THE ROAD TO TMDL IS PAVED WITH GOOD INTENTIONS - TOTAL MAXIMUM DAILY LOADS FOR A WILD AND SCENIC RIVER IN THE SOUTHERN APPALACHIANS

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ABSTRACT

We monitored water quality in the Chattooga River Watershed (NE Georgia, NW South Carolina, and SW North Carolina) to compare sediment TMDLs with observed water quality. A judicial consent decree required the EPA to establish TMDLs in one year. The EPA was unable to fully characterize the sediment budgets of these streams and consequently issued phased sediment TMDLs which can be revised "…because information on the actual contributions of sediment to the Chattooga River Watershed from both point and nonpoint sources will be much better characterized in the future." The EPA listed streams as sediment impaired based upon aquatic indicator species data and relied upon total suspended solids (TSS) data and modeling to establish the sediment TMDLs. We found that TSS concentrations do not reflect mineral sediment concentrations because the organic and mineral components of TSS were highly variable between streams. TSS in forested streams could get quite high and were largely organic whereas TSS in streams more heavily impacted by land use change and roads were mostly mineral sediment. TSS and mineral sediment in a stream listed as being sediment impaired were significantly lower than streams listed as being only threatened. We also monitored bed material transport and sampled sediment mineralogy on one of our study streams. The sand and fine gravel in this stream were very dynamic. In-stream scour and deposition occurred frequently. No in-stream deposition occurred during small events; when road runoff was negligible. During larger events, road runoff and in-stream sediment deposition occurred. This suggests that the existing sediment TMDLs may not address the causes of sediment impairment of the aquatic ecosystems. The EPA's issuance of phased sediment TMDLs was insightful because it acknowledged our lack of understanding of the impacts of land usage and sediment dynamics on streams in the Chattooga River watershed.

KEYWORDS. TMDL, TSS, water quality, sedimentation, organic matter, forest roads.

INTRODUCTION

The Chattooga River Watershed encompasses 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 Chattooga River is a federally designated Wild and Scenic River and is one of few large unregulated rivers in the United States. However, excessive sedimentation is a significant threat to the aquatic resources of the Chattooga River (EPA, 2001). More than 80% of this sediment is sourced from unpaved rural roads (Van Lear, et al 1995).

The EPA has established Total Maximum Daily Loads (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

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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.

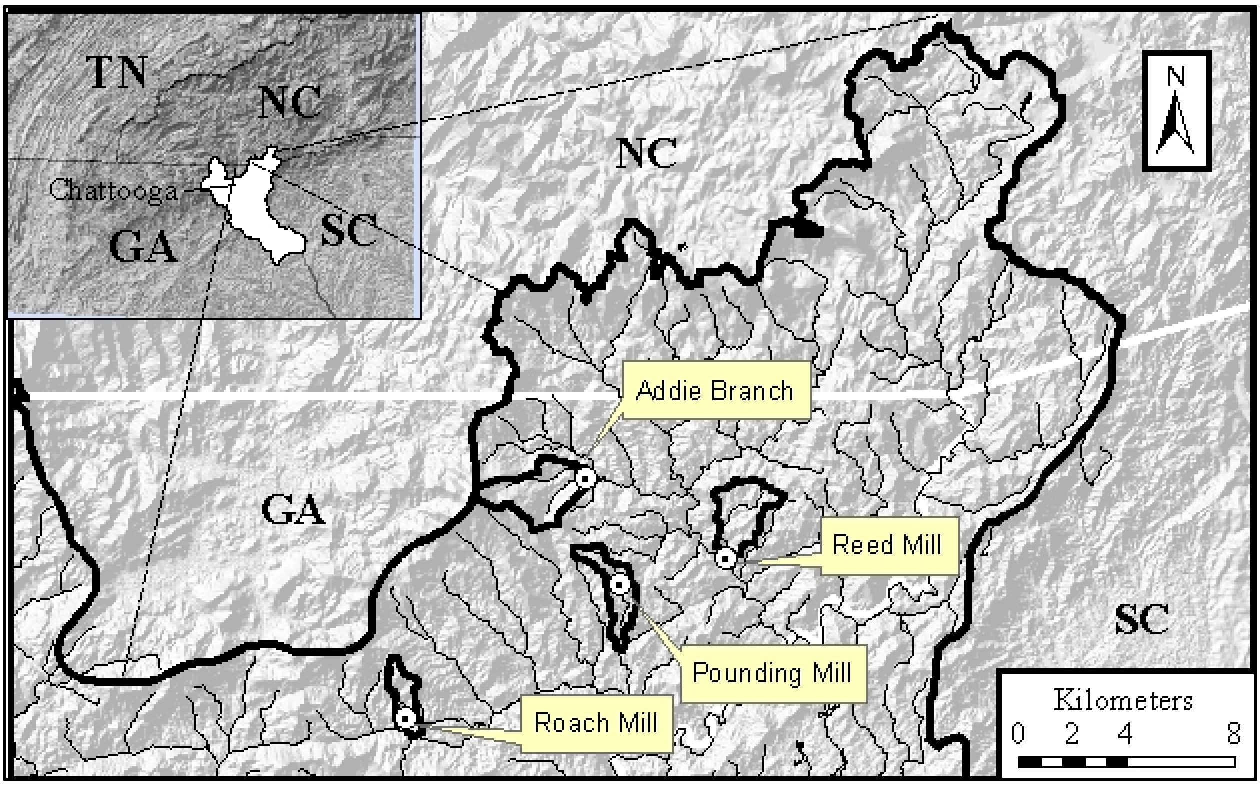

Figure 1: Chattooga River Watershed Location Map.

