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TURBIDITY AS A SURROGATE FOR ESTIMATING SUSPENDED SEDIMENTS

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TURBIDITY AS A SURROGATE FOR ESTIMATING SUSPENDED SEDIMENTS

1. Purpose.

a. This Public Works Technical Bulletin (PWTB) presents a regulatory review of impacts of nonpoint source (NPS) pollution on water quality and elevated levels of suspended sediments in streams, both of which are a result of accelerated erosion from upland watersheds. This information will assist Army environmental managers to successfully manage future water-quality requirements and activities.

b. Information in this PWTB is based on experiences at Fort Benning, Georgia, but the lessons learned are transferable to other Army installations. Lessons learned from the Fort Benning stream water-quality program include: design, development, selection of sampling locations, field installation, variable selection, sample collection, data analysis, and using water-quality information to support planning and implementation activities.

c. All PWTBs are available electronically at the National Institute of Building Sciences' Whole Building Design Guide webpage, which is accessible through this link:

http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215

2. Applicability

This PWTB applies to all environmental managers at US Army facilities within the United States and engineering activities that relate to monitoring water quality at installations.

3. References

a. Army Regulation (AR) 200-1, “Environmental Protection and Enhancement,” revised 13 December 2007.

b. Clean Water Act (CWA), 33 U.S.C. §1251 et seq. (1972), as amended 1977.

c. Unified Facilities Criteria (UFC) 3-210-10, “Low Impact Development,” 15 November 2010 (supersedes UFC 3-210-10 dated 25 October 2004).

d. Georgia Erosion and Sedimentation Control Act of 1975 (ESCA), as amended by State of Georgia HB285, 2003.

4. Discussion

a. AR 200-1 contains policy for environmental protection and addresses federal, state, and local environmental laws and Department of Defense policies for preserving, protecting, conserving, and restoring the quality of the environment. It also develops and implements pollution prevention and soil erosion control strategies in accordance with applicable federal laws and regulations. The regulation sets forth requirements for reducing pollutants at source in order for improving environmental quality. This regulation incorporates policies, procedures, and responsibilities to manage natural resources existing on Army lands. The regulation further addresses management of natural resources, minimizing soil sedimentation, procedures for protection of wetlands and forest ecosystems, as well as, control of NPS pollution; and proposes actions that enhance environmental quality.

b. The CWA and its subsequent amendments establish the basic structure for regulating discharge of pollutants in U.S. waters. The CWA defines water quality in terms of designated beneficial uses with numeric and narrative criteria that support each use. The Act requires that, at a minimum, beneficial uses must provide for the protection and propagation of fish, shellfish, and wildlife, and provide for recreation in and on water.

c. The updated UFC 3-210-10 specifically presents criteria necessary to handle stormwater runoff from development or redevelopment projects involving a federal facility with a footprint that exceeds 5,000 square feet. In general, the UFC provides guidelines for integrating low-impact development planning and design into a facility's regulatory and resource protection programs.

d. The federal government, however, currently does not have a numeric water-quality standard for suspended sediments or the transport of sediment loads in streams and rivers. The US Environmental Protection Agency (USEPA) has not established limits for suspended-sediment concentrations (SSC) or loads in streams or rivers, leaving it to the discretion of individual states.

e. Because the work for this PWTB took place in Georgia, the guidelines for that state were followed. The GEORGIA ESCA of 1975 describes the allowable limits from land disturbing and construction activities. The Act was amended in 2000 to require turbidity limits for runoff from construction and made recommendations for average in-stream turbidity. The 2003 amendment includes a mandatory requirement for a certification program for all individuals involved in land-disturbing activities in Georgia. Presently, several other states are evaluating their water quality standards to include narrative or numeric turbidity and/or SSC standards.

f. Military land-disturbing activities result in NPS water quality pollution and elevated concentrations of suspended sediments in streams, both of which are due to accelerated erosion from upland watersheds. These suspended sediments can compromise biotic integrity, degrade water quality, reduce aquatic habitat complexity, and result in downstream sedimentation. In addition, other pollutants such as hydrocarbons (e.g., oil and grease), nutrients, chemicals, harmful bacteria, pathogens, and heavy metals are often attached to soil particles that wind up in downstream water as contaminated sediments.

g. This PWTB presents information on stream water-quality monitoring that is appropriate for Army installations. Real-time monitoring of water quality and sediment loads in streams is expensive, extremely labor intensive, and requires years of monitored data before decisions can be made. Therefore, it is essential that sampling programs be well designed and diligently managed to prevent "data rich but information poor" monitoring plans. It is essential to have a well-planned approach to meet the requirements of federal legislation.

h. This PWTB concludes that the stream water-quality monitoring program used for Fort Benning demonstrated the value and ease of using an SSC-turbidity model as described. This success establishes that it is possible to effectively use existing stream monitoring stations and sensors without having to rely on expensive physical collection and analysis of water samples containing sediment. As previously stated, the lessons learned from this demonstration are transferable to other Army installations. Full lessons learned are detailed in Appendix D and summarized below.

- The field data showed a good correlation between turbidity and SSC.
- The sampling, analysis, and reported processes can be automated by using telemetry.
- Other water-quality parameters can be recorded continuously and real-time stream water-quality information telemetered to decision makers.
- Most of the suspended sediment is transported during a few large rainstorm events.
- Automated storm-data collection is essential to effectively capture major rainstorm events.
- Automated data collection is essential to effectively measure suspended sediment loads in storm events, particularly in small basins.

i. The appendices of this PWTB include:

- Appendix A discusses soil erosion, sediment, sedimentation, and NPS pollution.
- Appendix B addresses sediments on a national, state, and installation-specific basis.
- Appendix C discusses estimating loads by using turbidity as a surrogate.
- Appendix D discusses the approach taken, methods used, and results in determining Fort Benning’s water-quality characteristics.
- Appendix E summarizes the information in lessons learned and the work’s conclusions.
- Appendix F lists references used in this PWTB.

- Appendix G lists abbreviations along with a table of conversions from the inch-pound system of measure to the International System.

5. Points of Contact

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APPENDIX A:
SOIL EROSION, SEDIMENT, SEDIMENTATION, AND NPS POLLUTION

Background

Sediment pollution is receiving increased focus due to new laws governing Total Maximum Daily Load (TMDL) of sediment in streams. Soil erosion from construction and training activities that disturb military lands (Figure A-1) is becoming an increasingly high-profile sedimentation problem as concerns about water quality and nonpoint source (NPS) pollution increase and new TMDLs are implemented.

Figure A-1. Land disturbance caused by military training.

Sediment is the largest contaminant of surface waters by weight and volume (Koltun et al. 1997), and it is identified as the second-leading pollution problem in rivers and streams (USEPA 2003). Sediment usually is symptomatic of erosion in upstream tributary watersheds. NPS pollution occurs when stormwater runs over land, picks up pollutants, and deposits those pollutants in rivers, lakes, and streams.

The resulting suspended-sediment concentrations (SSCs) in surface waters can compromise biotic integrity, degrade water quality, reduce aquatic habitat complexity, and result in downstream sedimentation. Excessive suspended sediments can increase turbidity, thereby reducing the penetration of sunlight; in turn, this reduction inhibits photosynthetic plant growth and the ability of fish and sight-feeding microorganisms to locate food sources. Fish exposed to sudden and prolonged sediment increases may experience gill clogging and abrasion, eventually leading to fatal stress.

In addition, other pollutants such as hydrocarbons (e.g., fuels, oil, and grease), chemicals (e.g., phosphorous, chlorides and solvents), harmful bacteria and pathogens, and heavy metals are often attached to soil particles that wind up in downstream waters and thus, result in contaminated sediments. In the military installation context, some of these contaminants enter from upstream, some are added through nonmilitary activities, and some may be the result of military training and testing. In the latter case, explosives residues are potentially of great concern.

The following are the most common NPS pollutants found in sediments on Army lands.

- **Nutrients** including phosphorous, and nitrogen such as ammonia. NOTE: elevated levels of nutrients can promote the unwanted growth of algae. This can lead to oxygen depletion when algae die and decay. High concentrations of ammonia can be toxic to benthic (bottom-living) organisms.
- **Hydrocarbons** including oil and grease.
- **Chemicals** that may be very resistant to decay, such as polychlorinated biphenyls (PCBs).
- **Polycyclic aromatic hydrocarbons**, a group of organic chemicals that includes several petroleum products and byproducts.
- **Metals** such as iron, manganese, lead, cadmium, zinc, mercury, and metalloids such as arsenic and selenium.
- **Explosives residue**, from small firearms to large weapon systems.

On military lands, severe disturbances are normally most significant on local watersheds but may have far greater impacts on water quality and quantity, wildlife habitat, and other water quality attributes than some much larger scale disturbances. The occurrence of locally severe disturbances is a typical phenomenon on military lands as heavier and faster mobile weapon systems operate on these lands under all weather conditions.

Besides military-impact NPS pollution, other sources of NPS pollution include erosion from road shoulders (Figure A-2) and localized gullies, especially when it is made worse by lack of on-time repair and maintenance, as exhibited in Figure A-3.

Recognition of the military’s contribution to NPS pollutant loading to streams, lakes, and estuaries has led to increased environmental awareness and a resulting emphasis on water-quality monitoring on Army installations. However, real-time monitoring of water quality and sediment load in streams is expensive, extremely labor intensive, and requires years of monitored data before decisions can be made.

Figure A-2. Road shoulder erosion is among the most significant contributor of NPS pollution at Army installations.

Figure A-3. Lack of on-time repairs resulted in localized erosion and NPS pollution at Fort Benning.

Potential Soil Loss and NPS Pollution – Fort Benning, Georgia

In addition to routine military training impacts on its waters, Fort Benning may face added impacts on water quality as a consequence of the construction and operational use of the Digital Multiple Purpose Range Complex (DMPRC). Actions as a result of the 2005 Base Realignment and Closure (BRAC) will require more military and civilian personnel to be located at Fort Benning, resulting in new construction of additional support facilities to accommodate anticipated BRAC functions. These further requirements will lead to additional concerns and burdens on installation water-quality resources. The projected landscape construction and disturbance from DMPRC and BRAC will impact the structure and function of several catchments such as the Bonham, Sally, Pine Knot, and Good Hope watersheds.

For purposes of the work done for this PWTB, the erosion potential for the Fort Benning DMPRC area was estimated by using the Universal Soil Loss Equation (USLE) and the Revised USLE (RUSLE) approach within a geographic information system (GIS) using available data (elevation, land use, soils).

The maps in Figure A-4 depict the potential erosion for current conditions and for conditions during construction (no land-use cover). The average annual erosion within the Fort Benning DMPRC before construction was estimated at 1.9 tons/acre per year. During construction, erosion rates approached 17.5 tons/acre per year. Note that, in both instances, these are estimates of rill and inter-rill erosion; gully erosion was not considered. As expected, Figure A-4 shows virtually no erosion for “before construction” conditions in the mature forested area because the canopy formed by mature trees and understory and the litter on the forest floor shields the soil from erosion.

