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ASSESSING EFFORTS TO REDUCE SEDIMENT IMPACTS IN COTTONWOOD CREEK, BLACKFOOT BASIN, MONTANA

By

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Thesis

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Assessing Efforts to Reduce Sediment Impacts in Cottonwood Creek, Blackfoot Basin, Montana

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ABSTRACT

This thesis assesses efforts to reduce sediment impacts in Cottonwood Creek, a tributary to the Blackfoot River in western Montana. The first objective evaluated trade-offs in stream crossing improvements regarding short-term sediment impacts versus long-term reductions in sediment load from road surface erosion and possible culvert failures. Suspended sediment and turbidity measurements were taken during spring snowmelt the year before and after a culvert replacement by a bridge, and during the replacement activity. The two study years were typical snowmelt years; i.e., 2- and 4-year return intervals, based on a ten-year USGS period of record. Culvert fill and road surface erosion measurements were also taken. Likely sediment load from upgrading a culvert was compared to that of not upgrading a culvert. Upgrading probably produces less sediment over the long-term than not upgrading.

The second objective assessed other stream crossings in high-risk areas in the same watershed to determine culvert failure risk and to estimate how much sediment load could be produced from culvert failures and road surface erosion. The annual sediment yield from culverts predicted to fail within 20 years and from estimated road surface erosion modeled over ten years was much lower compared with the literature, even for undisturbed forests. Two hypothetical scenarios were compared—in one, culverts that were expected to fail were replaced with bridges; in the other, they were not replaced and did fail. Replacing the culverts with bridges resulted in a six percent increase in sediment load to Cottonwood Creek, but this amount of difference is likely within the error range of these estimates. Hence there seems to be little long term benefit in replacing the culverts.

The third objective critiqued the TMDL/Water Quality Improvement Plan for the Middle Blackfoot/Nevada Creek basins. While the TMDL involved considerable detail on sediment sources, quantities, and proposed reductions in loads, the implementation and monitoring features were weak.

Based on examining sediment reduction efforts in these three ways, this thesis concluded that stream crossing improvements, such as replacing culverts with bridges, are likely to reduce watershed sediment loading over the long-term despite short-term disturbances by these efforts.

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CHAPTER 1: INTRODUCTION

Background

Excessive sediment inputs to streams are a concern to regulatory agencies because of the risk of water quality degradation and thus, degradation of fish and macroinvertebrate habitat. Cottonwood Creek, a subbasin of the Middle Blackfoot watershed in western Montana, contains both westslope cutthroat trout and bull trout and is also a core habitat area for bull trout (MT DEQ, 2008).

However, habitat surveys conducted over the past ten years by regulatory agencies have revealed excess fine sediment accumulation in pools and substrates throughout Cottonwood Creek (MT DEQ, 2008). Because of the high level of siltation, as well as flow and habitat alterations, Cottonwood Creek has been listed as impaired by the state of Montana.

Besides impacting pool and substrate quality, fine sediments are also associated with whirling disease; this disease has been found in the middle and lower reaches of Cottonwood Creek (MT DEQ, 2008). High densities of *T. tubifex*, the host worm for the parasite that causes whirling disease, are often associated with substrates dominated by fine sediments (Krueger et al, 2006; Sacry, 2004).

Assessing the impact of replacing an undersized, perched culvert in Cottonwood Creek was a major focus of this thesis. Local regulatory agencies and nonprofit conservation groups identified this culvert as one that would likely fail in a large flood. In addition, it was perched a few feet above the stream, prohibiting fish passage of westslope cutthroat trout. Therefore it was replaced with a bridge in the fall of 2007. This endeavor was a partnership between the Lolo National Forest, Blackfoot Challenge, and Big Blackfoot Chapter of Trout Unlimited.

Section 303(d) of the federal Clean Water Act requires state regulatory agencies to identify water bodies that fail to meet water quality standards due to pollutant loads such as sediment, nutrients, and metals (MT DEQ, 2008). For those that do not meet water quality standards, the state must develop TMDLs (Total Maximum Daily Loads). A TMDL is the total amount of a pollutant that a water body can receive from all pollutant sources without exceeding water quality standards (MT DEQ, 2008a). Montana Department of Environmental Quality (MT DEQ) is currently developing TMDLs for all streams, rivers, and lakes in the state that are on the 303(d) list.

The final TMDL for the Middle Blackfoot/Nevada Creek (MBNC) basin was released in September, 2008. This document addresses pollutant sources and loadings such as sediment, nutrients, and metals for impaired waterbodies in the MBNC basin. This TMDL identifies sediment sources such as hillslope erosion, roads, and stream bank erosion (MT DEQ, 2008). The extent to which these sediment loads could be reduced through Best Management Practices (BMPs) is described in the TMDL.

One strategy for reducing long-term risk of high sediment loads at stream crossings is by either replacing culverts (which have a tendency to wash out, delivering large quantities of sediment) with larger ones, bridges or by decommissioning the road. However, the amount of sediment production during the culvert replacement or road removal procedures must be evaluated in terms of whether there is a net sediment reduction in the long-term. This thesis considers culvert replacements or road decommissioning as a potential sediment risk-reducing activity for the Cottonwood Creek watershed. This thesis focuses on evaluating sediment sources to Cottonwood Creek, emphasizing road-stream crossings.

Purpose/Need and Target Audience

Improperly designed stream crossings can cause a multitude of problems for aquatic ecosystem integrity in forested watersheds. In particular, undersized and aging culverts often result in degraded water quality and impacted fish habitat. There are two main types of sediment inputs to streams at road crossings: 1) chronic surface erosion: when undersized culverts become plugged with debris or sediment, water flows over the road instead of flowing through the culvert, washing road surface sediment into streams, 2) culvert failures: here, water is diverted at a plugged or undersized culvert, saturating the fill, and washing out the culvert and surrounding fill (Klein, 1987; Madej, 2001).

A solution to these problems is to replace undersized culverts with larger ones or bridges. However, culvert replacements involve major earth-disturbing work, which inevitably increases sediment delivery to the stream, regardless of mitigation measures. In addition, the new stream bank is devoid of vegetation for some time period afterwards and is vulnerable to erosion by spring snowmelt floods in the first year or two after the replacement.

Therefore, a question to ask when considering a culvert replacement project: is there a net sediment reduction when comparing sediment load from the replacement project to the sediment load from chronic road surface erosion or culvert fill failure potential? To help answer this question, this thesis measured sediment load that occurred from replacing a culvert with a bridge at one stream crossing in the Cottonwood Creek watershed. It also measured chronic sediment load before the replacement and estimated the likely sediment load of a culvert failure if the culvert was not replaced.

The thesis also broadens the analysis to examine other stream crossings in Cottonwood Creek to quantify potential culvert failures and road crossing erosion. While most of the literature asserts that the geology underlying the Cottonwood Creek basin (Precambrian Belt metasediments) is relatively resistant to erosion and landslides, (Anderson and Potts, 1987; Sugden and Woods, 2007; Packer, 1967), there are examples of mass wasting and erosion in these geology types (Clearwater National Forest, 2003). In addition, there are large areas of glacial till in Cottonwood Creek, which has been shown to be less stable, and more prone to erosion than Belt metasediments (Sugden and Woods, 2007; Idaho DEQ, 2002). Hence the thesis examined stream crossings in the Cottonwood Creek basin that are at high risk for road surface erosion and culvert failure, assessing what the sediment load might be for these. This analysis also considered the potential benefits in sediment load reduction by replacing inadequate culverts with bridges.

And, finally, there is a need to critique TMDLs as part of citizen oversight of Clean Water Act enforcement. Because there are various methods for measuring sediment loading, it is a good idea to critique these methods, using original research and the current available literature. Therefore, the last part of this thesis critiques the Middle Blackfoot-Nevada Creek Total Maximum Daily Loads and Water Quality Improvement Plan.

There are three objectives of this thesis. The first is to assess if there is likely to be a net sediment reduction from a culvert replacement at one stream crossing in Cottonwood Creek. The long-term risks of not replacing culverts (with potential culvert fill failure and chronic road surface erosion) are weighed against the short-term risks of a temporary increased sediment load from culvert replacement activities.

The second objective is to assess sediment sources at other stream crossings in the Cottonwood Creek basin and, based on measurements taken at each crossing, calculate how much sediment would enter streams from culvert fill failure and estimate how much is entering from chronic road surface erosion. This analysis also considered whether replacing culverts at risk of failure with bridges would reduce sediment loads to Cottonwood Creek.

The third objective provides an assessment for the larger basin in which Cottonwood Creek lies, by assessing levels of sediment load, inputs of sediment, and attempts to reduce sediment inputs in this broader watershed. Specifically, this objective critiques the Middle Blackfoot/Nevada Creek Basin TMDL's sediment load and reduction estimates for Cottonwood Creek and the Middle Blackfoot in which this sub-basin lies, using information gleaned from the first two objectives as well as the literature. It should be emphasized that the results of this study are only pertinent for similar streams in similar geologic types.

The target audience for this thesis includes scientists, students, non-profit environmental organizations, and regulatory agencies who are interested in water quality issues related to culvert replacement projects in forested watersheds. Specifically, the Lolo National Forest's hydrologists were interested in such a project due to the lack of studies that quantify sediment load from culvert replacement projects. For those who wish to undertake their own study of sediment impacts from culvert replacement projects, the field, analysis, and statistical methods in this thesis could help guide such future studies.

Organization of Thesis

Chapter One is the introduction, describing the needed background information to put the subsequent chapters in the proper framework. Chapter Two explains the study design and describes the study area. Chapters Three, Four, and Five are each devoted to one of the three research objectives, with each chapter covering the methods, results, and discussion for that particular objective. Chapter Six contains the conclusions for all the research objectives.