The Chattooga River Watershed is 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. 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 have been intensively monitoring water quality and streamflow on four tributaries of the Chattooga River. In this study we compare the results from intensive, long-term monitoring compare to those arrived at through the TMDL process. We anticipate that our results will differ from those of the EPA because the EPA employed total suspended solids (TSS) data as a surrogate for mineral sediment in their determination of sediment impacts (Pruitt, et al, 2001).

Site Description

We selected four tributaries, all of which were reviewed in the TMDL process, of the Chattooga River as study streams for this project, Table 1. The watersheds, except for a small part of Reed Mill, have been part of the US Forest Service National Forest System since the 1930's.

Table 1: Summary of characteristics for study streams.

Stream	303 (d) Listing Status	Watershed Size (km^2)	Mean Elevation (m)	Mean Slope (%)	Aspect	Samples (n)
Roach Mill	Impaired	0.8	712	16	ESE	263
Reed Mill	Threatened	4.4	700	14	S	377
Addie Branch	Unlisted	5.6	925	19	ENE	447
Pounding Mill	Threatened	1.3	706	14	ESE	511

Roach Mill has been identified by the EPA (303(d) list) 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 our 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 the most turbid of the study streams. Three percent of its watershed is privately owned. This land, adjacent to the stream, is agricultural and residential. There are also 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. 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 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

While the bedrock in the Blue Ridge belt is igneous and metamorphic, soils in the study area are derived exclusively from quartz-rich gneiss, mica-shist, and granitic bedrock. The loamy mountain soils are highly erodible when exposed (Van Lear, et al, 1995), but they are not subject to erosion under well-established forest cover.

Elevation and terrain in the southern Appalachians strongly influence climate, soils, and vegetation in the study region. The high precipitation and mild temperatures of the region are representative of the maritime, humid, temperate system of Koppen's climate classification (Swift, et al, 1988). 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). Representative National Weather Service data are summarized in 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 (National Weather Service climate station, Clayton, GA).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
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 (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
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 (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

Ridges and upper elevation south facing slopes tend to be relatively dry while slopes with northern aspects are moist and cool (Van Lear, et al, 1995). 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 reduced growing seasons.

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). To restore land quality, the USDA Forest Service incorporated vast portions of the southern Appalachians, including the study watersheds, into National Forests during the 1930’s.

METHODS

Discharge Measurement

We installed stream-gauging stations on each stream during spring, 2001. We measured stage and discharge weekly and during storm events according to standard USGS methods (Buchanan and Somers, 1969). We used these data to develop stage-discharge rating curves for each site.

Stream Sampling

We installed an automated pumping sampler and stage recorder at the gauging sites. These were maintained weekly. We programmed the samplers to log stream stage, control sampling regime, and to collect water samples. We also programmed stage discharge rating curves into each sampler which then tracked streamflow. Water surface elevation (stage) was measured with submerged pressure transducers affixed to steel rods, and stage was recorded on 5 to 15 minute intervals, depending upon the storm flow hydrograph characteristics of each stream. We validated the stage readings weekly by surveying stage to local benchmarks. Each sampler was able to pump and store 24 water samples via a fixed-point inlet that was attached to the steel rod in 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.

We checked our water quality data for bias in sampling via the fixed-point inlets by using a DH-48 depth-integrated sampler. We gathered depth-integrated samples weekly according to the methods of Thomas (1985). We compared these to a simultaneously pumped sample and found that, due to the highly turbulent nature of the mountain streams, the pumped samples obtained through the fixed-point inlets did not appear to be different from the depth-integrated samples.

We conducted this sampling regime for 17 months, during the period of March, 2001 – July, 2002. We have 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 TSS (mg and mg/l) by filtration to 1.5 μm as given USGS (1978a). We then analyzed the samples to determine the mineral and organic loading, as given by the USGS (1978b). The samples were burned in a muffler furnace to determine mineral content, as ash free dry weight (mg). Organic matter was estimated as the mass lost to combustion.

Streambed sediment source study

During this study, we noticed sand moving as bedload during low flows and as suspended load during higher flows on the study streams. This was especially true on Pounding Mill Creek when, during storms, overland flow from the roads entered the stream. To characterize bedload transport for Pounding Mill Creek, we installed three transects of scour and deposition pins across the streambed. Each transect consisted of a series of steel pins driven into the streambed, across the entire channel. We placed a freely moving washer on each pin. We set the pins weekly and following storm events during the summer of 2001. To set the pins, we placed the washer on the streambed and surveyed the elevation of the washer. With each return visit, we measured the depth of sediment deposited on top of each washer and how far the washer had fallen from the previous reading. Thus we measured scour depth (ds), deposition depth (dd) and net change in streambed elevation (dd-ds). We monitored the pins from June through October 2001 when leaves collected on the pins and affected sediment transport around them.