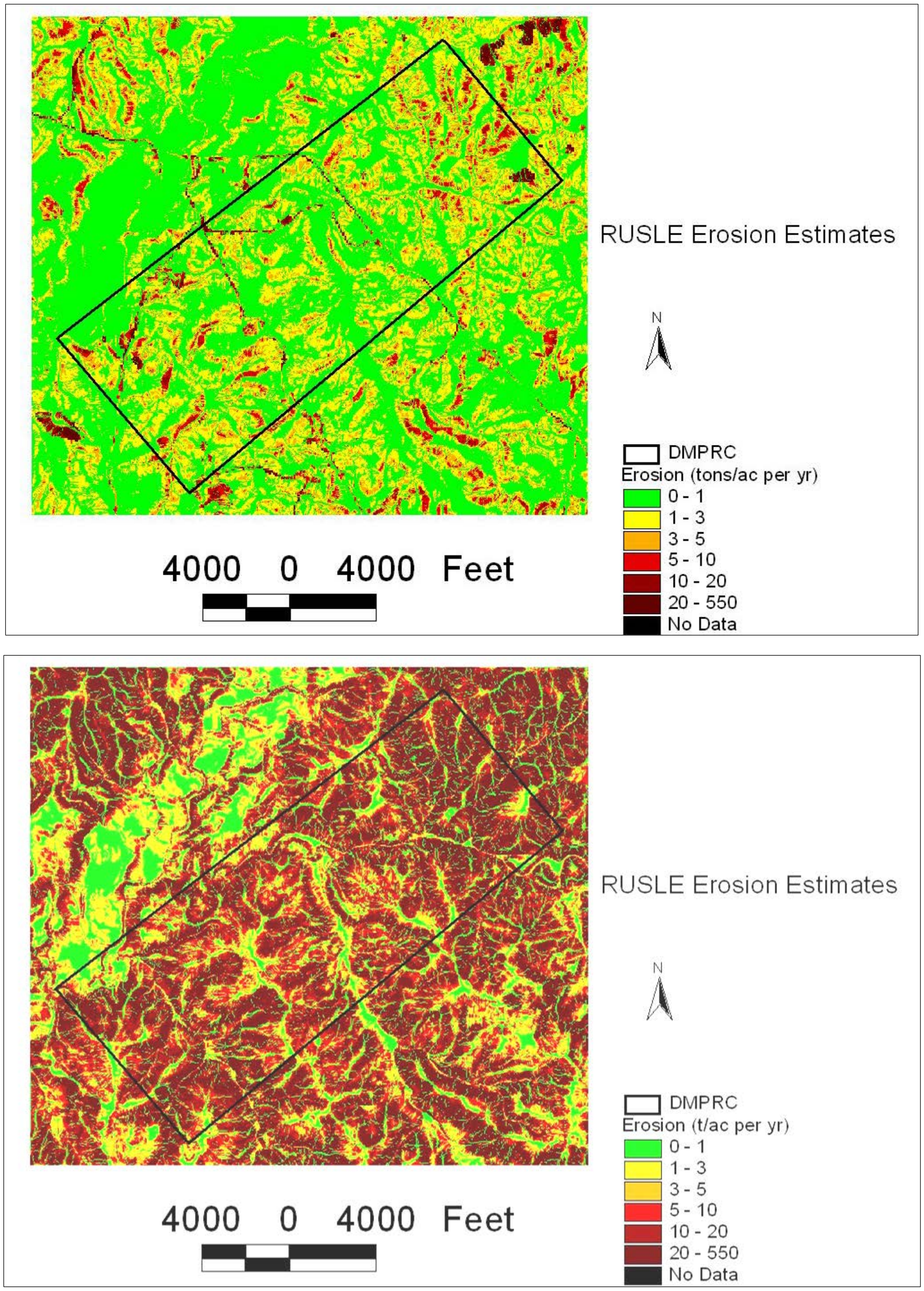

Figure A-4. DMPRC erosion potential (top) before and after construction (bottom).1

[1] Erosion potential is shown higher after construction because RUSLE model simulation software assumed entire pre- and post-construction area to be the same (i.e., not distinguishing DMPRC limits from entire land area).

APPENDIX B:
STREAM TURBIDITY AND SEDIMENT TRANSPORT

Effects of Suspended Sediments

In Georgia, Pruitt et al. (2001) reported sedimentation to be the leading determinant in loss of habitat and reduction in bed form diversity within the Chattooga River watershed. Of the six impaired streams at Fort Benning, sediment has been identified as the cause of impairment for five of them. Newcombe and Jensen (1996) reported that the severity of effects on fish will increase as a function of the level of SSCs and the duration of exposure. This effect is exhibited in Figure B-1, which shows that fish mortality increases both with time (duration) and increase in turbidity of suspended sediment.

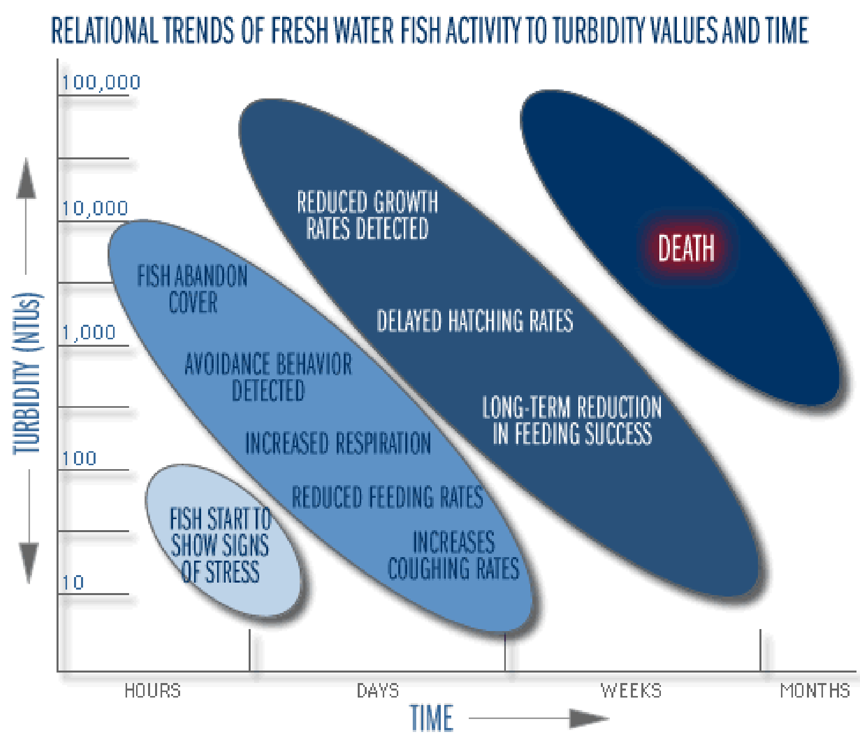

Figure B-1. Schematic on relational trends of fish activity to turbidity values (Adapted from "Turbidity: A Water Quality Measure", Monitoring Fact Sheet Series, University of Wisconsin-Extension Service, Environmental Resources Center).

Based on the Georgia Biological Index of total suspended solids (TSS), a TSS concentration greater than 284 mg/L adversely affects aquatic macro-invertebrate communities (Pruitt et al. 2001). Pruitt further observed that a TSS concentration of 58 mg/L or less during stormflow provides an adequate margin of safety and is protective of aquatic macro invertebrates in the

Blue Ridge physiography. Corresponding turbidity limits of 69 and 22 nephelometric turbidity units (NTU) established the threshold of biological impairment and margin of safety, respectively. Previously, a turbidity of 25 NTU was recommended for stream restoration management plans in Georgia.

USEPA (2005) reported that turbidity can be considered as a measure of water clarity and can also be used as an indirect indicator of SSC in water. The report also states that SSC can adversely affect stream ecosystems by filling pools and bottom voids (Figure B-2) that are critical to aquatic biota and flora. The USEPCA recommended that the monthly average concentration should be less than 40 mg/L.

Sigler et al. (1984) reported that turbidities as low as 25 NTU caused a reduction in juvenile steelhead and Coho growth. Lewis (1996) showed that turbidity can be considered a good method for estimating SSC in stream and rivers.

Figure B-2. The stream-bottom sediments on left provide spaces or voids for fish to lay eggs and for invertebrates to live and hide. Excess erosion has deposited fine-grained sediments on the stream bottom to the right, leaving no spaces for fish spawning or for invertebrate habitat (Courtesy University of Wisconsin, Madison).

In addition to various impacts on aquatic organisms, suspended materials in the water have other physical and chemical effects. Suspended solids absorb and concentrate trace metals and other contaminants and can transfer them from terrestrial to aquatic ecosystems. Turbid waters also absorb solar energy, so an increase in SSC that results in increased turbidity can cause water temperatures to increase and are often a source of thermal pollution.

Nationally, much information is available on the general effects of high SSCs and bed-load depositions on stream biota and habitat (Alexander and Hansen 1986; Barrett et al. 1992; Burkhead et al. 1997; Waters 1995). However, most of the SSC and bed-load effects can be withstood by aquatic biota over short periods of time. Therefore, if SSC is high only during storms, the biological community will not be significantly impacted (Mukundan et al. 2009).

SSC levels become a concern when they are elevated during normal base-flow conditions or continue for extended periods of time after storms. Also, high concentration of sediment becomes a concern if the fine bottom sediment particles are not fully flushed from the stream system during storms. If substantial amounts of fine sediment settle on the channel bottom after a storm, serious ecological effects may occur, as shown in Figure B-2. Many macro invertebrates depend on the hard surfaces of coarse substrate for feeding, and many live within the interstitial spaces of coarse substrate. If fine sediments cover these coarse sediment substrate and block the interstitial spaces, the macro invertebrate community shifts in composition (Waters 1995). Many fish communities in southeast streams are particularly sensitive to this type of habitat degradation (Burkhead et al. 1997). Available evidence suggests that among Georgia’s 283 freshwater fish species, many are sensitive to excess sediment concentrations (Sutherland et al. 1998, 1999; Meyer et al. 1999).

Sediment has detrimental effects beyond stream biota. Sedimentation results in loss of reservoir storage capacity, which can cause increased flooding. Sediment also degrades water for recreational uses such as swimming and reduces boating safety. High levels of sediment reduce the efficiency and increase the cost of drinking water purification. Sediment interferes with the disinfection of pathogens at municipal drinking water treatment plants (Holliday et al. 2003). For example, elevated sediment concentration (above 400 mg/L at the Athens-Clarke County [GA] Drinking Water Treatment Facility) cannot adequately be removed by coagulation and filtration prior to chlorination. As a result, the drinking water facilities must temporarily suspend treatment and rely on previously stored water in order to meet municipal demands (Holliday et al. 2003).

Regulatory Issues

The federal government does not currently have a numeric water-quality standard for suspended sediments or the transport of sediment loads in streams and rivers. The USEPA has not established limits for suspended-sediment concentrations or loads in streams and rivers. Rather, the USEPA has left it to the discretion of individual states. The GEORGIA ESCA of 1975[2] describes the limits from land disturbing and construction activities. This Act was amended in 2000 and 2003. The amended ESCA[3] requires that runoff from construction sites larger than 5 acres not cause an increase in turbidity of more than 25 NTU in receiving streams that are supporting warm water fisheries or more than 10 NTU for trout streams.[4] The Act also recommends an average in-stream turbidity standard of 25 NTU for warm-water fishing streams, with allowance for precipitation in excess of a 10-year event (Rasmussen 1995).

Presently, several states are evaluating their water-quality standards to include narrative or numeric turbidity and/or SSC standards. For instance, the neighboring states of Alabama and Florida use 50 NTU and 29 NTU, respectively, as the limit above background. South Carolina allows an increase of 10% above background, whereas North Carolina uses 10 NTU for trout streams, 50 NTU for non-trout streams, and 25 NTU for non-trout lakes. Holmbeck-Pelham and Rasmussen (1997) recommended reduction in average turbidity to below 25 NTU for stream restoration plans in Georgia. In addition, a turbidity of 25 NTU was recommended by the Georgia Board of Regents’ Scientific Panel as the in-stream turbidity standard (Kundell and Rasmussen 1995). Also, the report cited an SSC concentration of 80 mg/L as a threshold between moderate and low levels of protection for fish and aquatic invertebrates (NAS 1972).

Pruitt found that SSC concentrations greater than 284 mg/L resulted in biological impairment of macro invertebrate communities. They also observed that SSC concentrations of 58 mg/L or less during stormflows provided an adequate margin of safety and was protective of aquatic macro vertebrates in the Blue Ridge physiographic region. Corresponding turbidity limits of 69 and 22 NTU established the threshold of biological impairment and margin of safety, respectively. To summarize, the recommended limits for in-stream turbidity for Georgia and neighboring states are given in Table B-1.

[2] Official Code of Georgia [OCGA] sections 12-7-1.

[3] Georgia Rules and Regulations, 2001, Chapter 391-3-6-16.

[4] OCGA Section 12-7-6 (a)(2).

Table B-1. Regulatory limits for in-stream turbidity.

Alabama	Background + 50 NTU
Florida	Background + 29 NTU
North Carolina	Trout Stream = 10 NTU Non-trout streams = 50 NTU Non-trout lakes = 25 NTU
South Carolina	Background + 10%
Georgia	Construction Sites = background+ 50 NTU Stream Restoration = 25 NTU Stream Trout = 10 NTU Warm Water Fish = 25 NTU

Source: Technical Advisory Group (TAG 2002).

Differences in Definitions and Analytical Methods

Definitions

Several different terms are used in the literature to describe and quantify suspended sediment in water. It may be pertinent to clearly differentiate terms such as “total solids” (TS), “total dissolved solids” (TDS), “total suspended solids” (TSS), and “Suspended Sediment Concentration” (SSC) that are so commonly mentioned and oftentimes used interchangeably in the literature.

SSC is the amount of solids retained by a filter of 2 microns or smaller in pore size. (Suspended solids are the materials in water that are neither dissolved nor settled.) SSCs are usually expressed in units of milligram (mg) per unit of water (such as mg/liter or mg/L) or as parts per million (ppm).

TDS is the material that passes through a filter of 2 microns in size or smaller. TDS may also be defined as the material residue left behind after evaporation or drying of a sample of water in an oven at 103°C to 105°C or as the total weight of all solids (minerals, salts, metals, etc.) that are dissolved in a given volume of water, usually expressed in units of milligrams per liter or parts per million.

Note that there is no difference between SSC and TSS by definition, as both refer to the amount of solids retained on the filter during filtration. The difference is based on the laboratory analytical techniques used to quantify them.

