# Breakout Session III, Bed-Material and Bed-Topography Measurement: Data Needs, Uncertainty, and New Technologies

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## Introduction

Breakout session III focused on current and emerging bed-material and bed-topography data-collection techniques and methods. How these data are used by each of the represented agencies and uncertainties associated with these data were also discussed. The experience and interests of the participants were skewed more toward measurement of bed topography. Various surveying technologies applicable to bed-topography measurement received considerably more deliberative time and attention than bed-material measurement techniques, although many of the technologies identified were applicable to both types of measurements and to bedload measurements. Discussions focused on new technologies with agreement that traditional technologies are the standards for evaluation of surrogate technologies.

### Discussions

Participants were sent key questions prior to the workshop to facilitate discussion. These key questions are similar to those posed in other breakout sessions and are shown below in italics. The responses to each question represent participant consensus.

1. What are your agency's/organization's/cooperator's (organization) needs for this type of sediment data? How are these data used by your organization?

Bed-topography and bed-material data are collected and used generally as a basis for resource-management decisions. Monitoring programs are common for reservoir capacity, habitat conditions, navigation routes, channel and coastal evolution (geometry and bed-material size), discharge capacity, sediment transport and contaminant movement. The decisions may involve operation, maintenance, planning, design, construction, or compliance issues. Decisions often must be made that involve multiple issues and constraints. Predictive models used as tools to compare alternatives and project impacts often require bed-topography and bed-material data as independent variables.

2. Does your organization have any accuracy standards for collecting theses types (bed topography or bed material) of sediment data?

National and international mapping standards such as those maintained by the USGS National Mapping Program, Federal Geographic Data Committee, the National Institute of Standards and Technology, and the North Atlantic Treaty Organization's Digital Geographic Information Exchange Standard were referred to for topographic and hydrographic data. Survey manuals and guidelines have been published by the U.S. Army Corps of Engineers (2002), American Society of Civil Engineers (1975), ASTM International (2003), and the International Hydrographic Organization (1997).

The accuracy requirements for topographic and hydrographic data usually are based on budget constraints and are spelled out specifically for individual data-collection efforts. The group emphasized that metadata accompanying all terrain/bed data should include data-collection details and documentation of data accuracy. Generally, 0.3- to 0.7-meter contour intervals are sufficient for most large-scale fluvial applications when data are collected via remote methods such as aerial photogrammetry or LIDAR for long reaches. An example of accuracy requirements would be 90 percent of points within ± 0.15 meter, and 100 percent of points within ±0.3 meter. In small-scale, complex situations at least ±0.03 meter accuracy may be required and can be obtained with a good control network using land surveying techniques.

In the U.S. Army Corps of Engineers' (USACE) EM 1110-2-1003 (2002), several error components are described for electronic echo sounding depth measurement methods used in bathymetric surveys of underwater bed topography. These sources of error include: measurement system accuracy, velocity calibration accuracy, sounder resolution, draft/index accuracy, tide/stage correction accuracy, platform stability error, vessel velocity error, and bottom reflectivity/sensitivity. These combined errors result in an estimated accuracy of an individual echo-sounding depth falling between ±0.1 and ±0.3 meter for average river and harbor project conditions. Airborne technologies have similar error sources. Accuracy (closeness of a measurement to the actual value) should not be confused with the precision or repeatability of measurements.

There was little discussion concerning accuracy standards for bed-material data. Depending upon the homogeneity of the surface and subsurface bed material, the location, density, and timing of sampling can impact the accuracy of bed-material data as much as the sampling and analysis equipment and procedures. Many technical society and government references provide guidance for the collection and analysis of bed-material samples including a USGS publication (Edwards and Glysson, 1999); Forest Service publications (Bunte and Abt, 2001a; 2001b); U.S. Army Corps of Engineers (1995); International Organization for Standardization (1997); American Society of Civil Engineers (1975); ASTM International (2003); and Canadian publications by Yuzyk and Winkler (1991), Ashmore and others (1988), and Yuzyk (1986).

