2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 1110633

Influence of Forest Roads and BMPs on Soil Erosion

J. McFero Grace III, Research Engineer

U.S. Department of Agriculture, Forest Service, Southern Research Station, 521 Devall Drive, Auburn, AL 36830, jmgrace@fs.fed.us .

William J. Elliot, Team Leader and Research Engineer

U.S. Department of Agriculture, Forest Service, RMRS, Air, Water & Aquatic Environments Science Program, 1221 South Main Street, Moscow, ID 83843, welliot@fs.fed.us .

Written for presentation at the
2011 ASABE Annual International Meeting
Sponsored by ASABE
Gault House
Louisville, Kentucky
August 7 – 10, 2011

Abstract. *Mitigating sediment export from the forest road prism and potential delivery to forest streams will require a more complete prospective on forest road erosion and benefit of BMPs in reducing the risk of degrading environmental impacts. Sediment control systems have clearly been presented as effective in minimizing sediment travel distances downslope and are likely the key to reducing the environmental impact of road systems. In an attempt to address the questions related to the impact of forest roads and the effectiveness of BMPs to control sediment and its introduction to the forest floor downslope, a study was installed in northeast Georgia within the Chattooga River Ranger District of the Chattahoochee-Oconee National Forest. This paper reports the storm runoff and sediment loading results of a 6-year study that evaluates the effectiveness of road BMPs in controlling sediment movement from the road prism. The three sediment control treatments investigated were hay bale barrier, sediment basin, and sediment basin with riser control. The mean runoff reduction ratios (P=0.634) and runoff coefficients (P>0.098) for road sections was not detected as significantly different for the treatments. Outlet runoff volume from the sediment basin with riser control was found to be significantly less than the other treatments. Mean trap efficiency for the sediment basin with riser control, haybale, and sediment basin treatments were 99, 97, and 94 percent, respectively. Based on this analysis, no differences were detected in the haybale and sediment basin with riser control and sediment basin treatment. The fact that the haybale treatment was not different from the other treatments likely indicates that runoff reductions found for all treatments resulted in significant reductions in sediment transport.*

Keywords. Forest Roads, BMPs, Storm Runoff, Sediment Control, Soil Erosion, Sediment Basins

Introduction

The potential for accelerated sediment delivery from forest roads, over those typically observed under forested conditions, has been well documented in previous works (Anderson et al., 1976; Aubertin and Patric, 1974; Aust and Blinn, 2004; Authur et al. 1998; Binkley and Brown, 1993; Clinton and Vose, 2003; Grace, 2005; Grace and Clinton, 2007; Swift, 1984; Van Lear et al., 1995). Roads are far from the undisturbed forest condition in terms of properties, erosion rates and erosion control methods. Roads exhibit characteristics, such as infiltration capacities, vegetative and surface cover, subsurface hydrology, and surface drainage patterns that are quite different from the undisturbed forest floor (Grace, 2005). This fact makes forest road management a critical area in the sustainable development and management of the forest resource (Grace and Clinton, 2007). Over the years, there have been investigations reporting accelerated soil erosion losses but only a few have linked these losses to sediment delivery (Elliot and Tysdal, 1999; Litschert and MacDonald, 2009; Rivenbark and Jackson, 2004). However, some investigations have indicated that forest road erosion rates do not necessarily dictate that this eroded sediment reaches stream channels (Grace and Davis, 2010).

Elliot and Tysdal (1999) suggested that road length, road gradient, and soil type are the critical factors in forest road erosion. In addition, this work indicated that road proximity to the stream should guide the level of mitigation measures to control sediment delivery. Disconnecting the forest road from stream systems is one of the major focuses of forest road sediment control BMPs. These BMPs minimize the influence of roads on downslope water resources by incorporating proper drainage spacing, vegetating disturbed areas, retaining road storm runoff, and dispersing storm road runoff onto the forest floor to capitalize on its optimal runoff (and soil erosion) reduction characteristics. BMPs emphasizing retaining road storm runoff typically decreases sediment yield and the potential for sediment delivery. One such BMP relates to sediment control structures at lead-off ditch outlets to minimize runoff and sediment that has to be filtered by the forest floor.

