Characterizing Hysteretic Water Quality in Southern Appalachian Streams

Mark S. Riedel, James M. Vose and Paul V. Bolstad

USDA Forest Service, Coweeta Hydrologic Laboratory, 3160 Coweeta Lab Rd, Otto, NC 28763

Biographical Sketch

Mark S. Riedel (mriedel@fs.fed.us) is a Research Hydrologist at the USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory. Dr. Riedel's research interests include land use legacy influences on water quality and fluvial processes, riparian land use impacts on stream stability, and the cumulative effects of forest roads on erosion and sedimentation.

Abstract

Water quality in mountain streams of the southern Appalachians varies seasonally and with storms. In an effort to validate Total Maximum Daily Loads (TMDLs) for sediment in the Chattooga River Watershed (NE Georgia, NW South Carolina, and SW North Carolina), we studied four tributary streams over an eighteen-month period. Two of the streams had completely forested watersheds; one stream was a benchmark with exceptional water quality for the purposes of TMDL establishment while the other was impaired by excessive sedimentation. The third stream, with a completely forested watershed, was adjacent to a gravel road. This stream was threatened by excessive sedimentation. The fourth, while mostly forested, had residential development and gravel roads in its riparian corridor. This stream was also threatened by excessive sedimentation. We measured stream flow continuously and sampled Total Suspended Solids (TSS) to characterize the hydrology and water quality of these streams during baseflow and storm flow conditions. TSS data on the benchmark stream and a forested stream exhibited strong hysteresis and were elevated on the rising limbs of hydrographs and declined rapidly on the recession limbs. While there was weak hysteresis apparent in the constituent concentrations and loadings of the impaired streams, it was not statistically significant. Thus, we could not simply characterize loadings with typical constituent vs. discharge rating curves. We filtered TSS and discharge data into rising and recession limb data based upon hydrograph slope and analyzed the data separately. We constructed a series of rating curves based upon hydrograph thresholds that allow us to predict loadings as a function of hydrograph dynamics. This modified approach facilitates the establishment of TMDLs because the hydrograph threshold-rating curves can be used to directly link loading rates to discharge frequency and duration relationships.

Introduction

The Chattooga River is a federally designated Wild and Scenic River that drains 450 square kilometers of the Blue Ridge Ecosystem in the southern Appalachian Mountains of NE Georgia, NW South Carolina, and SW North Carolina (Figure 1). The United States Environmental Protection Agency (EPA) (2001) identified numerous tributaries to the Chattooga that are impaired and many additional kilometers of streams whose aquatic health is threatened by excessive sedimentation. The EPA consequently established TMDLs for several sediment-impaired streams in the Chattooga Watershed (EPA, 2001). Due to difficulties stemming from the interpretation of Georgia's water quality standards, the characterization of stream sedimentation, and judicially imposed time limitations for the establishment of TMDL's, the EPA adopted a phased approach to developing TMDLs for the Chattooga River Watershed. The EPA has published these TMDLs (2001) stating that they will be revised in 2004.

The Chattooga River Watershed is also one of twelve USDA Forest Service Large Scale Watershed Restoration projects. The Forest Service has been working to improve water quality and watershed health throughout the watershed, 68% of which is National Forest lands. Van Lear, et al (1995) estimated that more than 80% of the sedimentation threat to streams in the Chattooga River watershed is caused by unpaved gravel roads. One of the primary actions is the reduction of runoff, erosion, and sedimentation from forest roads through road closure and reconstruction. As part of this work, we monitored water quality and streamflow on four tributaries of the Chattooga River.

Site Description

We instrumented and monitored stream flow and water quality on four tributaries of the Chattooga River (Table 1). Each of these streams had previously been evaluated by the EPA to determine if the streams were supporting designated uses in compliance with Georgia State water quality standards (EPA, 2001). With the exception of a small portion of the Reed Mill watershed, all of the watersheds have been managed as part of the Chattahoochee National Forest by USDA Forest Service since the early 1930's. Aside from the small portion of private land in Reed Mill watershed, the forests of the watersheds are intact. The only significant site disturbances at the time of this study were the use and maintenance of forest roads.

Table 1: Summary of characteristics for study streams. The ability of each stream to support its designated uses is indicated by 303 (d) list status.

Stream	303 (d) Status	Watershed Size (km^2)	Mean Elevation (m)	Mean Slope (%)	Aspect	Streamflow record (mos.)
Roach Mill	Impaired	0.8	712	16	ESE	18
Reed Mill	Threatened	4.4	700	14	S	18
Addie Branch	Unlisted	5.6	925	19	ENE	15
Pounding Mill	Threatened	1.3	706	14	ESE	13

Roach Mill has been identified by the EPA as an impaired stream due to sediment impairment of its biological community and habitat (EPA, 2001, page 7). The site location used to gather TMDL data was adjacent to a paved county highway immediately downstream of private residential and agricultural land. We were unable to install sampling equipment at this location and had to install it upstream, on national forest land. There were no roads or development upstream of this site. Watershed land use is 100% forested (26% deciduous, 24% coniferous, 50% mixed).

Reed Mill is generally the most turbid of the study streams. Three percent of its watershed is privately owned. This land, adjacent to the stream, is a mixture of agricultural and residential and accessed by numerous gravel roads. The EPA listed Reed Mill as being threatened by sedimentation. The remaining 97% of the watershed is forested (17% deciduous, 37% coniferous, 43% mixed).

