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EFFECTIVENESS OF ELEVATED SKID TRAIL HEADWATER STREAM CROSSINGS IN THE CUMBERLAND PLATEAU

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Agriculture
at the University of Kentucky.

By

Christopher David Reeves

Lexington, Kentucky

Director: Dr. Jeffrey Stinger, Extension Professor

Lexington, Kentucky

2012

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ABSTRACT

EFFECTIVENESS OF ELEVATED SKID TRAIL HEADWATER STREAM CROSSINGS IN THE CUMBERLAND PLATEAU

One of the primary concerns associated with timber harvesting is the production of sediments from stream crossings. While research has shown that using improved haul road crossings can mitigate sediment production in perennial streams compared to the use of unimproved crossings little research has been undertaken on temporary skidder crossings of headwater streams, a situation common to a significant percentage of ground skidding operations. This experiment consisted of a controlled replicated testing of the effectiveness of four types of temporary skidder stream crossings (unimproved ford, corrugated culvert, wood panel skidder bridge, and PVC pipe bundle) relative to suspended sediment production. Automated samplers were used to monitor sediment and bedload production during the construction, use, removal, and post-removal phases associated with the use of these temporary crossings. Results showed that improved crossings mitigated total sediment production compared to unimproved fords. Further, wood panel bridges yielded lower amounts of sediment than culverts but pipe bundles show no difference between bridges or culverts. Sediment production varied by crossing type and use phase. While no differences were found among crossings types during construction, there was a difference between improved crossings and fords during use. Further, bridges and pipe bundle crossings produced significantly less sediments than culverts during both their removal and during post-removal sampling and fords produced the largest amount of sediments during these phases.

KEYWORDS: improved stream crossings, suspended sediment, headwater streams, pipe bundle, stream morphology

/s/ Christopher Reeves

31 July 2012

EFFECTIVENESS OF ELEVATED SKID TRAIL HEADWATER STREAM CROSSINGS IN THE CUMBERLAND PLATEAU

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_31 July 2012_____

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Chapter 1: Headwater Streams and Site Description

The definition of headwater streams varies widely but generally refers to upper tributaries of a drainage basin (Helms 1998). In the Pacific Northwest any channel with a drainage area less than 1,000 ha is classified as a headwater stream and are generally up to 10 m wide (Brummer and Montgomery 2003). Defining the downstream end point of headwater channels is also vague and has been identified as the colluvial-alluvial erosion transition point with alluvial processes become more dominant on higher-order perennial streams (Stock and Dietrich 2003). This downstream transition point has been defined as occurring at a drainage area of at most 100 ha to as small as 10 ha in the Pacific Northwest (May and Gresswell 2004, Madsen 1994). In the east, headwater streams are generally smaller than the Pacific Northwest and for the purposes of this experiment a headwater stream is defined as an ephemeral channel, intermittent stream, or a first order perennial stream.

Headwater streams possess physical and biologic characteristics that are unique or significantly different from higher-order (3rd order or greater) or mid-reach perennial streams. Headwater streams generally have a closed canopy compared to higher-order perennial streams and rely heavily on surrounding areas for inputs including leaf litter and coarse woody debris (Richardson and Danehy 2007). The closed canopy and high stream edge to surface area creates a microclimate that ameliorates daily changes in humidity and temperature. Headwater streams are steep and have the potential to harbor significant populations of benthic macroinvertebrates but are often too small to support significant fish populations (Wiginton et al. 2006). Lower fish populations allows other aquatic animals to take advantage of reduced predation thereby improving propagation.

The hydrology of headwater streams is characterized by small base and peak flows compared to higher-order perennial streams (Richardson and Danehy 2007). The limited flow peaks restrict the streams ability to manipulate the surroundings and change the morphology of the channel providing for greater stability of structure and streambank integrity (Moore and Wondzell 2005). Because of this lower flow, large wood and other debris tends to accumulate in the stream channel and leads to storage of organic matter and sediment and allows for the slow release of organic matter to downstream reaches. These stable features provide consistent habitat for aquatic and riparian species of headwater streams. Low flow can also create a physical isolation that increases the probability for genetically isolated species (Gomi et al. 2002). Rare, threatened, and endangered species are sometimes found in headwater streams because of this isolation. An example is the blackside dace (*Phonixus cumberlandis*), which is a federally endangered species present in headwater streams in southeastern Kentucky (Slone and Wethington 1998). Logging can remove canopies surrounding headwater streams, increased temperatures that can cause thermal stress as well as potentially increase sediment loads interfering with habitat and reproduction.

Because of their small size, headwater streams are especially sensitive to natural and anthropogenic disturbances including higher peak and total flows resulting from timber harvests (Richardson and Danehy 2007). There also may be quicker responses to rain events due to soil compaction near headwater streams (Brenda et al. 2005). Forest inputs into headwater streams are diminished after a timber harvest and a temporary flux of nutrients and suspended sediments affecting turbidity often occurs (Hassan et al. 2005). The removal of vegetation, increased sunlight, and increases in peak and average

daily water temperatures result in increases in primary productivity leading to a shift in invertebrate species composition (Hassan et al. 2005).

Shredders are the dominant benthic macroinvertebrate group of headwater streams (Vannote 1980). Shredders utilize the coarse particulate organic matter inputs from surrounding vegetation and have a significant dependence on the associated microbial biomass. Headwater streams also have a lower gross primary productivity to community respiration ratio than the higher-order perennial streams characterized as midreaches or lower reaches. This increase in the ratio of primary productivity to respiration is due to lower levels of shading and vegetation present on the banks of higher-order perennial streams. These higher-order streams are dominated by the collectors group of benthic macroinvertebrates that filter or gather material from the fine and ultra-fine material moved into the streams from the headwater streams.

Study Site

The study was conducted at the University of Kentucky's Robinson Forest (37° 27' N, 83° 08' W) in Breathitt, Perry, and Knott counties in southeastern Kentucky. Robinson Forest is a 5,983 ha research, extension, and educational facility in the Cumberland Plateau physiographic region occupied by the hardwood forests of central Appalachia (Braun 1950).

Robinson Forest lies in the interior rugged section of the Cumberland Plateau physiographic province (Hayes 2006). The Cumberland Plateau is comprised of a band of hills and tablelands running from southwest to northeast Kentucky, east of the Pottsville Escarpment. The interior rugged section of the Cumberland Plateau is

underlain by non-calcareous sandstones, shales, and coals from the Pennsylvanian period that were formed 325-360 million years ago.

All headwater streams involved in the study were located in the 1,700 ha Cole's Fork watershed of Robinson Forest (Fig. 1.1). Pictures of select streams are available in appendix A. Selective harvesting associated with initial settlement culminated in intensive harvesting by the Mowbray-Robinson Lumber Company between 1890 and 1920 at Robinson Forest (Overstreet 1984). The climate is classified as temperate-humid-continental with warm summers and cool winters (Overstreet 1984). Average annual precipitation for southeastern Kentucky is 116 cm while the 26-year average for three precipitation collectors at Robinson Forest is 118 cm (Cherry 2006). Average monthly precipitation at Robinson Forest is 9.8 cm and March tends to be wetter than average and October dryer (Cherry 2006). Table 1.1 provides rainfall amounts and dates for rainfall events during the portion of the study determining suspended sediment loads. Over the course of the entire experiment a drought occurred resulting in 26.8 cm less rainfall than normal for the 13 months of the entire experiment (Table 1.2).

The soils at the headwater stream study locations are of the Cloverlick-Shelocta-Cutshin complex (Hayes 2006). Cloverlick soils are described as deep and very deep, well drained soils formed in loamy colluvium derived from sandstone, siltstone, and shale. Permeability is moderate and the soils are on steep side slopes, benches, and coves. Shelocta soils consist of deep and very deep, well drained soils formed in loamy colluviums weathered from sandstone, siltstone, and shale. Permeability is described as moderate and Shelocta soils are located on steep and very steep side slopes, benches, and toe slopes. Cutshin soils consist of deep and very deep soils formed in loamy colluviums

derived from sandstone, siltstone, and shale. Cutshin soils are of moderate permeability and are located on steep side slopes, benches, and coves mostly on cool slopes.

Figure 1.1. Map of stream crossing locations within Robinson Forest

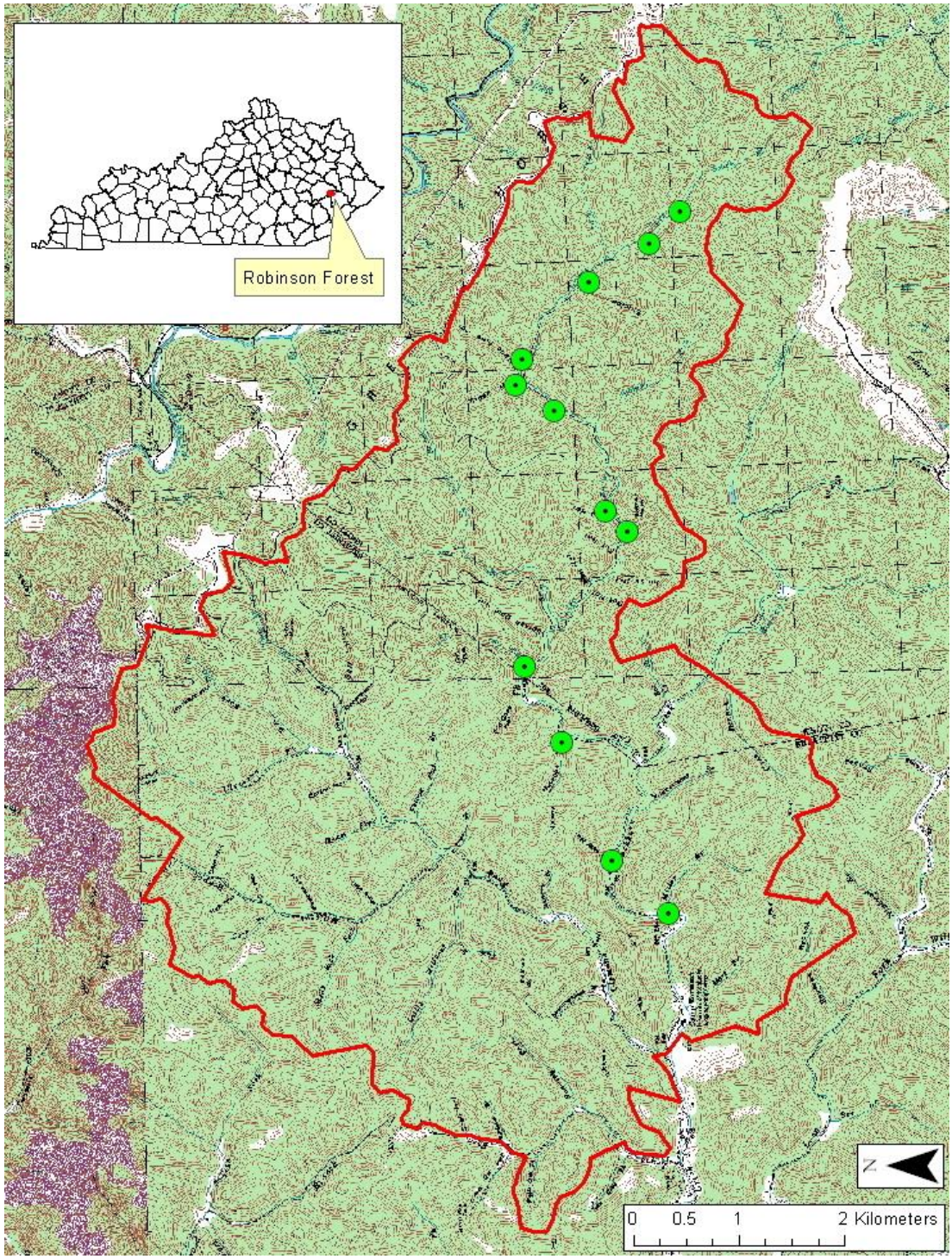

Table 1.1. Rain event dates and amounts during sediment load monitoring

Rain Event	Date	Amount (cm)
1	16 May 2007	2.2
2	1 June 2007	4.0
3	4 June 2007	2.3
4	5 June 2007	2.5
5	18 June 2007	2.2
6	26 June 2007	1.1
7	6 July 2007	0.8
8	19 July 2007	1.8
9	30 July 2007	0.6
10	4 August 2007	2.4
Total	---	20.0

Table 1.2. Monthly rainfall amounts and difference from normal

Month	Normal Monthly Rainfall (cm)	Monthly Rainfall During Study (cm)	Difference (cm)
May 2007	12.58	8.51	-4.07
June 2007	10.16	8.48	-1.68
July 2007	10.36	7.16	-3.2
August 2007	8.04	3.39	-4.65
September 2007	7.82	2.80	-5.02
October 2007	6.75	7.00	0.25
November 2007	8.41	8.08	-0.33
December 2007	8.76	11.66	2.9
January 2008	7.42	5.77	-1.65
February 2008	8.29	6.36	-1.93
March 2008	8.99	8.50	-0.49
April 2008	8.74	9.14	0.4
May 2008	12.58	5.29	-7.29
Total	118.9	92.14	-26.76

Table 1.3. Headwater stream characteristics

Name	Drainage Area (ha)	Crossing Type Assigned
John Miller Branch	12.6	Pipe Bundle
Cucumber Branch	24.5	Ford
Suicide Branch	20.6	Ford
Spruce Pine Hollow	30.0	Pipe Bundle
Steer Hollow	33.8	Pipe Bundle
Rockhouse Branch	33.9	Bridge
Pep Hollow	9.3	41 cm (16 in) Culvert
Beechnut Hollow	28.6	46 cm (18 in) Culvert
White Oak Fork	88.5	Bridge
Bucklick Branch	28.6	61 cm (24 in) Culvert
Grassy Hollow	15.1	Bridge
Miller Branch	118.6	Ford

Chapter 2: Water Quality

Introduction

In 2004 Kentucky's forest industry contributed 6.4 billion dollars to Kentucky's economy and employed over 37, 500 people in 110 out of 120 counties in Kentucky (Thomas et al. 2007). The economically important and ubiquitous nature of the forest industry justifies study of the impacts of forest operations on natural resource sustainability including water quality. A majority of the wood for Kentucky's forest industry is harvested with ground skidding methods using wheeled skidders typical for operations in eastern deciduous forests. This type of harvest creates roads and stream crossings that expose bare mineral soil that can contribute to nonpoint source pollution. A majority of sediment from timber harvesting comes from the construction and use of haul roads and constructed skid trails (Corbett et al. 1978, Kochenderfer 1970, Megahan and Kidd 1972, Patric 1976, Swift 1984). On these roads and constructed skid trails, stream crossings are the most frequent sources of sediment introduction because stream crossings serve as direct conduits of sediment into the hydrological system (Rothwell 1983, Swift 1985, Taylor et al. 1999).

While Kentucky is the only state in the south and one of the few in the U. S. that has legislated best management practices (BMPs) that regulate timber harvests to control nonpoint source pollution all states in the south have similar voluntary BMP guidelines (Grace 2005, Stringer and Thompson 2001). BMPs are designed to mitigate the possible adverse effects of timber harvesting on streams including increased delivery of sediment, increased water temperature, and other pollutants associated with forest operations. BMPs address issues that are potentially important relative to stream pollutions such as:

the placement, construction, use and retirement of haul or access roads, skid trail, and landings; use of streamside management zones, management of logging debris; control of runoff; and protection of wetlands, sinkholes, and other sensitive places. Kentucky's BMPs require loggers to use bridges or culverts (or other elevated crossings) to cross perennial, intermittent, and ephemeral channels where economically and technically feasible (Stringer and Perkins 2001). Perennial streams are typically classified as having water flow for greater than 90% of the year, intermittent streams 90 - 10% of the year, and ephemeral channels less than 10% flow throughout the year (Hedman and Osterkamp 1982). In Kentucky, perennial streams are defined operationally as streams that hold water throughout the year, intermittent streams that hold water during wet portions of the year, and ephemeral channels as a channel formed by water during or immediately after precipitation events as indicated by an absence of forest litter and mineral soil and are hydrologically connected to intermittent or perennial streams (Stringer and Perkins 2001). In a recent unpublished study of BMP implementation 97% of all stream crossings are on headwater streams a statistic that is consistent with Sidle et al. (2000) estimate that 75% of all watershed areas are drained by headwater streams (Stringer 2006). Only 9% of all crossings of any type were found to be elevated and only 4% of crossings of headwater streams are elevated (Stringer 2012). These statistics indicate that headwater stream crossings are important potential sources of pollutants from ground skidding operations and research to determine effective and efficient headwater stream crossing technology is justified.