In a solute, TS may be defined as: (1) The portion of suspended solids retained by a filter of 2 micron or smaller in pore size, plus (2) the portion of TDS that passes through a filter of 2 microns or smaller in pore size.

$$\text{TS} = \text{Suspended Solids} + \text{TDS} \tag{1}$$

Laboratory Analytical Methods

There are essentially three different laboratory analytical techniques used to quantify concentration of suspended solids (for TSS and SSC) in stormwater. Recall that both the terms SSC and TSS refer to the solids retained on the filter during filtration. Thus, none of these three methods include the amount of TDS in SSC and TSS estimates because TDS passes through the filter during the filtration process.

The three laboratory analytical methods used for the quantification of suspended solids in drinking water, waste water, and stormwater are:

1. USEPA’s Method 160.2 – Also known as the gravimetric method for suspended solids dried at 103°C-105°C (USEPA 1999). This method is recommended by the USEPA for stormwater analysis and uses the term SSC for describing suspended materials in water.

2. Standard Method for TSS, also known as American Public Health Association (APHA) Method 2540 D (APHA 1995). This method is used for analysis of wastewater and drinking water by municipalities and uses the term TSS for describing suspended materials in water.

3. American Society for Testing and Materials (ASTM) Method D3977 (ASTM 2006). This is the US Geological Survey (USGS) standard for determining concentration of suspended material in surface water samples. The USGS uses both TSS and SSC interchangeably in describing suspended material in water.

All three of the above methods determine the amount of suspended material contained in the water samples through filtering the water, and drying/weighing the residue left on a filter 2 microns or smaller in pore size. However, the three methods differ in the subsample preparation. The USEPA 160.2 Method uses the whole sample for filtration. The Standard Method stirs and collects the subsample using a pipette to draw from the whole sample container. ASTM Method D3977 uses the whole sample.

Concentration of suspended material obtained by any of the above analytical methods may be described as:

$$SSC = \frac{(A - B) * 1000}{Sample\ Volume,\ mL} \qquad \textbf{(2)}$$

Where:

SSC = suspended-sediment concentration (mg/L)
A = final weight of sand + filter after drying (mg)
B = initial weight of filter (mg)
Sample Volume = the amount of sample used during analysis (mL)

The Standard Method is used primarily for municipalities for wastewater and drinking water analyses. Both ASTM D3977 and USEPA 160.2 methods are used for analysis of suspended solids in surface and stormwater analyses. The USGS uses the ASTM Method, while USEPA recommends the USEPA 160.2 Method.

Gray et al. (2000) and Gue (2006) found little difference between methods that use whole or subsamples when the suspended material was not high in sand; they were very close to the true concentration of suspended materials. They observed that, if a sample contained a substantial percentage of sand-sized material and was more than 25% by weight of sand size (>500 microns), then stirring, shaking, or otherwise agitating the sample before obtaining a subsample may not produce an aliquot representative of the whole suspended material. When the sample is high in sand, the methods using subsampling tend to underestimate suspended material, because it is difficult to obtain a representative sand aliquot, especially by pipette suction.

Filter Preparation Procedure

Both the Standard Method 2540 D and USEPA 160.2 share a common filter preparation procedure. This procedure requires filter rinsing with three successive 20-mL aliquots of reagent-grade water under vacuum, then drying, desiccating, and weighing the filter to 0.0001 g. The ASTM method used by the USGS does not require the extra step of filter preparation.

Sample Storage and Holding Times

The USGS, ASTM, and USEPA methods do not require refrigeration and/or holding times. The sand and silt in water do not deteriorate over time and, thus, there is no time limit for performing analyses for sediments.

Standard Methods 2540 B–F are suitable for determining solids in potable water and wastewater, whereas Method 2540 G is suitable for determining solids in stormwater sediments. Wastewater and drinking water samples must be placed on ice and refrigerated at 4°C up to the time of analysis to minimize microbial decomposition. It is preferred that samples not be held more than 24 hr. In no case should samples be held more than 7 days.

APPENDIX C:
ESTIMATING SEDIMENT LOADS USING TURBIDITY AS A SURROGATE

Background

An important cornerstone of the amended Clean Water Act (CWA) of 1977 is the requirement stating that tribes, territories, and stakeholders adopt water-quality standards to protect public health and support wildlife. They must also take measures to enhance and improve water-quality sources to remain useful to both human and aquatic life. CWA Section 303 requires that the waters of the United States meet standards associated with designated uses. These designated uses include drinking water supply, swimming and recreation, aquatic habitat for fish and wildlife, and navigation.

The primary use of waters at Fort Benning is to support aquatic and terrestrial wildlife species as well as swimming and recreation. As previously stated, the most significant pollutant for Fort Benning streams is sediment that can be delivered from both off-site and onsite sources. The identification and characterization of sediment sources are critical to the successful development and implementation of watershed management plans and the control of pollutant loadings into installation streams. Characterization and quantification of sediment loading can provide information on the relative magnitude and influence of each source and its impact on stream water quality.

In developing Fort Benning Watershed Management Plans, watershed assessments and analyses were needed to quantify source loads, characterize impacts, and estimate load (NPS pollutant) reductions needed to meet goals and objectives. For implementing watershed plans, indicators should be quantitative so that the effectiveness of management measures can be shown and quantitatively documented to substantiate installation efforts in addressing their control effectiveness.

According to the Natural Resources Conservation Service (NRCS) of the US Department of Agriculture (USDA), almost $27 billion per year is lost in productivity on cropland and pasturelands (USDA 2003). An additional $17 billion loss is estimated annually for off-site environmental costs (e.g., for increased water treatment due to erosion). Estimated costs for in-stream and off-stream impacts due to sedimentation in the United States exceed $11.6 billion dollars annually (Herzog et al. 2000).

Approach and Methods

NPS pollutants in Fort Benning waters can be delivered from various sources originating from within and beyond installation boundaries. The identification and characterization of these sources and their respective loadings is critical to the successful development, implementation, and realization of watershed management goals to protect and improve water quality. Source identification is also critical to document the net contribution of Fort Benning NPS pollution to determine whether the installation is acting as a “sink” (repository) or an additional source of sedimentation of downstream waters.

A major goal of this work was to establish Fort Benning’s net contribution of off-site sediment discharge into the neighboring Chattahoochee River. The term “net contribution” may be defined as the difference between sediment entering and leaving the installation. Mathematically, it can be expressed as:

$$\textit{Net Sediment Contribution} = \textit{Sediment (Entering – Leaving) Fort Benning} \qquad \textbf{(3)}$$

If the net sediment contribution is positive, the installation is acting as a sink. If it is negative, then the installation is acting as an additional source of sediment contribution into the Chattahoochee River.

Additional objectives were to investigate, monitor, document, and address water-quality characteristics of Fort Benning surface waters with specific reference to proposed DMPRC and BRAC watersheds. This will provide a baseline or reference data set for comparison with future water-quality conditions potentially impacted from planned construction and operational use of these DMPRC and BRAC functions. A final goal was to determine Fort Benning’s environmental conservation efforts and regulatory compliance in meeting “designated uses” of water quality. The final goal was then to develop and implement best management practices to meet regulatory compliance for improved water quality.

Fort Benning’s water-quality program comprises the major components listed below.

1. Installation of an extensive network of sampling stations across the military reservation.

2. Unattended, continuous, real-time sampling of turbidity, water quality, gage, velocity, and streamflow.

3. Capability to access remotely monitored data in real-time ny using telemetry.

4. Statistical data analyses for determining measured sediment loads.

5. Development of regression model(s) to provide continuous real-time stream sediment loads from turbidity and stream-flow measurements.

As of now, there is no known reliable and practical method to directly measure SSC in streams and rivers. Traditional methods require utilizing grab samples during actual storm events, which is difficult when these events occur during non-work hours (e.g., weekends or overnight). Traditional sampling techniques are also often labor intensive, prohibitively expensive, and difficult (if not impossible) for inaccessible or remote locations such as Upatoi Creek North, which enters Fort Benning at the north end of the installation.

On-site data collection has the potential to be unsafe during runoff events, and typically there can be long time delays between sample collection, analysis, and providing results for decision making. In addition, concentrations of water-quality constituents (e.g., SSC) generally vary during storm events, and traditional grab-sampling techniques that provide water-quality concentrations (such as flow and sediment flux) may not be representative of the overall storm hydrograph. Surrogate(s) must be found for continuous monitoring of stream water quality if sound and intelligent decisions are to be made for the protection of aquatic species habitat, environmental conservation, and improved water quality. One surrogate to consider is to measure turbidity.

Use of Turbidity to Measure Sediment Loads

Turbidity (suspended sediment in the water column) reduces clarity, which can be measured in NTUs by using optical sensors. The use of turbidity sensors to continuously provide turbidity measurements through all baseflow and storm events may provide more accurate estimates of sediment loads and “instantaneous” fluctuations due to local bank failures or other activity. Continuous turbidity measurements permit assessment of short-term variability or spikes in sediment concentrations that stress aquatic life (Ehlinger 2002). The Technical Advisory Group (2002, p 6) of Georgia reported that NTU measurement has become the standard for determining turbidity in Georgia and that it can also be used as an indirect indicator of the SSC in water (USEPA 2005, pp 4-12).

In view of the above observations, it was decided to develop a regression model using turbidity for the estimation of SSC and sediment loads in Fort Benning streams and creeks. The following procedures and methods were used to develop, calibrate, and demonstrate this regression model, hereinafter referred to as the SSC-NTU model.

1. Develop an SSC-NTU regression model using Fort Benning soils data in laboratory-controlled environment.

2. Develop and calibrate the model from measured data collected from Fort Benning major streams.

Development of SSC-NTU Model under Laboratory-Controlled Environment

A series of soil samples were collected from different Fort Benning training areas (Figure C-1) during the summer of 2004. Soil samples were collected in 6-in. increments up to 4-ft depths.

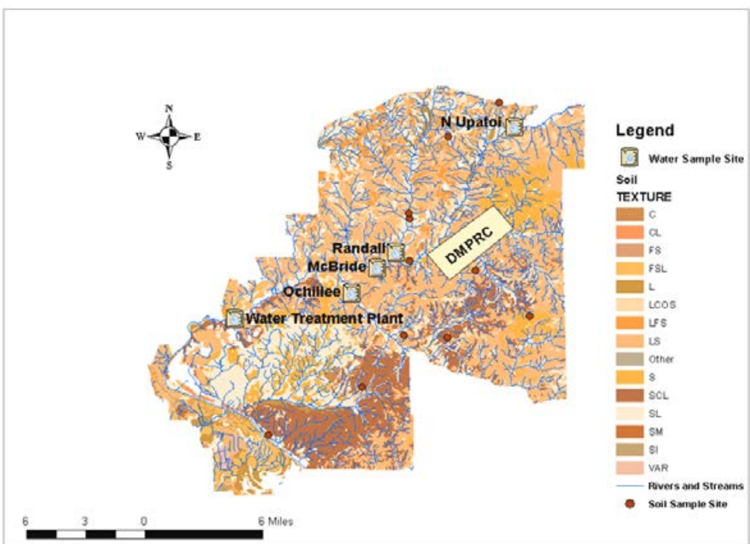

Figure C-1. Soil sampling sites and soil types at Fort Benning, GA.

Approximately 100 samples from 14 sites (Table C-1) were collected for textural analysis and SSC-turbidity tests. The samples were sent to the Agricultural and Biological Engineering Department, Purdue University, W. Lafayette, Indiana, where laboratory measurements for turbidity were made by using the commercially available Hach Model 2100AN Laboratory Turbidimeter

(Figure C-2). This turbidity meter meets EPA 180.1 Method requirements for sample analysis.[5]

Table C-1. Site locations where soil samples were collected

Site #	Site Name Where Soil Sample Collected	Site #	Site Name Where Soil Sample Collected
1	Cactus Road	8	A-14
2	D-15 Sally Branch	9	Q-2
3	D-14	10	E-7
4	Bonham Creek	11	K-6
5	D-2 Sally	12	O-9
6	D-13	13	L-6
7	River Bend Road	14	M-2

Note: The alpha-numeric designation in column 2 represents Fort Benning training areas (see also Figure C-5) wherein A-14 denotes Alpha 14, D-5 denotes Delta 5, etc.

Figure C-2. USEPA-compliant Hach 2100 AN Laboratory Turbidity Meter.

[5] Available online at http://www.hach.com/2100n-laboratory-turbidimeter-epa-115-vac/product?id=7640450970

The purpose of this sampling effort was to develop relationships between turbidity and suspended sediments for Fort Benning training-area soils under a laboratory-controlled environment. In the laboratory, each soil sample was processed to eliminate structures/lumps, to facilitate sieve analysis and suspension of the soil. Soil textural classification was performed for each sample using sieve analysis. A series of SSC for each soil sample was created, and corresponding turbidity measurements were made to develop SSC-turbidity relationships. To do so, a beaker with de-ionized water was set up for each soil sample. A known mass of soil was added to a known volume of de-ionized water to create a range of values for suspended concentrations. After adding the known mass of soil to the water, the beaker was shaken to suspend the sediment, and a turbidity measurement taken using a Hach 2100AN Laboratory Turbidimeter. Turbidity measurements were replicated three times for each sample concentration and their average value used during analyses. This process was repeated for each of the soil samples.

