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The Effects of Stream Crossings on Total Suspended Sediment in North Carolina Piedmont Forests

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This study determined total suspended sediment (TSS) at six stream crossings that represented a range of site conditions and forest operations in the Piedmont of North Carolina. Two wood and three steel bridgemats and one culvert were installed to cross the streams. The road classes for the crossings included four temporary skid trails and two permanent forest haul roads. Baseflow and stormflow water samples and continuous stream discharge were measured using the upstream-downstream approach to determine the effects of stream crossings on TSS concentrations and loads. Upstream and downstream TSS concentrations from grab samples were not significantly different at any site during the study period. Baseflow TSS concentrations averaged 21.7 mg/l upstream and 21.1 mg/l downstream across study sites and periods. Stormflow TSS concentrations averaged 84.8 mg/l upstream and 84.7 mg/l downstream across all sites and periods. TSS loads were also comparable to exports from unharvested Piedmont watersheds and other stream crossing studies that used forestry best management practices (BMPs) to protect water quality, averaging 82 kg/ha/year upstream and 80 kg/ha/year downstream of the crossing. Our results add to the body of research indicating that stream crossing BMPs designed in mountain systems can be effectively applied to other regions to protect water quality.

Keywords: stream crossing, best management practices, Piedmont, total suspended sediment

Experimental forests in the Mountains and Coastal Plain regions offer a long history of watershed hydrology and water quality data related to management of forest and water resources after silvicultural activities (Douglass and Swank 1975) and application of forestry best management practices (BMPs) (Swift 1985). The applications on how to properly manage for water quality protection on forest haul roads, skid trails, and stream crossings in the Piedmont are based primarily on data from the Mountains and Coastal Plain. Topography and climate conditions are unique to each area, resulting in a range of potential sediment responses to land management practices. Quantifying sedimentation from forest operations within and across regions will be useful information to land and forest managers as they develop strategies and make decisions for sustaining water quality and forest resources across the state of North Carolina (Wear and Greis 2002). Few data on sedimentation production from bridgemat and skid trail BMPs are available for the Piedmont portion of the state (Cristan et al. 2016). Piedmont studies that define the range of stream sediment variability at road and skid trail crossings are needed to adequately address water quality and sediment export concerns and fully satisfy regulatory requirements.

North Carolina considers forestry BMPs as a collection of practices (e.g., placing structures across streams, gravel on haul roads, and slash on skid trails) designed to reduce the risk to water quality from non-

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft. millimeters (mm): 1 mm = 0.039 in.; hectares (ha): 1 ha = 2.471 ac; milligrams (mg): 1 mg = 0.015 grain; liter (l): 1 l = 1.057 quart (liquid).

point sources during harvest operations and other forestry-related and site-disturbing practices (Jones 2011). Stream crossing, forest haul roads, and temporary skid trails deliver more sediment to streams than any other BMP category (i.e., streamside management zone and site preparation), particularly when they are not properly implemented (Jones 2011). To minimize sedimentation at stream crossings during forest operations, loggers should avoid streams when possible, cross them at a 90° angle, approach the stream on a gentle slope, minimize the number of crossings, ensure that enough gravel, waterbars, or slash is on the road or trail to slow water movement, and cross with the proper type of stream crossing structure (Grace 2005, Litschert and MacDonald 2009). Culverts, fords, and wood or steel portable bridgemats are some common structures used to cross streams. Bridgemats can be used on haul roads and skid trails (Aust et al. 2011), and in many ways portable bridgemats are a better type of structure for crossing streams. They can be installed with minimal disturbance to the streambanks and without obstructing flow, fashioned into various widths and lengths, and reused. When slash and mulch with seed treatments are applied to skid trails (Wear et al. 2013) and BMPs are properly applied on forest roads (Turton et al. 2009), they have been shown to prevent sedimentation to surface water.

Reeves (2012) found that bridgemats produce less sediment than culverts and improved rock fords. Morris et al. (2015) reported that a culvert crossing produced 2.9 g/l of sediment concentration, whereas a ford and bridge produced 1.4 and 0.2 g/l, respectively. They concluded that current BMPs for stream crossings are effective for reducing sedimentation compared with stream crossing structures with no BMPs. In contrast, a study in the Piedmont of Virginia found that total suspended sediment (TSS) loads produced from bridgemat, culvert, and ford crossings were similar (Carroll 2008). When BMPs are not applied properly on forest access roads across North Carolina, water quality is reduced 14% of the time (Jones 2011). Streams with no crossing structure cause the largest impacts to water quality compared with sites that implement forestry BMPs (Thompson and Kyker-Snowman 1989, Tornatore 1995). The combination of controlling sediment from entering the stream at the crossing structure and preventing rapid mobilization of sediment from the approachways (i.e., roads and skid trails) that are connected to stream crossings will probably have the most positive influence on reducing the risk to water quality on active harvest sites across the Mountains, Piedmont, and Coastal Plain (Jones 2011, Brown et al. 2015).

The objectives of this study are the following: to quantify TSS loads across a range of site conditions (e.g., steep and gentle slopes, and clayey and sandy soils) and forestry operational BMPs (i.e., bridgemats and forest haul road and skid trail stream crossings) that are used in the Piedmont of North Carolina to protect water quality; and to improve our understanding of watershed hydrology and sedimentation related to sustainability of water resources after forest operations.

Materials and Methods

Study Sites

This stream crossing study used the upstream-downstream approach to monitor TSS concentrations and loads and stream discharge in six watersheds across the Piedmont of North Carolina (Table 1; Figures 1 and 2). Site conditions (different watershed size, discharge rate, road class, crossing, soil, and slope) varied across study locations. The size of the study watersheds ranged from 17 to 343 ha. A perennial stream channel was located in each catchment, and all had a rocky substrate. Land cover varied across the landscape. The General Electric (GE) site was estimated to be about 30% urbanized, but all monitored watersheds were dominated by forest cover with different dominant soil types (Soil Survey Staff 2015, Table 1). The Montgomery County (MC) soil type had greater clay characteristics than the other sites. Slope on the approach to the stream crossing ranged from 1 to 20%. The permanent haul road at MC had the steepest approaches to the crossing.

Study sites were on both public and private lands. The Hill Demonstration Forest (HDF1), MC, and Orange County (OC) sites are owned and managed by state and county governments, and the private lands of Duke Forest (DKF1 and DKF2), and GE are managed by staff and consulting foresters. Wood bridgemats were used for the skid trails, steel bridgemats were used on the skid trails and haul road, and the culvert was used on a forest haul road to cross the streams (Figure 3A–F). North Carolina Forest Service forestry BMPs were followed at each crossing to protect water quality during each logging operation—a seed tree harvest at DKF1, a thinning at GE and HDF1, and a clearcut at DKF2, MC, and OC.

Trail and Road Construction and Stream Crossing Installation

The temporary skid trails at HDF1, DKF1, DKF2, and GE were constructed along the flattest part of the slope that approached a relatively straight section of the stream. The widths of the trails were 4–5 m wide. The approach section of the trail to each stream ranged from 9 to 21 m in length. The temporary skid trail at DKF2 had the longest and steepest approach. Turns, bends, and water diversions were placed along each trail where appropriate to slow the overland water flow, divert water off the trail, disperse sediment across the forest

Management and Policy Implications

Stream crossing best management practices (BMPs) can serve to help water resource managers meet current water policy pollution load requirements and other regulatory measures aimed to protect fish and other aquatic species. Given the variability in soils, topography, forest management, and previous land uses within and across regions in the state of North Carolina, some sites might experience more sediment production at stream crossings than others. Thus, it is important to keep improving our knowledge of how water quality is affected by stream crossings. Stream crossings did not significantly increase total suspended sediment (TSS) at any of the study sites during preharvest, harvest, or closure. Even though site conditions and forest operations can vary within the Piedmont and across the state, maintaining adequate BMP measures seems to prevent increased risks for soil erosion to streams at road and stream crossing sites. These protective measures may also help resource managers improve their ability to minimize sediment loads generated in source water catchments to meet state water quality standards. Water resource and land managers should incorporate TSS data from this study into their decision support system to help estimate sediment concentrations and exports from stream crossings, haul roads, and skid trails in Piedmont forests and to further refine state BMP guidelines.

