Operational Forest Stream Crossings Effects on Water Quality in the Virginia Piedmont

Wallace M. Aust, Mathew B. Carroll, M. Chad Bolding, and C. Andrew Dolloff

ABSTRACT

Water quality indices were examined for paired upstream and downstream samples for 23 operational stream crossings and approaches during four periods. Stream crossings were (1) portable bridges (BRIDGE), (2) culverts backfilled with poles (POLE), (3) culverts with earth backfill (CULVERT), and (4) reinforced fords (FORD). The four operational periods were (1) prior to crossing installation (INITIAL), (2) after installation (INSTALL), (3) during harvest (HARVEST), and (4) after road closure (CLOSURE). Differences (Δ) in water samples collected above and below stream crossings were analyzed for Δtotal dissolved solids (ΔTDS), ΔpH, Δconductivity, Δtemperature, and Δsediment concentration. Data were analyzed as a completely randomized design with unequal replication (four to seven replications). Significant differences were observed ($\alpha < 0.10$) among crossing types for Δtemperature, ΔTDS, ΔpH, and Δconductivity. Overall, the least disruptive crossing type for water quality was BRIDGE, but road standards and approach characteristics were also important. Modeled estimates of erosion demonstrated that CULVERT approaches had higher potential erosion than other crossings. Water quality parameters were most negatively affected during INSTALL and HARVEST and were apparently improving during CLOSURE. Permanent crossings were associated with significantly greater temperatures than temporary crossings, likely because of increased width of streamside management zone removal. Water quality effects could be minimized by installing appropriate best management practices during all harvest periods rather than waiting until CLOSURE. Findings should be used cautiously because individual site factors such as climate, site, soil, and operational variability will alter effects.

Keywords: forest roads, stream crossings, water quality, forestry best management practices

Stream crossings are often considered to be the forest road segment with the greatest potential to introduce sediment into streams (Rothwell 1983, Swift 1985, Milauskas 1988, Aust and Blinn 2004, Harris et al. 2008). Typical stream crossings found on current timber harvest operations include fords, culverts, and bridges (Brinker 1997, Blinn et al. 1998, Aust et al. 2003). There has been considerable research that has evaluated water quality problems associated with individual stream crossing types, including fords (Thompson and Kyker-Snowman 1989, Tornatore 1995), culverts (Thompson et al. 1995), pole crossings (Tornatore 1995), and portable panel bridges (Hassler et al. 1990, Thompson et al. 1995, Tornatore 1995, Taylor et al. 1999b). Generally, the previous research indicates that different types of forest road stream crossings have the potential to degrade water quality (Thompson and Kyker-Snowman 1989, Taylor et al. 1995, 1999b, Thompson et al. 1995, Tornatore 1995, Sample et al. 1998, Grace 2005). However, the majority of previous research has often been limited to either intense measurements of only one crossing type or has been limited to a specific phase, such as installation. This study was designed to investigate relatively simple measures of water quality and indices of potential erosion on multiple replications of four forest stream crossing types. This study incorporated the findings of Taylor et al. (1999a, 1999b) and Harris et al. (2008) and evaluated stream crossing approaches and phases of use with the overall goal of identifying potential improvements for stream crossing best management practices (BMP). As suggested by Loftis et al. (2001), upstream and downstream data were collected during all phases, which provided a control for comparison.

This study had three research objectives. Objective 1 was to evaluate the effect of four widely used stream crossing types and the associated road approaches on stream water quality (sediment concentration, total dissolved solids [TDS], pH, conductivity, and temperature) in the piedmont of Virginia by comparing in-stream water samples measured 8 m upstream and downstream from each crossing. Objective 2 was to estimate the average potential erosion associated with the stream crossing approaches by using two common erosion models, the Universal Soil Loss Equation (USLE)-Forest Version (Dissmeyer and Foster 1984) and the Water Erosion Prediction Project for forest roads (WEPP-Road) (Elliot et al. 1993, Elliot and Hall 1997, Rhee et al. 2004). Objective 3 was to examine the influence of four time periods associated with stream crossings on the water quality parameters. Periods evaluated were prior to installation of crossing (INITIAL), immediately after crossing installation (INSTALL), during harvest operations (HARVEST), and after road closure (CLOSURE).

