EFFECTIVENESS OF FORESTRY BMPS FOR STREAM CROSSING SEDIMENT REDUCTION USING RAINFALL SIMULATION

Brian C. Morris, M. Chad Bolding, and W. Michael Aust[1]

Abstract--Recent decisions by the United States Supreme Court and United States Environmental Protection Agency (EPA) have re-emphasized the importance of forestry best management practices (BMPs) at stream crossings. Stream crossings are potential major sources of sediment due to their direct connectivity between the potential erosion source and the stream, which eliminates potential sediment reduction provided by filter/buffer strips and streamside management zones. The effectiveness of stream crossing BMPs for sediment control were tested for a permanent bridge crossing, culvert crossing, and improved ford crossing on three first-order streams in the Virginia Piedmont using rainfall simulation. The three crossings were located on a low standard legacy road having unimproved ford crossings before experimentation. All legacy fords received three levels of rainfall intensity via simulation prior to crossing installation. Following crossing installation, rainfall simulations were performed at each of the crossings under the following three treatments: (1) minimal levels of BMP erosion control (Low); followed by (2) installation of BMPs recommended by the Virginia BMP Manual (Medium); and (3) erosion control measures beyond the Virginia BMP Manual (High). Stream sediment (TSS) was monitored upstream and downstream during rainfall simulations to determine total sediment contribution from each individual crossing. The comparison of minimal BMPs, recommended BMPs, and extensive protection provides insight into the erosion associated with the crossing types and the effectiveness of current BMPs for nonpoint source pollution (NPSP) reduction. The Culvert crossing produced a sediment concentration (2.9 g/L) that was double the concentration produced by the Ford crossing (1.4 g/L) and over 10 times the concentration of the Bridge crossing (0.2 g/L).

INTRODUCTION

Forestry best management practices (BMPs) have proven to be effective (Aust and Blinn 2004, Briggs 1998, Shepard 2006, Wynn and others 2000). However, stream crossings have been identified as the primary source of stream sedimentation in forested landscapes (Taylor and others 1999). This sedimentation associated with stream crossings is due to the stream crossing approach and structure providing a source area for erosion (i.e. road surface, cut and fill slopes) that is able to flow directly into the stream channel (Lane and Sheridan 2002). The lack of water-control structures between the crossing structure and the stream results in a high sediment delivery ratio. Current methods of reducing erosion from non-point source pollutants (NPSP) (i.e. stream crossings) and subsequent sedimentation are based upon BMPs which are administered by individual states in accordance with the Federal Water Pollution Control Act of 1972 (Ice and others 2010). BMP requirements and their administration differ by state (i.e. regulatory or voluntary BMPs); however, recent U.S. Supreme Court cases (i.e. Decker versus Northwest Environmental Defense Center) have emphasized the national importance of forestry activities associated with stream crossings. The U.S. Supreme Court overturned a Ninth Circuit Court ruling that would have required National Pollutant Discharge Elimination System (NPDES) permits for any concentrated waste water discharge on forest roads, including stream crossings and ditched roads. The court ruling allows for states to maintain their current BMP systems for stream crossings; however, the Environmental Protection Agency (EPA) has clarified the treatment of forest roads as NPSP. The probability of future lawsuits that will call the rules into question emphasizes the need to consider stream crossing BMPs. These potential changes have increased interest in finding erosion control measures that will be both environmentally and economically efficient (Boston 2012). To better understand the sediment production from specific types of stream-crossing structures, studies must be designed to isolate sediment that is produced from the crossing structure from sediment produced upstream or on the road approach (Taylor and others 1999).

OBJECTIVES

This study was designed to isolate the sediment production from stream-crossing structures. This approach allowed us to determine the sediment contribution from three different crossing structures (Ford, Culvert, and Bridge). Three levels of BMPs were also applied to each crossing; Low (no BMPs), Medium (BMPs equivalent to Virginia Department of Forestry Standards) and High (BMPs beyond Virginia Department of Forestry Standards).