Literature Review on Stream Sedimentation from Roads and Culvert Failures

In 2005, there were 609,300 km of unpaved forest roads on national forest land (Foltz et al, 2008), with less than 20% maintained according to their originally specified environmental standards (Foltz et al, 2008). Unpaved forest roads are often noted as a significant source of sediment in streams (Reid and Dunne, 1984). Roads and road construction have been found to deliver more sediment to streams than logging activities. Increases in fine sediments from road related erosion degrade fish habitat and other aquatic life (McCaffery et al, 2007). Fine sediments can clog the interstitial gravels, which reduces egg development, and can also trap emerging fry. Macroinvertebrates also are detrimentally impacted by fine sediments.

Roads contribute sediment to streams via mass failures and erosion of the road surface and cut and fill slopes (Duncan et al, 1987; Lane and Sheridan, 2002; Bilby et al, 1989). Roads constructed in wetter climates and on steep slopes, in areas of convergent topography or unstable geology are most prone to mass failures. Surface erosion rate from native (natural) surface forest roads depend on a multitude of factors including precipitation intensity and amount (Sugden and Woods, 2007), geology and soils (Anderson and Potts, 1987; Burroughs and King, 1989; Sugden and Woods, 2007; Packer, 1967), road gradient (Best et al, 1995), road construction method (Best et al, 1995), and the frequency and type of road traffic. Precipitation characteristics such as the rainfall intensity as well as slope and geologic factors determine the rate and velocity of overland flow and hence the sediment transport capacity, whereas geology and traffic frequency determine the availability of sediment (Bilby et al., 1989).

Road erosion rates are usually highest when the road is newly constructed due to the availability of loose sediment and the lack of vegetation on cut and fill slopes, but quickly decline and become increasingly supply limited as the road surface becomes more stable and compacted, and cut and fill slopes develop a vegetation cover. However, grading as well as disturbance by vehicles can temporarily increase erosion rates by renewing the supply of loose sediment on the road surface (Luce and Black, 1999).

Transport distances for the sediment eroded from roads are generally quite short, even in steep terrain, so that most of the sediment actually delivered to streams comes from drainage outfalls located near road stream crossings and from the road sections leading into stream crossings. When undersized culverts become plugged with sediment or wood, the road fill at the stream crossing can be washed out (culvert “failure”) by high flows (Madej, 2001). Plugged culverts can also cause streams to be diverted, causing road surface erosion. Best et al (1995), in a survey of stream crossings in Humboldt County, CA, found that stream diversions caused by plugged culverts caused 68 percent of road-related fluvial erosion; 12 percent of erosion was due to failure of road fills at stream crossings.

Road decommissioning (removing roads from service) is popular for addressing roads with low resource management priority, high risk of failure, or that lie in sensitive areas (Foltz, et al, 2008). Methods of road decommissioning range from blocking the road entrance to completely removing and recontouring the road (Foltz, et al, 2008). Road obliteration is a type of road decommissioning that decompacts the road surface, removes culverts, re-establishes stream channels, and reshapes the road bed (Foltz, et al, 2008).

Studies have been done to determine if decommissioning roads reduces sediment inputs compared with leaving roads intact. In Redwood National Park (RNP), chronic mass wasting problems led the Park to obliterate over 300 km of roads between 1978 and 1992 (Madej, 2001). Obliteration activities included removing stream crossing structures, road fill, and restoring the stream channels. Madej (2001) conducted measurements of cumulative sediment reduction from restored stream channels at former road crossings in RNP after obliteration activities were completed. Between 1980 and 1997, the total volume of erosion from 207 stream crossings following road obliteration treatments was 10,500 m^3 (approximately 50 m^3 per crossing). Mass movement, bank erosion, channel incision, and gullying were the post-road removal erosion characteristics measured. The author concluded that had the crossings not been obliterated, the volume of erosion would have been at least four times greater from probable culvert failure. This was based on measurements in a basin adjacent to the study area, in which the average erosion from 75 failed stream crossings that had not been treated was 235 m^3 (Madej, 2001). Other studies in RNP found similar results; obliterated roads delivered significantly less erosion and sediment to channels than un-obliterated roads (Bloom, 1998).

While the above studies suggest a long-term benefit of sediment reduction by decommissioning roads, there is an implicit assumption that the long term benefits outweigh any short term sediment impacts from the obliteration process. Removing culverts and recontouring the stream bed are major excavation processes and can produce significant levels of sediment to the stream; however, there are few studies that address this (Foltz, et al, 2008; Foltz and Yanosek, 2004).

Foltz and Yanosek (2004) measured the sediment yield from removing a culvert during road obliteration activities in the Nez Perce National Forest, which lies in the highly erosive Idaho Batholith. Removal of the culvert sections resulted in sediment concentrations which peaked at 21,000 mg/l but decreased to 5,000 mg/l in 15 minutes. Rip rap placement in the stream bed caused higher sediment concentration peaks, at 28,000 mg/l, which decreased to 10,000 mg/l in one hour. Sediment concentrations rapidly declined once disturbance ceased, decreasing by a factor of ten within two hours after culvert removal at a monitoring site 20 meters downstream.

On the Flathead National Forest in Montana, Sirucek (1999) modeled the effects from a culvert removal compared to a culvert being plugged and causing part of the road prism eroding away. Different scenarios of different combinations of soil conditions, depth of culvert, mitigation levels, and culvert removal versus failure were modeled. Except in cases where the culvert depth was shallow, the scenario in which the culvert was plugged produced 30- 300 percent more eroded material than a culvert removal scenario in which limited mitigation practices were employed. Most of the stream crossings in this study were in glacial till materials derived from Precambrian metasedimentary bedrock (Sirucek, 2009).

In terms of sediment delivery to streams, Foltz et al (2008) compared their study to a rain-on-snow event in the Clearwater National Forest in 1995-1996, which resulted in over 500 road-related landslides. This area is a highly erosive and unstable area in the Idaho Batholith Border Zone. These landslides occurred on roads similar to those obliterated in the Foltz et al (2008) study, with an average of 400,000 kg of sediment transported to each stream from each landslide. In comparison, sediment yields from culvert removals in the Foltz et al (2008) study only ranged from 2.6 to 170 kg per stream crossing. Based on these comparisons, the authors suggested that sediment delivery from culvert removal is small compared to that from culverts plugging and failing.

Casselli et al (2000) assessed the impacts of a culvert removal project on downstream suspended sediment levels in three streams in the Lolo National Forest. They found that sediment concentrations decreased to near pre-culvert removal levels within about 24 hours after culvert removal work ceased.

Foltz et al (2008), in a study of culvert removals at eleven stream crossings in northern Idaho and western Washington, found that the activities that caused the greatest increase in suspended sediment concentrations were removing culvert sections, moving the excavator across the stream, and placing rocks in the stream channel. Peak suspended sediment concentrations below the culvert outlet were 30 to 2,840 times higher than concentrations above the culvert. Three of the stream crossings had suspended sediment concentrations during the culvert removal process that exceeded 6,000 mg/l for more than one hour.

Culvert replacement operations are helpful for understanding the short-term impacts of road obliteration; culvert replacements are similar to culvert removal activities because both operations involve the removal of the culvert and fill (Foltz et al, 2008). Jakober (2002) monitored a culvert replacement project in the Bitterroot National Forest in which the old culvert was replaced by a larger diameter one. Ninety-five percent of the sediment from the removal activity was introduced into the stream during the first two hours of removal, and suspended sediment concentrations returned to pre-work levels within 26 hours of the start of the removal project. None of the above studies (Foltz and Yanosek, 2004; Foltz et al, 2008; Casselli et al, 2000; and Jakober, 2002) measured suspended sediment during spring high flows.

While there are few studies that consider the short-term impact compared with the long-term impact of culvert removal/replacement operations, there are even fewer studies done in the Belt metasediment geology, which is the geological parent rock in which the thesis study site lies. Most studies have been done in Batholith granites (Foltz et al, 2008; Jakober, 2002), or in other unstable geological types. Cottonwood Creek lies in the Belt series metasediments, which are Precambrian sediments that were subjected to metamorphism (Alt and Hyndman, 1986; Taylor et al, 2007; MT DEQ, 2008; Anderson and Potts, 1987). Soils developed from Belt metasediments are inherently stable due to their chemical and physical makeup (Packer, 1967).

Of the studies discussed above, Casselli et al (2000) and Sirucek (1999) were the only ones done in Belt metasediments. There are two studies that compared the erodibility of soils derived from Belt metasediments to other soil types. Packer (1967), in assessing the erodibility of secondary logging roads, looked at six soil groups in which secondary logging roads were built (hard sediments, basalt, granite, glacial silt, andesite, and loess). The author found that hard sediments (derived from slates and shales) and basalts were the least erosive, while glacial silt, andesite, and loess were more erodible. Belt geology includes hard sediments.

The Sugden and Woods (2007) study on road surface erosion described earlier found that erosion rates were significantly higher in glacial till than Belt supergroups; roads in glacial till produced four times as much sediment as roads in Belt geology. Sediment production from roads built in Belt geology was also lower than typical erosion rates from forest roads built in granitic geology parent rock.

While the Packer (1967) and Sugden and Woods (2007) studies indicate that soils derived from Belt sediments are stable, other studies found otherwise. In McClelland et al (1997), the Northern Region of the Forest Service identified five landslide indicators, including geologic parent material. Of six different geologic parent materials, Belt series metasediments were rated second in landslide frequencies, just after Border Zone metamorphics, and just preceding Idaho Batholith granitics. Therefore, in this study, Belt metasediments had higher landslide frequencies than Idaho Batholith granitics.

Logging roads were built in Belt metasediments near Lake Pend Oreille in northern Idaho (Idaho DEQ, 2002). The area is dominated by glacial scour and deposition, and glacial till makes up the subsoil and substratum layers of the soil. The area was plagued by fill slope failures and plugged culverts, which caused water quality problems from increased sediment loads. One area in particular, where a road crossed steep drainages, was considered one of the most erosive landtypes on the Idaho Panhandle National Forest (Idaho DEQ, 2002). This study serves to illustrate that glacial tills (presumably derived from Belt parent rock) can be very unstable. This is also consistent with the results from Sugden and Woods (2007).