Data uncertainty also was discussed. Participants viewed uncertainty as being inherent in traditional and new technologies. There are many potential sources of error: user, equipment, interpretation, and data processing. Uncertainty also is dependent upon system spatial and temporal variability. As stated previously, accuracy requirements tend to be project-specific and time- and budget-driven. We agreed that data accuracy and uncertainty information should accompany all data.

3. What methodologies and equipment are currently used to collect bed-topography and bed-material data in your organization? What are their strengths and limitations? What uncertainties are associated with them?

**Bed topography:** The historical standard for bed topography incorporated the measurement of set range lines by conventional land surveying equipment and techniques using stadia rods, transits, and total stations. Traditional methods are labor intensive and require considerable ground access and cleared site distance. Advances in global positioning systems (GPS) have in most applications eliminated the need for manual horizontal measurements. GPS-based methods were considered to be the most accurate (± millimeter range) and are used to calibrate, ground truth, and check other methods.

Photogrammetric mapping or non-contact stereo aerial surveying was considered to be the more established, less costly, passive surveying technology. The accuracy of this technology depends upon the amount of ground truth-data available. The mosaic of individual photographic images can be used to develop cross sections and topographic maps. A limitation of this technology is the inability to obtain underwater prism information or ground surface elevations through dense vegetation.

Light Detection and Ranging (LIDAR) remote sensing systems applications are increasing with advancements in this new technology. This technology also needs clear sight distance so ground surface data cannot be obtained in heavily vegetated areas. Early successful applications were in coastal surveys. More recent applications have incorporated airborne LIDAR bathymetry technology (1-kilohertz laser deployed with a 10-kilohertz topographic laser and a digital camera, e.g. Optech's SHOALS-1000T system) to obtain bathymetry data in addition to topography. LIDAR bathymetry technology is largely dependent upon water clarity; turbidity and turbulent white water conditions can cause problems. The system can detect channel-bottom elevations up to about 2.5 times the Secchi depth, in coastal applications possibly up to 30 meter or more. Underwater data need to be corrected for the adsorption rate of water. The spatial density of points is related to the flight height; flight elevations can be higher for topography data collection than bathymetry.

Bathymetric surveying techniques have developed rapidly in the past decade due to recent developments in multi-beam depth sounders. The multi-beam system provides the option of complete coverage of the underwater areas, thus removing the unknowns of previously unmapped underwater areas. There are high-grade GPS collection systems, real-time kinematic surveying, that accurately measure the altitude of the moving survey platform with obtainable centimeter accuracies for both horizontal and vertical measurements. There also are several versatile commercial software packages capable of simultaneously receiving data from multiple devices during collection and then processing the collected data for complete analyses. In addition to collecting data from numerous instruments simultaneously, the computer and software can be set up to integrate data from various sensors such as gyros, acoustic systems, heave-pitch-roll indicators, magnetometers, and seabed identifiers (Bureau of Reclamation, in press).

Advances in computer systems and surveying technologies in recent decades have dramatically increased the volume of data and the rate of data acquisition and processing. These technologies have become widely accepted because of the increased coverage and reduced costs. Survey productivity has increased by a factor of 75 times since the 1960s and 10 times since 1990s (U.S. Army Corps of Engineers, 2002). The productivity increases are mainly related to the electronic and computer development. Many of these new technologies, instrumentation, and associated software programs continue to evolve rapidly and are designed to be applied by a frequent user as considerable time is required to become proficient in their use.