[1]Graduate Research Assistant, Associate Professor, and Professor, respectively, Virginia Polytechnic Institute and State University, Department of Forest Resources and Environmental Conservation, Blacksburg, VA 24061.

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METHODS

This study was conducted on Virginia Tech's Reynolds Homestead Forest Resources Research Center in Critz, VA. The site is along the western edge of the Piedmont physiographic region. Stream crossings and BMPs were installed on three first-order streams that cross a single legacy (> 100 years old) road. All three original stream crossings on the legacy road were unimproved legacy ford crossings with native stream beds, with steep and non-perpendicular approaches. The road was built prior to current BMPs and road design standards. Prior to conducting the study, ISCO 3700 automatic water samplers (Teledyne ISCO, Lincoln, NE) were installed 66 feet upstream and 66 feet downstream of each crossing, and HOBO® water level loggers (Onset Computer Corporation, Bourne, MA) were also installed upstream of each crossing. The three legacy ford crossings were replaced by a Bridge (100-acre watershed), a Culvert (42-acre watershed), and an improved Ford (80-acre watershed). The Bridge installation included abandoning the old ford crossing and approximately 25 feet of the approach to allow for a 24- by 12- by 0.75-foot white oak (*Quercus alba* L.) stringer bridge, consisting of three 4-foot-wide panels. The 25 feet of the crossing approach were abandoned to allow for the bridge to be aligned perpendicular to the stream. The western approach required the construction of an abutment to support the 9-foot span. This was completed using 3-foot-wide by 3-foot-tall gabion baskets that were filled with #3-0 rock (2- to 8-inch stone). Both approaches were covered with geotextile and 3 inches of #357 (1/2- to 2-inch stone) drain rock prior to installing the bridge panels to prevent the panel from sitting directly on the soil. The initial rainfall simulation with Low BMPs consisted of the bridge installed to drivable conditions with bare soil on the approaches and fill material. The Medium level of BMPs included the addition of gravel to the running surface of the road, and the High level of BMPs included the addition of rip-rap to the fill slopes and covering of all bare soil. The gravel was applied from the crossing structure beyond the next brake in slope, resulting in no bare soil on the road surface subjected to rainfall simulation.

The legacy ford replaced by the Culvert crossing consisted of steep approaches that did not cross the stream at right angles. Legacy approaches were abandoned, and a new road alignment was located. A 40-foot-long by 36-inch-diameter culvert replaced the legacy ford. The channel was excavated with a New Holland TN 750, 75 hp farm tractor with a three-point backhoe attachment. The culvert pipe was installed at the natural stream gradient and at an elevation which allowed for bed load material to be transported into and settle in the culvert bottom, providing a natural stream bed within the culvert. Fill material was sourced from the road realignment, pushed over the culvert, and compacted with a John Deere 450E bulldozer. Approximately 3 feet of fill material was added on top of the culvert to allow for proper vertical road alignment. The fill slopes were compacted with the bulldozer. The Low treatment consisted of no BMPs which resulted in bare soil on the road surface and fill slopes with no water-control structures between the road surface and the stream. The Medium level of BMPs included the addition of geotextile and gravel on the running surface of the road, and the High level of BMPs consisted of the addition of rip-rap to the fill slopes directly above the channel and the application of grass seed and straw mulch on all bare soil.

The improved Ford crossing was constructed within the original legacy ford. The Low level of BMPs included limited rock on the road surface and re-grading the approaches to allow for easier truck traffic, simulating a disturbance that would be created if a log truck crossed the stream. The Medium level of BMPs consisted of improving the road alignment slightly and adding gravel down to the water line of the stream within the running surface of the road. The High level BMP treatment included the installation of Geo-Web in the stream bed and the application of gravel within the running surface in the Geo-Web. The installation of the Geo-Web required excavating the stream channel 6 inches below the natural gradient and backfilling with Virginia Department of Transportation (VDOT) #5 (average ¾-inch stone) gravel.

