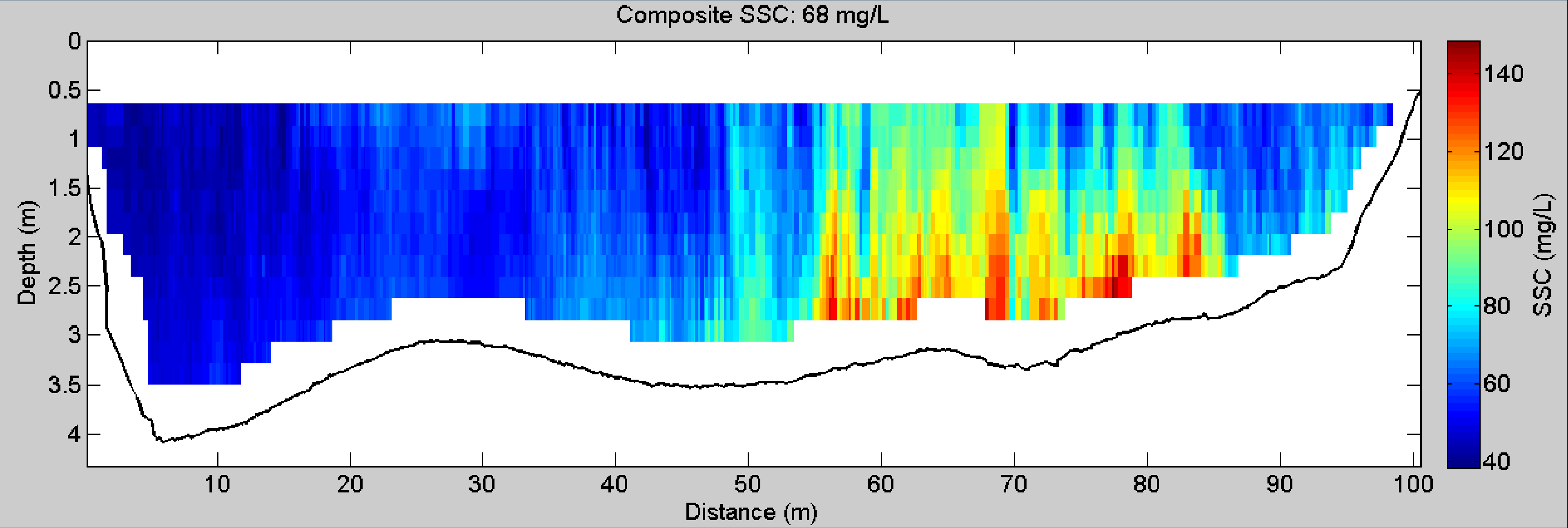


Measured Backscatter (dB)



Suspended Sediment Concentration (mg/L)

EDI = 71.4 mg/L



Surrogate Acceptance Criteria
(Gray and Gartner, 2009)

- Generalized from laser diffraction instrumentation

Table 1. Acceptance Criteria for Suspended-Sediment Concentrations[a]

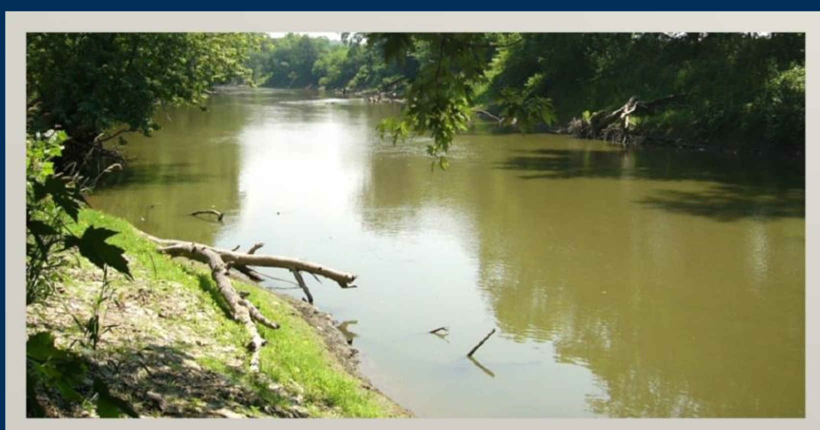
Suspended-Sediment Concentration Minimum, g/L	Suspended-Sediment Concentration Maximum, g/L	Acceptable Uncertainty, %
0	<0.01	50
0.01	<0.1	50–25 computed linearly
0.1	<1.0	25–15 computed linearly
1.0	–	15

[a]Suspended-sediment data produced are considered acceptable when they meet these criteria 95 percent of the time [*Gray et al.*, 2002].

