QUANTIFYING TRAIL EROSION AND STREAM SEDIMENTATION WITH SEDIMENT TRACERS

Mark S. Riedel, Ph.D.

USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory, Otto, NC
current address: Baird & Associates, Madison, WI 53711, mriedel@baird.com, (608)273-4786 x305

Abstract--The impacts of forest disturbance and roads on stream sedimentation have been rigorously investigated and documented. While historical research on turbidity and suspended sediments has been thorough, studies of stream bed sedimentation have typically relied on semi-quantitative measures such as embeddedness or marginal pool depth. To directly quantify the impacts of a functioning off-highway vehicle (OHV) trail on stream sedimentation, we employed a marked-recapture sediment tracer approach that allowed us to directly measure the movement of sand eroded from the trail and transported through the stream. We seeded a controlled section of an operating OHV trail with manufactured limestone sand (MLS). Fine fractions of the MLS were washed from the road and increased stream water calcium concentrations, [Ca2+]. Stream water [Ca2+] began to return to pre-treatment levels within 12 weeks. Coarser fractions, greater than 0.5 mm, were eroded from the road with rain events and moved along the study reach in pulses. Much of the coarse sediment appeared to be within the study reach eight weeks following application of the tracer. Tracer results and estimated stream bed sediment transport times indicated the small section of OHV trail had contributed at least 2.45 kg (302 kg/ha) of coarse sediment to the stream bed in 8 weeks (1,960 kg/ha/yr).

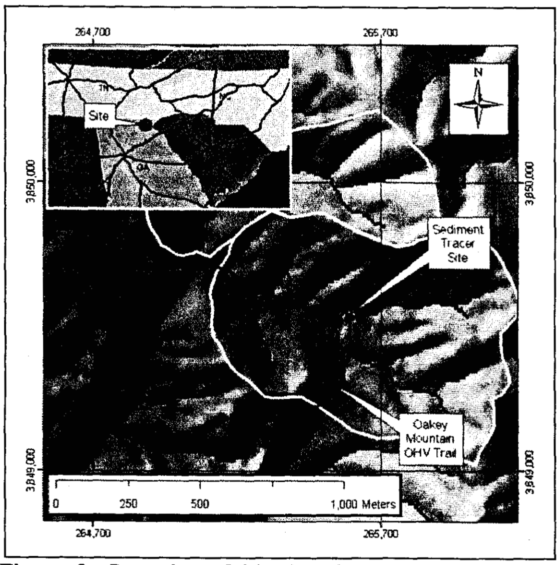
INTRODUCTION

Multiple use management of USDA Forest Service (USFS) National Forests allows for public use of off-highway vehicles (OHV) on designated trails. The National Forests in the southern Appalachian Mountains are within a few hours drive for millions of potential users and provide a wide selection of OHV recreation opportunities on hundreds of kilometers of trails. Roads have been identified as a significant source of sediment in southern Appalachian streams (Riedel, and others, 2003) however, the influences of OHV trails and OHV use on stream sedimentation have not been documented. While OHV trails are similar to roads, OHV trails have not been regularly maintained. This is an important difference in the southern Appalachian Mountains where average annual rainfall often exceeds 230 cm per year (Riedel, 2006a) and fine grained micaceous soils are highly erosive (Van Lear and others, 1995). Although anecdotal evidence indicates OHV trails cause significant soil erosion and stream sedimentation in the southern Appalachian Mountains (Figures 1 and 2, Riedel, 2006b), the long-term effects of OHV trails on stream bed sedimentation have not been documented. We conducted a research trial of a sediment tracer methodology on an OHV Trail in the Nantahala Mountains of northeastern Georgia. The purpose of this study was to test the development, application, and utility of using manufactured limestone sand (MLS) as a coarse sediment (0.5mm to 2mm) tracer. Preliminary results are reported.


Figure 1: Typical erosion of an OHV trail in the southern Appalachians.
Figure 2: Resultant stream sedimentation - sediments included fine to coarse grained sand (0.5mm – 2mm).