The above studies suggest that culvert failure risk and road surface erosion can be reduced by either culvert removal or replacement by larger culverts or bridges. There were few studies that compared sediment yields from culvert removals/replacements to culvert failure; these found that the former produced far less sediment than the latter, making culvert removals or replacements a worthwhile endeavor. Most studies that compared erosion rates between different geological formations suggested that Belt metasediments are more stable than other formations, although there were cases where Belt metasediments were associated with high frequencies of landslides and erosion. Glacial till was associated with higher erosion rates than other geologic groups, such as the Belt supergroups or basalts.

Based on the above studies, it was expected that this thesis would find a lower sediment yield from replacing a culvert with a bridge than from a culvert failure. The study area lies in Belt metasediments and glacial till geology; the stream crossing lies in glacial till, and the area upstream is a mix of the two geologies**.** Based on the literature, it was expected that there could be a high level of sediment yield from the replacement, but unlikely; field visits found the stream banks and upper reaches stable in terms of erosion (i.e., well-vegetated areas and lack of sediment in the stream).

CHAPTER 2: STUDY DESIGN

Study Design

This is an observational and quasi-experimental study; only a few parameters can be controlled or manipulated (for example, sampling upstream and downstream at the same time provides some control. In addition, removing the culvert is a manipulation). Thus, there are many factors that can affect the outcome, producing measurement and method “errors” and difficulty in interpretation.

Research Objectives and how each is Addressed

Research Objective #1: Net Sediment Yield Analysis for Culvert to Bridge Replacement

The first research objective compared (a) estimated annual sediment load that included a culvert failure and chronic road surface erosion from an undersized culvert with (b) estimated annual sediment load that included replacing a culvert at a stream crossing with a bridge in Cottonwood Creek. Estimates were based on two time periods, when most of the annual sediment load is expected to occur: during the culvert upgrade project and during the spring snowmelt both before and after the upgrade.

The approach to estimating the sediment load is as follows: If the culvert was not upgraded to a bridge, what would the sediment load likely be from road surface erosion and a culvert fill failure? To answer this, the following measurements are needed:

- Load based on culvert fill volume that could be delivered to the stream during a failure.
- Spring snowmelt load (from suspended sediment and discharge measurements taken during 2007 spring snowmelt, the year before upgrade), which is a baseline for suspended sediment levels.
- Estimated load from sediment delivered to the stream from road surface erosion with an undersized culvert.

If the culvert is upgraded to a bridge, what is the sediment load due to the upgrade operation? To answer this, the following measurements are needed:

- Sediment load during the upgrade operation (from suspended sediment and discharge measurements taken during the upgrade).
- Spring snowmelt sediment load (from suspended sediment and discharge measurements taken during the 2008 spring snowmelt, the year after the upgrade).
- Estimated load from sediment delivered to stream from road surface erosion with a bridge in place; road surface erosion is expected to be less than with an undersized culvert.

Measurements taken during spring snowmelt the year before and the year after the upgrade, and during the upgrade itself, were each discrete time periods; sediment load is only calculated for those time periods. These three time periods are assumed to represent much of the annual load. The total sediment load for the culvert upgrade situation is then compared to that of the non-upgrade situation to determine which produces a lower load over the long-term – with or without an upgrade. An important assumption in this analysis is that without an upgrade, the culvert will eventually fail.

Research Objective #2: Risk Assessment of Cottonwood Creek Stream Crossings

Other stream crossings throughout the Cottonwood Creek watershed that are high risk sites for culvert failure and road surface erosion were assessed in this research objective. Peak flows were calculated at different recurrence intervals and using this information, the capacity of each culvert at each stream crossing was determined for each return flow. This was determined by taking measurements of the dimensions of each culvert, and using a nomograph to determine the capacity. For culverts that failed to meet the necessary capacities for any given return flow, the amount of sediment load that would enter the stream should the culvert fail, was found using the measurements of culvert fill at each crossing. A scenario of replacing undersized culverts predicted to fail with bridges was compared with a scenario in which these culverts were not replaced. Sediment loads for each scenario were compared to see if replacing these culverts resulted in a net decrease in sediment delivery to Cottonwood Creek.

For road surface erosion, using the WEPP model, the amount of chronic road surface erosion for each high-risk stream crossing was determined for a ten-year period. The WEPP model documentation gave no guidelines for how long a time period should be modeled, so a ten-year period was arbitrarily chosen.

Research Objective #3: Critique of Middle Blackfoot/Nevada Creek TMDL Sediment-Related Issues

This research objective critiqued the final Middle Blackfoot and Nevada Creek TMDL, focusing on Cottonwood Creek and the Middle Blackfoot basin, to determine if this document adequately assessed sediment sources, sediment load, and estimates for sediment load reduction. This critique was based on literature review and findings from the first two research objectives.

Study Area Description

Study Area Location: Cottonwood Creek, Tributary of Blackfoot River

The study area lies within the Cottonwood Creek watershed, a 69 square mile (17,871 hectare), third order tributary to the Blackfoot River. Cottonwood Creek lies approximately eight miles east of Seeley Lake, Montana. **Figure 1** shows the location.

Climate

The Continental Divide strongly influences the climate of this region. The study area lies west of the Divide, in a modified north Pacific coast type of climate (Western Regional Climate Center, 1985). There is thus a maritime influence from the Pacific Ocean, and winters are milder than east of the Divide. Precipitation is higher than east of the Divide and is also more evenly distributed throughout the year, with cooler summers and lighter winds. Humidity is slightly higher than in the eastern part of the State (Western Regional Climate Center, 1985).

Climate information for the study area was obtained from the Western Regional Climate Center for the Seeley Lake Ranger Station Climate Station (Western Regional Climate Center, 2009a) and Ovando 9 SSE Climate station (Western Regional Climate Center, 2009b). For the Seeley Lake Station, climate data was based on average monthly climate records from 1938 to 2008. The average annual maximum temperature was 55.3 degrees (F), and average minimum temperature was 27.3 degrees (F). Average total precipitation was 20.93 inches, and average total snowfall was 120.1 inches. The Ovando 9 SSE Climate Station covered a period of record from 1976 to 2009. The average annual maximum temperature was 54.2 degrees (F), and average minimum temperature was 23.8 degrees (F). Average total precipitation was 12.4 inches, and average total snowfall was 36.4 inches. **Appendix A** gives the complete monthly averages for both climate stations. Because of climate changes in recent decades, these data may be inaccurate; temperatures may be increasing, while precipitation and snowfall levels are decreasing.

Hydrology

The Cottonwood Creek watershed is a dendridic-shaped drainage basin with streams flowing from the north and northwest to the south. Elevations range from 4600 to 8100 feet, and the drainage density is 0.07.

Cottonwood Creek’s major tributaries are: North Fork Cottonwood Creek, Little Shanley Creek, Shanley Creek, and Black Canyon Creeks. The headwaters of all these creeks lie in the high alpine mountains of the Bob Marshall Wilderness. These streams carry the majority of water to Cottonwood Creek. The lower reaches of Cottonwood creek flows through grasslands and drains into the Blackfoot River just south of Highway 200.

All the streams in the Cottonwood Creek watershed have a snowmelt-dominated hydrograph that generally peaks between April and June. None of these streams are gaged; to determine flood frequencies at different return intervals (Q2, Q5, Q10, Q25, Q50, and Q100 floods) for the basin, regression equations developed by Omang (1992) were used. These equations were developed for the West Hydrologic Region, which includes the Blackfoot watershed (USGS, 2007). These equations use basin area (square miles) and annual precipitation (inches) as explanatory variables to determine peak flows for each return interval. **Appendix B** shows these equations with the standard error of prediction associated with each (Omang, 1992).

Peak flows were estimated for the entire Cottonwood basin; i.e., upstream from the mouth at the Blackfoot River. The basin area was determined to be 69 square miles by using GIS measuring tools, and the average annual precipitation was 42 inches (NRIS, 2009). **Table 1** shows these peak flows(in cfs) for the Q2, Q5-, Q10-, Q25-, Q50-, and Q100- return intervals. For each return interval, one standard error above and below the predicted return interval is also given. The “one standard error” is based on the standard error of prediction (percent) for each return flood as shown in **Appendix B**.

Omang (1992) stated that the average standard error of prediction at an ungaged site measures the expected accuracy of the regression model’s ability to estimate a given return flood. The true value of a given return flood is within plus or minus one standard error of prediction from the predicted value approximately two out of three times.

Actual peak flow data were not available for the Cottonwood Creek watershed, so to gain an idea of what return floods the 2007 and 2008 study years were, peak flow data from a nearby gaged stream, the North Fork Blackfoot River, was examined. This is approximately four drainages to the east of Cottonwood Creek, but is still in the same hydrologic region (i.e., similar climate) as Cottonwood Creek. Therefore, it can be used to estimate what return floods 2007 and 2008 were for Cottonwood Creek.

Annual peak flows for the North Fork Blackfoot River were obtained from the USGS Water Resources of Montana website (USGS, no date(a)). To determine the return interval for 2007 and 2008, flood frequency curves were developed for the North Fork Blackfoot River using the methods in Dunne and Leopold (1978). The results shown in **Appendix C** indicated that 2007 was a 2-year return interval, and 2008 was a 4-year return interval, which are typical snowmelt years (as opposed to, say, a 50-year return interval).

However, the North Fork Blackfoot River peak flow data only covered a ten-year period (1998- 2008); stating that the study years were 2- and 4-year return intervals is only relevant for the last ten years and not necessarily for longer periods of time. A search of other nearby gaged sites on the USGS website failed to find any others that covered longer time periods.

