The Effects of Stream Crossings and Associated Road Approaches on Water Quality in the Virginia Piedmont

Matthew B. Carroll

Thesis submitted to the faculty of
Virginia Polytechnic Institute and State University
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
Forestry

APPROVED:
W. Michael Aust, Chair

C. Andrew Dolloff

Robert M. Shaffer

May 22nd, 2008

Keywords: forest stream crossings, water quality, forestry best management practices,
Piedmont, riparian forest, fords, bridges, pole crossings, culverts

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Matthew B. Carroll
W. Michael Aust, Chair
Department of Forestry

(ABSTRACT)

Stream crossings are an integral component of forest road systems that provide access for timber harvesting and silvicultural activities. Stream crossings and their associated approaches are often the most critical point of concern for water quality along forest roads. Several types of crossings are used for extracting timber, but limited studies actually compare different types of stream crossings with regard to their effect on water quality. The objectives of this study were to examine four different stream crossing structures: 1) steel bridges, 2) pole bridges (pipe with poles), 3) standard culverts, and 4) re-enforced fords (with GeoWeb or Geotextile) to determine the influence of stream crossing type on water quality and to evaluate erosion associated with stream crossing approaches. We also evaluated each site at four different time intervals to determine if water quality was more affected during different stages of the operations. Prior to operational timber harvests, we identified six replications for each type of crossings (4 fords) and collected data at four time intervals: 1) prior to reopening or installation of crossing, 2) after crossing installation, 3) during harvest operation, and 4) after road closure. Potential erosion rates from approaches to the crossings were estimated by collecting the road/site information necessary to estimate erosion with the Water Erosion Prediction Project for forest roads (WEPP) and the forest version of the Universal Soil Loss Equation (USLE). In-stream water samples were collected at fixed locations above and below each crossing and were evaluated for total dissolved solids (TDS), pH, conductivity, water temperature, and total suspended solids (TSS) or sediment concentration.

Steel bridge crossings generally caused the least amount of water quality disturbance. Model-generated estimates of erosion demonstrated that culvert crossings were associated with the highest average soil loss potential. Although steel bridge crossings had the best overall results, pole bridges proved to be a viable option for ephemeral or intermittent streams due to low potential of soil loss. Ford crossings were found to impact water quality indicators, but showed a decrease in total dissolved solids (TDS) after installation, prior to harvest. Overall, the steel skidder bridges were generally the best crossing type, but any of the crossings can be used effectively with minimal impact under specific site conditions and with judicious installation, use, and closure. Road/skid trail location and adherence to existing road grade, water control, cover, and closure best management practices are critical for protection of water quality at stream crossings.

Acknowledgements

I would like to express a great amount of appreciation to my advisor and committee chairman, Dr. W. Michael Aust, for his continuing advice, patience, and professional assistance with my research and academic inquiries. Dr. Aust has shared his expertise in forest roads and water quality by helping with data collection and providing detailed explanations for my study. I also wish to thank the members of my graduate advisory committee whom I have gained a great deal of respect for, Dr. Robert M. Shaffer, Jr. and Dr. C. Andrew Dolloff. Dr. Shaffer and Dr. Dolloff provided assistance with my program of study and offered a great deal of guidance.

I also want to thank the employees of MeadWestvaco Corporation (Greg Scheerer, Chris Mewborn, Easton Loving, David Mitchell, Steve Delappe), Huber Engineered Woods (Brad Fuller and Ben Cole), Ontario Hardwoods (John Gee), and Virginia Department of Forestry (Rodney Newlin and Joe Rossetti) who assisted with locating study sites for my research.

Several logging crews and their respective foremen were more than accommodating during sampling of my study sites. These crews include: Tapscott Brothers Logging (Tracy Tapscott), Wayne Davis Logging (Dennis Taylor), Brady Jones and Sons Logging (Jay and Seth Jones), and W.E. Ragland & Sons Inc. (Gene Ragland).

A special thanks is in order to my fellow graduate students and good friends Benjamin Bradburn, Brandon Martin, Katie Baker, and Charley-Gail Stull for their assistance with data collection in the field.

I am also grateful for the efforts of Tracey Sherman, Sue Snow, and Kathie Hollandsworth. These individuals are very detail oriented and made logistical matters easier to handle during my graduate program.

The necessary funding and technical support of both the National Council for Air and Stream Improvement, Inc. (NCASI) and MeadWestvaco Corporation made this project and my Master’s program possible. Photographs within this document were taken by the author, Matthew B. Carroll.

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INTRODUCTION

Forest harvesting in Virginia

Timber harvesting supplies the raw materials necessary for the forest products industry, which currently generates $25.2 billion annually in Virginia (VDOF 2007). Recent changes in landownership patterns (decreased industrial ownership, increased real estate investment trusts (REITs) and timber investment management organizations (TIMOs)) combined with increased urbanization and fragmentation in state, have increased pressure on the existing forest landbase for timber supply (VDOF 2007). The trend in selling forestland extends past large forest industry companies within the Commonwealth. Currently, the trend in forestland cover is decreasing at a rate of 27, 300 acres (11,053 ha) per year according to statistics from 2006-2007 (VDOF 2007). Loss of forests creates challenges to produce higher volumes of timber on areas that are increasing in population, but decreasing in the amount of area available for harvest.

Advances in forest harvesting equipment and technology, reforestation efforts, and genetic improvement of tree species all help support the volume of timber harvested (Fox 2000). In 1995, roundwood output from Virginia's forests totaled over 455 million cubic feet (16.1 million m^3), a 4 percent increase since 1992 (Johnson et al. 1997). Recently, over 229,000 total acres (92,713 ha) in 2007-2008 were harvested annually, which is a large increase compared to the 100,000 total acres (40,486 ha) harvested in 1989-1990 (VDOF 2008). Annual timber harvest totals in the Virginia Piedmont can be impacted due to rugged terrain, soil characteristics of harvest sites, and the weather conditions of a certain year. Furthermore, forestland managers and loggers must also conduct harvest activities in a manner that will protect water quality.

The passage of the Federal Water Pollution Control Act of 1972 and amendments led states to develop specific forestry best management practices (BMPs) designed to protect, maintain, and improve water quality (Aust 1994a). Potential water quality pollutants have become recognized as important issues and stewards of the land are working to protect this natural resource. Forest harvesting typically has minimal impacts on water quality, yet associated operations such as roads, decks, and skid trails have the potential to seriously degrade water quality, particularly if they are not installed and managed properly (Aust and Blinn 2002). More specifically, stream crossings are the most critical section of road influencing water quality (Swift 1985). Loggers are challenged to extract timber across streams and drainages while protecting water quality and it is critical to identify crossing sites that meet logical, economical, feasibility, and environmental constraints.

Stream crossings can produce a number of water quality pollutants, but sediment is usually the primary concern. Research indicates that roads create more pollution, in the form of sediment, than harvesting activities. Furthermore, stream crossings are the most frequent sources of sediment introduction (Rothwell 1983). Road construction and associated stream crossings are common activities for conventional harvest operations. Sediment produced at stream crossings originates from two primary sources: the stream crossing structure itself, and the road approaches to the crossing (Taylor et al. 1999b).

Locating the least steep approaches for stream crossings and choosing good locations are common BMPs recommended for minimizing sediment pollution. The potential for water quality impacts other than sediment also exist at stream crossings. Nutrients attached to sediment particles, which are transported directly to stream systems may also present additional non-point source problems in forested watersheds (Grace 2005). Petroleum products may also enter the stream from road surfaces. Thus, improved understanding of forest stream crossings could lead to substantive improvements in both BMPs and stream water quality.

The Federal Water Pollution Control Act of 1972 and subsequent amendments (known as the Clean Water Act) have the overall goal of maintaining and improving the physical, chemical, and biological integrity of the waters of the nation. However, the Clean Water Act also recognizes the practical need for certain agricultural and silvicultural management activities to occur without excessive restrictions. Therefore, silvicultural operations (and agricultural activities), including roads and stream crossings, have a special permit status under the Federal Water Pollution Control Act of 1972 (and amendments) known as the "silvicultural exemption". These silvicultural exemptions are in reality a special type of blanket permit that require no application process. Normal farming and forestry activities are exempt from the permit application process. Section 404 of the 1977 Clean Water Act provided the exemption as long as the following criteria are met: (1) the activity is not a conversion of a wetland to an upland; (2) the activity is part of an ongoing operation; (3) the activity has not lain idle so long that hydrologic operations are necessary; (4) the activity does not contain toxic pollutants; and (5) the activity uses normal silvicultural operations that comply with certain Best Management Practices (BMPs) (Aust 1994b, VDOF 2002)). The silvicultural exemption implies that state BMPs should be met but it requires compliance with 15 federal BMPs for road construction and maintenance (VDOF 2002). The 15 mandatory federal BMPs address two main types of concerns: 1. road impacts such as road density, road proximity to streams, stream crossings and the need to minimize channel restrictions, stabilization of road fill, minimizing traffic contact with streams, minimizing stream disturbance, ensuring aquatic species movements, not using borrow material from streams, minimizing toxic pollutants, and restoration of elevations for temporary crossings and 2. habitat concerns such as minimizing impacts on endangered species, waterfowl reproduction areas, shellfish production areas, and national wild and scenic rivers. All of these federal BMPs can have relevance with regard to forest stream crossings.

State BMP Program

Silvicultural exemptions and voluntary forestry BMPs should not lead landowners to assume that BMPs are not necessary in Virginia. The Virginia Department of Forestry is responsible for preventing excessive sediment from entering streams. While the Commonwealth of Virginia has voluntary BMPs (except in the immediate vicinity of the Chesapeake Bay), the State Forester has the legal authority to protect water quality from excessive sedimentation originating from silvicultural operations on any stream in Virginia under the Silvicultural Water Quality Law (Code of Virginia sections 10.1-1181.1 through 10.1-1181.7). This legal authority allows the VDOF to issue fines and stop work orders to landowners and/or operators who are conducting activities that lead to a significant increase in stream sediment. The severity of fines increases with subsequent offenses. Also, the Virginia Marine Resources Commission requires a permit for a stream crossing used for any stream which has a watershed area of 3,000 acres (1,215 ha) or greater (VDOF 2002). VDOF distributes "BMPs for Water Quality" manuals which contain recommendations for road construction and forest harvesting and provides technical assistance from employees. Stream crossings tend to be areas where assistance in design and construction are needed due to the sensitive riparian environment. Choosing a proper stream crossing for the correct location is a critical aspect of BMP implementation.

Objectives and Research Purposes

Research indicates that stream crossings can potentially have significant impacts on water quality (Grace 2005, Taylor et al. 1999b). However, the potential advantages and disadvantages with regard to water quality effects of different types of crossings used for extracting timber have seldom been compared. The objectives of this study are to (1) evaluate the effect of four commonly used stream crossings and the associated roads upon stream water quality in the Piedmont of Virginia by comparing in-stream water samples above and below each crossing; (2) investigate the influence of each stream crossing and approach during four time intervals: prior to reopening/pre-installation, after installation, during harvest, and after road closure; (3) estimate the amount of erosion produced from the installed stream crossings using two widely used erosion models. The null hypotheses associated with my objectives are:

HO1: Different types of stream crossings (portable bridges, culverts, pole bridges, and hardened fords) will not affect water quality.

HO2: Stream crossing approaches and associated characteristics will not affect potential water quality as estimated by erosion models.

HO3: Stream crossings and approaches will not have different water quality during different phases of installation and use (before opening/construction, after construction, during harvest, after closure).

LITERATURE REVIEW

Sediment generated by forest operations to streams are a major concern to society and landowners/managers (Binkley and Brown 1993). Sediment is generally considered the most important water pollutant in the United States and increased stream sediments have been associated with decreased aquatic organism health and reproduction, increased storage of water treatment and stream channel/ditch maintenance costs, loss of aesthetic appeal, and loss of channel storage during flood events (Binkley and Brown 1993; Grace 2005; Kirk 1994; Kochenderfer and Helvey 1987; Shepard 1994; Taylor et al. 1999b; Thompson et al. 1996). Increased sediment levels due to forest harvesting activities have been reported by several different researchers (Beasley 1979; Miller 1984; Van Lear et al. 1985; Beasley and Granillo 1988; Robichaud and Waldrop 1994). These suspended and dissolved mineral sediments often carry attached organic materials or nutrients and other pollutants (Wynn et al. 2000). Concentrations of suspended sediment are closely related to turbidity values (Gippel 1989). Results from a study by Cornish (2001) strengthened the belief that high turbidity during higher discharges is influenced by forest roads and their stream crossings. Selecting an appropriate type of stream crossing is vital to limit the impacts of sediment.

The length of time the road must remain open will influence the selection of stream crossing. In instances where a permanent crossing is desired; fords, culverts, or steel bridges are constructed or installed on-site. Temporary crossings often consist of reusable or natural materials that can be used for multiple harvests or left on-site. Portable steel bridge panels, portable wooden bridge segments, steel culverts, plastic culverts, and wood poles are commonly used to create temporary stream crossings (Aust et al. 2003).

Fords

Ford stream crossings, although less commonly used in the Piedmont, are a common type of permanent stream crossing. A ford is a type of low-water stream crossing that uses the stream bed as part of the road (Blinn et al. 1998). Fords re-enforced with GeoWeb, geotextile material, mats, and/or stone are located where a natural rock or hard bottom exists, and often have very low costs relative to other stream crossings, ranging from \$100-\$2,000. However, potential environmental impacts caused by fords include high sedimentation levels if not properly constructed or maintained (Aust et al. 2003). Fords also commonly have the disadvantage of restricted access during high water periods. Fords are included in the general category of low water stream crossings, which are defined as any ford, culvert, or bridge that will be overtopped at least annually (Carstens and Woo 1981). Ideal ford locations have the following characteristics: (1) traffic use can stop during high water periods, (2) normal flow depth of the stream is no more than six inches (15 cm), and (3) soil characteristics and other site conditions allow vehicles to traverse a stable stream bottom from both approaches with minimal risk of soil erosion (Milaukas 1988). The installation, design, and maintenance of fords must anticipate high water levels and minimize the probability of washouts.

Thompson and Kyker-Snowman (1989) evaluated crossings, including fords, being used as skidder crossings in Massachusetts. High turbidity levels were detected, but the turbidity proved to be statistically insignificant directly downstream from an unmitigated ford crossing. Specific conductivity, pH, or nitrate levels were not significantly different when taken before vehicle crossings and compared with samples taken after use. Turbidity was not affected by stream-flow rate or traffic type. Although ford crossings have the potential to influence water quality, no significant impacts were observed in this study.

Tornatore (1995) observed short-term impacts from a gravel ford in Pennsylvania by collecting water samples before, during, and after installation and during use of the crossing and also during periods of high stream flow from snowmelt. Upstream and downstream sediment concentrations were not significantly different before, during, or after installation. The ford crossing did show a significant difference between upstream and downstream sediment during log truck use. The downstream sediment concentration was very low (6 milligrams per liter). A study in northeast Alabama reported that mean and peak sediment concentration increases measured immediately downstream from a gravel ford were 50 and 1,200 milligrams per liter, respectively, when log trucks used the crossing during a two-month timber harvest (Welch et al. 1998).

Natural or re-enforced fords can be used where acceptable approaches exist. Acceptable approaches have gentle grades and soil properties that will support vehicle traffic close to the stream bank. Reinforcing or hardening fords may be necessary on soils that lack bearing capacity. Sample et al. (1998) compared stream water quality below earthen and hardened fords in Kansas, and found that the earthen fords have higher concentrations of turbidity, total solids, and total suspended solids.

Culverts

Culverts offer another option for permanent stream crossings on haul roads. Culverts are hydraulic structures (pipes) that conduct streamflow under a roadway (Taylor et al. 1999b). Common materials used for constructing culvert stream crossings are plastic, aluminum, steel, and corrugated steel pipes. Although culverts are generally more expensive to install and maintain than fords, their water quality impacts are generally *perceived* to be less than those of fords (Taylor et al. 1999b). This perception may not always prove true if culverts are not installed and maintained properly. Poor planning and installation can result in clogs and/or wash outs, which allows fill material surrounding culverts to enter the stream (Hagans and Weaver 1987). Properly installed culverts typically cost $200-$2000, but may limit fish and aquatic organism passage, restrict storm flows, and increase stream water velocity below the pipe (Aust et al. 2003). Stream crossing structures should be at least as wide as the natural full-bank cross section so stream flow is not widened or constricted, and allow for passage of crawling species for most of the year (Clarkin et al. 2006). Fish passage can occur at low flows and most flow levels (Clarkin et al. 2006).

Thompson et al. (1995) collected water samples upstream and downstream during installation of a corrugated metal culvert in Alabama. During a six-hour installation, mean and peak downstream sediment concentrations were, respectively, 344 and 950 milligrams per liter higher than upstream samples. Total sediment introduced into the stream was 26 kilograms. This study also focused on the sediment concentration activity during storm events after installation. Mean downstream sediment concentration levels were 340 milligrams per liter greater than that of up-stream water samples. During peak downstream concentration these levels rose to nearly 2,250 milligrams per liter. This study by Thompson et al. (1995) demonstrated that culverts have the potential to produce sediment concentrations comparable to ford stream crossings.

Other studies have observed short-term impacts from culvert installations. Looney (1981) reported that during a culvert installation and removal, 198 kilograms of sediment was introduced into the stream. Another study in Michigan (White Water Associates 1997) documented sediment concentrations during installation of a culvert in a 2.2 meter-wide stream. When the culvert was installed, peak sediment concentration increase was 1,350 milligrams per liter, and 219 kilograms of sediment was introduced to the stream. As previously mentioned, culverts are used more widely by land managers than fords, and culverts are often perceived to be better in terms of water quality. However, both fords and culverts can produce over 1,000 milligrams per liter of sediment during installation or use periods.

Pole Bridges

A variation of the culvert crossing may use shale or small logs for backfill. When small logs or poles are used for backfill the crossing is called a pole crossing. Pole crossings also can be used without a culvert for temporary crossings of ephemeral or small intermittent drains. Tornatore (1995) reported sediment production from 0.38 meter-diameter culverts installed on skid trails and haul roads using both shale and log backfill. This study deals with backfill using logs to create a pole bridge. A median increase in downstream sediment concentration was 412 milligrams per liter, while peak sediment concentrations were over 1,000 milligrams per liter for the culvert with log fill. Following installation of the culvert with shale fill, it took approximately 96 hours for stream sediment to revert to insignificant levels. In summary, the crossing with shale fill produced less sediment than the crossing filled with poles. The pole bridge is a non-preferred method of crossing, although it is installed in ephemeral and intermittent streams as a temporary crossing due to low cost and limited water flow (VDOF 2002).

Portable Bridges

Bridges, either permanent or portable, are a common type of stream crossing found in the Piedmont of Virginia and across the country. Portable bridges are widely recommended and used. They require significant capital investment but can be removed and reused on additional sites. Loggers involved in this research project reported 3-panel portable steel bridge costs ranging from \$8,000 to \$14,000 depending on the length of the bridge panels. Taylor et al. (1999a) reported similar costs for glue laminated bridges for skidder (\$9,300) and truck (\$14,825) traffic. The bridges examined by Taylor et al. (1999a) are not exactly the same as used in my study, but these estimates do provide a documented cost estimate comparable to the input of logging crews within the study area. Portable bridges are used often due to the ability to reuse these structures and minimal site disturbances that have been reported.

Tornatore (1995) discussed installation of a portable folding steel bridge on a skid trail and a temporary wooden bridge on a haul road. Peak downstream sediment concentration values were near 1,000 milligrams per liter during the installation of the steel bridge crossing. Within 24 hours after the bridge installation, downstream sediment concentration stabilized at insignificant levels. While skidders were crossing the bridge, median sediment concentrations were 2.0 and 13.5 milligrams per liter for upstream and downstream samples, respectively. Tornatore recognized that several options such as culverts can be used as stream crossings, but concluded that portable bridges may have less impact on water quality. Hassler et al. (1990) investigated stream water quality impacts using a portable stress-laminated timber bridge in West Virginia. Data were collected downstream, beginning two days prior to stream crossing installation lasting until three days afterward. No significant changes regarding conductivity, pH, or turbidity were reported from this study.

Some studies indicate that sediment levels are not influenced by installation of portable bridges due to the ability of workers and machine operator to install these crossings with minimal impact on the stream or stream banks. Thompson et al. (1995) evaluated sediment production during the installation of two portable glum-laminated timber bridges. Water samples were taken during storm events following construction and installation which yielded mean sediment concentration increases of 67 milligrams and 38 milligrams per liter at the stream crossings. No significant levels of sediment were detected because the stream channels were not altered and no additional soil was placed in the streams. These sediment levels for portable bridges are considerably lower than previously mentioned studies on ford and culvert crossings.

Road Approaches

Taylor et al. (1999b) found that the sediment contribution due to road approaches to the stream crossings was actually greater than the installation phase for a case study evaluating a culvert, portable bridge, and ford. Thus, sediment estimates from adjoining approaches to stream crossings are needed. The forestry version of the USLE is an older and widely accepted technique that can be used for relative estimates of erosion on forest road approaches. This model is effective for predicting sheet and rill erosion on forest land

(Dissmeyer and Foster 1984). The USLE is based on six major components of erosion, which when multiplied together produce a predicted erosion rate for a certain area (Dissmeyer and Foster 1984; Wischmeier and Smith 1978). Newer models, such as the Water Erosion Prediction Project (WEPP)-Roads Versions have been developed that are more specifically suitable for forest road erosion prediction technology (Grace 2007).