**Bed Material:** Most participants reported that their agencies continue to use standard, physical, bed-material sampling equipment (hand-held samplers US BMH-53, US BMH-60, and US BMH-80 and the cable-and-reel US BM-54 sampler; Federal Interagency Sedimentation Project, 2004, Home page) and standard analysis techniques to accurately measure bed-material particles finer than about 16 millimeters. Sampling procedures for larger particles include pebble counts and grid or areal sampling for surface materials. The US SAH-97 hand-held particle size analyzer (Federal Interagency Sedimentation Project, 2004, Home page) and a sampling frame (Bunte and Abt, 2001b) are among recent equipment developments to improve pebble-count accuracy. Submerged surface and subsurface materials are sampled using a shovel or backhoe, pipe or barrel samplers, and freezer or resin core sampling techniques. The cost of collecting, transporting, and analyzing bed-material samples has severely limited the amount of data collected. Several participants had used digital photographic data and software to determine the size gradations of surface bed material in lieu of pebble counts in coarse-bed streams. Hand rodding and dynamic cone penetrometer testing has been used to locate subsurface layers.

4. What are the new technologies that may be useful in this area?

    -- Is the new technology on the verge of being deployed at a large scale?

    -- What limitations of existing equipment or methods would this technology improve on?

    -- Is the new technology limited to specific application conditions?

    -- What are the uncertainties associated with the new technology?

Several new technologies and their potential applications to bed-topography or bed-material data collection were discussed. The technologies were divided into three broad categories: acoustic, electromagnetic, and optic. The information presented in table 5 reflects the opinions and experience of the participants, and should be used only as a qualitative assessment of the various technologies. Many of these technologies have been applied successfully in coastal and marine environments, and research is currently being conducted for riverine applications that include greater turbidity, bed variation, and flow velocities than are found in marine systems.

**Table 5.** Bed-topography measurement technologies

[ADP is acoustic Doppler profiler; ADCP is acoustic Doppler current profiler; ± is plus, minus]

| Technology | Accuracy | Cost in dollars (thousands) | Limitations, strengths, weaknesses | Research |
|---|---|---|---|---|
| **Acoustic Technologies** | | | | |
| Normal incident (single beam) | ±1 percent depth in marine environments | 15-30 | Simple, commercial available, minimal processing time, increased acquisition time | Multi-frequency analysis |
| ADP/ADCP (backscatter) | ±1 percent of comparable methods | 15-20 | Convenient, can infer suspended-sediment concentrations | Main focus currently is on suspended sediment |
| Multi-beam | ±1 percent depth marine environment | 100-500 | Commercially available, many more data points collected, greater coverage, processing intensive (10x single beam), problems with turbulence and platform motion are magnified from single beam | Backscatter to characterize bed material, evolving on many fronts |
| Side scan sonar, Dual Frequency Identification Sonar (DIDSON) | Qualitative, well-refined image | 30-100 | Commercially available; superior image resolution; real-time views of bed-surface features, texture, and object location; works even in turbid water where optical systems would fail; towed in a fish, stability could be an issue | Draping image on georeferenced multi-beam image |
| **Electromagnetic Technologies** | | | | |
| Ground Penetrating Radar (GPR) | ±5 percent (precision unknown) | 50-60 | Non-contact; would be good for monitoring during floods; restricted use; freshwater applications, conductivity affects depth range | Has focused on discharge measurements, applications in sediment just starting |
| Time Domain Reflectometry (TDR) | < 5 millimeters | 10-15 | Must be installed in stream; uses a cable to conduct signal; measures continuously air/water/soil interfaces; remote system; probe signal impacted by scour or aggradation | Stream applications are being researched |

**Table 5.** Bed-topography measurement technologies—Continued

[ADP is acoustic Doppler profiler; ADCP is acoustic Doppler current profiler; ± is plus, minus]

| Technology | Accuracy | Cost in dollars (thousands) | Limitations, strengths, weaknesses | Research |
|---|---|---|---|---|
| **Optical Technologies** | | | | |
| Laser (LIDAR, Light Detection and Ranging) | Considered "very good" | 80-150, 10-20 | Vegetation can cause problems; non-contact, above ground or aerial deployment; considerable post-processing usually by contractor; commercially available, purchased less often; potential to obtain underwater prism in some cases; active | In developing stages |
| Hyperspectral Irradiance | | 50-70 | Non-contact; passive system; currently mainly used for land classification; limited to shallow (10 meter), clear water applications; data must be collected in daylight hours; dynamic range limits resolution | Ongoing for coastal sediment applications, future field applications proposed |