Addie Branch creek is the most remote watershed. It is highest in elevation (exposing it to greater precipitation), steepest and the most northerly facing watershed in this study; conditions that typically generate more runoff in

the southern Appalachians (Jackson, et al, 2004). The EPA has established Addie Branch as the benchmark, minimally impaired stream in this region (Pruitt, et al, 2001). There is one road crossing approximately 1 km upstream of the Addie Branch monitoring site. Addie Branch watershed is completely forested (33% deciduous, 25% coniferous, 42 % mixed).

Pounding Mill Creek is adjacent to, and receives runoff directly from, a heavily used gravel road for nearly its entire length and is on the 303(d) list for being threatened by sedimentation. Land use is 16% deciduous, 40% coniferous and 44% mixed forest.

Background

Given the close proximity of the study watersheds to each other, bedrock and quaternary geology of the study watersheds are quite similar. This region of the Blue Ridge Mountains is dominated by igneous and metamorphic bedrock geology. The study watersheds are all located in a region underlain by Metagraywacke interspersed with mica schist, quartzite, amphibolite and conglomerate (GGS, 1976). Soils in the study area are derived exclusively from quartz-rich gneiss, mica-shist, and granitic bedrock and typically underlain by thick saprolite. While the loamy mountain soils are highly erodible when exposed, they are not subject to erosion under well-established forest cover (Van Lear, et al, 1995).

Elevation gradients and terrain of the southern Appalachians strongly influence climate, soils, and vegetation in the study region. The high precipitation distributed throughout the year and mild temperatures place this region in the maritime, humid, temperate system of Koppen's climate classification (Swift, et al, 1988). Ridges and upper elevation south facing slopes tend to be relatively dry while slopes with northern aspects are moist and cool (Jackson, et al, 2004). Swift, et al (1988), summarizing decades of data from the nearby Coweeta Hydrologic Laboratory, reported that water yield and streamflow increase with elevation due to higher rainfall, shallower soils, steeper slopes and shorter growing seasons. Average annual rainfall at upper elevations is 230 cm per year while lower elevations receive approximately 180 cm of rainfall per year (Swift, et al, 1988). During this study, the region was in the 3rd and 4th years of record drought. Annual precipitation was 20 to 40 percent below average while temperatures were 12 to 15 percent above average (Table 2).

Table 2: Summary of rainfall and temperature data during the study. Long-term rainfall and temperature averages are from 39 years of record. Data extracted from the National Weather Service climate station in Clayton, GA, located approximately ten km from the study streams.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Study period rainfall (cm)	15.0	5.7	19.1	5.0	13.4	13.0	15.7	16.2	13.6	7.0	6.7	9.8	140.2
Average rainfall (cm)	16.3	15.6	18.9	13.7	16.9	13.9	14.8	15.5	14.6	13.0	15.0	17.0	185.1
Study period temperature (C)	5.4	5.2	8.5	15.2	17.5	21.4	23.4	23.5	18.7	12.8	11.8	7.9	15.6
Average temperature (C)	3.8	5.4	9.6	13.8	17.7	21.3	23.1	22.7	19.8	14.3	9.7	5.4	13.9

Private forest harvesting in this region began in the late 1800's (Van Lear, et al, 1995). By 1900, standing forest stocks had been reduced from approximately 18,000 to 3,000 board feet per acre (Ayres and Ashe, 1904). Mountain farming became widespread by the early 1900's. Marked increases in soil erosion and stream sedimentation occurred at this time (Leigh, 1996). The USDA Forest Service incorporated vast portions of the southern Appalachians, including the study watersheds, into the National Forest System during the 1930's to facilitate restoration and sustainable management of the forests in this region.

Methods

Stream Sampling

We installed stream-gauging stations on each stream during spring, 2001 and measured stage and discharge (Marsh McBirney Flowmate 2000 Portable Flow Meter) weekly and during storm events according to standard USGS methods (Buchanan and Somers, 1969). American Sigma 900MAX (TM) automated pumping samplers and stage recorders were co-located at each gauging site. These were maintained on a weekly basis. We programmed the samplers to log stream stage, control sampling regime, and to collect water samples. Stream stage was logged on 5 to 15 minute intervals, depending upon stream flow responsiveness to precipitation, with submerged pressure transducers. We validated the stage readings weekly by manually surveying stream stage to survey monuments. The stage records were processed with stage discharge rating curves to construct stream flow hydrographs (Figure 2a).

Each sampler could draw 24 samples via a fixed-point inlet anchored to each streambed. The samplers drew a 750ml sample under two discreet sampling regimes, baseline conditions and storm flow conditions. The baseline regime collected samples on a flow proportional basis, such that sampling frequency increased with flow. The storm flow regime sampled on a time proportional basis during the rising limbs of hydrographs and reverted to the flow proportional basis during the recession limbs. During baseline sampling, the samplers typically gathered two samples per day. During storm flow sampling, the samplers typically gathered eight to fifteen samples during the rising limb of the storm flow hydrograph with the remaining samples collected during the recession limb. This allowed us to fully characterize storm event and seasonal trends (Riedel, et al, 2003; Figure 2b) in TSS.