Development of SSC-NTU Model Using Measured Data from Fort Benning Streams

Fort Benning has a network of hundreds and hundreds of first-, second-, and higher-order streams scattered all over the installation. Approximately 30 of these streams are major perennial or ephemeral streams (Figure C-3) that span significant drainage areas at the installation. For reasons explained in Appendix D, it is neither logistically possible nor economically feasible to monitor each and every stream. In order to determine water quality and sediment loads in Fort Benning streams, it was decided to develop a simple regression method of the following form:

$$C_{sed} = f\ (T_{ntu}) \qquad \textbf{(4)}$$

To accomplish the requirements for developing the SSC-NTU model in Equation 3, a water-quality monitoring network was developed, and three sampling stations were initially installed within DMPRC watersheds during 2005. As funds became available, an additional five sampling stations were added in 2006 with four more added during 2007 to make a total of 12 stations (as shown in Figure C-3). Table C-2 provides full descriptions of these stations, with stream names, location by Universal Transverse Mercator (UTM) grid location, and their respective drainage areas above the point of sampling locations.

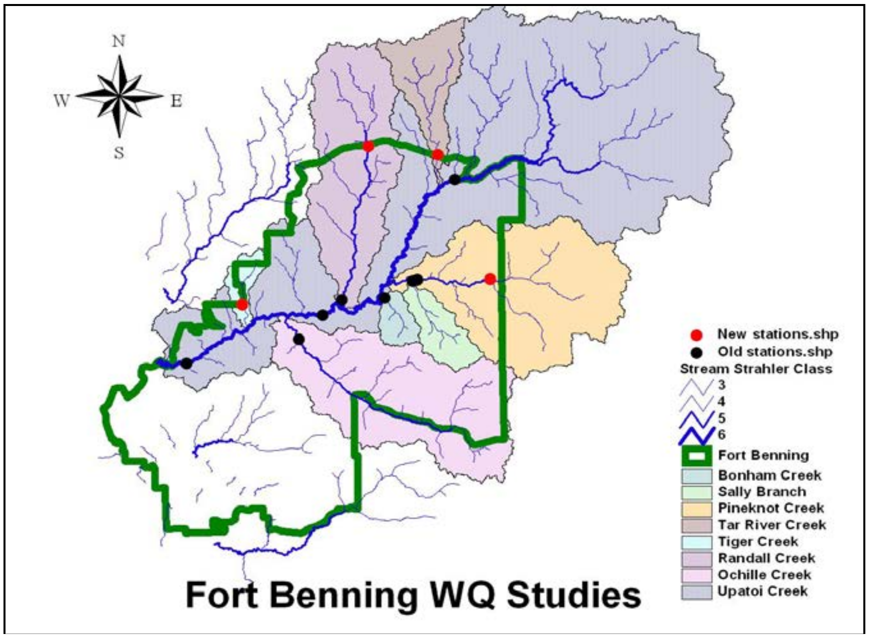

Figure C-3. Water-quality sampling sites at Fort Benning, GA.[6]

At each of the sampling stations, both YSI Model 6920 Sondes and Isco 6700 series automatic samplers were installed to collect suspended storm samples, stream gauge, velocity, precipitation, water quality, and flow data in unattended mode. The multi-parameter 6920 YSI Model has the ability to continuously measure water-quality parameters such as temperature, depth, pressure, salinity, pH, specific conductance, turbidity, TDS, dissolved oxygen (DO), nitrate-nitrogen, ammonia/ammonium-nitrogen, chloride, salinity, pH, chlorophyll, rhodamine, and fecal coliform. However, we collected only the turbidity measurements necessary to accomplish project objectives. Major components of a sampling station are shown in Figure C-4 and described below.

Figure C-4(A) is an Isco™ 6700 automatic sampler, which is designed to collect water samples at pre-determined stream levels following rainfall. Besides water samples, the sampler also stores monitoring data such as stream level, velocity, and turbidity, rainfall, and water-quality parameters. Figure C-4(B) is a water-quality and turbidity-monitoring YSI™ Sonde Model 6900. The solar collector shown in Figure C-4(C) recharges the “deep cycle” 12-volt battery shown next to Isco sampler in Figure C-4(A). Shown in Figure C-4(D) and Figure C-4(E) are of the box (in open and closed positions) that houses the 6700 Isco sampler and battery, providing protection from the weather.

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[6] NOTE: Due to size of graphic, DMPRC is not shown on this figure (nor C-5) because it is approximately 2000-acre firing range inside the installation (1% of entire land area).

(A)

(B)

(C)

(D)

(E)

Figure C-4. Major components of a sampling station: (A) Isco™ 6700 automatic sampler; (B) YSI™ Sonde Model 6900; (C) solar collector that recharges the “deep cycle” 12-volt battery shown next to Isco sampler in (A); (D) and (E) shows the box (in open and closed positions) that houses the Isco 6700 sampler and battery (all photos by ERDC-CERL).

Identification of Sampling Locations

Preferred criteria in the selection of sampling locations is that the selected sites should provide easy access and have prismatic stream cross sections to provide “hydraulic controls” for easy flow measurements using Manning’s Equation. In real-life field applications, these criteria are seldom met. Criteria were considered in the selection of sampling sites, as stated below.

- locations where major streams enter and exit Fort Benning
- locations where streams are perennial or flow most of the year
- locations that are potentially significant sources of military-impacted erosion/sediment production within installation boundaries
- locations that have prismatic cross sections and, thus, offer attractive “hydraulic controls” for flow measurements using manning’s equation
- locations that have “stable” cross sections for long-term monitoring
- locations providing ease of accessibility

In most cases, the overriding criterion in the selection of sampling sites was accessibility, for reasons of manageability and safety. Since one of the pressing objectives of this work has been to determine “net sediment contribution” (see Equation **3**) or regulatory compliance, the requirement necessitated overriding all or most of the above criteria. For example, Upatoi Creek spans over 447 sq mi of drainage basin and encompasses 151.7 sq mi (34%) of watershed drainage area outside of Fort Benning, before entering the installation at a location in the north that is practically inaccessible except with an all-terrain vehicle. To determine stream sediment loads before the creek enters the installation, we installed a sampling station at the Fort Benning boundary. Similarly, three additional sampling stations (Little Tar River, drainage area 17.5 sq mi; Randall North, drainage area of 18.7 sq mi; and Pine Knot East, drainage area of 46.9 sq mi) were installed at hard-to-reach remote locations for determining stream water quality before the water entered the Fort Benning boundary (Figure C-5).

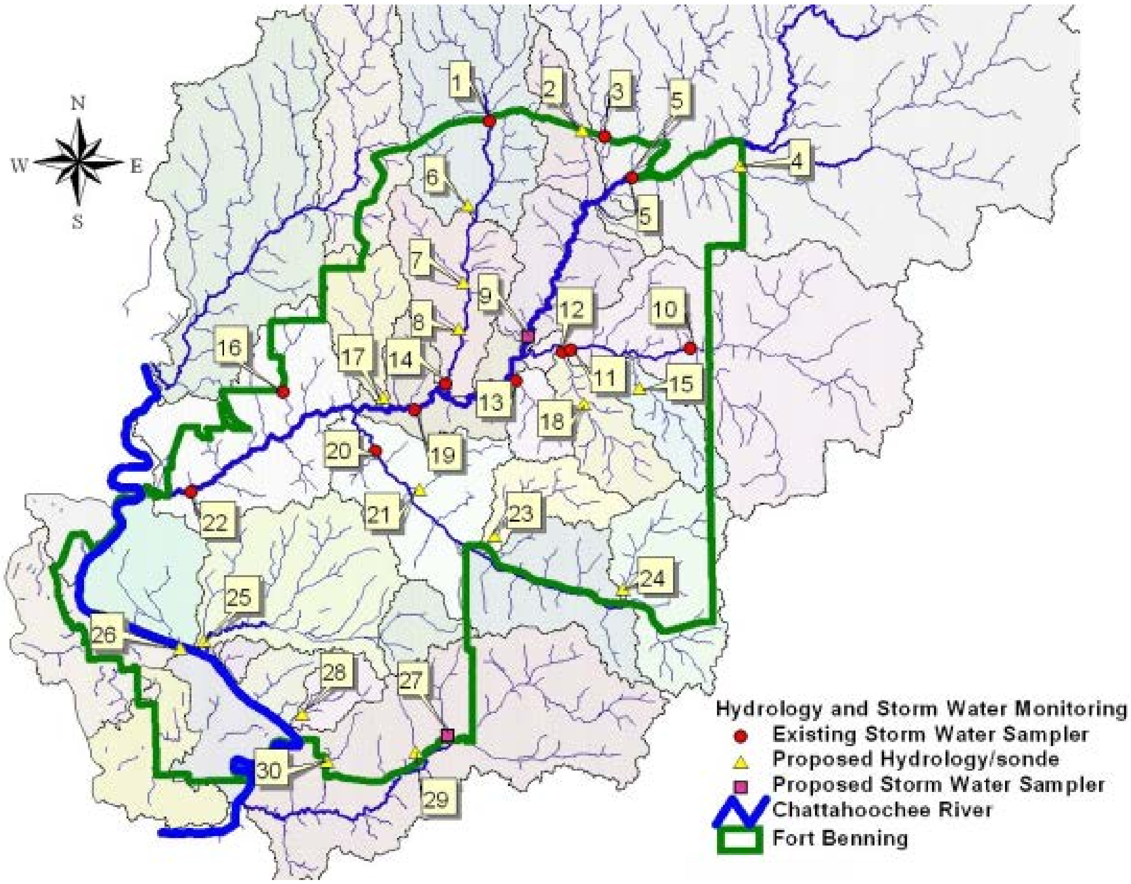


Figure C-5. Map of Fort Benning water-monitoring sampler sites and boundaries.

Among the 12 sampling stations (Table C-2), only Bonham Creek, Pine Knot East, Pine Knot Buena Vista, and Randall 2nd Armored Division Road were located at sites that have stable cross sections and were close to "hydraulic control" structures (bridges) so that controls can be used with confidence to apply the Manning Equation for estimating streamflows.

The McBride sampling site on Upatoi Creek is located a few hundred feet downstream from a permanent gauging station,[7] which is operated and maintained by the USGS. Thus, for all practical purposes, gauge and flow data for the McBride sampling station site will be essentially the same as that obtained and reported by the neighboring USGS station. No (or little) stormwater enters or leaves between these two sites.

[7] Station Name: Upatoi Creek near Columbus, GA; Station No.: 02341800; HUC: 03130003

Table C-2. Sampling site locations and their corresponding drainage areas.

Station	Name	UTM Grid Location		Watershed Drainage Area	
		Eastern	Northern	Acres	Square Mile
1	Upatoi Creek, North	716240	3600304	69,568.30	108.7
2	Upatoi Creek, McBride	704998	3588273	258,,854.4	342.2
3	Randall Creek, North	708877	3603279	11,946.70	18.7
4	Randall Creek, South	706579	3589629	32,758.40	51.2
5	Bonham Creek	710244	3589781	2,968.40	4.6
6	Sally Branch	712638	3591274	6,216.50	9.7
7	Little Tarr River	714808	3602476	11,204.20	17.5
8	Tiger Creek	698150	3589216	2,400.60	3.8
9	Ochille Creek	702926	3586140	41,133.20	64.3
10	Upper Pine Knot, East	719295	3591451	29,997.80	46.9
11	Pine Knot, Buena Vista	713074	3591390	41,834.30	65.4
12	Water Treatment Plant	693380	3583980	285,243.80	445.7

Installation of Samplers and Execution of Sampling Program

Site selection was followed by sampling equipment installation. Selection of monitoring equipment depends on project data needs, such as what in-situ parameters need to be measured and how data will be retrieved whether going physically to the site or via telemetry. In our situation, telemetry was used to retrieve data remotely and site visits were made to collect storm samples and provide routine repair and maintenance.

In view of projected field measurements and corresponding data needs, the monitoring system consisted of the major components listed below.

1. Isco Model 6712 Automatic Sampler in a 24-bottle configuration, which is a full-size sampler for SSC sample collection and data logging from all system components. (It is the “CPU” of the stormwater monitoring program.)

2. Isco Model 750 Area-Velocity Flow Module to measure stream gauge and velocity.

3. Isco Model 720 Submerged Sensor for level and velocity measurements. This sensor has a pressure transducer for level and Doppler technology for velocity measurements. Both the 750 and 720 modules work together to send the signal to the 6712 sampler and triggers sampling at preset “level” rainfall conditions.