Erosion Models for Forest Roads

WEPP is a soil erosion model developed by the United States Department of Agriculture (USDA) Agricultural Research Service in response to the need of land managers to predict impacts on soil and water resources and is available at no cost on the internet. WEPP has recently been applied and used for forest road applications (Elliot and Hall 1997). The WEPP model considers both sheet (interrill) and rill erosion and any erosion that may result from detachment by water in channels (Grace 2007). Elliot et al. (1993) define rill erosion as “being driven by the detachment and transport of sediment by concentrated channel flow”. Grace (2007) defines interrill erosion as “the detachment and transport of sediment by raindrop impact and shallow overland flow”.

Forest managers look for actual data to support models such as the WEPP model to prove their validity. A study by Forsyth et al. (2005) studied two roads in the coastal plain of Australia to compare actual erosion data to estimates made by WEPP: Road version. The two road classes in the study were an A-class road (Class I road) and a C-class road (Class III road). Regression analysis of WEPP-predicted versus observed runoff and soil loss showed a strong relationship for both road classes indicating that WEPP: Road is suitable for predicting total runoff and sediment loss for the road classes studied (Forsyth et al. 2005). Feldt (2006) compared the Forestry version of the USLE, the Revised USLE (RUSLE), WEPP –Roads Version, and SEDMODL2 to sediment values and found the Forestry Version of the USLE and WEPP-Roads Version were most similar to the actual sediment values.

Forest research has developed a newer erosion model specifically developed for forest roads: SEDMODL2. This model has successfully been used on the west coast, but Feldt (2006) found that the existing model does not predict erosion from forest roads in Virginia and West Virginia as well as WEPP or the USLE.

BMPs

BMP implementation is critical throughout the process of installing, removing, and closing out stream crossings used in timber harvests. Results from a paired watershed study by Wynn et al. (2000) found that BMP implementation in the coastal plain of Virginia, including road and skid trail BMPs, resulted in significantly less sediment as compared to a watershed where no BMPs were intentionally used. However, BMPs do have associated costs for loggers and/or landowners, who may be tempted to reduce BMP implementation costs in order to obtain the maximum profit. A study by Shaffer et al. (1998) estimated BMP costs on 46 randomly selected harvest sites in Virginia, 15 of which were in the Piedmont region. This study indicated that the median BMP cost in the Virginia Piedmont was $25.75/harvest acre ($63.60/harvested hectare). Costs can be difficult to gauge in the Piedmont region due to the variable and complex terrain. BMP maintenance and implementation research over several decades has indicated that traffic intensity and road maintenance are two of the main sources of erosion on forest roads

(Grace 2006). Properly locating, constructing, installing, and maintaining approaches and stream crossings are vital to water quality protection (Aust and Shaffer 2001).

Overall, the literature reveals that forest road stream crossings and approaches can negatively affect water quality and the effects are quite variable. The literature also supports our approach of using erosion models and water quality samples to evaluate the different crossings.

METHODS

Study Site Description

Counties involved in this study are located in the central region of Virginia, known as the Piedmont Physiographic region (Figure 1). The Piedmont has rolling hills with small drainages. Geologically, the Piedmont is the product of erosion of ancient mountains and has a gentle slope from the mountains to the Coastal Plain (Daniels et al. 1973). The interior of the province typically has a gently rolling landscape with a relief of 50 feet (15.24 m) bounded by steeper, deeper valleys of modern streams (Daniels et al. 1973). Study sites for this project are located as far west as Pittsylvania County and extend as far east as Amelia County.

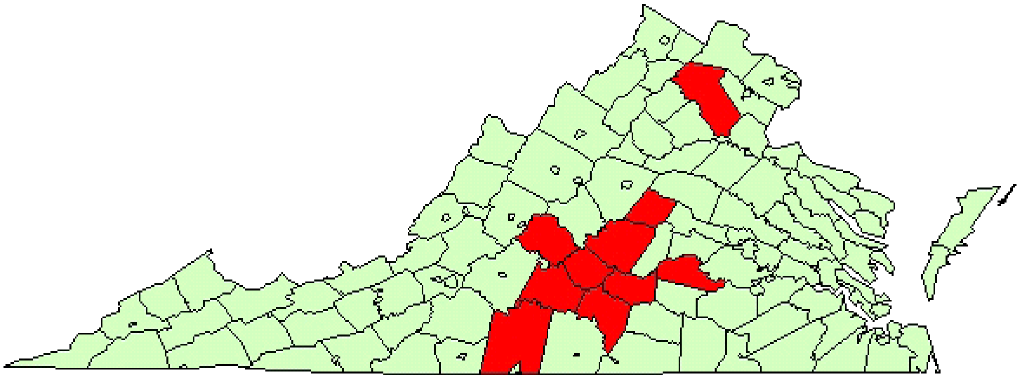

Figure 1. Map of Virginia with marked study counties.

Charlotte County, which is typical and central in the Virginia Piedmont, has a moderately high plateau, and is so dissected by numerous streams that the surface relief ranges from undulating and rolling to hilly, steep, and broken (Soil Survey of Charlotte County, VA 1974). The less steep terrain can be found near the broader interstream ridges and on stream terraces (Soil Conservation Service, 1974). The primary parent material of the area is metamorphic rock. Charlotte County like most of central Virginia experiences warm summers and mild winters. Average total precipitation for the county is 43.4 inches (110.2 cm) per year. Average summer and winter daily temperatures are 73 degrees Fahrenheit (23 degrees Celsius) and 40 degrees Fahrenheit (4 degrees Celsius), respectively.

The dominant parent material of the region is metamorphic and igneous rock except in the Triassic basin (Daniels et al. 1973). Common soil series include Wehadkee-Chewacla complex (fine-loamy, mixed, active, nonacid, thermic fluvaquentic endoaquepts-dystrudepts), Wilkes (loamy, mixed, active, thermic, shallow typic hapludalfs), Appling (fine, kaolinitic, thermic typic kanhapludults), Madison (fine, kaolinitic, thermic typic kanhapludults), Codorus (fine-loamy, mixed, active, mesic fluvaquentic dystrudepts), Bremo (loamy-skeletal, mixed, semiactive, mesic typic dystrudepts), and Toccoa (course-loamy, mixed, active, nonacid, thermic typic udifluvents). These series occur near the streams used for this study and on the approaches. Wehadkee-Chewacla complex consists of silt loam soils that are deep, poorly and somewhat poorly drained, nearly level soils on flood plains. Wilkes sandy loam soils are well-drained, sloping to steep soils on uplands. Toccoa fine sandy loam soils are deep, well-drained, and found on nearly level flood plains of major streams (Soil Conservation Service, 1974).

The Piedmont of Virginia is strongly influenced by previous land use history. European settlers utilized the flood plains and terraces for agricultural crops and home sites and later cleared the uplands to grow tobacco, corn, and cotton. Abusive agricultural practices on this steep topography resulted in a loss of up to two feet (0.6 m) of topsoil. In most areas of the region the A horizon is now absent and a “plow pan” has often been created from tillage of the soil. Channels of streams were to a large extent filled with sandy sediment, from the acid igneous soils, and this resulted in the raising of the stream levels followed by formation of gullies (Ward and Trimble 2004). The southern Piedmont is a region that suffered massive historical soil erosion, but was somewhat stabilized by soil conservation measures and reforestation starting in the 1930s (Ward and Trimble 2004).

Most study sites were located on individual private properties or on land owned by MeadWestvaco or Huber Engineered Woods. Stands harvested ranged from mixed hardwood with white oak (*Quercus alba*) and yellow poplar (*Liriodendron tulipifera*) to loblolly pine plantations (*Pinus taeda*). A range of road classes were used to acquire all four types of stream crossings, ranging from skid trails (Class IV roads) to permanent haul roads (Class II-III roads) (Walbridge 1990).

Treatment Description

Four different stream crossing treatments were implemented for this study: skidder bridges (steel), pole bridges, fords, and culverts. Six replications of the four crossings, with the exception of fords (4 replications) and pole bridges (7 replications), were installed and monitored to create a total of 23 stream crossings for the project. Skidder bridge crossings, which are commonly used in this area, consisted of 30 or 40-foot long steel panels. Pole bridge crossings used a pipe or culvert to allow water to flow through and poles placed on top of the pipe to fill the stream cross-section. Some crossings had logs placed over the pipe both parallel and perpendicular to the stream channel. Ford crossings were re-enforced with Geotextile and/or GeoWeb and had rip-rap stone or limestone gravel placed on top of the material. Culvert crossings consisted of either single or double corrugated steel pipes. These culverts were new crossings installed on permanent haul roads. All crossings were installed by contractors working for Mead Westvaco or landowners which have contracts with MeadWestvaco or Huber Engineered Woods. These contractors had a wide range of experience in forest road construction and stream crossing installation. Typical examples for each of the four crossings are provided in Figures 2-5.

Figure 2. Typical 3-panel steel skidder bridge.

Figure 3. Pole bridge constructed with a steel pipe and white oak logs both parallel and perpendicular to stream channel.

Figure 4. Typical ford crossing re-enforced with geotextile and stone.

Figure 5. Typical corrugated steel culverts used as a stream crossing.

Field Methods

Field visits were conducted during four different phases of the harvesting operation: 1) before reopening or installation of the road or skid trail, 2) after installation/before harvest, 3) during harvest, and 4) after harvest. Stream crossings were associated with permanent haul roads, temporary haul roads, or skid trails. It was necessary to include representatives of all of these different road types to achieve the desired number of replications and to provide a more complete representation of the entire harvest road system. The streams were identified as perennial, intermittent, or ephemeral. Watershed acreage, soil series, Rosgen stream bank stability classification, and the Manning-Chezy water yield equation were used to characterize the stream and surrounding area. Rosgen's classification separates streams into the major, broad stream types (A-G), and further divides stream types into subtypes based on slope ranges and dominant channel material particle sizes (Harrelson et al. 1994). This commonly used classification system helps predict streambank stability. The Manning-Chezy equation is used to calculate the discharge of a channel or river (Ward and Trimble 2004). Although these data were not central to our objectives, Rosgen classification and the Manning-Chezy data are provided in Appendix A.

During each site visit, in-stream water samples were carefully collected in order to limit disturbance of the stream. These were taken at permanent points located approximately 25 feet (8 meters) above and below each crossing. Samples were analyzed for suspended sediment in the lab. Also, in-stream data was collected at the same locations with a water meter (ExStik EC500 manufactured by Extech Instruments Corporation) for pH, total dissolved solids (TDS), conductivity, and stream temperature. A comparison of these readings was done above and below each crossing throughout the different phases of a harvest schedule. These in-stream samples were taken during lower flow conditions.

Site and road data were collected for both approaches for each crossing so that erosion estimates could be obtained. Data included weather information, slope length, slope width, slope percent, slope shape, road management, soil texture, bare soil, residual binding, soil reconsolidation, canopy, steps (formed by debris accumulation, roots, or other obstacles), onsite storage (detached soil which is stored in depressions along the slope), invading vegetation, and organic matter content. Data were subsequently used to estimate the approach erosion values with the WEPP (Forsyth et al. 2005) and forestry version of the USLE (Dissmeyer and Foster 1984). Height of instrument (HI) rods, Abney level, and 30-meter tape were used to characterize the slope of the approaches. The USLE model also was used to predict erosion from the approaches.

Best management practices (BMP) details for each stream crossing approach were identified. This included documentation of water control structures and the frequency, the type of cover and percent bare soil (i.e. % bare soil, % seeded grass cover, % natural vegetation, % native rock, gravel type and depth). Streamside management zones (SMZs) near the crossing were also noted. The width of the SMZ was measured along with the tree species present and basal area (ft^2/acre).

Laboratory and Model Methods

I measured the amount of sediment (ppm) in each of the in-stream water samples collected above and below each crossing. Crucibles were dried in an oven for approximately four hours at 105 degrees Celsius and were then placed in a decicator to cool for 10 minutes. Immediately after cooling the crucibles were weighed to an accuracy of four decimal places. Next, each water sample was shaken and placed in a crucible which each crucible was weighed again. These samples were placed in an oven at 380 degrees Celsius for approximately 42 hours. The crucibles were removed with a glove and placed in the decicator for 15 minutes. After cooling, each crucible was weighed with the sediment only and the weight was recorded (David Mitchem, personal communication 2007).

Erosion prediction models were used to estimate the amount of sediment being contributed to the stream each year on a per acre basis. An older version of this model was used to estimate sheet and rill erosion (Forsyth et al. 2005). Inputting weather station, slope, road management, and soil texture information in this program allow it to predict erosion (tons/acre/year). The program was run to predict erosion for a 10-year period and obtains an average soil loss value. The less complex USLE model also was used to predict soil erosion. Estimated soil erosion is represented by the following equation for USLE:

$$\text{Estimated soil erosion} = A \text{ (tons/acre/year)} = RKLSCP$$

Where:
R=Rainfall and Runoff index
K=soil erodibility
LS=slope length and steepness
CP=Cover-Management Practice Factor for Untilled and Tilled Forest land

The CP factor has several sub factors that influence the estimate. (Dissmeyer and Foster 1984). Factors in the above equation were derived from provided diagrams and equations in the USLE manual.

Data Analysis

The study design was a completely randomized design with unbalanced replication. Estimates of soil erosion from the WEPP and USLE models were analyzed using the Number Cruncher Statistical System (NCSS 2005). One-way analyses of variance (ANOVA, $p = 0.10$) tests were used for all four phases of the harvesting process.

Tukey-Kramer multiple comparison tests were used to determine differences between means of significantly different treatments (NCSS 2005). F-ratios and associated probability levels were evaluated also to determine how probable a difference occurred among treatments within a certain phase of harvest. Probability levels or p-values are used to be able to fail to accept (basically reject) the null hypothesis (H_o) which is that the mean values of all treatments do not have significant differences (Hildebrand et al. 2005). P-values less than the alpha level show significant differences among treatments.

Response variables used for analysis of water quality were treatment (type of stream crossing), harvest phase (time condition), and stream position (above or below the crossing). Independent variables included: total dissolved solids (TDS), pH, conductivity, stream temperature, and total suspended solids (sediment concentrations). Statistical significance was determined using ANOVA and Tukey-Kramer's multiple comparison tests ($p = 0.10$).

RESULTS

The Erosion Estimates for the Stream Crossing Approaches

Both the WEPP and USLE model estimates of erosion at the approaches of the four types of crossings showed significant for the during harvest phase (WEPP: p = 0.07, USLE: p = 0.0006) (Table 1). Additionally, USLE estimates interpreted were significantly different between the four stream crossings at the post-installation/pre-harvest phase (p = 0.08), during harvest phase (p = .0006), and post-road closure phase (p = 0.055).

Table 1. P-values associated with WEPP and USLE estimates for each phase of harvest.

Model	Pre-reopening/ Pre-installation	Post-installation/ Pre-harvest	During harvest	Post-Road Closure
WEPP	0.201	0.892	0.075*	0.147
USLE	0.160	0.079*	0.001*	.055*

*Term significant at alpha = 0.10

WEPP Estimates of Approach Erosion

The erosion rates associated with the approaches to the various stream crossings using the WEPP model were not significantly different between the four stream crossing types for the pre-installation phase (p = 0.20), post-installation/pre-harvest phase (p = 0.89), or post-road closure phase (p = 0.15). However, erosion rates during the harvest phase resulted in significant differences between the four stream crossings (Table 2) (p = 0.07). During harvest phase, culvert crossing approaches had significantly higher estimated erosion rates (46.2 tons/acre/year) than ford or pole bridge crossings (18.6, 21.6 tons/acre/year) and the steel skidder bridge had intermediate values (29.7 tons/acre/year) (Table 2). Higher erosion estimates at the pre-installation phase may be due to pre-existing road construction conditions for culvert, ford, and steel bridge stream crossings. Standard error values of WEPP estimates show variability of mean values (Table 3).

Table 2. Mean values of approach erosion for the four stream crossing types during each sampling period as predicted by the WEPP model. Lower case letters indicate statistical significance at the α = 0.10 level. ns = none significant.

		Sampling Periods		
Stream Crossing Type	Pre-reopening/ Pre-installation (p = 0.201)	Post-installation/ Pre-harvest (p = 0.892)	During harvest (p = 0.075)	Post-Road Closure (p = 0.147)
		tons/acre/year		
	----------------------	**(tonnes/hectare/year)**	---------------------	-----------------------
Culverts	10.7 (24.0) ns	26.2 (58.7) ns	46.2 (103.5) a	24.4 (54.7) ns
Fords	22.2 (49.7) ns	15.8 (35.4) ns	18.6 (41.7) b	19.9 (44.6) ns
Pole bridges	6.2 (13.9) ns	23.0 (51.5) ns	21.6 (48.4) b	11.8 (26.4) ns
Steel bridges	11.9 (26.7) ns	22.1 (49.5) ns	29.7 (66.5) ab	25.5 (57.1) ns

Table 3. Standard error values of approach erosion means for the four stream crossing types during each sampling period as predicted by the WEPP model, where n = sample size.

		Sampling Periods		
Stream Crossing Type	Pre-reopening/ Pre-installation	Post-installation/ Pre-harvest	During harvest	Post-Road Closure
		tons/acre/year		
	---------------------	**(tonnes/hectare/year)**	---------------------	-------------------------
Culverts	4.8 (10.8) *n = 12*	7.1 (15.9) *n = 10*	7.6 (17.0) *n = 12*	4.7 (10.5) *n = 12*
Fords	5.8 (13.0) *n = 8*	11.3 (25.3) *n = 4*	9.3 (20.8) *n = 8*	6.7 (15.0) *n = 6*
Pole bridges	4.4 (9.9) *n = 14*	8.0 (17.9) *n = 8*	7.0 (15.7) *n = 14*	4.4 (9.9) *n = 14*
Steel bridges	4.8 (10.8) *n = 12*	8.0 (17.9) *n = 8*	7.6 (17.0) *n = 12*	4.7 (10.5) *n = 12*

The WEPP erosion estimates for road approaches were significantly different at the during-harvest phase. These erosion rates were compared to the average slope length of road approaches for all four types of stream crossings (Figure 6). Erosion rates associated with the approaches to culvert stream crossings were significantly different and had an average slope length of 324 feet, maximum of 473 feet (99 m, max. of 144 m) (Figure 6). Slope length is a factor of the WEPP model, so noticing a positive relationship of slope length and erosion rates was expected. The culvert crossing approach slope lengths (324 feet) were greater than those used for ford, pole bridge, or steel bridge crossings (122, 145, and 232 ft; respectively).

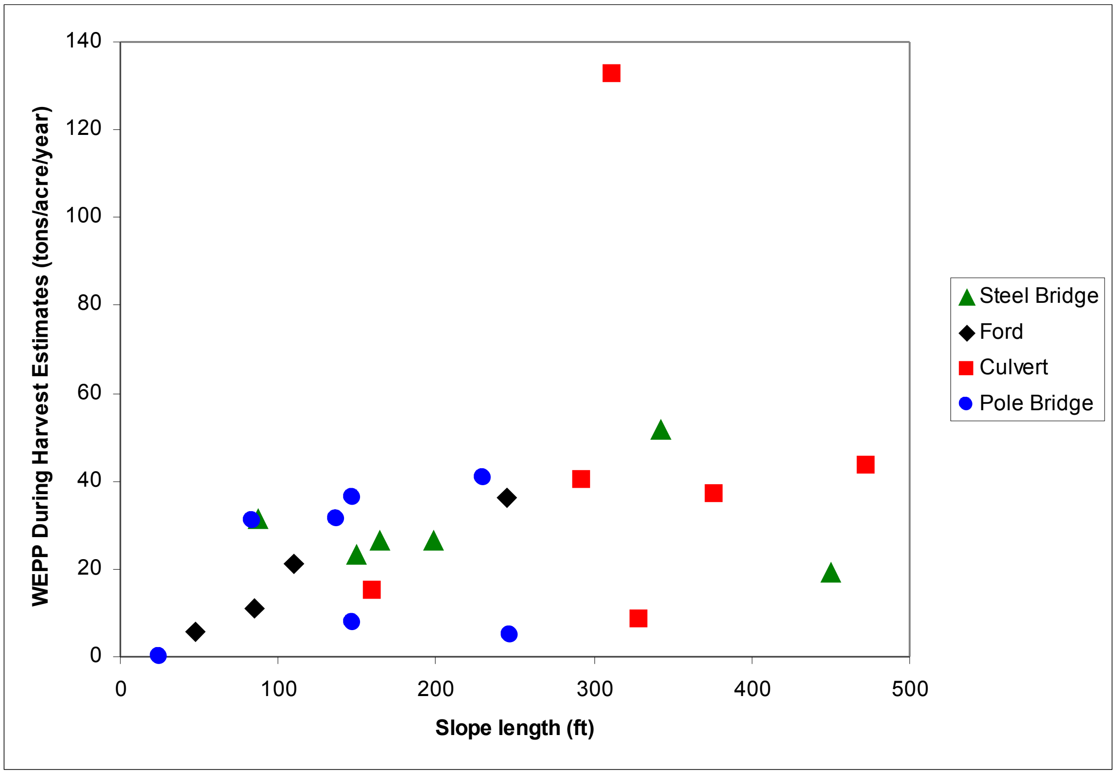

Figure 6. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to slope length of approaches for each study site.