We tested for bias in the water quality samples by using a DH-48 depth-integrated sampler (FISP, 1965). We gathered depth-integrated samples weekly in accordance with Thomas (1985). We compared these to simultaneously pumped samples and found the constituent concentrations in the samples obtained by pumping through the fixed-point inlets consistent with those obtained from the depth-integrated samples.

We conducted this sampling regime for 17 months, during the period of March, 2001 – July, 2002. We analyzed the data for the one-year period of June, 2001 - June, 2002 because the first few months of data represent the calibration phase of this study during which we debugged the samplers and refined our methodologies. We gravimetrically analyzed the total volume of the samples for total suspended solids (TSS) by filtration to 1.5 μm as given USGS (1978).

Data Analysis

We paired TSS data with the corresponding discharge at the time of sampling. Riedel, et al (2003) found, due to the highly variable nature of TSS, these were not simply related to discharge on the study streams (with the exception of a weak dependence of TSS on Q for Reed Mill Creek). Visual inspection of the TSS data indicated that a simple linear regression (SLR) was not appropriate (Figure 3). Indeed, the data from all of the study sites, especially Pounding Mill Creek, exhibit clustering that suggest the data are sampled from different populations. Attempting to force the TSS into SLR models would violate two primary assumptions of SLR namely; 1) the data are normally distributed and 2) the data are sampled from the same population. This is important because it is common practice in water quality evaluations to construct TSS rating curves from limited datasets; such that loading or concentrations may be predicted from stream flow (Rosgen, 1980). Some of the variability of TSS is explained by seasonal differences in TSS loading and concentrations however; even when analyzed on a seasonal basis, TSS were extremely variable with discharge (Riedel, et al, 2003).

When the data are viewed on a storm event basis, strong hysteresis becomes apparent in the data (Figure 4a). As Dinehart (1997) observed, "Discharge and instantaneous sediment concentration may not have a stationary relation during a single storm flow. The tendency for sediment concentration to have different values at identical stream discharges (a "hysteresis" effect) is the primary drawback to application of transport curves during storm flow." This hysteresis greatly complicates the analysis of the water quality data for single storm events as well as for large data sets. A typical rating curve of TSS regressed on discharge for a single storm event on Roach Mill Creek reveals the importance of the hysteresis in these data (Figure 4b). While a log-transformation normalized

the TSS data for the entire event, all of the rising limb data would be greatly underestimated by the regressed mean function while the recession limb data would be significantly overestimated.

We addressed the above concerns by filtering all of the data according to whether the samples were pumped during the rising or recession limbs of storm flow hydrographs, the hydrograph regime, dQ/dt. We computed dQ/dt as the difference in stream flow over three consecutive stream stage logging intervals. We then converted dQ/dt to percentage change in hydrograph slope. Using a trial-and-error approach, we found that a one percent threshold for dQ/dt most consistently differentiated hydrograph regime. Larger thresholds (steeper changes in hydrograph slope) filtered out many of the data that were still part of small storm events and hysteretic in nature. Smaller thresholds (flatter portions of the hydrographs) included baseflow data from between storm events that were not hysteretic in nature. We categorized the filtered data into hydrograph regime as follows;

Percent change in slope	Hydrograph regime
$dQ/dt > 1\%$	Rising Limb
$-1\% < dQ/dt < 1\%$	Baseflow
$dQ/dt < -1\%$	Recession Limb

For example, all of the data on the rising limb on the hydrograph in Figure 4a were sampled when dQ/dt was greater than one percent. Similarly, all of the data on the recession limb of the hydrograph of Figure 4a were sampled when dQ/dt was less than negative one percent. These data were filtered into rising limb and recession limb stream flow regime categories respectively, and analyzed separately.

We applied additional filtering to data from Pounding Mill Creek because it was evident that there are two distinct TSS transport regimes in Pounding Mill Creek (Figure 3). The relationship between TSS concentrations with discharge change dramatically at approximately 20 l/s. Riedel, et al (2003) monitored the movement of sand formations and bed material along the streambed of Pounding Mill Creek and found the sand dune formations in this streambed to be quite dynamic. We speculate that the streambed mobilizes at the threshold discharge of approximately 20 l/s, completely changing the transport regime of this channel. Thus, we analyzed the data separately for flows above and below this 20 l/s threshold.

Due to the statistical distribution and broad magnitudes of TSS and discharge, it was necessary to employ power based regression analyses to develop the TSS regression analyses on discharge. Equations take the general form;

$$TSS = b_0 Q^{b1},$$

$$TSS = TSS\ (mg/l),$$

$$Q = discharge\ (l/s).$$

where b_0 corresponds to the intercept and b_1 corresponds to slope in the equivalent SLR model;

$$\log(TSS) = \log(b_0) + b_1 \operatorname{Log}(Q)$$

Results

The results of the TSS regressions on discharge were significant for each of the study streams (Table 3, following page). The TSS regressions for Roach Mill and Addie Branch were unique on the rising limbs and recession limbs of the hydrographs. The slopes of the regressions for the rising limb data were markedly steeper ($p < 0.01$) than they were for the recession limb data (Figure 5). While TSS concentrations increase steadily with discharge during the rising limb of hydrographs on these streams, they decline suddenly with the passage of the hydrograph peaks.