This investigation was initiated to monitor and evaluate forest road erosion and the efficacy of sediment control structures in capturing sediments eroded from Southern Appalachian road sections. The specific objectives of the study were (1) to evaluate storm runoff and sediment loading associated with forest road sections in the Southern Appalachians, (2) determine and compare the runoff reductions achieved through sediment control structures, (3) compare the trap efficiency of three forest road sediment control structures in this application on Southern Appalachian road sections. This paper reports the hydrology and sediment loading of study road sections, runoff reductions, and trap efficiency results.

Methodology

Study Area Description

The study area is located within the Chattooga River District in the Chattahoochee-Oconee National Forest in northeast Georgia (35^{o} latitude and 83^{o} longitude) (Figure 1). The study road traverses an area denoted as Patterson Gap with an elevation of approximately 900 m above mean sea level. The temperate climate in the area is characteristic of the Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow Province of the Appalachian-Cumberland Ecoregion (Bailey, 1980, 1995). Long-term average annual precipitation in the study area is 1800 mm with 65 percent as rainfall. Soils are Hayesville series (fine, kaolinitic, mesic Typic Kanhapludults) surface soil overlaying clay loam subsoils (USDA SCS, 1981).

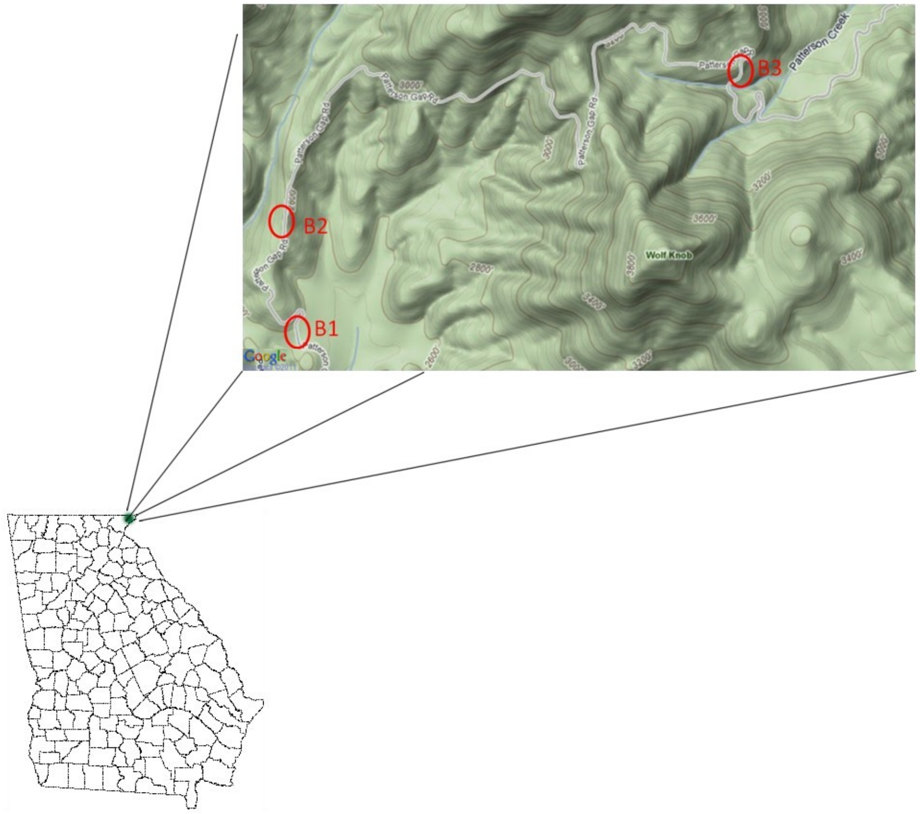

Figure 1. Location of study area in northeast Georgia (background terrain imagery courtesy of Google Maps). Blocking along the Patterson Gap road designated as B1 (block 1), B2 (block 2), and B3 (block 3).

Experimental Design

The experimental design was a randomized complete block design (RCBD) with blocking by road location (Figures 1 and 2). Three blocks, each containing three different treatments were used to investigate sediment delivery from the forest road and sediment basin effectiveness during a 6-year study period (Figure 2). Precipitation, storm runoff, and runoff concentrations were continuously monitored for the study area from September 2003 to September 2009. Precipitation was monitored with replicated recording tipping bucket rain gauges in combination with accumulating manual gauges.