The flow duration was calculated for the region (i.e., the larger Blackfoot watershed area) using monthly mean data for Monture Creek for a period of record between 1973 and 1983 (USGS, no date). Parrett and Hull (1985) delineated hydrologic regions in western Montana that had similar characteristics that influenced hydrology, such as climate. Streams within a given hydrologic region could be expected to have similar flow duration curves. Monture Creek is in the same hydrologic region as Cottonwood Creek (and they are both in the Blackfoot watershed). To obtain a regional flow duration curve, Monture Creek’s monthly mean discharges were divided by its basin area (140 square miles); the result was monthly mean discharges per square mile (USGS, no date). This “normalized” the monthly mean discharges to the larger hydrologic region. **Figure 2** shows this normalized regional flow duration curve. Approximately two percent of the time, discharge exceeds 6 cfs per square mile for the region, and 20 percent of the time, it is above 2 cfs per square mile.

Topography

The topography in Cottonwood creek is diverse, ranging from highly dissected mountains, to flat, rolling valleys. The headwaters of Cottonwood, Shanley, and Black Canyon lie in high elevation wilderness areas, and have alpine ridges, glacial cirque headwalls, and steep mountain slopes (Sasich and Lamotte-Hagen 1989). This is a generally northerly facing aspect. Mid elevations (4,600-6,600 feet) are steep, subalpine mountain slopes, with moderate relief and varying aspects, while the riparian areas lie in either gently rolling hills or high relief mountain valley bottoms in glaciated valleys (Sasich and Lamotte-Hagen 1989). Lower elevations are flat plains and rolling hills, in large glaciated valleys composed of glacial outwash associated with major valley and continental glaciations (Sasich and Lamotte-Hagen 1989).

Geology and Soils

The Cottonwood Creek watershed lies in Precambrian Belt sedimentary formations (MT DEQ, 2008). Belt rocks originated from thick deposits of sediments that accumulated beginning about a billion years ago (Alt and Hyndman, 1986). Metamorphosis in some areas followed, producing argillites and quartzite (Thompson and Turk, 1993). Glaciation in the Pleistocene era carved the landscape, dumping glacial till on the area (Alt and Hyndman, 1986). Glacial till is mainly derived from the surrounding Belt series and sedimentary parent rock (Sugden and Woods, 2007). Soils derived from Belt series and glacial till in western Montana have a high amount of coarse fragments, which reduces erodibility.

Appendix D shows a map of the geology types in the Cottonwood Creek watershed; all are sedimentary, with a combination of Belt series, alluvium, and glacial till. There are two types of Belt series-Missoula and Piegan. Both are Precambrian, and contain mainly argillite, limestone, quartzite, and shale (MT NRIS, 2009a). As shown in the map, alluvium lies mainly in the lowest elevations, but there are some in higher elevations. Glacial deposits make up the majority of the geology types in the watershed, and lie at lower elevations.

Soils information was obtained from the Natural Resources Conservation Service (NRCS) soil survey geographic (SSURGO) database for the Missoula and Powell County Areas (USDA NRIS, 2004; USDA NRIS, 2009). The northwest area of Cottonwood Creek lacks soils information, likely because it lies in a wilderness area so was not mapped.

Most of the soils in Cottonwood Creek were formed in volcanic ash-influenced loess overlying either metasedimentary bedrock, alluvium, or glacial till derived from metasedimentary rocks (Sasich and Lamotte-Hagen 1989). Soils are generally gravelly loams, cobbly loams, silt loams, sandy loams, and clay loams (USDA NRCS, 1995; USDA NRCS, 2003). Most of the soils are well-drained, or moderately-drained, due to their derivation from glacial till (Sasich and Lamotte-Hagen 1989, USDA NRCS, 1995; USDA NRCS, 2003). Some of the soil types in the lower elevation large glaciated valleys are poorly drained (Sasich and Lamotte-Hagen 1989; USDA NRCS, 2009; USDA NRCS, 2004).

Stream Morphology

The steep headwaters streams are classified as A or B, using the Rosgen methodology (Rosgen, 1996). These areas are laterally confined, and flow through steep, narrow valley bottoms (MT DEQ, 2008). At mid-elevations, these streams transition into more sinuous gravel bed C type channels, and at lower areas, where the topography is composed of rolling hills with grasslands, mixed grasslands/forests, and willow-dominated areas, there are a range of stream types (C, Da, E, and F type channels), depending on level of entrenchment and width-depth ratio (MT DEQ, 2008).

Vegetation

Vegetation is diverse, reflecting the varied landscape within Cottonwood Creek. Vegetation types were derived from the Lolo National Forest Land Systems Inventory (Sasich and Lamotte-Hagen 1989) for the forested areas, and Missoula and Powell County soil surveys for the grasslands (USDA NRCS, 1995; USDA NRCS, 2003). These documents describe vegetation community types associated with different landforms and soil types; this thesis uses the same classification method to describe some of the major vegetation community types found in the Cottonwood Creek watershed (there are too many vegetation types to list all of them):

1. High elevation (above 6000 feet) ridges and mountain faces: This contains the upper subalpine forests, mixed forests with subalpine fir, spruce, whitebark pine, with an understory of sitka alder, menseiza, mountain maple, grouse whortleberry, woodrush, and beargrass.
2. Mid-elevation (4000-6000 feet) ridges and mountain faces: This area has mixed forests of lodgepole pine and douglas fir, with occasional ponderosa pines and western larch in southerly facing aspects. The understory includes blue huckleberry, beargrass, pinegrass, snowberry, rocky mountain maple, spirea, and blue bunch wheatgrass. The more northerly facing slopes contains western larch, douglas fir, lodgepole pine, spruce, subalpine fir, grand fir, and mountain hemlock, with an understory including beargrass, sitka alder, menzeisa, rocky mountain maple, elderberry, and blue huckleberry.
3. Mountain valley bottoms, narrow stream valleys, and large glaciated valleys: This low- to mid-elevation area (3600-6600 feet) is a moist, mixed community, with subalpine fir, spruce, western white pine, western red cedar, lodgepole pine, western white pine, western larch, grand fir, and douglas fir. Ponderosa pine is present in some southerly aspects. The understory includes menzeisa, blue and dwarf huckleberry, queencup beadlily, Oregon grape, serviceberry, sitka alder, rocky mountain maple, elderberry, and beargrass.
4. Riparian areas of flat glacial outwash plains: This mid-elevation area (3200-4600 feet) contains an overstory of subalpine fir, spruce, lodgepole pine, and cottonwood. The understory includes queenscup beadlily, false hellebore, arnica, red osier dogwood, rocky mountain maple, mountain alder, twinberry, various species of willow, and beargrass.
5. Stream breaklands and flat outwash plains: This is a dry, mixed douglas fir community, with ponderosa pine, lodgepole pine, western larch, and douglas fir predominating as overstory. Understory includes ninebark, twinflower, serviceberry, dwarf and blue huckleberry, oceanspray, snowberry, Oregon grape, knickknick, woods rose, beargrass, and pinegrass.

6. Grasslands and mixed grasslands-forests: These are the lower elevations of the watershed and are composed of douglas fir, ponderosa and lodgepole pines, and western larch. The understory includes blue and dwarf huckleberry, arnica, ninebark, snowberry, spirea, elk sedge, bear grass, pippsiwa, Oregon grape, blue bunch wheatgrass, and fescue.

CHAPTER 3: RESEARCH OBJECTIVE #1, NET SEDIMENT YIELD ANALYSIS FOR CULVERT TO BRIDGE REPLACEMENT

Methods

Field Sampling Methods

Suspended Sediment and Discharge Measurements; Sampling during Spring Snowmelt: Field sampling for suspended sediment and discharge was done during three time frames: spring snowmelt 2007, during the culvert replacement (fall, 2007), and spring snowmelt, 2008. For both snowmelt sampling years, ISCO automated samplers were used to collect water samples for Total Suspended Sediment (TSS) and turbidity analysis. A probe on the end of a tube collected water samples at predetermined times.

Samples were collected simultaneously from upstream and downstream of the stream crossing. Upstream samples were compared to downstream samples to determine how much sediment was added by the stream crossing.

Appendix E describes how locations for the ISCO probes were determined. The ISCO samples were programmed to collect samples every three to five hours, depending on the frequency of visits. At each visit, manual flow measurements were taken across a cross-section in order to calculate a stage-discharge curve. In addition, stage measurements were taken at each visit from a stage gage placed near the downstream ISCO probe.

Due to logistical constraints, sampling in 2007 did not begin until mid-May, and based on the hydrograph for the nearby North Fork Blackfoot River, it is believed that peak flows occurred a week prior to the beginning of field work (USGS, 2008). Therefore the rising limb and peak flows were not captured that year. In 2008, field work began about two weeks before peak flows, so the rising limb and peak flows were captured for that year.

The stage gage was removed during the culvert replacement operation in September, 2007, and was re-installed in 2008. In 2008, during peak flows, it was removed by high flows; it was replaced, but the stream bed had changed, so a new stage-discharge relationship was necessary. Therefore there are two stage-discharge curves for spring snowmelt 2008.

Because the ISCO samplers lacked a continuous flow meter, a water level recorder was used to measure continuous water levels. Each water sample collected by the ISCO samplers was matched with a water level recorder value by correlating the times each was collected. The stage discharge curve was used to determine the associated discharge with each water level value. The water level recorder was installed with its probe in a stilling well near the downstream ISCO sampling probe, located at a riffle crest. When peak snowmelt flows had passed, the ISCO samplers and water level recorder were removed. For 2007, ISCO samplers were in place between May 11 and June 4, and for 2008, samplers were in place between May 6 and June 27.

Problems and Sources of Error for Spring Snowmelt Sampling: There were several problems and sources of error with sampling for suspended sediment and turbidity during spring snowmelt. One error was that the rising limb was only measured in 2008, but not in 2007; therefore, the complete hydrograph for 2007 was missing and could not be compared with 2008. Only the falling hydrographs were compared between the two snowmelt years, which exclude some critical data because most of the suspended sediment during spring snowmelt occurs on the rising limb (Thomas, 1988; Anderson and Potts, 1987).