Using a triple acid digest of HF, HNO_3, and HCl, we conducted total elemental analysis on samples of the native soil, the roadbed, and streambed sediments to determine the source of sediments in the streambed. Element concentrations were measured by inductively coupled plasma spectrometry by Chemex, Incorporated.

RESULTS

As the 2001 growing season progresses from May through September, there is a decreasing trend in daily mean flow for each of the streams (Figure 2). As the growing season ends in the autumn, daily mean flow begins to increase. Stream flow continues to increase through winter and into early spring of 2002. It then decreases as the 2002 growing season begins.

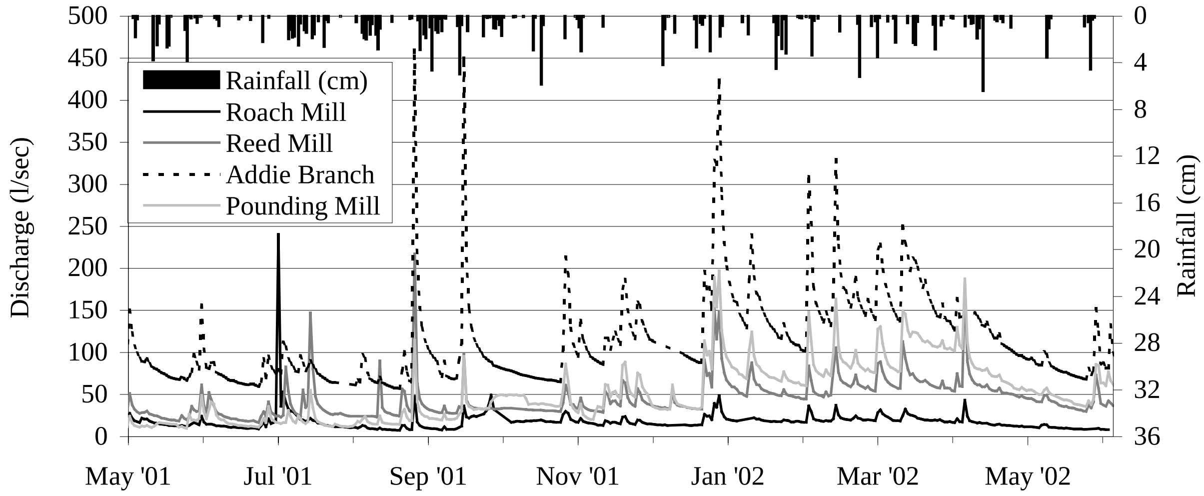

Figure 2: Daily mean flows for each of the study streams.

We plotted mean daily discharge, divided by drainage area, against the frequency of occurrence to illustrate the stream flow regime of each study stream (Figure 3). The stream flow regimes of Roach Mill and Addie Branch are quite similar. The discharge frequency curve of Reed Mill, while similar in shape and slope to those of Addie Branch and Roach Mill, shows significantly lower water yields. Pounding Mill is also similar to Addie Branch and Roach Mill during low flows. However, flow magnitude increases more dramatically as frequency decreases.

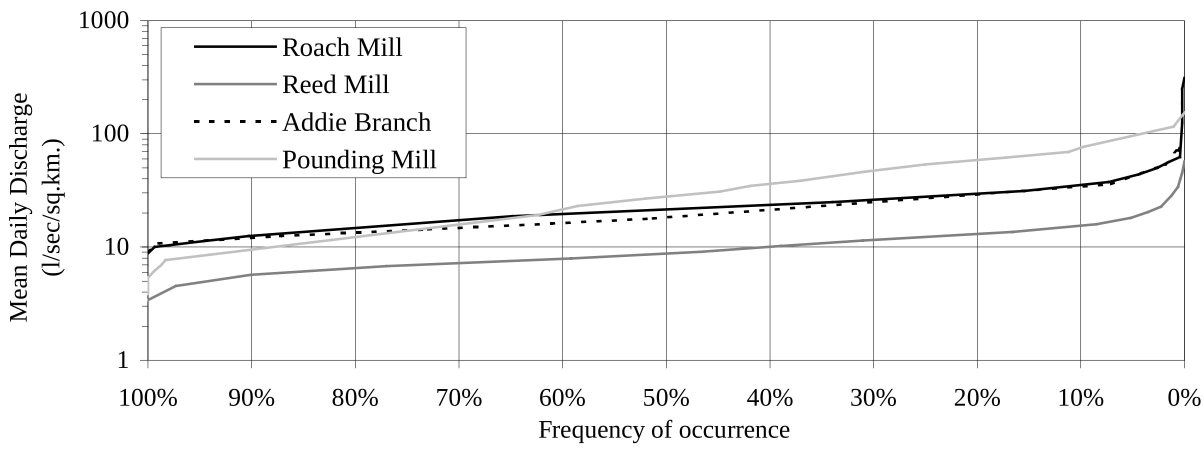

Figure 3: Mean daily discharge frequency curves for each of the study streams.