Table 1. Details of six stream crossing study sites in the Piedmont of North Carolina.

						% slope before approach to the crossing	
Site, location	Mean total suspended sediment concentration (mg/l)	Watershed size (ha)	Road class, type of crossing	Total suspended sediment and streamflow data collected	Dominant watershed soil series and streambed	From right bank	From left bank
Duke Forest 1, Durham, NC	DKF1	17	Temporary skid trail, wood bridgemat panels	April 2011–August 2011	Helena sandy loam, rocky streambed	1	1
Duke Forest 2, Hillsborough, NC	DKF2	68	Temporary skid trail, steel bridgemat panels	July 2012–January 2014	Georgeville silt loam, Goldston channery silt loam, rocky streambed	8	6
General Electric, RTP, NC	GE	343	Temporary skid trail, steel bridgemat panels	November 2010–February 2011	White Store sandy loam, Chewacla and Wehadkee soils, rocky streambed	2	1
Hill Demonstration Forest 1, Bahama, NC	HDF1	58	Temporary skid trail, wood bridgemat panels	March 2011–August 2011	Herndon silt loam, Appling sandy loam, rocky streambed	1	2
Montgomery, Montgomery County, NC	MC	58	Permanent haul road, culvert 0.76-m diameter	April 2013–January 2014	Herndon silt loam,Georgeville silt loam, rocky streambed	20	8
Orange County, Orange County, NC	OC	164	Permanent haul road, steel bridgemat panels	March 2013–July 2015	Enon loam, Tarrus silt loam, rocky streambed	8	10

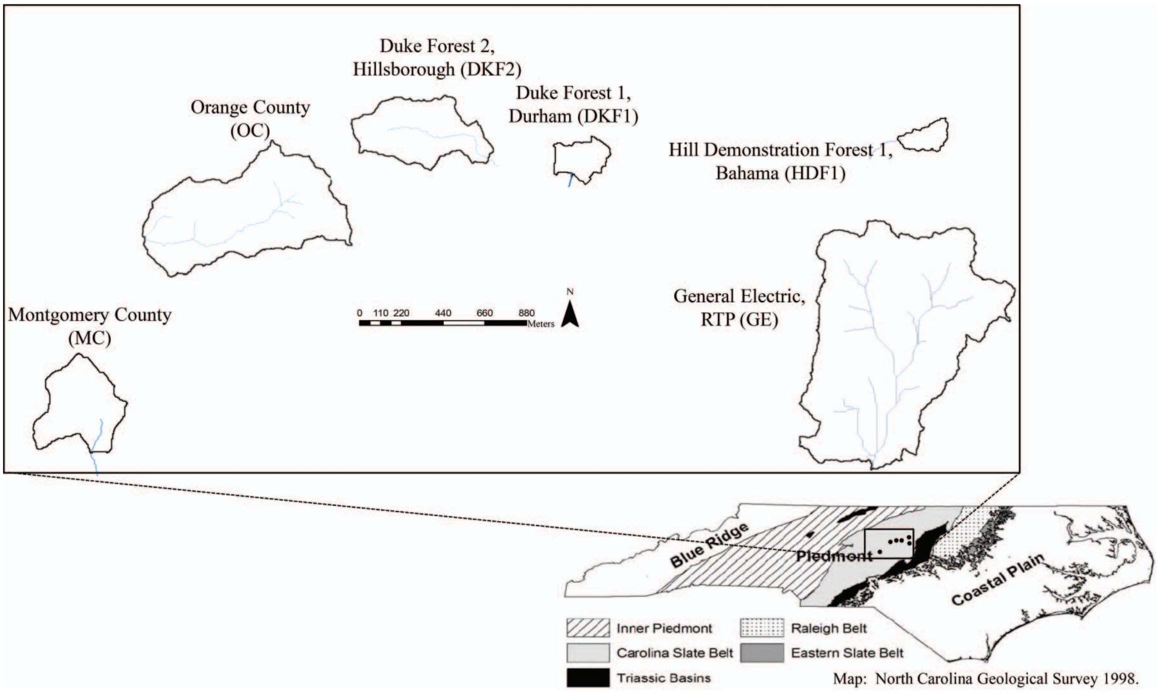

Figure 1. Watersheds used in stream crossing study across the Piedmont of North Carolina.

floor, and reduce erosion along the trail. Bumper trees (trees used by the skidder driver to help guide logs across the stream crossing) were left along the edge of the stream to minimize damage to the streambanks from branches and to maintain bank stability and along bends to pivot long logs around turns. Slash was redistributed along the entire downslope length of the skid trails to hinder soil movement and to minimize soil disturbance. The bridgemats were placed on stable banks across the channel with the grapple of the skidder (Figure 3D). This technique limited sediment from entering the stream during the installation and removal of the bridgemat. After the harvest was complete, a section of each approachway near the stream was grassed (i.e., seed, straw, fertilizer, and/or lime were applied), and any debris that fell into the stream was removed according to North Carolina Forest Practices Guidelines (02 NCAC 60C 0.0202) as part of the site closure process.

The MC site had an existing forest road, whereas the road at OC was newly constructed. The MC haul road was improved by adding fill and properly spaced broad-based dips (Swift 1985). Based on the amount of expected discharge within the watershed area, the existing culvert at MC

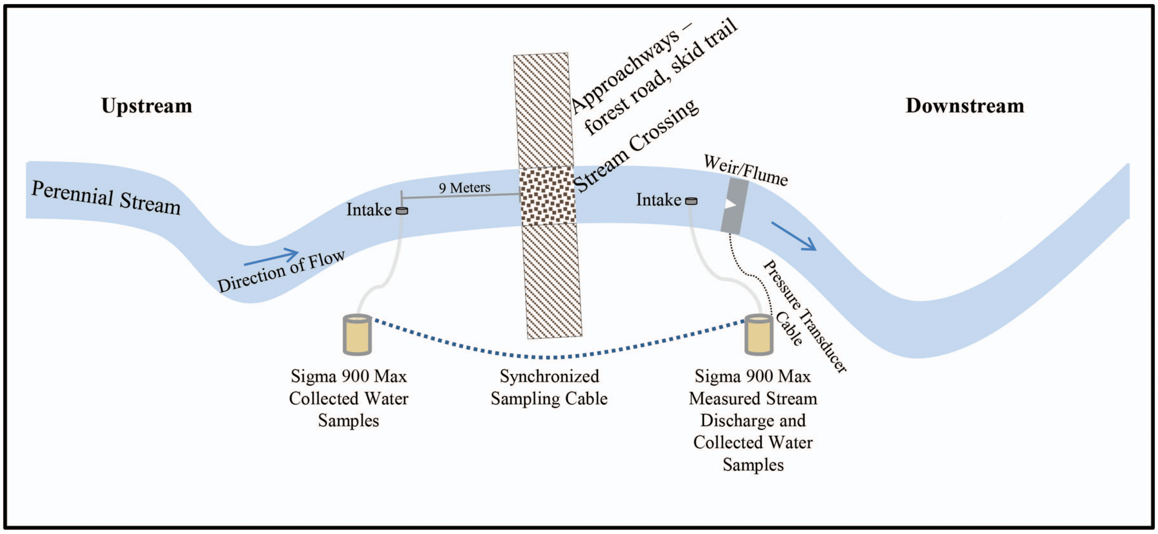

Figure 2. Upstream-downstream approach to monitor stream discharge and collect stormflow water samples for TSS concentrations.