Acoustic Backscatter Applications

Spoon River near Seville, IL

- 1,636 mi^2 drainage area
- Up to 25% sands in suspension



Sontek
Argonaut SL

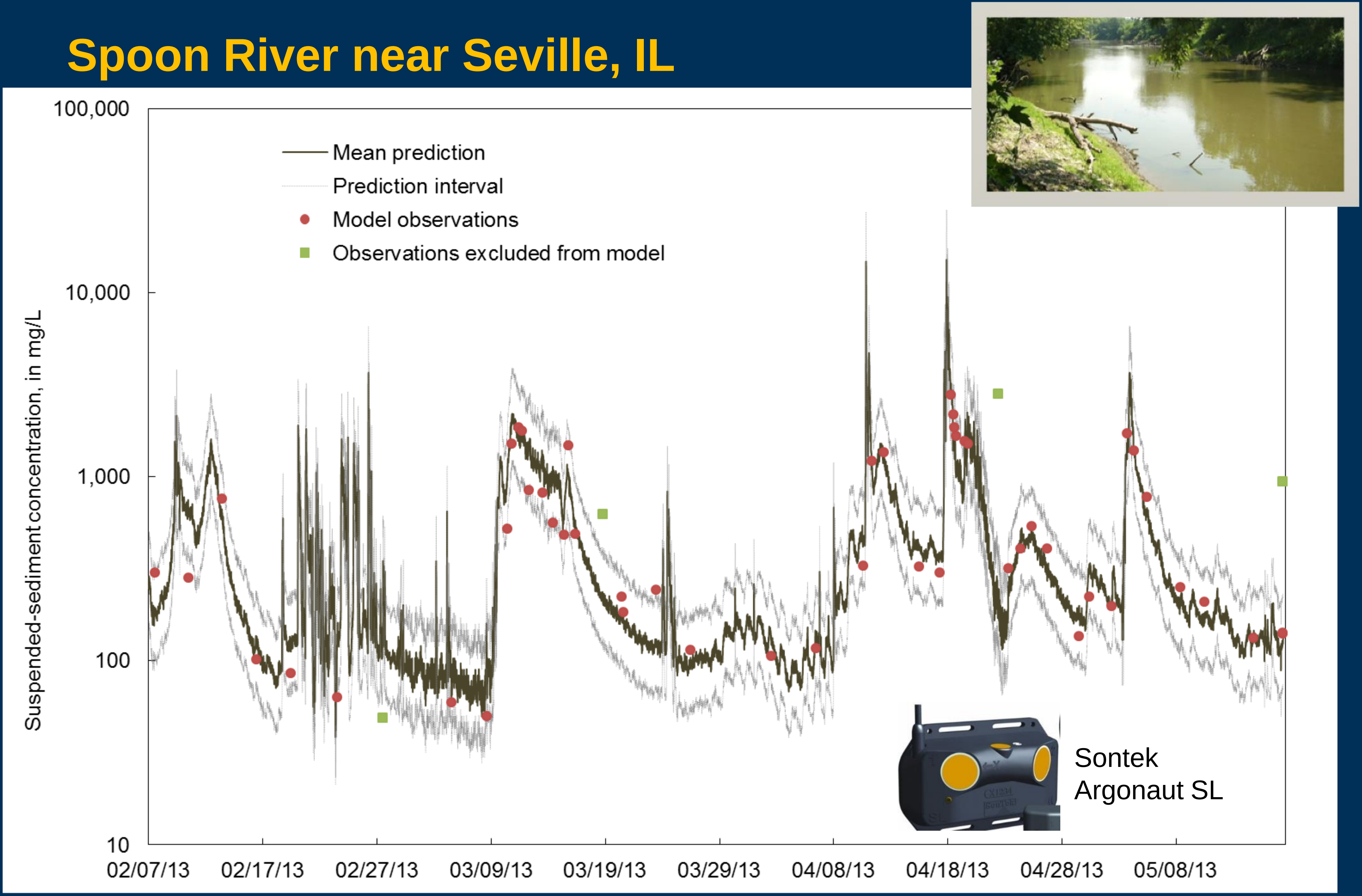
Illinois River at Florence, IL

- 26,870 mi^2 drainage area
- 4 M tons of sediment annually
- USGS sediment and nutrient superstation