Methods

Study Site Description and Selection

This study was conducted in the Piedmont physiographic region of central Virginia (Figure 1), and detailed site information is provided by Carroll (2008). Landscapes are rolling, with sideslopes of

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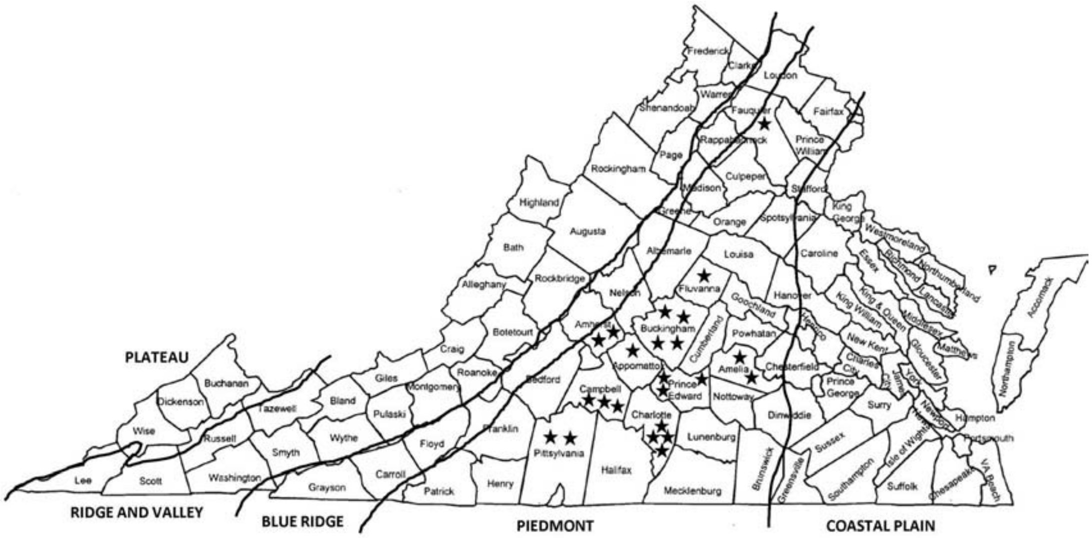

Figure 1. Virginia physiographic provinces and counties showing the location of the 23 stream crossings evaluated in the Piedmont.

10–40%. Many ephemeral and intermittent streams in this landscape have unstable banks because they are recovering erosion gullies caused by abusive agricultural practices used in the region in the 1700s and 1800s (Trimble 1974). Common soils of the approaches and stream crossings include the Wehadkee, Chewacla, Wilkes, Appling, Madison, Codorus, Bremo, and Toccoa soil series (USDA Soil Conservation Service 1974).

Personnel from three timber procurement organizations and the Virginia Department of Forestry identified potentially suitable stream crossings prior to installation. The first available stream crossings that met the desired criteria was selected, where permission from landowners to make repeated visits could be obtained and where the timing of operations allowed evaluation of the crossing from preinstallation through closure. All stands accessed by the crossings were clearcut harvested and included natural upland hardwood stands and loblolly pine (*Pinus taeda* L.) plantations. Stream crossings selected were on low-volume forest roads (class 2 permanent roads and class 3 temporary roads) or bladed skid trails (class 4) (Walbridge 1990). The different road classes were included for two reasons, to acquire the desired replications of the crossings in a timely manner and because the different classes represent the overall tract level access system. The roads, skid trails, and crossings included in this study were designed or selected by a company forester or forest engineer and implemented by logging contractors. One difficulty in acquiring the required numbers of stream crossings for the study was caused by the rapid selection and placement of crossings by loggers, which sometimes precluded the required preinstallation measurements.

Treatment Description

Four stream crossing treatments were evaluated: portable steel skidder bridges (BRIDGE), pole-filled culverts (POLE), reinforced fords (FORD), and standard earth-fill culverts (CULVERT). The initial experimental design sought to install six replications of each crossing structure. However, because of the difficulty in finding more than four sites that were suitable for the FORD, the final design consisted of 6, 6, 4, and 7 replications for the BRIDGE, CULVERT, FORD, and POLE treatments, respectively. Therefore, a total of 23 stream crossings were monitored during the project.

Figure 2. BRIDGE treatment using portable steel panels for a temporary haul road stream crossing.