For 2008 spring snowmelt, only the rising and falling limb data was collected; there is no peak flow data. High floods during the night of May 18 removed the water level recorder and buried the downstream ISCO probe under four inches of bedload. Thus, the sampler was unable to fill bottles with suspended sediment.

Another source of error was assuming constant discharge and suspended sediment concentrations in between the sample collection events. The time in between sample collection ranged between three hours and several days (operator error was the cause of the longer time intervals). Because discharge and suspended sediment fluctuate rapidly during the rising and falling limbs of the hydrograph, assuming they were constant for such long periods of time imparts much error.

When either the upstream or downstream ISCO sampler did not collect samples, the result was unpaired data. Unpaired data were not used, because there was no way to know if the missing sampler data coincided with a large increase or decrease in suspended sediment.

There are also possible spatial sampling errors; water quality samples were collected by an ISCO probe at one location in the stream. This could introduce bias into the sampling if suspended sediment in the water column was not thoroughly mixed. This may have been a problem in 2008; the upstream samples had higher suspended sediment load than downstream. It is suspected that these high loads came from a stream bank slumping across from the upstream sampler probe during peak flows. It is speculated that the upstream ISCO probe caught the unmixed sediment plume; by the time the sediment reached downstream, it was more mixed, and the dilution effect resulted in lower suspended sediment levels for downstream samples.

Stream discharge measurements were indirectly calculated from the water level recorder data. This method assumed there was a strong linear relationship between discharge and stage, so that stage could be used to predict discharge. For 2007, the R^2 between discharge and stage was 0.68. For 2008, there were two curves; one with an R^2 of 0.99 (but this was based on only two data points) and one with an R^2 of 0.31. Therefore, using stage to predict discharge for these curves contains errors due to a lack of a good fit between these two variables.

The water level recorder stopped collecting data at different times due to operator error and being ripped out during peak flows. Missing water level recorder data was estimated using a combination of manual flow measurements and extrapolating between known recorder values. However, as these are estimates, there is some error with these values.

A challenge in comparing snowmelt years was created by differences in stream discharge between the years. Because 2008 had higher flows than 2007, it is difficult to compare the two spring flows; were the higher levels of suspended sediment in 2008 due to the culvert replacement or due to higher flows?

Suspended Sediment and Discharge Measurements; Sampling during Culvert Replacement: The field methods during the culvert replacement project were slightly different than for spring snowmelt sampling. The two-day project involved removing the culvert, building rock weirs just downstream and upstream of the culvert's original location, and putting in a bridge in the old culvert's location. The first day, two rock weirs were built downstream, and the second day, the culvert was removed and the newly exposed stream channel was excavated to adjust its slope. Then two more rock weirs were placed upstream.

Grab samples using a one-liter bottle were taken just upstream and downstream of the disturbance. Grab samples were taken the day before and just prior to culvert work to establish base conditions.

Stream discharge was measured two days prior to, the night before and the morning of the culvert work. Because it was not expected that discharge would change, stream flow measurements were taken only once during the operation, when there was light precipitation. The discharge did not change due to the rain.

The sampling intervals during the culvert upgrade work varied. During work, it was every 10-15 minutes; when work stopped for a period of time, it was done every 20-30 minutes. Sampling continued after work stopped for the day until the stream “ran clear,” which was within an hour.

Only samples taken from riffles were analyzed for suspended sediment to see if there was a significant difference between upstream and downstream samples. Turbidity was assessed to determine if it exceeded state standards, and to consider if there was a turbidity-suspended sediment relationship.

Problems and Sources of Error for Culvert Replacement Sampling: There are significant errors. Much of the suspended sediment entering the stream was not captured correctly; for the second day of culvert work, approximately half the samples were collected in pools, not riffles. Samples from pools cannot be used in the data analysis. Therefore, about half the data is missing for the second day. The true value of the sediment load is therefore likely to be about twice that of the existing data.

Other sources of error were locations and timing of suspended sediment water quality collection. When there was a disturbance pulse, i.e., a boulder dropped in the creek, sample collection was done downstream. Attempts were made to collect samples where the suspended sediment had become well-mixed, yet not had a chance to settle; there may have been over- or under-representation of suspended sediment if samples were not correctly collected.

Another error was assumption of constant suspended sediment concentrations in between measurements. Sampling was done frequently, approximately every 10-15 minutes during work and 20-30 minutes when work ceased. However, because the sediment settled sometimes within minutes, a more frequent measurement protocol would have captured more subtle variations. Lack of sufficient quantities of bottles precluded more frequent sampling.

Stream Bank Erosion: Stream bank erosion measured after the spring flood of 2008 was quantified using methods from Harrelson et al (1994) and Madej (2001). Bank erosion volume was measured using a combination of erosion pins and estimations of the amount of sediment from the voids left after bank slumping. A source of error could be due to incorrectly measuring the amount of sediment eroded away. Most of the erosion pins were removed by the flood, so the original bank edge location was estimated, along with the voids left by the eroded sediment. Madej (2001) found an error of plus or minus 25 percent with this method. Total volume of eroded stream bank was estimated and multiplied by the soil bulk density for the soil type located at the stream crossing to determine load. Soil bulk density information was acquired from the Natural Resources Conservation Service's (NRCS) Soil Data Mart website (USDA NRCS, 2009a).

Determination of Culvert Fill Volume if Culvert Failed: Geometric measurements of the fill around the culvert were taken before it was removed. It was assumed if a culvert failed, the entire amount of fill would enter the stream. To determine the volume of fill that could enter a stream should the culvert fail, the fill volume (length*width*height) minus the volume of culvert void space $[\pi*(d/2)^2*l]$ was calculated (RDG, 2006). This was multiplied by soil bulk density to calculate sediment load (kg). The total amount of fill was multiplied by the soil bulk density for the soil type in the area to obtain the sediment load in kilograms. The error here would be incorrectly measuring the geometric dimensions of the fill area.

Estimation of Road Surface Erosion using WEPP model: To assess chronic surface erosion from roads at high risk stream crossings, the Water Erosion Prediction Project (WEPP) model was used (USDA, 2008) to model erosion annually (for a ten-year period). Several parameters were used in this model, and entered in the interactive online WEPP model. **Appendix Q** shows these parameters. The developer of the model recommended setting buffer length to the minimum possible because the buffer is generally negligible (Elliot, 2008). There is approximately plus or minus 50% error with WEPP (Elliot, 2008).

Substrate and Stream Morphology Assessments: Analysis of stream substrate and channel morphology was done prior to and after the culvert upgrade. This was not part of the research objectives, but was a useful analysis to determine if any changes had occurred to stream substrate or channel form after the upgrade. **Appendix S** contains this information.

Laboratory Analysis of Water Samples

Once water quality samples were collected, they were kept as cool as possible to prevent degradation until they were analyzed. Laboratory procedures were the same for the three sampling time periods (spring snowmelt 2007, the culvert removal event, and spring snowmelt, 2008). Analysis for total suspended solid concentrations and turbidity were done in a laboratory, using standard analysis procedures (APHA, 1998; Hach, 2007).

A Hach 2100 P portable nephelometric turbidimeter, with a range between 0.01 to 800 NTUs, was used to analyze turbidity. Turbidity measurements followed the protocols described in the manufacturer's manual (Hach, 2007) and the methods described in Anderson (2005). Turbidity is sensitive to degradation and therefore samples should be kept cool after collection, and should be analyzed for turbidity within five days of collection (Suplee, pers com.). However, this was not always possible when there were large numbers of samples to process; some samples were kept for up to two weeks. Some degradation is possible.

Prior to sample analysis, the turbidimeter was calibrated according to manufacturer's specification, using StableCal Primary Standards. Following calibration, each standard was run to ensure the turbidimeter was reading known standards correctly. In addition, the stray light value was read, where the turbidimeter was run without a sample in the cell. The value was always less than 0.10 NTU, the maximum reading recommended by the manufacturer. All these procedures were done before each set of 24 samples were run. For each set of samples (approximately 24), three replicates and three blanks were run.

For turbidity analysis, samples were first warmed to room temperature, then gently inverted five to seven times to mix the sample while minimizing introduction of air bubbles (air bubbles could elevate turbidity readings) (Hach, 2007). Approximately 15 mls of sample was poured into a clean glass cuvette provided by the turbidimeter manufacturer. The same cuvette was used for all samples.

Each sample was run three times in the turbidimeter to allow for variation in readings. Each run produced ten readings, and the median of these 30 readings was taken. There was considerable variation among the 30 readings, which was attributed to air bubbles and lack of sample representativeness. For each sample, the variation between these 30 readings ranged from zero to 200 percent. In between runs, samples were gently inverted to keep particles suspended.

When samples exceeded 800 NTUs, they were diluted with tap water. To determine the turbidity of the sample, this formula was used (Anderson, 2004):

$$Ts = Td \times \frac{(Vo + Vs)}{Vs}$$

Where Ts= turbidity of the sample, Td=turbidity of the diluted sample, Vo = volume of turbidity-free water in the diluted mixture, and Vs= volume of the sample in the diluted mixture.

Analysis for total suspended solid concentrations was conducted using the standard gravimetric procedures described in the American Public Health Association’s “Standard Methods for Examination of Water and Wastewater, 20th Ed. (APHA, 1998). The samples were analyzed within three weeks of collection for total suspended solid concentrations, which was well within the time range of 120 days recommended by the Kentucky District Sediment Laboratory (2006).

To determine total suspended solid concentrations, a vacuum was applied to a measured volume of each thoroughly-mixed sample, which was drawn through a glass filter (Pall type A/E, glass fiber filter, 47 mm) of known weight, using a vacuum apparatus. The filter and filtered sample were dried in an oven at 105 degrees Celsius for a few days, placed in a dessicator, and weighed on a Mettler H20T analytical balance with a precision (standard deviation) of plus or minus 0.01 mg.