New technologies discussed for bed-material measurements included expanding bed-topography acoustic technologies to obtain bands of bed-material size gradations and stratigraphy. Optical technologies including the underwater microscope system and analysis algorithm (U.S. Geological Survey, 2001; Rubin, 2004) were presented in the plenary session. This system has the capability to acquire and analyze digital images of sediment grains on a riverbed or sea bottom eliminating the need to manually collect or physically analyze sediment samples. This type of technology holds the promise of reducing the costs associated with the acquisition of bed-material data. Digital photography and video technologies should be further developed to provide more continuous coverage and to provide the ability to utilize multiple cameras for mixed bed applications. Electromagnetic technologies could be expanded to provide some stratigraphy or gross bed-material identification.

5. Is there any research planned in your organization to improve the collection or analysis of bed-topography or bed-material data?

Presentations, workshop extended abstracts, and discussions about current and planned research and applications of new technologies are summarized below.

**Time domain reflectometry for real-time and continuous stream monitoring, presented by Vince Tidwell.** Time domain reflectometry (TDR) operates by propagating a radar frequency electromagnetic pulse down a transmission line while monitoring the reflected signal. As the electromagnetic pulse propagates along the transmission line, it is subject to impedance by the dielectric properties of the media along the transmission line (e.g., air, water, sediment), reflection at dielectric discontinuities (e.g., air-water or water-sediment interface), and attenuation by electrically conductive materials (e.g., salts, clays). Taken together, these characteristics provide a basis for integrated stream monitoring; specifically, concurrent measurement of stream stage, channel profile, and aqueous conductivity. Requisite for such application is a means of extracting the desired stream properties from measured TDR traces. Analysis is complicated by the fact that interface location and aqueous conductivity vary concurrently and multiple interfaces may be present at any time. For this reason, a physically based multi-section model employing the $S_{11}$ scatter function and Cole-Cole parameters for dielectric dispersion and loss is used to analyze acquired TDR traces. Tidwell and Brainard (in press) explored the capability of this multi-section modeling approach for interpreting TDR data acquired from complex environments, such as found in stream monitoring.

A series of laboratory tank experiments were performed in which the depth of water, depth of sediment, and conductivity were varied systematically. Results indicate that the measured TDR traces respond to changes in interface position and aqueous conductivity in a manner consistent with multi-section model simulations. In fact, the multi-section model was found to accurately fit the measured traces over a broad range of test conditions. Comparisons between modeled and independently measured data indicate that TDR measurements can be made with an accuracy of $\pm 3.4 \times 10^{-3}$ meter for sensing the location of an air/water or water/sediment interface and ±7.4 percent of actual for the aqueous conductivity.

Recently, TDR monitoring systems have been installed on the Rio Grande in New Mexico and Paria River in Arizona. The USGS streamflow gaging station on the Rio Grande at Albuquerque includes seven TDR probes for monitoring changes in channel morphology, while another probe measures stream stage and aqueous conductivity. The TDR system at the USGS streamflow gaging station, Paria River at Lees Ferry, is designed to measure stream stage and aqueous conductivity. In both cases, TDR measurements are compared directly with measurements made by the USGS using standard float, pressure transducer, and (or) radar technologies.

**Naval Research Laboratory acoustic sediment classification system presented by Don Walter.** This system collects bathymetry data and impedance values to output sediment properties such as: attenuation, density, porosity, sediment type, mean grain size, compressional velocity, shear velocity, and shear strength (semi-quantitative) up to a maximum of 4 meters below the bed. The technology was used traditionally for mine location and can be applied from surface ships, submarines, and air-borne craft. Echo-strength lines and segment data time/depth line, represent separation of gradations. An example of a lake bottom application was presented. Gas bubbles and density of bottom material impact the return intensity; bubbles can make the system lose the bottom location. Turbulence also can cause bubble pulse problems. These problems can be overcome by using different frequencies. Bottom roughness is an issue, depending upon beam width; bed forms can be identified. Future application will include using side scanning sonar to cover a swath of the bed.