Time series analysis of mean daily TSS concentrations reveals significant seasonality of TSS on each of the study streams (Figure 4). The seasonality of TSS concentrations is desynchronized from that of streamflow. Peak TSS concentrations occurred in the summer of 2001, while baseline streamflow was at a minimum. TSS then declined going into autumn, as baseline streamflow was increasing. The concentrations of TSS reached minimum values during late winter, when streamflows were highest. TSS levels then increased in late spring and early summer of the following year, as streamflow started to decline. While the seasonal nature of the TSS minima and maxima were the same for each of the study streams, TSS concentrations were not. TSS concentrations on Roach Mill were intermediate between the lowest values on Addie Branch and the highest values on Pounding Mill and Reed Mill. We did not find distinct seasonal trends in the mineral and organic components of TSS.

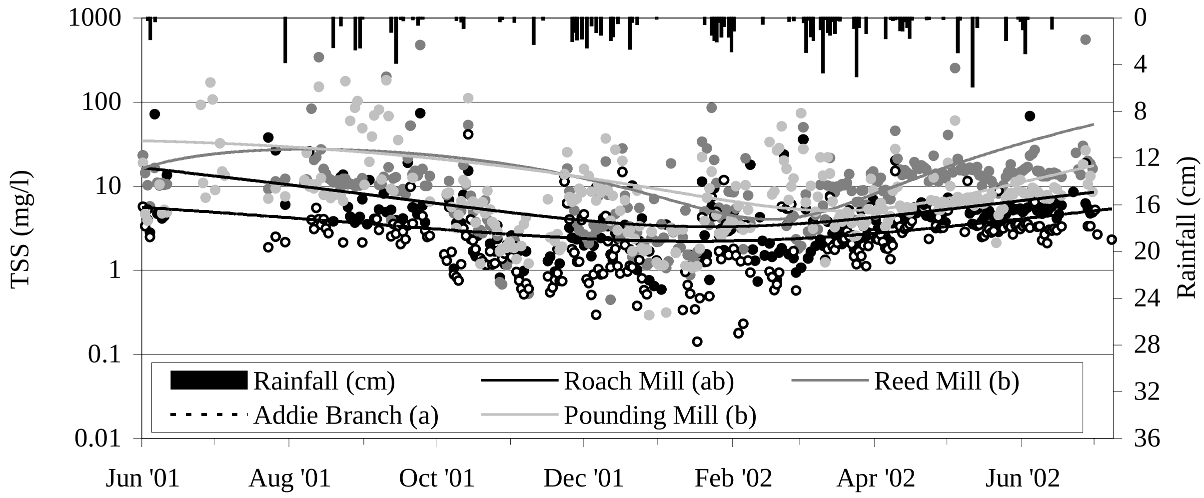

Figure 4: Time series regression (3rd order polynomial) of mean daily TSS. TSS in Addie Branch (a) is lower than that of Reed Mill (b) and Pounding Mill (b) (Difference indicated by lower case letters, alpha = 0.05). Seasonality of maxima and minima are not different.

From TSS rating curves (Figure 5), it is apparent that the only significant relationship (albeit weak) between TSS and discharge was on Reed Mill creek. The data on Pounding Mill Creek reveal a break in TSS concentrations occurring at flows of approximately 12 liters per second. We observed similar patterns when we plotted the mineral, organic and mineral to organic matter ratio of TSS against discharge (data not shown). The data from Pounding Mill Creek again showed a break at approximately 12 liters per second.