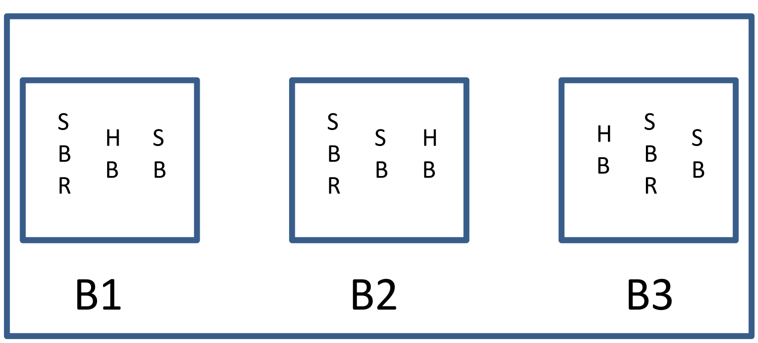

Figure 2. Location of study treatments within road blocks in the randomized complete block design for the investigation. Three blocks designated as B1, B2, and B3 with three treatments: sediment basins (SB), sediment basin with riser control (SBR), and hay bale barriers (HB).

Storm Hydrology Monitoring

Road section hydrology and sediment concentration data were collected from 9 road sections with similar soils, forest cover, and road design for storm events the study period. The study and monitoring design were described by Grace (2006). Storm runoff and sediment from nominal 50-m road sections was routed to road lead-off ditch through an inlet sampling station, a sediment control structure, and outlet sampling station before discharge onto the downslope forest floor. This component of the investigation concentrates on the inlet sampling station to determine hydrology and sediment yield from study road sections. Storm runoff volume and sediment concentrations were monitored at inlet sampling stations consisting of 1.8-m (6 ft) trapezoid approach section in combination with a 0.3-m (1-foot) trapezoidal flume, submerged probe flow level sensor and recorder, and a stormwater sampler (Figure 3). Outflow storm runoff volumes and sediment concentrations were monitored at the outlet sampling station which consisted of a 5:1 flow divider in combination with a runoff tipping bucket, event recorder, and stormwater sampler. Flow volume at the inlet and outlet sampling locations of each study treatment were measured continuously and logged at 5-minute intervals using data loggers. Inflow was determined using instantaneous flow level measurements upstream of the trapezoidal flume outlet. Outflow was determined by accumulating tips of the runoff tipping buckets after flow passed through the flow divider at the outlet of the sediment control treatment. The runoff coefficient, r_c, was calculated as the ratio of storm runoff depth to observed precipitation for a given storm event. The runoff reduction ratio was calculated as ratio of sediment control structure inflow to outflow.

Figure 3. Inlet sampling station in road erosion and sediment control investigation. Sediment basin with riser control treatment illustrated here.

Sediment Yield Monitoring

Sediment yield was monitored for the study road sections for storm events during the 6-year study period. Sampling periods typically consisted of more than a single storm event during the period covered by this study with the exception of larger storm events which required immediate attention. A composite storm sample was collected for sampling periods with stormwater samplers (Grace, 2006). The composite samples were analyzed for total suspended solids (TSS) by gravimetric filtration (Method 2540D) (APHA, 1995).

Data Analysis and Model Evaluation Procedures

Sediment yield (loading) from road sections was determined as the product of sediment concentrations and the associated flow volumes at the sampling locations for composited events. Observed hydrology and sediment yields were summarized for each of the study road sections for the study period. Storm runoff, sediment loading, and trap efficiency deviated from normality and were normalized using a logarithmic transformation before performing the analysis of variance (ANOVA). Data were tested for significant trends and differences with repeated measures analysis of variance (ANOVA) procedures using the Statistical Analysis Systems (SAS) statistical software (SAS Institute, 2004). Response variables were tested for treatment effects using SAS MIXED repeated measures procedures, with repeated collections over time. The least square means (LSMEANS) procedures were used to separate the means. Significant treatment effects in the response variables, in this analysis, were evaluated at either the 0.05 or 0.10 significance level using Tukey multiple comparison procedures to adjust p-values to an experimental-wise error rate.