The BRIDGE treatment consisted of 9.1–12.2-m (30–40-ft) long steel panels that were 1.2 m (4 ft) wide. Three panels were used for each crossing (Figure 2). POLE crossings used either steel gas line pipes or corrugated steel culverts with pole-sized stems used to fill the stream cross-section (Figure 3). All POLE crossings had stems placed parallel to the pipe as fill; however, some POLE crossings had additional poles or logging mats placed perpendicular to the stream channel to provide a traffic surface. FORD crossings were reinforced with geotextile or mats topped with gravel (Figure 4). Two of four FORD crossings involved simple reinforcements of existing fords on farm roads rather than construction of new fords. CULVERT crossings consisted of either single or double corrugated steel pipes with earth fill (Figure 5). In general, BRIDGE and POLE structures were used for temporary crossings on smaller streams, and CULVERT and FORD structures were used for more permanent roads and larger streams. However, all crossing types were used in at least one instance for both permanent and temporary crossings. These uses match the basic attributes of the crossings: BRIDGE and POLE crossings are better suited for temporary crossings on smaller streams and are often used for skid trails. CULVERT and FORD crossings

Figure 3. POLE crossing used a steel pipe and poles for a temporary skid trail stream crossing.

Figure 4. FORD crossing was reinforced with geotextile, gravel, and mat for a temporary haul road.

can more easily be constructed to support the heavier loads of tractor-trailer log trucks; thus, they are favored for haul roads. This mixture of stream crossings was considered because both permanent and temporary crossings are part of the harvest access system for many tracts.

Methods

Field data collection began in January 2007 and continued through March 2008 as potential stream crossings became available.

Figure 5. Culverts used for a permanent haul road stream crossing.

Field measurements were collected during four periods of the harvesting process, and all four periods were typically completed within 2–4 months. Periods included (1) the phase prior to installation of the road or skid trail (INITIAL), (2) during installation and construction of the crossing but before harvesting (INSTALL), (3) during the harvest operation (HARVEST), and (4) after harvest was complete and closure BMP were applied to the tract (CLOSURE). For the INSTALL treatment, water quality and potential erosion data were collected for the identified location of the stream crossing and the flagged gradeline of the approach. For two of the FORD crossings, preexisting fords on farm roads were reinforced; therefore, the existing ford conditions were recorded as INITIAL. These fords were accepted because the pre- and postimprovements provided both INITIAL and INSTALL periods, and FORD crossings were the least common crossing. Access roads and trails were categorized as primary skid trails (class 4), temporary haul roads (class 3), or permanent haul roads (class 2). Streams were characterized as perennial, intermittent, or ephemeral. Soil series were determined from existing published soil surveys, web soil survey maps, or field examinations. In-stream measurements were collected to categorize streams and channels (Harrelson et al. 1994, Ward and Trimble 2004). Measurements occurred throughout the year as suitable harvest tracts and crossings could be located and measured. The 23 HARVEST period measurements occurred in spring (7), summer (6), fall (5), and winter (5) seasons.

Grab water samples were collected once during each of the four operational periods (in situations where all periods existed) using methods indicated by Danielson (2004). Samples were collected from fixed stations located approximately 8 m upstream and downstream from the edge of each crossing. Samples were subsequently analyzed for suspended sediment concentrations. Also, in-stream data were collected at the same upstream and downstream locations with a portable water quality meter (ExStik EC500 manufactured by Extech Instruments Corporation), which was calibrated before each use. In-stream measurements included stream pH, TDS (organic and inorganic solids), conductivity, and stream temperature. The paired upstream data (above) were subtracted from downstream data (below) to evaluate differences (Δ). During a portion of the data collection period (Apr. 2007-Mar. 2008) the Piedmont region experienced a drought and as a result in-stream samples were

Table 1. Stream crossing and approach characteristics for 23 forest road stream crossings located in the Virginia Piedmont. Average values for each type of crossing are displayed in italics.

Stream crossing type and replication	Road class[a]	Approach length (m)	Approach slope	Bare soil during harvest	Bare soil after closure	Watershed size (ha)	Width of SMZ removed by crossing[b] (m)
			....	.(%)	....		
BRIDGE 1	3	103	15	55	32	38	6
BRIDGE 2	3	57	8	100	97	83	8
BRIDGE 3	4	39	11	73	25	102	5
BRIDGE 4	4	39	10	28	30	33	6
BRIDGE 5	4	95	10	55	30	34	15[c]
BRIDGE 6	4	25	9	55	25	8	7
Average		*59.6*	*10.5*	*61.0*	*39.8*	*49.7*	*7.8*
CULVERT 1	3	48	11	7	17	177	12
CULVERT 2	2	82	11	99	100	54	23[c]
CULVERT 3	2	118	11	97	95	19	18[c]
CULVERT 4	2	88	7	98	87	13	23[c]
CULVERT 5	2	85	7	45	45	1349	15[c]
CULVERT 6	2	63	14	99	35	81	31[c]
Average		*80.7*	*10.2*	*74.1*	*63.2*	*282.1*	*20.3*
FORD 1	3	32	4	18	3	330	11
FORD 2	2	68	9	93	93	16	12
FORD 3	2	20	8	40	40	2586	15[c]
FORD 4	2	25	5	45	35	1302	15[c]
Average		*36.2*	*6.5*	*49.0*	*42.8*	*1058.5*	*13.3*
POLE 1	3	18	2	50	35	2	15[c]
POLE 2	4	33	11	65	8	2	6
POLE 3	4	46	13	15	45	10	6
POLE 4	4	55	8	55	82	8	9
POLE 5	4	59	15	50	25	35	5
POLE 6	4	37	17	83	38	3	6
POLE 7	4	31	12	57	25	6	10
Average		*39.9*	*11.1*	*53.6*	*36.9*	*9.4*	*8.1*