**ADCP bridge scour studies; multi-beam survey applications; CHARTS and SHOALS LIDAR technologies; DIDSON sonar technology; and potential new research in radar applications presented by Dan Eng.** Various research studies being conducted by the USACE were presented. ADCP technologies are being deployed remotely with internal pitch and roll compensation for bridge scour studies. LIDAR technologies being jointly research by the USACE and Navy, which incorporate above- and below-water surface topographic data collection, include the currently under-development CHARTS (Compact Hydrographic Airborne Rapid Total Survey) system, an improved version of the SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system. DIDSON (Dual Frequency Identification Sonar) technologies obtain high resolution underwater acoustic images for object identification, with some modifications to the sensor array this technology could be used to obtain 3-dimensional data on bed profile and bedload transport especially in turbid waters. Repeat multi-beam surveys are being used to quantify changes in bed topography over time (this work was presented in the bedload breakout session II; see the extended abstract by Abraham (listed in appendix 4). Research into the aerial application of ultra wide-band radar similar in frequency to ground penetrating radar is in the early stages. There is the potential to obtain data quicker and with better resolution than some of the other technologies. The widespread use of these radar frequencies may be limited because of communication interference and health concerns. Synthetic aperture radar, currently used in military mapping applications, is an acoustic technology that could potentially provide information similar to LIDAR without light restrictions.

**Underwater Microscope System and bed-topography measurement techniques applied in the Grand Canyon presented by Dave Rubin and Matt Kaplinski.** Dave Rubin had presented very promising results on the application of a underwater microscope system in the opening plenary session for the measurement of bed sediments with the location of sampling sites obtained within a few meters. The challenges created by the vertical canyon walls in the Grand Canyon to the application of surveying technologies such as GPS, which rely on satellite communication, were highlighted. Photogrammetry contour errors vary because of vegetation and ground-truthing problems. They typically can obtain photogrammetry data with an accuracy of about 0.25 meter, with reduced accuracy in forested areas.

Bed-topography data are collected in the Grand Canyon about every two years or before and after floods. Although GPS in combination with total stations are used to establish a closely spaced control network on the canyon rim, a robotic range azimuth system is used to establish location in the canyon. Multi-beam bathymetry data are collected at flows of 230 cubic meters per second; gravel bar data are supplemented with data from 850 cubic meter per second flows. Bathmetry data are collected using a RESON 8125 with 240 beams; ½-degree beam width down to a 0.5 meter. This narrow swath is sorted on a 0.6-meter x 0.6-meter grid spacing.

QTC Multiview, a post-processing software, uses backscatter data from the multi-beam equipment with data from known sediments to obtain the distribution of sediment types (for differentiation between gravel versus sand deposits; possibly also between silt versus clay deposits). This technology obtains high-resolution data and can almost measure the texture of the bottom. Some difficulties have been encountered when collecting backscatter data and topography data using the same transducer. Side scanning sonar data have been collected and once registered spatially, a time consuming process, can also be combined with aerial photography. Although bedload is not as significant as the suspended load in Colorado River sediment transport, side scanning sonar data have been used to estimate bedload transport (½ dune height times the dune movement rate). Dave Rubin encouraged participants to explore the possibility of working with a lab sponsored by the National Science Foundation to collect and process LIDAR data.

The following additional extended abstracts listed in appendix 4 contain information on bed-topography and bed-material measurement technologies.

*Dinehart, R.L., Spatial analysis of ADCP data in streams:* This extended abstract describes using ADCP data to obtain bathymetric data and velocity to infer sediment transport.