All three crossings received three levels of rainfall simulation. Simulations were conducted utilizing an 18-hp centrifugal pump with a 4-inch-diameter suction hose submerged in a pond that was downstream of the crossings. The pump pressurized 3-inch-diameter (50- to 100-foot length) fire hose which fed a 2-inch PVC manifold that was used to distribute water to eight sprinkler risers which were 10-feet tall with 1-inch PVC pipe connected to Wobler© sprinkler heads. The sprinkler heads were chosen due to the ability to change the nozzle diameter and the simulated rainfall intensity. This resulted in three distinct rainfall intensities during the simulations Low (0.5 to 1.0 inch per hour), Medium (1.5 to 2.0 inches per hour) and High (2.0 to 2.5 inches per hour). Each of the three rainfall simulations was conducted for 30 minutes. The sprinklers were arranged to allow for rainfall on the stream-crossing structure with minimal rainfall application to the approaches beyond the crossing structure and surrounding area. During the simulations, water samples were collected by the upstream ISCO at 10-minute intervals, downstream at 5-minute intervals during the simulation, and for 30 minutes after rainfall ended. Water samples were processed for total suspended solids (TSS) concentration in g/L by vacuum-filtering 250 ml of stream water through 47-mm ProWeigh filters. The filters with the sediment were dried for 24 hours at 105 °C and weighed. The HOBO water level loggers were used to monitor stream stage during the events. Stream discharge was determined through the use of state-discharge relationships that were created by comparing stage measurements with discharge measurements made with the salt dilution method (Moore 2004, 2005). The sediment concentration and stream discharge were used to determine mass of sediment produced by the crossing during the simulated storm events.

RESULTS AND DISCUSSION

Rainfall simulation experiments were effective at creating artificial storm events for all three crossings. The High-intensity rainfall simulation resulted in rainfall intensities of 2.0 to 2.5 inches per hour while the Medium-intensity simulation resulted in rainfall intensities of 1.5 to 2.0 inches per hour, and the Low-intensity simulation resulted in a rainfall intensity of 0.5 to 1.0 inches per hour over a 30-minute rainfall duration. When all rainfall intensities are combined for each BMP level and crossing type, the Low level of BMPs on the Culvert crossing produced the greatest TSS concentration while the Medium BMP level on the Ford results in the second greatest TSS concentration, and all three BMP treatments on the Bridge produce maximum sediment concentrations below the Culvert and Ford (fig. 1). The maximum sediment contribution for the Culvert crossing was 2.9 g/L while the maximum sediment contribution for the Ford was 1.4 g/L, and the maximum sediment contribution for the Bridge was 0.2 g/L. When comparing the crossings by BMP level, the High level of BMPs for all three crossings resulted in decreased stream sediment, although the Bridge showed little response in sediment levels for the three levels of BMPs. The sediment concentrations for the three levels of BMPs for the Ford showed a different pattern than the Culvert, with the maximum concentration occurring when the Medium level of BMPs was subjected to rainfall simulation. However, the High level of BMPs on the Ford still resulted in lower sediment concentrations than the Medium and Low. The average TSS concentration during the rainfall simulations shows the Low BMP treatment on the Culvert producing the greatest TSS concentration while the ranking of treatments for the Ford follows that of the Culvert with the Low level of BMPs producing the greatest average TSS concentration followed by the Medium BMP level and the High BMP level producing the lowest average TSS concentration (fig. 2). The Bridge crossing produced average TSS concentrations below the average concentrations of Culvert and Ford crossings at all levels of BMPs (fig. 2).

The increased TSS concentrations produced by the Culvert crossing suggest that in order to further reduce sedimentation from stream crossings the Culvert crossing should be an area of focus. The Culvert crossing showed greater maximum TSS concentrations during the High and Medium rainfall intensities than the Low rainfall intensity with the Medium rainfall intensity and the Low BMP level producing the greatest Maximum sediment concentration (fig. 3). The maximum TSS concentration for the construction phase was 2.5 g/L while the maximum concentration for the High rainfall