[a] Class 2 roads are permanent haul roads, class 3 roads are temporary haul roads, and class 4 roads are primary or bladed skid trails (Walbridge 1990)
[b] Refers to the width of the stream crossing through the streamside management zone (SMZ).
[c] Where stream crossings are 15 m or greater, shade was effectively removed by the crossing.

primarily taken during low flow conditions. Although the in-stream data reflect actual conditions encountered for the operations, the erosion model data may provide relative erosion rates for the approaches that better reflect erosion rates during average precipitation.

For each crossing site, data were collected for both approaches (entrance and exit) to obtain erosion estimates from two soil erosion models, USLE-Forest and WEPP-Road (Elliot and Hall 1997, Hood et al. 2002, Feldt 2006, Grace 2007). All distances were taped, and bare soil and cover estimates were based on three to five transects across roads at 0.5-m intervals. Soil erodibility values were based on soil textural analyses and soil survey recommendations. Rainfall and runoff values were based on the nearest weather station having publicly available data. The WEPP-Road (version 2008) program was run to predict erosion for a 10-year period and obtain an average soil loss value; thus, the WEPP-Road data reflect average rainfall and erosion potential. The 10-year average was used because the crossings were designed for 10-year-or-less flood events (Virginia Department of Forestry 2002). Data required by the models included weather, road characteristics, soil properties, and management practices used. Data were subsequently used to estimate the approach erosion values with the USLE-Forest (Dissmeyer and Foster 1984) and the WEPP-Road (Elliot et al. 1993, Elliot and Hall 1997). A study on bladed skid trails in the Piedmont (Wade et al. 2010) found that both USLE-Forest and WEPP-Road had similar values to sediment collected by sediment traps. After erosion estimates were modeled, the entrance and exit subsample values for potential erosion were averaged.

Best management practices were inspected during each phase and recorded on the basis of the Virginia Department of Forestry audit process. These primarily focused on road location and grade characteristics; presence, type, and spacing of water control structures; percentage of bare soil and or type of cover; and streamside management zone (SMZ) width and presence (Virginia Department of Forestry 2002).

Statistical Analyses

The overall study design was a completely randomized design with unbalanced replication (Ott 1993). The in-stream measurements collected above and below each crossing were paired to provide the changes (Δ) for in-stream variables that were calculated as below minus above measurement. Independent variables used for water quality analyses included stream crossing type (BRIDGE, POLE, CULVERT, FORD) and harvest operation period (INITIAL, INSTALL, HARVEST, CLOSURE). Dependent variables included approach potential erosion (tonnes ha^{-1} yr^{-1}), ΔTDS (mg L^{-1}), ΔpH, Δconductivity (μS cm^{-1}), Δstream temperature (°C), and Δsuspended sediment concentrations (mg L^{-1}). Statistical significance for analyses of variance and the Tukey-Kramer multiple comparison tests were evaluated at α levels of 0.10 rather than 0.05 because of the operational nature of the study. Data were analyzed using the Number Cruncher Statistical System (Hintze 2005).

Results and Discussion

CULVERT and FORD crossings were primarily associated with permanent (class 2) roads (83 and 75%, respectively), whereas BRIDGE and POLE crossings were usually found on skid trails (66 and 86%, respectively) (Table 1). BRIDGE and POLE watersheds

Table 2. Average change (Δ) in total dissolved solids (TDS), conductivity, pH, stream temperature, and sediment values based on the difference between above and below crossing measurements (below–above) for the four types of stream crossings. *P* values for stream crossing effects are displayed above each parameter.