While research on timber harvesting stream crossings has been conducted the majority of this work is on higher-order perennial streams not headwater streams (Taylor

et al. 1999). In-channel crossings with no improvement (fords) have been shown to cause the most impact to water quality because streamflow passes over the skid trail (Looney 1981, Thompson and Kyker-Snowman 1989, Thompson et al. 1996, Tornatore 1995, Tufts et al. 1994, Welch et al. 1998, White Water Associates 1997). Fords introduce sediment directly into the stream during construction and use. Fords are at higher risk of sediment introduction from sediment traveling down the skid trail approaches onto the crossing and flowing directly into the stream. Elevated crossings, especially those that minimize the volume of soil placed into the channel, are generally preferred options for crossing smaller streams and ephemeral channels. Culverts, bridges, and pipe bundles are termed elevated crossings for this study because the structures elevate the skid trail out and off of the streambed. Of the common types of elevated temporary crossings used in timber harvesting, culverts are considered to be the next most detrimental in terms of sediment introduction (Kochenderfer 1970, Looney 1981, Thompson et al. 1995, Tornatore 1995, White Water Associates 1997). Because culverts are typically buried with soil into the channel this introduces sediment directly into streams during construction and use and often soil is left in channels after removal. Bridges are generally considered to be the least detrimental in terms of sediment introduction into streams and channels, as they span the stream without inhibiting streamflow (Aust et al. 2011, Cesa et al. 1998, Hassler et al. 1990, Thompson et al. 1996, Tornatore 1995). A large number of other crossing options also exist. One of these, the polyvinyl chloride (PVC) pipe bundle shows promise for use as a temporary crossing of headwater streams but has not been researched to determine its effectiveness for mitigation of sediment introduction (Blinn et al. 1998, Mason 1990). The variable shape of the pipe bundle

conforms to the shape of the channel, requires less backfill than a culvert, and allows for more thorough removal of disturbed soil from the channel after crossing is retired.

Most of the research on stream crossings associated with timber harvesting has dealt with the crossing of higher-order perennial streams often with permanent structures for timber hauling and not skidding. It is not known if conclusions drawn from research on higher-order perennial streams can be extended to headwater streams where temporary crossings are typical and skidding is the predominant use.

The overall objective of this study was to determine the effectiveness of several types of temporary crossing structures including fords, metal culverts, portable skidder bridges and PVC pipe bundles on headwater streams. Specifically several water quality characteristics including suspended sediments, bedload, nitrogen, turbidity, and electrical conductivity were evaluated during the installation, use, and removal of the crossings as well as a period of time after the crossings were retired. The potential for the stream crossing structures themselves affected the surrounding stream features were investigated. Time and costs of installation and removal of the crossings were also measured.

Water Chemistry

pH

pH can be used as a surrogate for measuring specific increases in harmful nutrients (Brooks et al. 2003). pH can also represent a threshold measurement for many aquatic organisms. Freshwater fish can tolerate pH values between 6.5 and 8.4 (Brooks et al. 2003). Algae likewise cannot survive pH values higher than 8.5. Toxic drinking

water has a pH less than 4.8 and greater than 9.2. Previous studies have shown that water draining small undisturbed forested watersheds was generally neutral range from 6.7 to 7.1 and studies at Robinson Forest have shown that pH on a watershed scale does not significantly change when harvesting takes place (Arthur et al. 1998, Tiedemann 1988).

Electrical Conductivity

Electrical conductivity is the ability of water to conduct electricity and is positively related to dissolved solids (Brooks et al. 2003). A value of 2.00 µS is considered detrimental to freshwater fish (Brooks et al. 2003). Generally undisturbed watersheds range 0.26 and 0.36 µS (Tiedemann 1988) and small watersheds in Robinson Forest averaged 0.29 µS (Tiedemann 1988, Cherry 2006). Timber harvesting has been shown to raise electrical conductivity 12 – 75 µS in southern Mississippi (Keim and Schoenholtz 1999).

Nitrogen

Nitrogen is the most commonly studied ion because of its volatility, biological significance, and because unlike other ions many land uses and disturbances can cause nitrogen concentrations and surpasses maximum water quality standards (MacDonald et al. 1991). Nitrogen can be released into watersheds in many compounds such as nitrite but for this study nitrate (NO_3^-) and ammonium (NH_4^+) were the primary focus. Nitrate is typically the primary form of nitrogen pollution in disturbed forested watersheds (Vitousek et al. 1979). Fish life can be negatively affected if nitrate levels exceed 4.2 mg/L and human health begins to be affected when levels exceed 10 mg/L (EPA 1976).

Undisturbed forested watersheds normally have ammonium values between 0.002 and .015 mg/L and values of 0.001 and 0.09 mg/L for nitrate (Tiedemann 1988, NCASI 2001). The average nitrate and ammonium concentration levels in small undisturbed watersheds in Robinson Forest were 0.09 and 0.02 mg/l, respectively (Cherry 2006). Clearcutting has been shown to significantly increase nitrate however, all of the sources are not well understood (Tiedemann 1988). Possible sources of nitrate pollution including decomposing forest harvest residue and suspended sediments. Tiedemann (1988) has also shown that significant increases in nitrate do not occur in association with selective harvests indicating that road and stream crossings are not a source of nitrate pollution.

Turbidity

Turbidity is a measure of the cloudiness or clarity of water. The lower the turbidity value, the clearer the water. Turbidity can be caused by suspended clays, silt, sand, organic matter, or other solid particles (Brooks et al. 2003). It is important to note that turbidity cannot be a complete surrogate for suspended sediment because of the effect that particle weight can have on turbidity values. Turbidity values for Robinson Forest in small undisturbed watersheds average 2.59 NTU during storm events (Cherry 2006). Turbidity has been shown to increase during and immediately after timber harvesting activities and maximum values of 3,300 NTU have been recorded during the failure of a culvert (Martin and Hoenbeck 1994, Hornbeck et al. 1986).

Bedload

Stream bedload is defined as the solid material which is transported above the streambed which is not suspended in solution with stream flow (Bagnold 1977). Bedload can be any material with a diameter greater than 1.0 mm with materials less materials less than 0.1 mm transported as suspended sediment load (MacDonald et al. 1991). For the purposes of this study it is assumed that any material with a diameter less than 2.0 mm is sampled during the suspended sediment collection and analysis. Throughout this study the term bedload will only focus on this course bedload material (2 mm to boulder size material). Large scale bedload movement is generally limited to infrequent high flows that are difficult to predict (Bunte 1996). Bedload has been shown in some studies to be 55% of total sediment load and as low as 0% (Turowski 2010).

Methods

Study Design

Fifteen headwater streams were identified in the Cole's Fork watershed for possible temporary skidder crossing installation. These fifteen streams had similar soils and similar drainage area, easy equipment access, and similar adjacent morphology. Twelve streams were randomly selected and assigned a crossing type. Table 1.3 provides specific headwater stream characteristics including drainage area and crossing type assigned. The study had a one-way classification structure with four different treatment types replicated three times. For all study locations, crossings were installed upslope from their approaches removing any confounding effects of sediment entering the crossing location from the skid trails. No activities, including timber harvesting, took

place in the watersheds located upstream from the crossing locations for the entire length of the study. This ensured that all sediment generated from the study was derived from the crossing and not associated disturbance.

It is reasonable to assume that different phases of a crossing's use would contribute sediment and other pollutants to differing degrees. Determining the sediment delivery by phase provides practitioners with information that potentially can be used to make effective and efficient choices relative to pollution prevention. The study was designed to determine pollution generation during installation, use (as defined by periods when a loaded skidder was passing over the crossing), rain events, removal, and a post-removal period. Response variables during these phases were partitioned and comparisons among crossing types were made. However, because of a lack of rain during the removal phase that caused all headwater streams to cease flow it was impossible to partition between the removal and post-removal phases and they were combined.

Directly prior to installation of the structure, an upstream and downstream grab samples (200 ml) were collected. At five minute intervals downstream samples (200 ml) were collected until installation was complete (Reid 1993). One upstream sample was presumed to be sufficient based on the short period of time required for installation (maximum time of 19 minutes). Once installation was completed grab sampling continued every ten minutes for one hour.

A 540 John Deere cable log skidder skidding 35.6 cm (14 in) diameter, 6.1 m (20 ft) in length yellow-poplar (*Liriodenron tulipifera*) and white oak (*Quercus alba*) logs was driven over each crossing a total of 22 times over a period of six weeks comprising

the use period. There is no published data to support the selection of 22 crossings. This determination was based on the investigator's best estimate to test the effectiveness of the structures and time constraints associated with the study. This was considered the use phase of the study. Before each of the structures were crossed, an upstream and downstream grab sample (200 ml) were collected. Downstream grab samples (200 ml) were taken immediately after at 5, 10, 15, and 30 minutes after each pass. This length of time ensured that any pollutant generated by the skidder and logs passing over the structure was collected. Further, all crossings were passed over a similar number of times in a given day to ensure that no single headwater stream was crossed more times than another between rain events.

Water samples were also collected during high flow events caused by heavy rains. ISCO automatic water samplers (Reledyne ISCO, Lincoln, NE) were installed upstream and downstream of every crossing with liquid level actuators set to initiate sampling when water levels had risen. The samplers were installed three months ahead of time to calibrate the actuators. Once activated, a 200 ml sample was taken every 10 minutes until the flow subsided. Samples were combined for each rain event and the composite sample subjected to analysis.

Sampling during the removal of the structures was initially planned to be similar to installation. However, drought eliminated flow from some of the headwater streams during this phase of the study. It was determined to sample those streams that still had flow at 5 minute intervals until removal was completed and 10 minute intervals for 1 hour after. Those that had no flow were not sampled. Because of this the last two phases, removal and post-removal, were combined and it was not possible to determine

whether the sediment was from the act of removing the cross structure or was washed out during a rain event post removal. After removal, rain events were continually monitored for three months with the ISCO samplers using the same sampling intervals and procedures described for rain events during the pass over phase.

Construction, Installation, and Removal of Crossings

Temporary crossing types chosen for experimentation included unimproved fords (fords), and three elevated crossings including metal corrugated culverts using dirt fill (culverts), PVC pipe bundles (pipe bundle), and wood panel skidder bridges (bridge). Fords were used in this study without added bank or approach protection which is typical for skidder crossings. To install the fords, streambanks were cut down and approaches smoothed with a John Deere 550G bulldozer. There was no armoring of the approach or streambed. For removal, the 550G bulldozer smoothed out ruts and rebuilt streambanks. The 550G bulldozer did not attempt to repair the streambed during the removal phase because it would have potentially caused further detriment to the stream. Directly after removal, winter wheat (*Triticum aestivum*) was seeded at a rate of 39.2 kg/ha (35 lb/ac) on exposed mineral soil surrounding the crossing location to aid in streambank stabilization.

The diameter of culvert for each crossing was determined based upon the drainage area and ten-year rain event flow levels (Table 1.3) using Helvey and Kochenderfer (1988). A culvert size that can handle a ten-year rain event was chosen because of the temporary nature of the crossings and represents an effective size that can be easily obtained, transported, and installed by loggers. The 6.1 m (20 ft) length culvert was

pushed into the channel by two people and positioned in the bottom of the channel so that the flow would not pond behind the culvert. The 550G bulldozer was used to backfill soil into the channel around the culvert. Backfill was placed around the culvert until it was level with the bank. As is typical for temporary skidder crossings, there was no armoring of the approach or top of the structure. To remove the culvert, backfill was removed until the thickness of fill on top of the culvert would not significantly impede its extraction. After enough backfill was removed, a choker from a John Deer 540 cable skidder was wrapped around an exposed end of the culvert and the culvert was pulled from the stream. After the culvert was removed the 550G bulldozer continued to remove backfill until the streambank and bed were restored to approximate original contour. After removal winter wheat was seeded at a rate of 39.2 kg/ha (35 lb/ac) on exposed mineral soil surrounding the crossing to aid in streambank stabilization.

The pipe bundle design and construction methods were developed by the U.S. Forest Service (Mason and Moll 1995). The pipe bundles were constructed of 18 pieces of 10.2 cm (4 in) PVC pipe 4.57 m (15 ft) long with two 0.8 m (2.5 ft) 10.2 cm (4 in) PVC pipe spacers between each 4.57 m (15 ft) piece (Figure A.7). The spacers allowed for a greater surface area for the stream to flow through with a lower cost of materials and weight the latter an important factor in installation and transport. Each piece and spacer were strung together with 0.48 cm (3/16 in) galvanized steel wire. Two meters (10.8 ft) of wire was fastened around the cable loops holding the bundle together and used as an extraction wire to aid in removal. During installation, the structure was dragged across the stream by three people and folded on itself to rest on the stream bottom and within the stream channel. The top end of the pipe bundle was placed on the

opposite streambank so that when the pipe bundle was extracted all the backfill on top of the structure was pulled on bank limiting the amount of backfill left in the stream. The extraction line used to pull out the structure was placed to the side of the structure for access when the backfill was placed on top of the structure. The pipe bundle was then overlaid with geotextile that prevented backfill from settling though the bundle into the stream but allowed passage of infiltrated precipitation to the bundle. Backfill was gathered from the adjacent skid trail and placed on top of pipe bundle and geotextile with the 550G bulldozer and smoothed until level with the streambank. No gravel or other armoring was used. The design of the pipe bundle allows it to conform to the shape of the channel and requires a reduced amount of fill compared to the culverts (Fig. A.9). Further, the top fold of the bundle is approximately level and the majority of the fill on top of the bundle can be easily reached by a bulldozer of skidder blade and pushed off prior to extraction. For removal, the 540 John Deere skidder was backed to the edge of the channel, the extraction wire was attached to the wench cable, and the pipe bundle was extracted by moving the skidder forward. After the pipe bundle was extracted the soil backfill was smoothed out over the skid trail. No streambed reshaping was required since backfill was not left on the streambed. After removal, winter wheat was seeded at a rate of 39.2 kg/ha (35 lb/ac) on exposed mineral soil surrounding the crossing.

Bridges were composed of three panels constructed of six 25.4 cm (10 in) by 25.4 cm (10 in) eastern white pine[1] (*Pinus strobus*) cants bolted together with 19 cm (3/4 in) threaded rods, washers, and nuts to form three separate panels that when placed together

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[1] While eastern white pine was opportunistically used in this study, it is typically not recommended for operational use due to its lack of longevity

was 4.6 m (15 ft) in width. Panels were either pushed across the stream with a 550G bulldozer or wenched across the stream with the 540 cable skidder. The skidder and bulldozer then straightened and positioned the panel to minimize slope across the bridge to reduce the probability of lateral movement of the equipment off the bridge while crossing the structure. After all three panels were in place the bulldozer used soil to build small ramps on the ends of the bridge to facilitate skidder movement onto the structure. During removal the skidder blade was used to separate the panels so that a chocker could be wrapped around each panel. After the choker was secured around a panel, the skidder pulled the panel from the stream. The skidder then smoothed out the skid trail surface directly adjacent to the banks. After removal winter wheat was seeded at a rate of39.2 kg/ha (35 lb/ac) on exposed mineral soil surrounding the crossing location.