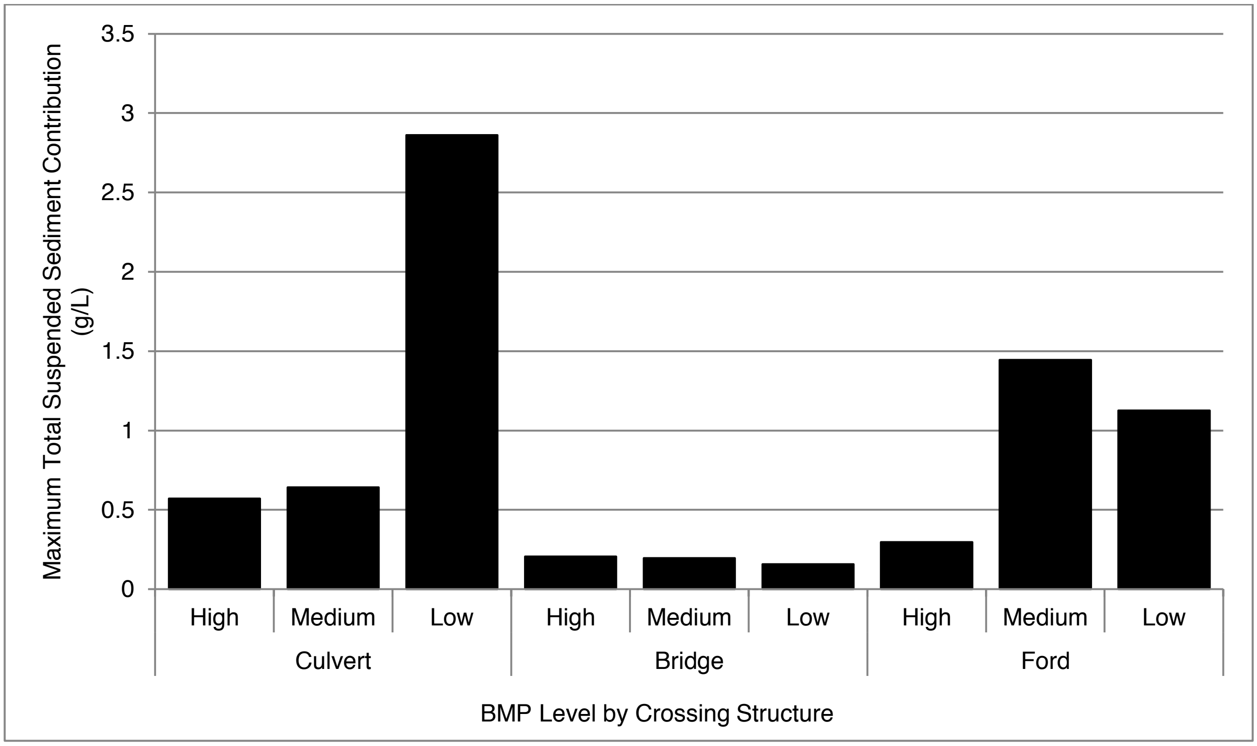

Figure 1--Maximum total suspended sediment concentration (g/L) by BMP level and crossing structure for all levels of rainfall simulation.