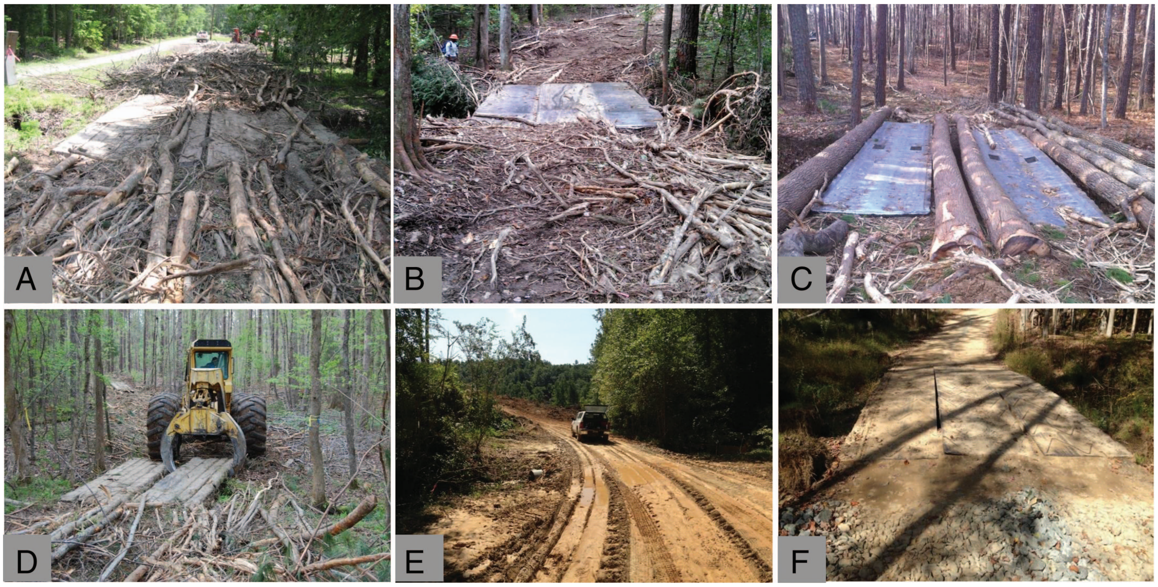

Figure 3. Stream crossing sites. A. DKF1 wood bridgemats on temporary skid trail. B. DKF2 steel bridgemats on temporary skid trail. C. GE steel bridgemats on temporary skid trail. D. HDF1 wood bridgemats on temporary skid trail. E. MC 0.76-m diameter culvert on permanent haul road. F. OC steel bridgemats on permanent haul road. To convert m to ft, multiply m by 3.28.

was undersized and not suitable for use. Therefore, the culvert was replaced with a 0.76-m-diameter, 9-m-long riveted galvanized corrugated steel pipe. The new culvert was installed in the center of the existing streamflow and set such that the downslope grade did not impede streamflow (Brogan et al. 2006). A section on both sides of the road that approached the stream crossing was raised slightly (but not crowned) with fill to adequately stabilize and cover the height of the steel culvert. Although adding a surface-hardening material to the approach is recommended in the North Carolina BMP manual, no riprap or wash stone was observed on the approachways to provide vehicle support or to minimize soil erosion during or after harvest operations (Figure 3E). Some seed, straw, and rock were added around the inlet and outlet of the culvert. However, based on the recommendation in the North Carolina BMP manual, the amount did not seem sufficient to completely prevent soil erosion and sediment movement.

Two 26-m-long sections on both sides of the permanent haul road at the OC tract that approached the stream crossing were excavated to a depth of 0.7 m and width of 4.9 m. At the base of the excavated area a 5.2-m-wide Huesker P45/45 woven fabric was placed at the bottom for the entire length of the excavated area with a 15-cm overlap to extend up the outer sides. Class A riprap and washed stone were placed on top of the fabric for a total depth of 30 cm across the entire excavated area on both sides of the stream. A forknit 20 geo-grid fabric was then placed on top of the no. 57 washed stone. Aggregate base course gravel was then placed on top of the geo-grid fabric at a depth of 25 cm or to the top of the existing grade. The slopes and banks were stabilized with lime, fertilizer, and a permanent erosion blanket. Straw or hay bales were used in roadbed channels when needed to prevent sediment from reaching the stream. The bridgemats were positioned on stable banks across the channel by a grapple skidder to minimize disturbance around the stream.

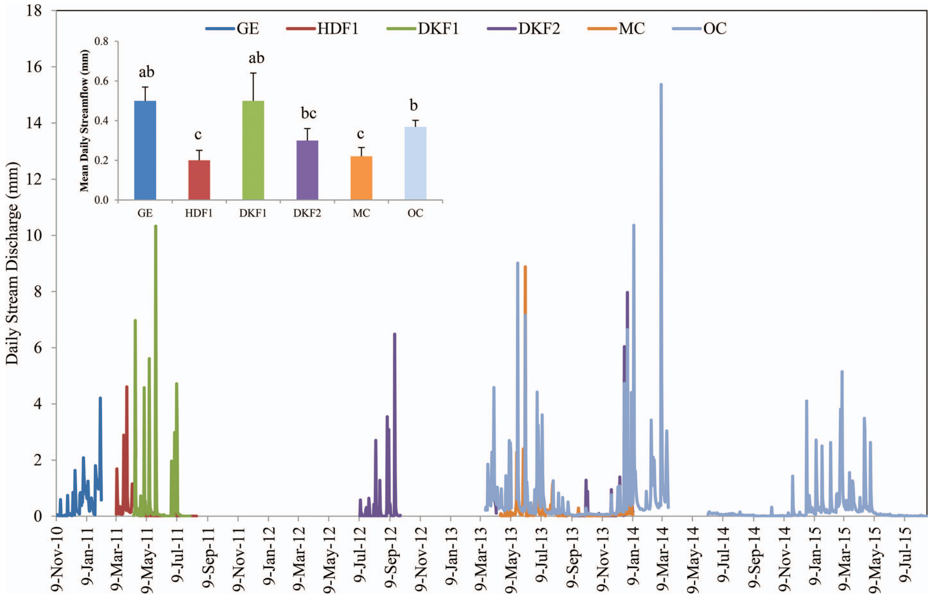

Figure 4. Daily stream discharge for stream crossing study sites in the Piedmont of North Carolina. Inset depicts mean daily stream discharge during the monitoring period. To convert mm to in., divide mm by 25.4.

Stream Discharge and TSS Measurements

Depending on the size of the watershed, a 90° V-notch weir or a 2-H or 3-H flume was used as the flow control structure at the outlet of the catchment. Two Sigma 900 Max water samplers, one with a pressure transducer and intake tube and the other with just an intake tube, were placed 6–9 m downstream and upstream of the crossing to measure discharge data every 10 minutes and/or to collect stormflow water samples (Figure 2). Discharge data were collected in units of l/sec. The discharge values were then divided by the watershed size and converted to mm to normalize the data and make them comparable across watersheds. The 900 Max water samplers were connected with a synchronized sampling cable so that upstream and downstream water samples could be collected at the same time. The Sigma sampler was programmed to collect 12 stormflow water samples based on an increase in the flow rate of change (e.g., 1.1 l/sec). The downstream intake tube was placed at least 2 m from the weir or flume to lessen any influence this structure could have on stormflow and TSS concentrations. Grab water samples were collected at least biweekly under baseflow conditions. TSS concentrations and loads were quantified at each crossing during three periods (preharvest, harvest, and closure periods). Each period ranged from 4 to 27 months.