Sontek
Argonaut
SL500, 1500, 3000

Acoustic Backscatter Applications

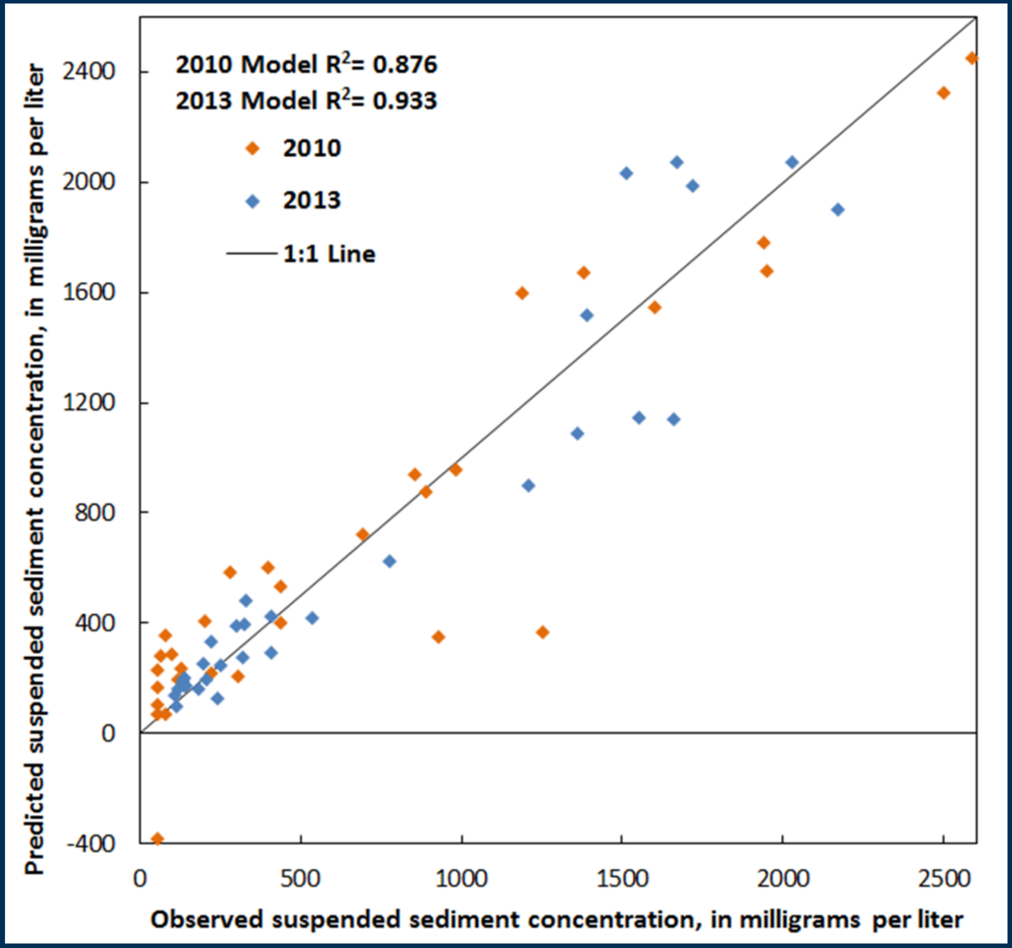
Spoon River near Seville, IL



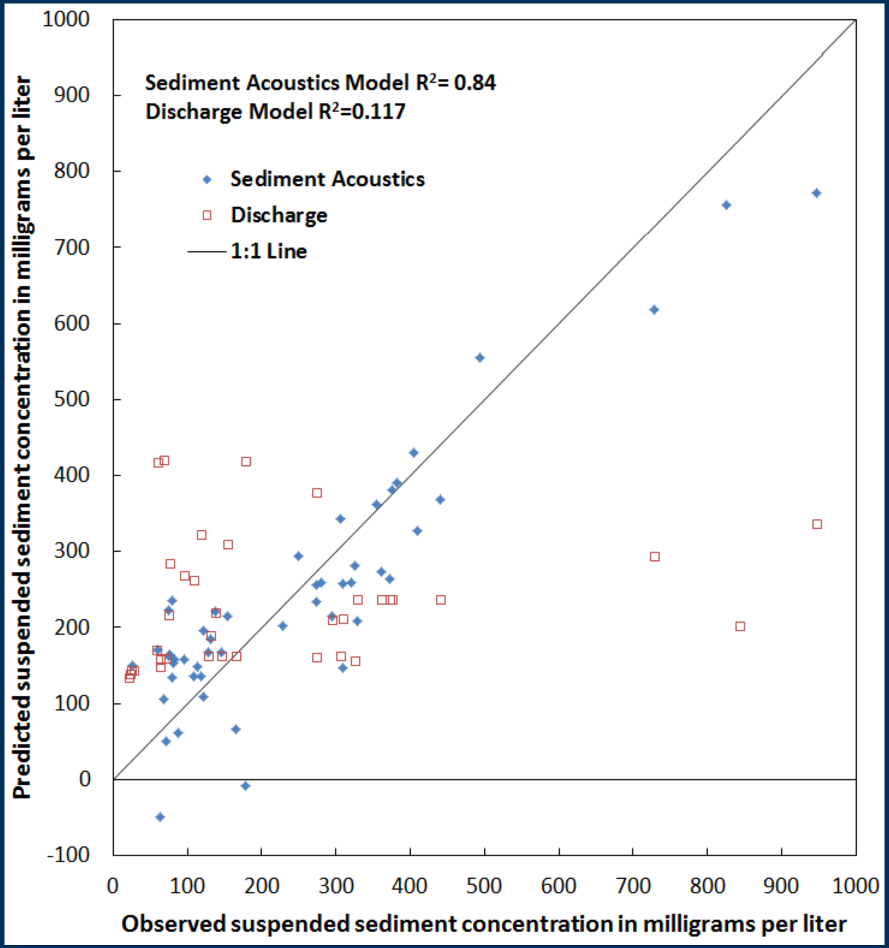
Sontek Argonaut SL

Acoustic Backscatter Applications

Spoon River near Seville, IL

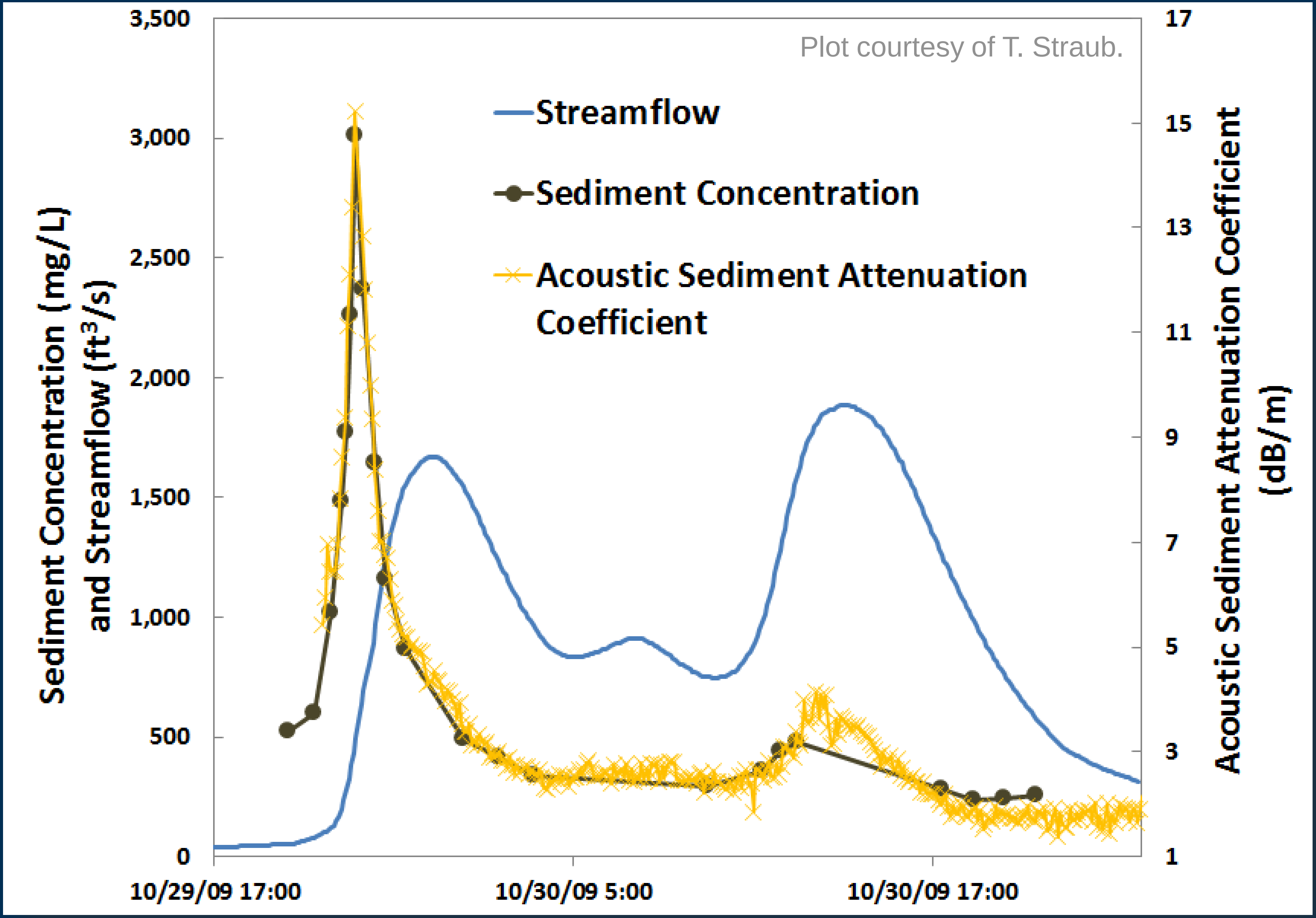


Illinois River at Florence, IL

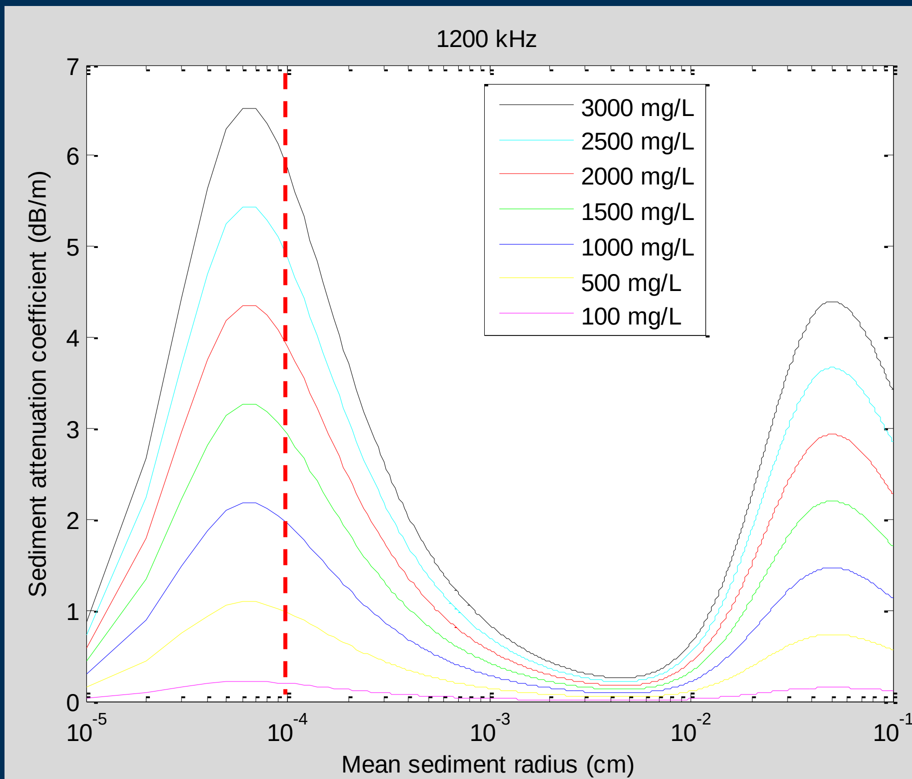


Sediment Concentration & Attenuation Coefficient

October 2009 Storm



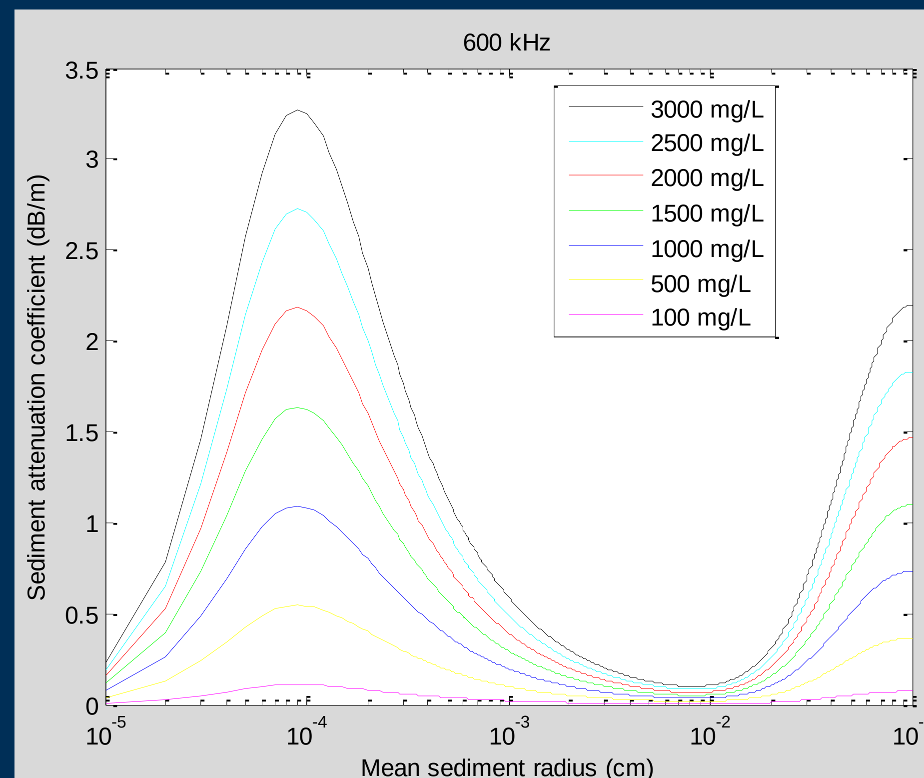