Results and Discussion

Precipitation for storm events observed during the study period from September 2003 – September 2009, totaled 5600 mm (Figure 4). A total of 156 observed storm events initiated runoff events from at least one of the nine road sections in the investigation over the study period. Mean precipitation for the observed storm events was 32 mm. Event storm intensities ranged from 0.3 to 80.0 mm/hr for the 156 storms observed in this investigation. The majority (70 percent) of these intensities were at the lower end of this range which is evident by the overall mean storm intensity for the events of 4.5 mm/hr. Some storm events were omitted from the analysis because they occurred during freezing periods and data are missing due to equipment malfunction. Flow monitoring equipment, and to a lesser extent precipitation monitoring equipment, did not perform satisfactorily during periods with temperatures less than 0 ^{o}C due to freezing of the submerged probes and within the tipping bucket apparatus. Due to the higher elevation of the study area, temperatures often dropped below this threshold temperature during the late fall and winter months (November –March). Precipitation in the form of rainfall occasionally occurred immediately following periods of freezing temperatures which resulted in the loss of a portion of the rising limb of the storm hydrographs until the equipment thawed and resumed accurate measurement of storm runoff.

In addition, one storm occurring in August 2004 and another two occurring in September 2004 were excluded from the analysis. The August 2004 storm overwhelmed the monitoring system and had missing precipitation record due to equipment malfunction. However, the incomplete data record indicates that greater than 200 mm of rainfall occurred during the storm. The two September 2004 storms totaled more than 250 mm each, which is greater than the 100-year, 24 hour rainfall for the study area. The equipment was designed for a 25-year, 24 hour design storm of 220 mm. The two September 2004 storms were associated with the remnants of Hurricanes Frances and Ivan which successively moved through the area during a two week period in mid-September. The remnant storm associated with Hurricane Frances (September 6-8, 2004) alone resulted in more than 350 mm or rainfall on the area in less than 36 hours. These two storms also overwhelmed the monitoring system and were excluded in the analysis.