Samples were weighed to the nearest 0.00001 gram. The filters were then returned to the oven for another day and reweighed. If the two weights differed by more than 0.0005 grams or 4 percent (APHA, 1998), the filter was re-dried until the difference in weights were within this 0.0005 gram/ 4 percent standard.

Many filters with samples weighed less than the weight of the filter alone. To determine why, several blank filters were dried and weighed, then a constant quantity of water was filtered through them. These were then dried and weighed. Approximately half of these blanks weighed less after filtering than before (the mean was 0.003 grams less). It was speculated that glass fibers were lost during the filtering process. To compensate, 0.003 grams were added to the weight of all samples after they were filtered. As part of QA/QC, three blank filters were run for each set of samples (approximately 20-24 samples).

Problems and Sources of Error: Sources of error with the turbidimeter included air bubbles in the samples, and samples not representing the larger samples. The larger sample was inverted to mix the contents; this risked adding air bubbles, even if inverted gently. Air bubbles increase the turbidimeter readings, while pouring contents too slowly (so particles settle) decrease the turbidimeter readings.

For suspended sediment analysis, both the analytical balance and filtering procedures added error. For the analytical balance, there was variation in the analytical scale from normal drift. The error from normal drift was determined by measuring known standards repeatedly and calculating the standard error. The standard errors for the 5, 10, 100, and 500 mg, and 1 gram standards were 0.2%, 0.1%, 0.01%, 0.002%, and 0.002%, respectively.

Data Analysis

Suspended Sediment Analysis: There were three time frames of analysis: snowmelt the spring before the culvert replacement (spring, 2007), during the culvert replacement (fall, 2007), and snowmelt the spring after the culvert upgrade (spring, 2008). **Table 2** shows the period of time for each time frame.

Only upstream/downstream sample pairs were included in data analysis; non-paired samples were not, but are discussed in the Results section. Determination of total suspended solids (TSS) and sediment load was done using the same Excel spreadsheet techniques for all three time frames. To determine suspended sediment on filters, the difference between the filter weight before the sample was filtered onto it and the filter weight after the sample was filtered onto it was taken. The 0.003 gram correction factor (to compensate for fiber loss during filtering) was added to this value.

To calculate the total suspended solid concentrations (milligrams of sediment per liter of water), the following equation was used, a modified version from APHA (1998):

$$\text{Milligrams total suspended solids/Liter} = \frac{[(A-B) + 0.003\ \text{g}] \times (1000)}{\text{sample volume, ml}}$$

where: A = weight of filter + dried residue, grams

B = weight of filter, grams

The modification was adding the 0.003 gram correction factor to the difference between A and B. The end result was multiplied by 1000 to convert it to milligrams/liter.

Each total suspended solid/liter value was examined to see if it was below the detection level, which was 6 milligrams/liter. **Appendix F** explains how the detection limit was determined.

To determine sediment load, stream discharge data were needed. For the spring snowmelt period in 2007 and 2008, this was indirectly calculated from the water level recorder data (during the culvert upgrade, stream discharge was directly measured using a flow meter). The corresponding water level recording was determined for each suspended sediment sample, using a stage discharge curve. These discharge values (liters/second) were entered into the Excel spreadsheet and multiplied by their corresponding total suspended solids concentration (mg/liter) to obtain sediment load (mg/second).

Sediment load was expressed as kilograms per time interval between sample collection events, rather than per day, or per year. To do this, sediment load (mg/second) was multiplied by the time interval between ISCO sample collection events and finally divided by 1000 to obtain sediment load per time interval in kilograms. To find the total load for the snowmelt time period, the sediment loads per time interval were summed.

Because none of the data were normally distributed, the nonparametric Wilcoxon Sign Rank test was used to see if the difference between paired downstream and upstream suspended sediment load data were significantly different from zero. The same test was used to compare the pairs for spring snowmelt 2008 with the pairs for spring snowmelt 2007 to determine if they were significantly different from zero.

The Wilcoxon Sign Rank test compares medians, not means, which are a more robust measurement of central tendency and is an appropriate test when data are not normally distributed (Ott and Longnecker, 2001). Medians are not strongly affected by outliers, as in the case with means; therefore the median is a better estimator of the central value of skewed data than the mean (Helsel, 1990).

For each snowmelt year, and for the culvert replacement, upstream and downstream pairs of sediment loads were compared to determine if they were significantly different from zero. The null (Ho) hypothesis was that the distribution of differences is symmetrical around zero i.e., the distribution for downstream and upstream is the same. The expected (Ha) hypothesis was that the differences between downstream and upstream sediment load are larger than zero (as a result of sediment released by the culvert removal).

The upstream and downstream pairs of sediment loads for spring snowmelt 2007 and 2008 were then compared, using the Wilcoxon Sign Rank test. The null (Ho) hypothesis was that the distribution of differences is symmetrical around zero i.e., the distribution for 2007 and 2008 snowmelts are the same. The expected (Ha) hypothesis is that the differences between 2007 and 2008 snowmelt are larger than zero. A sediment rating curve was also created to help understand how varying discharges affected levels of suspended sediment, and how these curves were different for the two spring snowmelt years.

Turbidity Analysis: The descriptive statistics for turbidity results were described, and the medians of the turbidity samples in each period of interest (each snowmelt before and after the culvert upgrade, and during the upgrade) were examined to see if they exceeded state water quality standards. Each turbidity value was examined to see if it was below the detection level, which was 5 NTUs. Appendix E explains how the detection limit was determined. The relationship between suspended sediment concentrations (TSS) and turbidity was examined using linear regression, to see if turbidity could be used to predict TSS. Because turbidity is easier to determine than TSS, it is desirable to use turbidity to predict TSS if there is a strong linear relationship between these variables.

Comparing Culvert Replacement to Non-Replacement for Key Loading Periods: To estimate the total sediment load from the culvert replacement, downstream-upstream sediment loads for spring 2008 snowmelt and the culvert replacement project were summed. To estimate total sediment load from not replacing the culvert with a bridge, estimated sediment load from a culvert fill failure was added to the sediment loads from road surface erosion (estimated from each scenario) and downstream-upstream spring 2007 snowmelt.

Quality Assurance/Quality Control

Water Level Recorder: There were several quality assurance/quality control measures used. To check the accuracy of the water height measured by the water level recorder, manual stage measurements were taken at each field visit, using a yardstick as a dipstick in the stilling well. The difference between water level recorder heights and manually-taken heights ranged between 0.03 and 1.83 inches; the relative percent difference between each water level recorder height and a manually-taken height measurement ranged between zero and 18 percent for spring 2007, and from 10 to 20 percent for spring 2008. It is recommended that the relative percent difference between a sample and its duplicate be below 25 percent (Ministry of Environment, Lands and Parks, British Columbia. 1998). In most of these measurements, the water level recorder height was higher than the yard stick height.

To measure how well water level-derived discharge measurements corresponded to manual flow measurements, the relative percent difference between each manual flow measurement and its corresponding water level-derived discharge measurements was taken. For 2007, the difference between these measurements ranged between zero and 50 percent, while for 2008, it ranged from zero to 80 percent. The high percent differences were attributed to the fact that the water level recorder was not working during certain time periods due to operator error, and thus the water level heights were extrapolated from water level readings before the equipment ceased working.

ISCO Sampler: Manual grab samples were taken at each visit to check the accuracy of the ISCO samplers. While the ISCO sampler collected a sample, samples using a depth-integrated DH48 sampler were taken in four locations across the stream to see if the ISCO sampler was capturing samples that represented other cross sections of the stream. Suspended sediment concentrations were compared between ISCO and DH48 manual samples to see if they were similar.

For spring snowmelt 2007, two QA/QC sample sets were taken. The relative percent difference between the upstream ISCO sample and its replicate DH48 manual sample was 21 percent, and for downstream, 20 percent. These are within the suggested guidelines of 25 percent (Ministry of Environment, Lands and Parks, British Columbia, 1998). For one sample set, the ISCO samples had higher concentrations, while in the other sample set, the reverse was true.

For spring snowmelt 2008, six QA/QC sample sets were taken. The relative percent difference between the upstream ISCO sample and its replicate DH48 manual sample ranged between zero and 120 percent, while for downstream, the range was between zero and 140%. Many of these replicates exceed the 25% limit suggested in the literature (Ministry of Environment, Lands and Parks, British Columbia, 1998). The variation may be due to the fact that the ISCO sampler collected samples in only one location, while the DH48 sampler collected samples across the stream; variations in TSS may thus be due to spatial influences. ISCO samples had higher concentrations than DH48 samples about 60 percent of the time, and eight percent of the time they were the same.

Turbidity and Suspended Sediment: For turbidity quality assurance, replicates were run for the culvert upgrade and both spring snowmelt years; however, samples and their replicates for 2007 were all below detection so were not analyzed for level of variation. For 2008 snowmelt, two to three replicates were run for each set of 24 samples, which represented ten percent of the total number of samples. However, only three were above detection. The relative percent difference ranged between zero and nine percent for downstream samples and their replicates; none of the upstream samples and replicates were above detection. The variability for the downstream samples is well within the recommended guidelines of 25% (Ministry of Environment, Lands and Parks, British Columbia. 1998).

For the culvert upgrade, seven replicates were run for downstream samples, which represented 13 percent of the total number of samples. All upstream samples were below detection, so replicates were not analyzed. The relative percent difference for downstream samples and their replicates ranged between zero and 40 percent; several samples and their replicates had levels of variability that exceeded the recommended limit of 25%. Variability in turbidity readings was a problem at all levels of turbidity; running the same sample repeatedly often resulted in very different readings. This phenomenon was attributed to factors such as air bubbles and variations in how the turbidimeter read particles in the sample for subsequent readings of the same sample.

In addition, three turbidity blanks were run for each set of samples (approximately 20-24 samples), for the culvert upgrade and for spring snowmelt 2008 data. Blanks were not run for 2007 snowmelt data. Tap water was used for the blanks because it was found to have a lower turbidity value than de-ionized water (which was collected in a thoroughly rinsed plastic bottle, yet still had high turbidity readings). Blanks ranged between 0.05 and 0.09 NTUs, with a mean of 0.06 NTUs. These were acceptable values; Hach considers values below 0.10 NTU acceptable for empty cell readings, so blanks that fall within these readings should be satisfactory.