Water Quality Monitoring

Trapezoidal Rule Measurements

The trapezoidal rule was used for determining suspended sediment, pH, electrical conductivity, and turbidity means. This method allows for estimation of variables between samples. For this study grab samples were collected at intervals of 0, 5, 15, and 30 minutes after each skidder pass. To estimate the variable average between sample times a linear change in values was assumed. The average of two consecutive sampling periods was taken and multiplied by the time period length. This was done for all the sampled time periods and then summed. This sum was then divided by the total sampling period to determine the mean for the entire sampling period. This method was used for installation, grab samples taken during each crossing event, and removal.

Sediment Load

Samples were vacuum filtered through a 0.1 µm glass fiber filter placed in a 40 ml capacity Gooch crucible according to American Public Health Association Guidelines (Greenberg et al. 1992). The filter was washed with deionized water to conform to the shape of the crucible. The filter and crucible were then heated to 103° C for an hour to evaporate any remaining moisture and cooled to ambient temperature. The filter and crucible were weighed and a 100 ml subsample was removed from each sample and pulled through the filter with vacuum. The remaining filtered solids were washed with deionized water. After filtering the sample, crucible, and paper were dried at 103º C for one hour to evaporate any remaining moisture and placed in a desiccator. After reaching ambient temperature the sample, crucible, and filter were reweighed. Sample concentration was determined by the difference between the weights divided by the amount of water filtered.

To determine the flow at each crossing site the velocity of the water was multiplied by the stream's cross sectional area. The Manning's equation [$V= (k/n) * (R^{2/3}) * (S^{1/2})$] was used to estiamte velocity for each stream. Where V is the velocity of the water, k is a conversion constant (1.0 in the case of metric units), n is the Manning coefficient, R is the hydraulic radius, and S is the slope of the water surface. The Manning coefficient is based upon the channel roughness and shape and was determined by looking at photographs and tables of predetermined n values to determine a value for the study streams (Arcement and Schneider 1989, Barnes 1967, Brooks et al. 2003, Chang 2005). For streams in this experiment an n value of 0.035 was used as has been recommended for small mountain streams with vegetation. The hydraulic radius is the

cross sectional area divided by the wetted perimeter. The wetted perimeter is the perimeter of the cross sectional area. To determine these values a surveyed cross section was established and a pressure transducer was placed on the stream bottom and a pressure measure taken every 15 minutes to determine water depth (stage height). Along with an established cross section established at a downstream riffle, the stage height determined from the pressure transducers was entered into RIVERMorph (RIVERMorph, LLC) to determine the variable values for the Manning's equation.

To determine total mass of suspended sediment (kg), concentration levels (mg/l) were multiplied by the flow at the time sampled (l). Comparisons among crossing types were completed using ANOVA and least square difference procedure to determine significant differences among crossing types. Although only estimations of suspended sediment were provided because of the use of the Manning's equation to determine flow, making comparisons to other studies difficult, it is important to note that the comparisons among crossing types were still important and necessary to determine the best crossing type to mitigate excessive sedimentation from stream crossings.

Bedload

Total bedload was estimated at each crossing location. Bedload consists of gravel, cobble, or larger sized materials (> 2 mm) that are not accounted for in the suspended sediment samples. Bedload traps consisting of frames built out of a 12.7 mm (0.5 in) PVC tube frame with T joints to hold the pieces in place were designed and constructed similarly to Bunte et al. (2004). Bags to trap the bedload were constructed out of 2 mm screen door wire to catch the appropriate sized material while allowing silt,

sand, and clay to pass. The nets were sewn together and attached to the frame with 10 lb test monofilament line. Any particles smaller than 2 mm were assumed to be captured and accounted for in the suspended sediment sampling.

Traps were placed upstream and downstream as close to the thalweg of each stream as possible directly before installation. Traps were removed at the end of the post removal phase. Some streams had bedrock beds that forced the samplers to be located near the banks to provide support. Two pieces of 6.35 mm (0.25 in) x .46 m (1.5 ft) rebar we hammered into the streambed through the holes of the T joints on the sampler frame. Another piece of rebar was bent in the shape of a U and hammered over the bottom support of the trap's frame to prevent it from floating off of the two side supports during high flow events. This also insured that no materials would go under the sampler.

Analysis of bedload was completed at the end of the post removal phase and only allowed for one measurement for the entire experiment. This protocol provided only total bedload generated over all phases. After monitoring the samples were consecutively wet sieved through 2, 4, 8, 16, 31.5, and 64 mm sieves. The sieve and bedload mass was determined by weighing the sieves and collected bedload material and sieve tare weight was subtracted to determine bedload mass. The bedload generated by each crossing was the difference between bedload mass from the upstream and downstream traps expanded for the entire width of the stream by taking the average active streambed upstream and downstream, dividing it by the width of the trap (0.3 m or 1 ft), and multiplying it by the bedload collected in the trap. The active stream bed was defined as the bankfull width subtracted by any obstructions such as logs protruding into the bankfull area.

Comparisons among crossing types by total bedload and by size class were determined using ANOVA and least square difference procedure.

Total Sediment Load

Average total sediment load for each of the four crossing types over the entire study period (kg) was determined by summing suspended sediment load during all four phases and total bedload. Total sediment load was used to determine the percentage of sediments contributed by each phase of the study.

Water Chemistry

Samples taken during installation, passes over the structures, removal, post removal, and rain events were analyzed and compared to the upstream control sample for changes in pH and electrical conductivity using a YSI 85 Multifunction Meter. Individual sample data were subjected to the same statistical analysis as suspended sediment samples.

Because of budgetary constraints and the greatest flush of nitrogen compounds occurs during high flow events nitrogen levels were determined for only samples taken during rain events. Increases in nitrate and ammonium levels were determined by subtracting the downstream concentration level from the upstream concentration level. Nitrate and ammonium concentrations (mg/L) were analyzed with a Braun:Luebbe Auto Analyzer 3 using the Colorimetric procedure (APHA 1992).

Samples taken during installation, passes over the structures, removal, post removal, and rain events were analyzed and compared to the upstream control sample for

changes in turbidity. Turbidity was measured with a LaMotte 2020 Turbidimeter. Statistical comparisons among crossing types was completed using ANOVA and least square difference procedure.

Results and Discussion

Suspended Sediment

Overall Phases

Overall F tests on total suspended sediment production indicated a highly significant difference among treatments ($p < 0.0001$). Results indicated that average suspended sediment production over all elevated crossing types (204 kg ± 65) (mean ± standard error) was significantly less than the average for the fords (7,888 kg ±1,614) (Fig. 2.1). Kentucky's legislatively mandated BMPs stating that operators should "use or install bridges or culverts to cross streams (perennial or intermittent) or ephemeral channels, where feasible" (Stringer and Perkins 2001) is supported by these results. Using any type of elevated crossing results in a 97% decrease in suspended sediment production compared to fords.

Significant differences were found among elevated crossing types relative to total suspended sediment production (Fig. 2.2). Bridges yielded significantly lower amounts of suspended sediments than culverts, but pipe bundles were not significantly different from bridges or culverts. Culverts mean total suspended sediment value (432 ± 38 kg) was significantly higher than the mean total suspended sediments for bridges (28 ± 15 kg). The performance of bridges relative to culverts was anticipated and mirrors studies conducted on higher-order streams (Looney 1981, Thompson et al. 1995, Tornatore

1995). These results are also similar to those of Witt et al. (2011) showing the effectiveness of elevated stream crossings at mitigating sediment contribution. Witt found that bridges and culverts reduced total suspended solids concentrations 88% and 85% respectively. Pipe bundles were able to reduce total suspended solid concentrations 77%. Similar reductions were found with turbidity values. The pipe bundles mean total sediment (154 kg ± 71 kg) was not significant different from culverts or bridge. Although not statistically different from the other tested elevated crossing types the results do indicate that pipe bundles could be recommended as an improved crossing type to mitigate sediment from headwater streams.

Installation

While the numeric average suspended sediment mass was greater for the culvert compared to other treatments during installation there were no significant differences among all crossing types ($p = 0.56$) (Fig. 2.3). The lack of difference among crossing types during installation may reflect the low flow levels that were present at that time. It was hypothesized that the backfill required for a culvert would cause significantly higher sediment levels than the other crossing types. Bridges introduce sediment only from being dragged across the channel for installation and construction of approach ramps up to the edge of the wood panel structure. The pipe bundle only has backfill across the top of the structure and large amounts of sediment do not come into contact with the stream flow itself. The low flow of headwater streams during this time may have not generated the energy required to move significant amounts of sediment that was being placed in the stream as backfill during culvert installation.

Use

While no differences were found among crossings types during installation, there was a significant difference between elevated crossings and fords during use. Fords generated a total of 6,556 kg (± 2,521) of suspended sediment during the 22 passes over the structure. This was significantly higher than the overall average of 50 kg (± 23) for the elevated crossing types ($p < 0.0001$). Even with low flows, having the skid trail go down directly into the stream channel increased suspended sediment. There were no significant differences among elevated crossing types during the actual passes by a loaded cable skidder (Fig. 2.4). This indicates that once the elevated structures were in place, they successfully mitigated suspended sediment introduction into streams.

Rain Events

During rain events, while the crossings were installed, there was a significant difference ($p < 0.05$) among crossing types (Fig. 2.5). Fords and culverts were not significantly different ($p < 0.05$) but were significantly higher than bridges and pipe bundles during rain events while the structures were still in place (Figs. 2.5 and 2.6). There were no differences between pipe bundles and bridges. It is probable that the high storm event flow levels generated the energy needed to dislodge backfill soils used for culvert installation. Loose soil drug into fords from skidding washed from the knocked down stream banks. Pipe bundles and bridges did not have the backfill in the stream compared to culverts or have sediment remaining in the stream that was not carried away like fords. There was backfill for the pipe bundles but it was above the stream and did not come into contact with the stream even during the higher flow events. A geotextile

sheet between the structure and backfill prevented dirt from entering the stream as well. This indicates that bridges and pipe bundles may be better options for streams with higher flow rates compared to culverts. Further, they may be better choices during periods were high rainfall and increased flows are expected.

Removal and Post-removal

During removal and post-removal activities fords produced significantly higher amounts of suspended sediment than elevated crossing structures ($p < 0.05$). Fords generated 396 kg (± 189) compared to 96 kg (± 33) for all elevated crossing types. Even though there was no disturbance occurring after removal and skidder ruts and streambanks were stabilized, fords continued to contribute suspended sediment to streams. Among elevated crossing types bridges and pipe bundles produced significantly less suspended sediments than culverts during both removal and post-removal periods ($p \leq 0.05$) (Fig. 2.7). Culverts contributed significantly lower amounts of suspended sediment than fords but higher than pipe bundles and bridges because of the sediment remaining in streams after the culvert was removed. The 550G bulldozer attempted to get down into streams and to clean out as much backfill as possible. However, the size of headwater streams made it difficult to do so and sediment could not be fully extracted. This situation is also supported by observational evidence of active timber harvesting operations (Stringer personal communication 2012). Sediment remained in the channel after removal and it eventually flowed out of the crossing area during high flow events. It is reasonable to expect that the extraction of backfill sediments might be more effective

in larger, higher-order streams.

Hard Bottom Fords

Considering that fords were the highest contributor of suspended sediment in the study a recommendation could be made to eliminate or severely limit their usage. A recommendation that is frequently made is that the streambed should be bedrock or other hard surface when a ford is constructed. In this study streams were randomly assigned crossing types without regard to streambed type. Out of the three streams assigned the unimproved ford treatment one had bedrock and two soft bottoms. Observations indicated that the two soft bottom streambeds quickly became rutted and produced large amounts of suspended sediment while minimal rutting of the streambed was associated with the hard bottom ford. Although not statistically valid a comparison of the hard bottom ford compared to the average for the soft bottom ford found the mean suspended sediment amount for the soft bottom fords was 9,603 kg and 5,285 kg for the hard bottom ford. Even with the best case scenario of having a bedrock base for the ford, the suspended sediment generated was still 10 times greater than culverts, the next highest suspended sediment generator (432 kg). Based on these preliminary numbers, it is reasonable to suggest that these results give support of the Kentucky BMPs indicating the use of bridges or culverts (or other elevated crossings) be used where feasible. These observations support the results of Sample et al. (1998) that fords constructed through bedrock (hardened) streambeds do not negatively affect water quality when compared soft bottom (earthen) fords on non-logging roads. Sample et al. (1998) found that hardened fords had average turbidity values 6,090 NTU less than earthen fords and 7,620

mg/L less suspended sediment values. The results of this study indicate that installation of fords should be severely restricted to areas that are being minimally crossed, even when fords can be constructed through hard bottom streambeds, and used only during periods of low flow. If a ford must be installed, mitigating the suspended sediment from entering the approaches by armoring the stream banks with gravel or geowebbing is recommended but future studies could determine if a hard bottom ford with armored approaches mitigates suspended sediment comparable to elevated crossings (Tornatore 1995).

Bedload

Overall F tests indicate there were no significant differences in total bedload generated or particle size distribution among crossing types and phases ($p > 0.05$). Table 2.1 provides the averages and standard errors for the total bedload generated and size distribution for all crossing types and phases. Results indicated that bedload mass was a fraction of suspended sediment mass. The highest total bedload value among all cross types was 0.7 kg for fords, a relatively small amount, only 2.5% of total suspended sediment generated from the lowest polluting crossing type (bridge). The disparity between bedload and suspended sediment was probably a result of the low flows associated with these headwater streams and bankfull stage was also not reached during the study period. The maximum stormflow value during the installation period was 55% of bankfull flow. This stormflow value was higher than the 33-50% of bankfull discharge needed to potentially begin flow of sand sized particles and small gravel (Schmidt and Potyondy 2004). Larger and coarser bedload materials begin to move at 50

to 70% of bankfull discharge rates just to begin to move 60% of bedload materials. Although one storm event did occur in the range to begin to move some bedload material, full potential movement of all sizes of bedload material begins to occur when bankfull stages are met during storm events. During the study there was simply not enough energy generated by elevated storm flows to move significant amounts of large particle sizes. The results indicate that bedload is a very small pollutant when compared to suspended sediment but are inconclusive when considered creating and addressing best management practices for temporary skid trail crossings of headwater streams. Future studies will need to include at least one bankfull stage flow event to definitively determine effects of the crossings on changes in bedload. The results do demonstrate that when flow levels are low and in soil types similar to this study bedload is not a significant source of stream materials.

Total Sediment Load

As would be expected from the small amount of bedload found total sediment load (total load) followed the same statistical pattern as suspended sediments. Significant differences for total sediment load did occur ($p < 0.05$) between fords and elevated crossings (Table 2.2). Among elevated crossings total sediment load from culverts were significantly higher than bridges and pipe bundles were not significantly different from culverts or bridges.

Water Chemistry

pH

The average upstream pH value was 6.99, within the range of acceptable standards for drinking water and health of aquatic organisms. No statistical changes in pH caused by the crossing of the streams were detected in the downstream sample values obtained in this study are consistent with data from other watersheds in Robinson Forest and with similar streams in the region (Cherry 2006 and Tiedemann 1988). Overall F tests indicate there are no differences among all crossings types and phases in mean weighted change in pH ($P > 0.05$). Table 2.3 provides the averages and standard errors for the mean weighted change in pH for all crossing types and phases. The lack of pH changes indicates that adjustments in chemical ion concentrations of pollutants did not occur because of temporary skid trail headwater stream crossings.