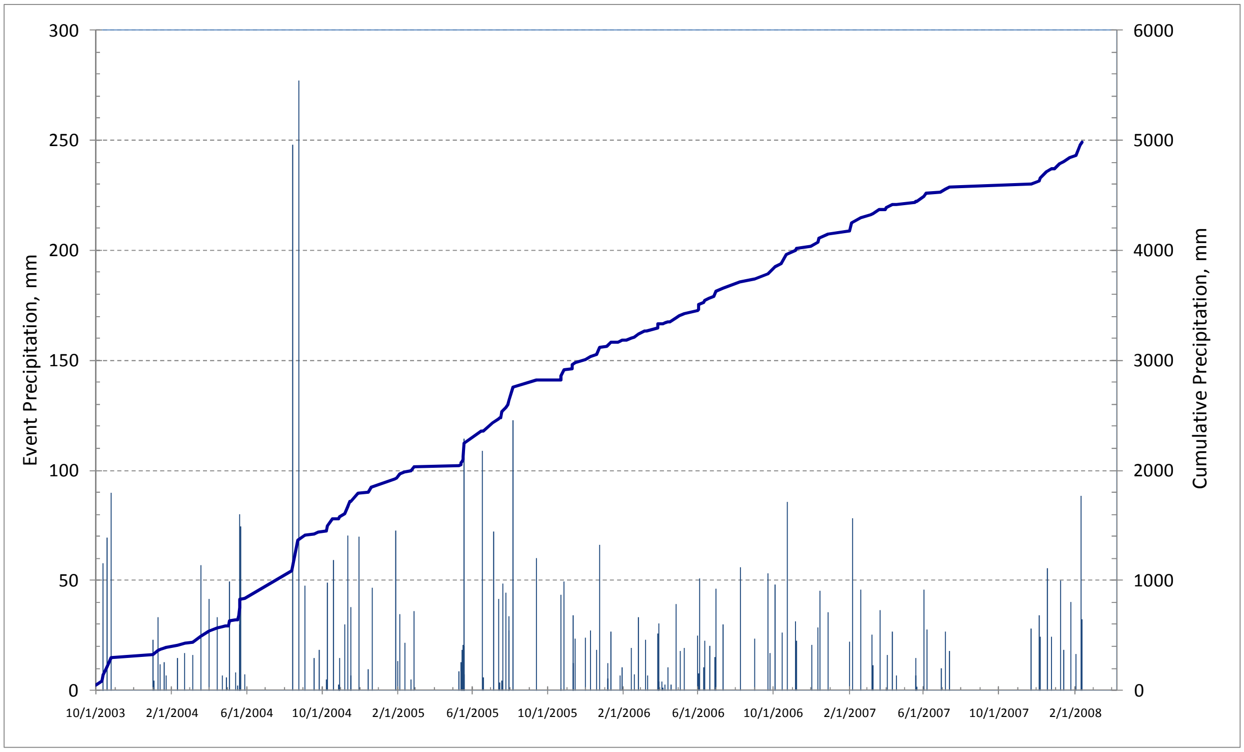

Figure 4. Observed event precipitation and cumulative precipitation during the study period.

Storm Runoff

During the entire 6-year study period from September 2003 to September 2008, 156 precipitation events produced storm runoff from at least one of the nine road sections in the investigation. Storm runoff distributions deviated from normality and required normalizing using a logarithmic transformation before performing the ANOVA. The r_c for road sections in the investigation were highly variable, ranged from a low value of 0 to a high value of 1.18. This variability was reflected in the high standard deviation for r_c values of 0.27 for road sections in the investigation. The road sections were expected to have r_c values less than 1.0 since runoff depth from bounded road sections emanating from a given precipitation event should be less than precipitation amount. However, values greater than 1.0 indicate that flow was contributed from either intermittent subsurface flow, from surrounding cutslopes, or upslope areas that are normally hydrologically disconnected from the delineated contributing area (road section area). This was the case for several events during the study period; 3 events for road section HB1 (events occurring on 11/15/2005, 11/20/2005, & 10/27/2006), 3 events for HB2 (events occurring on 2/27/2005, 6/10/2005, & 8/23/2005), 2 events for road section SB1 (events occurring on 5/26/2006 & 12/25/2006), 2 events for SBR2 (events occurring on 9/27/2004 & 12/8/2005) and 1 event for SBR3 (event occurring on 3/1/2007). The high value of 1.18 for road section SBR3 occurred during a storm event during the late winter of 2007 (3/1/2007 0800 EST – 3/2/2007 0600 EST) and was likely the result of contributing intermittent subsurface flow from the cutslope. Kahklen and Moll (1999) observed that in some cases, roads completely intersected water moving through the soil, whereas on nearby sites, other road segments allowed water to pass beneath the road. In our data set, it appears that SBR3 generally allows groundwater to pass under the road, and hence the total overall runoff (Table 1), but during the biggest runoff event, there was more upslope lateral flow than could pass under the road, likely leading to the appearance that road runoff exceeded precipitation falling on the road surface.

Table 1. Summary of observed inlet storm runoff data for the 9 road sections in the investigation.

Road Section	Total Storm Runoff[a] (mm)	r_c[b] (mm/mm)	Total Sediment Load[c] (kg/m^2)	Mean Sediment Concentration (mg L^{-1})	Road Section Area (m^2)
HB1	7040	0.21	125	870	195
HB2	8750	0.23	190	920	150
HB3	5520	0.093	19	490	85
SB1	7210	0.25	4.4	1210	150
SB2	5420	0.17	9.4	620	120
SB3	1440	0.12	0.3	200	150
SBR1	6730	0.11	2.6	560	90
SBR2	4310	0.15	1.7	1280	150
SBR3	5850	0.25	2.5	790	150

[a]Observed storm runoff measured at the drainage outlet for study road sections during study period.

[b] Runoff coefficient = observed storm runoff / observed precipitation.

[c]Sediment load at the drainage outlets for road sections for observed storms.

The ANOVA detected no significant treatment or block effects on the runoff coefficients (r_c) variable in the investigation (Table 2). The mean r_c value of 0.17 for road sections was not detected as significantly different among the treatments (P>0.098). However, both significant treatment effects (P=0.004) and block effects (P=0.002) were detected in the analysis of inlet runoff volumes. The mean inlet storm runoff volumes were 7.2, 6.4, and 4.8 m^3 for HB, SB, and SBR treatments, respectively (Table 2). In order to remove the influence of road section area, inlet runoff was compared on the basis of storm runoff depths (runoff volume per unit road area expressed as a depth). The inlet runoff volumes on a depth basis were 50.3, 45.7, and 37.1 mm for HB, SB, and SBR treatments, respectively. The SBR treatment yielded less inlet runoff than the HB treatment (P=0.003), but was not significantly different from the SB treatment (P=0.133). Inlet storm runoff depths for the treatments exhibited high variability among events for road sections.