The significant erosion rates estimated by the WEPP model for the during harvest phase were compared with cover management practices. As could be expected when evaluating a WEPP model component, the comparison of these estimates to the percentage of bare soil on the approaches associated with the four types of stream crossings showed a positive relationship (Figure 7). The significant differences of erosion rates for the approaches of culverts is evident in this relationship, as the majority of approaches of culverts have over 80% bare soil (Figure 7). A comparison of WEPP estimates to the percentage of natural vegetation cover on the approaches associated with the different types of crossings showed an inverse or negative relationship (Figure 8). The significant difference of approaches leading to culverts during harvest can be seen in the relationship, as the approaches of culverts have less than 30% of natural vegetation cover (Figure 8). These relationships show how cover management practices impact erosion rates of approaches.

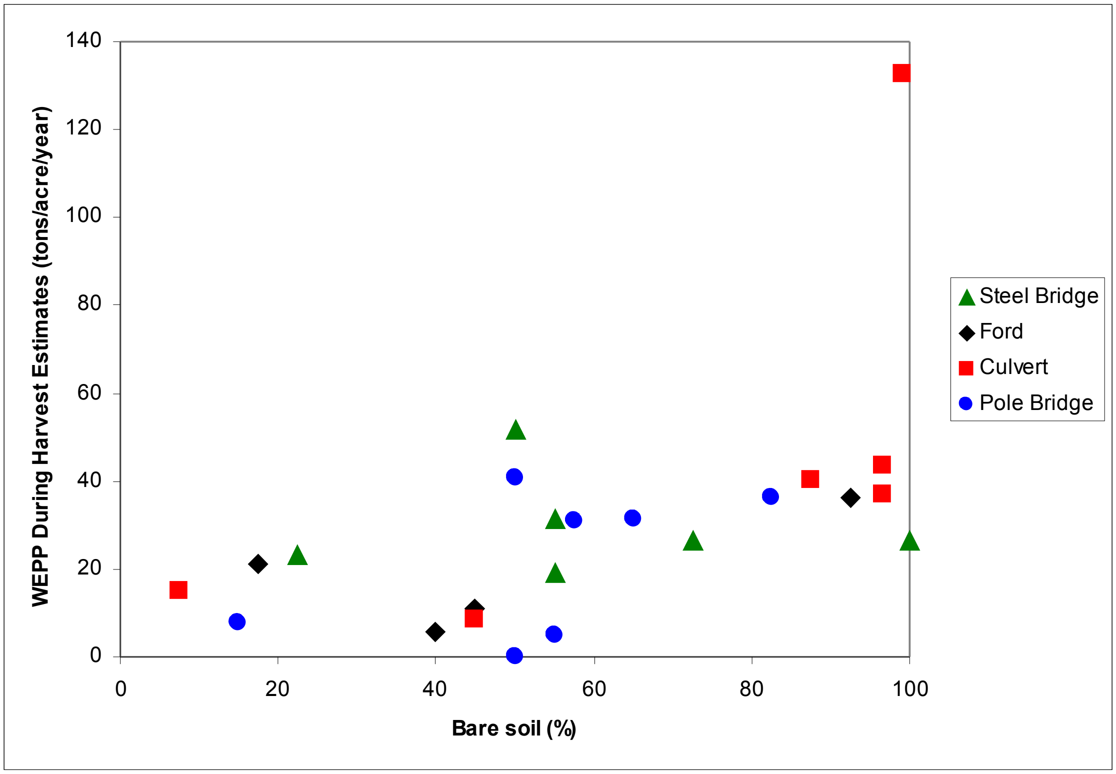

Figure 7. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to percentage of bare soil of approaches for each study site.

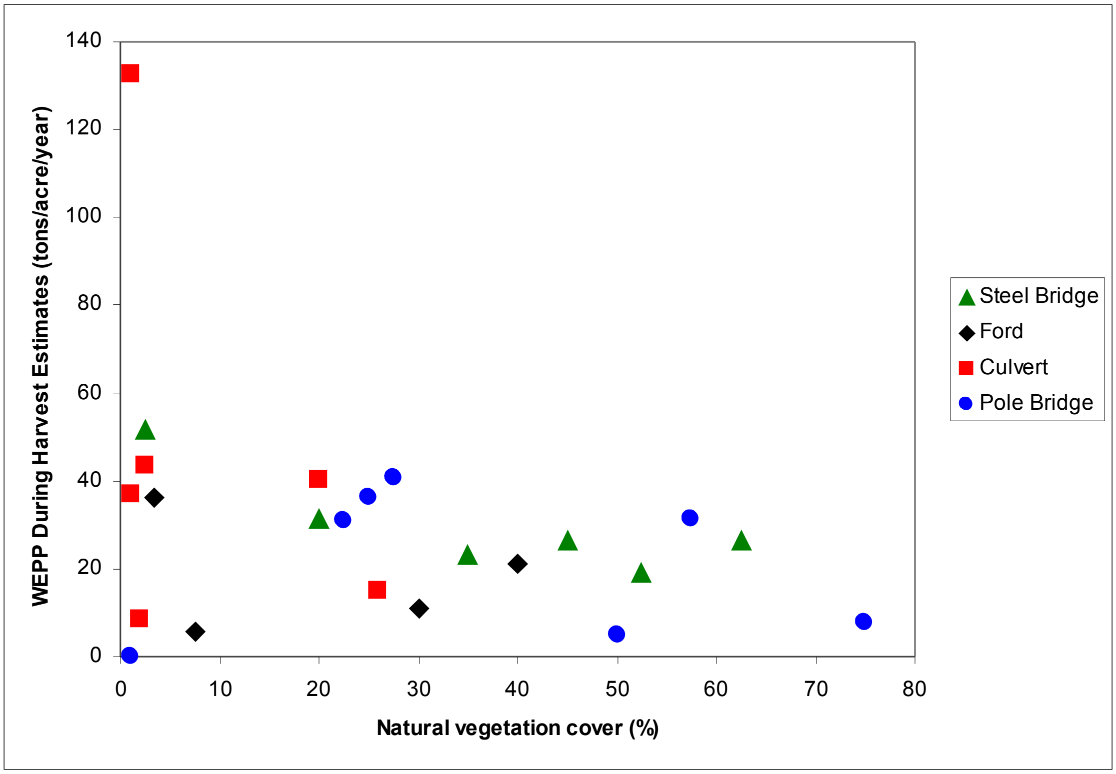

Figure 8. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to percentage of natural vegetation cover of approaches for each study site.

The significant erosion rates estimated by the WEPP model for the during harvest phase were analyzed for a relationship with BMP management practices. A ranking system was created for BMP implementation that showed that the more BMPs applied to approaches of stream crossings, the lower the erosion rates tend to be (Figure 9). No or minimal BMP application resulted in the highest erosion estimates during the harvest phase among all study sites (132.6 tons/acre/year). Most BMP attention to pole bridges was cover management due to the fact that most of these crossings were located in more gentle terrain where grade control was not as much of an issue as the other crossings installed.

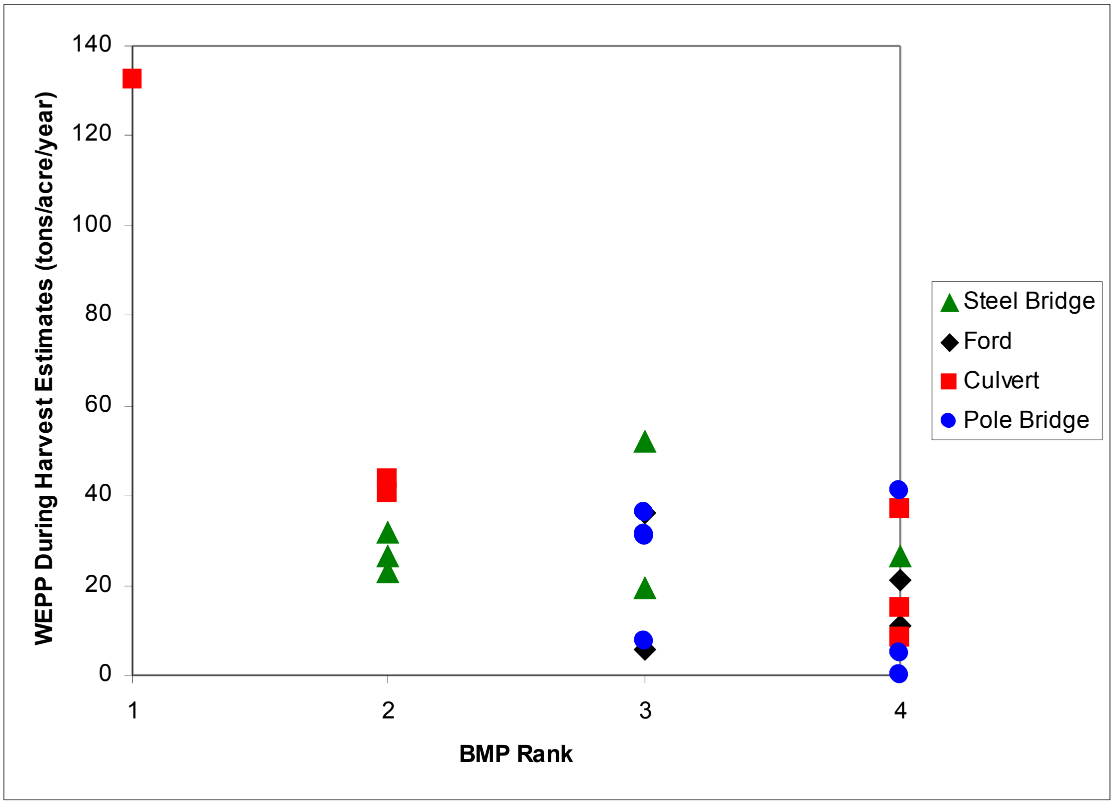

Figure 9. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to BMPs implemented on approaches for each study site. BMP rank system: 1= None or minimal BMPs, 2= Water control structures or grade control BMPs, 3= Cover management (gravel, seeded, or natural cover) BMPs, 4= Water/grade control BMPs *and* Cover management BMPs.

USLE Estimates of Approach Erosion

Estimation of the erosion rates associated with the approaches to the studied stream crossings using the USLE model indicated no significant differences between the four stream crossing types for the pre-installation phase (p = 0.16). However, erosion estimates for the post-installation/pre-harvest phase (p = 0.08) and the during harvest phase resulted in significant differences between the four stream crossings (Table 4) (p = 0.0006). Also, the post-road closure phase resulted in significant differences among the four crossings (Table 3) (p = 0.055). Post-installation/pre-harvest approach erosion estimates resulted in higher rates for culverts and steel bridges (34.4, 34.2 tons/acre/year) than ford or pole bridge crossings (9.8, 1.7 tons/acre/year). During-harvest approaches associated with culvert crossings resulted in significantly more estimated erosion (85.8 tons/acre/year) than the ford, pole bridge, or steel skidder bridge (23.4, 4.5, 18.7 tons/acre/year, respectively) (Table 3). Culverts, fords, and steel bridges showed a decrease in estimated erosion (50.5, 20.6, and 15.6 tons/acre/year, respectively) at the post-road closure phase. Pole bridge approaches increased from the during harvest phase estimated erosion rate of 4.5 tons/acre/year to 10.3 tons/acre/year following road closure. Standard error values of USLE estimates show variability of mean values (Table 5).

Table 4. Mean values of approach erosion for the four stream crossing types during each sampling period as predicted by the USLE model. Lower case letters indicate statistical significance at the α = 0.10 level. ns = none significant.

	Sampling Periods			
Stream Crossing Type	Pre-reopening/ Pre-installation (p = 0.160)	Post-installation/ Pre-harvest (p = 0.079)	During harvest (p = 0.001)	Post-Road Closure (p = 0.055)
	tons/acre/year ---------------------- **(tonnes/hectare/year)** -------------------- ----------------------			
Culverts	3.8 (8.5) ns	34.4 (77.1) ns	85.8 (192.2) a	50.5 (113.1) a
Fords	2.7 (6.0) ns	9.8 (22.0) ns	23.4 (52.4) b	20.6 (46.1) ab
Pole bridges	0.1 (0.22) ns	1.7 (3.8) ns	4.5 (10.1) b	10.3 (23.1) b
Steel bridges	2.2 (4.9) ns	34.2 (76.6) ns	18.7 (41.9) b	15.6 (34.9) ab

Table 5. Standard error values of approach erosion means for the four stream crossing types during each sampling period as predicted by the USLE model, where n = sample size.

Stream Crossing Type	**Sampling Periods**			
	Pre-reopening/ Pre-installation	Post-installation/ Pre-harvest	During harvest	Post-Road Closure
	---------------------	**tons/acre/year** **(tonnes/hectare/year)**	---------------------	-----------------------
Culverts	1.2 (2.7) *n = 12*	9.3 (20.8) *n = 10*	13.8 (30.9) *n = 12*	11.0 (24.6) *n = 12*
Fords	1.5 (3.4) *n = 8*	14.7 (32.9) *n = 4*	16.9 (37.9) *n = 8*	15.5 (34.7) *n = 6*
Pole bridges	1.1 (2.5) *n = 14*	10.4 (23.3) *n = 8*	12.7 (28.4) *n = 14*	10.2 (22.8) *n = 14*
Steel bridges	1.2 (2.7) *n = 12*	10.4 (23.3) *n = 8*	13.8 (30.9) *n = 12*	11.0 (24.6) *n = 12*

Evaluation of slope length, a critical component of erosion rates, was compared to the USLE during harvest estimates (Figure 10). Slope length is a factor of the USLE method and is taken into account by the “LS factor”. Therefore, the expected positive relationship exists between slope length and the USLE during harvest erosion rates. Most of the approaches associated with the stream crossings with slope lengths exceeding 300 feet (91 m) were culvert crossings. Culvert approaches also showed the highest average erosion rates with the USLE model.

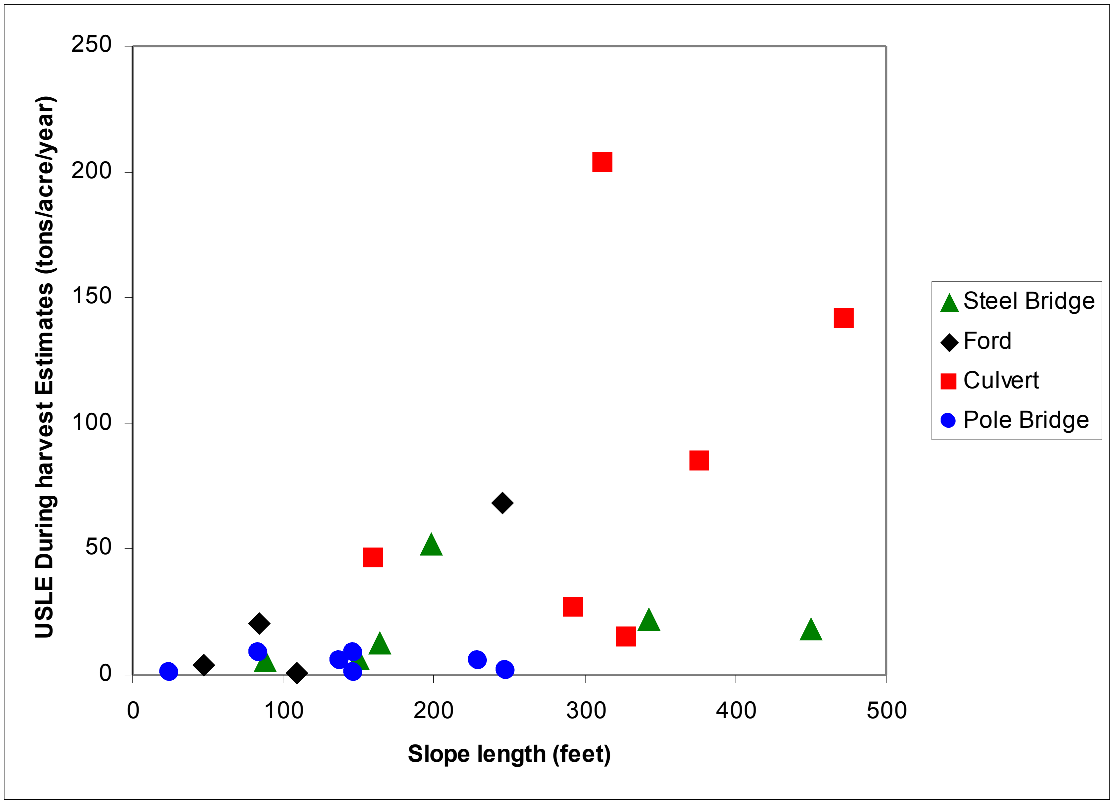

Figure 10. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to slope length of approaches for each study site.

Cover management practices were also compared to the USLE during harvest erosion rates. The percentage of bare soil and USLE estimates had a positive relationship (Figure 11). All approaches to stream crossings require some bare soil to be present for timber harvesting, but approaches associated with culverts displayed the most amount of bare soil. Noticeably, the approaches with the larger amounts of bare soil showed the higher erosion rates through the USLE model. Cover management is built into the USLE model as the "CP factor". A comparison of USLE erosion rates during harvest to the percentage of natural vegetation cover showed an inverse relationship (Figure 12). Stream crossing approaches with more residual natural vegetation demonstrated lower rates of erosion. Culvert approaches did not have residual natural vegetation cover exceeding 30% contributing to the higher estimates.

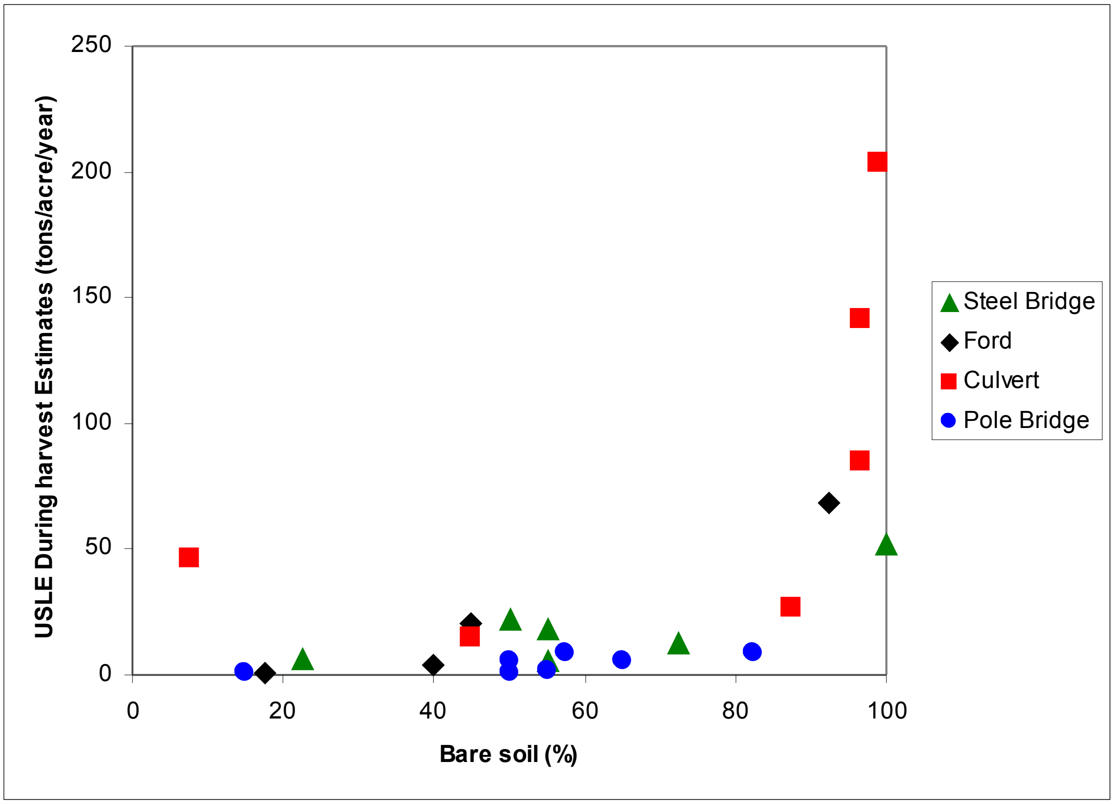

Figure 11. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to percentage of bare soil of approaches for each study site.

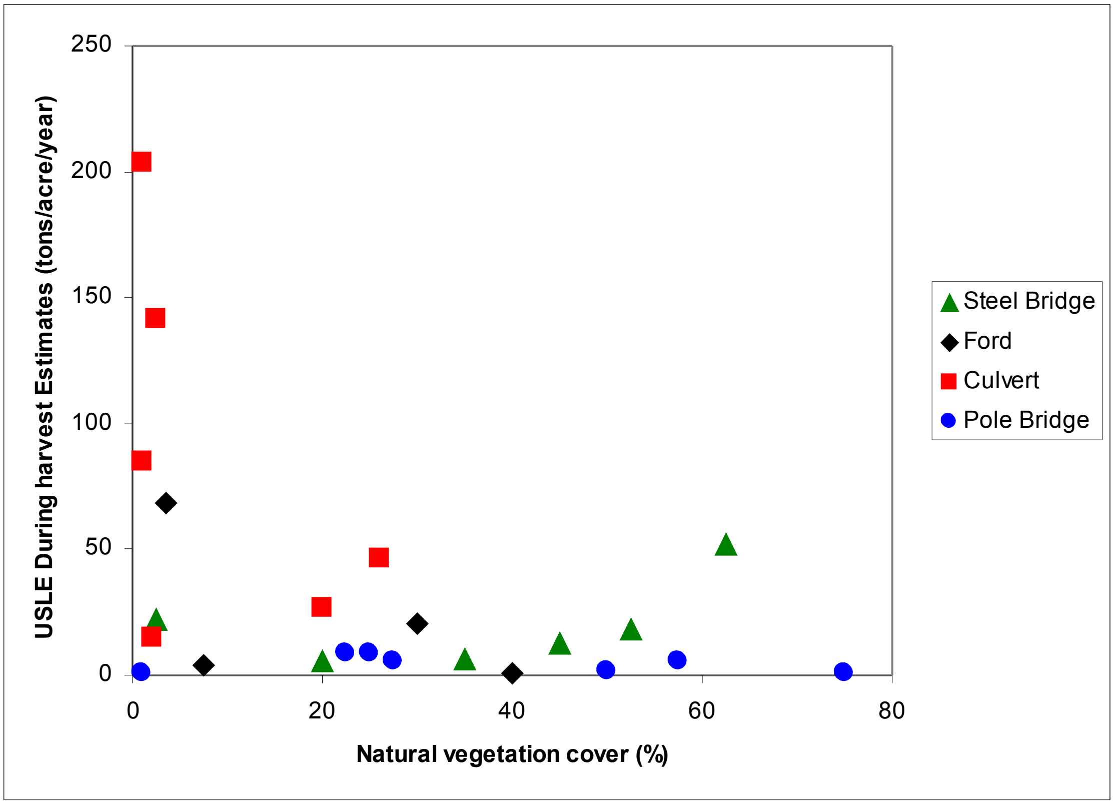

Figure 12. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to percentage of natural vegetation cover of approaches for each study site.