Electrical Conductivity

Overall F tests indicate there are no differences among all crossings types and phases in mean weighted change in electrical conductivity ($P > 0.05$). There were no averages above 0.01 µS for the entire study and the highest recorded value for the entire study was a value of 0.04 µS that occurred during a pass over of the ford crossing type. This is far below the minimum value of 0.40 µS that begins to impair macroinvertebrate health and the average value of undisturbed forest watersheds at Robinson Forest (Pond and McMurray 2002 and Cherry 2006). The lack of changes in electrical conductivity indicate that other dissolved solids besides suspended sediment did not occur as pollutants in temporary skid trail crossings of headwater streams.

Nitrogen

There was no significant change in ammonium or nitrate concentrations associated with crossings. Overall F tests indicate no significant difference between upstream and downstream concentrations in nitrate concentrations during rain events for all crossing types ($P > 0.05$). The mean difference between upstream and downstream concentrations of nitrate (mg/L) was 0.10 (± 0.07) for fords, 0.07 (± 0.04) for culverts, 0.01 (± 0.07) for pipe bundles, and 0.34 (± 0.31) for bridges.

Overall F tests indicated no significant difference between upstream and downstream concentrations in ammonium concentrations during rain events for all crossing types ($p = 0.69$). The mean difference between upstream and downstream concentrations (mg/L) of ammonium was 0.05 (± 0.03) for fords, 0.04 (± 0.03) for culverts, 0.01 (± 0.02) for pipe bundles, and 0.03 (± 0.01) for bridges. These fluctuations keep the overall nitrate and ammonium concentrations far below the threshold value of 4.2 mg/L that begins to impair aquatic organisms. These results indicate that nitrate and ammonium are not significant pollutants from headwater stream crossings by skidders in eastern Kentucky for all crossing types including fords in the study area with similar soils.

Turbidity

Average upstream turbidity was 1.22 (± 0.13) NTU, within the range of acceptable standards for clean drinking water and comparable to previous studies at Robinson Forest (Cherry 2006). Overall F tests indicate no difference among crossings

types and phases in mean weighted change in turbidity ($P > 0.05$). Table 2.4 provides the averages and standard errors for the mean weighted change in turbidity for all crossing types and phases. Significant differences in turbidity were probably difficult to detect due to the flow levels of the headwater streams. The generated sediment was diluted by the higher flows and in turn lowered the turbidity but still generated the same or greater amount of sediment as the lower flow stream. Turbidity was not an adequate indicator of determining the level of sedimentation compared to directly measuring suspended sediment load but did increase after disturbance as indicated by other investigations (Martin and Hoenbeck 1994, Hornbeck et al. 1986).

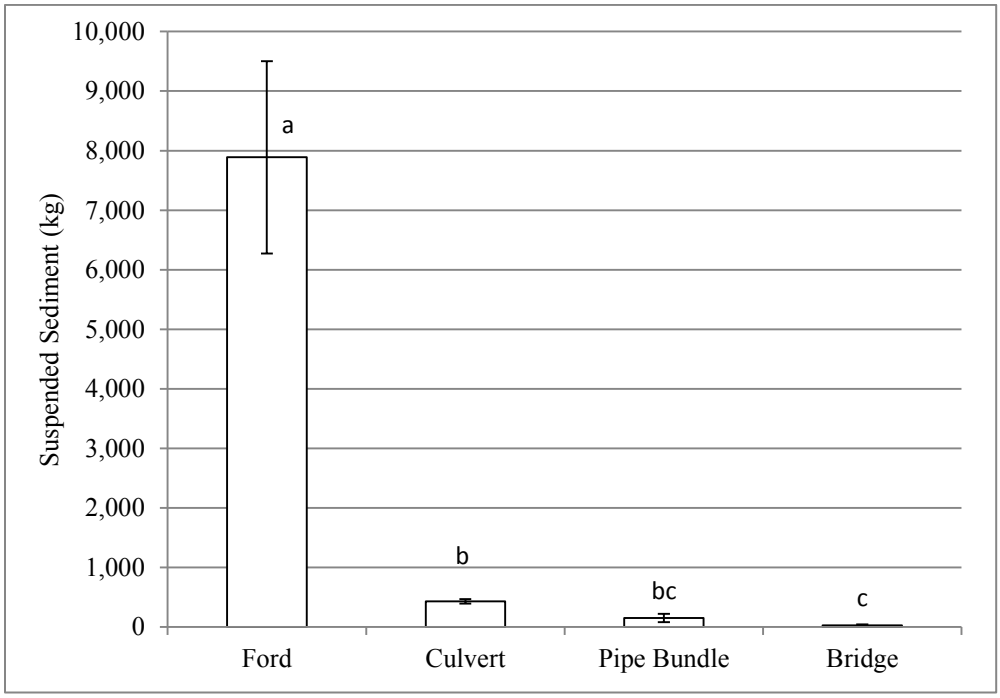

Figure 2.1. Total suspended sediment (mean and standard error) among all crossing types. Different letters indicate significant differences ($p \leq 0.05$) using least squares difference

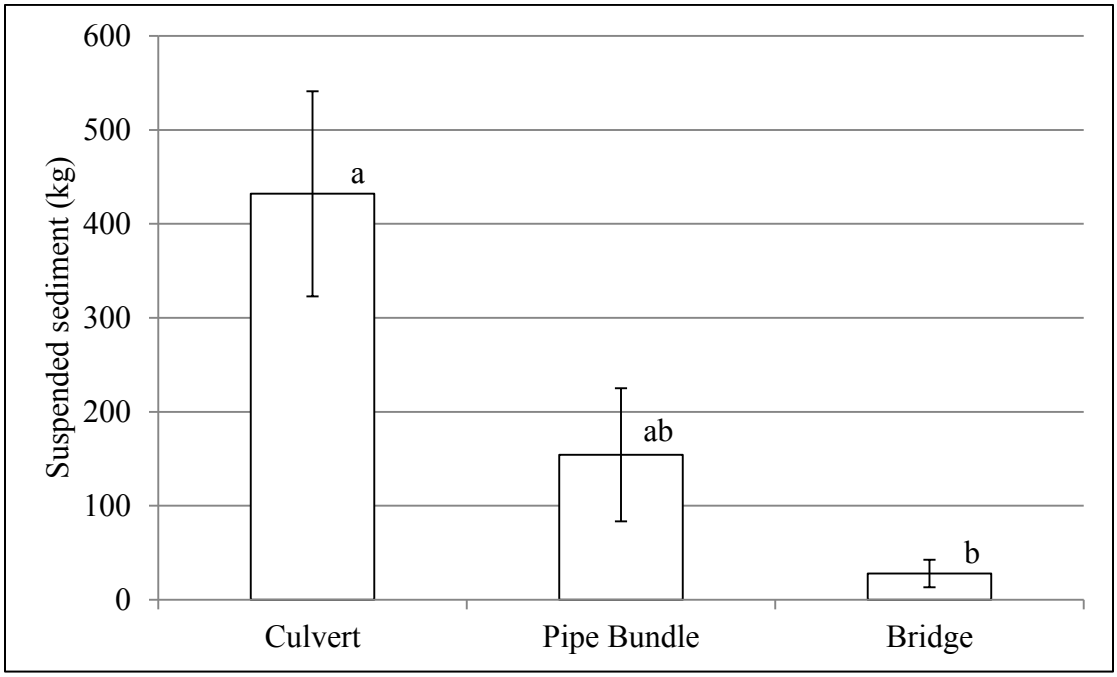

Figure 2.2. Total suspended sediment (mean and standard error) among elevated crossing structures. Different letters indicate significant differences ($p \leq 0.05$) using least squares difference

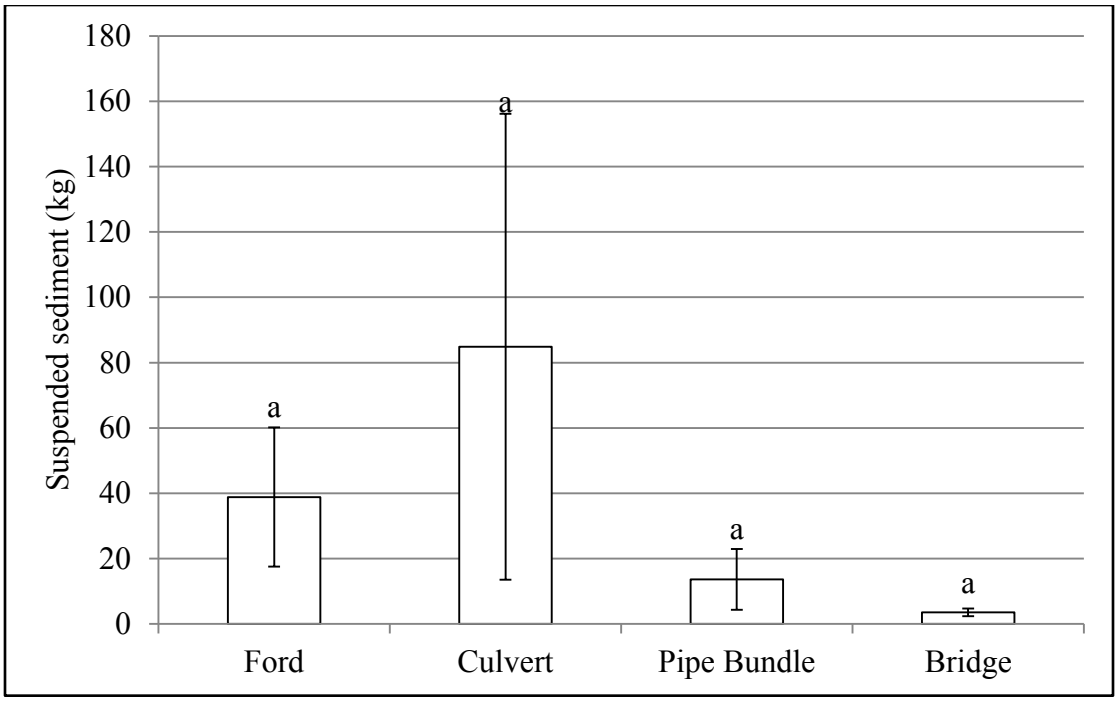

Figure 2.3. Installation produced sediment (mean and standard error) among crossing type. Different letters indicate significant differences ($p \leq 0.05$) using least squares difference

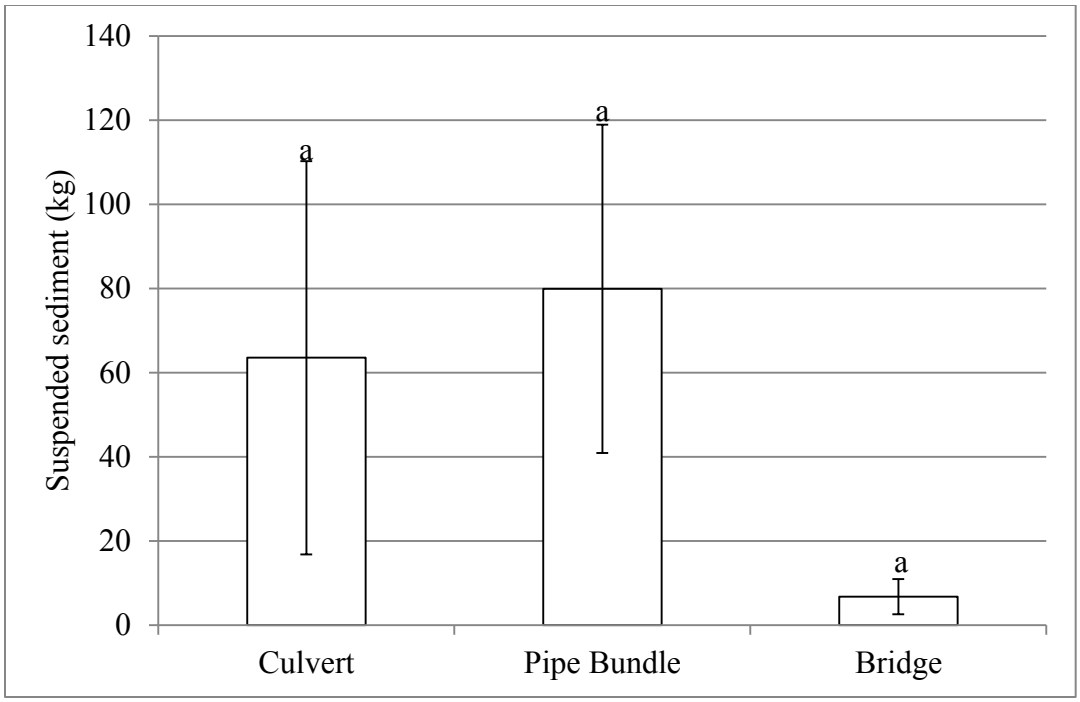

Figure 2.4. Equipment passes produced total suspended sediment (mean and standard error) among elevated structure types. Different letter indicate significant differences ($p \leq 0.05$) using least squares difference

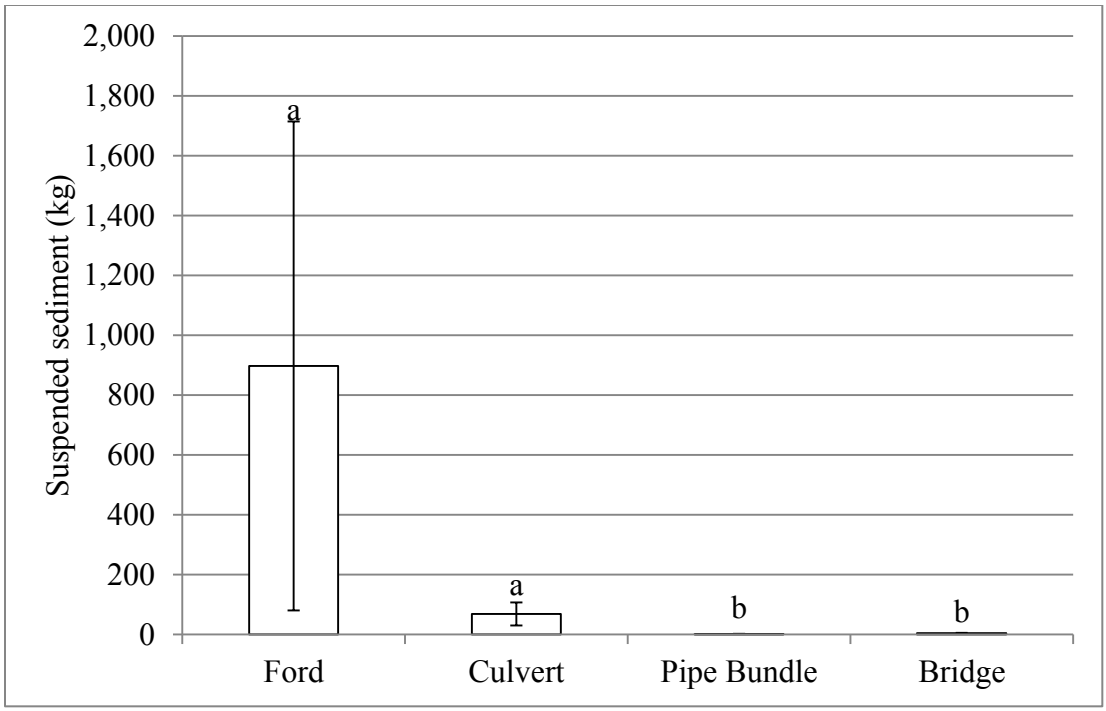

Figure 2.5. Rain event total suspended sediment (mean and standard error) produced among all crossing types. Different letters indicate significant differences ($p \leq .05$) using least squares differences