*Jackson, W.L., Regulated river restoration monitoring:* The Elwha River dam removal and restoration project. This extended abstract emphasizes the need for real-time data collection and evaluation especially when dealing with dam removal sediment loading conditions; and provides details on monitoring plan for Elwha River Restoration Project which includes bed-material size measurements and channel geometry as monitoring sub-categories.

*Martini, Marinna, USGS capabilities for studying sediment transport in the ocean*: This extended abstract describes several technologies being investigated by the USGS

Coastal and Marine Geology Program including: applying side scanning sonar, sector scanning sonar, Differential Global Positioning System (DGPS), and sub-bottom profilers for mapping and coastal and sea bottom imaging; photographic systems that show promise for determining grain size such as a version of underwater microscope system discussed previously which recently underwent its first full field trial and the SEABOSS that can obtain real time video of the bottom, take 35-millimeter still images, and acquire a grab sample; and mechanical sampling systems such as the hydraulically damped slow corer that does not disturb the sediment-water interface during sampling and the Honjo trap, a long-term, in-situ time series settling trap consisting of a large-diameter collecting cone attached to a rotating carousel of collection bottles that collects samples on a preset schedule.

*Parchure, T.M., Sobecki, T.M., and Pratt, T.C., Fine sediment parameter measurement for sedimentation studies*: This extended abstract describes the need for research of fine sediment parameters and the development of inexpensive equipment and procedures for testing fine sediments.

6. What are the priorities for research in this area?

Many current and suggested research items have been previously discussed. The participants agreed that industry has taken the lead in the development and adaptation of the latest technology for the instrumentation and associated software used to collect and analyze bed-topography data. Research and development of bed-topography technologies should be left mostly to industry with agencies providing consistent feedback. A collective voice in feedback would be more effective. Research priorities include:

- Combining technologies and expanding existing capabilities (e.g. bed-topography technologies expanded to provide bed-material characterizations)
- Applied research on non-contact, continuous systems
- Further investigation of opportunities to adapt coastal/marine or ocean applications to the riverine environment
- Continued development of optical and acoustical surface bed material measuring and analysis technologies
- Shared development and distribution of post-processing applications

The ideal sampler or measurement technology would have the following characteristics:

- Adaptable under a variety of conditions
    - -- Marine, estuarine or riverine
    - -- Clear or turbid
    - -- Soft, fine or hard, gravel/cobble beds
    - -- Steep or flat terrain
    - -- Underwater/shoreline interface
- Provide quantifiably accurate results
- Reliable
    - -- Low maintenance, non-fouling, rugged
    - -- Simple to use, user-friendly
    - -- Easy to calibrate
- Cost effective
- Portable
- Repeatable
- High density output relative to traditional methods
- Continuous, autonomous sampling
- Efficient post-processing and interpretation

7. What recommendations does the breakout session III group have for the Subcommittee on Sedimentation regarding bed-material and bed-topography data needs, uncertainty, and new technologies?

Breakout session III participants recommend that the Subcommittee on Sedimentation thoroughly review the proceedings from this workshop and collectively help support coordination and funding to address the identified research and data needs.

8. Where to from here? Would a Sediment Monitoring Instrument and Analysis Research Program, such as that proposed by the Turbidity and Other Sediment Surrogates Workshop (Gray and Glysson, 2003), and expanded on by Gray and Glysson (listed in appendix 4) be useful for attaining the fluvial-sediment-data needs of the Nation?

The participants agreed that a collective effort would help agencies to attain needed fluvial-sediment data. We suggest that FISP or another SMIAR Program group act as a clearinghouse for data and information on successes as well as problems with new technologies; develop or coordinate focused training programs or special sessions in conferences; be available to provide research assistance to develop site-specific solutions to problems encountered with new technologies; and promote effective communication among agencies between workshops. The Subcommittee on Sedimentation or FISP web pages should be expanded to include new technology information for each breakout session topic and pertinent links to data and research. Email groups, user groups, or bulletin boards should be established as needed for specific topical areas.