METHODS

A portion of the USDA Forest Service Oakey Mountain OHV trail system in the Chattahoochee National Forest of NE Georgia was selected for this study (Figure 3). Though not closed during the study, trail use was typically limited to small groups of a few riders during weekends because of the remote site location and difficult site access. Vehicles driven on the trail included "4-wheelers", "moto-cross bikes", and the 4-wheel drive "mule" used by study personnel; large boulder and log obstructions at the visitor access points (approximately 45 minutes away by OHV travel) prevented access by larger vehicles. A field inspection of the watershed revealed no other trails, roads, human induced forest disturbance, or illegal trails affected the study site. A ford allowed OHV users to cross the stream at a low point in the trail (Figure 4).



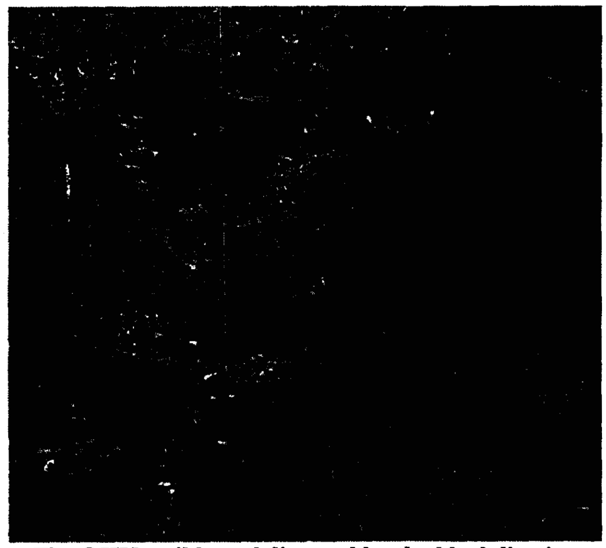


Figure 3: Location of OHV sediment tracer study site. The OHV trail loop delineated by the black line is part of the Chattahoochee National Forest Oakey Mountain OHV trail system.
Figure 4: Study site showing OHV trail and stream ford.

<u>Discharge, Precipitation, and Stream Water Chemistry</u>

Site location and installation of an automated stream pumping sampler in June, 2005 followed standard federal protocols (Wagner, and others, 2000). A pressure transducer, used to log stream stage, was placed in a PVC stilling well to minimize interference from wave action. The sampler logged stage on ten minute intervals. Stage readings were validated weekly by manually surveying stage and measuring discharge (Buchanan and Somers, 1969). A stage-discharge regression was developed and used to convert stage data to time series discharge data. Precipitation data were obtained from the National Weather Service weather station in Clayon, GA; this was approximately 6 km northeast of the study site. Flow data were processed following standard protocols (Riedel and others, 2004, Hibbert and Cunningham, 1967). The sampler was also used to collect stream water samples on a flow proportional basis; sampling frequency increased with flow. The fixed sampling inlet was anchored to a 1 m rebar pin in the streambed. While sampler capacity was limited to 24 one liter samples, composite sampling was used to draw four discrete, 250ml samples per bottle at a proportionately higher sampling frequency. Between storm events, an average of four to six one liter composite samples (16 to 24 250ml samples) were collected daily. Water quality samples were analyzed at the USDA Forest Service Coweeta Hydrologic Laboratory using a Perkin Elmer 2100 Atomic Absorption Spectrophotometer and following standard methods for total cation determinations (K^+, Na^+, Ca^{2+}, Mg^{2+}) (Deal and others, 1996).

<u>Trail and Stream Bed Sediment</u>

We used a rod and self leveling-transit to survey the stream and trail. The trail descended to the stream from both valley sides and crossed at a ford (Figure 5). Average trail slope was 14 % and the runoff contributing area was 0.0081 ha. The stream survey began upstream of the trail crossing and continued downstream to the confluence with Raper Creek (Figure 6). Perpendicular stream channel cross sections were surveyed at 7 m intervals along the stream. The first cross section, zero, was upstream of the ford. Subsequent cross sections began immediately downstream of the trail ford (cross section 1) and continued to the sampler just upstream of Raper Creek. The stream featured step-pool morphology and an average slope of 6 %.