		Average change of in-stream parameters (below–above)				
Stream crossing type	n	P = 0.064; ΔTDS (mg L^{-1})	P = 0.047; Δconductivity ($\mu S\ cm^{-1}$)	P = 0.001; ΔpH (unitless)	P = 0.001; Δtemperature (°C)	P = 0.536; Δsediment (mg L^{-1})
BRIDGE	48	22.7^{a}	40.3^{a}	0^{b}	0.5^{a}	221.4 (NS)
CULVERT	48	226.9^{b}	121.0^{b}	0^{b}	0.9^{b}	252.8 (NS)
FORD	32	292.1^{b}	421.2^{c}	0.3^{c}	0.9^{b}	249.3 (NS)
POLE	56	162.6^{b}	194.7^{b}	-0.3^{a}	0.4^{a}	144.6 (NS)

[a,b,c] Numbers followed by different letters are significantly different at $\alpha = 0.10$ based on the Tukey-Kramer multiple comparison test. NS, not significant.

Table 3. Average values for Universal Soil Loss Equation-Forest Version (USLE-Forest) and Water Erosion Prediction Project for forest roads (WEPP-Road) estimates of erosion (tonnes $ha^{-1}\ yr^{-1}$) for approaches to four types of stream crossings. *P*-values for stream crossings effects are displayed above each erosion model.

		Potential erosion estimate	
Stream crossing type	n	P = 0.001; USLE-Forest	P = 0.10; WEPP-Road
		. . . . . .(tonnes $ha^{-1}\ yr^{-1}$)	
BRIDGE	48	39.0^{b}	$49.0^{a,b}$
CULVERT	48	95.8^{c}	60.2^{b}
FORD	32	31.1^{b}	$42.9^{a,b}$
POLE	56	9.2^{a}	35.0^{a}

[a,b,c] Numbers followed by different letters are significantly different at $\alpha = 0.10$ based on the Tukey-Kramer multiple comparison test.

averaged 49.7 and 9.4 ha, whereas watersheds of CULVERT and FORD averaged 282.1 and 1,059 ha (Table 1), indicating the load bearing potential of CULVERT and FORD and their utility for permanent roads.

Stream crossing treatments and their associated approaches were associated with significant differences ($\alpha = 0.10$) for six of the seven response variables (Tables 2 and 3). Four of the seven response variables were significantly different with respect to period (INITIAL, INSTALL, HARVEST, CLOSURE) (Tables 4 and 5). Only one response variable (USLE-Forest) was found to have a significant stream crossing and period interaction (Table 6).

CULVERTS and FORDS were used for more permanent roads in larger watersheds (Table 1); therefore, CULVERT stream crossings required significant earth fill. CULVERT crossings also had longer approaches than other crossing types (Table 1). Approaches for CULVERTS were often wider, and ditches were used on several of the approaches. POLE and BRIDGE structures tended to be used for temporary crossings on narrower roads that crossed smaller streams with more gentle approaches. FORD crossings, by their very nature, tended to be located in areas having wide, shallow streams and gentle approaches.

Four of the in-stream variables (ΔTDS, Δconductivity, ΔpH, and Δtemperature) differed significantly among stream crossing treatments (Table 2). Interestingly, Δsediment concentrations were not found to be significantly different for the treatments. However, a paired t test of all above and below sediment data for all crossings indicated that the average stream crossing Δsediment concentrations were significantly increased ($\alpha = 0.05$) below the crossings. The average increase for below-crossing sediment as compared with above-crossing sediment was 217 mg L^{-1}. These data were influenced by the drought conditions and resultant low stream flows, and greater differences would be expected during storm events, as reported by Tornatore (1995). BRIDGE crossings had minimal effects on TDS and conductivity (Table 2) as compared with the other treatments. The may be due to the fact that installation of BRIDGE treatments require less stream channel disturbance than the other stream crossings, which require earthen fills (CULVERT), pipe and pole installation (POLE), or geotextile and/or gravel additions (FORD). CULVERT, POLE and FORD treatments had higher ΔTDS (Table 3). Results from this study are similar to those of Taylor et al. (1999b) and Tornatore (1995). Taylor et al. (1999b) indicated that bridges have less of an effect on water quality than fords or culverts. Tornatore (1995) also found lower impacts for a bridge than for a culvert or pole crossing.