Plots of α_s vs. a_s for 1200 kHz & 600 kHz



$$\alpha_S = SSC_V\left[k(\gamma-1)^2\left\{\frac{s}{s^2+(\gamma+\tau)^2}\right\}+\left\{\frac{k^4 a_s^{\,3}}{5(1+1.3k^2a_s^{\,2}+0.24k^4a_s^{\,4})}\right\}\right]4.34$$

Hybrid Urick-Sheng-Hay equation for the sediment attenuation coefficient (α_s)

(Urick, 1948), (Sheng and Hay, 1988), (Landers, 2010)



Questions:

- **How to determine mean sediment radius (a_s)?**
- **Use D_{50} or something else?**

Backscatter to SSC equations

Two-way transmission loss:

$$2TL = 20Log_{10}(\psi r) + 2\alpha_f r + 2\alpha_s r$$

r = range along beam

Near field correction:

(Downing et al., 1995)

$$\psi = \frac{1 + 1.35z + (2.5z)^{3.2}}{1.35z + (2.5z)^{3.2}}$$

$$z = \frac{R\lambda}{\pi a_t^2}$$

$$R = r + \frac{H_B}{4}$$

R = range/distance along beam

Water attenuation coefficient:

(Schulkin and Marsh, 1962)

$$\alpha_f = 8.687 \times \frac{3.38x10^{-6} f^2}{f_T}$$

$$f_T = 21.9x10^{\left[6-\left(1520/_{T+273}\right)\right]}$$

Sediment attenuation coefficient:
(Urick, 1948)
(Sheng and Hay, 1988)
(Landers, 2010)

$$\alpha_S = SSC_V \left[k(\gamma-1)^2 \left\{ \frac{s}{s^2 + (\gamma+\tau)^2} \right\} + \left\{ \frac{k^4 a_s^{\,3}}{5(1 + 1.3k^2 a_s^{\,2} + 0.24k^4 a_s^{\,4})} \right\} \right] 4.34$$

RL = reverberation level (aka measured backscatter, MB) →
using the average of beams 3 and 4

$$SCB = RL + 2TL$$

$$\log_{10} SSC = a \times SCB + b$$

$$SSC = 10^{(a \times SCB + b)}$$

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