USLE erosion rates for the during harvest phase were analyzed and compared to BMPs for relationships between the two factors. The same ranking system was used to reflect BMP implementation as for the WEPP model estimates. USLE during harvest estimates showed that the more BMPs applied to approaches of stream crossings, the lower the erosion rates tend to be (Figure 13). Minimal or no implementation of BMPs resulted in a mean of 203.86 tons/acre/year (456.65 tonnes/ha/year) for a culvert crossing during harvest. Culvert approaches showed the highest rate of erosion for all BMP ranks with the exception of rank 3 (cover management).

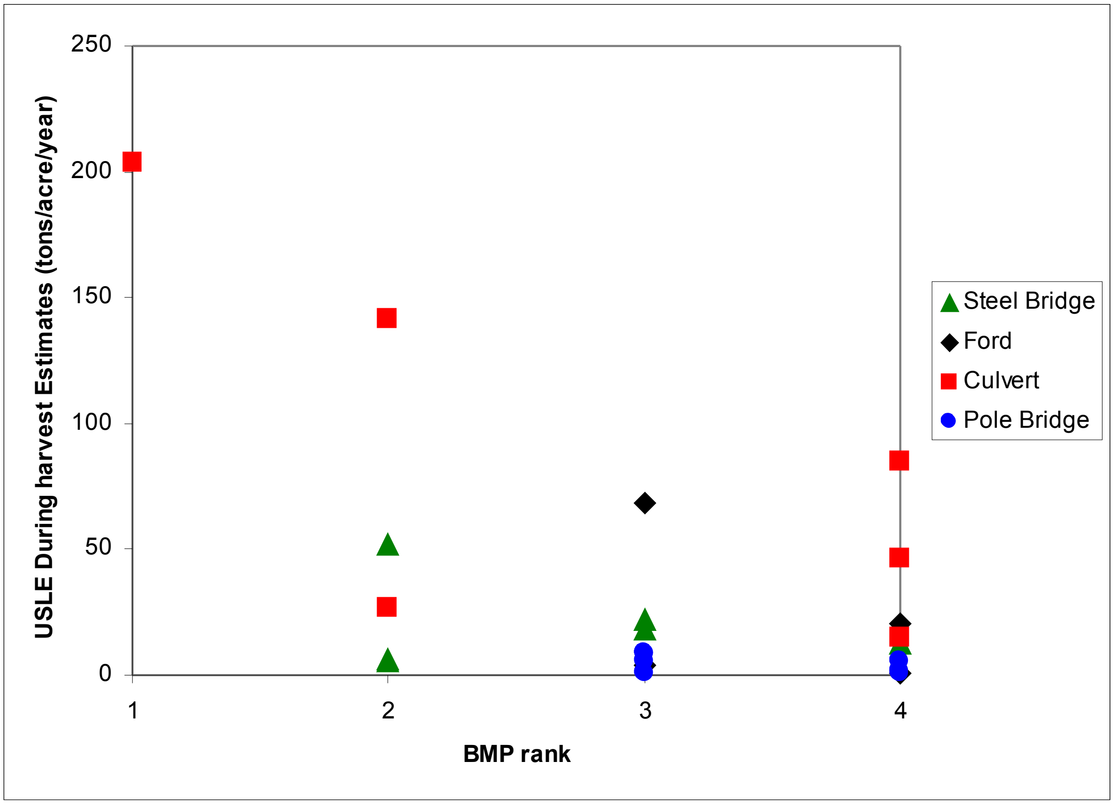

Figure 13. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to BMPs implemented on approaches for each study site. BMP rank system: 1= None or minimal BMPs, 2= Water control structures or grade control BMPs, 3= Cover management (gravel, seeded, or natural cover) BMPs, 4= Water/grade control BMPs *and* Cover management BMPs.

Evaluation of slope length was compared to the USLE post-road closure estimates (Figure 14). Slope length showed an overall average decrease for each type of stream crossing with the exception of the ford. However, one ford crossing did not have road-closure estimates recorded, which may contribute to the slight increase. A positive relationship exists between slope length and the USLE post-road closure erosion rates ($p = 0.0001$; $R^2 = 0.54$). The approaches of crossings which still have a slope length of greater than 200 feet (61 m) still have higher estimates than those approaches with shorter slopes.

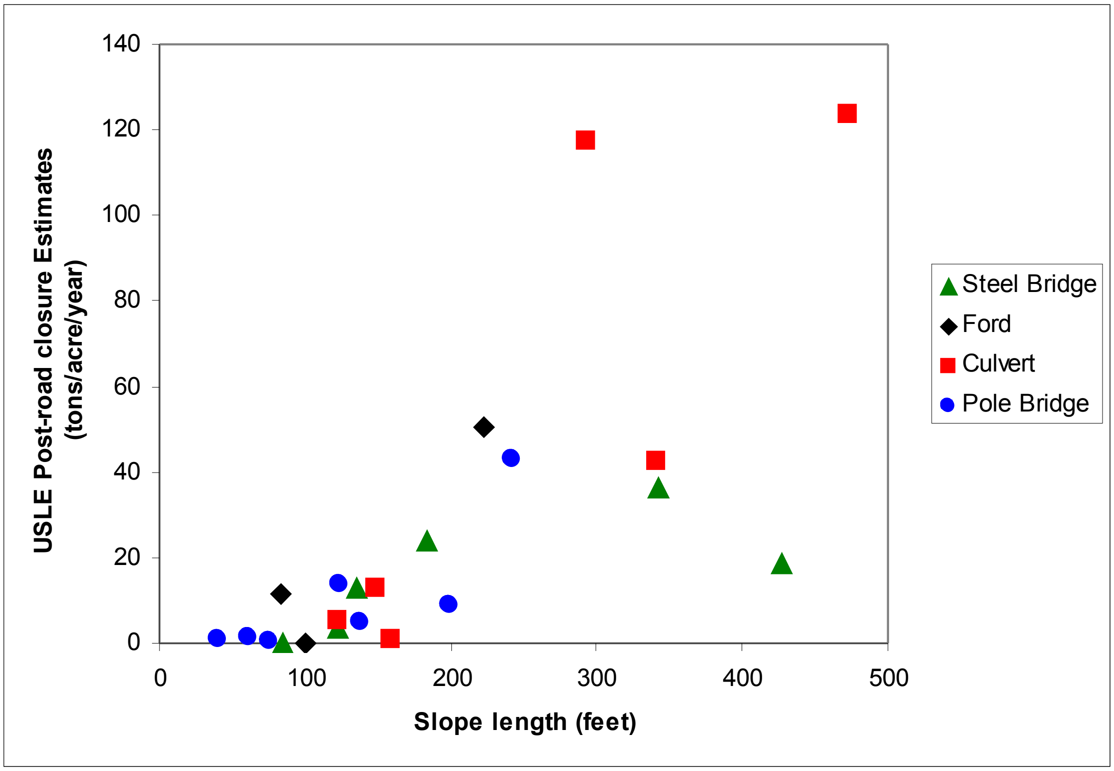

Figure 14. Mean values of the four stream crossing types at the post-road closure harvest sampling period as predicted by the USLE model compared to slope length of approaches for each study site.

Cover management practices were compared to the USLE post-road closure erosion rates. The percentage of bare soil and USLE estimates had a positive relationship (Figure 15). The associated approaches of all four types of stream crossings displayed decreases in the percentage of bare soil from the during harvest phase to the post-road closure phase. Pole bridge approaches had the lowest overall average percentage of bare soil (37%). A comparison of USLE erosion rates after road closure to the percentage of natural vegetation cover showed an inverse relationship (Figure 16). Stream crossing approaches with more natural vegetation remaining demonstrated lower rates of erosion. After the harvesting process was complete, pole bridge and steel bridge approaches showed the highest percentage of remaining natural vegetation (35.64% and 43.17% respectively). Culvert approaches had the lowest overall average remaining natural vegetation (2.3%).

Approaches associated with ford stream crossings showed 30.8% of natural vegetation remaining on-site.

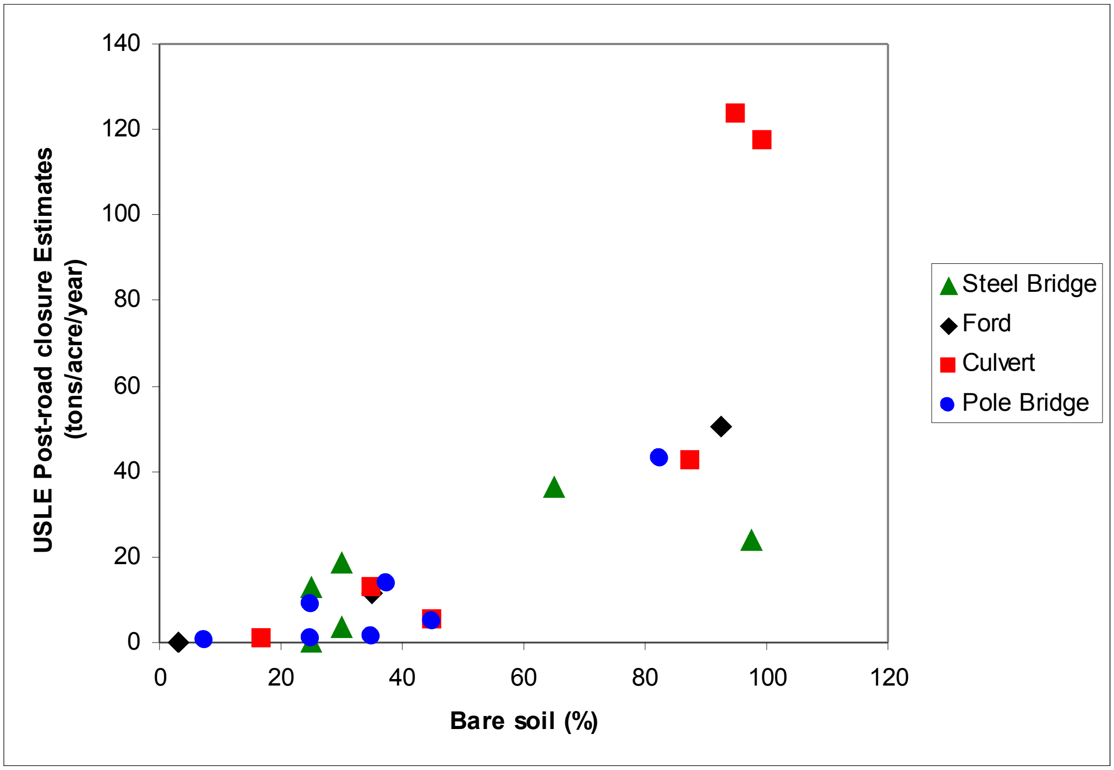

Figure 15. Mean values of the four stream crossing types at the post-road closure sampling period as predicted by the USLE model compared to percentage of bare soil of approaches for each study site.

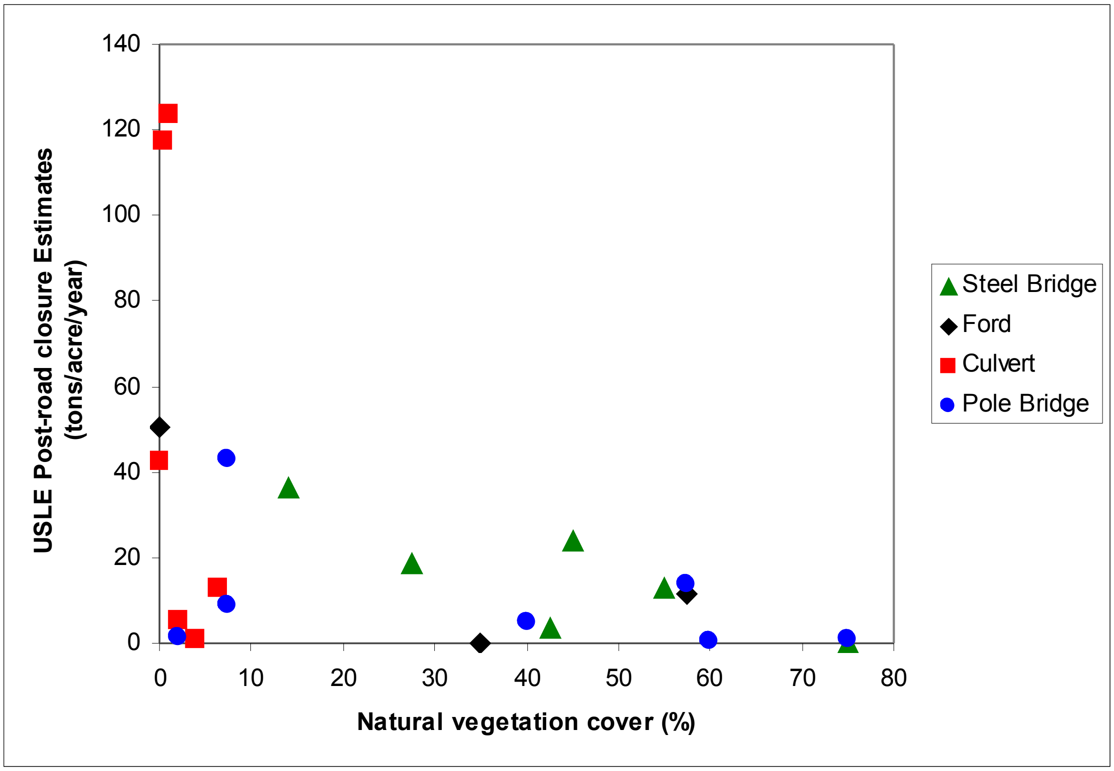

Figure 16. Mean values of the four stream crossing types at the post-road closure sampling period as predicted by the USLE model compared to percentage of natural vegetation cover of approaches for each study site.

The significant erosion rates estimated by the USLE model at the post-road closure phase were analyzed for a relationship with BMPs. The same ranking system was used to reflect BMP implementation as for the WEPP model estimates. USLE post-road closure estimates showed that the more BMPs applied to approaches of stream crossings, the lower the erosion rates tend to be (Figure 17). All approaches showed some type of BMP implementation, an improvement from the during harvest phase observations. Again, culvert approaches showed the highest overall erosion rates, but at lower levels than during harvest.

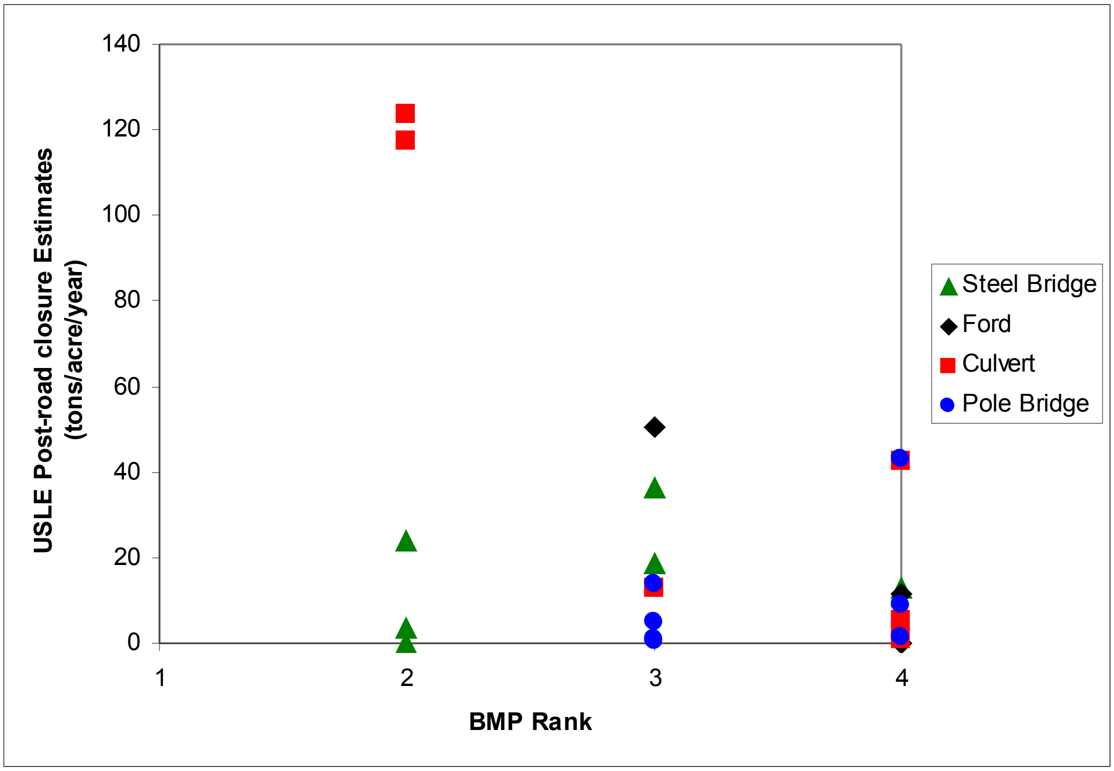

Figure 17. Mean values of the four stream crossing types at the post-road closure sampling period as predicted by the USLE model compared to BMPs implemented on approaches for each study site. BMP rank system: 1= None or minimal BMPs, 2= Water control structures or grade control BMPs, 3= Cover management (gravel, seeded, or natural cover) BMPs, 4= Water/grade control BMPs *and* Cover management BMPs.

Use Level for Different Crossings

Differences in management among study site locations resulted in various harvest volumes being transported across the structure and a range of durations in which the crossings were used. Fords and culverts were used on more haul roads to serve larger areas while pole bridges and skidder bridges were used more often for smaller tracts or more temporary crossings (Tables 6 and 7).

Table 6. Mean harvest tonnage transported across the different types of stream crossings.

Tonnage	Culverts	Fords	Pole bridges	Steel bridges
	------------------------ Tons (tonnes) --			
Mean	3989 (3619)	3861 (3503)	1119 (1015)	1288 (1168)
Maximum	6545 (5938)	6046 (5485)	3600 (3266)	3600 (3266)
Minimum	1800 (1633)	1936 (1756)	195 (177)	195 (177)

Table 7. Harvest duration estimates (days) which the different treatments were used for timber harvesting.

Duration	Culverts	Fords	Pole bridges	Steel bridges
		(Days)		
Mean	19	42	8	11
Maximum	35	90	25	25
Minimum	8	25	2	2

Mean estimates showed a difference in the tonnage and duration of the various treatments. Notable circumstances are the minimum and maximum volumes and days that impact the mean values. Ford and culvert stream crossings were used for extracting more timber than pole bridges or steel bridges (Table 4), and longer duration periods (Table 5). Harvest tonnage and duration were not statistically analyzed as this information was collected to merely observe the installation of treatment types in relation to forest management decisions.

The WEPP erosion estimates for the stream crossing approaches during harvest phase were compared with harvest volumes (Figure 18). The linear relationship between these mean estimates and harvested volume was not significant ($p = 0.69$). Notably, steel bridges and pole bridges were utilized for harvests of less than 2,000 tons. An exception to this observed volume limit was a pole bridge and steel bridge installed on a pre-existing road for a harvest of 3,600 tons (Figure 18). In this situation the ford crossing was used to cross the stream with the largest watershed acreage. Another comparison regarding harvest duration and WEPP estimates of the approaches of crossings during the harvest was made to indicate any relationship between these factors (Figure 19). The linear relationship between these mean estimates and duration was not significant (p = 0.57) and the correlation ($R^2 = 0.02$) was weak. Observations of harvest duration showed that steel bridges and pole bridges were used for harvests less than 20 working days. Again, an exception to this is the steel bridge and pole bridge incorporated into the aforementioned road network which was used for a duration of 25 days (Figure 19).