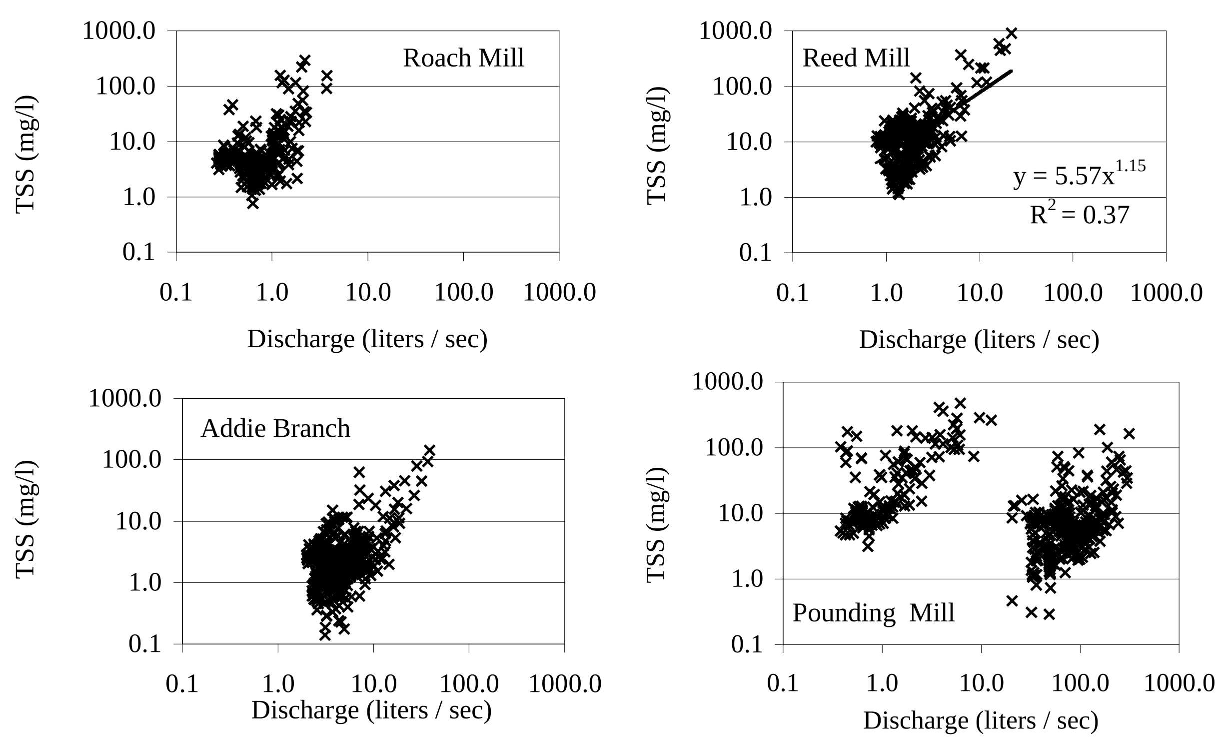

Figure 5: TSS concentrations plotted against discharge for each of the study streams (α=0.05).

TSS concentrations are strongly correlated with the mineral and organic loading (Figures 6 and 7). While TSS increases most dramatically with mineral sediment loading on Addie Branch and Pounding Mill (steepest trendlines), TSS concentrations are less than one half of those on Roach Mill and Reed Mill when mineral loading is low.

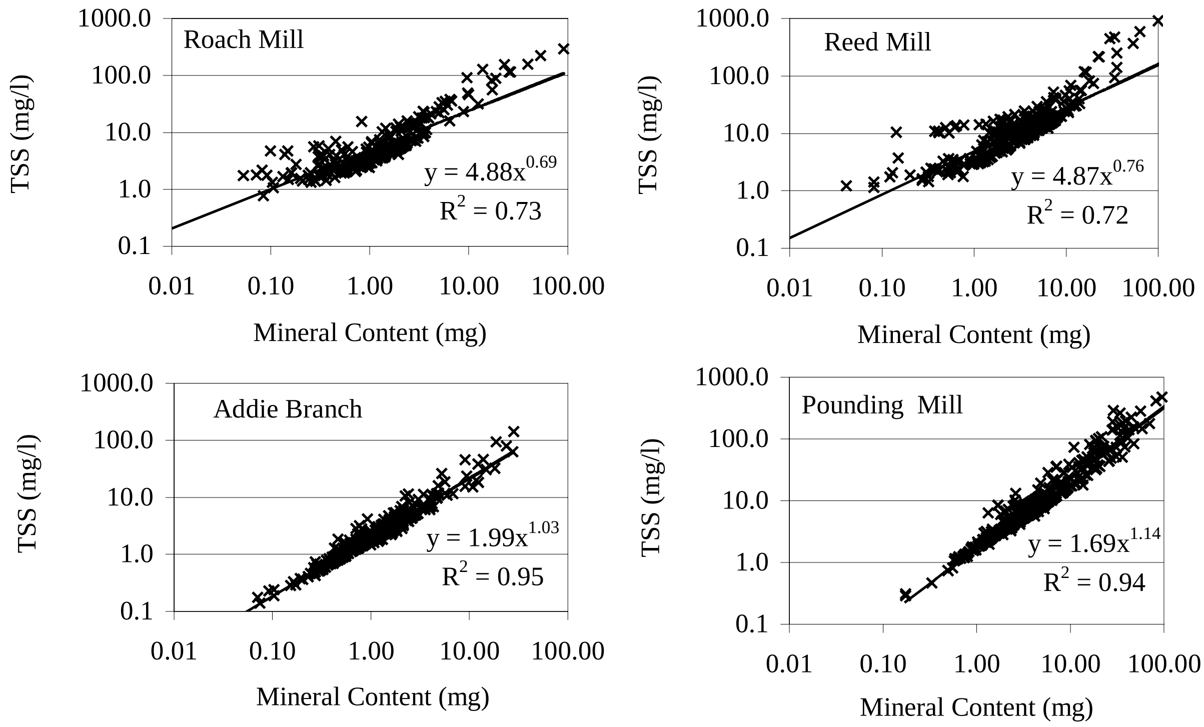

Figure 6: Mineral content of TSS regressed against TSS concentrations for study streams (α=0.05).