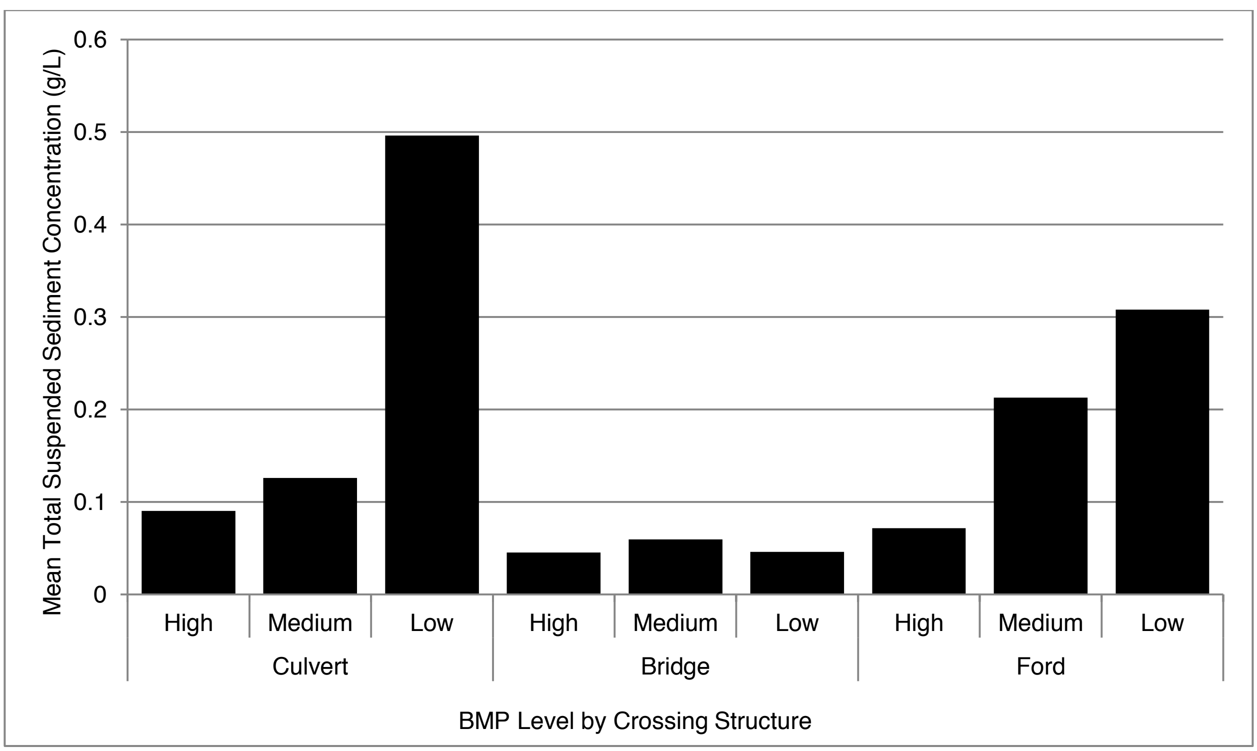

Figure 2--Mean downstream total suspended sediment concentration (g/L) by BMP level and crossing structure for all levels of rainfall simulation.