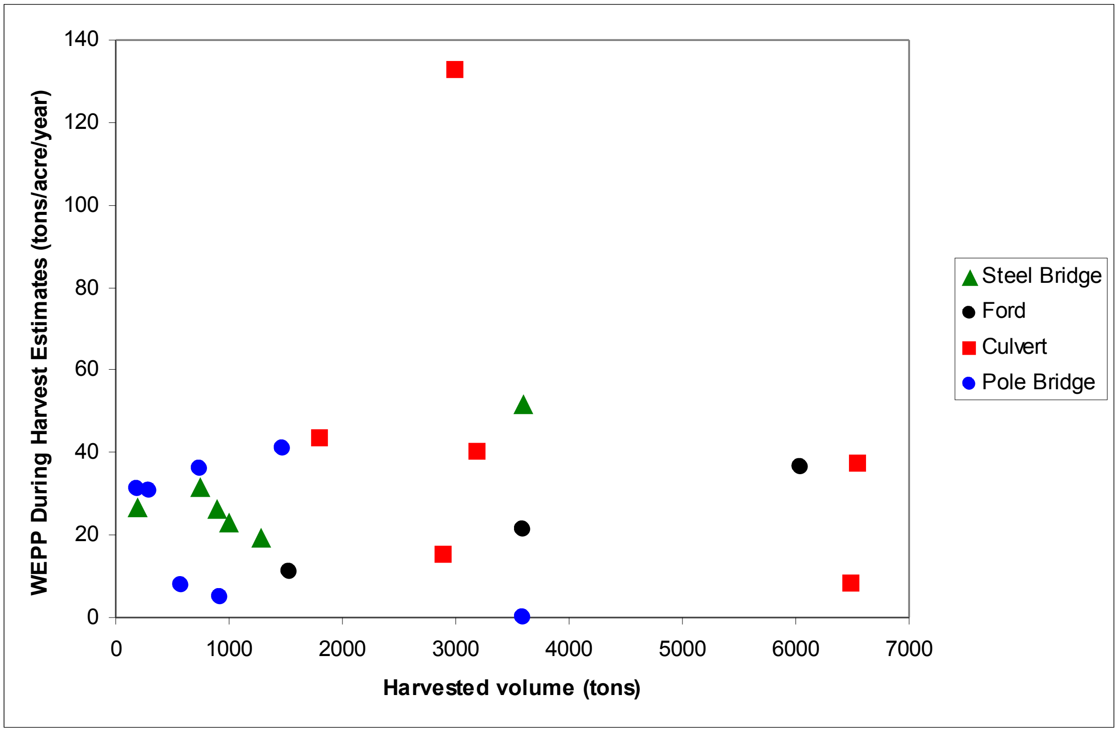

Figure 18. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to harvest volume of each study site.

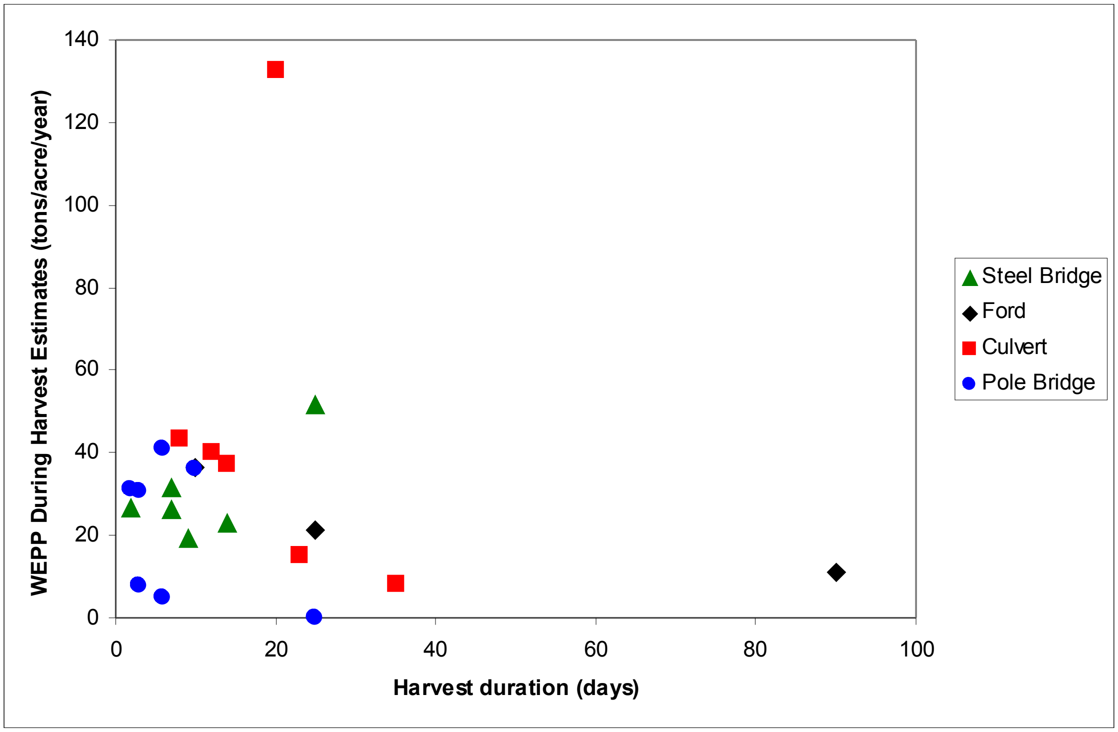

Figure 19. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to harvest duration of each study site.

Evaluation of WEPP erosion estimates for the approaches of stream crossings for the during harvest phase were significant and compared to watershed size to investigate any relationship between these factors (Figure 20). A positive or direct relationship is noticed; as watershed size increases so does the estimated erosion rate. A noticeable limitation of pole bridges is that they are used for harvests with much smaller watershed acreages than the other crossings. Watershed sizes for streams where pole bridges were installed were on average 23 acres (9 ha) with a maximum size of 87 acres (35 ha). All other crossings were used for an average size watershed of 100 acres (40 ha) or more.

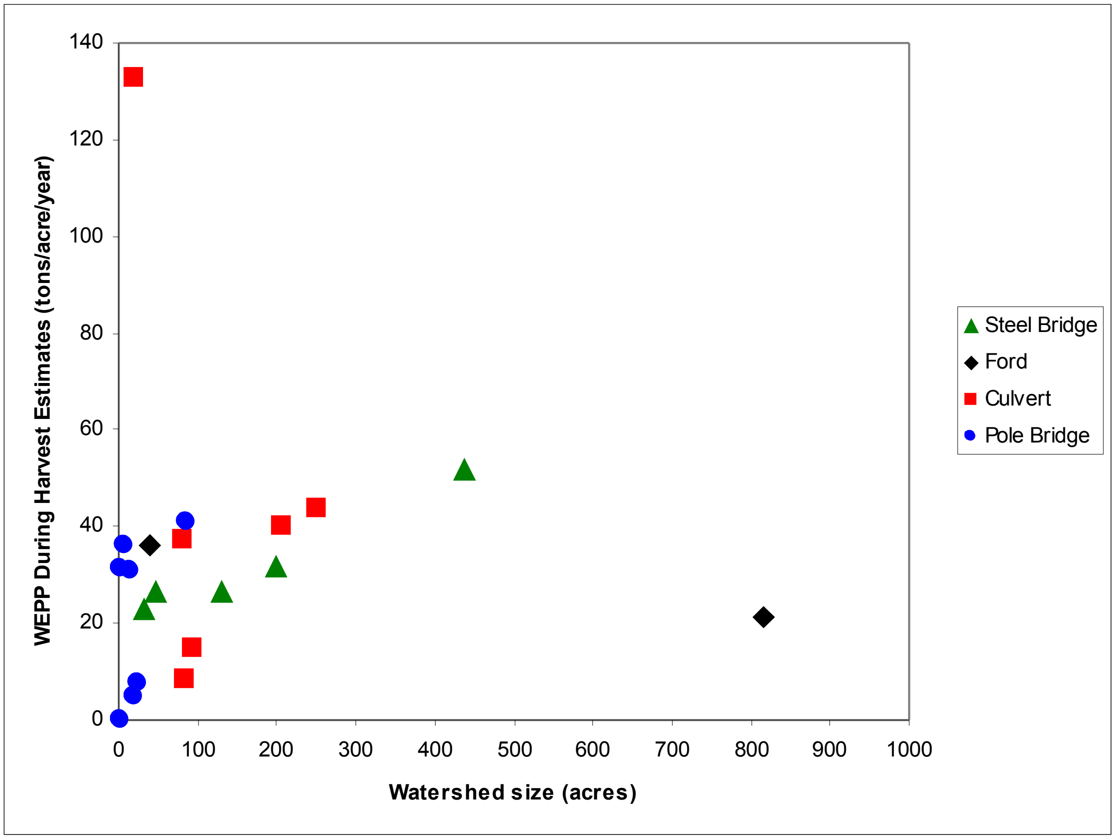

Figure 20. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the WEPP model compared to watershed size of each study site. Not shown are two fords and one steel bridge with watersheds exceeding 3,000 acres.

The USLE model estimates of erosion rates for the approaches of the different stream crossings for the during harvest were compared to harvest volume estimates of study sites (Figure 21). Again, steel bridges and pole bridges were mostly used for harvest volumes below 2,000 tons. Stream crossings supporting larger volumes of timber removed were culverts and fords. Also, harvest duration was compared to the significant USLE estimates during harvest (Figure 22). Longer harvesting activities depended more on culverts and fords to extract timber across streams, rather than steel bridges or pole bridges (Figure 22).

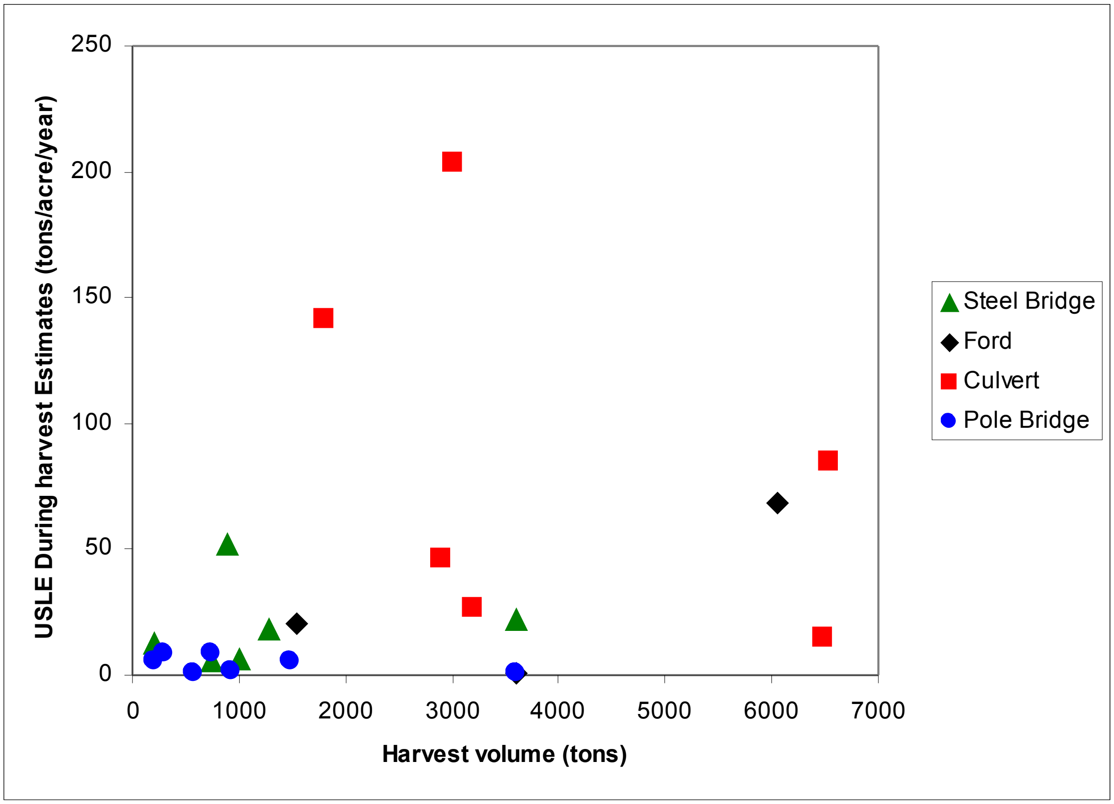

Figure 21. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to harvest volume of each study site.

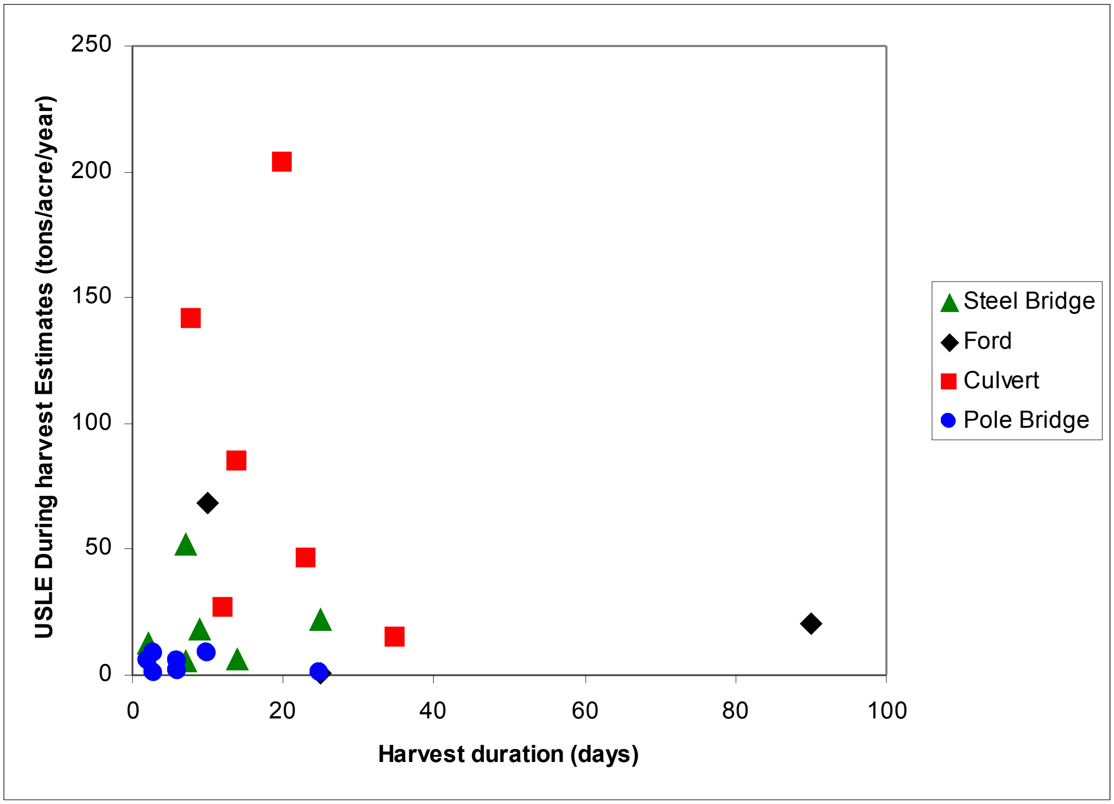

Figure 22. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to harvest duration of each study site.

To examine relationships of the USLE during harvest erosion estimates with site characteristics, erosion rates were compared to watershed acreage. Different watershed capacities for the stream crossings were realized in this comparison (Figure 23). There was a positive relationship between USLE during harvest erosion rates and watershed size. Limitations of pole bridges regarding stream flow restricted their use to watersheds less than 100 acres (41 ha), with the maximum being 87 acres (35 ha). Pole bridge approaches had lower erosion rates as estimated by USLE. Versatility of the steel bridge crossing displays its ability to be used for smaller watersheds (less than 100 acres) to streams with watersheds over 3,000 acres (1,214.6 ha) not displayed in Figure 23.

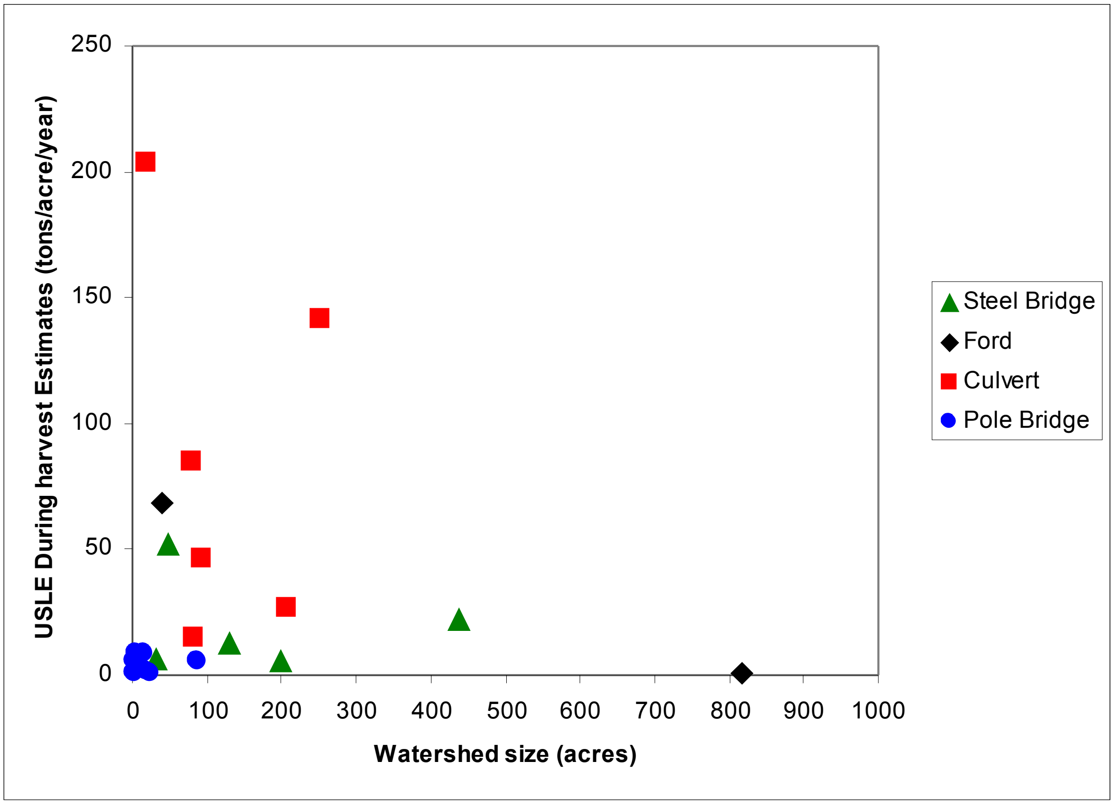

Figure 23. Mean values of the four stream crossing types at the during harvest sampling period as predicted by the USLE model compared to watershed size of each study site. Not shown are two fords and one steel bridge with watersheds exceeding 3,000 acres.

Stream Water Quality as Affected by Stream Crossing Type

Evaluation of the water quality indices measured at the various stream crossings indicated significant differences between the four types of stream crossings (Table 8). Total dissolved solids (TDS) (p = 0.031), pH (p = 0.000008), and conductivity (p = 0.030) were significantly different between the different types of stream crossings (Table 9). TDS levels associated with steel bridges resulted in significantly lower levels (79 ppm) than the culvert, ford, or pole bridge (272, 330, and 269 ppm; respectively). Stream pH values associated with pole bridges were significantly lower (6.53) and those associated with fords were significantly higher (7.47) than other types of crossings. The pH values of steel bridge crossings (6.938) and those of culvert crossings (6.943) did not show significant difference between the various stream crossings. Average water temperature was significantly different (p = 0.000012), but this is probably misleading since stream measurements were collected year round and some types of crossings were implemented more at a certain time of the year than others. Total suspended sediment (TSS) or sediment concentration between the crossings did not show significance between the four types of crossings (p = 0.77). Standard error values of water quality estimates show variability of each type of stream crossing mean (Table 10).

Table 8. P-values associated with response variables for each of the water quality indicators.

Response Variable	TDS (ppm)	pH	Conductivity (µS/cm)	Temperature (Fahrenheit)	TSS/Sediment (ppm)
Stream Crossing Type	0.031*	0.001*	0.030*	0.001*	0.768
Harvest Phase	0.062*	0.623	0.124	0.105	0.710
Stream Position	0.959	0.662	0.666	0.692	0.765

*Term significant at alpha = 0.10

Table 9. Mean values of the treatment response variable for each water quality parameter measured. Lower case letters indicate significance at the α = 0.10 level. ns = none significant.

Stream **Crossing Type**	**TDS** (p = 0.031)	**pH** (p = 0.001)	**Conductivity** (p = 0.030)	**Temperature** (p = 0.001)	**TSS/Sediment** (p = 0.768)
	ppm		**µS/cm**	**Fahrenheit (Celsius)**	**ppm**
Culverts	272.1 b	6.94 b	320.3 ab	69.6 (21) a	1256.0 ns
Fords	329.8 b	7.47 c	476.7 b	70.8 (22) a	271.0 ns
Pole Bridges	269.1 ab	6.53 a	391.1 b	57.8 (14) b	335.1 ns
Steel Bridges	78.6 a	6.94 b	114.6 a	62.5 (17) b	735.4 ns

Table 10. Standard error values of means of the treatment response variable for each water quality parameter measured, where n = sample size.

Stream Crossing Type	**TDS**	**pH**	**Conductivity**	**Temperature**	**TSS/Sediment**
	ppm		**µS/cm**	**Fahrenheit (Celsius)**	**ppm**
Culverts *n = 36*	60.39	0.09	81.18	1.73	662.90
Fords *n = 16*	90.58	0.14	121.76	2.59	994.35
Pole Bridges *n = 32*	64.05	0.10	86.10	1.83	703.11
Steel Bridges *n = 44*	54.62	0.08	73.43	1.56	599.61

The multiple comparison tests indicated that the mean TDS for the steel bridge crossing was significantly different from all the other crossings due to much lower levels

(78.63 ppm). TDS levels are presented as averages for the four different types of stream crossings across the entire timber harvest (Figure 24).