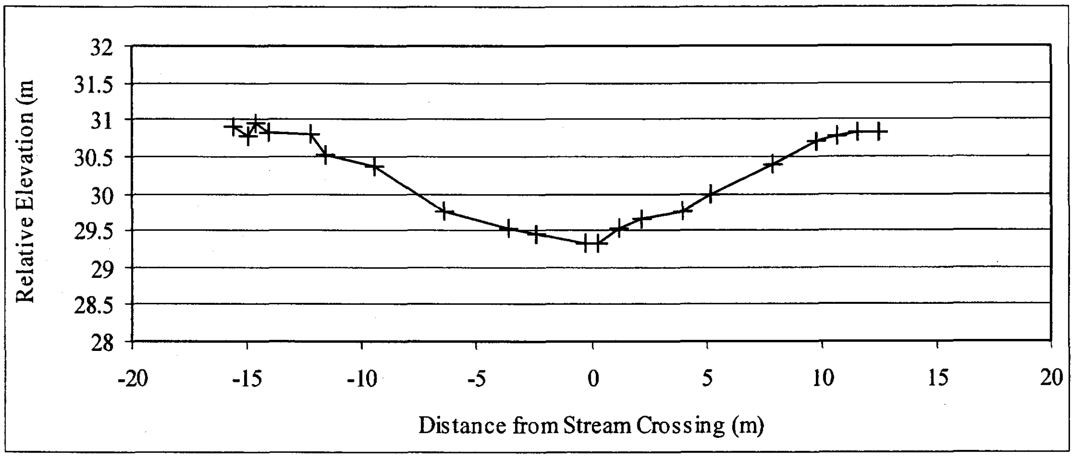


Figure 5: Survey of OHV Trail showing location of stream crossing at zero. The crests at each end of the trail determined the area of the trail that contributed runoff to the stream.

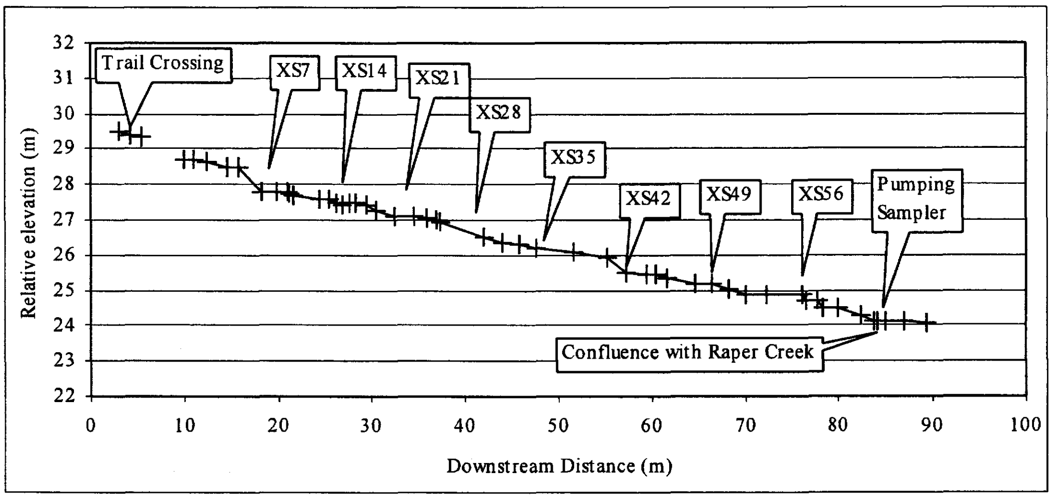


Figure 6: Longitudinal survey of study reach showing approximate locations of sediment sampling locations, trail crossing and automated pumping sampler. Average stream slope was 6%.

Samples of sediment were gathered from the trail and stream before and after the placement of the MLS sediment tracer (described below). Trail sampling was conducted by gathering replicate cores along the trail, on both sides of the ford. Stream bed sediment samples were composites of five replicate samples at each cross section. These consisted of one sample at the cross section with four others spaced at 1 m intervals upstream and downstream of the cross section. Hence, the samples represented 5 m long sections of the streambed centered on each cross section. Each of the five individual samples at a cross section was collected as a series of smaller samples taken across the width of the stream bed. Sediment sample volume was one liter and samples were taken to a depth of approximately 10 cm. Initial sampling was conducted immediately before the placement of the MLS on July 15, 2005. Subsequent samples were gathered following storm events. While sampling continued through December, 2005, analyses have only been completed through September. Laboratory analyses of the sediment samples provided calcium concentrations ([Ca2+], the "tracer") in parts per million (ppm).