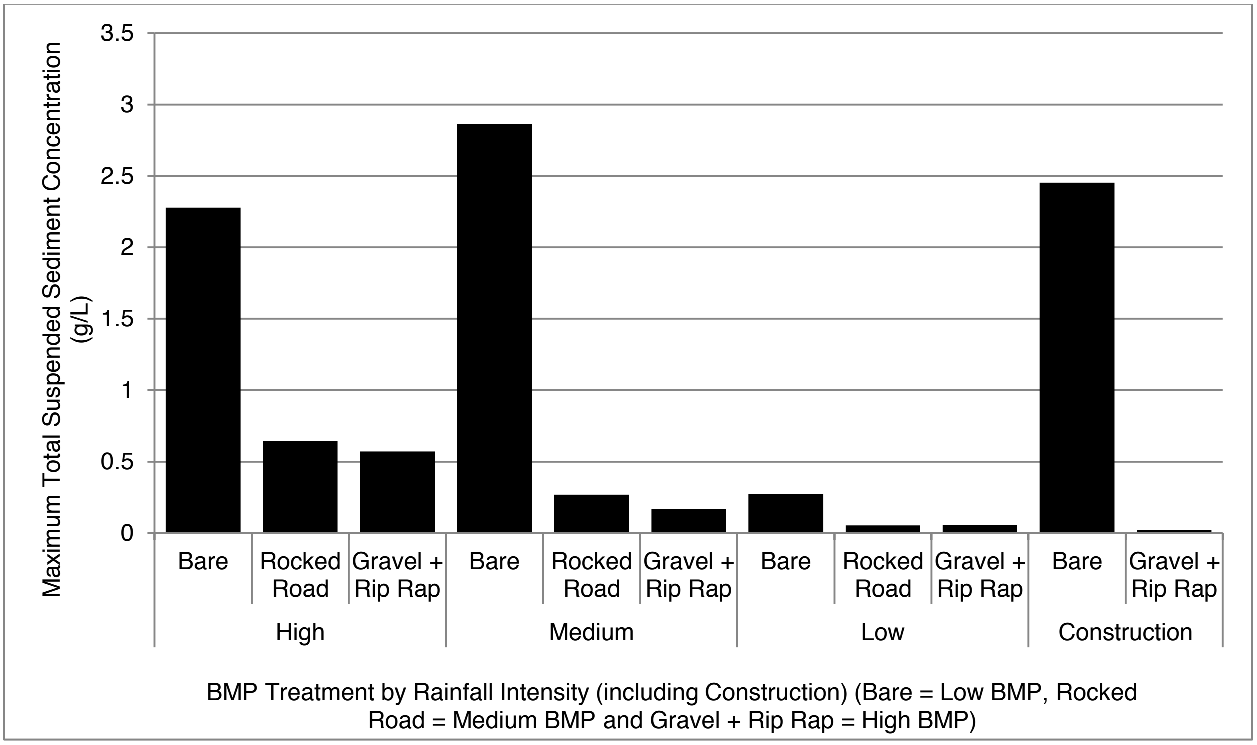

Figure 3--Maximum total suspended sediment concentration (g/L) at the culvert crossing by BMP treatment and rainfall intensity, including the construction phase (no rainfall during construction phase).

intensity was 2.3 g/L and the Medium rainfall intensity was 2.9 g/L. For all three levels of rainfall simulation, the greatest TSS concentration was observed during the Bare (Low) BMP treatment with the Rocked Road (Medium) BMP and Gravel + Rip Rap (High) BMP treatments resulting in reduced TSS concentrations, though the difference between Low BMPs and Medium BMPs was greater than the difference between Medium BMPs and High BMPs. (fig. 3). The mean TSS concentrations followed a similar pattern; however, at the High rainfall intensity the difference between the mean TSS concentration for the Rocked Road (Medium) BMP level and Gravel + Rip Rap (High) BMP was < 0.03 g/L, with the High BMP treatment resulting in a slightly greater mean (fig. 4). The maximum and mean TSS concentration was greatest during the Medium rainfall simulation. This was likely due to overland flow that filled a depression near the inlet of the culvert. Near the end of the Medium rainfall simulation on the Low BMP treatment, the water in the depression had overtopped the stream bank and entered the stream. This was not the result of a BMP failure; rather, it was the result of construction practices and the legacy road alignment, as the depression was formed near the outlet of a water turnout on the legacy road which had been abandoned when the culvert was built.

The maximum sediment concentration for the rainfall simulations occurred during the Low BMP treatment as did the maximum sediment delivery. The construction phase resulted in the introduction of 3.8 tons of sediment into the stream over an 8-hour construction period, compared to 2.5 tons during the 30-minute Low BMP High rainfall intensity simulation, and 4.1 tons of sediment being produced during the Medium rainfall intensity simulation on the Low BMP treatment (fig. 5). The 2.5 tons produced during the Low BMP and High rainfall simulation, as well as the 3.8 tons produced during construction phase, are comparable to the 2.8 tons produced during rainfall events and 3.5 tons produced during construction activities on a culvert in the Central Highland of Australia (Lane and Sheridan, 2002). Although the TSS produced during rainfall simulation are similar to the 2.8 tons produced during Lane and