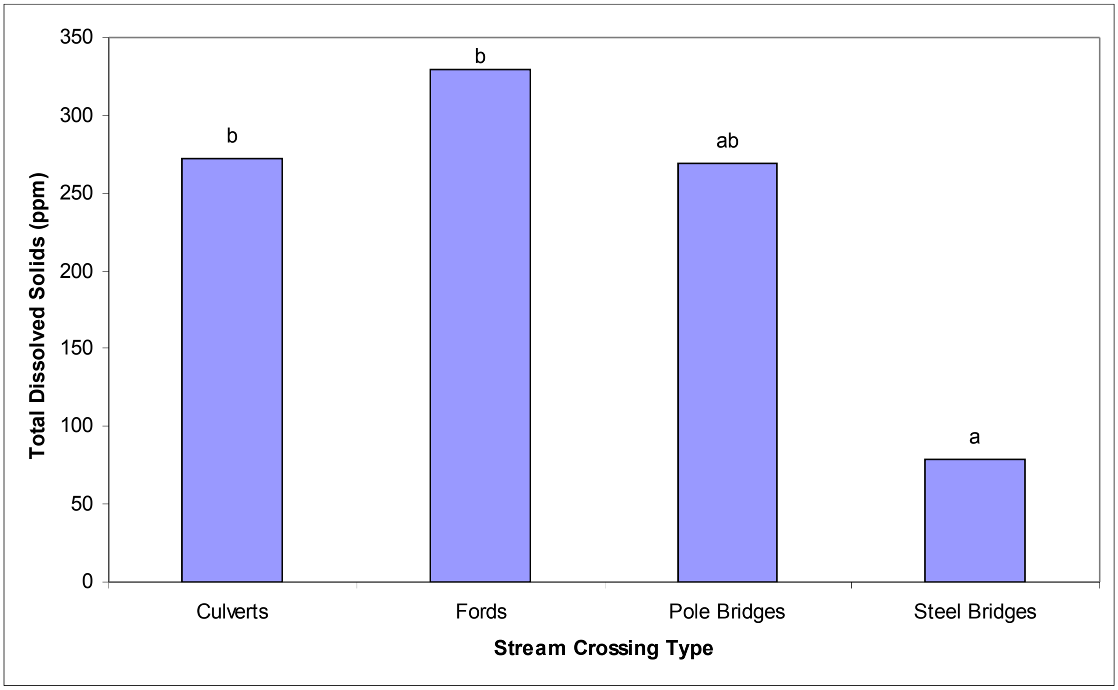

Figure 24. TDS (ppm) mean values for all four types of stream crossings. Lower case data labels indicate significance at the α = 0.10 level.

Mean pH values were determined significant among the four types of stream crossings through the multiple comparison test (Figure 25). Stream water pH associated with fords (pH = 7.47) and pole bridges (pH = 6.53) were significantly different from the other stream crossings studied (p = 0.001).

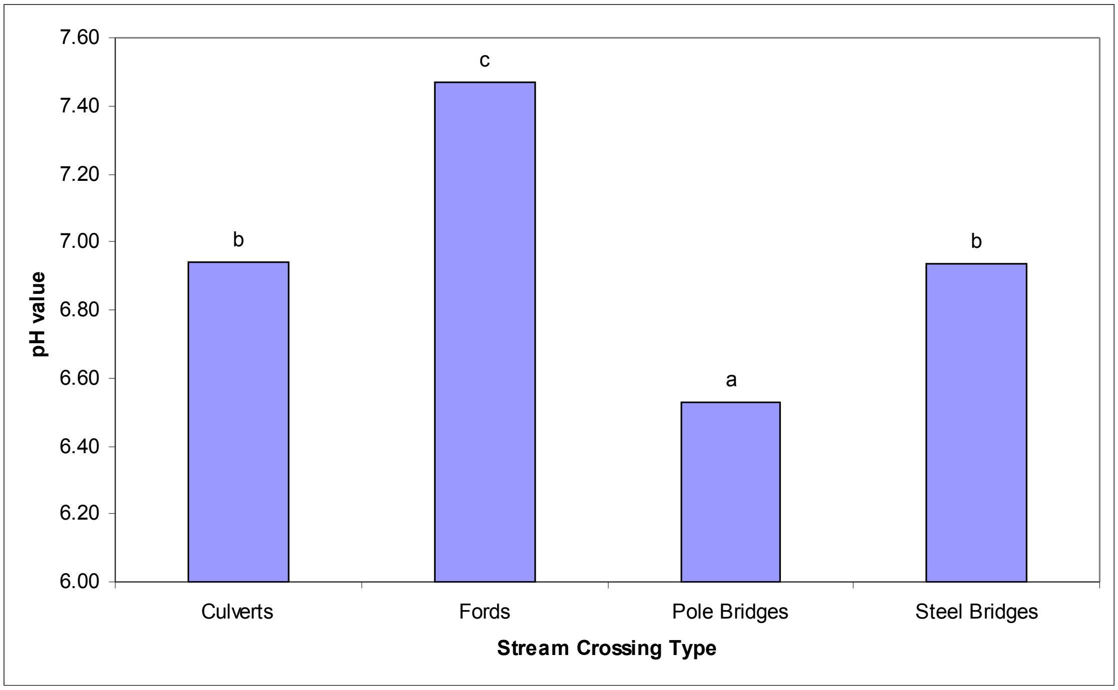

Figure 25. pH mean values for all four types of stream crossings. Lower case data labels indicate significance at the $\alpha = 0.10$ level.

Conductivity mean values for the stream crossing response variable were calculated over the entire harvest process (Figure 26). Units for conductivity are micro Siemens (S) per centimeter. Siemens is a unit used to measure electrical conductivity which is measured at a certain distance in water. Conductivity associated with steel bridge crossings was also significantly different ($p = 0.03$).

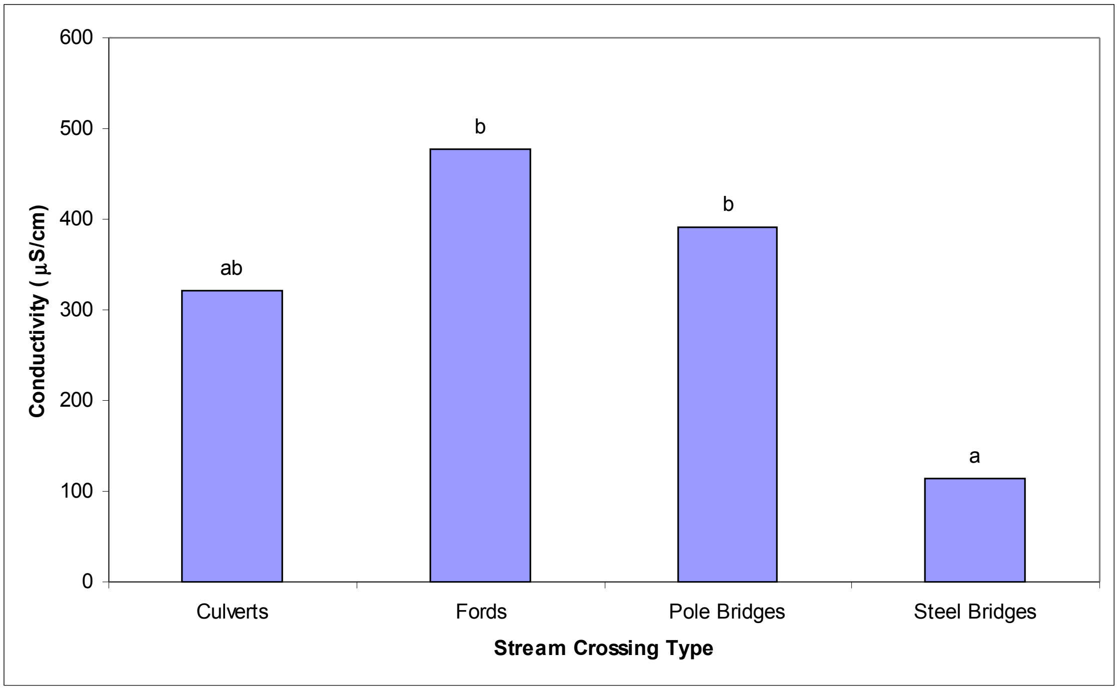

Figure 26. Conductivity (µS/cm) mean values for all four types of stream crossings. Lower case data labels indicate significance at the $\alpha = 0.10$ level.

TSS or sediment concentration mean values were calculated over the entire harvest process (Figure 27). The multiple comparison test showed no significant difference among the four types of stream crossings for this water quality indicator ($p = 0.77$).

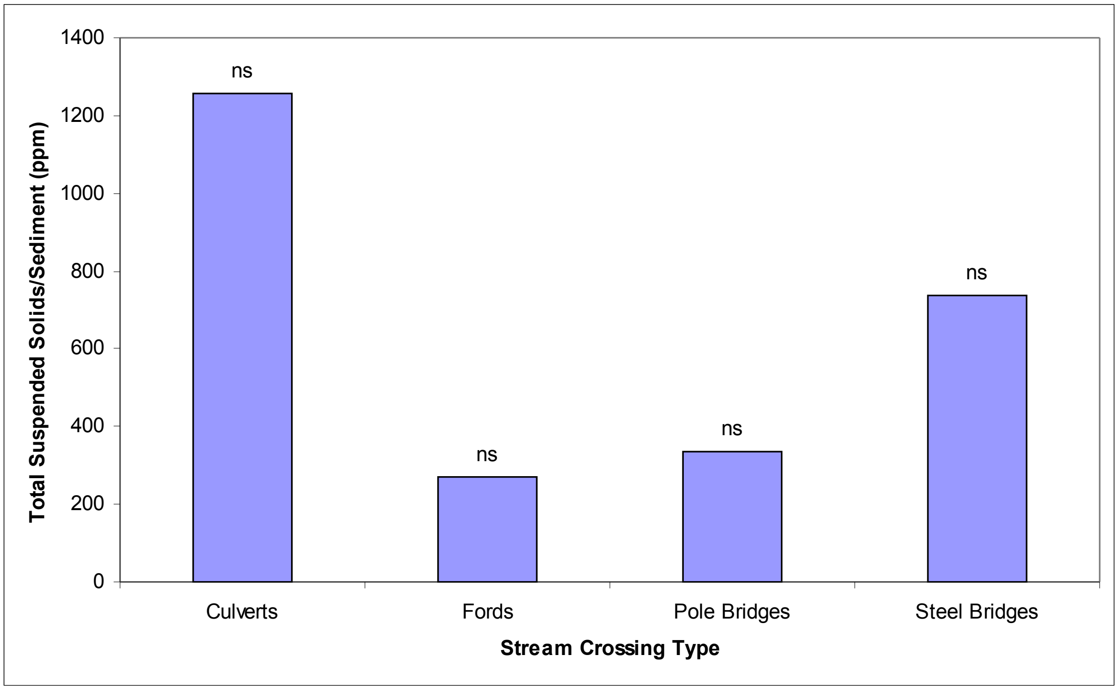

Figure 27. TSS (ppm) mean values for all four types of stream crossings.

Stream Water Quality as Affected by Harvest Phase

Evaluation of the water quality indicators measured at the various stream crossings indicated significant differences among harvest phases. TDS ($p = 0.062$) was the only indicator that showed significance among the different phases over the harvest schedule (Table 11). TDS levels before any harvesting activity (95.87 ppm) and those during harvest (254.40 ppm) were significant among the different phases of harvest. Mean values at the post installation/pre-harvest (245.07 ppm) and post-road closure (356.24 ppm) did not show significant differences between phases. Indicators deemed insignificant were pH ($p = 0.62$), conductivity ($p = 0.12$), average water temperature ($p = 0.105$), and TSS ($p = 0.71$). Standard error values of water quality estimates show variability of each phase of harvest mean (Table 12).

Table 11. Mean values of the harvest phase response variable for each water quality parameter measured. Lower case letters indicate significance at the α = 0.10 level. ns = none significant.

Harvest Phase	TDS (p = 0.062)	pH (p = 0.623)	Conductivity (p = 0.124)	Temperature (p = 0.105)	TSS/Sediment (p = 0.710)
	ppm		µS/cm	Fahrenheit (Celsius)	ppm
Pre-Reopening/ Pre-install.	95.9 a	6.90 ns	144.1 a	63.7 (18) a	658.5 ns
Post-install./ Pre-harvest	245.1 ab	7.05 ns	356.5 ab	68.5 (20) b	374.6 ns
During harvest	356.2 b	7.03 ns	439.1 b	66.6 (19) a	201.3 ns
Post-Road closure	252.4 ab	6.89 ns	362.8 ab	62.0 (17) b	1363.1 ns

Table 12. Standard error values of means of the harvest phase response variable for each water quality parameter measured, where n = sample size.

Harvest Phase	TDS	pH	Conductivity	Temperature	TSS/Sediment
	ppm		µS/cm	Fahrenheit	ppm
Pre-Reopening/ Pre-install. *n = 36*	60.4	0.09	81.2	1.7	662.9
Post-install./ Pre-harvest *n = 26*	71.1	0.11	95.5	2.0	780.0
During harvest *n = 32*	64.1	0.10	86.1	1.8	703.1
Post-Road closure *n = 34*	62.1	0.10	83.5	1.8	682.1

Mean values of TDS show differences for all phases of timber harvesting (Figure 28). The multiple comparison test showed significance of the pre-reopening/pre-installation phase (95.87 ppm) and the during harvest phase (252.40 ppm) among all four phases of the harvest process (p = 0.062). TDS levels are averages for the four different harvest phases with measurements from all four different types of stream crossings averaged into each phase. The four types of stream crossings are compared and TDS fluctuates over the entire harvest process (Figure 29).

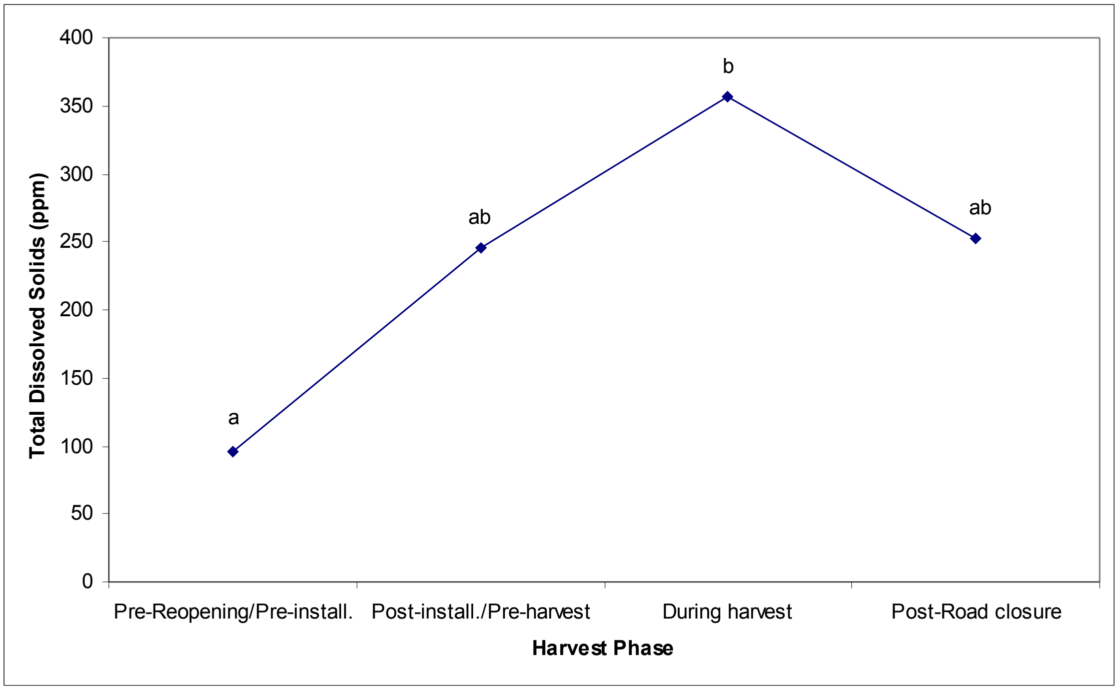

Figure 28. TDS (ppm) mean values over all phases of harvest. Lower case data labels indicate significance at the $\alpha = 0.10$ level.

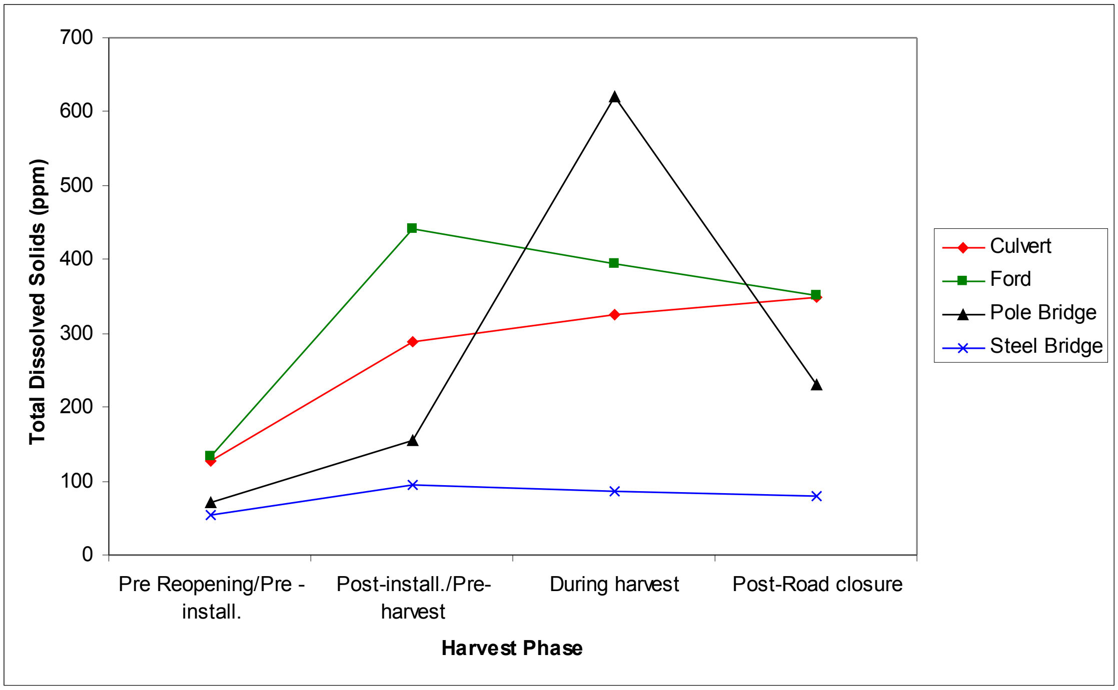

Figure 29. TDS (ppm) mean values for all treatments over all phases of harvest.

Differences among the four harvest phases are shown in Figure 30 for conductivity measurements (p = 0.12). Again, the significance observed for the harvest phase response variable of conductivity is comparable to those of TDS.

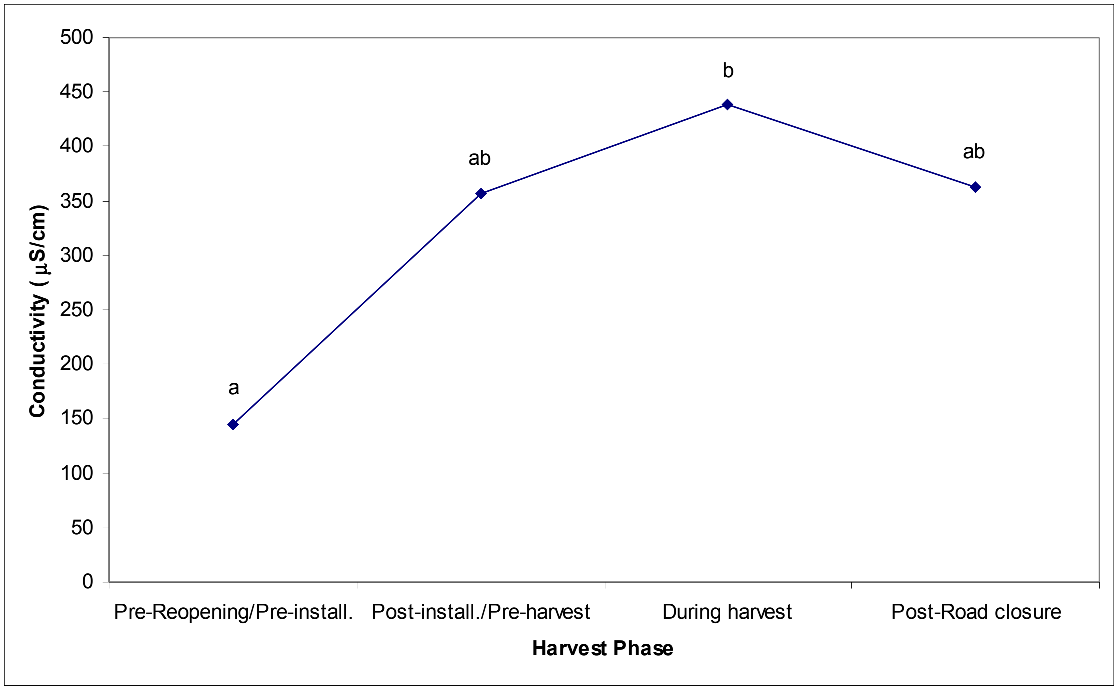

Figure 30. Conductivity (µS/cm) mean values over all phases of harvest. Lower case data labels indicate significance at the α = 0.10 level.