4. Isco Model 674 Rain Gauge for rainfall measurements.

5. A submerged perforated tube installed above the stream bed is used to collect SSC samples when Isco 6712 triggers (once the predefined triggering condition occurs).

6. Isco Cell Modem Telemetry for remotely accessing real-time data.

7. Deep-cycle, 12-volt marine/boat battery for powering the 6712 sampler during sample pumping.

8. A solar panel (40 watt) for charging and maintaining battery charge.

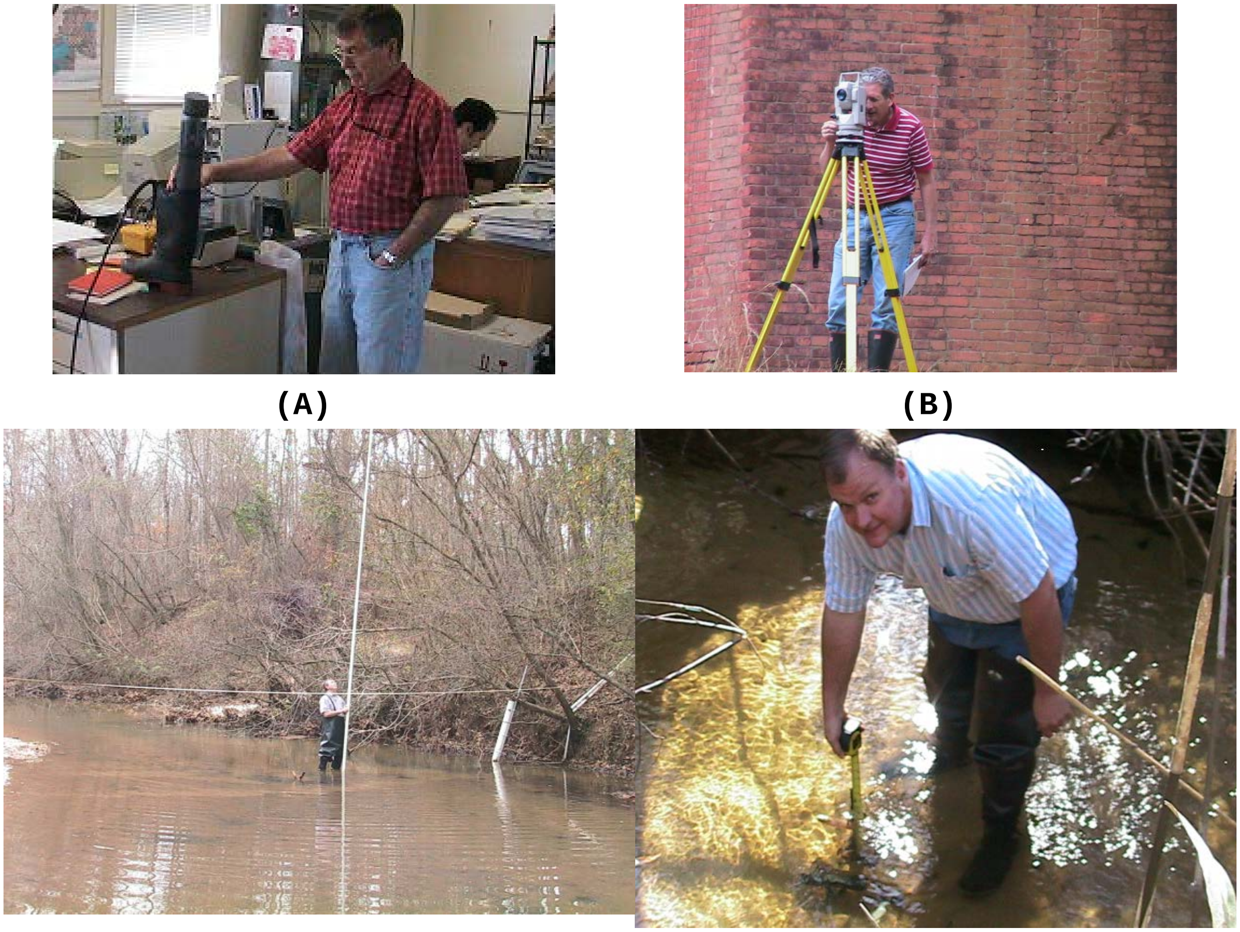
9. YSI Model 6820 or 6920 Multi-Parameter Sonde, along with turbidity probe and other water-quality sensors. This Sonde is compatible with the Isco 6712 sampler for data logging. The YSI 6820/6920 Sonde is used to measure turbidity and other water-quality parameters such as pH, DO, conductivity, and temperature.

10. Heavy-duty metal enclosure to house the equipment to protect against weather elements and potential vandalism.

The Isco 6700 series samplers have the capability for unattended data logging of stream gauge, velocity, flow, rainfall, and other water-quality parameters measured by the YSI Sonde. All data remain stored in the 6712 sampler memory without loss, even if the 12-volt battery fails. All logged data in the sampler can be downloaded manually onsite or accessed via telemetry.

Figure C-6 shows the major components of the sampling system and its field set up at Fort Benning. Some of the major steps followed during the set up shown in Figure C-6 are described below.

Figure C-6A shows field calibration of YSI Sonde Model 6900 used for the monitoring/recording of water-quality parameters. Figure C-6B and Figure C-6C show the land surveying equipment (Sokkia Total Station and Staff Rod) for determining the position of the station and the cross section of the stream at the point where water samples are collected. Figure C-6D is the point where the suction tube for collecting water sample and its depth from stream bottom is determined.



(A) **(B)**

(C) **(D)**

Figure C-6. Some of the steps during installation of a sampling system and field set up at Fort Benning: (A) shows field calibration of YSI Sonde Model 6900 for the monitoring/recording of water-quality parameters; (B) and (C) show the land surveying equipment (Sokkia Total Station and Staff Rod) for determining the position of the station and the cross section of the stream at the point where water samples are collected; (D) shows the point where the suction tube for collecting water sample and its depth from stream bottom is determined (all photos by ERDC-CERL).

Collection of Event-Based Automatic Suspended Sediment Samples

Isco samplers were programmed to trigger automatically once pre-defined stream level and/or rainfall condition became true to start sampling for each “storm event.” The “storm event” for this study was defined as one that met the following two criteria:

1. The storm must be significant enough to produce a minimum 6-in. rise in stream level to trigger the sampler for sample collection. At a monitoring site, however, if stream geometry and flow conditions dictated otherwise, a different level in rise was programmed to trigger the sampler.

2. The storm event must be preceded by a minimum of 72 hr of dry weather.

The automatic Isco samplers were programmed to collect SSC water samples as follows:

- Sample volume = 500 mL

- Number of samples collected each “storm event” = 24

- Duration of samples collected each “storm event” = 24 hours

- Sampling sequence. Isco samplers were programmed to collect 24 samples over a period of 24 hours following sampler-trigger in a sequence as described in Table C-3.

Table C-3. Sampling sequence for Isco samplers.

Item	Sample/ Bottle Number	Number of total samples collected	Time Interval Between Sample Collected (min.)	Cumulative Time (min.)
1	1	1	At trigger time	0
2	2-7	6	5	30
3	8-10	3	10	60
4	11-14	4	15	120
5	15-18	4	30	240
6	19-21	2	60	360
7	21-22	2	120	600
8	23	1	360	960
9	24	1	480	1,440

Collection of SSC samples at a non-uniform interval, as given in Table C-3, was based on the following two premises.

1. The significant component of suspended sediment is carried downstream at the head of the storm, rather than during a later part of the storm. Thus, most of the SSC samples were collected with increased frequency at the head of the storm.

2. For each storm event, all 24 SSC samples should be collected over a period of 24 hours because typically a storm seldom lasts longer than 24 hours and the

concentration of suspended sediment may change significantly during a storm.

Stream gauge and velocity measurements were made using Isco's sampling equipment. This system included a 750 Area-Velocity Flow Module (750 A-V Module), and a 6712 automatic sampler. A perforated suction tube was used to collect samples of suspended solids during storm events. This suction tube was installed 6-8 in. above the streambed. The suction tube and Low Profile Sensor moved up and down as the streambed level varied after storms. The sensor was installed 6-12 in. above the streambed, facing directly upstream. The Doppler component of the sensor recorded the time for the signal to travel back and forth and transmitted the information to the 750 A-V Module for processing into flow velocity. The processed velocity values were transmitted to the 6712 Controller where they are stored for data retrieval. The sensor also has a pressure transducer that monitors the pressure head and transmits the information back to the 750 A-V Module, where it is processed into level values and transmitted to the controller for storage and later data retrieval by the user.

Turbidity measurements were made using an YSI 6036 Turbidity Probe and YSI 6920 Sonde. The sonde was connected to the Isco controller for turbidity data storage. All information on stream gauge, velocity, flow, and turbidity was continuously recorded and stored in the controller at intervals defined by the user. Whenever the runoff water level rose to a predefined level during storm events, the 750 A-V Module sent the trigger signal to the 6712 Controller. The sampler was then triggered, and 24 samples of suspended sediment were collected by the 6712 Sampler (as explained previously).

The collected SSC water samples were then analyzed in the laboratory, and data stored manually in spreadsheets. On the other hand, gauge, velocity, flow, and turbidity data stored in the Isco Sampler were retrieved using the Isco Flowlink software program. Therefore, two separate datasets were maintained: (1) SSC data analyzed in the laboratory using USEPA 160.2 Method and (2) gauge, velocity, flow, and turbidity data stored in the Isco™ 6712 automatic sampler, which is retrieved and processed using Isco Flowlink software. Figure C-7 shows turbidity, stream level, and flow data collected and stored in Isco samplers for some typical storms.

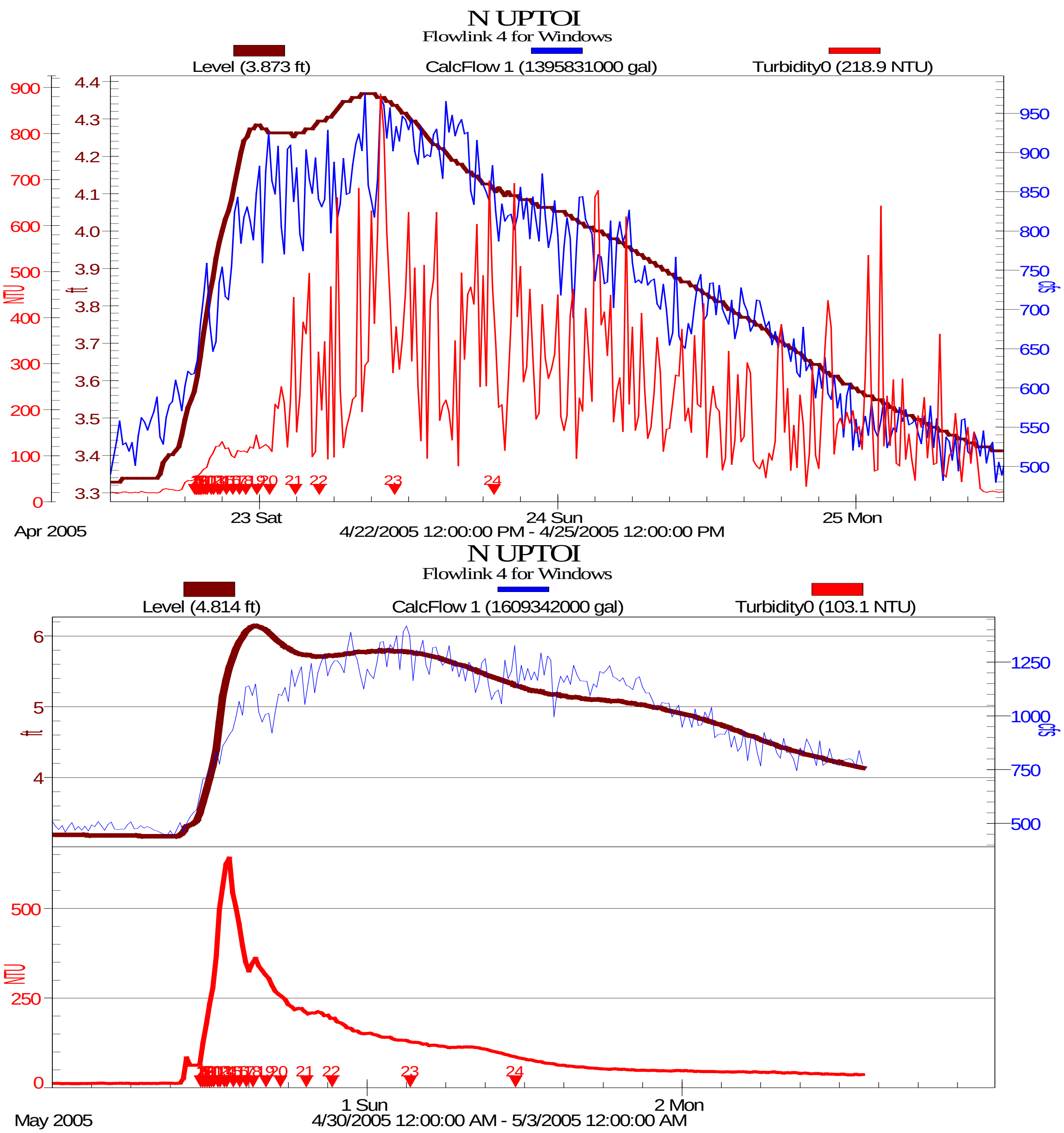


Figure C-7. Typical stream turbidity, stream level, and flow data collected and stored in Isco samplers.