The dependence of TSS concentrations on organic loading are similar for each of the study streams (Figure 7). The slopes and intercepts of these regressions are not significantly different.

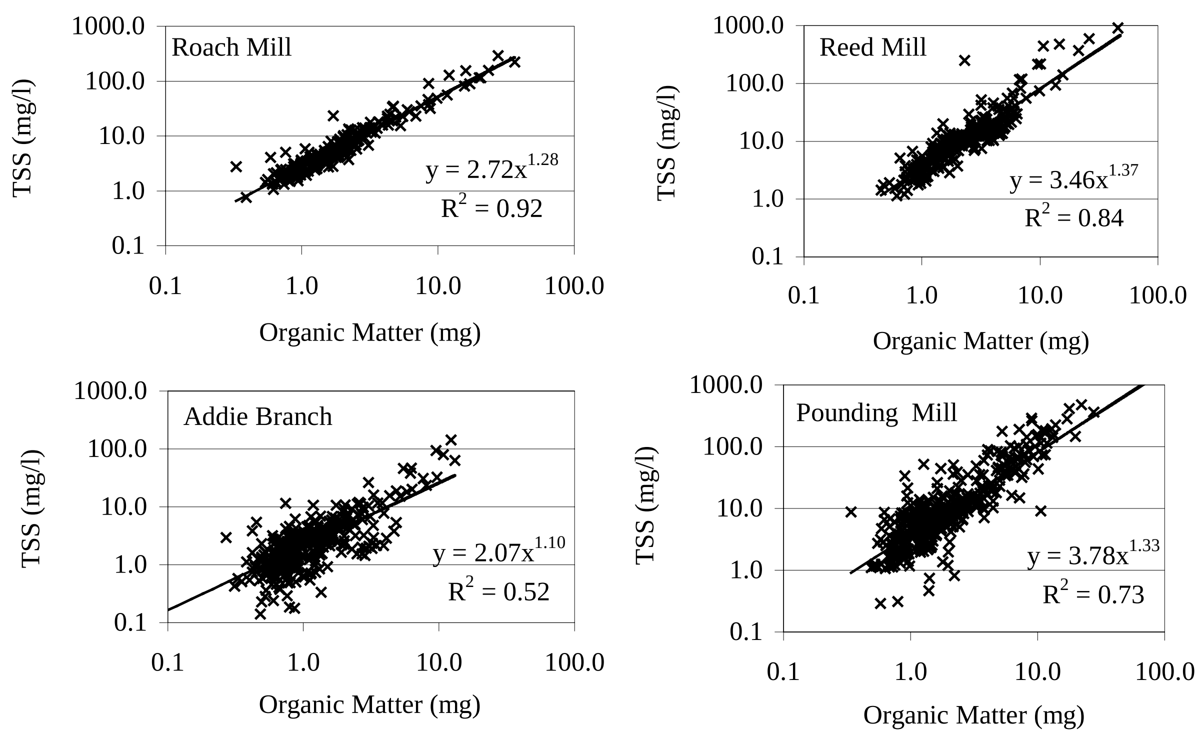

Figure 7: TSS concentration regressed on organic matter for study streams. Regressions are not significantly different (α=0.05).

TSS concentrations are not related to the mineral organic loading ratio in the study streams (Figure 8). Despite log/log transformations, curvature and clustering are evident in the data.