## References Cited, Breakout Session III:


American Society of Civil Engineers, 1975, Sedimentation engineering: American Society of Civil Engineering Manual No. 54, edited by V.A. Vanoni, 745 p.

ASTM International, 2003, Annual book of standards: ASTM International, section 11, volumes 11.01 and 11.02.

Ashmore, P.E., Yuzyk, T.R., and Herrington, R., 1988, Bed-material sampling in sand-bed streams. Sediment Survey Section, Water Resources Branch, Inland Waters Directorate, Report IWD-HQ-WRB-SS-88-4, 47 p.

Bunte K. and Abt, S.R., 2001a, Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring: General Technical Report RMRS-GTR-74. Fort Collins, Colo.; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 428 p.

Bunte K. and Abt, S.R., 2001b, Sampling frame for improving pebble count accuracy in coarse gravel-bed streams: Paper No. 00042 of Journal of the American Water Resources Association, v. 37, no. 4, p. 1001-1014.

Bureau of Reclamation, in press, Erosion and sedimentation manual: U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colo.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter C2, 89 p., accessed September 2, 2004, at *http://water.usgs.gov/osw/techniques/Edwards-TWRI.pdf*

Federal Interagency Sedimentation Project, 2004, Home page: Accessed August 31, 2004, at *http://fisp.wes.army.mil/*

Gray, J.R., and Glysson, G.D., 2003, Proceedings of the Federal Interagency Sedimentation Workshop on Turbidity and Other Sediment Surrogates, April 30-May 2, 2002, Reno, Nev.: U.S. Geological Survey Circular 1250, accessed September 3, 2004, at *http://water.usgs.gov/pubs/circ/2003/circ1250/*

International Hydrographic Organization, 1997, Standards for hydrographic surveys: International Hydrographic Organization Special Publication No. 44, Fourth Edition, Monaco.

International Organization for Standardization, 1997, Measurement of liquid flow in open channels – Bed material sampling: International Organization for Standardization, Publication No. ISO 4364:1997E, 39 p.

Rubin, D. M., 2004, A simple autocorrelation algorithm for determining grain size from digital images of sediment. Journal of Sedimentary Research, v. 74, no. 1, p. 160-165.

Subcommittee on Sedimentation, 2005, Home page, accessed February 11, 2005, at *http://water.usgs.gov/wicp/acwi/sos/*

Tidwell, V.C., and Brainard, J.R., in press, Laboratory evaluation of time domain reflectometry for continuous monitoring of stream stage, channel profile and aqueous conductivity: Water Resources Research.

U.S. Army Corps of Engineers, 1995, Sedimentation investigations of rivers and reservoirs: Engineering and Design Manual No. 1110-2-4000. Department of the Army, U.S. Army Corps of Engineers, Washington D.C., accessed September 2, 2004, at *http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-4000/toc.htm*

U.S. Army Corps of Engineers, 2002, Engineering and design hydrographic surveying: EM 1110-2-1003, Department of the Army, U.S. Army Corps of Engineers, Washington D.C, accessed September 2, 2004, at *http://www.nap.usace.army.mil/channel/em/toc.pdf*

U.S. Geological Survey, 2001, Underwater microscope system: U.S. Geological Survey Fact Sheet 135-01, 2 p., accessed January 26, 2005, at *http://geopubs.wr.usgs.gov/fact-sheet/fs135-01/*

Yuzyk, T.R., 1986, Bed material sampling in gravel-bed streams: Sediment Survey Section, Water Survey of Canada, Water Resources Branch, Inland Waters Directorate, Conservation and Protection, Environment Canada, Report IWD-HQ-WRB-SS-86-8, 62 p.

Yuzyk, T.R. and Winkler, T., 1991, Procedures for bed-material sampling: Lesson Package No. 28. Environment Canada, Water Resources Branch, Sediment Survey Section, Ottawa, Canada, 100 p.