The relationships between TSS concentrations and discharge on Reed Mill Creek were similar during the rising limb and recession limb (Figure 5) hence, these data were combined to generate a single regression relationship between TSS and discharge (Table 3). On Pounding Mill Creek, the relationships between TSS and discharge were similar during the rising and recession limbs of hydrographs however, unique regressions were required for flows less than 20 l/s and flows greater than 20 l/s. When flows exceed the threshold of 20 l/s, the regressions relating TSS to discharge change dramatically (Figure 5). For rising and recession limb flows under 20 l/s, TSS

concentrations are quite high and increase very rapidly with discharge, as compared to the other study streams. As flows pass the 20 l/s threshold, TSS concentrations decline abruptly. With flows increasingly exceeding the 20 l/s threshold, TSS concentrations being to increase again yet, at a slower rate than that for flows below 20 l/s.

Discussion and Summary

The transport and loading of TSS varies significantly amongst these study streams - despite identical geologic and climatic settings and very similar watershed land uses. Riedel, et al (2003) found that water quality (defined as TSS) on Reed Mill and Pounding Mill Creeks was degraded as compared to Addie Branch and Roach Mill. Degradation of Reed Mill Creek was attributed to private residential development, representing three percent of the watershed area whereas degradation of water quality in Pounding Mill Creek was caused by erosion of sediments from an unpaved gravel road that followed the creek for nearly its entire length.

Table 3: Regressions of TSS concentrations (TSS in mg/l) against discharge (Q in l/s), by hydrograph regime, for each study stream. Significant regression results shown in bold. Regression analysis of Pounding Mill Creek data was conducted separately on flows above and below 20 l/sec.

Stream	Q Criteria	Hydrograph Regime	TSS Rating Equation	r^2	Significance	Degrees of freedom
Roach	**N/A**	**Rising Limb**	**$TSS = 0.16\ Q^{1.22}$**	**0.28**	**$p < 0.001$**	**76**
Roach	**N/A**	**Recession Limb**	**$TSS = 0.31\ Q^{0.90}$**	**0.18**	**$p < 0.001$**	**74**
Reed	N/A	Rising Limb	$TSS = 0.13\ Q^{1.19}$	0.65	$p < 0.001$	99
Reed	N/A	Recession Limb	$TSS = 0.45\ Q^{0.90}$	0.39	$p < 0.001$	101
Reed	**N/A**	**Combined**	**$TSS = 0.25\ Q^{1.04}$**	**0.51**	**$p < 0.001$**	**202**
Addie	**N/A**	**Rising Limb**	**$TSS = 0.41\ Q^{1.26}$**	**0.40**	**$p < 0.001$**	**62**
Addie	**N/A**	**Recession Limb**	**$TSS = 0.87\ Q^{0.67}$**	**0.21**	**$p < 0.001$**	**98**
Pounding Mill	$Q < 20$ l/s	Rising Limb	$TSS = 19.47\ Q^{1.38}$	0.64	$p < 0.001$	76
Pounding Mill	$Q < 20$ l/s	Recession Limb	$TSS = 14.70\ Q^{1.22}$	0.65	$p < 0.001$	79
Pounding Mill	**$Q < 20$ l/s**	**Combined**	**$TSS = 16.86\ Q^{1.27}$**	**0.63**	**$p < 0.001$**	**155**
Pounding Mill	$Q > 20$ l/s	Rising Limb	$TSS = 0.054\ Q^{1.13}$	0.43	$p < 0.001$	71
Pounding Mill	$Q > 20$ l/s	Recession Limb	$TSS = 0.50\ Q^{0.60}$	0.13	$p = 0.0012$	75
Pounding Mill	**$Q > 20$ l/s**	**Combined**	**$TSS = 0.15\ Q^{0.89}$**	**0.28**	**$p < 0.001$**	**148**

The strongly hysteretic behavior of TSS during storm events on Addie Branch and Roach Mill Creeks suggests these creeks are in a supply limited sediment loading regime. This means the sediment transport capacity of these streams exceeds available sediment supplies. Conversely, the consistent nature of TSS with storm flows on Reed Mill and Pounding Mill Creeks indicates these streams are in a transport limited sediment loading regime. For a given discharge, these streams move sediment at their transport capacity. Hence, Reed Mill and Pounding Mill Creeks must have access to supplies of sediment that are not available to Addie Branch and Roach Mill Creeks.

Total suspended solids data from four forested, southern Appalachian streams, were highly dynamic. Simple regression analyses of these data against discharge is inappropriate because the data do not come from the same sample populations. While Riedel, et al (2003) identified that some of the variability in the data were due to seasonal differences, the majority of the variability on the minimally impacted Addie Branch and Roach Mill Creeks are caused by hysteretic supply and transport processes. Conversely, hysteresis was not found in the dependence of TSS data discharge in Reed Mill and Pounding Mill Creeks, two streams having elevated sediment supplies. Further, TSS and Qs rating curves are discontinuous at a threshold of approximately 20 l/s on Pounding Mill Creek. Riedel, et al (2003) speculated that this was caused by a highly mobile bed forms in this stream..