The water samples were preserved with sulfuric acid to pH <2 and were stored at 3.6° C before analysis. TSS was determined at the North Carolina State University Soil Science Analytical Laboratory using standard methods (Greenburg 1992). A clinometer was used to estimate the slope of the approaches. We performed qualitative assessments of sediment deposition or trapping (i.e., noted if we saw sediment building up in the stream) at each stream crossing site to determine whether the rocky streambed and in-channel woody debris at the crossing accumulated fine sediment.

Data Processing and Analysis

The stormflow samples were collected on a stratified sampling program. Intensive sampling (i.e., six samples in 1 hour) was done as streamflow increased and less intense sampling (six samples over 2 to 14 hours) was done as streamflow decreased. To avoid the potential to overemphasize one limb of the hydrograph (or to interpolate between measured times), time-weighted mean concentration for each constituent was computed, and then the flow-weighted concentrations were determined.

Water quality or TSS concentration was measured in mg/l. The values were then multiplied by discharge volume to determine outputs expressed as kg/ha/year. Despite some sites having less than 1 year of data, daily water yield and mean monthly TSS concentrations from most watersheds were fairly typical of forested catchments (i.e., 0.4 to 0.5 mm/day and 60 mg/l, respectively) (Boggs et al. 2013, 2016). As a result, we estimated annualized TSS exports based on the average water yield and TSS concentrations for the monitoring period for that site. For most sites, the final load calculations for the upstream location (considered the reference location) seem to provide reasonable estimates of annualized TSS exports compared with values in other Piedmont undisturbed forested watersheds (Boggs et al. 2013). Discharge at the MC site was on the lower end of what we typically observe in Piedmont of North Carolina forested watersheds (Boggs et al. 2016).

Three sets of stormflow samples from the OC site were discarded because it appeared that the intake tube collected bedload samples instead of suspended sediment. When these stormflow samples were collected, stormflow peak was around 5% (0.009 m^3/sec) of the estimated bankfull discharge (0.17 m^3/sec) needed to carry enough bedload to cover the intake. In addition, these stormflow samples were the first ones collected after the reinstallation of the intake tube after a break in monitoring. Therefore, we assumed that the large particles of sediment were collected as a result of the reinstallation process and not upstream sediment carried downstream by high flows.

We analyzed mean upstream and downstream TSS concentrations across preharvest, harvest, and closure periods using the Wilcoxon nonparametric method (SAS Institute, Inc. 2011). The Wilcoxon method was selected, and the significance level was $\alpha \leq 0.05$ to determine which group values (i.e., upstream versus downstream) were statistically different from each other. The *t*-test was used to determine significant differences between stream discharges across sites over the study period (SAS Institute, Inc. 2011). Significant difference was defined by $P \leq 0.05$.

Results

Stream Discharge

A seasonal trend in stream discharge was observed over the monitoring period. Most of the low values occurred during the growing season, May–October (Figure 4). Based on mean daily discharges, annual stream discharge ranged from 70 to 180 mm across the study sites. GE and DKF1 produced the highest water yield. Mean daily stream discharges at MC and OC were significantly lower than those at GE, DKF1, and OC (Figure 4, inset). Mean daily stream discharge at DKF2 was not significantly different from that at any other site.

Although the percentage of exceedances (i.e., a 5% exceedance means that daily discharge is expected to exceed that flow on 5% of the days monitored) varied across the watersheds, the daily flow frequency distribution showed a similar pattern among most watersheds (Figure 5). The percent exceedance line for watersheds with little to no impervious cover (DKF1, DKF2, HDF1, MC, and OC) was relatively flat from 0.0001 to 0.015 mm/day. After this point, the frequency of discharge decreased rapidly as stream discharge increased. This trend is typical for Piedmont forested watersheds in North Carolina (Boggs et al. 2016). Once daily discharge exceeded 0.75 mm, the high flows caused stream discharge at DKF1 (green line) to depart from the other sites. Eighty-five percent of the flow at DKF1 was produced during 10% of the monitoring period at this site. GE, which is about 30% urbanized, showed the narrowest range of discharge.

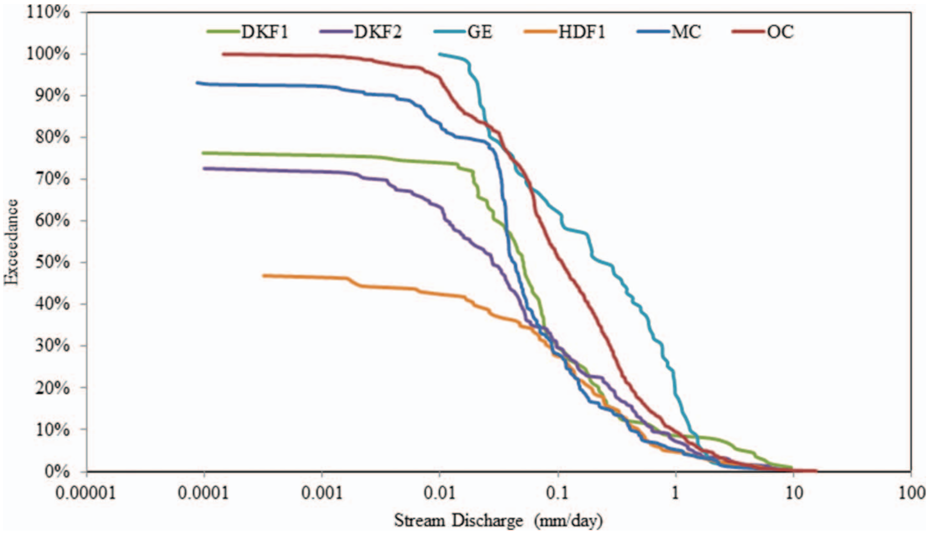

Figure 5. Percent exceedance of daily stream discharge across stream crossing study sites. To convert mm to in., divide mm by 25.4.

TSS Concentration

A total of 808 water samples were collected to quantify TSS concentrations in the preharvest, harvest, and closure periods across six stream crossing sites. Overall, TSS concentrations did not increase significantly at any road or skid trail stream crossing site during any period (Table 2). TSS concentrations from stormflow and grab + stormflow samples decreased significantly at HDF1 during the closure period. Sustained flow or baseflow TSS concentrations averaged 21.7 (SE, 2.6) mg/l upstream and 21.1 (2.7) mg/l downstream across study sites and periods. Stormflow TSS concentrations averaged 84.8 (12.7) mg/l upstream and 84.7 (13.0) mg/l downstream across all sites and periods. Within monitored periods, stormflow TSS concentrations were much higher than grab TSS concentrations at all sites. Variability (i.e., SE) in upstream and downstream stormflow TSS concentration increased from preharvest period to closure period in DFK2 and MC and remained relatively constant across periods at the other sites. HDF1 had the highest variability in upstream and downstream stormflow TSS concentrations in the preharvest and harvest periods (SE ranged from 24.8 to 33.3 mg/l) but some of the lowest SEs during the closure period (4.6–8.2 mg/l).

TSS Load

Annualized TSS load ranged from 22 to 114 kg/ha/year at the upstream station and from 26 to 115 kg/ha/year at the downstream station during the preharvest period (Figure 6A). Upstream and downstream TSS loads in the harvest and closure periods were similar to those in the preharvest period, all periods producing mean loads between 80 and 90 kg/ha/year (Figure 6A–C). DKF2 produced the highest export at 123 kg/ha/year during the closeout period (Figure 6C). MC had the biggest change in TSS load from the preharvest period to the closure period, increasing from 22 to 104 kg/ha/year upstream and 26 to 111 kg/ha/year downstream.