Table 2. Event means and statistics for runoff data from sediment control treatments during the study period.

Treatment	Inlet Runoff[a] m^3	Outlet Runoff[b] m^3	r_c[c]
HB	7.2 (44.5)a	0.39 (2.1)a	0.17 (0.26)a
SB	6.4 (34.8)b	0.54 (1.7)a	0.17 (0.25)a
SBR	4.8 (22.5)b	0.06 (0.3)b	0.17 (0.27)a

* Means with a different letter within a given column were detected as significant at the 0.05 significance level based on least squares means comparison tests. Values in parenthesis are standard deviations.

[a] Storm runoff at treatment inlet from observed storms.

[b] Storm runoff leaving the treatment area for observed storms.

[c] Runoff coefficient (ratio of runoff volume to observed precipitation volume) for the road sections associated with each treatment in the investigation.

The variability in inlet runoff depth was reflected in the outflow storm runoff depths which had a range from 0 to 233 mm. The mean outlet runoff depth was 2.7, 3.9, and 0.48 mm for HB, SB, and SBR treatments, respectively. Mean outlet runoff depth for SBR was significantly different from HB ($P<0.0001$) and SB ($P<0.0001$) treatments at the 0.05 significance level. However, outlet runoff depth between SB and HB treatments was not significantly different ($P=0.335$). The SBR treatment yielded 5 and 7 times less outlet runoff than HB and SB treatments, respectively. The results are consistent with conventional thinking that greater inlet volume would result in greater outlet volume for storm events above a given threshold. In this investigation, the threshold storm size (precipitation amount) was the design storm of 220 mm. However, our data suggest that the threshold value decreased over time for the treatments as the storage volumes decreased due to deposition of sediment within the treatment areas.

The runoff reduction capacity for treatments (reduction ratio) was evaluated in this analysis by comparing the ratio of treatment inlet runoff to outlet runoff (Table 3). This measure provides additional evaluation criteria for the treatments investigated in this work by looking at the efficacy of sediment control treatment in reducing inflow volumes. The mean reduction ratios were 104:1, 98:1, and 67:1 for HB, SB, and SBR, respectively. The treatment reduction ratios were not detected as significantly different ($P=0.634$).

Trap Efficiency

Sediment loads, runoff concentrations, runoff reductions, treatment containment, and trap efficiency over the study period for the treatments are presented (Table 3). Sediment loading at the inlet location was an order of magnitude greater for the HB treatment which had a mean value of 180 kg. The SBR and SB treatments were not different in relation to sediment loading at the inlet location with means of 3.6 and 7.3 kg, respectively. The greater sediment loading for the HB treatment is attributed to the consistently greater sediment loading for each of the three HB road sections, and this is likely due to the greater plot areas and greater runoff depths for this treatment (Table 1). This result was not expected due to experimental design blocked on road location to prevent confounding effects of road location (i.e. differences in precipitation patterns, topography, road standard, soils, drainage, traffic, elevation, etc.). Due to the close proximity of treatments within a block, confounding effects related to road location are not suspected to have caused the significantly greater sediment loading observed from HB road sections. The random permutation used to selected treatment locations in the RCB design did result in the HB treatment appearing at the most remote location for two of the three treatment blocks (B2 and B3)(Figure 2). This alone does not explain the increased loads at HB locations since B1 yielded runoff and sediment loads that were less than those in B2 and greater than in B3. The increases observed on the HB treatment can likely be attributed to either seepage, a changing boundary condition, or a steeper road grade. The greater runoff combined with larger plot size for this treatment may have been enough to result in more storms where ditch flows were sufficiently great that the critical shear of the ditch material was exceeded. Once critical shear is exceeded, concentrated flow erosion can occur, significantly increasing sediment detachment and delivery.