This hysteretic behavior of TSS with discharge is not atypical. Numerous authors have reported similar hysteretic sediment transport behavior with discharge (Glysson, 1987). Rosgen (1980) provides generalized examples of addressing hysteresis in suspended sediment transport data for streams with forested watersheds. Sawada and

Johnson (1997) reported on hysteretic sediment transport in Alaskan Rivers and Dinehart (1997) provides a summary of literature and observations of hysteretic sediment transport in mountain streams.

Conclusions

TSS transport dynamics in Roach Mill and Addie Branch Creeks exhibit strong hysteresis across storm flow hydrographs. TSS and Qs increases dramatically during the rising limb of hydrographs on these streams. As the storm flow peak passes through these streams and flow enters a storm flow recession limb regime, TSS decrease rapidly, despite the continued existence of high flows.

Conversely, in Reed Mill and Pounding Mill Creeks (during flows less than 20 l/s), TSS during the rising limb and recession limb of hydrographs are similar. TSS increase proportionately with flow during rising limb. As a storm flow peak passes and the streams enter recession limb dynamics, TSS decrease proportionately. As flows in Pounding Mill Creek increase beyond the threshold of 20 l/s, TSS concentrations drop suddenly.

The commonly applied approach of using simple regression analysis to develop TSS rating curves is insufficient to accurately identify and understand water quality dynamics in these mountain streams.

Acknowledgements

This research was supported by funding received from the USDA Forest Service, Chattooga River Large Scale Watershed Restoration Project, the USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory and by the National Aeronautical Space Administration, Land Cover Land Use Change Program. The authors thank reviewers for their valuable insights which improved this manuscript. Gratitude is extended to Charles "Chuck" Marshall, Patsy Clinton, Kate Seader and Brian Phillips for invaluable support efforts in maintaining stream samplers and processing water quality data.

Literature Cited

Ayres, H.B. & W.W. Ashe. 1904. Land Classification Map of part of the Southern Appalachian Region. Plate XXXVII in USGS Professional Paper no. 37.

Buchanan, T.J. & W.P. Somers. 1969. Discharge measurements at gauging stations. Chpt. A8 In: Techniques of water-resources investigations of the United States Geological Survey. U.S.G.S. Reston, VA

Dinehart, R.L. 1997, Sediment Transport at Gaging Stations near Mount St. Helens, Washington, 1980-90, Data Collection and Analysis: USGS Professional Paper 1573, 111 p.

EPA. 2001. Total Maximum Daily Load (TMDL) for sediment in the Middle/Lower Chattooga River Watershed, GA. April 30.

FISP. 1965. Operating instructions for US DH-48 suspended-sediment hand sampler. Federal Interagency Sedimentation Project Report J, May.

GGS. 1976. Geologic Map of Georgia (1:500,000). Georgia Geologic Survey, University of Georgia, Atlanta.

Glysson, G.D. 1987. Sediment-transport curves. US Geological Survey Open File Report 87-0218, Reston, VA. Pp 47.

Jackson, C.R., G. Sun, D. Amatya, W.T. Swank, M.S. Riedel, J. Patric, T. Williams, J.M. Vose, K. Trettin, W.M. Aust, S. Beasely, H. Williston, and G. Ice. 2004. Fifty years of forest hydrology research in the southeast - Some lessons learned. *A Century of Forest and Wildland Watershed Lessons*, J. Stednick and G. Ice, Editors. Society of American Foresters.

Leigh, D. S. 1996. Soil chronosequence of Brasstown Creek, Blue Ridge Mountains, USA. Catena, 26:99–114.

Pruitt, B.A, D.L. Melgaard, H. Howard, M.C. Flexner & A.S. Able. 2001. Chattooga River watershed ecological/sedimentation project. In Proc. 7th Federal Interagency Sedimentation Conf., March 25–29, Reno, NV.

Riedel, M.S., J.M. Vose & D.S. Leigh. 2003. The road to TMDL is paved with good intentions - Total Maximum Daily Loads for a Wild and Scenic River in the southern Appalachians. Proc. The Second Conference

on Watershed Management to Meet Emerging TMDL Environmental Regulations, Amer. Soc. Ag. Engr., Albuquerque, NM, Nov. 18 - 12.

Rosgen, D.L. 1980. Total Potential Sediment. Chpt VI in *An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook)*. Unites States Environmental Protection Agency. EPA-600/8-80-012, August.

Sawada, M. & P.G. Johnson. 1997. Hysteresis in the relation between suspended sediment concentration and discharge, Slims River, Yukon Territory, Canada, 1994. In Program and abstracts : 27th Arctic Workshop, Department of Geography, University of Ottawa, February 27-March 2, 1997. Edited by Antoni G. Lewkowicz and Steven V. Kokelj. Pp 200-202.

Swift, L. W., G. B. Cunningham & J. E. Douglass. 1988. Climatology and Hydrology. In Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta, W. T. Swank and D. A Crossley, Jr., eds. Springer Verlag New York, Inc., New York, NY.

U.S.G.S. 1978. Laboratory Analysis – Suspended-Sediment Concentration. Section 3.F.2.a. in Chapter 3 – Sediment of the National Handbook of Recommended Methods for Water Data Acquisition. United Stages Geological Survey, Office of Water Data Coordination, Reston, VA.

Van Lear, D.H., G. B. Taylor, & W.F. Hanson. 1995. Sedimentation in the Chattooga River Watershed. Clemson University, Department of Forest Resources Technical Paper No. 19.