TSS Concentration-Discharge Relationship

Mean daily TSS concentration responded significantly to high daily stream discharge ($\geq$0.75 mm/day) at both upstream (i.e., $r^2 = 0.22$, $P = 0.002$) and downstream (i.e., $r^2 = 0.23$, $P = 0.001$) locations (Figure 7). The slopes of the regression lines fitted to each set of data were not significantly different than each other (i.e., upstream slope versus downstream slope). Evaluation of the TSS interquartile range of the boxplot (this excludes the outliers) revealed a wider spread in daily mean TSS concentration during high daily discharge compared with low daily discharge periods (Figure 8A and B). Mean daily TSS downstream data were more skewed toward the lower values of the interquartile range, whereas mean daily TSS upstream data were more evenly distributed across the interquartile range.

The highest stormflow discharge data along the time series did not always show the highest concentration of stormflow sediment (Figure 9). The TSS concentration sometimes peaked before stream discharge peaked. DKF1, GE, MC, and OC upstream and downstream stormflow TSS concentrations increased initially (from 0 to 1 hour) and then decreased (Figure 9A, C, E, and F). The TSS concentration in DKF2 remained relatively high throughout the time series. In addition, DKF2 upstream TSS concentration increased from the 3- to 4-hour sampling interval whereas downstream TSS concentration decreased as discharge decreased during this same time period (Figure 9B). HDF1 upstream and downstream TSS concentrations remained high even though stormflow discharge had returned to prestorm levels (Figure 9D).

The TSS-discharge relationships resulted in a clockwise hysteresis (sediment decrease with time for a given discharge) for most sites (DKF1, DKF2 [downstream only], GE, and OC) and a counterclockwise hysteresis (sediment increase with time for a given discharge) for other sites (DKF2 [upstream only], and HDF1) (Figure 10). MC was the only site where TSS-discharge formed a counterclockwise and then clockwise hysteresis.

Table 2. Grab, stormflow, and grab + stormflow mean and monitoring peak upstream and downstream TSS concentration during preharvest, harvest, and closure periods across six stream crossing sites in the Piedmont of North Carolina.

Periods	No. of samples	Grab upstream TSS	Grab downstream TSS	Stormflow upstream TSS	Stormflow downstream TSS	Grab + stormflow upstream TSS	Grab + stormflow downstream TSS	Peak upstream TSS	Peak downstream TSS
		....	....	....	............(mg/l)	....	....	....	
Duke Forest 1, DKF1									
Preharvest	64	26.0 (2.8)	21.5 (2.3)	44.2 (5.2)	43.5 (5.0)	42.6 (5.3)	42.0 (5.4)	300	420
Harvest	15	29.7 (4.9)	36.3 (1.2)	45.6 (5.9)	56.4 (5.6)	45.5 (6.0)	55.1 (6.1)	150	120
Closure	15	36.0 (3.5)	33.0 (1.0)	53.1 (3.5)	57.9 (4.5)	50.9 (3.8)	54.1 (4.6)	68	110
Total	94								
Duke Forest 2, DKF2									
Preharvest	75	31.8 (9.1)	25.8 (10.5)	94.3 (14.7)	92.2 (15.0)	87.9 (15)	86.3 (15.1)	900	640
Harvest	2*	5.5 (0.5)	6.5 (0.5)			5.5 (0.0)	6.5 (0.0)		
Closure	27	7.5 (1.5)	9.0 (1.0)	117.6 (20.8)	110.9 (19.6)	115.0 (22.6)	107.6 (21.1)	369	335
Total	104								
General Electric, GE									
Preharvest	13	19.0 (0.0)	19.0 (0.0)	43.0 (4.0)	37.2 (3.9)	41.6 (4.5)	36.5 (4.2)	50	46
Harvest	14	26.5 (5.5)	29.5 (7.5)	66.4 (2.3)	67.7 (2.3)	61.4 (3.0)	63.6 (4.0)	84	84
Closure	50	31.5 (5.2)	23.0 (6.8)	50.3 (4.4)	45.6 (3.9)	47.5 (2.9)	42.6 (2.1)	200	180
Total	77								
Hill Demonstration Forest 1, HDF1									
Preharvest	46	45.3 (7.9)	47.7 (11.0)	180.7 (25.7)	182.3 (24.8)	171.8 (26.6)	173.8 (26.0)	800	850
Harvest	13	20.0 (0.0)	12.0 (0.0)	122.9 (32.0)	126.7 (30.8)	112.4 (33.3)	115.1 (32.5)	480	470
Closure	42	21.6 (3.8)	26.6 (3.9)	93.4 (4.6)a	75.5 (4.7)b	85.7 (8.2)a	68.7 (5.0)b	190	120
Total	101								
Montgomery County, MC									
Preharvest	52	21.4 (3.8)	23.6 (5.3)	29.4 (1.9)	35.2 (2.7)	28.3 (1.7)	33.3 (2.0)	73	93
Harvest	3*	10.7 (2.3)	11.0 (1.5)			10.7 (0.0)	11 (0.0)		
Closure	27	4.5 (0.5)	3.5 (0.5)	214.9 (30.2)	224.1 (26.9)	151.1 (27.2)	158.9 (30.1)	286	320
Total	130								
Orange County, OC									
Preharvest	178	15.5 (2.6)	15.1 (2.8)	50.7 (5)	55.5 (5.7)	46.5 (3.9)	51.1 (5.5)	386	673
Harvest		—†	—	—	—	—	—		
Closure	172	16.9 (2.4)	16.5 (1.8)	65.3 (6.9)	59.7 (8.2)	61.1 (7.5)	56.3 (8.7)	230	270
Total	350								

Means (SE) with different letters are significantly different at $P < 0.05$ using the Wilcoxon nonparametric method. No letter next to values indicates no statistical difference.

* Only grab samples were collected during this period (there was not enough rain to collect storm samples).

† There was no streamflow to collect grab or stormflow samples in this period. To convert mg/l to lb/gal, multiply by 0.00000834.

Discussion

Meeting State Regulatory Requirements and Challenges

This study provides rates of stream sediment concentrations across a range of site conditions in the Piedmont where stream crossing BMPs were used to meet the state of North Carolina water quality requirements and challenges. Establishing site-specific guidelines and determinations for stream crossing management practices for each North Carolina region (i.e., Mountain, Piedmont, and Coastal Plain) may improve a resource managers' capacity to estimate sediment exports and support proper BMP implementations to help protect aquatic resources (Jackson et al. 2004, Lee et al. 2004).

North Carolina has several mandatory performance standards to protect water quality during forest operations. The rule requirements are outlined by statewide regulations called Forest Practices Guidelines Related to Water Quality (FPGs). Regulations for access road and skid trail stream crossings rule (FPG .0203) require streams to be avoided when possible and forest haul roads and skid trails that cross intermittent or perennial streams or perennial water bodies to be "constructed so as to minimize the amount of sediment that enters the streams because of the construction" (North Carolina Forest Service 2014). Violation of FPG .0203 is the most frequent FPG rule violation observed in North Carolina during ground and implementation surveys (Jones 2011). Stream crossings associated with timber harvesting can alter water quality and have an impact on aquatic species, but the effects are usually localized (Schilling and Ice 2012). Local sedimentation inputs are some of the current and future challenges for water quality foresters and land managers. They must develop strategies to sustain water quality and accurately manage against nonpoint source pollution from forest operations to comply with existing state and federal regulations.