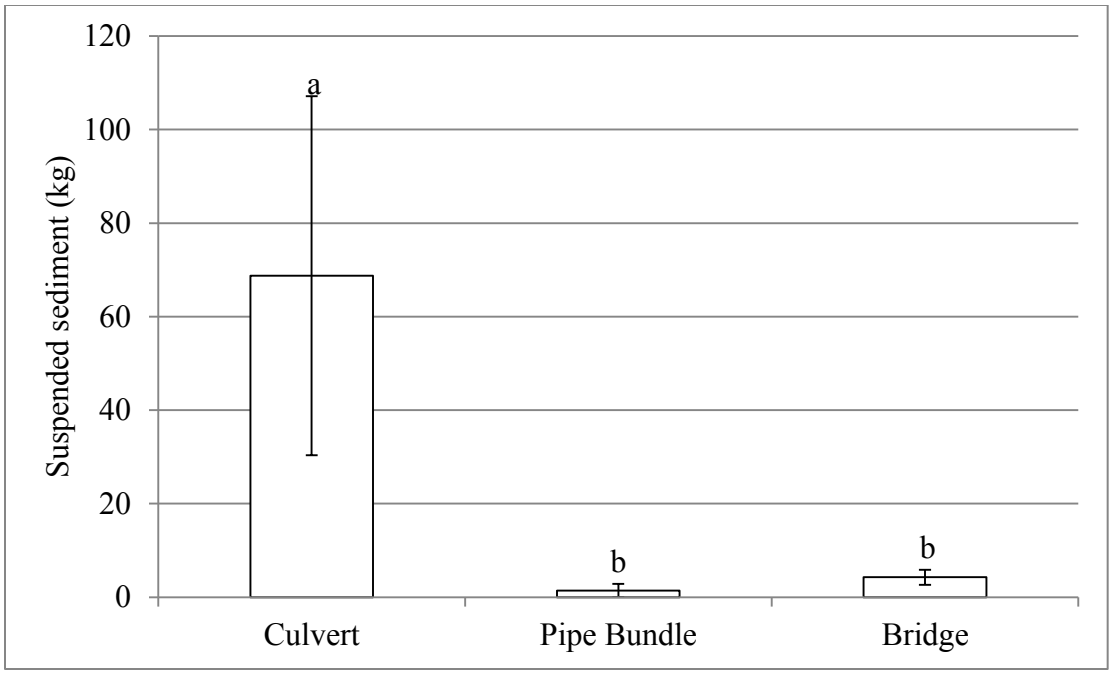

Figure 2.6. Rain event total suspended sediment (mean and standard error) produced among elevated crossing types. Different letters indicate significant differences ($p \leq 005$) using least squares differences

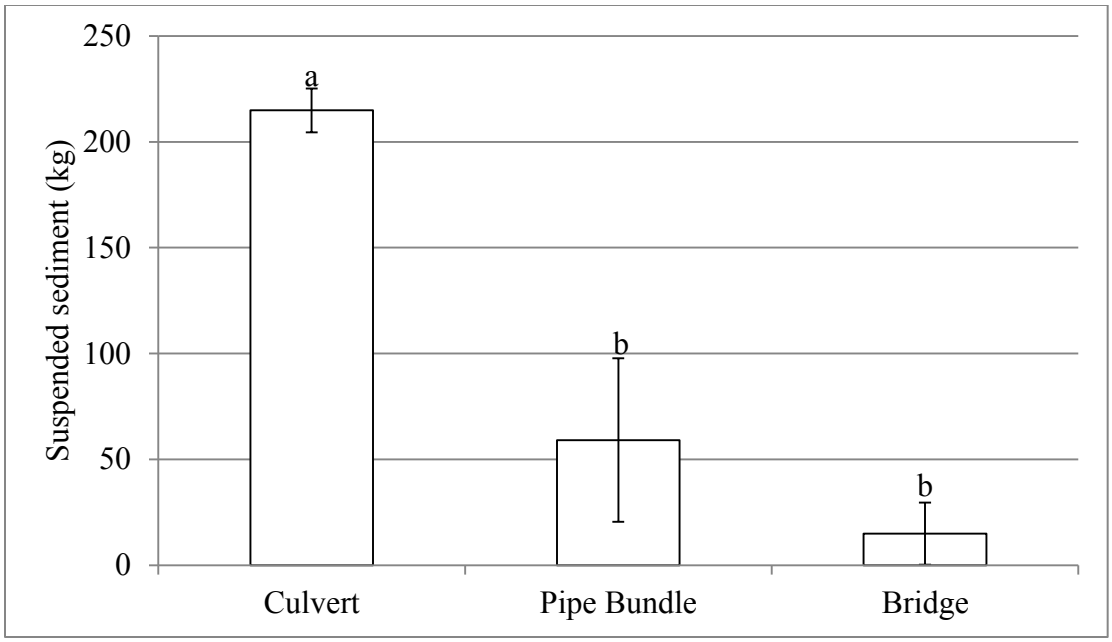

Figure 2.7. Removal and post-removal total suspended sediment (mean and standard error) among elevated crossing types. Different letters indicate significant differences ($p \leq 0.05$) using least squares differences

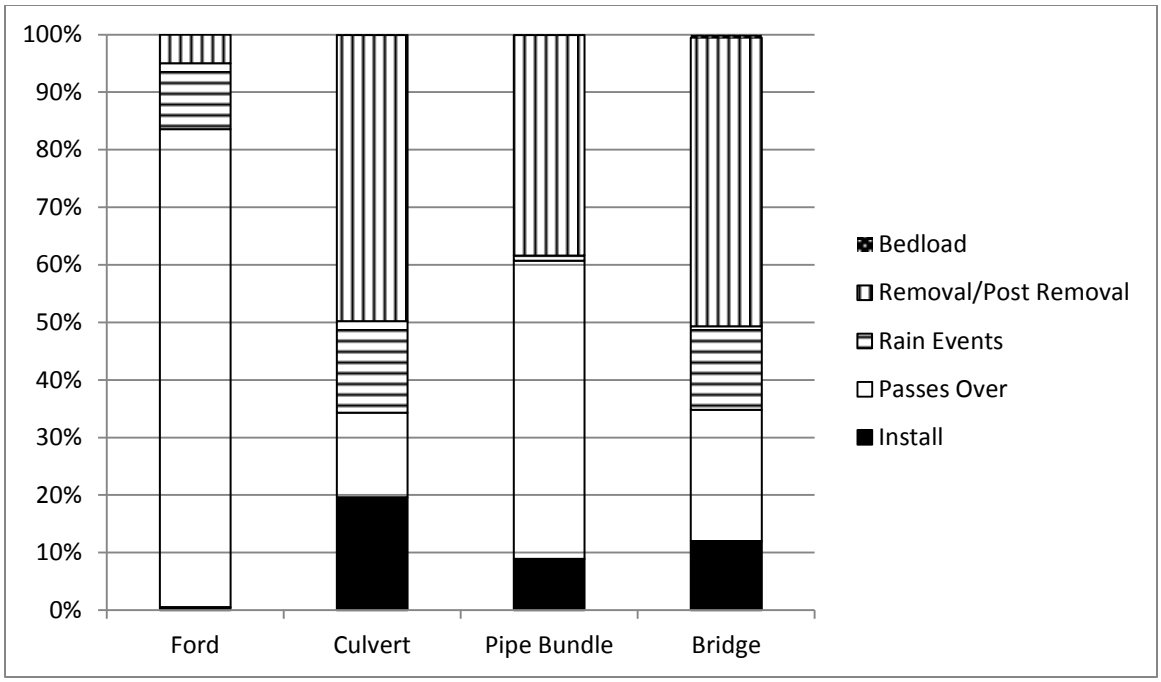

Figure 2.8. Percent of total suspended sediment by phase among all crossing types

Table 2.1. Total sediment load summary

Sediment Levels (kg)	Ford		Culvert		Pipe Bundle		Bridge	
Installation	38.85	a	84.85	a	13.65	a	3.55	a
Passes Over	6,555.85	a	63.58	b	79.93	b	6.78	b
Rain Events during Installation	897.85	a	68.76	a	1.42	c	4.28	c
Removal & Post-removal	395.77	a	214.87	b	59.13	c	14.91	c
Total Suspended Sediment	7,888.32	a	432.06	b	154.13	bc	29.52	c
Bedload	0.77	a	0.29	a	0.18	a	0.16	a
Total	7,889.09	a	432.35	b	154.31	bc	29.68	c

Different letters within a row indicate significant differences ($p \leq 0.05$)
Negative numbers indicate sediment deposition

Table 2.2. Bedload generated totals and size distribution means and standard errors (g) by crossing type

Size (mm)	Ford	Culvert	Pipe Bundle	Bridge
>63	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)
31.5 < 63	102.7 (± 90.4)	106.7 (± 81.0)	22.9 (± 18.7)	0.0 (± 0.0)
16 < 31.5	27.1 (± 20.6)	101.7 (± 65.2)	45.1 (± 98.6)	116.5 (± 123.5)
8 < 16	224.0 (±198.5)	42.2 (± 39.5)	18.7 (± 9.5)	41.2 (± 35.6)
4 <8	100.5 (±85.6)	5.06 (± 2.5)	43.0 (± 38.6)	4.1 (± 1.5)
2 < 4	74.0 (±57.5)	30.6 (± 25.6)	48.6 (± 40.5)	0.0 (± 0.0)
Total	771.8 (±730.2)	286.2 (±259.3)	178.2 (±156.4)	161.8 (±129.9)

Table 2.3. pH change (mean and standard error) among all crossing types and phases

Phase	Ford	Culvert	Pipe Bundle	Bridge
Installation	-0.32 (± 0.19)	-0.30 (± 0.01)	0.07 (± 0.02)	-0.05 (± 0.03)
Pass Over	-0.62 (± 0.35)	-0.08 (± 0.07)	0.00 (± 0.06)	0.01 (± 0.04)
Rain Events while Installed	-0.01 (± 0.01)	-0.05 (± 0.04)	-0.06 (± 0.14)	0.00 (± 0.06)
Removal/Post Removal	-0.16 (± 0.17)	-0.04 (± 0.02)	-0.03 (± 0.06)	-0.09 (± 0.05)

Table 2.4. Turbidity (NTU) change (mean and standard error) among all crossing types and phases

Phase	Ford	Culvert	Pipe Bundle	Bridge
Installation	424.0 (±108.9)	588.4 (± 209.7)	32.3 (± 10.0)	14.2 (± 9.0)
Pass Over	19,777.4 (± 9,969.8)	174.6 (± 168.6)	46.8 (± 30.9)	5.0 (± 4.88)
Rain Events while Installed	168.0 (± 59.1)	10.9 (± 1.4)	11.7 (± 4.2)	5.1 (± 3.9)
Removal/Post Removal	170.1 (± 59.1)	303.0 (± 193.4)	127.23 (± 106.2)	95.8 (± 74.6)

Chapter 3: Stream Channel Cross Sectional Morphology

Introduction

While the construction and use of crossings on headwater streams can affect the stream at the crossing point, the crossing also has the potential to affect the channel upstream and downstream of the crossing location. Previous studies have shown that permanent stream crossings alter downstream morphology but it is not known what time periods are required to cause change (Richardson et al. 1993, Kattell and Eriksson 1998). Specifically, localized changes in flow velocity and direction caused by crossing structures can potentially influence stream channel. Flow acceleration increases the amount of degradation and scour around and downstream from the crossing structure (Furniss et al. 1991). Scouring is one of the most common problems associated with crossing installation. Scour is defined as "localilzed removal of channel bed material by flowing water" and is the most common cause for bridge erosion and eventual failure on national forest lands (Brooks et al. 2003, Kattell and Eriksson 1998).

While scouring of streambanks and streambeds has been associated with culverts and bridges, research on this topic has been conducted primarily on permanent higher-order stream crossings. It is not known if conclusions drawn from research on higher-order perennial streams can be extended to headwater streams where temporary crossings are typically used for skidding and where a wide range of crossing methods are used. Studies have also focused on effects of general forestry operations such as clearcutting on stream channel morphology (Davies et al 2005).

Potential changes in stream morphology can be predicted by Lane's balance (Lane 1955). Alterations in stream flow and sediment levels are expected by the crossing

structures and Lane's balance equilibrium equation can used to predict morphological responses (aggregation or degradation). Lane's balance requires that when there is a change in the alluvial channel equilibrium equation there must be a reaction to compensate for the imbalance. Lane's balance is defined as $Q_s \cdot D_{50} \rightleftharpoons Q_w \cdot S$ where Q_s is sediment discharge, D_{50} is sediment particle size, Q_w is stream flow, and S is channel slope. If there is an increase in flow and no change in channel particle size, there must either be an increase in sediment discharge or increase in stream particle size to balance out the equation. If channel slope is increased by straightening out the channel and stream flow discharge remains the same, sediment discharge or particle size must increase. These imbalances are rectified by aggradation or degradation of stream channel morphology.

Methods

Changes in stream morphology were determined by measuring increases or decreases in channel cross sectional area by crossing type. Treatment type and study design for morphology analysis will be similar to those discussed in chapter 2. Time periods were adjusted from the previous study to determine effects before, during, and after treatments. Periods correspond with the following dates:

- Period 1 – 20 March 2007 – 22 April 2007 – before treatment (prior to installation)
- Period 2 – 23 April 2007 – 25 May 2007 – halfway through treatment period with ½ passes completed
- Period 3 – 26 May 2007 – 22 June 2007 – immediately post treatment

- Period 4 – 23 June 2007 – 3 December 2007 – six months after treatment
- Period 5 – 3 December 2007 – 5 May 2008 – one year after treatment

Periods were also pooled into active and inactive periods. The active period consisted of periods one, two, and three when machinery (bulldozers and skidders) were active on the site. Periods three, four, and five were pooled to form the inactive period. Changes in cross sectional area were determined for the active and inactive periods. A level and survey rod were used to establish cross sectional transects associated with each crossing locations at critical areas above and below the crossings according to methods established by Harrelsen et al. (1994). Four permanent cross sectional transects were installed, two above and two below the crossing structures location as follows:

- Upstream across the deepest part of the nearest pool to the crossing area
- Upstream across the middle of the nearest riffle to the crossing area
- Downstream across the deepest part of the nearest pool to the crossing area
- Downstream across the middle of the nearest riffle to the crossing area

Both sides of each cross sectional transect were marked with rebar pins driven into the streambank. A 15.3 m (50 ft) fiberglass tape was stretched between rebar pins and elevation measurements were recorded every 0.15 m (0.5 ft). Permanent benchmarks were established for repeated elevation measurements.

Elevation measures at each transect were input into RIVERMorph to determine cross sectional area area (m^2) and shear stress (lb/m^2) at bankfull stage were determined for each transect. Regional reference curves for the eastern Kentucky coalfield in addition to visual determination from graphing stream channel cross sectional profiles were used to establish bankfull elevations in RIVERMorph. While cross sectional area is

the measure used to describe channel morphology in this study the determination of shear stress is also important. Shear stress is the force exerted by the channel, because of its morphology, to potentially cause erosion and move pollutants such as suspended sediment and bedload materials (Brooks et al. 2003). Increases in shear stress could lead to greater levels of material movement (degradation) by overcoming the minimum level of shear stress needed to move streambed particles based upon their size. Conversely, if shear stress values are lowered materials there is less degradation and more potential for materials both bedload and suspended sediment to be deposited or aggregated directly downstream from the crossing.

Average daily rainfall was calculated from a weather station located adjacent the study site. Features (pools and riffles) were also placed into a categorical value based upon their location above or below the stream (locale) to determine if removing the feature type from analysis would show significance.

The general linear models in SAS (PROC GLM) for multivariate repeated measures analysis techniques was used to determine the effects that crossing type; time period; average daily rainfall; shear stress; locale; and the interaction among crossing type, period, and locale on changes in cross sectional area.