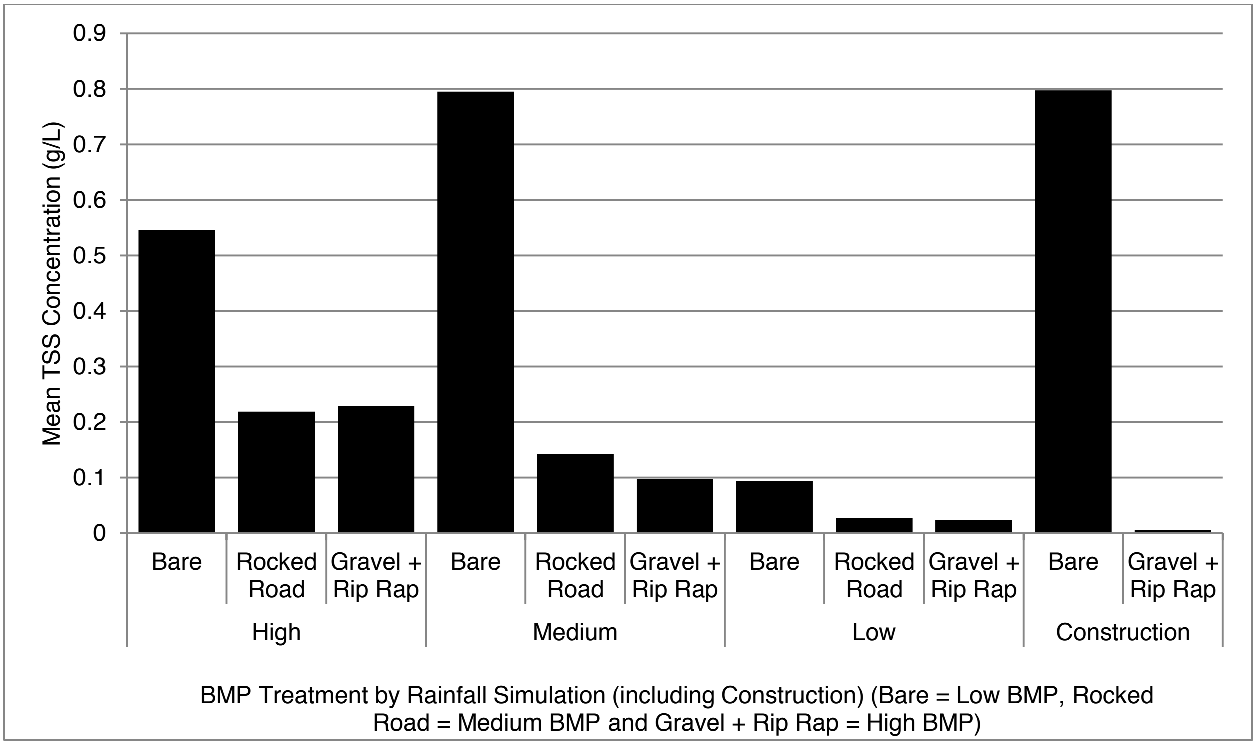

Figure 4--Mean total suspended sediment concentration (g/L) at the culvert crossing by BMP treatment and rainfall intensity, including the construction phase (no rainfall during construction phase).