Also, no significant difference was realized for the four different harvest phases (Figure 31), but TSS levels did display an interesting trend. There was no significant difference proven for the stream position response variable.

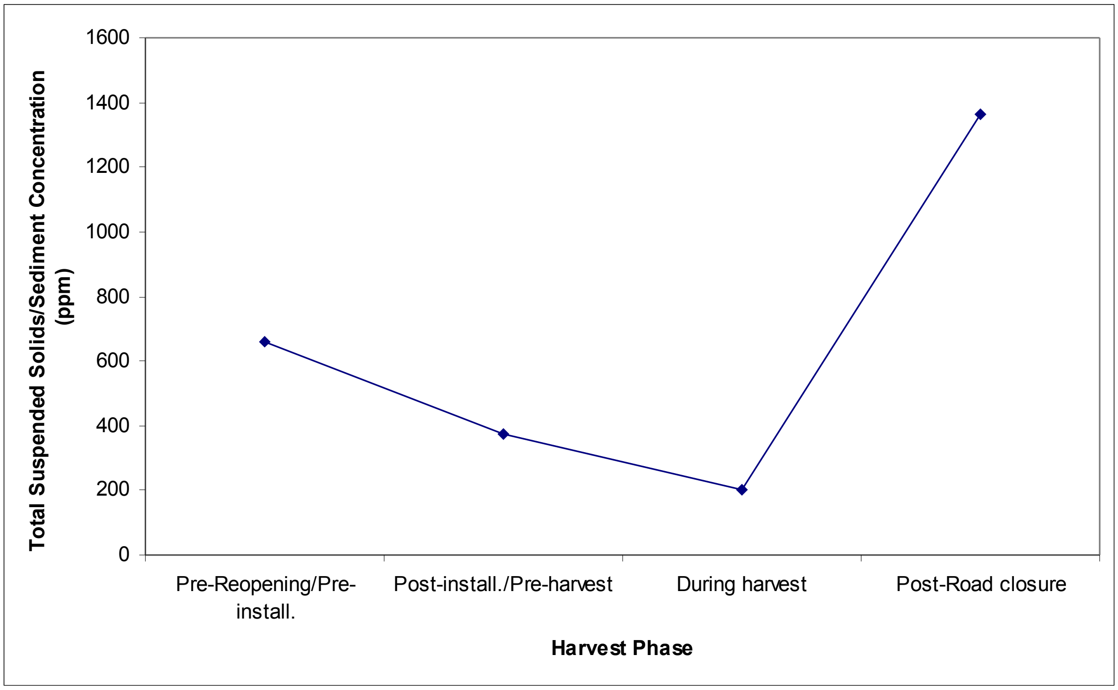

Figure 31. TSS (ppm) mean values over all phases of harvest.

DISCUSSION

The Erosion Estimates for the Stream Crossing Approaches and Harvest Phase

WEPP Erosion Estimates

Failure to detect differences in erosion estimates between treatments prior to installation of the crossings indicated that the subsequent treatments were being installed on relatively similar sites. This outcome can be expected due to low disturbance before any construction or harvesting activities have begun. Ground cover during this stage was typical leaf litter and ground duff on the forest floor for new crossing installations. For new crossing study sites the road management was classified as “forest” to reflect normal forest conditions in the model (Figure 32). Cover percentages/natural vegetation percentages were greater at this phase of harvest due to minimal disturbance which impact the amount of erosion potential (Figure 8). Previously used crossings had not been disturbed since closeout from earlier activity. These crossings received road management classifications such as “cut slope” or “road bladed forest” to represent conditions from previous construction, and thus yielded higher estimates at the pre-reopening/pre-installation phase.

Each of the four types of stream crossings had at least one crossing that was installed with pre-existing road conditions. One-half of the ford study sites were used for farming practices and existed before timber harvesting activities. These pre-existing conditions probably contributed to the higher levels of estimated erosion rates at the pre-reopening/pre-installation phase (Table 2). Also, the reopening of these pre-existing stream crossings involved loads of gravel being applied for timber harvesting. This action may have explained the overall decrease of estimated erosion of approaches for some types of crossings from the pre-reopening/pre-installation phase to the post-installation/pre-harvest phase. This was especially true for the pre-existing ford stream crossings.

Figure 32. Before-installation phase with a flagged grade line for an approach to a new culvert crossing.

Collection of data for WEPP erosion estimates at the post-installation/pre-harvest phase was limited due to a few circumstances. Some crossings were pre-existing in relation to data collection, thus measurements used to estimate erosion using the WEPP and USLE models were not taken at this phase for some locations. Another contribution to missing data was due to the immediate use of stream crossings after installation. This was not an issue with permanent crossings (i.e. culverts and fords), but some temporary crossings (i.e. pole bridges and steel bridges) were quickly installed often in an hour or less and used immediately following installation. No significant differences of WEPP erosion estimates among crossings for this phase of harvest may have been due to the small and uneven sample size of data collected for each of the stream crossings.

Several factors influenced the WEPP mean erosion estimates and their significance among treatments for the during harvest phase. Approaches associated with culvert crossings posed the biggest threat of erosion with a mean value of 46.2 tons/acre/year (103 tonnes/ha/year). Field observation and evaluation showed that the WEPP model projected a large amount of annual soil loss on approaches due to cover management practices and slope grade and length. Several approaches at culvert crossings had excessive slope lengths (greater than 300 feet or 91 m). This is displayed in Figure 6 where a positive relationship exists between WEPP erosion rates and slope length. Also, cover management practices at some of these crossings did not have much added or natural cover (Figure 8). Absence of rock or gravel, except within the SMZ where the stream crossings were installed, caused higher potential for erosion (Figure 33). This absence of gravel causes a higher percentage of exposed bare soil (Figure 7) which was evident at some study locations (Figure 34).

Previous studies supported the need for gravel on road approaches to limit soil loss. In a study by Swift (1985) soil loss from a graveled roadbed was only 3 to 8% of a bare soil roadbed. Both of the roads studied were of similar construction with application of gravel being the main difference. Swift (1984) reported sediment loss for an un-graveled road of 310 tons/km and 38 tons/km for a graveled road. Kochenderfer and Helvey (1987) also documented sediment losses of 225 tons/km and 80 tons/km for ungraveled and graveled roads, respectively.

The lower mean erosion estimates at ford approaches were due to emphasis on more gentle slope grades and shorter slope lengths (Figure 6). Road approaches associated with pole bridge crossings had lower mean erosion estimates, which can be attributed to the terrain and type of stream that they are utilized on. Waterways that were suitable for pole bridges were ephemeral or intermittent streams that had more gentle approaches and smaller watersheds (Figure 20).

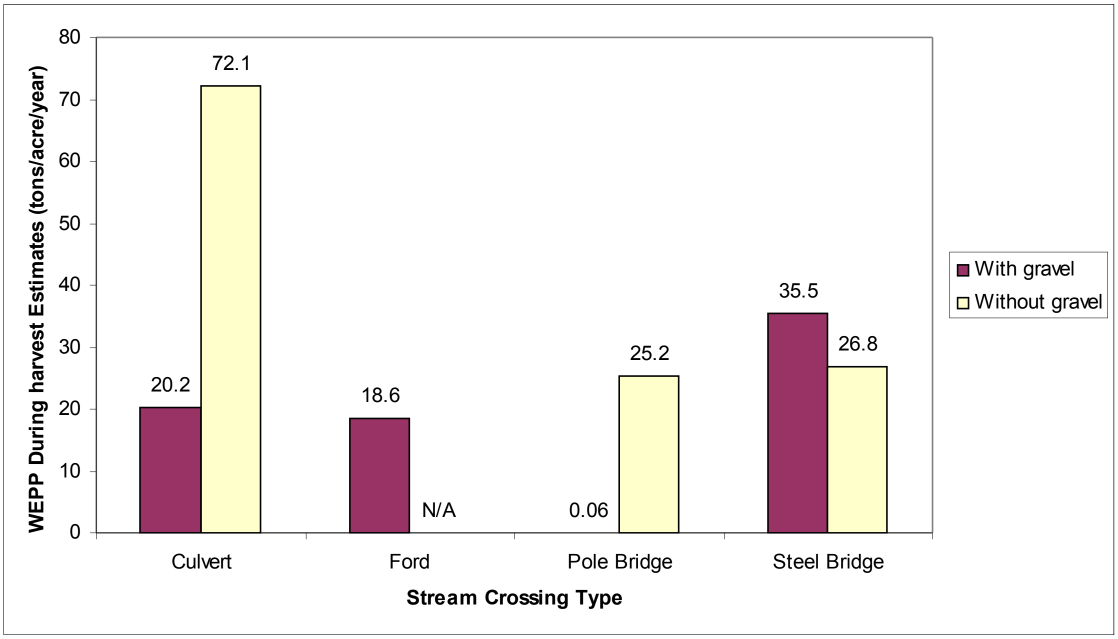

Figure 33. WEPP during harvest estimated erosion rates showing the differences in erosion rates for gravel/rock application to road approaches for each of the four types of stream crossings.


Figure 34. During harvest phase at crossing previously shown in Figure 32.

After harvest activities included implementing BMPs and reestablishing vegetation. Most stream crossing approaches decreased in WEPP erosion potential from the during harvest phase to the post-road closure phase with the exception of the ford stream crossing, which only slightly increased (Table 2). This showed the effectiveness of implementing cover management practices and installation of water control structures regardless of the type of crossing used. Not all measurements for this phase of harvest were able to be included in the statistical analysis. One ford stream crossing site was still currently being used and the after harvest data was not available until after road closure.

USLE Erosion Estimates

All stream crossings showed low erosion potential, less than 4 tons/acre/year (9 tonnes/ha/year) (Table 4). These mean estimates were lower than what the WEPP model predicted for the before installation phase. Again, minimal disturbance and conditions before silvicultural activities revealed normal levels, less than 5 tons/acre/year (11 tonnes/ha/year), of annual soil loss potential.

Post-installation/pre-harvest data recorded for this phase of harvest were limited due to factors already discussed. This limited amount of data affected the Tukey-Kramer multiple comparison test. This type of multiple comparison test is designed for unbalanced replications among treatments, but was too conservative for this phase of harvest. Multiple comparison test results would not show a significant difference among crossings due to too large of a difference among sample sizes. Pole bridge stream crossings had approaches with the lowest mean value due to the topography and stream order of these crossing locations. Culvert approaches and steel bridge approaches had the highest potential for erosion. Longer approaches and steeper grades were associated with these types of crossings due to the limitations of the fords and pole bridges. Although steel bridges are temporary stream crossings, they are often used for log truck traffic at wider streams due to minimal construction. However, these steel bridges are often not rated for log truck traffic and may not be designed by professional engineers.

USLE mean erosion estimates displayed a significant difference among stream crossing approaches during harvest. Culvert crossing approaches displayed the highest erosion potential with a mean of 85.8 tons/acre/year (192.2 tonnes/ha/year). The Tukey-Kramer multiple-comparison test showed that culvert treatments differed from all other stream crossing types. Approaches associated with pole bridge crossings maintained a low potential of erosion with a mean value of 4.5 tons/acre/year (10.1 tonnes/ha/year). Slope length (Figure 10) and cover management relationships with the USLE model helped to explain the erosion rate differences among approaches for the four types of stream crossings. Long slopes tended to produce more annual soil loss.

Residual natural vegetation had an inverse relationship with erosion estimates from the USLE model (Figure 12). More natural vegetation remains along temporary road systems such as skid trails where mostly pole bridges and steel bridges were used which produced lower erosion rates than areas with less residual natural vegetation. Another aspect of cover management is to examine the amount of bare soil on approaches to stream crossings. A higher percentage of bare soil on a road approach will reflect higher estimates of erosion (Figure 11). Culvert and ford approaches found on permanent roads often require more work and can attribute to the amount of bare soil.

Road closure requirements impacted the mean USLE mean erosion estimates. Approaches to stream crossing erosion means decreased from the during harvest phase to the after harvest phase with the exception of road approaches associated with pole bridge crossings (Table 3). Possible explanations of this increase for pole bridge approaches from 4.5 tons/acre/year (10.1 tonnes/ha/year) during harvest to 10.3 tons/acre/year (23.1 tonnes/ha/year) after harvest were increases in bare ground and removal of natural vegetation. Often loggers will remove “rub” trees which are commonly used to change the direction of a skidder’s load of timber to minimize stream channel contact. This removal of trees adjacent to the approach decreases the amount of cover. Upon removal of pole bridge crossings, the logs and pipe used in the stream channel will pull existing slash and cover material away from the approaches of these crossings. Again, the result is less natural vegetation and ground cover which cause an increase in erosion potential. Additional gravel application as well as installation of silt fence, straw bales, and water control structures can minimize the potential for erosion upon road closure.

Erosion Estimates and Models Used

Before any activity or establishment of stream crossings, erosion estimates were lower than other phases in the harvesting schedule. However, two of the ford crossings were previously used and located on existing road systems. The WEPP model had some limitations in cover management options available for hillslope projects. These ford locations were in a forest buffer area on existing cut slopes. In the WEPP model, if the "forest buffer" option in the cover management input was selected the estimate would be zero tons/acre/year soil loss. This estimate was not practical since the stream crossing is bisecting the SMZ. Some modifications may be available to change the cover management regimes in a programming manner, but that was outside of the objectives of this study. USLE data collection and input requires more information regarding bare ground and vegetation cover in the approach area. Pre-reopening/pre-installation estimates require more consideration of cover and bare ground percentage. The USLE model considers more of these factors in the equation and data collection and showed estimates lower than the WEPP model for this phase.

Road approaches change drastically after a stream crossing has been installed and the remainder of the road has been graded and stabilized. The most notable change is removal of natural vegetation and ground cover. These activities reduce the percentage of ground cover along the road approaches and cause several changes in soil behavior in these areas. Natural vegetation has the ability to provide infiltration of water during and following storm events. An inverse relationship exists; infiltration rates decrease as the loss of natural vegetation increase. When precipitation is unable to infiltrate, it gains velocity and leads to runoff issues. Numerous studies have proven that at least 90% of non-point source pollution is caused by construction of road systems and landing areas for timber harvesting activities (Walbridge 1990). Compaction issues also impact the amount of erosion potential which will occur. After removing the necessary vegetation, road construction crews and contractors must stabilize the road through soil compaction. An increase in soil compaction reduces the ability of precipitation from storm events to infiltrate into the ground.

Both models accounted for the changes which occur in road installation. However, USLE did not show as large of an increase for pole bridges and ford treatments as did WEPP. Possibly, the USLE model could not adequately account for the road template installed in an accurate manner. An increase in soil loss was noted for steel bridge and culvert treatments where steeper and longer slopes were found. Also, USLE estimates likely account for cover which is present on short approaches that are closer to the stream buffer. The more sophisticated WEPP model allows more complete characterization of road approaches. WEPP programming efforts can also reflect specific site cover management conditions on road approaches. However, for this study cover management types which were already installed in the WEPP program, Forest Roads version were used to predict soil loss for road approaches.

During harvest activity showed a significant difference between stream crossings for both models used. Also, both the WEPP and USLE models recognized culvert treatments and their approaches as a significantly different group. This recognition is likely attributed to long approaches (Figure 10), steep grades, and soil displacement from installation that were present at some culvert study locations.

Another factor that may have influenced the separation of treatment groups was the absence of cover, in this instance gravel, at road approaches. WEPP has a cover management option, which allows a road approach to include or exclude the application of gravel. USLE can account for gravel cover in the C factor evaluation by estimating percent bare soil. Increased erosion potential levels from both models were anticipated due to several factors. Removal of vegetation has already occurred before this phase, which already has increased the estimate levels. Timber harvesting activities are at a peak and truck and skidder use of these approaches cause more exposed soil and absence of additional vegetation. It is likely that an increased percentage of bare soil caused increased estimates in erosion potential by both models in general. Exceptions to this typical increase were the pole bridge approaches as estimated by the WEPP model and the steel bridge approaches as estimated by USLE. These exceptions can be explained by BMPs being implemented during harvest operations. Practices such as applying additional slash and debris to approaches were likely measures that caused erosion estimates to decrease for these types of crossings. Adding slash and logging debris to approaches and skid trails was typically associated with temporary stream crossing areas being used by skidders and not trucks. Modifications to the slope length also may have impacted these slight decreases.

Road closure and BMPs implemented on the approaches of the stream crossing sites appeared to impact the erosion potential. Both USLE and WEPP models predicted that pole bridges had the lowest erosion potential after road closure. However, the USLE model indicated an increase in erosion potential for pole bridges from the during harvest phase to the after harvest phase by approximately 6 tons/acre/year (13.4 tonnes/ha/year). It is likely that removal of vegetation near the SMZ caused this increase. WEPP model estimates indicated a decrease in erosion potential, except for a slight increase (approximately one ton/acre/year) of ford approaches. Compaction of gravel on the approaches of these crossings has a tendency to occur with more traffic which can increase erosion potential. The use of BMPs aims to return sites to the condition prior to forest management activities. Only the WEPP model indicated that the ford crossings were restored to erosion potential levels at the pre-reopening/pre-installation phase. Some ford crossings in the study were existing crossings which could impact the model's similar estimate of erosion potential at the pre-reopening/pre-installation phase and the post-road closure phase.

WEPP model estimates showed a closer range of erosion potential values of treatments among the four different harvest phases. However, the program authors indicate that WEPP has a tendency to overestimate average soil loss when hillslope lengths are longer than 150-300 feet (50-100 meters). This limitation should be considered since many slope lengths in this study exceeded that threshold. A wider range of erosion estimates is noticed with longer slopes during the harvest (Figure 6). Another limitation of this model was the cover management options. Gravel covered road options were limited to only one choice of gravel depth for each soil texture. Realistically, several different depths of gravel can be applied to approaches to minimize soil loss and erosion. As previously mentioned there are options to program specific cover management options into WEPP, but additional pre-programmed options would create an even more user-friendly version of this program.

Management Decisions for Stream Crossings

This study indicates that there are differences in water quality impacts regarding the types of crossings chosen for the forest management needs. Culvert and ford crossings on Class II-III haul roads were used to haul mean volumes of 3,989 tons (3,619 tonnes) and 3,861 tons (3,503 tonnes) of timber, respectively (Table 6). The steel bridge and pole bridge crossings were used on temporary roads or skid trails where lower volumes were being harvested. Steel bridge crossings supported an estimated mean value of 1,288 tons (1,168 tonnes). Pole bridge crossings were used for an estimated mean value of 1,119 tons (1,015 tonnes) (Table 6). Data collected for mean volume estimates included a variety of management practices such as clearcut and thinning harvests. These harvests included types of merchantable wood such as pulpwood, sawtimber, chips, and chip and saw.

Ford and culvert crossings were used as permanent road crossings for log truck traffic. The pole bridge and steel bridge crossings were mostly used for skidder traffic and as temporary crossings for an average duration of eight days and eleven days, respectively. These temporary types of crossings were used for a maximum of 25 days as a truck crossing in the same road network for a large timber harvest. The culvert and ford crossings averaged 19 days and 42 days of use respectively. This difference is an average of one week or more of use. Also, the temporary crossings were used to extract less than half of the average volume, which the permanent crossings were used for. The differences in stream crossing construction and road preparation were reflected in the duration and amount of timber that was extracted from the study locations. Also, the portability and ease of installation of the pole bridges and steel bridges lends them to temporary use. For instance, the minimum each of these crossings experienced was two days. From field observations, a properly constructed ford or culvert stream crossing requires more than two days for installation and grading of approaches. Cost analysis of these stream crossings is certainly a consideration when management decisions are made. Although no strong relationships or correlations were evident between stream crossing use (harvest volume or duration) and erosion estimates for either model, the variety of stream crossings installed was noticed to handle certain levels of timber harvesting activities. Although, all four types of crossings studied are suitable as temporary crossings, fords and culverts are often established as permanent stream crossings. Managers should be aware of the different standards of permanent crossings if used in place of temporary crossings.

Stream Water Quality as Affected by Stream Crossing Type

TDS

Steel bridge crossings showed significantly lower TDS levels than all other types of crossings (Figure 24). Steel bridges were used as temporary crossings mostly for skidder traffic during this study. Rapid road construction often did not involve excavators or bulldozers, which are required for permanent stream crossings. Also, steel bridge installation required minimal excavation or activity in the stream (Figure 35). Typical installation was done by a grapple skidder operator pushing the panels with the blade to the opposite side of the stream bank. This allows the machine to cross the stream without directly contacting the streambed. After the skidder has crossed the panels, the operator uses the grapple to pick up and position the panels so they are close together and properly overlap onto the approach. To minimize limbs and slash extending over the edge of the bridges, some panels had a raised metal lip welded on or poles placed on the side (Figure 36).

Figure 35. Steel bridge installation by a skidder. This particular set of bridges is 40 feet long and consists of three panels.

Figure 36. Steel bridge panels with poles on the side during harvest.

Ford stream crossings had the highest mean TDS value for all types of crossings over the harvest process. This can be attributed to the direct contact with the stream by trucks used to transport timber. Also, material from the actual ford, such as limestone gravel, can contribute calcium deposits directly to streams. Culvert treatments showed the second highest mean TDS value over the harvest process. Through the multiple comparison test, culverts and fords were significantly different from steel bridge crossings.

Conductivity

This measurement is very closely related to TDS measurements and can be converted to reflect TDS (ppm). Electrical conductivity reflected the dissolved particles present in streams and how easily electricity could be conducted through those particles.