Laboratory Analysis

Following the occurrence of a specified "storm event," water samples were manually picked up from the sampler box, labeled, processed, and sent to Columbus State University, Georgia, for analysis. All data logged in the 6712 sampler (both from the sampler and the YSI Sonde) were downloaded using an Isco Rapid Data Transfer device or a laptop. Sample bottles were replaced by a clean set of 24, 1-L bottles to be ready for the next storm.

Laboratory analysis for SSC was made using USEPA Method 160.2. Using a Hach Model 2100AN Laboratory Turbidimeter, turbidity measurements for each sample were also taken during laboratory SSC analyses. These measurements were taken to compare with field measurements made by YSI Sondes. Another objective of taking turbidity measurements in the laboratory was to use them in case a YSI Sonde malfunctioned and failed to record turbidity measurements in the field.

Statistical Analysis of Monitored Data for $C_{sed} = f\ (T_{ntu})$ Model Development

Measured sediment and turbidity data were analyzed using standard regression methods for developing a relationship between concentration and turbidity. Results of this analysis are given in Appendix D.

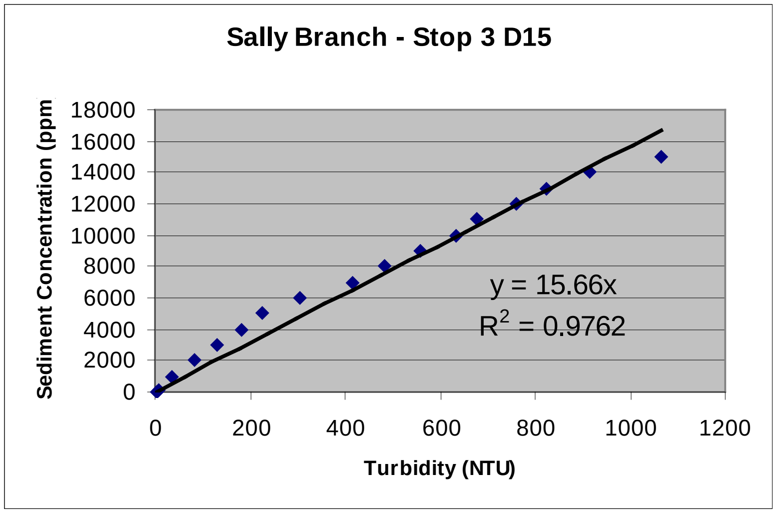
APPENDIX D: RESULTS

Laboratory-Controlled SSC-Turbidity Correlation Results

Turbidity-suspended regression correlations were developed for Fort Benning soils under a laboratory-controlled environment. The regression results for all 14 sites used for soil collection are given in Table D-1. However, regression plots for only two representative sites (D15 Sally Branch and Bonham Creek) are given in Figure D-1 for illustration. The coefficient of determination (R^2), which was over 98% for almost all of the soils tested, indicates a strong relationship between SSC and turbidity. These statistical results show that it is possible to estimate concentrations of suspended sediment using turbidity as a reliable surrogate measurement.

Table D-1. Laboratory-controlled SSC-Turbidity correlations.

Dataset	Site Name	Soil Texture -Sieve Analysis	Linear Equations	R^2
1	Cactus Road	Sand = 90-96%Silt = 4%Clay = 4%	SSC = 13.179 * turb	98.4
2	D-15 Sally	Sand = 90-96%Silt = 4%Clay = 4%	SSC = 15.66 * turb	98.6
3	D-14	Sand = 88%Silt = 6%Clay = 6%	SSC = 12.947 * turb	99.6
4	Bonham Creek	Sand = 88%Silt = 6%Clay = 6%	SSC = 13.509 * turb	98.6
5	D-2 Sally	Sand =60-70%Silt = 10%Clay=>20%	SSC = 6.6974 * turb	97.8
6	D-13	Sand = 98%Silt = 2%Clay = 0%	SSC = 19.268 * turb	99.6
7	River Bend Rd	Sand = 90%Silt = 6%Clay = 4%	SSC = 8.1488 * turb	99.3
8	A-14	Sand = 90%Silt = 6%Clay = 4%	SSC = 12.26 * turb	96.7
9	Q-2	Sand = 80%Silt = 16%, Clay =4%	SSC = 4.0438 * turb	97.1
10	E-7	Sand = 72%Silt = 18%, Clay =10%	SSC = 9.6328 * turb	99.2
11	K-6	Sand = 76%Silt = 8%, Clay =16%	SSC = 5.9684 * turb	98.2
12	O-9	Sand = 96%Silt = 2%,Clay = 2%	SSC = 6.2301 * turb	95.6
13	L-6	Sand = 88%Silt = 6%, Clay=6%	SSC = 15.613 * turb	97.2
14	M-2	Sand = 64%Silt = 22%, Clay =14%	SSC = 20.44 * turb	98.8



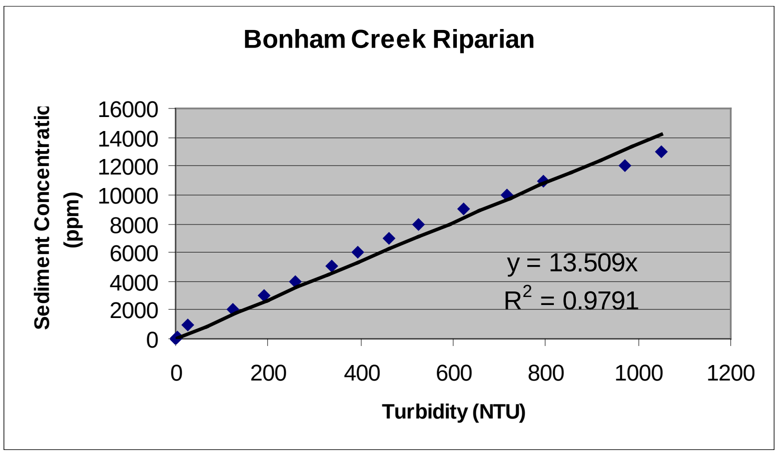


Figure D-1. Bonham Creek and Sally Branch regression correlations.

Stream-Flow Discharge as a Surrogate for SSC

Historically, the only available surrogate for SSC has been streamflow (Lewis 2003). To determine whether streamflow can be used for estimating stream sediments at Fort Benning, a regression comparison was made between measured SSC and the corresponding streamflow measured at McBride Bridge, Upatoi Creek. These data were reported by the USGS for the period 1977–1984.

The USGS permanent streamflow-gauging station at McBride Bridge at Upatoi Creek has been in commission since it was established in 1958. Besides providing continuous gauge and stream-flow measurements for the past 50 yr, this station provides random data on other water-quality parameters including SSC, turbidity, temperature, fecal coliform, and stream bed particle size analysis. The station has an SSC dataset for 75 measurements made from 1977–1984, as given in Table D-2. Using this dataset, a regression correlation was developed using discharge (Q_{cfs}) as an indicator for suspended concentration. The regression results, as given in Equation 5 and illustrated in Figure D-2, show an R^2 value of 86%. The results clearly show that stream-flow rates can be used with confidence for estimating suspended concentrations and sediment loads in Fort Benning's streams and creeks.

The linear regression equation developed from the McBride Bridge at Upatoi Creek dataset is:

$$SSC\ (mg/L) = 2.243 + 0.1334\ Q_{cfs} \qquad \textbf{(5)}$$

The significance of the above regression model (Equation 5) is that it was developed for a large drainage basin that spans a watershed area of 343 sq mi (218,880 acres). All major tributaries at Fort Benning drain into Upatoi Creek.

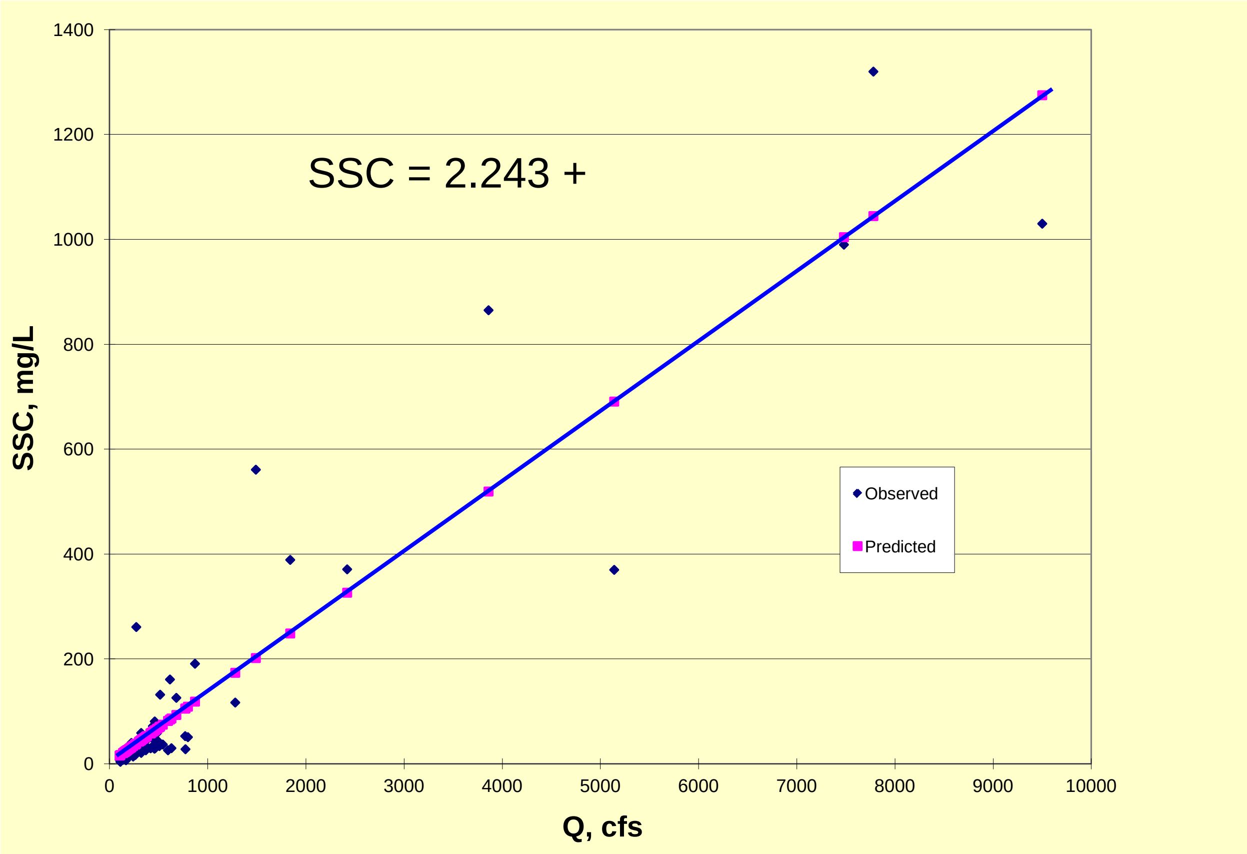


Figure D-2. Regression results depicting relationship between flow and suspended-sediment concentration.

Table D-2. Original dataset – McBride at Upatoi Creek.