We used [Ca2+] to compute stream bed sediment budgets and bed material residence times. This allowed for the determination of OHV induced stream bed sedimentation magnitude and duration in the study reach. The computational methods used mass conservation as applied in "marked capture-recapture" studies (e.g. soil erosion or wildlife population studies, see Zhang and others, 2001, Bergstedt and Bergersen, 1997, Wilcock, 1997, Bavley, 1993, Arkell and others, 1983) and required typical assumptions;

1. Full mixing of MLS (tracer) and "native" OHV trail sediments,
2. equal mobility of similarly sized MLS and "native" OHV sediments hence,
3. "native" sediment and MLS left the trail in direct proportion to the seeding rate (concentration).

The percentage of stream bed sediments that originated from the OHV trail was computed as the ratio of post-seeding stream bed [Ca2+] to the average background [Ca2+] at the site. This percentage was divided by the initial MLS tracer concentrations on the OHV trail to estimate the mass of sediments in the stream that originated from the OHV trial. Bed material residence times were estimated as the amount of time it took the initial MLS tracer pulses to be detected at each transect.

MLS Sediment Tracer

MLS was employed as a tracer in this study for two reasons. First, the [Ca2+] of the MLS was orders of magnitude higher than background levels from highly weather feldspars found in OHV trial, stream bed and soil samples. This degree of difference has been necessary for a tracer to provide sufficient enrichment and allow differentiation between introduced and background sediment sources (Zhang and others, 2001). Field sediment samples were analyzed for [Ca2+] by hot-plate/hydrogen peroxide consumption. Numerous samples of the MLS, estuarine standards, and blanks were analyzed during the study to characterize calcium content and to document the reliability and stability of the laboratory methodology and MLS tracer. From six independent sets of analyses spread over 6 months, the MLS and estuarine standard averaged 23.5 % and 0.32 % calcium, respectively ($n = 25, 15$; $s_x = 1.2$ %, 0.05 %). Background [Ca2+] from the stream, trail and soils ranged from 0.2 to 0.3 %.

Second, the particle size distribution of the MLS and particle density of the coarse fraction (0.5 mm to 2 mm sand) were very similar to that of the native soils and stream bed sediments. This was an important requirement as similitude between introduced MLS tracer and native sediments was necessary to maintain similar hydraulic behavior, sediment availability and transport characteristics. The fraction of fines in the MLS was intermediate between those of the stream bed and OHV trails sediments.

The MLS was scattered (seeded) on the OHV trails with a spreader and gently spread to assure uniform distribution. While efforts were made to minimize disturbance of the trail surface, OHV traffic was frequent enough to maintain a disturbed soil surface on the trail and mix the MLS into the trail surface. While no OHV traffic occurred during spreading of the tracer, it did occur immediately afterward and during subsequent site visits. Sediment samples collected before and immediately following application of the MLS verified uniform application.

RESULTS

Discharge, Precipitation, and Stream Water Chemistry

Stream flow and precipitation were typical for the region with a few larger storm events interspersed among numerous small storm events (Swift and others, 1989). While streamflow generally responded to precipitation events, there were a couple of localized rain events not captured by the rain gauge (Figure 7). Average post-treatment, stream water [Ca2+], 1.00 mg/l, were higher than pre-treatment, 0.65 mg/l ($p<0.01$). During relatively large events, stream water [Ca2+] decreased during storm flow and then increased significantly after the events.

Bed Material Sediment

[Ca2+] of trail and stream bed sediments responded to the application of the MLS (Figure 8). Pre-treatment stream sediment [Ca2+] averaged 2.56 ppm. Post-treatment [Ca2+] varied significantly with distance from the trail. Spikes in [Ca2+] three orders of magnitude greater than background occurred near the OHV trail whereas no [Ca2+] response was observed farthest downstream. For the first few weeks following tracer application, stream bed [Ca2+] was elevated above background levels in only the first four transects. An increase in both magnitude and the number of transects with elevated [Ca2+] occurred following relatively large rain events in August. Upstream [Ca2+] before and after tracer application were not different.