Wallace, J. Bruce, J.R. Webster, G.J. Lugthart, K. Chung & B.S. Goldowitz. 1991. Export of fine organic particles from headwater streams: Effects of season, extreme discharges and invertebrate manipulation. Limnol. Oceanogr., 36 (4): 670 – 682.

Figure 1: General study site location in the southern Appalachian Mountains. Total relief is approximately 1,200 meters.

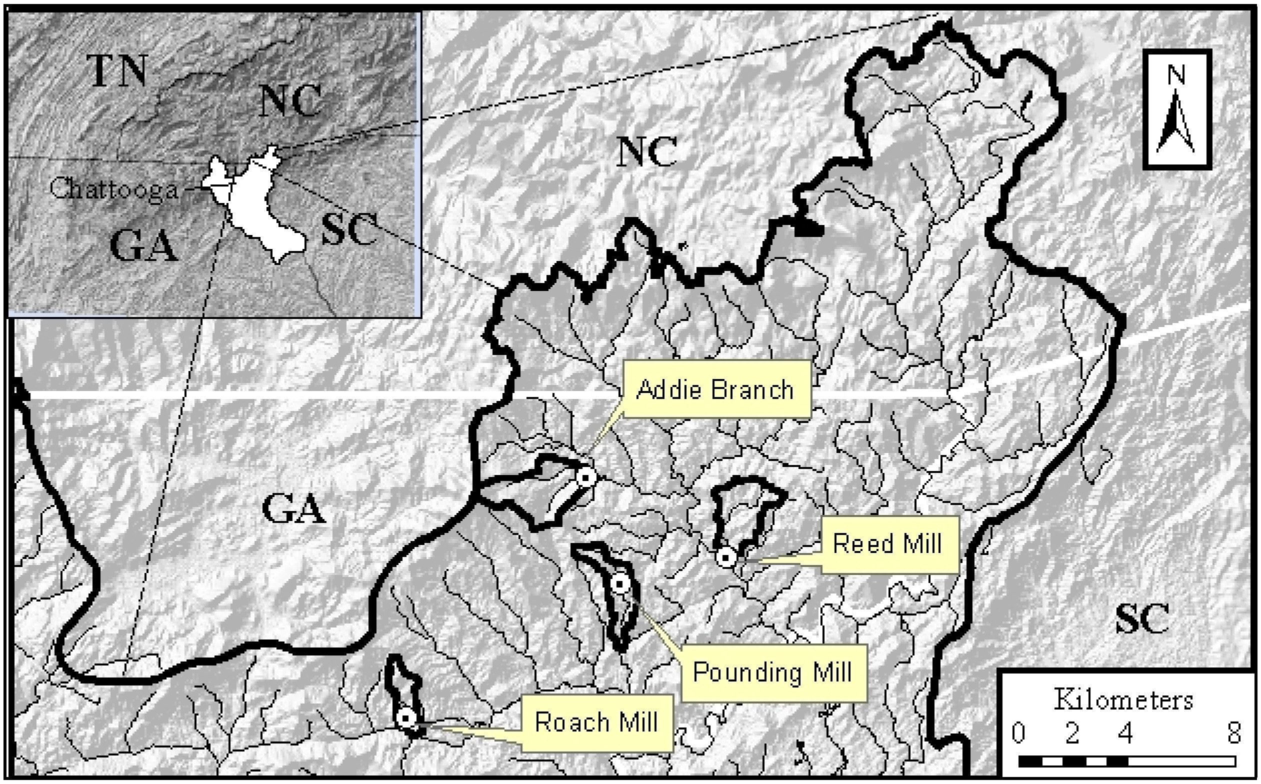

Figure 2a: Study duration stream flow hydrographs from each stream (adapted from Riedel, et al, 2003).

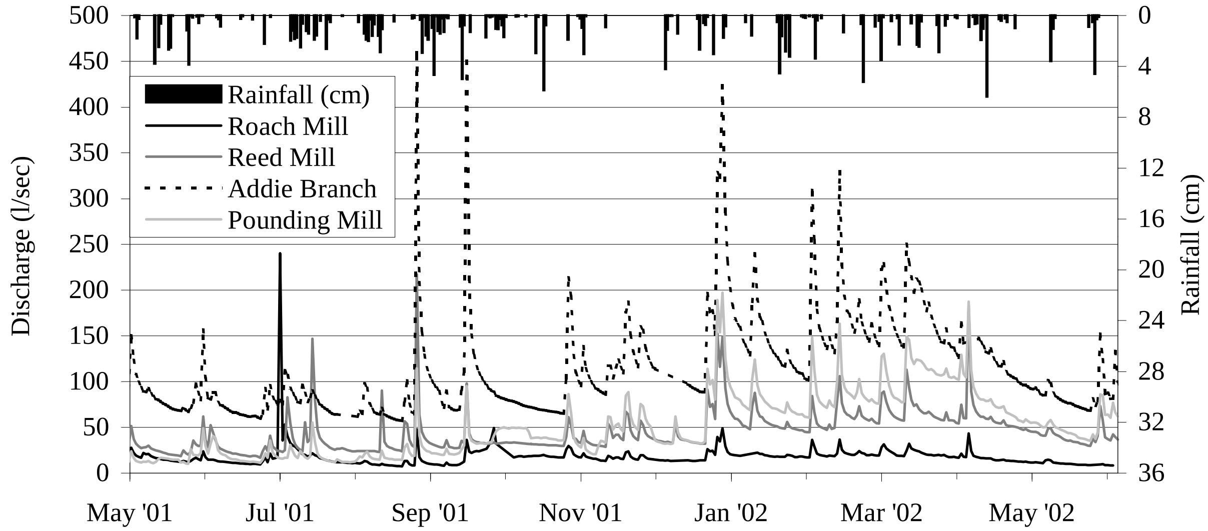

Figure 2b: Seasonal variability of TSS in study streams. Third order polynomial regressions are all significant ($p < 0.01$). Differences between regressions are indicated by labels in parentheses shown in the figure legend (reprinted from Riedel, et al, 2003).