Sample Date/Time	Flow stream (Q_{cfs})	SSC Suspend (mg/L)		Sample Date/Time	Flow Stream (Q_{cfs})	SSC Suspend (mg/L)
1977-11-21 12:30	220	20		1981-04-08 12:25	770	53
1978-01-25 13:15	7780	1320		1981-05-27 19:00	441	72
1978-03-31 10:00	416	30		1981-06-16 15:35	164	22
1978-05-02 14:30	680	126		1981-07-17 10:00	102	8
1978-05-16 16:40	542	37		1981-07-28 09:15	107	8
1978-06-22 19:15	460	81		1981-08-25 15:55	140	11
1978-08-01 08:30	870	191		1981-09-17 10:00	167	7
1978-08-17 11:00	343	38		1981-10-05 17:55	110	4
1978-09-30 08:30	171	27		1981-10-28 10:35	262	17
1978-10-11 09:15	153	18		1981-12-03 13:20	309	36
1978-11-05 10:40	151	13		1982-01-14 16:30	1280	117
1978-12-06 09:30	372	31		1982-02-25 12:35	457	29
1979-01-30 12:00	420	30		1982-04-01 09:35	322	21
1979-02-12 17:20	484	45		1982-04-06 11:10	3860	865
1979-02-25 17:30	5140	370		1982-04-15 17:45	426	50
1979-03-08 10:10	798	51		1982-05-06 09:05	357	31
1979-04-04 16:30	7480	990		1982-05-20 07:55	319	33
1979-04-25 17:35	1840	389		1982-07-30 09:05	207	19
1979-06-12 08:50	213	29		1982-09-13 11:05	182	11
1979-07-03 09:30	172	15		1982-10-13 16:45	222	40
1979-07-20 08:30	300	43		1982-12-01 10:45	515	132
1979-08-20 11:30	137	8		1983-01-12 09:45	465	30
1979-10-05 11:10	322	59		1983-03-02 15:25	773	28
1980-01-10 12:45	272	261		1983-04-06 14:50	630	30

Sample Date/Time	Flow stream (Q_{cfs})	SSC Suspend (mg/L)		Sample Date/Time	Flow Stream (Q_{cfs})	SSC Suspend (mg/L)
1980-02-20 17:40	450	35		1983-05-11 09:40	336	27
1980-04-01 18:50	1490	561		1983-05-18 13:00	380	32
1980-06-20 10:30	260	26		1983-06-29 11:25	370	44
1980-07-30 09:40	174	13		1983-07-12 10:40	158	12
1980-09-18 10:55	170	21		1983-08-10 11:35	196	19
1980-09-29 11:35	140	10		1983-09-13 18:25	265	30
1980-10-10 09:15	154	12		1983-10-05 09:50	172	14
1980-11-13 09:10	165	10		1984-01-05 16:40	508	34
1981-01-16 09:45	180	12		1984-02-01 10:45	505	40
1981-02-02 12:45	260	40		1984-04-05 13:10	595	26
1981-02-12 16:25	2420	371		1984-05-17 09:40	240	14
1981-02-24 17:50	485	59		1984-06-27 11:05	153	10
1981-03-17 12:05	369	26		1984-07-31 11:15	615	161
1981-04-02 13:50	9500	1030				

(Source: US Geological Survey – Water Resources Division)
http://ga2.er.usgs.gov/LibAreportPDF/2004/Discharge/sp02341800.pdf

The USGS permanent monitoring station continuously monitors real-time streamflow at McBride Bridge.[8] This information is available on the USGS web-site in real time. Using our regression model and the USGS stream-flow data, it is possible to provide Fort Benning real-time suspended concentration and sediment loads, as illustrated in the example below.

Example: Suspended Sediment Load Calculation

The general form of the model is:

$$SSC\ (mg/L) = f\ (Q_{cfs}) \qquad \textbf{(6)}$$

Where:

[8] Upatoi Creek near Columbus, Georgia – Hydraulic Unit Code: 0313003 – McBride Bride – Fort Benning

SSC = Suspended Sediment Concentration (ppm or mg/L)

Q_{cfs} = *Stream flow (cfs)*

Using USGS data for McBride Bridge, the model relationship is:

$$SSC = 2.243 + 0.1334 * Q \tag{7}$$

and it can be shown that:

$$L_{sed} = 2.69 X 10-3 X Q_{cfs} X SSC \tag{8}$$

Where:

L_{sed} = Sediment Transport Load (ton/day)

Q_{cfs} = Streamflow or discharge (cfs)

SSC = Suspended Sediment Concentration (mg/L or ppm)

Substituting Equation 7 into Equation 8, we get:

$$L_{sed} = 2.69 X 10-3 X Q_{cfs} * [2.243 + 0.1334 Q_{cfs}] \tag{9}$$

Simplifying Equation 9, we get:

$$L_{sed} = 0.360 * 10-3 * [16.814 Q +Q2_{cfs}] \tag{10}$$

Equation 10 shows that the sediment transport load can be estimated from its discharge flow rate. Thus, this information can be telemetered directly to Fort Benning to provide real-time sediment transport data from USGS stream-flow measurements being continuously recorded at McBride Bridge.

Estimated Sediment Loads for USGS Site HUC 03130003

Equation 9 was used to estimate sediment loads for typical 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr storms for USGS Site HUC 03130003 at McBride Bridge for a drainage area of 342 sq mi. Using the USGS design stormflow rates, estimated stream sediment loads for Upatoi Creek for different design storms are given in Table D-3 and shown in Figure D-3.

Table D-3. Estimated sediment load in Upatoi Creek for the design flood discharges at recurrence intervals given.

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	500-yr
USGS (cfs)	6,390	10,800	14,600	20,600	26,200	32,800	40,700	53,300
Estimated L_{sed} (t/day)	14,738	42,056	76,826	152,894	247,277	387,501	596,583	1,023,043

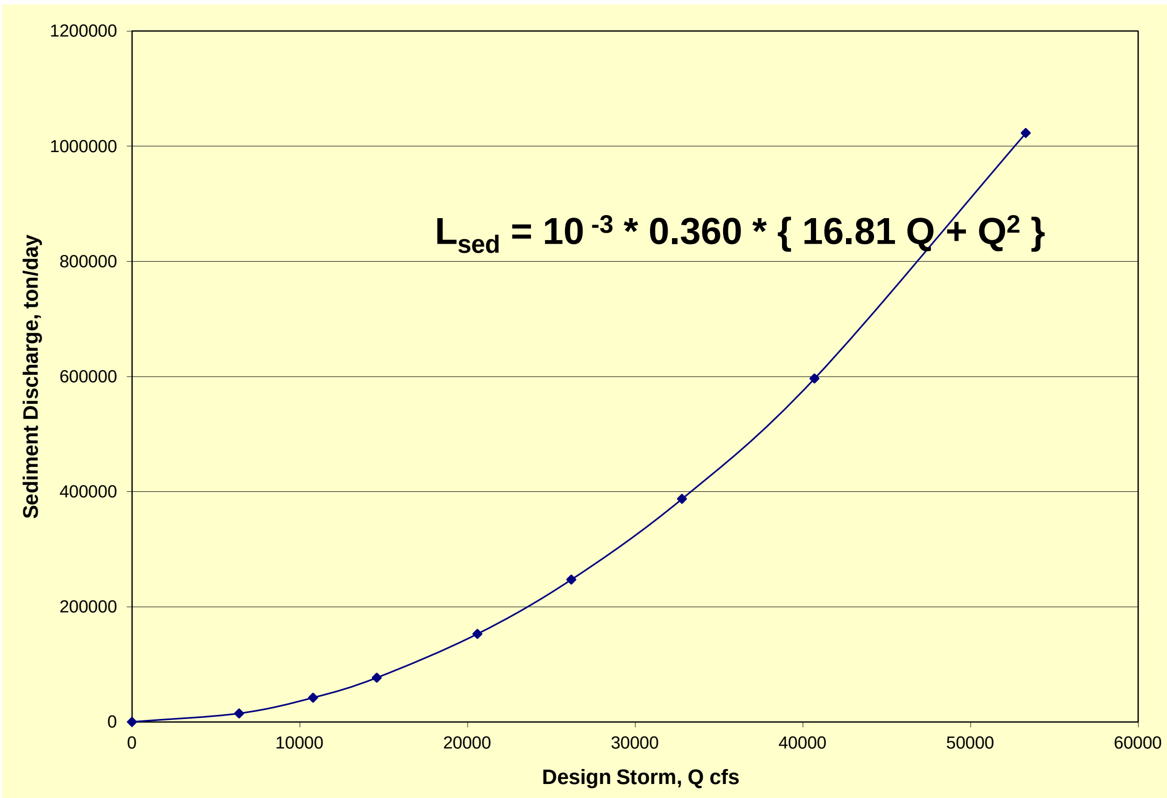


Figure D-3. Estimated sediment loads in Upatoi Creek, Fort Benning, GA. (Source: USGS Design Storms; http://ga.water.usgs.gov/)

Sediment Load Estimation

For the purpose of this report, data for Tiger Creek was analyzed and used to develop regression correlations. Tiger Creek results were found to be representative of other sampling sites. The results are shown in Figure D-4.

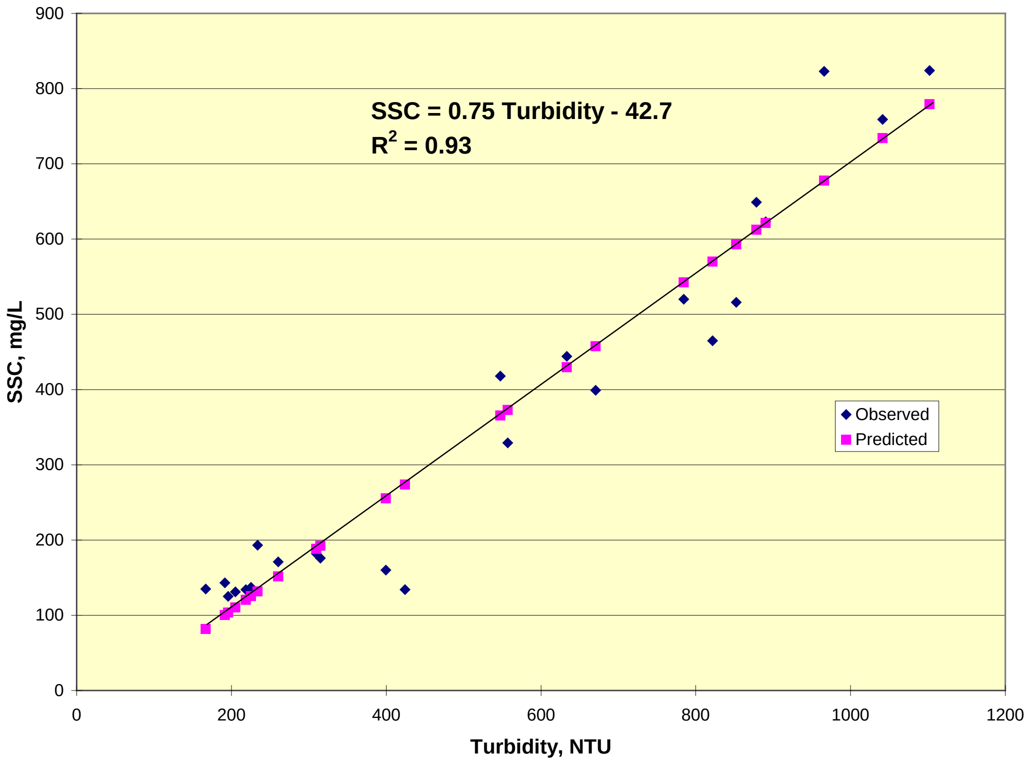


Figure D-4. Tiger Creek — SSC-Turbidity relationships.

The regression model shown in Figure D-4 is:

$$SSC = 0.75 * Turbidity\ (NTU) - 42.7\ (R2 = 0.93) \qquad \textbf{(11)}$$

Results show a strong correlation between SSC and turbidity, with an R^2 value of 93%. This suggests that turbidity can be used as an alternate surrogate measurement for estimating SSC and sediment transport load of suspended sediments, by using only turbidity and stream-flow measurements. For example, using measured turbidity, the estimated value of SSC is obtained from Equation 11; then sediment load can be estimated by using Equation 12.

$$L_{sed} = 2.69 * 10\text{-}3 * Q * SSC \qquad \textbf{(12)}$$

Where:

L_{sed} = Stream sediment load, ton/day

Q = stream discharge, cfs (measured or estimated from rating curve)

SSC = sediment suspension, mg/L (from Equation 11)

Thus it prove possible to telemeter and provide continuous real-time information on stream SSC and sediment load to Fort Benning decision makers (provided rating curve data are available for the streams).

APPENDIX E: LESSONS LEARNED

Summary of Lessons Learned

- **The field data showed a good correlation between turbidity and SSC.** Results suggest it is feasible to estimate SSC from turbidity measurements in Fort Benning streams and other streams with similar hydrologic characteristics.

- **The sampling, analysis, and reported processes can be automated by using telemetry.** Turbidity can be monitored and recorded continuously. SSC and sediment load can be estimated from the turbidity and water discharge data and telemetered in real time to Fort Benning. The method of estimating SSC and sediment loads from turbidity measurements suggests the possibility for computing SSC and sediment loads even for remotely inaccessible sites such as Upatoi North.

- While the focus of this effort has been on SSC and turbidity, **other water-quality parameters can be recorded continuously and real-time stream water-quality information telemetered to decision makers** at Fort Benning. Hydrolab and YSI Sondes have the capability of monitoring over 20 water-quality parameters simultaneously.

- **Most of the suspended sediment is transported during a few large rainstorm events.** For example, following the major storm of June 2005 (shown in Figure E-1), measurement showed that over 7 in. of sediment was deposited on top of a 4-ft pier at Randall Creek, 2nd Armored Division Road.

Figure E-1. At Randall Creek, 2nd Armored Division Road, one storm dumped 7 in. of sediment on a pier almost 4 ft above streambed.