The differences in stream pH values from above the crossing to below the crossing (ΔpH) indicated that BRIDGE and CULVERT crossings were similar but that ΔpH values were significantly greater for the FORD and lower for the POLE treatments. Hassler et al. (1990) sampled stream water quality during installation of a portable stress-laminated bridge in West Virginia and found no significant differences in stream pH during installation. However, significant increases in pH and calcium concentrations in runoff from two forest roads on the Fernow Experimental Forest were found in a study by Helvey and Kochenderfer (1987). The authors were uncertain whether applying limestone gravel to logging roads would have a noticeable influence on the water chemistry of a perennial stream. The ΔpH observed for both the FORD and POLE crossings are apparently related to the fill material used for the crossings. POLE crossings used white or red oak poles, and installation and subsequent traffic tended to debark the stems and may have added tannic acids to the stream. FORD crossings, because of the proximity of quarries, were created or reinforced with limestone gravel.

BRIDGE and POLE treatments did not have significant different stream temperatures, but the CULVERT and FORD crossings had significantly higher stream temperatures below the crossing (Table 2). Examination of the timing of operations did not indicate any clear seasonal pattern that would explain the differences. However, examination of the width of SMZ removal by the crossing (Table 1) indicated that the average widths of SMZ removals were 7.8 and 8.1 m for the BRIDGE and POLE crossings, respectively, whereas the CULVERT and FORD created 20.3- and 13.3-m-wide paths through the SMZs. These data support minimal removal of shade directly over the stream.

Both erosion models predicted generally similar patterns of potential erosion for the stream crossing treatments (Table 3). The POLE crossing had the lowest average for predicted erosion (USLE-Forest = 9.2 tonnes $ha^{-1}\ yr^{-1}$, WEPP-Road = 35.0 tonnes $ha^{-1}\ yr^{-1}$), and the CULVERT had the greatest (USLE-Forest = 95.8 tonnes $ha^{-1}\ yr^{-1}$, WEPP-Road = 60.2 tonnes $ha^{-1}\ yr^{-1}$). Both BRIDGE and FORD had intermediate values of potential

Table 4. Average change (Δ) in total dissolved solids (TDS), conductivity, pH, stream temperature, and sediment values based on the difference between above and below crossing measurements (below − above) for the four periods of stream crossing operations. *P* values for stream crossings effects are displayed above each parameter.

Stream crossing type	n	Average change of in-stream parameters (below − above)				
		$P = 0.073$; ΔTDS (mg L^{-1})	$P = 0.143$; Δconductivity ($\mu S\ cm^{-1}$)	$P = 0.611$; ΔpH (unitless)	$P = 0.098$; Δtemperature (°C)	$P = 0.074$; Δsediment (mg L^{-1})
INITIAL	48	12.5^{a}	2.5^{a}	0.0^{a}	0.5^{a}	5.4^{a}
INSTALL	48	$237.1^{b,c}$	104.1^{a}	0.2^{a}	0.9^{b}	406.3^{c}
HARVEST	32	318.9^{c}	72.8^{a}	0.2^{a}	0.5^{a}	132.2^{b}
CLOSURE	56	135.9^{b}	60.4^{a}	0.1^{a}	0.5^{a}	$317.0^{b,c}$

[a,b,c] Numbers followed by different letters are significantly different at $\alpha = 0.10$ based on the Tukey-Kramer multiple comparison test.

Table 5. Average values for Universal Soil Loss Equation-Forest Version (USLE-Forest) and Water Erosion Prediction Project for forest roads (WEPP-Road) estimates of erosion (tonnes $ha^{-1}\ yr^{-1}$) from stream crossing approaches. *P* values for stream crossings effects are displayed above each erosion model.

Stream crossing type	n	Potential erosion estimate	
		$P = 0.001$; USLE-Forest	$P = 0.10$; WEPP-Road
		......(tonnes $ha^{-1}\ yr^{-1}$)......	
INITIAL	46	4.9^{a}	28.6^{a}
INSTALL	46	44.0^{b}	48.7^{b}
HARVEST	46	72.8^{c}	65.0^{c}
CLOSURE	46	53.3^{b}	45.7^{b}

[a,b,c] Numbers followed by different letters are significantly different at $\alpha = 0.10$ for all columns and rows, based on the Tukey-Kramer multiple comparison test, and represent the average of 8 to 14 erosion estimates.

Table 6. Average values for Universal Soil Loss Equation-Forest Version (USLE-Forest) estimates of erosion (tonnes $ha^{-1}\ yr^{-1}$) from the interaction of stream crossing approaches and periods. *P* value for stream crossing-period interaction = 0.004.