The analysis of trap efficiency data found significant treatment effects at the 0.10 level of significance. Trap efficiency of the SBR treatment was 99 percent and was significantly greater than the SB efficiency of 94 percent (P=0.0795). The SBR treatment mean trap efficiency was not significantly different (α = 0.10) from the HB mean trap efficiency of 97 percent (P=0.738). Similarly, the HB mean trap efficiency was not different from the SB treatment (P=0.195).

Table 3. Comparison of sediment loads, runoff concentration, ratios, sediment containment, and trap efficiency for the HB, SB, and SBR treatments.

Treatment	Inlet Sediment Load[*a] kg	Inlet Runoff Conc.[*] mg L^{-1}	Outlet Sediment Load[*b] kg	Outlet Runoff Conc.[*] mg L^{-1}	Reduction Ratio[*c]	Containment[*d] kg	Trap Efficiency[†e] %
HB	180 (730)a	760 (1430)a	0.24 (0.87)a	810 (1230)a	104:1a	154.1 (707)a	97 (12)ab
SB	7.3 (41)b	540 (720)b	0.31 (0.83)a	490 (400)b	98:1a	3.2 (30.9)b	94 (19)b
SBR	3.6 (12)b	900 (1400)a	0.05 (0.14)b	460 (320)b	67:1a	1.3 (6.7)b	99 (5)a

[*] Means with a different letter within a given column were detected as significant at the 0.05 significance level based on least squares means comparison tests adjusted for Tukey multiple comparisons. Values in parenthesis are standard deviations.

[†]Means with a different letter within a given column were detected as significant at the 0.10 significance level based on least squares means comparison tests adjusted for Tukey multiple comparisons. Values in parenthesis are standard deviations.

[a] Sediment loading from observed storms at the treatment inlet.

[b] Sediment loading from observed storms leaving the treatment area.

[c] Treatment runoff reduction capacity determined as a runoff reduction ratio (Inlet runoff: Outlet runoff)

[d] Treatment containment, determined as the difference between inlet sediment load and outlet sediment load.

[e] Treatment trap efficiency for observed storms.

The high trap efficiencies were primarily due to the large runoff reduction capacities (as much as 104:1) exhibited by the treatments. These reduction capacities likely had an influence despite the failure of the analysis to detect significant differences in the reduction ratios. Storm to storm variability in reduction ratios influenced the ability of the analysis to detect treatment differences. Standard deviations in the ratios ranged from 250 for the SBR to 2200 for the SB treatment, with the HB ratio standard deviation being 1800. The HB treatment had the greatest outlet runoff concentrations and a mean outlet concentration (810 mg L^{-1}) consistent with its mean inlet runoff concentration (760 mg L^{-1}). The relatively high mean outlet runoff concentration was influenced by the reduction in runoff observed for the treatment.

Trap efficiency for treatments in this investigation was directly related to inlet runoff parameters (runoff volume and concentration). The SBR had the greatest mean inlet runoff concentration, which increased the potential for concentration reductions with runoff detention. The deposition rate is greatly increased with increasing detention time particularly with inlet concentrations as high as seen in the SBR treatment. Inlet runoff with higher concentrations potentially have a greater quantity of sediment to be retained (and thereby greater trap efficiency) by the sediment control treatments in this investigation. The SBR had a mean inlet runoff concentration (900 mgL^{-1}) nearly twice as great as the SB treatment (540 mgL^{-1}) which represents twice the sediment load for a given quantity of runoff volume. Based on this result, we would expect greater trap efficiency for the SBR given similar outlet runoff concentrations and less outlet runoff volume. The high sediment concentration of the SBR plots may have also been influenced by the low runoff rates, increasing retention time and trapping efficiency in the SBR basins.

Summary and Conclusions

The capacities of three sediment control BMPs to reduce storm runoff and retain (trap) sediment were compared on Southern Appalachian forest road sections during a 6-year study period. The three sediment control BMPs in this comparison included hay bale barrier (HB), sediment basin (SB), and sediment basin with riser control (SBR) treatments. Storm characteristics and runoff (inlet and outlet) were monitored from 9 locations blocked by road location for 156 storm events during the study period. From this study, we conclude that the sediment control structures reduced runoff by more than 98 percent and the sediment delivery by 94 to 97 percent. The high variability within and between treatments made it difficult to discern differences in sediment control effectiveness. The large reductions in runoff mean that a much smaller buffer may be needed to absorb road runoff and minimize sediment delivery if sediment control structures are installed.