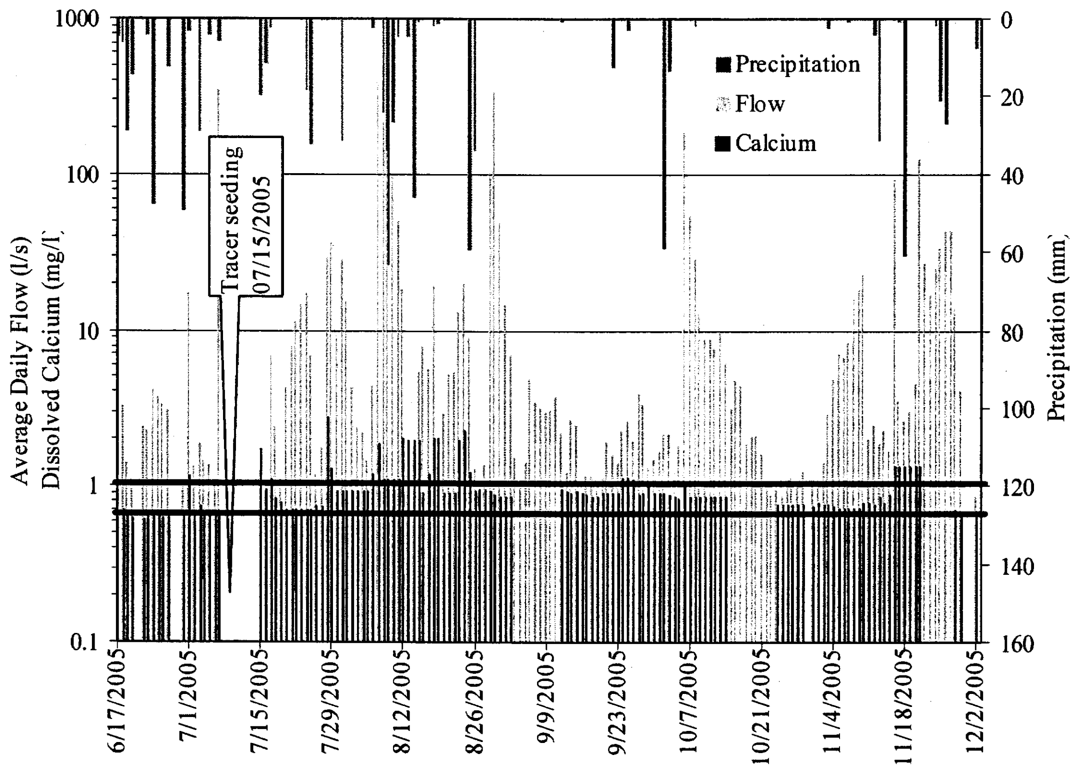


Figure 7: Precipitation, discharge and flow weighted Calcium concentration during the period of the study. Limestone tracer sand was applied 7/15/2005. Black lines at 0.65 mg/l and 1.00 mg/l denote average pre-treatment and post -treatment calcium concentration in stream water.

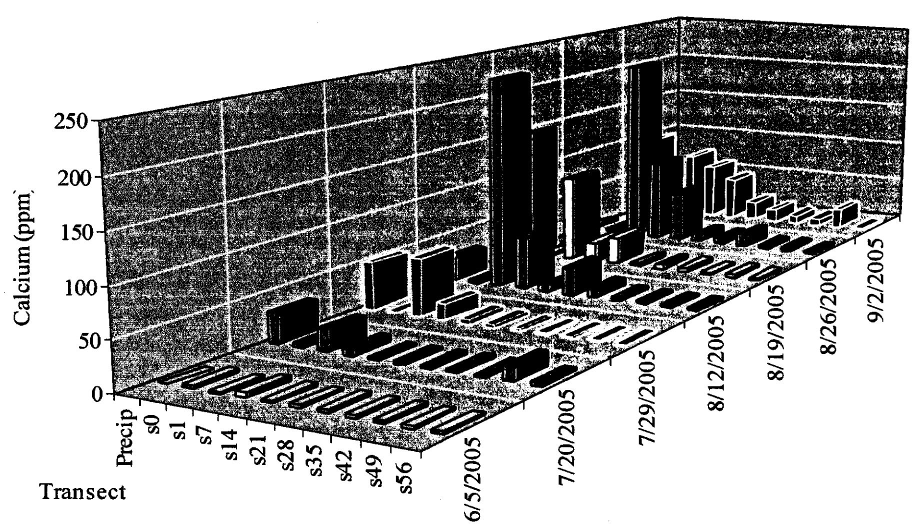


Figure 8: Total storm precipitation and post-treatment stream bed sediment calcium concentrations by sampling date. Transect s0 represents natural background concentrations.