Results and Discussion

Results show no significant predictor between cross sectional area and crossing type ($p = 0.90$) when all feature locales (upstream and downstream) and types (pool and riffle) are combined. However, results show that the cross section's locale (upstream or

downstream) or relative position to the crossing structure's location was found to be more important in changes to stream channel cross sectional area.

Active Period

For the active period, the upstream and downstream features of culverts and downstream features of fords had cross sectional changes greater than 10% (Table 3.1). Upstream features of culverts had losses of 10.1% of stream crossing area indicating aggradation of stream materials. This was expected as the decrease in flow velocity resulted in the deposition of sediments and maintenance of stream channel equilibrium. Downstream features, including both riffles and pools, associated with culverts had a 21.5% overall increase in cross sectional area indicating degradation of the stream channel morphology. Previous studies have found that scouring of these downstream features occurred with the increase in stream flow velocity from water being forced into a narrow culvert (Merrill and Casaday 2001). Flow is initially slowed and routed through the culvert, accelerating and concentrating flow out of the pipe. The energy inherent in the concentrated flow can erode the streambed directly downstream of the culvert causing scouring of the streambed. These results were unexpected since bankfull stage storm flows did not occur but degradation of stream channel cross sectional area happened even with modest storm flow levels that occurred during the study period.

Downstream features of fords had a 15.0% loss of cross sectional area during the active period indicating aggradation of stream materials (Table 3.1). These results are supported by the sediment load data associated with fords (chapter 2) indicating that large amounts of materials were moved downstream and deposited into the downstream

features of the fords altering the stream channel morphology. Upstream features of fords, downstream and upstream features of bridges, and upstream and downstream features of bridges had little change in cross sectional area.

Inactive Period

For the inactive period having a duration of one year after the crossing structures were removed, only downstream features of both culverts and fords had changes greater than 10% (Table 3.1). Downstream features of fords continued to aggragate materials exhibiting a 15.7% loss of stream cross sectional area. In contrast, downstream features of culverts reversed their initial degradation having a 30.9% loss of stream cross sectional area indicating an aggradation of stream materials for both stream location and cross types. Even though stream banks were reestablished during crossing removal the fords downstream features continued to aggregate stream materials even after equipment stopped being present on the site. Downstream features began to rehabilitate themselves after the culverts were removed. During the active period the cross sectional areas were degraded and eroded but as soon as the structure was removed the reverse occurred even though a majority of the backfill around the structures was removed allowing a more natural dispersed flow to occur. This was in contrast to fords where material continued to be generated at the crossing location and moved and deposited in the downstream features. The percent change of stream cross sectional area change for the active period, (15.0%) is very similar to the inactive period and indicates that erosion continues at the cross location even though skidders are no longer using the streambed for a crossing location.

Only downstream features associated with culverts and fords experienced any cross sectional are changes greater than 10% for the entire study period (Table 3.1). Downstream features of culverts had a loss of cross sectional surface area of 16.0% indicating an overall aggradation of stream materials. Even though there is scouring during the active period that resulted in an increase of cross sectional area there was enough aggradation of material during the inactive period to have an overall increase in cross sectional area of 16.0%. The results indicate that the temporary scouring and erosion of the downstream features of culverts was temporary. Six months after the culverts were removed (period four measurement) only a 3.4% increase over the original cross sectional area remained (Fig. 3.1). Twelve months after removal, the cross sectional area of the downstream culverts was 16.0% greater. However, these results indicate that the backfill used to stabilize the culvert in the channel that remains in the stream when the culvert is removed eventually moves downstream and results in a greater effect on the downstream feature cross sectional area than the amount of scouring produced by increased flow velocities during the active period. The results are contradictory of those found by Harris et al. (2008). In their study, permanent haul road culvert crossings when properly sized and installed had minimal effects on downstream stream morphology. Harris et al. (2008) used permanent culverts, sized for 100-year flood events, on permanent forest haul roads across headwater streams while this study used culverts sized for 10-year events which were deemed appropriate because of the temporary nature of these crossings. Even with low flows and bankfull stage not occurring the higher velocity caused by focusing water from culverts did alter stream channel cross sectional area. Future studies could focus on the length of structure

installation periods and maximum peak flows to determine when or if the structures begin to have effects on stream morphology.

Downstream features associated with fords had a 28.3% loss in cross sectional area indicating aggradation of stream materials for the entire study period. During all periods streambed material primarily from the crossing location is being deposited. The channel is attempting to create a new steeper slope in order to maintain channel equilibrium but even after one year of removal the crossing location appears to be still aggregating stream material into the downstream features. The stream could have also not experienced a storm event that would cause a bankfull stage flow after removal that could potentially bring balance back to the stream equilibrium.

All Periods

For the entire study period bridges had a 6.7% and 1.3% loss in cross sectional area for both downstream and upstream features, respectively (Table 3.1). Scouring around permanent bridges usually occurs around and downstream from abutments and piers within the stream channel (Richardson et al. 1993). As the higher flow enters the crossing area, it narrows within the bridge opening and accelerates due to constriction between the piers and abutments. The bridges used for the crossing study were not typical of those used in permanent forest haul road crossing structures; they did not require abutments or piers in the streambed for support. The bridges were typical for skid trail crossings since they were placed directly on the streambanks and did not require streambed alterations. Scouring that would potentially occur for downstream features of

bridges did not occur because the streams that the structures were installed over were narrow enough to not require any type of in stream abutments, support, or piers.

Results also show cross sectional area and average daily rainfall ($p = 0.43$) for any period when all feature locales (upstream and downstream) and types (pool and riffle) are combined. No significant prediction was also found for cross sectional area and locale ($p = 0.26$) without regard to crossing type.

Shear stress was found to be a significant predictor for changes in cross sectional area ($p = 0.0009$). Results indicate for every one percent increase in shear stress results in a 0.3493 percent increase in cross sectional area indicating a degradation of channel fill. This is to be expected as previous studies have shown that stream channel cross sectional area are positively correlated with changes in stream channel cross sectional areas (Gangloff and Feminella 2007, Schwendel 2010). The average shear stress value for all periods, crossing types, and locales was 0.187 lb/m^2 and is currently below the limiting shear stress value of 0.214 lb/m2 for large cobble (Julien 1995, Fishenich 2001). The greatest change in cross sectional area for the entire study period was a 28.3% decrease in cross sectional area for the downstream features of fords. This 28.3% cross sectional area decrease corresponds to a 9.9% decrease in shear stress. Using the average shear stress value of a 9.9% decrease would record a value of 0.168 lb/m^2 still below the threshold value for beginning to transport large cobble material but above the limiting threshold of transporting small coble material. The calculated shear stress values emphasize that there was potential for bedload materials to be moved from the crossing locations but did not occur because of storm flow events not reaching bankfull level stage.

Tested interactions among all variables indicated no significant predictors for any interactions except the interaction between crossing type and locale on cross sectional area for periods two ($p = 0.01$), three ($p = 0.03$), four ($p = 0.02$), and five ($p = 0.03$). Installing any crossing type did show effects on stream morphology because of period one having no significant differences and the other four periods showing effects of the interaction between crossing type and stream location. However, varying significant differences among the interactions of crossing type and stream location across all periods make it difficult to determine if specific combinations can reduce impacts to stream channel morphology but are still presented in appendix B.

From a practical standpoint, bridges and pipe bundles mimicked undisturbed streams and resulted in little anthromorphic alterations to occur because of the unaltered low base flow of headwater streams (Moore and Wondzell 2005). The unique configuration of the pipe bundles may have also reduced the possibility of morphological change. Pipe bundles are placed directly on the streambed and cover the entire width of the channel. This may act to dissipate flow velocities across the width of the channel compared to culverts. Further, the cross sectional area at the crossing was not altered or blocked by bridges or pipe bundles.

The short time of the active period (six weeks) may have not been sufficient enough for significant changes in cross sectional area to occur for the pipe bundle crossing type. During treatment several rain events occurred increasing flow but not enough to raise stream flows to bankfull stage. The highest amount of rainfall while the pipe bundles were installed occurred on 1 June 2007 with a total of 3.99 cm (1.57 in) during a 13 hour period (Table 1.1). During the study bankfull stage did not occur and

stream flow never overtopped pipe bundles, culverts, or bridges. It is possible that cross sectional area changes could have been detected in this study if a flow event of a significantly greater magnitude occurred during the study period. Also, since bankfull stage flows did not occur, large amounts of debris (leaves, branches, bedload material) did not have the opportunity to move into the crossing area potentially causing an obstruction in the various openings in the pipe bundle. From this study it is not possible to make a conclusion on the effectiveness of pipe bundles in relation to effects on cross sectional area of stream features for all flow conditions. However, the study does demonstrate that if used during drier conditions when flows are low and a bankfull level storm event is not likely to occur, pipe bundles and bridges are effective at mitigating cross sectional area changes to upstream and downstream features.

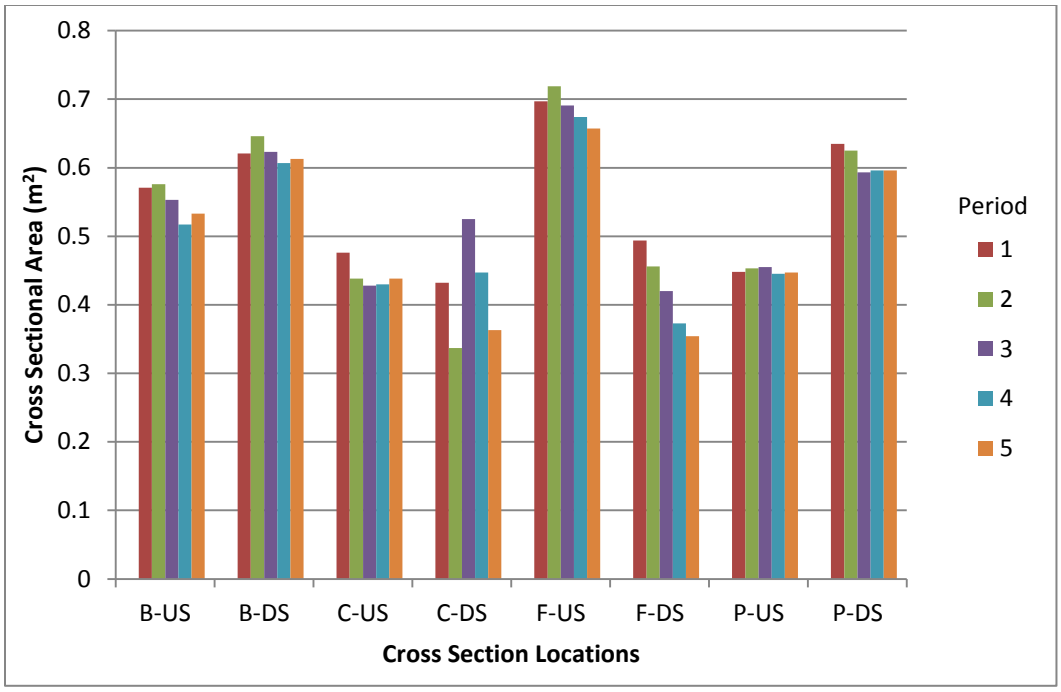

Figure 3.1. Cross sectional area for all periods for all crossing types

Table 3.1 Percent change in stream channel cross sectional area

Crossing Type	Bridge		Culvert		Ford		Pipe Bundle	
Stream Location	Up	Down	Up	Down	Up	Down	Up	Down
Active Period	-3.2%	0.3%	-10.1%	21.5%	-0.9%	-15.0%	1.6%	-6.6%
Inactive Period	-3.6%	-1.6%	2.3%	-30.9%	-4.9%	-15.7%	-1.8%	0.5%
All Periods	-6.7%	-1.3%	-8.0%	-16.0%	-5.7%	-28.3%	-0.2%	-6.1%

Chapter 4: Time, Cost, and Efficacy Analysis

Introduction

Best management practices (BMPs) have been demonstrated to alleviate environmental impacts from timber harvesting and are recommended or required for all forest operations in the United States (Patric 1976, Arthur 1998). However, there have been a limited number of studies that have attempted to estimate BMP costs, an important consideration for landowners and harvest operators. Ellefson and Miles (1995) estimated that a 59% reduction in net revenue occurred on eighteen national forest timber sales as a result of strict BMP implementation. In Washington, Oregon, and California landowners had $13.99[2] to $43.72 reductions in revenue per thousand board feet of stumpage sold through the use of BMPs (Henly et al. 1988). Shafer et al. (1998) estimated a total cost of $31.28 per acre loss in revenue because of BMP implementation for harvests less than 75 acres in Virginia. Woodman and Cubbage (1994) found that BMP costs for Georgia range from $33.67 per acre for industry land and $57.65 per acre for family forest land. Regionally Lickwar et al. (1992) determined that implementation of state BMPs would result in $18.22 per acre reduction in revenues in the southeast.

Streamside management zones (SMZs) a BMP used in riparian areas around perennial, intermittent, or ephemeral streams limits harvesting equipment access and generally restricts harvesting of trees. In eastern hardwood forests LeDoux (2006) found that by implementing a wide range of SMZ widths and retention percentages the opportunity cost of inaccessible timber to landowners and loggers is between $156.89 and $686.00 per acre. Cubbage (2004) estimated that using SMZs accounted for 3% of

[2] All dollar values adjusted to 2007 values using the Consumer Price Index inflation values

the BMP costs for forest industry and 10% for family forest owners. In the Cumberland Plateau of eastern Kentucky the estimated opportunity cost of SMZs were $447.22 per acre of SMZ based on timber revenue left in the SMZ (Dickinson 1992). Spreading the SMZ costs across all the acreage of a watershed was found to lower the cost to $26.49 per acre. Another study found that SMZs cost 26.4% of revenue on eighteen national forest timber sales in the Midwest (Ellefson and Miles 1985).

The cost of retiring skid trails (filling ruts, berm removal, and seeding) has also been determined. Shouse et al. (2001) found that retiring skid trails cost an average of $10.29 per acre. Waterbar construction averaged $5.80 per acre in Kentucky (Shouse et al. 2001) or $23.20 per waterbar and $46.39 per broadbase dip in West Virginia (Lickwar et al. 1992). Shouse et al. (2001) found that skid trail retirement and revegetation reduced gross revenue by 2.1% in Kentucky.

Specific costs of stream crossings have not been thoroughly studied and when reported are usually estimates. Lickwar et al. (1992) reported a general cost of $614.62 per culvert on haul roads. Costs for permanent crossing structures of streams in Appalachia have also been examined (Visser et al. 2003). The cost of a low water concrete ford was found to be $25,657.27 and wood bridges ranged from $1980.07 for a lumber streass-laminated bridge to $8,798.21 for a wood stringer bridge. Visser et al. (2003) also estimated $565.58 for a steel pipe culvert crossing an intermittent stream and for a gravel bottom improved ford the total cost was $507.57. Specific costs are for permanent crossings and generally span larger, higher-order perennial streams. Also they do not take into account the option of reusability that some temporary crossing structures would offer.

The objective of this analysis was to determine the direct costs associated with using temporary skidder rossings and to determine costs relative to sediment mitigation.

Methods

Time and Cost

To determine overall costs of using different crossing types the cost of crossing structures were determined and combined with equipment and labor data for crossing installation and removal. Twelve headwater streams were selected and randomly assigned one of the four treatment types (ford, culvert, pipe bundle, bridge; see chapter 2).

Cost estimates of the structures included materials and the labor time required to assemble them. The cost of the pipe bundle crossings included 14 pieces of 6.1 m (20 ft) 10.2 cm (4 in) diameter PVC pipe, approximately 15.2 m (50 ft) of 0.47 cm (3/16 in) galvanized steel wire, and 8 wire rope clamps. The assembly time to cut the pipe, drill holes for the wire to be threaded through, threading the wire, and attaching the clamps was timed with a stop watch. The labor cost was determined using an hourly rate of $12.00. The corrugated steel culverts were purchased from a local farm supply store and an average retail value was determined. Even though the wood panel bridges were made in house, there are a number of companies that sell comparable bridges. Three companies were contacted for quotes for a similar skidder bridge and an average was taken to determine the cost of procuring the structure. There is no cost of materials or labor for the ford.