To check that the turbidity standards were being read correctly, each standard was run through the turbidimeter ten times. Each ran at 99 percent or higher precision. Other quality assurance measures were to calibrate the turbidimeter between every set of samples, and run calibration standards to ensure the turbidimeter was consistently reading samples.

For suspended sediment quality assurance, three blank filters were run for each set of samples (approximately 24 samples). Twenty filter blanks were run during processing of the culvert upgrade samples; the mean was 6.0 mg, and the standard deviation was 0.81 mg.

Results and Discussion

Hydrograph for Spring Snowmelt 2007 and 2008

The hydrographs in **Figure 3** show both the water level-derived and manual discharge measurements for each snowmelt year. Each hydrograph is a combination of water level-derived and manual discharge measurements for a given year. Spring 2007 only captured the falling limb, while spring 2008 captured both the rising and falling limbs. Peak flows were not measured for either year. It is speculated that peak flows for 2007 occurred approximately a week before sampling began in 2007, judging by a hydrograph for the North Fork Blackfoot River, a nearby drainage (USGS, no date (b)). The spring 2007 hydrograph begins a week after peak flows; the reader should note that the falling limb is incomplete as there is a week of data prior to the first discharge measurements.

While only the falling limbs of the two snowmelt years can be compared, the entire hydrograph for spring 2008 is shown to aid in understanding the stream. However, the peak flow was not measured due to the high flows removing the water level recorder. The estimated peak discharge for spring 2008 is shown with a large circle (68 cfs) in Figure 3. This estimate was based on evidence on the stream banks indicating that the water rose about two inches after the last manual discharge was taken for the day. Using the stage gage, the corresponding discharge was extrapolated assuming a linear relationship between stage and discharge. However, the stream discharge is most likely even higher because stream velocity increased that night, as well as stage.

Comparing 2007 to 2008 falling limbs, spring 2007 had its peak flow two weeks prior to that of spring 2008. Spring 2008 had more discharge, which can be seen by comparing the falling limbs in the hydrographs. The winter of 2007-2008 had a higher snowpack than winter 2006-07, which caused higher peak flows and falling limbs of the spring 2008 hydrograph. As noted earlier, spring snowmelt peak flows for 2007 were approximately a two-year flood event, while the following year, it was a four-year return interval.

Hydrograph for Culvert Removal

The culvert replacement took place over a period of two days in September, 2007, during base flows. Stream discharge was constant throughout the replacement, at 9.9 cfs.

Total Suspended Sediment (TSS) and Sediment Load

TSS, Spring Snowmelt 2007 (before Culvert Replacement): For spring snowmelt 2007, thirty nine pairs of upstream-downstream suspended sediment samples were collected by the ISCO sampler during the falling limb of the hydrograph. This represented 17 sampling days. Only paired data were used; samples that lacked a pair were not used for statistical purposes. Unpaired data was examined to see if it was different than paired data (see Section 3.b.2.5.).

Of the 39 upstream-downstream pairs, 92% had one or both members of the pair below the detection level ("nondetects"). Nondetects were substituted by one-half the detection limit (i.e., one-half 6 mg is 3 mg), and all were used in the statistical analysis. It should be noted that substitution methods are controversial[1] . Helsel et al (2005) advocate more complex statistical methods such as Maximum Likelihood Estimation, Regression on Order, and nonparametric methods because they more accurately depict the true values of nondetects than do substitution methods. The flaw with substitution methods is that the values of the data could vary tremendously, depending on whether the nondetects were substituted by zero, half the detection limit, or just below the detection limit (Helsel, 2005). The literature does note that when data sets have over 70% censored data, no technique provides good estimates of summary statistics (Antweiler and Taylor, 2008). Therefore, it seems adequate to use substitution methods for this thesis.

The dataset for spring 2007 suspended sediment (TSS) concentrations was not normally distributed, even after a log normal transformation. The data were skewed to the right, with some extreme outliers. **Figure 4** shows the histograms for TSS concentrations for upstream and downstream data, respectively.

Boxplots for upstream and downstream suspended sediment are shown in **Figure 5** and depict the extreme outliers. The outliers were not discarded because they were actual suspended sediment collected at high discharges, rather than measurement errors. The median and IQR are appropriate measures of central tendency when there is skewness and severe outliers. The median for both upstream and downstream TSS was 3 mg/L. The boxplots show the lack of an Interquartile Range (IQR); the 25th, 50th , and 75th percentiles are all identical. This is because 80 percent (34 out of 39 pairs) of the data are below detection and thus have the same value (3 mg/l) because they were set at one-half the detection limit. Log transforming upstream and downstream suspended sediment concentration data did not improve the distribution of the data, probably because most of the data is set at a constant value of 3 mg/l.

Summary statistics were done using SPSS 16.0 and are shown in **Table 3**. **Table 3** shows that the TSS values are low; the highest value was 15 mg/liter, while the median was only 3 mg/liter. The median for upstream and downstream was identical, as was the mean.

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[1] There are three substitution methods: setting nondetects at zero, one-half, and just below, the detection limit.

<u>Sediment Load, Spring Snowmelt 2007 (before Culvert Replacement):</u> **Table 4** shows the summary statistics for sediment load, which were derived using SPSS 16.0. There were 39 upstream-downstream pairs.

Sediment load ranged between 12 and 792 kg for downstream data, and 15 and 1260 kg for upstream. This very large range resulted in huge standard deviations that exceeded the means. The dataset was not normally distributed, even after a log transformation; histograms of upstream and downstream data are shown in **Figure 6**, which shows skewness to the right.

Boxplots in **Figure 7** show the presence of outliers that skew the data to the right; the median and IQR are therefore the appropriate statistical measures due to the high variability and outliers. None of the values were below detection.

To determine if there was a difference in sediment load between upstream and downstream samples, the nonparametric Wilcoxon Sign Rank test was used to determine if the difference between upstream and downstream sediment load samples was significantly different from zero. Because the datasets were not normally distributed, a nonparametric test was appropriate. The Wilcoxon Sign Rank test was run with a 95% confidence level, with alpha at 0.05. The hypotheses are as follows:

Ho: distribution of differences (D0) is symmetrical around zero (D0 is zero), i.e., the distribution for DS and US is the same.

Ha: The differences (DS-US) between DS and US tend to be larger than zero

The test statistic was calculated using the methods from Ott and Longnecker (2001), as described for samples less than 50, and the data was manipulated in an Excel spreadsheet. **Appendix G** explains this process and shows the results. Ho was rejected if the test statistic was less than or equal to the critical value. Because the test statistic was greater than the critical value, Ho was not rejected, at p = 0.05, and the difference between upstream and downstream sediment load pairs is not significantly different from zero. In other words, there is no significant difference between upstream and downstream sediment load for spring snowmelt 2007. It should be noted that the difference may have been greater during the rising hydrograph, but that information was not available.

TSS, Spring 2008 (after Culvert Replacement): Suspended sediment samples for 2008 were collected through the entire hydrograph (both rising and falling limbs). To be able to compare the 2007 and 2008 snowmelt years, 2008 data collected in the same time period as in 2007 was used for statistical comparisons. A total of 17 sampling days was done in spring 2007, starting eight days after peak flows. Therefore, for spring 2008, only data beginning eight days after peak flows and ending 17 days afterwards was used. The full dataset for 2008 (both rising and falling limbs) will be considered later in this chapter as a sediment rating curve.

Only paired upstream and downstream samples were used. Unpaired data were examined to see if these differed from paired data, and are discussed later in this chapter. Seventy-one pairs of upstream-downstream suspended sediment samples were collected by the ISCO sampler during the 17 day time period of the falling limb of the hydrograph. Of the 71 pairs, 85% had one or both members of the pair below the level of detection. Data below the level of detection ("nondetects") were substituted by one-half the detection limit, and all the nondetects were used in the analysis.

The dataset for spring 2008 snowmelt was skewed to the right with some outliers. Log transforming the data did not make it more normally distributed. **Figure 8** shows histograms of upstream and downstream, respectively, which show the skewness of the data. The outliers were not discarded because they were actual suspended sediment collected at high discharges, rather than errors in measurement. **Figure 9** shows boxplots for both upstream and downstream data, depicting the outliers.

Summary statistics were performed on the total suspended solid concentrations (TSS) using SPSS 16.0 and are shown in **Table 5**. **Table 5** shows that the TSS values have a larger range of values than with the spring 2007 dataset. The mean is larger than the median because it is more sensitive to outliers. The standard deviation exceeded the mean due to the high level of variability in the data.

Sediment Load, Spring Snowmelt 2008 (after Culvert Replacement): There were 71 upstream-downstream pairs for sediment load data, spring snowmelt 2008, using the same time frame as with spring snowmelt 2007. Only paired upstream-downstream samples were used, and all nondetects were used in the data analysis, and were substituted as one-half the detection level. **Figure 10** shows the histograms for upstream and downstream sediment load data, respectively. The data were not normally distributed, and were skewed to the right. The boxplots in **Figure 11** shows the extreme outliers.

Table 6 shows the summary statistics, which were determined using SPSS 16.0. **Table 6** shows that sediment load values have a larger range than with the spring 2007 sediment load dataset. Sediment load ranged between 31 kg and 1100 kg for downstream, and between 31 kg and 6800 kg for upstream. This very large range, and thus variability, resulted in huge standard deviations that exceeded the means. Because of the non-normality of the data, the median is best for describing measures of central tendency, and the IQR for describing spread. The mean was much higher than the median due to outliers.

The nonparametric Wilcoxon Sign Rank test was used to see if the difference between upstream and downstream sediment load samples was significantly different from zero. SPSS 16.0 was used for this test, and it was run with a 95% confidence level, where alpha = 0.05. The hypotheses are as follows:

Ho: distribution of differences (D0) is symmetrical around zero (D0 is zero), i.e., the distribution for DS and US is the same.