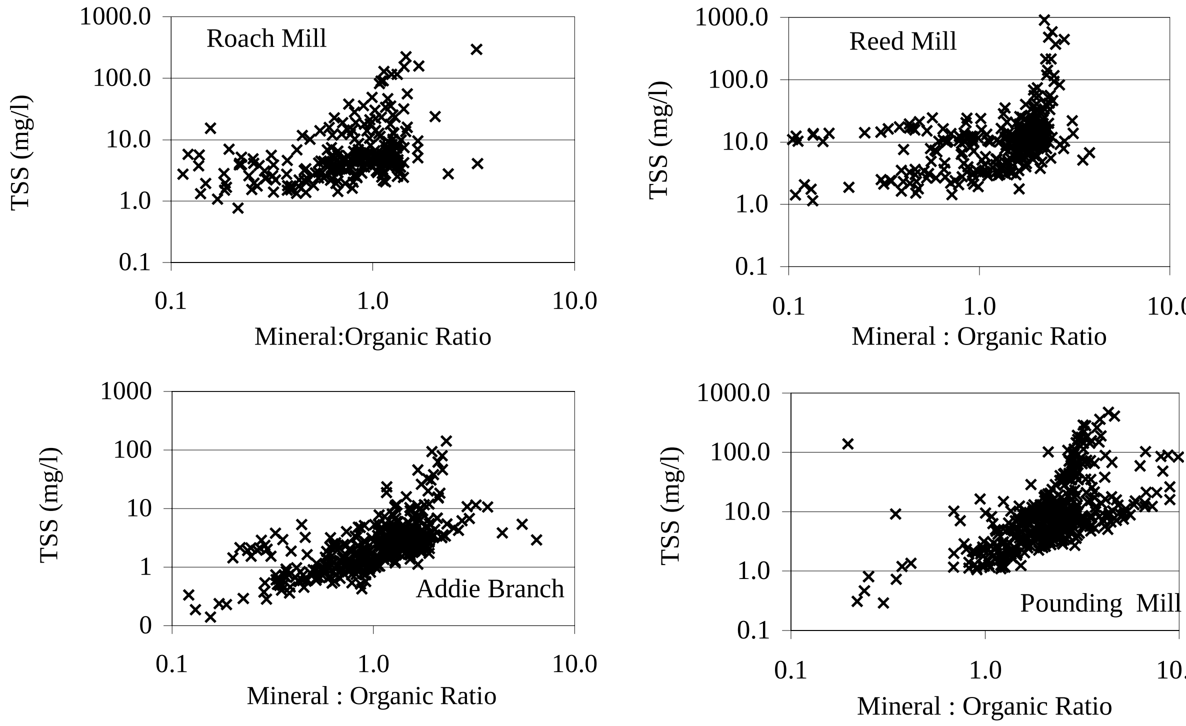

Figure 8: TSS concentration plotted against the mineral:organic ratio for each study stream.

The streambed sediment monitoring revealed that the sand and gravel in the streambed of Pounding Mill Creek were highly mobile. While both deposition and scour took place, net streambed incision of approximately 7 cm occurred from June through September (Figure 9).

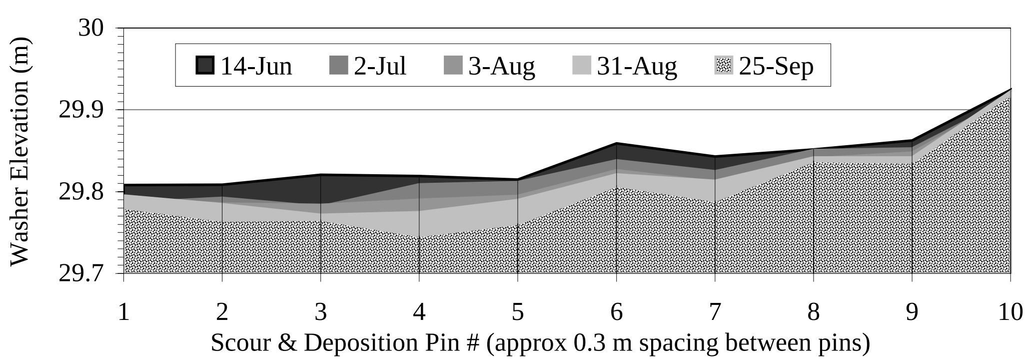

Figure 9: Changes in streambed elevation measured with scour pins on Pounding Mill Creek

The results of the mineralogical analysis of sediments from native soils, the roadbed and streambed show an enrichment of easily weathered calcium and sodium minerals in the streambed relative to the levels found in native soils (Figure 10).

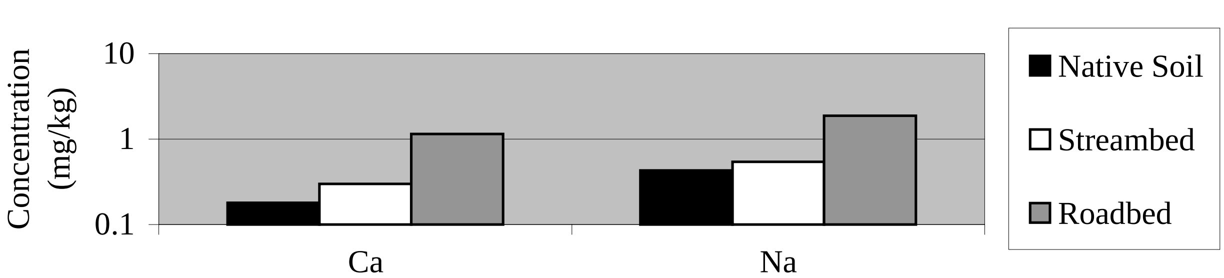

Figure 10: Results of elemental analysis of easily weathered minerals in the Pounding Mill basin.

DISCUSSION

While we found anticipated differences in the hydrologic regimes and water quality of the study streams, none of the water quality parameters we measured were dependent simply upon discharge. The seasonal cycles of stream flow and TSS concentrations are essentially opposites of one another. This suggests that seasonal patterns in stream flow are attenuating TSS concentrations. However, our results show no corresponding cycles in the mineral and organic makeup of the TSS. Rather, the mineral and organic loading are independent of discharge, suggesting that the makeup of TSS in stream flow varies with the passage of each hydrograph. TSS concentrations were strongly dependent upon the loading of mineral and organic sediments; however, this result simply reflects autocorrelation between the data. While results suggest that TSS concentrations may be used as a surrogate variable for estimating mineral and organic loading, TSS concentrations are not related to the mineral : organic loading ratio. This suggests that this ratio is dynamic throughout the year. Wallace, et al (1997), reporting results from long-term studies on the seasonal dynamics of TSS and organic matter cycling in streams of the southern Appalachians reported similar seasonal trends for organic matter. Wallace et al (1991) attributed this to interactions between the incorporation of coarse organic matter into streams by summer storm flows, temperature, the occurrences of the annual invertebrate population maxima and invertebrate feeding habits and annual leaf litter standing crop maxima. While such processes are likely at work in our study streams, our sampling methods were not intended to quantify the complicated dynamics of organic matter cycling in aquatic ecosystems.