The cumulative stream bed sedimentation attributable to the MLS ranged from 400 g to over 600 g per event (Figure 9). Declines of MLS in the stream beds on July 27th, August 19th and September 2nd were precluded by large rain events. These events removed more MLS from the stream bed than was introduced from the OHV trail. The cumulative storage of OHV sediments within the stream bed fluctuated as sediments were alternately transported into and out of the study reach (Figure 10). Given the original MLS application rate on the OHV trail was 24.5% and the previously mentioned assumptions, the OHV trail produced at least 2.45 kg of the observed stream bed sedimentation during this study. This is equivalent to 302 kg/ha or 1,900 kg/ha/yr of coarse sediment yield (0.5 mm to 2 mm) to the stream bed.

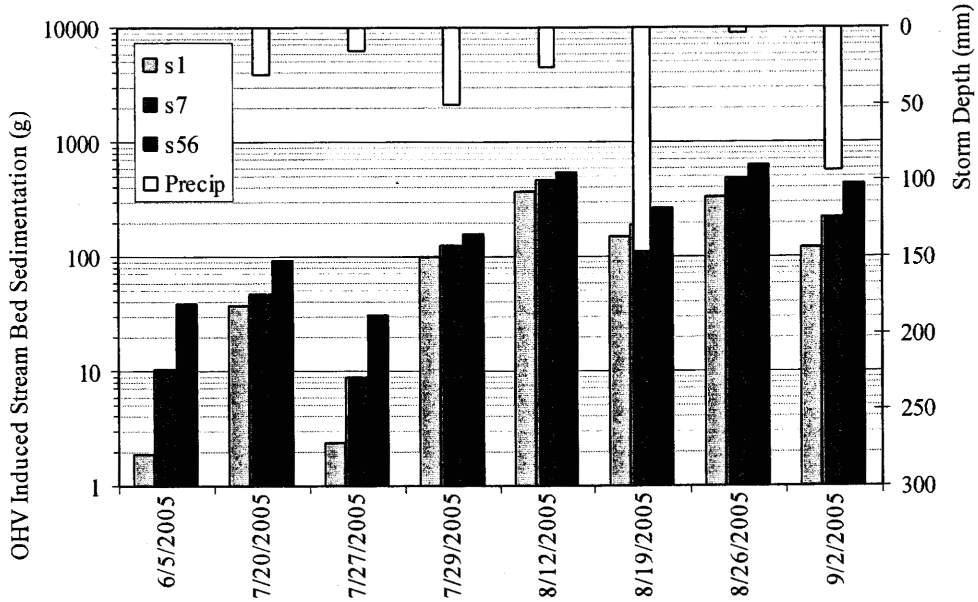


Figure 9: Cumulative stream bed sedimentation along the study reach as estimated from Calcium concentrations in stream bed sediments. Values do not include sediment that passed through the entire length of the reach during a single storm event.

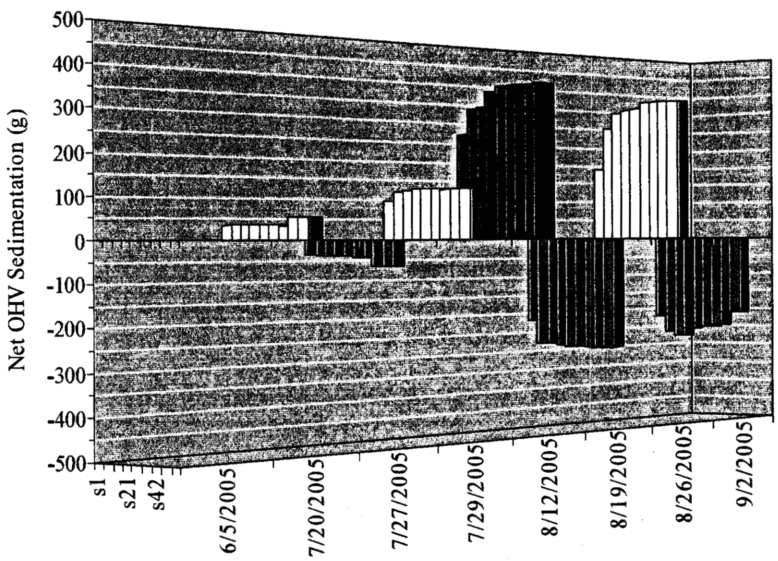


Figure 10: Cumulative change in OHV induced stream sedimentation along the study reach as estimated from changes in MLS concentrations. Positive values indicate net influx of OHV sediments while negative values indicate net efflux of OHV sediments.