Stream crossing type	Period			
	INITIAL	INSTALL	HARVEST	CLOSURE
	.........(Erosion tonnes $ha^{-1}\ yr^{-1}$).........			
BRIDGE	4.9^{a}	75.2^{c}	41.4^{b}	34.3^{b}
CULVERT	8.4^{a}	75.6^{c}	188.5^{d}	$110.9^{c,d}$
FORD	5.9^{a}	$21.5^{a,b}$	51.5^{b}	45.3^{b}
POLE	0.5^{a}	3.8^{a}	9.9^{a}	$22.7^{a,b}$

[a,b,c,d] Numbers followed by different letters are significantly different at $\alpha = 0.10$ for all columns and rows and represent the average of 8 to 14 erosion estimates. Mean separations are based on the Tukey-Kramer multiple comparison test.

erosion. CULVERT are associated with the more permanent and larger haul roads, and the approaches of the CULVERT crossings were longer and had more bare soil during HARVEST CLOSURE periods. POLE crossings are generally for skid trails having smaller areas for approaches and were often closed with piled slash. The higher potential erosion associated with the CULVERT appears to be more of a reflection of the road standard and approach BMP than of the crossing type.

In-stream water quality values of ΔTDS ($P = 0.073$), Δsediment ($P = 0.074$), and Δtemperature ($P = 0.098$) varied significantly by period (Table 4). In-stream Δconductivity and ΔpH values were not significantly different during different periods. As expected, the INITIAL period, before operations disturbances began, had low values for all in-stream variables (Table 4). INSTALLATION, HARVEST, and CLOSURE had significant increases for both ΔTDS and Δsediment (Table 4). These operational periods all require degrees of construction and associated erosion. Significantly greater Δtemperature was measured during the INSTALL period (Table 4), which is the period when the least shade would be cast over the stream by the SMZ or the structure.

Both erosion models predicted similar soil erosion patterns with the INITIAL period having the lowest estimated erosion (< 10 tonnes $ha^{-1}\ yr^{-1}$ for USLE-Forest and < 50 tonnes $ha^{-1}\ yr^{-1}$ for WEPP-Road) and the CULVERT HARVEST having the highest USLE-Forest and WEPP-Road values (188.5 and 103.5 tonnes $ha^{-1}\ yr^{-1}$, respectively) (Tables 3 and 4). Observations indicate that future versions of WEPP-Road that might allow bare soil, aggregate, and cover to be better integrated into final estimates would be useful. The general patterns of erosion for the different stream crossings and approaches can be explained by the nature of the crossing.

WEPP-Road ($P = 0.001$) and USLE-Forest ($P = 0.10$) models predicted significant increases in potential erosion for INSTALL, HARVEST, and CLOSURE periods for the stream crossing approaches (Table 5). As expected, both models indicated that INITIAL conditions would have the lowest potential erosion values and that the HARVEST period would have the highest erosion estimates (USLE-Forest = 72.8 tonnes $ha^{-1}\ yr^{-1}$, WEPP-Road = 65 tonnes $ha^{-1}\ yr^{-1}$). Both the WEPP-Road and USLE-Forest models estimated that the INSTALL and CLOSURE periods were not significantly different one another (Table 5). These data reflect the short duration and lower traffic levels of the INSTALL period relative to the HARVEST period and the effect of BMP during the CLOSURE period.

During INSTALL, the site was disturbed in short durations for construction (2 days maximum), but subsequent HARVEST operations were more disruptive and longer lasting. BRIDGE and POLE crossings were used for an average of 11 and 8 working days, respectively, and 1,171 and 1,017 tonnes of wood were transported across the respective structures during this time. FORD and CULVERT crossings were used for an average of 42 and 19 working days to extract approximately 3,510 and 3,626 tonnes of wood, respectively. During HARVEST, it was noted that road water control and cover BMP were commonly not installed until CLOSURE. This reduced the total cost and time for BMP implementation yet increased the potential erosion during HARVEST. Following HARVEST, the reduction of potential sediment during CLOSURE also indicates that road and trail closure BMP do facilitate recovery.

The interactions between stream crossings and approaches with period were investigated, but only one variable was found to have a significant interaction: predicted erosion using the USLE-Forest ($P = 0.004$) (Table 6). During the INITIAL period, no stream crossing had significant differences, and all stream crossing approaches had estimated erosion values less than 8.4 tonnes

Table 7. Number and percentage of stream crossings approaches by best management practices (BMP) sufficiency rating and stream crossing type following closure.