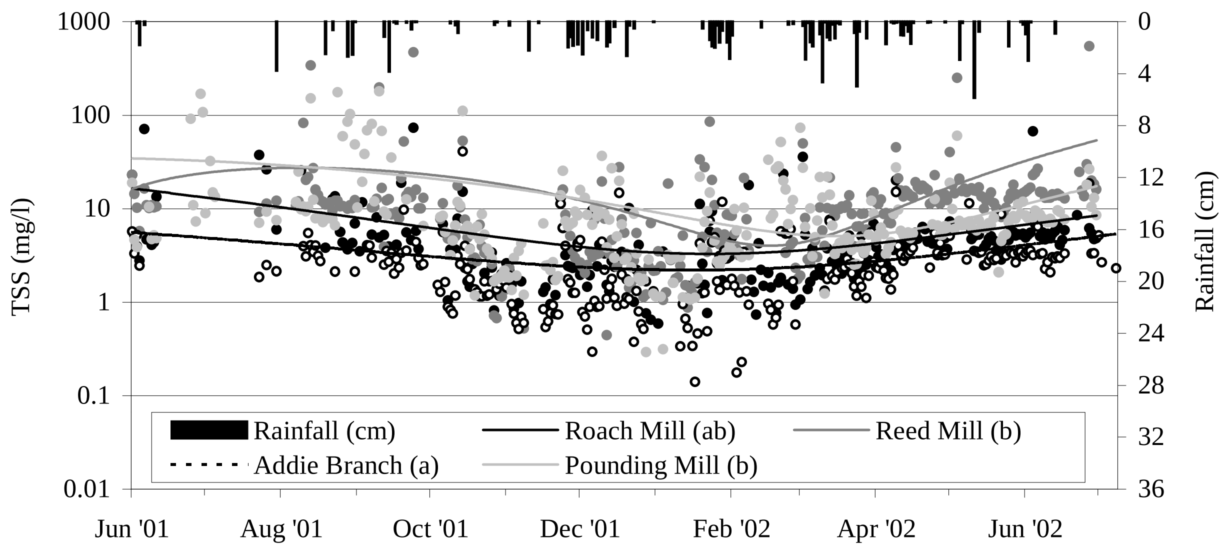

Figure 3: TSS plotted against stream flow discharge for each study stream. Only the relationship for Reed Mill Creek is significant (p<0.01) (adapted from Riedel, et al, 2003).

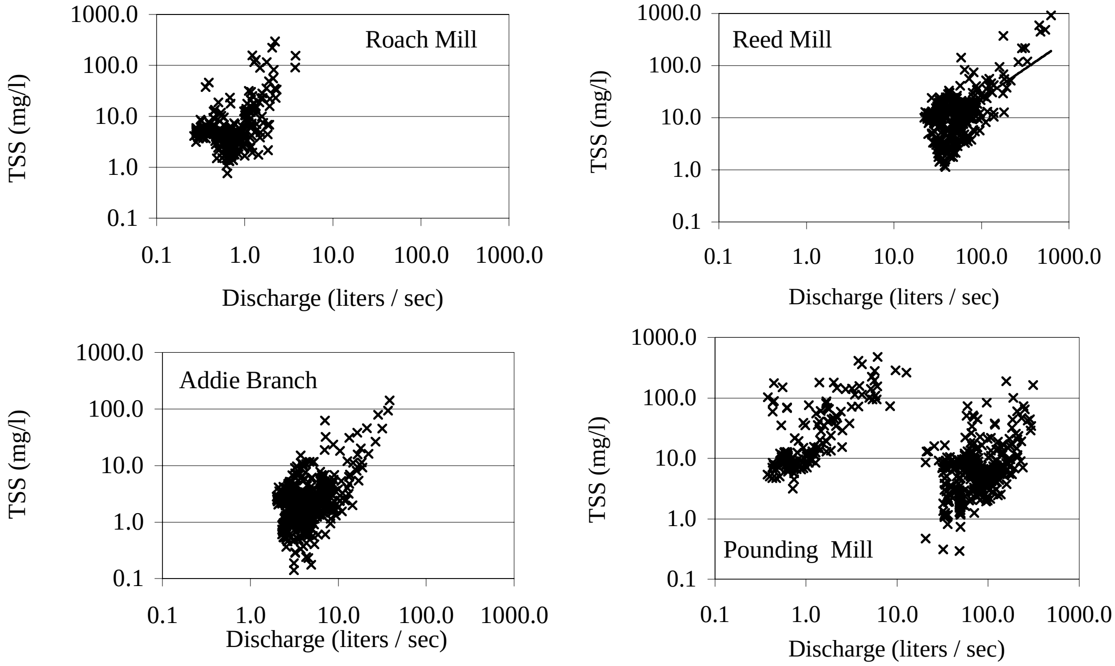

Figure 4a: Stream flow hydrograph and sedigraph for the single storm event of June 6, 2001 on Roach Mill Creek. TSS concentration (mg/l) is indicated by bubble size and adjacent numerical labels. The hysteretic behavior of TSS is manifested as significantly higher TSS concentrations for a given discharge during the rising limb as compared to that during the recession limb.