DISCUSSION

Discharge, Precipitation, and Stream Water Chemistry

Precipitation, discharge and stream water [Ca2+] data generally followed expected patterns following the introduction of the MLS tracer; discharge and [Ca2+] generally increased following rain events. Relative to the duration of increased discharge in response to storm events, the spikes in stream water [Ca2+] were very short in duration. This could most likely be attributed to the short period over which overland flow from the OHV trail was running into the stream. With the cessation of precipitation, no additional MSL would be introduced to the stream even though discharge remained elevated. Following this spike, [Ca2+] declined rapidly. After about six weeks, stream water [Ca2+] began to decrease as discharge increased and only returned to higher levels as flows subsided. It is likely that by this time, the finer fractions of the MLS had been washed from the OHV trail and flushed through the stream. Thus, the study reach began to exhibit more typical water quality response to storm events in this region – a dilution of cations as the relative proportion of stream flow sources shifted from ground water to quickflow fed by runoff and shallow soil water. There were a couple of storm flow events unassociated with measured precipitation, and vice versa. This was due to the highly variable spatial distribution of late summer storm events in the mountains; while the rain gauge was a relatively short distance from the study site, it was not within the immediate area.

Bed Material Sediment

Sedimentation of the streambed in response to the MLS tracer application developed over time and occurred in pulses. Runoff from individual rain events washed new sediments into the stream while those from previous storms were transported short distances down stream or flushed entirely from the reach. As no MLS was detected immediately downstream of the junction between the study reach and Raper Creek, these events must have flushed the MLS sediments beyond the study boundary. Despite these large flushing events, additional MLS was still being transported from the OHV trail to the stream at rates approximately 400 times greater than background levels (100 ppm vs. 0.25ppm). This was evident as subsequent pulses of the MLS were detected in stream bed sediments. This result suggested there was a mechanism that influenced the availability of coarse sediments for erosion from the trail. The Author suggests the most likely mechanism would be OHV traffic and disturbance of the trail surface.

While one potential use of the MLS method would be to estimate bed material transport rates, sampling intervals were not frequent enough given the highly dynamic nature of the stream bed. With the efflux of OHV sediments out of the stream, it was not possible to discern the MLS mass centroid needed to estimate transport rates and residence.

CONCLUSIONS

The results of this study were preliminary in nature as they have not been replicated. Despite this, they indicated the OHV trail was having enormous impacts on water quality, sediment yield and stream bed sedimentation in the study reach. Most importantly, the use of MLS as a sediment tracer showed great promise as a tool to document soil erosion impacts on stream water quality and stream bed sedimentation. This method allowed for the direct quantification of sand and fine gravel transport into, through, and out of the stream bed. These processes define stream bed sedimentation and strongly influence stream ecology by affecting nutrient cycling (Boulton and others, 1998), development of aquatic invertebrate communities (Chiao and Wallace, 2003), and ultimately the survival and reproduction of numerous river fishes (Suttle and others, 2004).

AKNOWLEDGEMENTS

This work would not have been possible without the support of Jack Holcomb, Hydrologist, USDA Forest Service, Region 8, Atlanta, GA and Dr. James Vose, Project Leader, Coweeta Hydrologic Laboratory. The author extends his gratitude to Charles Marshall, Derek Gregory, Cindi Brown and Jim Deal for their assistance with the necessary field work and sample analysis to support this project.

LITERATURE CITED

Arkell, B.L., Newson, M., Oldfield, F., 1983. Trapping and tracing: some recent observations of supply and transport of coarse sediment from upland Wales. Special Publications of the International Association of Sedimentologists 6(1983)107-119.

Bayley, P.B. 1993. Quasi-likelihood estimation of marked fish recapture. Can. J. Fish. Aquat. Sci, 50(10)2077-2085.

Bergstedt, L.C. and Bergersen, E.P. 1997. Health and movements of fish in response to sediment sluicing in the Wind River, Wyoming, Can. J. Fish. Aquat. Sci. 54(2):312-319.

Boulton, A.J., FIndlay, S., Marmonier, P., Stanley, E.H. and Valett, H.M. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics, 29:59-81.