Acknowledgements

This project was aided significantly by the efforts and support provided by the U.S. Department of Agriculture, Forest Service, Tallulah Ranger District of the Chattahoochee-Oconee National Forests. The authors gratefully acknowledge the contribution of Mr. Randy Fowler and Mr. Preston Steele toward the completion of this project.

Literature Cited

Anderson, H. W., M. D. Hoover, and K. G. Reinhart. 1976. Forest and water: Effects of forest management on floods, sedimentation, and water supply. General Tech. Rep. PSW-18: 115. Berkley, California: USDA Forest Service, Pacific Southwest Forest Experiment Station

Aubertin, G.M. and J.H. Patric. 1974. Water quality after clearcutting a small watershed in West Virginia. *J. Environ. Qual*. 3(3): 243-249.

APHA. 1995. Standard Methods for the Examination of Water and Wastewater. 19th ed. A. D. Eaton, L. S. Clesceri, and A. E. Greenberg. eds. New York, N.Y.: APHA.

Aust, W.M. and C.R. Blinn. 2004. Forestry Best Management Practices for timber harvesting and site preparation in the Eastern United States: an overview of water quality and productivity research during the past 20 years (1982-2002). *Water, Air, and Soil Pollution: Focus* 4: 5-36.

Arthur, M. A., G. B. Coltharp, and D. L. Brown. 1998. Effects of best management practices on forest stream water quality in eastern Kentucky. *J. American Water Resource Assoc*. 34(3): 481-495.

Bailey, Robert G. 1980. Description of the ecoregions of the United States. U. S. Department of Agriculture, Miscellaneous Publication No. 1391, 77 pp.

Bailey, R.G. 1995. Description of the Ecoregions of the United States. http://www.fs.fed.us/land/ecosysmgmt/index.html. March 1995.

Binkley, D. and T.C. Brown. 1993. Forest practices as nonpoint sources of pollution in North America. *Water Res. Bulletin* 29(5): 729-740.

Clinton, B.D. and J.M. Vose. 2003. Differences in surface water quality draining four road surface types in the southern Appalachians. *Southern J. Applied Forestry* 27(2): 100-106.

Elliot, W.J. and L.M. Tysdal. 1999. Understanding and reducing erosion from insloping forest roads. *J. Forestry* 97(8): 30-34.

Grace, J.M. III. 2005. Forest operations and water quality in the South. *Trans. ASAE* 48(2): 871-880.

Grace, J.M. III. 2006. A new design to evaluate erosion and sediment control. In: Pp. 153-162; Environmental Connection 06, Proceedings of Conference 37; 20-24 February 2006; Long Beach, California. International Erosion Control Association, Steamboat Springs, CO.

Grace, J.M. III and B.D. Clinton. 2007. Protecting soil and water in forest road management. *Trans. ASABE* 50(5): 1579-1584.

Grace, J.M. III and E.L. Davis. 2010. Effectiveness of Buffer Zones in Disconnecting Roads and Streams in the Coastal Plain. ASABE paper No. 108434. St. Joseph, MI: ASABE. 9 p

Kahklen, K. and J. Moll. 1999. Measuring effects of roads on groundwater: Five case studies. USDA Forest Service Technology and Development Program 9977 1801 – SDTDC. San Dimas, CA: USDA Forest Service Technology and Development Center. 13 p.

Litschert, S.E. and L.H. MacDonald. 2009. Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. *Forest Ecol. Mgmt* 259(1): 143-150.

Rivenbark, B.L. and C. R. Jackson. 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern Piedmont, USA. J. Am. Water Res. Assoc. 40(4): 1043-1052.SAS Institute. 2004. SAS OnlineDoc 9.1.3. SAS Institute, Cary, NC.

Swift, L. W., Jr. 1984. Gravel and grass surfacing reduces soil loss from mountain roads. *Forest Sci*. 30(3): 657-670.

USDA SCS. 1981. Soil Survey of Rabun and Towns Counties Georgia. Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service.

Van Lear, D.H., G.B. Taylor, and W.F. Hansen. 1995. Sedimentation in the Chattooga River Watershed. Tech. Pap. No. 19. Clemson, SC.: Clemson University, Department of Forest Resources.