Our study results showed that installation of stream crossings and the construction of forest haul roads and skid trails did not significantly increase downstream TSS concentrations compared with upstream TSS concentrations (Table 2). Although we did not observe significant increases in sedimentation at the streams, it is notable to mention that stormflow TSS concentrations increased at some sites. For example, during the closure period, the TSS concentration increased by 4.8 mg/l at DKF1 in downstream samples compared with upstream and by 9.2 mg/l at MC downstream samples compared with upstream. These increases are probably linked to a combination of sedimentation around the culvert, steep slopes, and clayey soil conditions at MC and high discharge rates at DKF1. A heavy thunderstorm on May 27, 2011, was responsible for the high discharge observed at DKF1 (Fig-

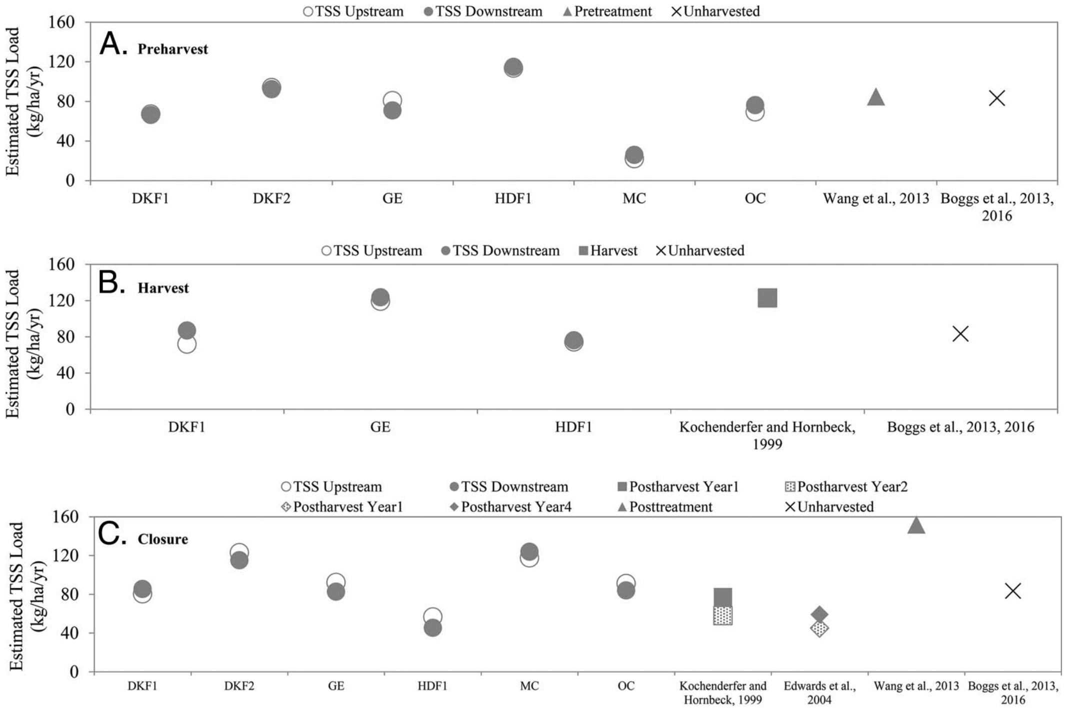

Figure 6. Annual upstream and downstream total suspended sediment (TSS) load across all study sites during preharvest (A), harvest (B), and closure periods (C). Our study data are plotted against TSS loads from other stream crossing studies (Kochenderfer and Hornbeck 1999, Edwards et al. 2004, Wang et al. 2013 and from unharvested forested watersheds in the Piedmont of North Carolina (Boggs et al., 2013, 2016). To convert kg/ha/year to lb/ac/year, multiply by 0.89.

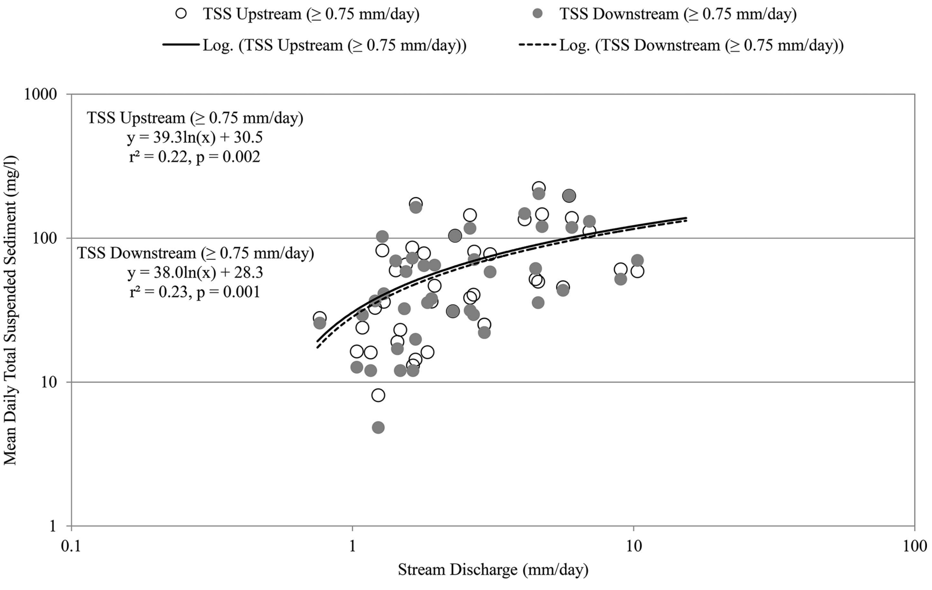

Figure 7. Relationship between mean daily upstream and downstream TSS concentration (mg/l) during high stream discharge (≥0.75 mm/day) across all study sites and all periods (preharvest, harvest, and closure). To convert mg/l to lb/gal, multiply by 0.00000834.

ure 9A) where 41.7 mm of rainfall fell in 3½ hours of which 25.4 mm fell in about 1 hour (State Climate Office of North Carolina 2016). HDF1 received some rainfall from this storm, but produced a less dramatic discharge response because stream discharge was zero at the time of the storm. A large percentage of the rainwater probably went to recharge and storage at HDF1.

The lack of significant increases in sediment between upstream and downstream locations during both baseflow and stormflow periods suggests that water quality and the macroinvertebrate community supported by these streams (i.e., Ephemeroptera [mayfly], Plecoptera [stonefly], and Trichoptera [caddisfly]) (EPT) were not negatively affected by sedimentation from the crossings, forest roads, or skid trails. Boggs et al. (2016) found that a 5.0 mg/l increase in TSS concentrations (i.e., 28.6–33.6 mg/l) did not have a negative impact on EPT taxa richness or functional feeding group categories (e.g., collector gatherers, scraper collectors, shredders, and predators). Gray and Ward (1982) reported that an increase in sediment of 20 to 80 mg/l could reduce desirable invertebrate populations. Upstream and downstream sustained and stormflow TSS concentrations in this study were below the threshold sediment concentrations (300 mg/l) that may cause shifts in the macroinvertebrate communities (Moring 1982, Appelboom et al. 2002). Auld and Schubel (1978) found that concentrations >100 mg/l significantly reduced the survival of shad larvae continuously exposed for 96 hours in an estuarine system. TSS concentration above 100 mg/l for more than 96 hours were not observed in this study.