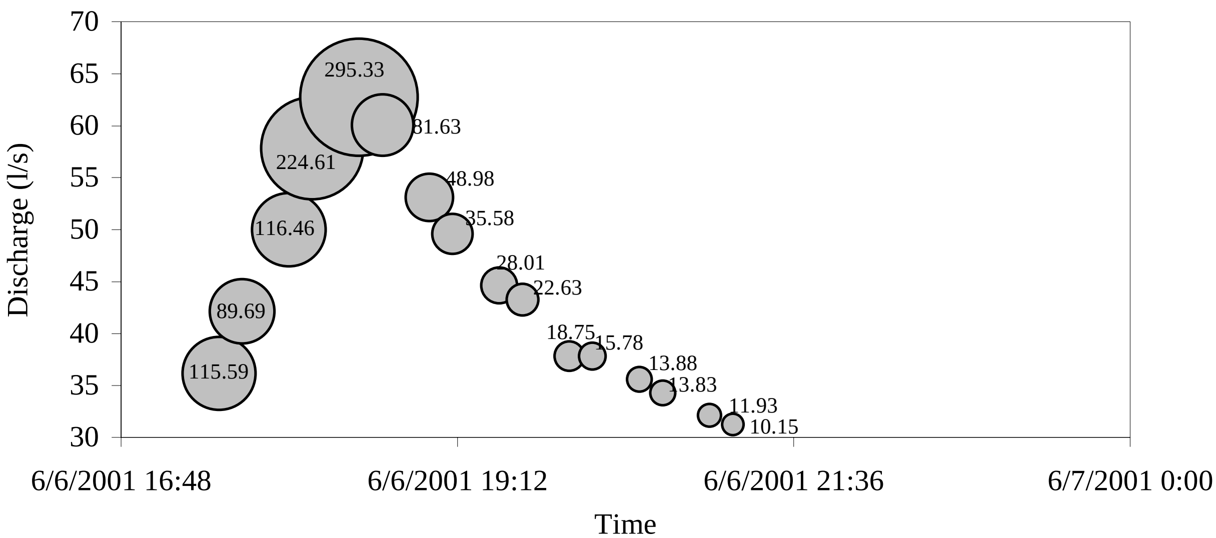

Figure 4b: TSS data plotted against discharge for June 6, 2001 storm on Roach Mill Creek (from Figure 4a). The military time stamp for each sample is indicated by the adjacent numerical labels. While the fit regression equation is significant, it is actually based upon data from two distinct populations.

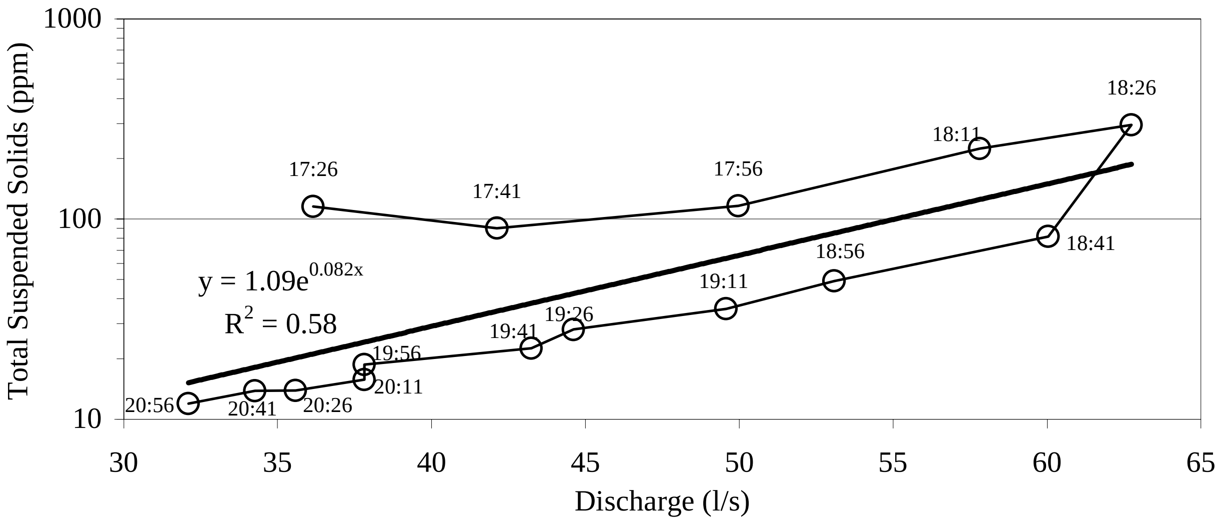

Figure 5: Rising and recession limb TSS trends with discharge.