Stream crossing type	BMP rating			
	Excellent[a]	Good[b]	Fair[c]	Poor[d]
	. . . .(No. of sites)			
BRIDGE	1 (16.6%)	3 (50.0%)	2 (33.4%)	
CULVERT	3 (50.0%)		2 (33.4%)	1 (16.6%)
FORD	2 (50.0%)	2 (50.0%)		
POLE	3 (42.8%)	4 (57.2%)		

[a] Road grade, water control structures, and cover management BMP used.
[b] Water control structures, grade control, or cover BMP used.
[c] Cover management BMP used (seeded, mulch, slash).
[d] Minimal or no BMP used.

ha^{-1} yr^{-1}. After the INITIAL period, USLE-Forest erosion estimates were higher for the CULVERT crossings during all phases (Table 6). POLE crossings had low USLE-Forest erosion estimates during all phases, and BRIDGE and FORD values were intermediate. These results reflect the specific site and approach characteristics and degree of disturbance associated with each period and crossing.

Overall, results support the water quality impacts associated with fords (Helvey and Kochenderfer 1987, Thompson and Kyker-Snowman 1989, Tornatore 1995, Sample et al. 1998, Welch et al. 1998), culverts (Thompson et al. 1995), pole crossings (Tornatore 1995), and bridges (Hassler et al. 1990, Tornatore 1995). However, few of these studies other than Taylor et al. (1999b) compared the range of crossings or considered the periods of operations and BMP applied. In general, the approach erosion and in-stream data both indicated that the BRIDGE crossings had resulted in fewer water quality problems. A portion of the differences may simply be due to inherent differences in small versus large watersheds and permanent versus temporary crossings. However, the BRIDGE requires fewer modifications to the stream channel than other crossing types. Any of these stream crossings can potentially be used effectively if conditions are matched to the crossing type, additional water control and cover BMP are used on approaches, and appropriate BMP are implemented during the harvest phase. For example, CULVERT crossings had the longest approaches, the highest percentage of bare soil, and more traffic and SMZ disturbance than POLE or BRIDGE crossings (Table 1). The CULVERT crossings and approaches also had the poorest overall BMP implementation (Table 7). Fifty percent of the culvert sites were ranked as having only fair or poor BMP implementation following harvest. No other stream crossing had a poor BMP implementation rating, indicating that our CULVERT approach and in-stream values could be improved with additional planning and implementation of BMP. The BMP implementation is also linked to the road class. Temporary skid trails can be effectively closed with waterbars, seeding, or slash, yet permanent roads cannot be closed with either water bars or slash. Permanent haul roads are also more expensive to cover with stone. However, Harris et al. (2008) found that aggressive use of a combination of armor, silt fences, water control, and erosion vegetation practically eliminated water quality concerns associated with 30 stream crossings on public lands in California.

Conclusions

These research findings provide the basis for five major conclusions.

1. Stream crossing type can potentially affect water quality. Overall, portable panel bridges were found to have the lowest impact on in-stream water quality. However, these findings must be applied with caution because each crossing type may be suitable for a particular situation.
2. Stream crossing approaches can influence water quality. WEPP-Road and USLE-Forest estimates indicated that potential erosion rates on steep approaches with high levels of bare soil could be greater than 50 tonnes ha^{-1} yr^{-1}. Higher predicted erosion values were found for the approaches of the CULVERT crossing and HARVEST period, and these results indicate that BMP compliance is extremely critical on these approaches.
3. Periods influenced potential erosion and in-stream ΔTDS. As expected, the INITIAL period had less potential erosion for the approaches and better ΔTDS. The HARVEST period had poorer ΔTDS and higher estimated erosion, but both indices of water quality showed potential improvements with CLOSURE. However, additional attention and use of BMP could be used to improve these values.
4. Overall, satisfactory BMP compliance rates were observed (78% of sites had good or excellent BMP compliance), particularly following closure, and compliance levels were similar to those found across the state during Virginia's BMP audits (Dr. William Lakel, Virginia Department of Forestry, December 2008). However, BMP implementation can be improved. The loggers were aware of and willing to comply with the BMP following harvest, but several of the tracts had lower BMP implementation during the actual harvest. Additional attention should be paid to water control structures during harvest (e.g., install wing ditches before closure; gravel approaches before closure; and seed, straw mulch, and/or armor crossing sideslopes before closure).
5. These findings should be tempered with professional judgment because climate, topography, soil, and operational considerations can alter the stream crossing effects on water quality. Each crossing type is potentially suitable under certain situations and can potentially be used with minimal effects on water quality with sufficient planning, careful installation and use, and adequate use of BMP.

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