Buchanan, T. J. and W. P. Somers. 1969. Discharge measurements at gauging stations. Techniques of Water-Resources Investigations of the United States Geological Survey. U.S.G.S. Reston, VA.

Chiao, E. and Wallace, J.B., 2003. Bioassessment Metrics and Deposited Sediments in Tributaries of the Chattooga River Watershed, 2003 Georgia Water Resources Conference. USGS, Athens, GA.

Deal, J M, Brown, C., and Holland, C.G. 1996. Procedures for chemical analyses at the Coweeta Hydrologic Laboratory, USDA Forest Service, Southern Research Station, Otto, North Carolina (unpublished manual).

Hibbert, A.R. Cunningham, G.B. 1967. Streamflow data processing opportunities and application. International Symposium on Forest Hydrology, National Science Foundation Advanced Science Seminar, Pennsylvania State University, Pennsylvania, Aug 29 - Sept 10, 725-736.

Riedel, M.S. 2006a. North Atlantic oscillation influences on climate variability in the southern Appalachians. Proc. Federal Interagency Sedimentation and Hydrologic Modeling Conferences, Reno, NV, April 2-6.

Riedel, M.S. 2006b. Influences of off-highway vehicles on fluvial sediment regimes. Proc. Joint 8th Federal Interagency Sedimentation and 3rd Hydrologic Modeling Conferences, Reno, NV, April 2-6.

Riedel, M.S., Vose, J.M., and Bolstad, P.V. 2004. Characterizing hysteretic water quality in southern Appalachian streams. Proc. 2004 National Water Quality Monitoring Conference, United States Advisory Committee on Water Information, National Water Quality Monitoring Council, Chattanooga, TN, May.

Riedel, M.S., Vose, J.M. and Leigh, D.S. 2003. The road to TMDL is paved with good intentions - Total Maximum Daily Loads for a Wild and Scenic River in the southern Appalachians. 2nd Conference on Watershed Management to Meet Emerging TMDL Environmental Regulations ASAE, Albuquerque NM, Nov.

Suttle, K.B., Power, M.E., Levine, J.M. and McNeely, C. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile Salmonids. Ecological Applications, 14(4): 969-974.

Swift, L.W., Cunningham, G.B. and Douglass, J.E. 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.

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

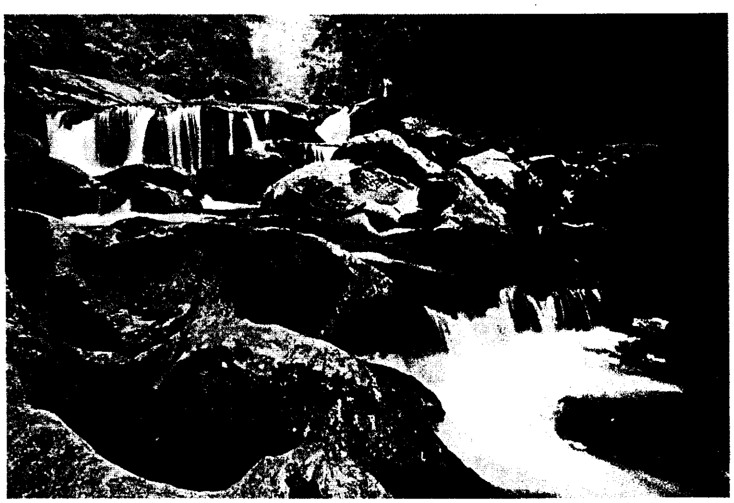
Wagner, R.J., Mattraw, H.C., Ritz, G.F. and Smith, B.A. 2000. Guidelines and standard procedures for continuous water-quality monitors: site selection, field operation, calibration, record computation, and reporting," U.S. Geological Survey Water-Resources Investigations Report 00–4252.

Wilcock, P.R. 1997. Entrainment, displacement and transport of tracer gravels. Earth Surface Processes and Landforms, 22(12)1125-1138.

Zhang, X.C., Friedrich, J.M., Nearing, M.A. and Norton, L.D. 2001. Potential Use of Rare Earth Oxides as Tracers for Soil Erosion and Aggregation Studies. Soil Science Society of America, 65(5)1508-1515.

Second Interagency Conference on Research in the Watersheds

May 16 – 18, 2006



USDA SRS Coweeta Hydrologic Laboratory

1934-2006