- **Automated storm-data collection is essential to effectively capture major rainstorm events.** When major storms occur, which is infrequent and difficult to predict, trained personnel may not be available to collect on-site storm information. In addition, automated data collection and reporting systems provide a more detailed picture of sediment transport processes than is normally available by traditional methods. Continuous records of turbidity and associated sediment concentration and load estimates would indicate instantaneous fluxes or pulses of sediment from sudden sediment input that result from events such as bank failure, debris flows, and anthropogenic or military activity upstream. Such pulses can provide an instantaneous alert to watershed problems that may require closer investigation. For example, an unusually high fecal count of 3,200 was observed by the USGS for McBride Bridge at Upatoi Creek. An automated water-quality system would have transmitted the information to Fort Benning instantaneously and alerted them for immediate investigation and a problem solution.

- **Automated data collection is essential to effectively measure suspended sediment loads in storm events, particularly in small basins.** Continuous turbidity measurements can be used, along with discharge, in an automated system that makes real-time sampling decisions to facilitate sediment load estimation.

Monitoring Turbidity Continuously and Telemetering Information in Real Time

While turbidity cannot be a true substitute for SSC, it can be a tremendous asset as an auxiliary measurement. Turbidity can be used, along with stream discharge, in an automated mode to make real-time sampling decisions linking turbidity to concentration. The continuous turbidity record can reveal sediment pulses unrelated to discharge, providing information about timing and magnitude of landslides, streambank failure, or the failure of best management practices.

A method to estimate SSC was developed by using linear regression to correlate turbidity to SSC. The regression model was developed from a database that is currently limited in terms of the amount of data it includes. We evaluated only a small dataset from two streams. We conclude that, unless more data become available, these results may not be representative of overall stream conditions across the installation.

Evaluation of results from current data suggests that sediment pollution may not be significant enough to pose potential risk to aquatic life and/or sedimentation. Further evaluation will be required to confirm that sediment pollution impacts aquatic life or human health for any given sampling station or watershed. Many streams and water-quality stations need more data and monitoring to arrive at a decisive conclusion.

Significance of Fort Benning Effort

Recent development of several models of in-situ sensors has made it possible to continuously monitor turbidity in real time. The statistical relationships between turbidity and SSC obtained from this work made it possible to provide a real-time estimate of concentrations of SSC and sediment loads.

Turbidity can be continuously monitored. Monitoring throughout a storm event enables making a more informed decision about the potential sediment impact on the receiving waters. The advantage of regression estimates that use continuous turbidity measurements over discrete (traditional, occasional) sample collection is that continuous estimates represent all flow conditions regardless of storm magnitude or its duration, and sediment-discharge estimates are continuously available in real time.

Salient features of this SSC-turbidity model include its simplicity and ease of use. Except for streamflow, no additional data are required to run the model, and the streamflow can be automated if rating curves become available.

Conclusion

This study of a stream water-quality monitoring program conducted for Fort Benning demonstrated the value and ease of using an SSC-turbidity model. The only data needed are streamflow, once the original parameters have been determined. (It should be noted that treatment options such as sediment ponds or biofilters were not needed to minimize downstream turbidity because where the Upatoi stream exits installation and enter the river, both sides of the Upatoi stream are forested and protected with stabilized woodlands and require no additional buffer strips.)

As individual states determine whether or not to use numerical criteria for monitoring stream water quality, an approach has been established indicating it is possible using existing stream monitoring stations and sensors without having to rely on expensive physical collection and analysis of water samples containing sediment.

APPENDIX F: REFERENCES

Alexander, G. R., and E. A. Hansen. 1986. “Sand Bedload in a Brook Trout Stream.” *North American Journal of Fisheries Management* 6:9-23.

APHA (American Public Health Association). 1995. 2540 D - *Standard Methods for the Examination of Water and Wastewater*. 20th Ed. Washington, DC: APHA.

APHA, American Water Works Association (AWWA), and Water Environment Federation (WEF). 1995. In A. D. Eaton. L. S. Clesceri, and A. E. Greenberg, Eds. *Standard Methods for the Examination of Water and Wastewater* (19th edition). Washington, DC, 2-56.

ASTM (American Society for Testing and Materials). 2006. “Method D 3977-97 Standard Test Method for Determining Sediment Concentration in Water Samples.” In *Annual Book of Standards, Water and Environmental Technology*, Vol. 11.02. West Conshohocken, PA.

Barrett, J. C., G. D. Grossman, and J. S. Rosenstein. 1992. “Turbidity-Induced Changes in Reactive Distance of Rainbow Trout.” *Transactions of the American Fisheries Society*. 121:437-443.

Burkhead, N. M., S. J. Walch, B. J. Freeman, J. D. Williams. 1997. “Status and Restoration of the Etowah River, an Imperiled Southern Appalachian Ecosystem.” In G.W. Benz and D.E. Collins (eds.), *Aquatic Fauna in Peril*. Decatur, GA: Southeast Aquatic Research Institute, Lenz Design and Communications, 375-444.

Ehlinger, T. 2002. *Monitoring of Stream Habitat and Aquatic Biotic Integrity*. Interim Report. Milwaukee, WI: Department of Biological Science, University of Wisconsin. http://www.uwm.edu/~ehlinger/data/

Georgia Rules and Regulations for Water Quality Control. 2001. Chapter 391-3-6-16. Revised October 2001.

Gray, J. R., G. D. Glysson, L. M. Turcios, and G. E. Schwarz. 2000. *Compatibility of Suspended Sediment Concentration and Total Suspended Solids Data*. USGS Water Resources Investigation Report 00-4191. Reston, VA: USGS.

Gue, Qizhong. 2006. *Correlation of Test Methods*. Final Report. Trenton, NJ: New Jersey Department Environment Protection, Division of Science, Research, and Technology.

Herzog, M., J. Harbor, K. McClintock, K. Harbor, J. Law, and K. Bennett. 2000. “Are Green Lots Worth More Than Brown Lots? An Economic Incentive for Erosion Control on Residential Developments.” *Journal of Soil and Water Conservation* 55(1):43–49.

Holliday, C. P., T. C. Rasmussen, and W. P. Miller. 2003. “Establishing the Relationship Between Turbidity and Total Suspended Sediment Concentration.” In *Proceedings of the 2003 Georgia Water Resources Conference* held April 23-24, 2003, at the University of Georgia, Athens.

Holmbeck-Pelham, S. A., and T. C. Rasmussen. 1997. “Characterization of Temporal and Spatial Variability of Turbidity in the Upper Chattahoochee River.” In P*roceedings of the 1997 Georgia Water Resources Conference*, K. J. Hacher, ed. Athens, GA: University of Georgia.

Koltun, G. F., M. N. Landers, K. M. Nolan, and R. S. Parker. 1997. “Sediment Transport and Geomorphology Issues in the Water Resources Division.” In *Proceedings of the US Geological Survey Sediment Workshop*, 4–7 February 1997. Reston, VA: US Geological Survey.

Kundall, J. E., and R. C. Rasmussen. 1995. “Erosion and Sedimentation, Scientific and Regulatory Issues.” Developed for Georgia Board of Natural Resources, Georgia Board of Regents’ Scientific Panel on Evaluating the Erosion Measurement Standard Defined by the Georgia Erosion and Sedimentation Act.

Lewis, J. 1996. “Turbidity-Controlled Suspended Sampling for Runoff-Event Load Estimation.” *Water Resources Research* 32(7):2299-2310

Lewis, J. 2003. “Turbidity-Controlled Sampling for Suspended Sediment Load Estimation.” In *Workshop on Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances* held 19–21 June in Oslo, Norway.

Meyer, J., A. Sutherland, K. Barnes, and D. Walters. 1999. A Scientific Basis for Erosion and Sedimentation Standards in the Blue Ridge Physiographic Region. In *Proceedings of the 1999 Georgia Water Resources Conference,* 321–324.

NAS (National Academy of Sciences) and National Academy of Engineering. 1972. *Water Quality Criteria*. Report of the Committee on Water Quality Criteria. Washington, DC: Environmental Studies Board.

Mukundan, R., D. E. Radcliffe, and J. C. Ritchie. 2009. "Sediment Source Tracking in the Georgia Piedmont." In *Proceedings of the 2009 Georgia Water Resources Conference*, held April 27-29 at the University of Georgia, Athens, GA.

Newcombe, C. P., and J. O. T. Jensen. 1996. "Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact." *North American Journal of Fisheries Management 16(4):693-727.*

Pruitt, A. B., D. L. Melgaard, M. C. Flexner, and A. S. Able. 2001. "Chattooga River Watershed Ecological/Sedimentation Project." In: *Proceedings of the Federal Interagency Sedimentation Conference*, held 26-30 March in Reno, NV.

Rasmussen, T. C. 1995. *Erosion and Sedimentation: Scientific and Regulatory Issues*. Report developed by Georgia Board of Regents scientific panel on evaluating the erosion measurement standard defined by the Georgia Erosion Sedimentation Act. Atlanta, GA: Georgia Board of Natural Resources.

Sigler, J. W., T. C. Bjornn, and F. H. Everest. 1984. "Effects of Chronic Turbidity on Density of Steelheads and Coho Salmon." *Transactions of the American Fisheries Society* 113:142-150.

Sutherland, A. B., K. H. Barnes, J. L. Meyers, and B. J. Freeman. 1998. "Effects of Sediment on Biodiversity in Southern Appalachian Rivers and Streams." Atlanta, GA: Georgia Water Resources Program, Georgia Institute of Technology.

Sutherland, A. B., J. L. Meyer, and N. Gardener. 1999. "Effects of Land Use on Sediment Transport and Fish Assemblage Structure in Southern Appalachian Streams." In *Proceedings of the 1999 GA Water Resources Conference*, 318–320.

Technical Advisory Group (TAG) for Georgia Conservancy. 2002. *A Protocol for Establishing Sediment TMDLs*. TAG White Paper. TAG was formed jointly by the University of Georgia River Basin Center and the Georgia Conservancy.)

USDA (US Department of Agriculture). 2003. *The United States Department of Agriculture, Soil Survey of Russell County, Alabama*. Washington, DC: USDA Soil Conservation Service.

USEPA (US Environmental Protection Agency). 1999. Region 5. Central Regional Laboratory. "Standard Operating Procedures for the Analysis of Residue, Non-Filterable (Suspended Solids), Water Method 160.2 NS (Gravimetric, 103-105 C)." Washington, DC: USEPA. http://www.epa.gov/rmdcrl/sop/sopdoc/AIG018.pdf

______. 2000. Water Quality Conditions in the United States. *National Water Quality Inventory 2000 Report to Congress.* http://water.epa.gov/lawsregs/guidance/cwa/305b/2000report_index.cfm

______. 2003. Development of Water Quality Criteria for Suspended and Bedded Sediments (SABS). Draft. Washington, DC: USEPA, Office of Water, Office of Science and Technology.

______. 2005. *Handbook for Developing Watershed Plans to Restore and Protect Water Quality* (Draft). EPA #841-B-05-005. Washington, DC: Office of Water, NPS Branch.

Waters, T. F. 1995. *Sediments in Streams; Sources, Biological Effects and Control.* Bethesda, MD: American Fisheries Society.

APPENDIX G:
ABBREVIATIONS AND UNIT CONVERSIONS

Abbreviations

Term	**Spellout**
APHA	American Public Health Association
AR	Army Regulation
ASTM	American Society for Testing and Materials
A-V	area-velocity
BRAC	Base realignment and closure
CECW	Directorate of Civil Works, U. S. Army Corps of Engineers
CEMP-CE	Directorate of Military Programs, U. S. Army Corps of Engineers
CERL	Construction Engineering Research Laboratory
CPU	central processing unit
CWA	Clean Water Act
DMPRC	Digital Multiple Purpose Range Complex
DO	Dissolved oxygen
ERDC	Engineer Research and Development Center
ESCA	Erosion and Sedimentation Control Act
GIS	geographical information system
HQUSACE	Headquarters, United States Army Corps of Engineers
NAS	National Academy of Sciences
NPS	nonpoint source
NRCS	Natural Resources Conservation Service
NTU	nephelometric turbidity units
OCGA	Official Code of Georgia
PCB	polychlorinated biphenyls
POC	Point of contact
PPM	parts per million

Term	**Spellout**
PWTB	Public Works Technical Bulletin
RUSLE	Revised Universal Soil Loss Equation
SABS	suspended and bedded sediment
SSC	suspended settlement concentration
TMDL	Total Maximum Daily Load
TDS	total dissolved solids
TS	total solids
TSS	total suspended solids
UFC	United Facilities Criteria
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USLE	Universal Soil Loss Equation
U.S.C.	United States Code
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

Unit Conversions

Unit Conversion Factors

acres	4,046.873	square meters
cubic yards	0.7645549	cubic meters
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	0.0254	meters
square miles	2.589998 E+06	square meters
tons (2,000 lb)	907.1847	kilograms