The temporary nature of skid trail headwater stream crossings allows structures to potentially be reused with obvious cost savings compared to permanent crossings. The cost of the purchase or construction of the temporary structures can be spread across the total number of reuses. For example, if a crossing structure costs $100 and can be used 5 times before having to be replaced the cost of the structure is $20 per use. However the variance in the types of equipment using the crossings, proficiency of equipment operators, and methods of transportation make determining the average number of reuses difficult. For the purposes of this research an estimate of number of uses based on experience of researchers and operational experience of loggers will be used.

The installation and removal of all the crossings were filmed with an 8mm digital video camera. The videos were then viewed and analyzed with Adobe Professional Studio video player providing a time stamp that could be used to determine accurate time data for installation and removal. Machine and person time was determined for each crossing installation and removal. Machine time (including the cost of the operator) was determined for the John Deere 550G bulldozer and John Deere 540 wheeled cable skidder. Also labor time was recorded for persons not operating equipment. Time was classified based on the activity being performed. Classifications for installation were physically installing the structure in the channel, collecting backfill, backfilling, smoothing backfill, and approach work. Classifications for removal included removing backfill, extracting structure, removing residual backfill, repairing streambanks, and smoothing ruts and backfill. The cost per hour of machine time was assumed to be $68.06 using previously determined rates for similar machines and adjusted using the Consumer Price Index inflation values (Brinker et al. 2002).

Certain cost variables were not taken into account during analysis and were assumed to be constant. Particularly travel from the landing to the crossing installation site and back were not included in this analysis. Average distances from landings to streams of logging operations are unknown and were assumed to be constant throughout the experiment. It is assumed that the further a stream is from the landing the more expensive it would be for equipment to transport the structures to the sites. For this experiment it took one trip with a skidder to transport the pipe bundles and culverts to the installation site. The bridges consisted of three panels that necessitated two trips by the skidder. Distance from landing site of stream crossings installations must be taken into account when determining a true cost of a crossings usage.

Cost Efficiency

Forest practitioners, forest owners, regulators, and policy experts are all interested in understanding the effectiveness of the money spent on BMPs for reducing pollution. In essence, it is important to know the cheapest ways to reduce the maximum amount of pollution. In this study, what expenditures for stream crossings yield the greatest reduction in suspended sediment? Since this study focuses on temporary stream crossings that can be reused, efficiency was expressed as dollars spent per kilogram of suspended sediment produced for a range of times that a crossing structure could be used. Crossing efficiency was determined by subtracting the average total suspended sediment generated from the three elevated crossing types from the average suspended sediment produced by the ford and divided into the dollars spent on each crossing including their installation, removal, and the cost of the structure spread out across the number of uses.

Results and Discussion

Time and Cost for Installation and Removal

The average time for installation and removal fords was 6:36 ± 1:37 (minutes:seconds) with a total cost of $7.50 ± $1.84 (Tables 4.1 and 4.2). The time spent on the crossing was cutting down streambanks during installation and smoothing streambanks for approaches and to repair banks and ruts during removal. It was not possible for the bulldozer to get into the stream to repair ruts in the stream without causing further environmental damage. The average time and costs for the ford were significantly lower than elevated crossing types ($p < 0.05$).

The average time for installation and removal of a culvert was 28:59 ± 3:25 with an associated installation and removal total cost of $32.44 ± 3.83 (Tables 4.1 and 4.2). The total time and cost for installation and removal of the culverts was the highest among all crossing types but not significantly different than pipe bundles or bridges but was significantly higher than fords. The costs for installation of culverts were not significantly different than bridges but were significantly higher than both pipe bundles and fords. Forty percent of the total cost of installation and removal was from the removal of residual backfill after the structure was extracted (Table 4.2).

The average time for installation and removal of a pipe bundle was 21:09 ± 1:01 with a cost of these activities averaging $19.61 ± $1.50 (Tables 4.1 and 4.2). Half of the installation time for the pipe bundle was for two persons to adequately orientate the structure in the stream. The structure must be installed so when removed the bundle carries the remaining backfill out of the stream. While 81% of the time was spent

working with the backfill during removal this was less than the 14:54 that was spent on backfill work for culverts.

The average time for installation and removal of a bridge was 25:39 ± 0:45 with a total cost of $29.11 ± $0.87 (Tables 3.1 and 3.2). Sixty-three percent of the cost and time of installing the bridge was machine time on dragging and placing the panels across the stream. The remainder of the install time was spent on building the approach ramps. All of the removal time was spent on extracting the structure since the use of bridges make repairing streambanks and in channel rut repair unnecessary.

Since temporary crossings can be reused (with the exception of the ford) the cost of a crossing varies based on the number of times used. Specific number of uses for elevated crossing types cannot be determined from this study however estimates can be made based upon research and operational experience. Table 4.3 provides costs for a range of estimated uses. A ford requires no fixed cost for the structure itself and the only reoccurring cost was the streambank preparation and restoration. The cost for each ford was $7.50 per use.

The average cost of culverts was $300 and estimated reuses ranged one to three uses. This range is based upon information provided by Kentucky Master Logger continuing education participants. Combining the cost of $32.44 for machine and person time for each installation and removal with the average price of the culvert, total culvert costs ranged from $332.44 for one use to $132.44 for three uses.

For pipe bundles the structure costs $326 and reuses ranged 10 to 20. This is a conservative estimate of reuse based on research and demonstrational experience and presumes that pipe bundles are installed correctly and used in a manner consistent with

this study. Combining $19.61 for machine and person time for each installation and removal to the cost of the structure resulted in total cost per use ranging from $52.21 for 10 uses to $35.91 for 20 uses.

For bridges the average structure itself cost was $1,150 and reuses ranged 10 to 20. Combining $29.11 for machine and person time for each installation and removal added to the cost of the structure resulted in total bridge costs per use of $144.11 for ten uses to $86.61 for 20 uses.

Discounting consideration of sediment production the most economical crossing was the ford (Table 4.3). The cost of installing and removing the ford was $28.41 less than the lowest estimated cost of an elevated crossing (pipe bundle with 20 reuses). This does not take into account indirect costs such as damage to logging equipment and reduction in skidding times that can occur when using a ford. Among elevated crossing types the pipe bundle had the lowest cost. The large amount of time spent on removing backfill from the culvert and the greater reusability of the pipe bundle compared to a metal corrugated culvert overcame the slightly higher initial cost of the pipe bundle. As would be expected the bridge with its higher initial cost was the most expensive to use. Even if the number of uses for the wood panel bridge is assumed to be 30 the cost per use is $67.44, which is still higher than the cost associated with use of the pipe bundle.

Cost Efficiency

Table 4.4 provides the kilograms of suspended sediment reduced per dollar spent for each elevated crossing type compared to a ford. In measuring the environmental and financial factors together the average suspended (kg) sediment prevented per dollar spent

for the culvert for one to three uses was 22.9 to 59.7.. The pipe bundle averaged 173.0 to 272.2 kilograms of suspended sediment prevented per dollar spent for 10 and 20 reuses and the wood panel bridge averaged 57.2 to 99.3 kg of suspended sediment prevented per dollar spent.

The pipe bundle resulted in highest efficiency ranking based on suspended sediment prevented per dollar spent potentially maximizing the amount of money spent by forest operators mitigating suspended sediment levels (Table 4.4). The pipe bundle was followed by bridges both providing significant improvements over culverts, useful information for decisions relative to BMP implementation. The initial cost and low reusability of culverts depressed the efficacy of this crossing. While bridges resulted in less total suspended sediment compared to the other structures, the high initial cost resulted in less efficiency compared to pipe bundles. However the reduction in sediment when using bridges compared to culverts allowed the bridges to be more efficient than culverts. If the number of uses for bridges can be extended to 30, the kilograms of suspended sediment prevented per dollar spent was raised up to 131.1. This is still smaller than kg of sediment prevented per dollar spent for the low range of the pipe bundle's usability values. Factors such as variable costs of supplies, different types of equipment used, and climate would affect the time and cost of crossing installation and removal. Suspended sediment levels would also vary based the number of passes over the structure, type of equipment used to install or remove the structures, or the sizes of the stream channel.

Total BMP Costs

With a more accurate cost value for temporary elevated crossings it is now possible to determine specific costs to implement BMPs on Kentucky's logging operations. There were an average of 4.3 skid trail (temporary) stream crossings per logging job in Kentucky and 0.03 crossings per acre in 2005 (Stringer personal communication 2012). Using the low range of $52.21 for 10 uses for a pipe bundle, the average logging job would spend a total of $224.50 on elevated stream crossings or $1.57 per acre. Combined with the $5.80 per acre for water bar construction, $10.29 per acre for retirement of skid trails, and $26.49 per acre opportunity loss for streamside management zone restrictions the total cost to Kentucky's loggers for BMP implementation would be $44.15 per acre or $6,181 per logging job (140 acre average in Kentucky) (Table 4.5) (Shouse et al 2003, Li et al. 2006, Dickinson 1992). Specific costs for haul road retirement are not available, have not been studied, and are not included in this estimate. For fords the total per acre cost of BMP implementation total falls to $32.27. For only one use of a culvert the total per acre cost of BMP implementation is $52.55 and goes down to $46.55 per acre for three uses. For ten uses of bridge the total per acre cost of BMP implementation is $46.91 and for 20 uses the cost lowers to $45.18 per acre.

Pipe bundles were only 3.6% of the total per acre cost of using BMPs assuming 10 reuses (Table 4.6). By using the highest cost per acre of using an elevated crossing (culvert with only 1 reuse), the crossings are still only 19.0% of the per acre cost of BMP implementation. This is a minimal amount of cost to prevent the most frequent source of nonpoint source pollution (Rothwell 1983).

A cost of $44.25 per acre for BMP implementation was greater than the $31.28 per acre in Virginia (Shafer et al. 1998). It was also greater than the $18.22 cost found for all of the southeastern United States (Lickwar et al. 1992). The calculated cost of BMP implementation for Kentucky was between the $33.67 cost for industry and $57.58 for family forest land in Georgia (1994). These referenced BMP implementation costs were calculated at a minimum of ten years before this experiment and it is expected that the costs would increase because of higher costs of fuel, materials, and labor.

Table 4.1. Mean time values for all crossing types (minutes:seconds)

	Crossing Type							
	Culvert		**Pipe Bundle**		**Bridge**		**Ford**	
	Machine	Person	Machine	Person	Machine	Person	Machine	Person
	Number of Participants							
Installation	1	3	1	2	2	0	1	0
Installing Structure	0:00	1:12	0:00	5:08	11:41	0:00	0:00	0:00
Collecting Backfill	7:51	0:00	2:53	0:00	0:00	0:00	0:00	0:00
Backfilling	2:08	0:00	0:58	0:00	0:00	0:00	0:00	0:00
Smoothing Backfill	0:41	0:00	0:56	0:00	0:00	0:00	0:00	0:00
Approach Work	0:00	0:00	0:00	0:00	6:40	0:00	2:36	0:00
	10:40	1:12	4:49	5:08	18:22	0:00	2:36	0:00
Total Installation	11:52 a		9:57 a		18:22 b		2:36 c	
Removal	1	0	1	0	1	0	1	0
Removing Backfill	3:25	0:00	8:30	0:00	0:00	0:00	0:00	0:00
Extracting Structure	2:13	0:00	0:53	0:00	7:17	0:00	0:00	0:00
Removing Residual Backfill	11:29	0:00	0:56	0:00	0:00	0:00	0:00	0:00
Repair Banks	0:00	0:00	0:15	0:00	0:00	0:00	0:24	0:00
Smooth Ruts and Backfill	0:00	0:00	0:37	0:00	0:00	0:00	3:35	0:00
	17:07	0:00	11:12	0:00	7:17	0:00	4:00	0:00
Total Removal	17:07 a		11:12 b		7:17 c		4:00 bc	
Installation + Removal	28:59 a		21:09 a		25:39 a		6:36 c	

Different letters within a row indicate significant differences ($p \leq 0.05$)

Table 4.2. Mean monetary values for all crossing types

	Crossing Type							
	Culvert		**Pipe Bundle**		**Bridge**		**Ford**	
	Machine	Person	Machine	Person	Machine	Person	Machine	Person
	Number of Participants							
Installation	1	3	1	2	2	0	1	0
Installing Structure	$0.00	$0.91	$0.00	$2.57	$13.27	$0.00	$0.00	$0.00
Collecting Backfill	$8.91	$0.00	$3.28	$0.00	$0.00	$0.00	$0.00	$0.00
Backfilling	$2.42	$0.00	$1.11	$0.00	$0.00	$0.00	$0.00	$0.00
Smoothing Backfill	$0.78	$0.00	$1.07	$0.00	$0.00	$0.00	$0.00	$0.00
Approach Work	$0.00	$0.00	$0.00	$0.00	$7.57	$0.00	$2.96	$0.00
	$12.11	$0.91	$5.46	$2.57	$20.84	$0.00	$2.96	$0.00
Total Installation	$13.01	a	$8.04	a	$20.84	b	$2.96	c
Removal	1	0	1	0	1	0	1	0
Removing Backfill	$3.88	$0.00	$8.51	$0.00	$0.00	$0.00	$0.00	$0.00
Extracting Structure	$2.52	$0.00	$1.01	$0.00	$8.27	$0.00	$0.00	$0.00
Removing Residual Backfill	$13.03	$0.00	$1.06	$0.00	$0.00	$0.00	$0.00	$0.00
Repair Banks	$0.00	$0.00	$0.28	$0.00	$0.00	$0.00	$0.46	$0.00
Smooth Ruts and Backfill	$0.00	$0.00	$0.71	$0.00	$0.00	$0.00	$4.08	$0.00
	$19.42	$0.00	$11.57	$0.00	$8.27	$0.00	$4.54	$0.00
Total Removal	$19.42	a	$11.57	b	$8.27	b	$4.54	b
Installation + Removal	$32.44	a	$19.61	b	$29.11	a	$7.50	c

Different letters within a row indicate significant differences ($p \leq 0.05$)

Table 4.3. Values per uses for crossing types

Number of Uses	Ford	Culvert	Pipe Bundle	Bridge
1	**$7.50**	**$332.44**	$345.61	$1,179.11
2	$7.50	**$182.44**	$182.61	$604.11
3	$7.50	**$132.44**	$128.28	$412.44
4	$7.50	$107.44	$101.11	$316.61
5	$7.50	$92.44	$84.81	$259.11
6	$7.50	$82.44	$73.94	$220.78
7	$7.50	$75.30	$66.18	$193.40
8	$7.50	$69.94	$60.36	$172.86
9	$7.50	$65.77	$55.83	$156.89
10	$7.50	$62.44	**$52.21**	**$144.11**
11	$7.50	$59.71	**$49.25**	**$133.66**
12	$7.50	$57.44	**$46.78**	**$124.94**
13	$7.50	$55.52	**$44.69**	**$117.57**
14	$7.50	$53.87	**$42.90**	**$111.25**
15	$7.50	$52.44	**$41.34**	**$105.78**
16	$7.50	$51.19	**$39.99**	**$100.99**
17	$7.50	$50.09	**$38.79**	**$96.76**
18	$7.50	$49.11	**$37.72**	**$93.00**
19	$7.50	$48.23	**$36.77**	**$89.64**
20	$7.50	$47.44	**$35.91**	**$86.61**
21	$7.50	$46.73	$35.13	$83.87
22	$7.50	$46.08	$34.43	$81.38
23	$7.50	$45.48	$33.78	$79.11
24	$7.50	$44.94	$33.19	$77.03
25	$7.50	$44.44	$32.65	$75.11
26	$7.50	$43.98	$32.15	$73.34
27	$7.50	$43.55	$31.68	$71.70
28	$7.50	$43.15	$31.25	$70.18
29	$7.50	$42.78	$30.85	$68.77
30	$7.50	$42.44	$30.48	$67.44