The similarity in conductivity and TDS is realized in the statistical analysis of this study. The Tukey-Kramer multiple comparison test resulted in steel bridge treatments being grouped alone and pole bridge and ford treatments being grouped together. Culvert treatments did not fall within either group specified by the analysis (Table 6). Results from the TDS analysis reflected similar results by categorizing steel bridges alone and all other treatments together.

Stream pH

The only response variable which was significant for stream pH was the stream crossing type ($p = 0.000008$). The Tukey-Kramer multiple comparison test showed significant groups being the ford treatment and the pole bridge treatment at the $\alpha = 0.10$ level.

Ford treatments had a mean stream pH value of 7.5 which was significantly greater than the pH values ($p = 0.001$) for all of the other crossings. This relative difference was detected during all phases and can be explained by the application of limestone gravel to the re-enforced fords during installation (Figure 37).

Figure 37. Applying limestone gravel (size #57) to a ford re-enforced with GeoWeb and geotextile.

Pole bridge treatments were found to have significantly lower stream pH values and different from all other crossings (p = 0.0001). This acidic level of pH value of 6.5 may be attributed to several factors. Pipe components (steel, rust, etc.) may add to the acidity of the stream crossing area. Also, the addition of poles, incidental addition of limbs and foliage and associated organic acids and tannins may lower the pH of the streams being disturbed (Figure 38). Another aspect to keep in mind is the type of streams which these crossings were used in. Ephemeral and intermittent streams may contain more course woody debris and leaf litter compared to faster moving perennial streams.

Figure 38. Pole bridge installed with pipe and white oak poles in an intermittent stream.

Steel bridge and culvert crossing pH measurements were grouped together by the multiple-comparison test and significantly different from either the ford and pole bridge crossings. Steel bridge crossings had a mean value of 6.94 and the culvert crossings had a value of 6.94. Hassler et al. (1990) sampled stream water quality during installation of a portable stress-laminated bridge in West Virginia. Results indicated no significant changes in pH over the installation process (Hassler et al. 1990). Similar and nearly neutral pH values for these two types of crossings can be attributed to the lack of material deposited into the stream and deep stream channels. Our study reported nearly neutral pH values for portable steel bridge crossings similar to previous studies.

TSS/Sediment Concentration

There were no significant differences for suspended solids for any of the response variables. However, some interesting results were found. Culvert treatments had the highest sediment concentration with a mean value of 1256 ppm. Also, the phase of harvest with the highest mean value was the after harvest phase. Culvert crossings continue to deposit fill material after timber harvesting activity has occurred. Interestingly, ford crossings had the lowest mean value of 271 ppm. This may be a result from samples not taken directly during use of the stream crossings. Ford crossings have a tendency to show peak levels of TSS approximately ten minutes following vehicle use, but begin to decrease afterwards to normal levels at distances of 20 meters downstream from the crossing (Thompson et al. 1996). Sampling during the harvest phase may not reflect elevated levels of TDS due to low production crews infrequently using the ford stream crossings. No sampling for this study was able to occur directly after use of fords due to irregular work hours of contractors.

Stream Water Quality as Affected by Harvest Phase

TDS

The four harvest phases had significantly different TDS means ($p = 0.06$). Pre-reopening/pre-installation values should be expected to be less than the other harvest phases due to presence of natural vegetation and little or no site disturbance before construction or excavation. As expected, during harvest levels were higher than those at the post-installation/pre-harvest phase. For all stream crossings, the during harvest phase was significant along with the pre-reopening/pre-installation phase (Figure 28). Timber harvesting traffic and activity was at its peak during this phase, explaining this significant increase. Mean TDS levels returned to levels near the post-installation/pre-harvest phase at the post-road closure phase (Figure 28). This indicates that BMPs are being applied to the study sites in an effective manner.

An increase of TDS averages occurred from the pre-reopening/pre-installation phase to the post-installation/pre-harvest phase. A study by Tornatore (1995) reported downstream sediment concentration near 1,000 mg/L during the installation of a portable steel bridge. These concentrations returned to levels of no consequence within 24 hours following installation (Tornatore 1995). A study of two portable glue-laminated timber bridges, showed no significant sediment production during the installation process (Thompson et al. 1995). The minimal impacts from the study by Thompson et al. (1995) were due to no equipment operation directly in the streams. During harvests TDS levels of our study decreased compared to post-installation/pre-harvest phase levels for portable steel bridges (Figure 29). The same study by Tornatore (1995) reported that median sediment concentrations were 2.0 and 13.5 mg/L, respectively, during skidding operations. These findings by Tornatore are similar to the decrease in sediment noticed after installation, during use.

Pole bridge treatments resulted in the highest mean TDS levels in the during harvest phase (Figure 29). However, this stream crossing treatment proved to have the second lowest average over the *entire* harvest process. Tornatore (1995) reported median increase in downstream sediment concentration was 412 mg/L, with peak concentrations above 1,000 mg/L in a study of a culvert with log fill. Contrary to this study, Tornatore (1995) had significant increases in downstream sediment concentrations. Only the steel bridge crossing had a mean value less than the pole bridge over the entire harvest process.

The pole bridge TDS levels occurred for a few reasons at the during harvest phase. Pipe installation was not permanent; therefore the pipe was not bedded solid in the stream channel. When a skidder crossed the pipe it would shift due to the machine and the load it was carrying causing soil to be rubbed off of the streambank and logs used as fill. Also, limbs and trees being transported across the pole bridge stream crossings would pull soil, foliage, and limbs from the approaches to the stream.

Ford crossing TDS levels were not highest during the harvest, but at the post-installation/pre-harvest phase. These TDS levels decreased with time after installation occurred. Tornatore (1995) collected water samples before, during, and after installation of a gravel ford and found no significant differences between upstream and downstream sediment concentrations for any of the previously mentioned time periods. Thompson and Kyker-Snoman (1989) examined skidding activities on an unmitigated ford, which demonstrated large but insignificant increases in turbidity levels directly downstream. Compared to the previously mentioned studies, post-road closure TDS levels returned to the levels less than those found at the post-installation/pre-harvest phase. An explanation for this can be attributed to frequency of direct contact with the stream. Following the post-installation/pre-harvest phase TDS levels were the highest due to direct disturbance during installation and construction. During the harvest TDS levels slightly decreased as log truck frequency was not as high as equipment used for stream crossing installation. These levels continued to decrease after harvest was complete due to very limited traffic and application of BMPs.

Culvert TDS levels showed an increase during the entire process. The most notable increase was noticed between the pre-reopening/pre-installation phase to the post-installation/pre-harvest phase. It is likely that construction and deposits of fill material caused this trend as evident in previous studies. Thompson et al. (1995) collected water samples downstream during a culvert installation to show mean sediment concentrations of 344 mg/L higher than upstream samples. Our study showed the highest average TDS levels were noticed at the post-road closure phase. This may be due to continued deposition of fill material in the event that germination was delayed of grass seed applied during BMP work due to lack of precipitation.

Conductivity

Although not significant, a difference of conductivity mean levels was realized for the harvest phase response variable through the Tukey-Kramer multiple comparison test (p = 0.12). Before installation and during harvest phases of the harvest process were found significant for the TDS water quality indicator. The same reasons apply to conductivity for why this difference was found. Minimal disturbance has taken place at the pre-reopening/pre-installation phase and during harvest involves the most amount of traffic and use of the stream crossings. Conductivity and TDS mean values were not identical due to a conversion factor but did show similar differences through the Tukey-Kramer multiple comparison test.

Stream pH

The peak mean pH level of the ford crossings was after the installation of the crossing, before harvest (Figure 41). Significant increases in pH, specific conductance, alkalinity, and calcium concentrations in runoff from two forest roads on the Fernow

Experimental Forest were found in a study by Helvey and Kochenderfer (1987). The application of limestone gravel is a probable explanation for the higher pH average of the fords compared to other crossings, which do not have gravel applied directly to the stream. Helvey and Kochenderfer (1987) did not think applying limestone gravel to logging roads would have a noticeable influence on the water chemistry of a perennial stream. However, the study mentioned did not observe application of limestone gravel directly to stream crossings incorporated into road systems. An initial assumption would be to think that using limestone gravel can increase stream pH. However, this positive change in pH would only be temporary as the limestone becomes attached to iron and aluminum hydroxide and causing a much slower release of calcium and magnesium carbonates (Pearson and McDonnell 1974). Our study supports this trend as the ford mean pH levels decrease following the post-installation/pre-harvest phase (Figure 39). Pole bridge mean pH values showed a different trend throughout the harvest process; pH levels peaked at the during harvest phase due to organic acids deposited by harvesting activities. An immediate decrease in pH values were not noticed following road closure due to the lower flow rates typical of the ephemeral and intermittent stream, which were suitable for pole bridge installation.

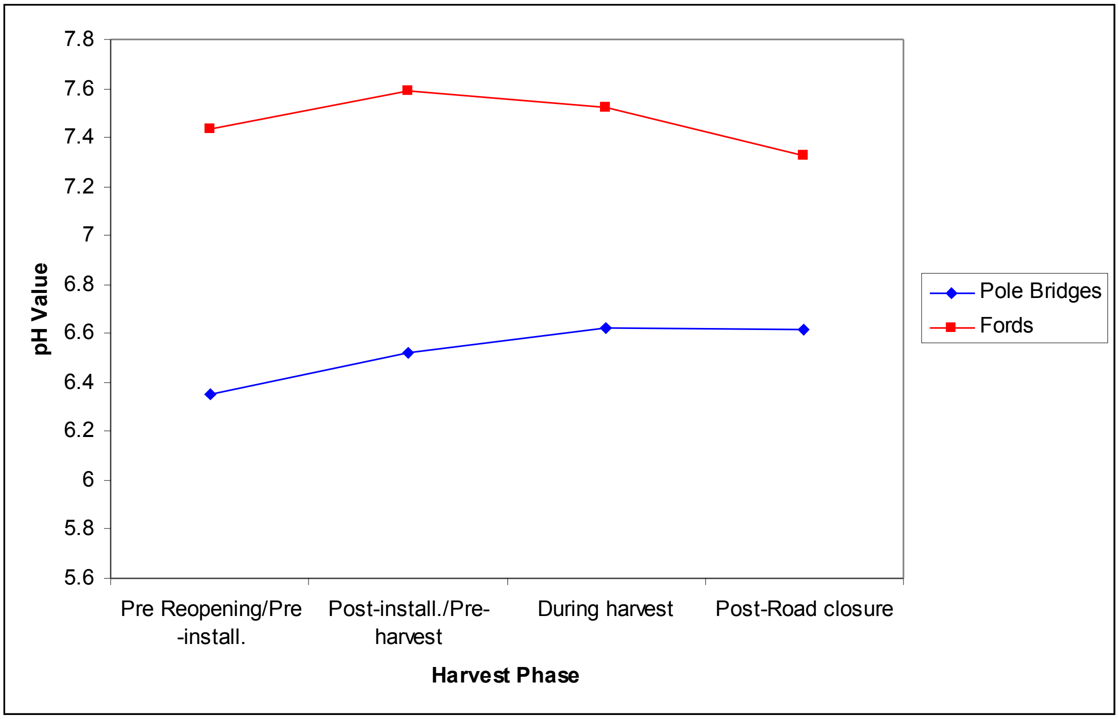

Figure 39. pH mean values of ford and pole bridge stream crossings across the entire harvest process.

SUMMARY AND CONCLUSIONS

Stream crossings involved in this study varied in the quality of installation and location of approaches. Based on our results, any of the four stream crossings may be appropriate if located and installed properly for the respective road class. Potential water quality problems could be avoided through better road and crossing location and careful installation. BMP selection and implementation can also impact the potential soil loss of approaches at any of the stream crossings.

Culverts

Culvert stream crossings and the associated road approaches had higher average estimated erosion for both erosion models. Both models indicated that the highest mean potential erosion occurred during the harvest phase. Culvert crossings require more excavation, stream channel alteration, and fill, and these activities cause higher erosion. Culverts are typically used for tracts having larger volumes of timber and associated harvesting traffic. Applying gravel to the approaches to the culverts will decrease the energy runoff towards the stream crossing. Also, installation of water control structures will help to limit the approach length at these crossing locations.

No significant difference was realized for any in-stream water quality indicators for culvert treatments. However, TSS levels had a trend of being higher for culverts than for other crossings. This can be explained by the amount of fill material added to the stream. Also, TDS levels continued to rise throughout the harvest process supporting the reasoning that fill material continues deposition until grass seed has stabilized the soil around the culvert.

Fords

Ford stream crossings and the associated road approaches showed significant differences for the WEPP and USLE model. Both models estimated similar soil loss potentials. Ford approach erosion estimates were significantly different from culverts and steel bridges at the during harvest phase as predicted by WEPP. USLE erosion estimates showed that ford approaches were different from culverts at the during harvest phase, and different from culverts and pole bridges at the post-road closure phase. Fords were significant from other stream crossings with regard to some in-stream water quality indicators. Application of limestone gravel directly to these crossings is likely the cause of the highest mean pH value of all crossings. Mean TDS levels were the highest for this type of stream crossing. Due to a decrease in the intensity of use, these TDS levels continued to decrease after the installation occurred. Studies have shown that although fords show heightened pH and TDS levels, this increase is only temporary and will return to normal levels over time. The trend of TDS levels recorded in this study support that tendency of TDS concentration to decrease with time. An unusual water quality result was that fords had the lowest mean TSS levels. Data that was not collected immediately after use or installation may be the result of this finding. Also, the perennial streams for which fords were used allow for water quality concentrations to quickly decrease due to the fast moving water.

Several managers, logging contractors, and excavation professionals seemed hesitant to use this type of crossing in the Virginia Piedmont. However, compared to other types of permanent stream crossing (culverts), fords are a viable option when located and installed correctly. Fords were also used to support some of the highest average volumes removed and longest durations of timber harvesting operations. These crossings only show short-term impacts of water quality indicators and if properly located will not produce erosion rates as high as approaches associated with culverts.

Pole Bridges

Pole bridge stream crossings and associated road approaches showed some significant differences for soil loss potential. WEPP estimates showed significance of pole bridges at the during harvest phase. USLE estimates showed significance at the after harvest phase. The USLE model estimated that the pole bridge crossing and its approaches had the lowest potential for soil loss. The amount of slash and residual natural vegetation throughout the process caused fluctuations of estimates throughout harvest operations.

Pole bridges had the lowest mean stream pH value which was significant ($p = 0.001$. This was perhaps due to organic acids in leaf litter, tree tops, and particles from the pipe reaching the stream channel. These crossings had the highest TDS level during the harvest phase which is most likely due to very low levels of stream flow and slow moving water which impacted measurements. Large quantities of logging debris should not be left in the stream due to the potential to change stream flow and cause bank erosion (VDOF 2002).

Steel Bridges

Currently, this type of crossing is the most widely used in harvesting operations in the Virginia Piedmont. WEPP erosion estimates of steel bridge approaches were significantly different from all other crossings at the during harvest phase. USLE erosion estimates of steel bridge approaches were significantly different from culverts at the during harvest phase and different from culverts and pole bridges at the post-road closure phase. Variability in the approaches and type of use of the approaches may have impacted these soil loss potential results.

Significant difference of TDS and conductivity mean values among stream crossings was realized. In both categories steel bridge stream crossings had the lowest mean levels over the entire harvest process. These low levels were influenced by minimal disturbance and time required for installation. This study indicates that these portable crossings cause the fewest problems with in-stream water quality parameters when other site factors are similar.

Practical Application and Future Study

This study showed that the portable steel bridge crossings are likely to create the least amount of water quality impacts. The versatility of these crossings for either skidder or log truck use (if properly rated) will continue to make them a favorite among logging contractors and forest managers. Attention should be given to the road approaches to the steel bridge crossings and the cover of those approaches. The minimal water quality impacts of these crossings should not negate proper attention to approach design which will impact soil loss potential. Pole bridge crossings may be acceptable especially in ephemeral or intermittent streams which support infrequent water flow. Pole bridge approaches have a low potential for soil loss and provide another option for skidder crossings. Several study sites used steel bridges and pole bridges simultaneously to remove timber from the forest allowing for shorter durations of stream crossing use.

Permanent road construction and use incorporated culvert and ford stream crossings. Culverts seemed to be the preferred type of crossing for permanent access, probably due to the relative ease of installation and the ability of culverts to support heavy loads. However, the results of this study do not support that preference, at least with regard to water quality. It is almost impossible to install culverts without pushing loose fill dirt into the stream and operators need to pay additional attention to the long slopes, lack of gravel and inadequate water control structures that were associated with the culvert crossings in our study. Fords actually had lower potential for soil loss according to both WEPP and USLE estimates. This can be attributed to the shorter approaches and less steep grades associated with ford crossings. Although water quality measurements show response to ford installation, previous studies report that these responses are short lived. Ford stream crossings are proper alternatives to culverts if located at a gentle grade, short approach, and installed correctly. Applying cover management practices for this type of stream crossing should be considered as well.

Evaluation of the harvest phases showed times during a harvest schedule when attention should be given to BMPs. Post-road closure estimates showed that BMPs are effectively being used for road closure, but BMPs are applicable at all phases of harvest. Applying gravel to approaches as a BMP can lower soil loss potential and result in less impact from rainfall.

Future studies should isolate the type of stream crossing being used. Evaluating both temporary and permanent stream crossings was difficult due to the different road construction standards and complexity of stream crossing installation. Also, variability of stream types should be kept to a minimum. Projects to come should consider implementing similar crossings on a single type of stream crossing. Alternative tools for measuring water quality indicators should be explored. Absence of data from the post-installation/pre-harvest phase due to the high efficiency of logging contractors and pre-existing crossings impacted soil loss potential and water quality estimates, and efforts should be made to collect data at this harvest phase. More programming efforts of the WEPP model could produce conditions more specific to certain study sites. Different contractors used to install stream crossings had different levels of experience and knowledge which impacted the quality of the installation job.

In summation, any of the stream crossings can be effectively used as long as careful attention is paid to proper road location and grade, crossing site selection, BMPs for water control and cover, and site closure. Streams can be crossed with minimal impact, but BMPs must be emphasized during all stages of harvesting.

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Appendix A. Rosgen and Manning-Chezy data collection sheets.

Estimation of flood water yield (Ft^3/s) via Manning-Chezy Equation for Estimation of Full Bank Flood Discharge at the stream crossing

1. Estimate the normal "high water" as determined by the stream channel banks.
2. Measure the stream channel width with the 100 foot tape. Hold the tape in place and use the Philadelphia rods to estimate the depth to the nearest 0.1 feet for at least 5 points in the stream in order to estimate average flood depth. Multiply the average flood depth X the flood channel width to determine the cross-sectional area (A).
3. Measure the wetted perimeter along the stream bottom for the flood channel using the cloth tape. Calculate the hydraulic radius (R) as follows: R = A/Wp
4. Use a transit or Abney level and Philadelphia Rod to determine the stream water slope for a 50 feet distance near your assigned point.
5. Select an appropriate n value from the abbreviated choices:

N values for minor (< 100 feet) natural streams

Clean straight, no pools or riffle	0.03
Same as above, some stones and weeds	0.035
Clean, winding, pools and shoals	0.04
Same as above, some stones and weeds	0.045
Sluggish reaches, weedy deep pools	0.07
Very weedy reaches, deep pools, tall vegetation	0.075

6. Calculate the stream discharge via the Manning-Chezy equation.

$Q = 1.49/n \times A \times r^{2/3} \times s^{1/2}$

Manning-Chezy Equation Worksheet

Stream Name_____________________________
Crew Names: ____

1. Stream Width at full bank = __________ (feet)
2. Average Stream Depth at full bank = (___+___+___+___+___)/5 = ____________
3. Average Stream Cross-sectional Area at full bank (Depth X width) = __________
4. Wp at full bank = ____________ (feet)
5. S = elevation _____/ distance _____ = ________
6. Indirect Calculation of Discharge

$Q = 1.49/n \times A \times r^{2/3} \times s^{1/2}$

Q = ____________ ft^3 / s

Determination of Stream Stability Classification

Determine the following for the stream crossing

a. Stream Drainage or Channel Pattern

Determine if the floodplain is best characterized as being single or multiple channels.

b. Entrenchment Ratio Category

Measure the width of the floodplain (flood plain not just channel) and the width of the full bank event. Use these values to determine the entrenchment ratio.

Entrenchment Ratio = Width of floodplain/ Width of bank-full channel
Entrenchment Ratio = _____________/___________

- a. Entrenched < 1.4
- b. Moderately entrenched = 1.4 – 2.2
- c. Slightly entrenched > 2.2

c. Stream Width to Channel Full Depth Ratio

Determine the maximum depth and width at full bank flow and then calculate the W/D ratio.

W/D ratio = _______/________

- a. Low W/D < 12
- b. Moderate = 12
- c. Moderately high W/D > 12
- d. Very high > 40 (multiple channels)
- e. Low < 40 (Multiple channels)

d. Sinuosity = ratio of stream channel distance/horizontal distance. Measure the distance along one edge of the stream vs the straight line distance for approximatey 50 feet upstream and 50 feet downstream.

Upstream Sinuosity = meander distance/straight distance = _______/________
Downstream Sinuosity = meander distance/straight distance = _______/________

e. Predominant Channel Material for you reach of stream.

- a. Bedrock
- b. Boulder
- c. Cobble
- d. Gravel
- e. Sand
- f. Silt/clay

f. Channel Slope: Use the abney level locked on zero % and HI stick and Philadelphia rod to measure the change in elevation for the water surface for at least 25 feet upstream and 25 feet downstream.

Upstream slope = _______ feet elevation/ ____________ feet distance
Downstream slope = _______ feet elevation/ ____________ feet distance