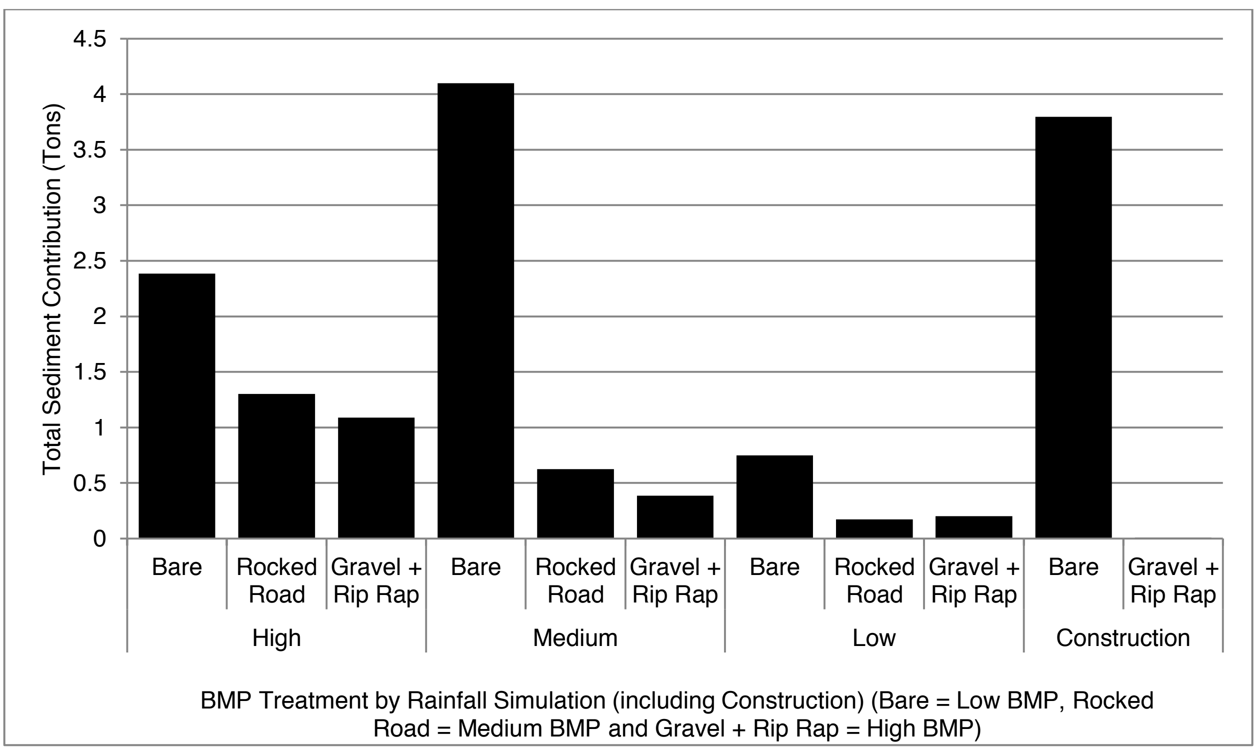

Figure 5--Sum of total sediment contribution (tons) for the culvert crossing during simulations and construction activities by BMP treatment and rainfall intensity (including construction).

Sheridan's (2002) experiment, their monitoring covered a timeframe of approximately 6 months. The single-event sediment production during the rainfall simulation could be due to differences in site-specific factors such as soil type, soil cover, and the time since soil disturbance. Total sediment production (tons) decreased with an increase in BMPs implemented for the Medium and High rainfall simulations while the difference between the Medium and High BMP treatments at the Low rainfall simulation was minimal. Additionally, the initial construction resulted in a large mass of sediment being introduced to the channel due to the required excavation of the channel. The addition of rip-rap to the fill slopes resulted in minimal sedimentation due to the rock being placed around the culvert and stream channel by hand. The use of larger equipment could result in increased sedimentation during this phase of construction.

The rainfall simulation experiment on the Culvert produced more sediment than the Ford or Bridge, suggesting that further investigation should focus on BMPs for culverts. Initial construction activities contributed almost 4 tons of sediment during an 8-hour construction period. Subsequent rainfall simulations resulted in a maximum sediment contribution of 4.1 tons during a 30-minute rainfall simulation. The construction resulted in a large sediment contribution due to the need to excavate the channel to place the culvert at the proper grade in the stream. The 4.1 tons of sediment were produced during the Low BMP simulations with no soil surface cover on the road surface and fill slopes. The addition of rock on the running surface and fill slopes further decreased the sediment contribution from the Medium and High BMP simulations. The addition of rock on the fill slopes and running surface will also facilitate a longer usable life for the crossing structure. The additional erosion that would be present without the rock, seed, and mulch would require additional maintenance as the running surface and fill slopes begin to erode. The use of rock will not only reduce the potential sediment contribution but could also reduce future maintenance needs of the crossing. The nature of constricting a stream to a culvert pipe will always require maintenance and attention to prevent the pipe from clogging and subsequent failure of the crossing which could result in a much greater sediment contribution. The current BMPs for stream crossings are effective at reducing sedimentation when compared to stream crossing structures with no erosion control measures (BMPs) in place. Additional BMPs may further reduce erosion; however, the cost of the additional BMPs must be compared to the stream health benefits obtained by further reduction erosion, and sedimentation.

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