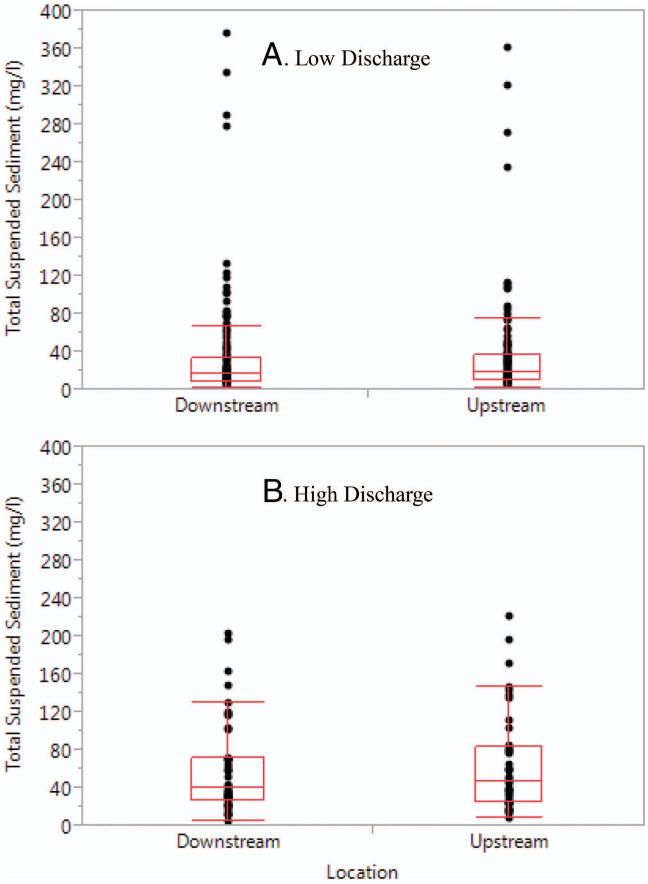

Figure 8. Boxplots of mean daily TSS concentrations (mg/l) at the upstream and downstream locations during low (≤0.75 mm/day) (A) and high stream discharge (≥0.75 mm/day) (B) across all study sites and all periods (preharvest, harvest, and closure). To convert mg/l to lb/gal, multiply by 0.00000834.

Sustaining Water Quality across Regions

TSS Concentration. Research from experimental forests in the North Carolina's Mountains and Coastal Plains has resulted in many years of watershed hydrology and water quality data after timber harvesting. However, because of differences in climate, soils, topography, and land-use history, these practical forest management data sets may not necessarily provide adequate protection to water quality during forest operations and at crossing structures in the Piedmont of North Carolina. In this study, we found that downstream mean daily TSS data were clustered on the lower end of the TSS interquartile range of the boxplot, which seems to underscore the trend that downstream TSS concentrations were less than upstream TSS concentrations across the Piedmont. TSS downstream concentrations decreased up to 17.9 mg/l from upstream concentrations at the HDF1 site. The lower downstream TSS concentrations compared with upstream TSS concentrations were probably due to sediment being trapped along the banks and behind debris and cobbles during both low and high flows (Tornatore 1995, Wiitala 2013). Study downstream TSS concentrations ranged from 56.4 (5.6) to 126.7 (30.8) mg/l during the harvest period in the Piedmont. These sediment concentrations are on the lower range

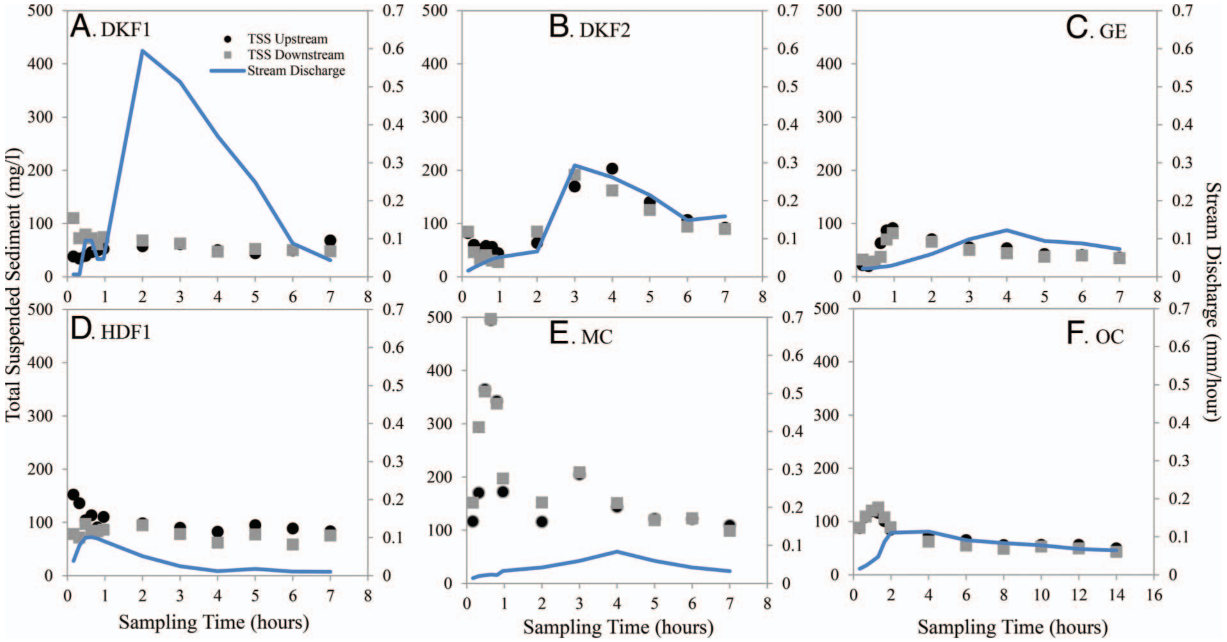

Figure 9. Time series of stream discharge and mean upstream and downstream TSS concentrations from all stormflow samples across each study site in the closure period. A. DKF1 wood bridgemats on temporary skid trail. B. DKF2 steel bridgemats on temporary skid trail. C. GE steel bridgemats on temporary skid trail. D. HDF1 wood bridgemats on temporary skid trail. E. MC 0.76-m diameter culvert on permanent haul road. F. OC steel bridgemats on permanent haul road. To convert mg/l to lb/gal, multiply by 0.00000834.