Bold indicates estimated uses

Table 4.4. Suspended sediment prevented (kg) per dollar spend for elevated crossings

Number of Uses	Culvert	Pipe Bundle	Bridge
1	**22.9**	22.9	6.7
2	**42.6**	44.2	13.2
3	**59.7**	64.0	19.4
4	74.6	82.6	25.4
5	87.8	100.0	31.2
6	99.5	116.4	36.8
7	110.0	131.8	42.3
8	119.4	146.3	47.5
9	127.9	160.0	52.6
10	135.7	**173.0**	**57.5**
11	142.8	**185.3**	**62.3**
12	149.3	**196.9**	**66.9**
13	155.3	**208.0**	**71.4**
14	160.8	**218.5**	**75.7**
15	165.9	**228.5**	**80.0**
16	170.7	**238.1**	**84.1**
17	175.1	**247.2**	**88.0**
18	179.2	**255.9**	**91.9**
19	183.1	**264.2**	**95.7**
20	186.7	**272.2**	**99.3**
21	190.1	279.9	102.9
22	193.3	287.2	106.4
23	196.3	294.2	109.7
24	199.1	301.0	113.0
25	201.8	307.5	116.2
26	204.4	313.8	119.4
27	206.8	319.8	122.4
28	209.1	325.6	125.4
29	211.3	331.2	128.3
30	213.4	336.6	131.1

Bold indicates estimated uses

Table 4.5. Time value analysis summary

Crossing Type	Single install/ removal cost	Cost of structure	Assumed Uses	Cost per reuse	kg sediment prevented per dollar of reuse
Ford	$7.59	$0	1	$7.50	---
Culvert	$32.44	$300.00	1-3	$332.44-$132.44	22.9 – 59.7
Pipe Bundle	$19.61	$326.00	10-20	$52.21-$35.91	173.0 – 272.2
Bridge	$29.11	$1,150	10-20	$144.11-$86.61	57.2 – 99.3

Table 4.6. Cost of stream crossings and total BMP costs per acre

Crossing Type	Uses	Cost per Crossing	Cost per Acre for Crossings	Total BMP Cost per Acre[1]	Percentage of BMP Cost of Crossings
Ford	1	$7.50	$0.23	$42.81	0.5%
Culvert	1	$332.44	$9.97	$52.55	19.0%
	3	$132.44	$3.97	$46.55	8.5%
Pipe Bundle	10	$52.21	$1.57	$44.15	3.6%
	20	$35.91	$1.08	$43.66	2.5%
Bridge	10	$144.11	$4.33	$46.91	9.2%
	20	$86.61	$2.60	$45.18	5.8%

[1]Assumes 0.03 crossings per acre, $5.80 per acre for waterbar construction, $10.29 for retirement of skid trails, and $26.49 per acre opportunity loss for SMZs

Chapter 5: Executive Summary and Management Considerations

Elevated crossings have been shown to significantly lower the amount of sediment generated at very low added cost compared to other required BMPs. With all the other BMPs that loggers must obey in Kentucky (SMZs, waterbar construction, and haul road and skid trail retirement, seeding erodible surfaces), the most expensive crossing structure used in this study (bridge), was only 9.2% of total BMP costs. Pipe bundles maximize forest operators expenses by having the largest amount of sediment prevented per dollar spent and were only 3.6% of total BMP costs. Pipe bundles would be the preferred option for those forest operators purchasing new crossing structures over bridges and culverts because of this efficiency. But if loggers already have other elevated crossing structures they would be effective over using an unimproved ford. Fords must only be used when necessary and must have a hard bottom streambed. Unimproved fords must be placed in the back of a harvest operation to minimize the number of passes through the stream.

In order to maximize the mitigation of sediment generated from pipe bundles, the structure should be built wider. The pipe bundles in use for this experiment were 4.6 m (15 ft) wide and the cable skidder has a footprint of 4.3 m (14 ft) wide. This led to dirt falling off the sides of the structure and into the channel. Using a different type of backfill on top of the pipe bundle would be recommended as well. It might be possible to use pole size trees or gravel to place on top of the pipe bundle to eliminate the dirt entirely.

For culverts it is recommended that greater time must be spent removing backfill after removal of the culvert. Like the pipe bundle, an alternative backfill could be used to

replace the dirt entirely. Gravel or pole sized trees could be placed around the culvert to reduce sedimentation. This could apply to similar culvert structures as well such as steel pipes or hollow logs.

Bridges should be installed and removed with grapple skidders instead of the cable skidders used in this study. Most of the sediment introduced during the use of the bridges was generated during the removal of the panels. The panels were just dragged across the channel. If a grapple skidder was used to lift the panels directly out of the channel this would limit sediment from entering the stream.

From the lack of significant changes in levels of pH, nitrate, ammonium, and electrical conductivity, results indicate that chemical ion pollutants are not significantly generated when using temporary fords or elevated crossing types of headwater streams in eastern Kentucky. Suspended sediment is the primary pollutant that should be prevented from being generated during the use of any type of stream crossing structure. Best management practices in eastern Kentucky should continue to focus primarily on suspended sediment as the main source of non-point source pollution from stream crossings. Emphasis should also be placed on reducing structure installation and use periods to as minimum a time as necessary. It is possible that the minimum effects seen on upstream and downstream features of pipe bundles and bridges were only because of the short-term nature of their usage.

Management Recommendations

Considering the percentage of suspended sediment generated during each phase recommendations can be made for harvest operators (Fig. 2.8). Eighty-four percent of all

suspended sediment generated from fords comes from the act of passing through the stream. Data indicates that:

1) Fords should be restricted to limited use (secondary or tertiary) skid trails.
2) Fords should be used when no flows are present during use such as first order perennial streams during summer dry periods result in no flow, intermittent streams during the dry season, or ephemeral channels were no flow is likely to occur.
3) Armoring of the approaches and stream bottom are necessary for fords constructed in channels with flow.

It is important to point out that the 6,555 kg of suspended sediment generated from fords during the 22 passes through the stream is larger than the average of the three elevated crossing types combined.

A culvert's greatest contribution of suspended sediment is during removal and post-removal phases. This indicates that if an operator has to use a corrugated culvert or similar structure (steel pipe or hollow log) it is important to reduce the need for backfill or remove as much backfill as possible. This may require the operator to spend enough time to ensure the removal of as much backfill as possible. It is also recommended that culverts be properly sized for the duration and time period that they are installed. If culverts are installed during the winter or long periods of time when flows are expected to be larger, operators should use culvert sizes recommended for larger storm events. The six week installation period allowed for the usage of culverts properly sized for ten-year rain events. While research into alternative culvert installation techniques would be

useful, the following recommendations are reasonable based on the information gathered from this study.

1) Only use culverts in channels that allow for easy and thorough removal of backfill.
2) Backfill with material other than soil that can be easily removed (i.e. pole sized trees).
3) Only use culverts in channels were limited fill is needed (i.e. small U-shaped channels).

The pipe bundle performed well compared to other structures. Fifty-two percent of the suspended sediment generated from the pipe bundle was generated during the 22 passes over the structures. Visual observations indicated that most of the suspended sediment generated during this phase was from dirt falling off the sides of the pipe bundle and from sediment laden water splashing into the stream off of the top of the structure. The pipe bundles in use for this experiment were 4.6 m (15 ft) wide and the cable skidder has a footprint of 4.3 m (14 ft). This led to dirt falling off the sides of the structure and into the channel. A wider structure would in all probability reduce or prevent this from happening. Recommendations include:

1) PVC pipe bundles can be used as a temporary crossing type even in streams where flows are present.
2) The width of pipe bundles should be adequate to control movement of sediments associated with equipment being used.
3) Produce PVC pipe bundles 3 to 4 feet wider than the skidder footprint or use two pipe bundles end to end.

For the bridges 50% of the total suspended sediment generated was from the removal and post-removal phase. However, the 15 kg of sediment generated in this phase would possibly not merit improvement. The sediment from this phase was observed to come from dragging the panels out of the channel. The cable log skidder was not able to lift the panels straight out of the channel like a grapple skidder would be able to. The panels were dragged across the stream and introduced a relatively minimal amount of suspended sediment into the channel. Data and observations indicate that:

1) Use skidder bridges under all flow conditions.
2) Where possible, lift panels during bridge removal as opposed to dragging across streambed and streambank.

Operational Experience

This study featured constraints to limit the confounding factors that might influence the results of the study. Stream crossing locations were selected based upon limiting sediment inputs from other sources other than those caused by the crossing itself. The crossing location approaches were flat and wide to require no cut and fill methods to create the trail. Cut and fill skid trail construction requires that a bulldozer cut into a side slope and use that removed dirt to fill in the opposite side of the trail to create a level surface. These cut and fill methods are used to create level skid trails on steep slopes. The stream banks and streambeds at the crossing locations were flat to avoid having sloped banks adding excessive sediment when the banks were cut down to install the crossings.

Forest harvest operators try to place crossing locations in flat and wide locations for environmental and economic reasons. Sometimes a crossing must be installed in a non-ideal location such as through a steep ephemeral channel. In other studies the investigators have permitted all the crossing types used in this study to be tested by forest operators during a commercial timber harvest (Witt et al. 2012).

During installation of a wood panel bridge across deep ephemeral channels multiple problems occurred. Initially bridges were not wide enough. In order to support the weight of the skidder and loaded logs the bridge must be placed deep in the channel to allow the ends of the panels to be placed on as much ground as possible. During construction the bulldozer had to cut and fill a trail somewhat into the channel to shorten the crossing width. These skid trail approaches had sharp turns that required the trails to be wider than normal since skidders are very large pieces of equipment. Skidder operators had to be extremely careful when crossing these bridges in order to successfully pass over the channel. By making the bridge wider skidder operators could pass over the structure quicker and safer. Ephemeral channel crossings could create drops of up to 20 m if the crossing fails.

Extra sediment that was not introduced during our controlled experience was generated during a commercial harvest. Sediment was introduced during construction of skid trails through the cut and fill techniques. During the controlled experiment the approaches were flat and required minimal construction. Sediment was dragged in by logs dragged by skidders because of the sharp turns approaching the crossings. Although using extra care to successfully pass over the crossings, skidder operators could not get

their loads to go over the structures. The logs would fall off the side of the trails and drag sediment into the stream with every pass over an ephemeral channel.

During use of a pipe bundle crossing in across a steep ephemeral channel several problems appeared. The length of the crossing structure, 4.57 m (15 ft), did not allow for the pipes to fully extend out from under the backfill. In one case it took three pipe bundle structures to successfully cross the channel. Although the crossing was only around 5.5 m (18 ft) across, the extreme slope necessitated using three pipe bundles in the streambed to allow for water to not come in contact with back fill. The pipe bundles used in these steep situations required a large amount of backfill to complete the installation. In the case of the crossing area using three pipe bundles, it took over 7.6 m (25 ft) high of backfill to complete the crossing installation. This large amount of backfill also created problems during removal. Because of the height of the backfill bulldozers could not get completely in the channel and remove all the backfill on top of the structure. One bulldozer that was successful in removing all the backfill on top of a crossing took over ten times longer than the controlled experiment to remove the pipe bundle. Even when removed some of the pipe bundles were severely damaged by equipment and the large quantity of backfill. Ongoing experiments and data analysis will determine if these visual observations of additional sediment generation during a commercial timber harvest are valid and if recommendations presented can be fully supported.

Appendix A – Stream and Crossing Photos

Figure A.1. Beechnut upstream from crossing location

A.2. Beechnut downstream from crossing location

A.3. Rockhouse upstream from crossing location

A.4. Rockhouse downstream from crossing location

A.5. White Oak upstream from crossing location

A.6. White Oak downstream from crossing location

A.7. Pipe bundle after removal

A.8. Culvert during storm event

A.9. Pipe bundle during storm event

A.10. Bridge during storm event

Appendix B – Stream Morphology Interactions

For period two the upstream and downstream features of bridges, upstream features of fords, and downstream features of pipe bundles were significantly larger than upstream and downstream features of culverts, downstream features of fords, and upstream features of pipe bundles (Table B.1).

For period three the interaction between downstream culvert features and upstream bridge features are not significantly different from any other crossing type and feature locations interactions (Table B.2). Downstream features and bridge interactions are significantly larger than downstream features and ford interactions but are not significantly different than upstream feature and culvert interactions, upstream features and ford interactions, or downstream and upstream pipe bundle feature interactions. Upstream feature and culvert interactions are significantly smaller than upstream ford features but are not significantly different than downstream feature and ford interactions or upstream and downstream and pipe bundle interactions. Upstream ford features are significantly different than downstream features of fords but not upstream and downstream features of pipe bundles. Downstream pipe bundle features are not significantly different than upstream pipe bundle features.

For period four downstream feature and bridge interaction are significantly larger than downstream features and ford interactions but no other crossing type and feature location interactions (Table B.3). Upstream feature and ford interactions and downstream feature and culvert interactions are not significantly different than each other and are both not significantly different than any other crossing type and feature location interactions. Upstream feature and culvert interactions are significantly smaller than

upstream feature and ford interactions but are not significantly different than downstream feature and ford interaction or upstream and downstream features and pipe bundle interactions. Downstream feature and ford interactions are significantly smaller than upstream features and ford interactions and upstream features and pipe bundle interactions but are not significantly different than downstream features and pipe bundle interactions.

For period five downstream features and bridge interactions are significantly larger than downstream features and ford interactions but are not significantly different than any other crossing type and stream location feature interactions (Table B.4). Upstream features and bridge interactions are not significantly different than any other crossing type and feature location interactions. Upstream and downstream features and culvert interactions are not significantly different than each other but are significantly smaller than upstream feature and ford interactions. However, downstream and upstream features and culvert interactions are not significantly different than downstream features and ford interactions or downstream and upstream features and pipe bundle interactions. Downstream features and ford interactions are significantly smaller than upstream features and ford interactions. The effect of downstream features and ford interactions are significantly smaller than downstream features and pipe bundle interactions but are not significantly different than upstream feature interactions with pipe bundles. Upstream feature and ford interactions are significantly larger than upstream feature and pipe bundle interactions but not downstream feature and pipe bundle interactions. Upstream features and pipe bundle interactions are not significantly different than downstream features and pipe bundle interactions.

Table B.1. Period 2 Crossing Type and Feature Location Interaction

Crossing Type	Location	
	Downstream	Upstream
Bridge	0.646 a	0.576 a
Culvert	0.337 b	0.438 b
Ford	0.456 b	0.719 a
Pipe Bundle	0.625 a	0.453 b

Table B.2. Period 3 Stream location and crossing type interaction

Crossing Type	Location	
	Downstream	Upstream
Bridge	0.623 ab	0.553 abc
Culvert	0.525 abc	0.428 bc
Ford	0.420 c	0.691 a
Pipe Bundle	0.593 ac	0.455 bc

Table B.3. Period 4 Stream location and crossing type interaction

Crossing Type	Location	
	Downstream	Upstream
Bridge	0.607 ab	0.517 ad
Culvert	0.447 ad	0.430 bcd
Ford	0.373 d	0.674 a
Pipe Bundle	0.596 ac	0.445 bcd

Table B.4. Period 5 Crossing Type and Stream location interaction

Crossing Type	Location	
	Downstream	Upstream
Bridge	0.613 ab	0.533 abc
Culvert	0.363 bc	0.438 bc
Ford	0.354 c	0.657 a
Pipe Bundle	0.596 ab	0.447 bc

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