We have summarized the results of our TSS analyses in Table 3. In columns 2-4, it is evident that TSS concentrations are the highest on Reed Mill and Pounding Mill, the streams most impacted by roads and land use conversion. TSS concentrations are lowest on Addie Branch while those of Roach Mill are intermediate. The mineral content of TSS varies significantly across all of the streams (Table 3, Column 6). However, the mineral content of TSS increases most rapidly with TSS on Roach Mill, Reed Mill and Addie Branch (Table 3, Column 5). Surprisingly, the mineral content of TSS increases less with TSS on Pounding Mill Creek, the study stream most affected by roads. As Pounding Mill Creek starts with the highest mineral content, this lower rate of increase could be due to the already elevated levels of mineral sediments.

Table 3: Summary of test results on coefficients of water quality figures. Numbers indicate relative magnitude of each coefficient (1 is highest) and similarity (a=0.05).

Column 1	Column 2 Figure 3	Column 3 Figure 3	Column 4 Figure 3	Column 5 Figure 6	Column 6 Figure 6	Column 7 Figure 7	Column 8 Figure 7
	Seasonal TSS	Seasonal TSS	Seasonal TSS	Mineral Content	Mineral Content	Organic Matter	Organic Matter
Stream	Amplitude	Minima	Maxima	Slope	Intercept	Slope	Intercept
Roach Mill	12	NA	NA	1	4	1	2
Reed Mill	1	NA	NA	1	3	2	2
Addie Branch	2	NA	NA	1	2	3	1
Pounding Mill	1	NA	NA	2	1	23	2

There is a similar pattern with the organic matter content of TSS in Addie Branch. This is apparent in Columns 7 and 8. While Addie Branch starts with the highest organic fraction in TSS, the trend for organic matter to increase with TSS is most gradual. The organic content of TSS on Roach Mill, Reed Mill and Pounding Mill is similar. Increases in the organic content of TSS with TSS are most rapid on Roach Mill, followed by Reed Mill and Pounding Mill.

If we interpret these results with regard to 303(d) status of the streams, we see some apparent inconsistencies. For example, TSS concentrations on Roach Mill (listed as impaired) are lower than those of Reed Mill and Pounding Mill, streams listed as being threatened. Roach Mill also has the lowest mineral content in its TSS and highest organic content in TSS. Thus, the TSS of Roach Mill Creek is disproportionately composed of organic matter. Does this mean that these three streams have been inappropriately categorized on the 303(d) list? Possibly, but the 303 (d) status of these streams were established based upon sediment impairment of habitat and biological indicators that were not addressed in this study. There is an apparent inconsistency in the TMDL process in that the TMDLs have been established to address loading of suspended solids whereas the sediment impairments of the aquatic habitat are largely occurring at the streambed. In addition, the impairment of Roach Mill was based upon data gathered at a sampling location that was influenced by two private residences and a small (< 1 ha) agricultural plot. The samples employed by the EPA were also obtained in the summer when organic loading and TSS are much higher. Clearly, sampling location, both in time and space, has a significant impact on water quality determinations.

From our monitoring of streambed scour and sediment mineralogy, we know that large amounts of bed material load, much of this sourced from roads, are moving on Pounding Mill Creek. In the most impacted reaches, we observed sand deposits that exceeded 30 cm in depth and sand accumulated in riffles during periods of low flow. Such sedimentation of stream substrates is detrimental to aquatic habitat and biota (EPA, 2001; Henley, et al, 2000).

CONCLUSIONS

From our continuous monitoring of streams in the southern Appalachians, we find that there are desynchronized, seasonal trends in stream flow and TSS concentrations. However, TSS, mineral sediment loading, and organic matter loading are not simply dependent on discharge, with the exception of the weak dependence of TSS on discharge on Reed Mill creek. While TSS is strongly correlated with mineral and organic loading for each of the study streams, it is not correlated with the mineral to organic ratio. Thus, simple point sampling of discharge and total suspended solids in these streams cannot be used to accurately characterize the loading of TSS, mineral sediments or organic matter in these streams. The use of TSS as a surrogate for mineral sediments in water quality studies may result in the misclassification of stream health or misappropriation of sediment TMDLs.

It is important to note that our research approach required investing significant human and financial resources on just four streams. This illustrates a fundamental challenge facing those responsible for characterizing the quality of water resources during the TMDL process; how to accurately determine causes and conditions of impairment with limited time and resources. The phased approach to TMDL development is insightful because it acknowledges that TMDLs may need revision as further inquiry allows us to unravel the complex interactions between watersheds, streams and their ecosystems.

Acknowledgements

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