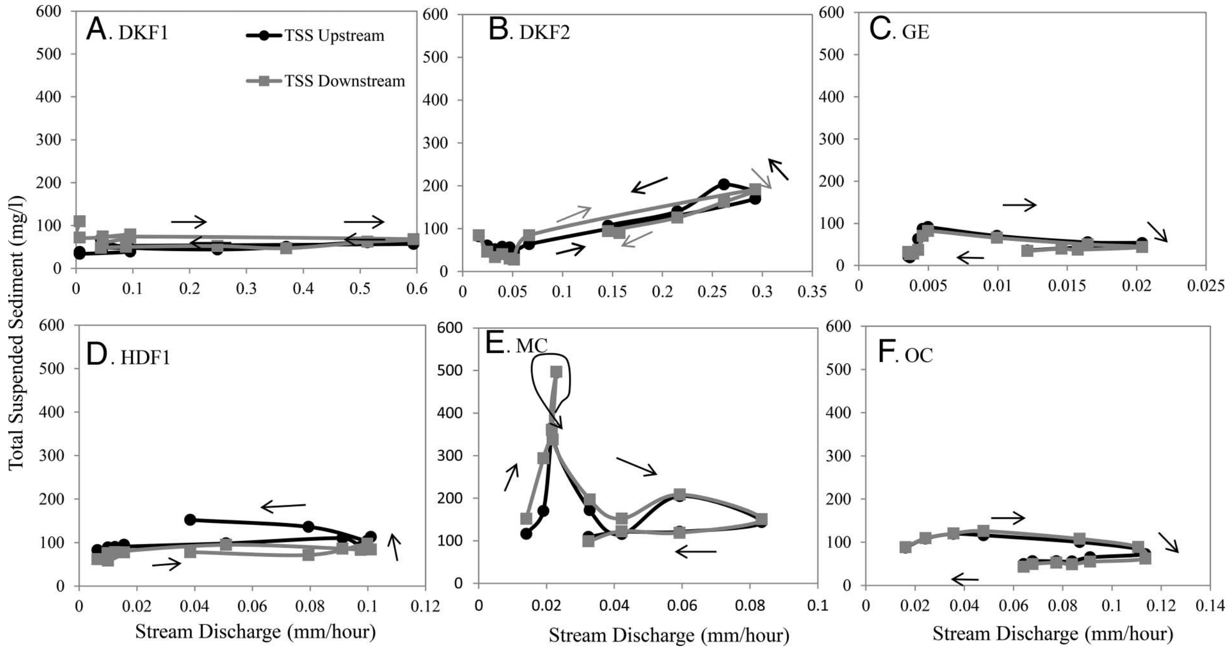

Figure 10. Mean stream discharge and mean TSS hysteresis from all stormflow samples across each study site in the closure period. A. DKF1 wood bridgemats on temporary skid trail. B. DKF2 steel bridgemats on temporary skid trail. C. GE steel bridgemats on temporary skid trail. D. HDF1 wood bridgemats on temporary skid trail. E. MC 0.76-m diameter culvert on permanent haul road. F. OC steel bridgemats on permanent haul road. Arrows depict hysteresis shape, clockwise or counterclockwise. To clearly show the hysteresis for each site, the *x* axes are not on the same scale. To convert mg/l to lb/gal, multiply by 0.00000834. To convert mm to in., divide mm by 25.4.

compared with sediment in streams in the Mountains and on the upper end compared with the Coastal Plains. Clinton and Vose (2003) found that in the Mountain region in the Southern Appalachians, sediment movement from road surfaces is highly variable within and among surface types and is related to levels of maintenance and road drainage. An unimproved graveled road section produced an average of 3,200 mg/l of TSS over their study period, whereas the improved gravel produced an average of about 1,470 mg/l and paved road generated an average of 153 mg/l. In the Piedmont of Georgia, Rummer et al. (1997) found no significant differences in sediment loss among forest road surface treatments (native material, native material with vegetative stabilization, 6 cm of gravel, and 15 cm of gravel with geotextile) and lower sedimentation was observed on the downstream than upstream roadbanks. On the Coastal Plain of North Carolina, Appelboom (2000) reported that graveling, vegetated strips, and continuous berms reduced the amount of sediment produced from forest access roads and the amount of sediment that was transported to roadside ditches. These Coastal BMP sites had sediment concentrations that ranged from a lower limit of 4.5 mg/l to an upper limit of 35.9 mg/l. Non-BMP or non-graveled road surfaces had sediment concentrations that reached 850 mg/l.

Soil erosion and direct paths of sediment to streams from access roads and skid trails will form differently, depending on topographic, site, and climate conditions (Swift 1985, Motha et al. 2003). The topographic relief across the Mountains, Piedmont, and Coastal Plain is around 1,000, 100, and 10 m, respectively. Sediment production from roads and skid trails are largely controlled by steep slopes and direct impact of rainfall on the road surface in the Mountains and to a lesser extent in the Piedmont. Given the steeper topographic features, the transport capacity of runoff is higher in the Mountain and Piedmont than Coastal regions, and sediment yield is probably source-limited (Rummer 2004). Our data set revealed several notable trends in TSS concentration and discharge. Stormflow TSS concentrations sometimes peaked in advance of peak stormflow discharge as a result of various factors that may include a lack of continued sediment source and production (Figure 9A, C, E, and F). In other cases, stormflow sediment persisted after a decline in stream discharge. For example, HDF1 stormflow TSS concentrations remained elevated even though discharge had returned to prestorm levels (Figure 9D). This particular pattern is indicative of a counterclockwise hysteresis (Figure 10D) (sediment increase with time for a given discharge) where a fairly constant source of in-stream sediment is probably generated from bank erosion and carried downstream (Loughran et al. 1986, Baca 2008). Sediment produced in-stream depends largely on stream discharge and the physical characteristics of the streambanks and streambed and tends to have relatively small standard errors around the mean (e.g., Table 2 SE = 4.6 mg/l; HDF1 stormflow upstream TSS during closure period) (Wood and Armitage, 1997). Sediment that travels from the uplands or surrounding landscape to the stream can also form a counterclockwise hysteresis and tends to have large variations between stormflow samples (e.g., Table 2 SE = 30.2 mg/l; MC stormflow upstream TSS during closure period).

In Coastal systems, overland flow and sedimentation generally occur from large volumes of water from upstream catchments (off-site flow) and long periods of flooding (Rummer 2004). The slopes are also usually very gentle and have little transport capacity in Coastal systems to create runoff on road and skid trail surfaces. Thus, sediment yield to downstream stakeholders in the Coastal Plain will partly be limited by the transport capacity of the runoff (i.e., transport-limited) not the amount of available sediment (Rummer 2004). This energy transport-limited sediment response does not occur in the Piedmont and Mountain regions.

TSS Load. As with TSS concentrations, TSS loads or yields also did not increase downstream from the crossing compared with upstream (Figure 6). These upstream and downstream export values were equal to or lower than exports from undisturbed forested watersheds (85 kg/ha/year) during a normal precipitation year (~1,300 mm) in the Piedmont of North Carolina (Boggs et al. 2013). This finding suggests that loads for this stream crossing study were within background levels for forested watersheds and probably did not pose a risk to water quality. Loads in other stream crossing studies range from 85 kg/ha/year during pretreatment to 152 kg/ha/year posttreatment (Figure 6) (Kochenderfer and Hornbeck 1999, Edwards et al. 2004). Wang et al. (2013) and Kochenderfer et al. (1987) point out that differences in watershed natural conditions and land uses might be driving some difference in TSS loads across their sites. In general, suspended sediment yield from streams tends to decrease eastward from the Mountains to the Coastal Plain across North Carolina.

Precipitation and Discharge. The percentage of intense precipitation events (i.e., events of more than 5 cm/24 hours) has increased by 27% across North Carolina since the 1950s, and that trend is expected to continue (Melillo et al. 2014). Boggs et al. (2016) found that forest vegetation removal plays a more significant role in affecting water balances, peak flows, soil moisture, and annual water yield in the Piedmont region than in the Mountains and Coastal Plains. These increases in discharge and precipitation suggest that there is a need to adequately apply BMPs to streams to control sedimentation that may be produced at stream crossings and during overland flow. State regulations require that sediment loss to lakes and streams be quantified to understand how improvements in land management might benefit water quality and prevent further degradation of reservoirs. Understanding the relationship between water quality and discharge rates will help land managers install and apply the most appropriate stream crossing and BMP management practices to protect and quantify water resources within and across regions. Even though discharge rates and sediment transport and source patterns differed across North Carolina, when stream crossing BMPs are properly applied, they appear to control sedimentation and maintain water quality. Although we did not consider climate change as part of this study, future intensification of rainfall will probably warrant adjustments and additional guidelines for how structures following stream crossing BMPs are installed and implemented.

Conclusions

This study measured total suspended sediment at stream crossings that covered a range of site conditions (different watershed size, discharge rate, road class, crossing, soil, and slope) and forest operations (bridgemats, forest roads, and skid trails) in the Piedmont of North Carolina. We concluded that forests can be effectively harvested around stream crossings using current BMPs to control sedimentation and protect water quality. Data from this project and results from other stream crossing studies in the Piedmont, Mountains, and Coastal Plains should help land managers identify the range of site and operational practices that would probably reduce sediment production from bridgemats, culverts, and approachways during logging activities. Matching forestry BMPs with site characteristics will continue to be an effective practice to prevent excess sedimentation downstream of stream crossings and reduced harm to aquatic species.

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