Ha: The differences (DS-US) between DS and US tend to be larger than zero.

Because the sample size was greater than 50 (N = 95), it was appropriate to standardize the data and use the normal distribution theory, as described in Ott and Longnecker (2001). Ho was rejected if $Z<Z\alpha/2$ (for a two-tailed test), where $\alpha == 0.05$, so Ho was rejected if $Z<- 1.96$. **Table 7** shows the results.

The Z value was -0.4, which is not less than the critical value of -1.96, and the p-value is also very large (p =.35; SPSS is run as a two-tailed test, so with a p-value of .7, it is divided by two to get .35). Therefore, Ho is not rejected, meaning the differences between upstream and downstream sediment loads are symmetrical around zero, and thus are not significantly larger than zero at $\alpha = .05$. In simple language, this means downstream and upstream sediment loads for 2008 were similar. It should be noted that the differences may have been greater during the rising hydrograph.

Comparing 2007 and 2008 Spring Snowmelt Sediment Loads: To see if there was a significant difference between spring snowmelt 2007 and 2008 sediment loads, the Wilcoxon Sign Rank Test using SPSS 16.0 was run comparing upstream 2007 to upstream 2008 sediment loads, and downstream 2007 to downstream 2008 sediment loads. The hypothesis tested was:

Ho: distribution of differences (D0) is symmetrical around zero (D0 is zero), i.e., the distribution for DS and US is the same.

Ha: The differences (DS-US) between DS and US tend to be larger than zero

Ho was rejected if $Z<-Z\alpha$, at a 95% confidence level; $-Z\alpha = -1.96$, and $\alpha == 0.05$; Ho was rejected if $Z<- 1.96$. **Table 8** and **Table 9** show the results.

For both upstream and downstream sediment load, there was a significant difference between snowmelt years. For upstream sediment load, the Z value was -2.4, which was smaller than $–Z\alpha$, and significant at $p = 0.01$ (dividing the two-tailed value of .02 by two). For downstream, the Z value was -2.4, which was also smaller than $–Z\alpha$, and significant at $p = 0.01$ (.02 divided by two). Therefore, Ho was rejected for both upstream and downstream, at a level of confidence of 95% (alpha = 0.05).

In other words, the sediment load for spring 2008 was significantly higher than for 2007, at least, for the measured time interval (falling limb of the hydrograph). It is important to note that the 17-day time interval for which 2007 and 2008 were compared, missed some important events. Peak flows and the rising limb were not part of the statistical analysis. However, it is likely that sediment load was indeed higher for 2008 than 2007 just by observing the impacts of the flood events (i.e., stream banks sloughing off).

Unpaired Data for 2007 and 2008 Spring Snowmelt TSS and Sediment Loads: Unpaired suspended sediment concentrations (TSS) and sediment load data were examined to see if there were any extreme values that were very different from paired data in the similar time frame. For both 2007 and 2008, snowmelt, TSS and sediment load for unpaired samples were similar to paired samples taken before and after the unpaired samples. If there had been a good relationship between discharge and TSS, then TSS could be predicted from discharge for the missing samples for the unpaired data. Unfortunately, as the section on sediment rating curves demonstrates, there is not a strong relationship.

TSS during Culvert Replacement: During the culvert replacement, 53 pairs of upstream-downstream suspended sediment samples were collected with the grab sample method. Because stream discharge was constant, upstream samples were just taken every other downstream sample to save bottles.

All the upstream suspended sediment samples were below the level of detection, so were assigned a value of one-half this detection limit; therefore, all the upstream values are the same value (3 mg/l). Therefore, there was no variability in upstream data. All the nondetects were used in the data analysis. Only seven percent of the downstream samples were below detection.

The histogram for downstream suspended sediment (**Figure 12**) shows the data to be skewed to the right (upstream data has no distribution as it is constant). The boxplot for downstream suspended sediment (**Figure 13**) shows there are no extreme outliers.

Summary statistics were performed on the total suspended solid concentrations (TSS) using SPSS 16.0 and are shown in **Table 10.** For downstream suspended sediment, the range of values was between 3 and 4,500 mg/l, which is a high level of variability; thus the standard deviation was higher than the mean.

Sediment Load during Culvert Replacement: Figure 14 shows histograms for upstream and downstream sediment loads, respectively, for the culvert replacement. Both upstream and downstream sediment load data are skewed to the right. The boxplots in **Figure 15** show that upstream data have some outliers with miniscule 25th and 75th quartiles that are not visible on the boxplot. Downstream data have some extreme outliers; these were determined to be actual samples, and not measurement errors.

Table 11 gives the summary statistics for sediment load during the culvert replacement. All the upstream sediment load values were below detection and were given half the detection limit (3 mg/l). Variation in the values is due to the normalization by time intervals.

To determine if there was a significant difference in sediment load between upstream and downstream samples, the Wilcoxon Sign Rank test was used. The hypothesis was:

Ho: distribution of differences (D0) is symmetrical around zero (D0 is zero), i.e., the distribution for DS and US is the same.
Ha: The differences (DS-US) between DS and US tend to be larger than zero

Ho was rejected if $Z<-Z\alpha$, at a 95% confidence level; $-Z\alpha = -1.96$, and $\alpha == 0.05$; Thus, Ho was rejected if $Z<- 1.96$. **Table 12** gives the results. Ho was rejected, with $p<.0005$, which indicates a very significant difference between upstream and downstream sediment loads during culvert replacement.

Stream Bank Erosion

Most of the stream bank erosion occurred just upstream of the stream crossing, at the right stream bank. Erosion pins installed during the rising limb of the hydrograph were washed out during peak flows, so the volume of stream bank erosion was estimated by measuring the voids where soil had eroded away, using the methods from Madej (2001).

The volume of soil eroded away from this stream bank was estimated at 1.80 m^3. The other area of erosion was where soil was packed in between rip rap. The volume here was estimated at approximately 0.04 m^3. The total volume of soil eroded from the stream bank and rip rap area was 1.80 m^3, which is approximately one-seventh of the volume of soil a dump truck could hold. Madej (2001) estimated a plus or minus 25 percent error using these methods; therefore, the actual volume of soil eroded is somewhere between 1.40 and 2.30 m^3.

To determine the load from the stream bank erosion, the volume of estimated material eroded from the stream bank was multiplied by the soil bulk density for the soils in this area, which was 1300 kg/ m^3 (USDA NRCS, 2009a). The total load was 2370 kg, with a range of 1780 to 2960 kg.

Culvert Fill Volume

The volume of fill around the culvert at the stream crossing was 69 m^3, and the soil bulk density for the soils in this area was 1300 kg/ m^3 (USDA NRCS, 2009a). These values were multiplied together to determine the mass of sediment, which was 90,000 kg, the load that would enter the stream if the culvert failed.

It was determined that the culvert could fail with a Q5 and higher return interval by using the regression equations developed by Omang (1992) to predict peak flows at various return flows. Section 2.2.3. describes these methods. To determine whether the culvert had the capacity for various return flows, the methods from Section 4.a.2.1. were used. **Table 13** shows the predicted peak flows for various return intervals, the capacity of the culvert to handle peak flows, and the peak flows at which the culvert would fail.

Table 13 shows that the predicted capacity of the culvert is 130 cfs, and that the Q5 and greater return intervals would exceed this capacity. There is a 50% error in these regression equations; **Table 13** shows the plus and minus one standard error for each return flood. From observations at this stream crossing, it is unlikely that the culvert would have failed at a Q5 flood; the estimate that it would fail is likely due to the large amount of error in the regression models.

Estimation of Road Surface Erosion using the WEPP Model

The Water Erosion Prediction Project (WEPP) model estimated that road surface erosion at the stream crossing before the culvert replacement was 99 lbs/year (45 kg/year) of erosion from the road prism, and 70 lbs/year (32 kg/year) from the buffer, for a total of 169 lbs/year (77 kg/year) sediment runoff annually from the road. With the plus or minus 50 percent error described by Elliott (2008), that is approximately between 38 and 116 kg annually.

WEPP was run again for the post-replacement scenario, and estimated 7 lbs/year (3 kg/year) from the road prism, and 0.4 lbs/year (0.2 kg/year) from the buffer, for a total of 7 lbs (3 kg/year) of sediment runoff annually from the road. With plus or minus 50 percent error, that is between 4 kg and 11 kg annually. Both estimates are based on ten-year mean annual averages. **Appendix H** shows the results for both scenarios.

WEPP therefore estimated that there was a reduction of 74 kg annual road surface-related sediment from upgrading the culvert to a bridge. This large difference in load is due to changes in the road length on either side of the crossing where sediment could enter the stream, as well as changes in fill gradient and length. The bridge was slightly elevated, causing the road to slope away from the crossing. In comparison, the crossing with the culvert was not elevated, so the road sloped slightly towards the stream.

There was no fill with the bridge, so the minimum values allowed in WEPP were used for fill gradient and length. While the rip rap under the bridge contained dirt in between the rocks, it was a negligible amount, compared with fill associated with culverts.

Discussion on Spring Snowmelts, 2007 and 2008

The low suspended sediment values (and little variability) for spring 2007 is consistent with what is known of the area. The Belt metasediment geology is very stable; this was observed during field visits, where there was very little evidence of erosion noted around the stream crossing area. As far as hillslope erosion, in the past, there was heavy logging and road building on the hills above the stream site, but the hills have grown over with enough vegetation to protect the soil from erosion.

Spring 2008 sediment loads were much higher than for spring 2007, and had higher variability due to pulses of sediment entering the stream, but it is not evident if this is due to the culvert replacement or just higher flows. It appears that most of the sediment load came from eroded stream banks just upstream of the stream crossing. These stream banks were vulnerable to erosion due to a lack of large trees and associated stabilizing root masses. During peak flows in 2008, a large portion of one of the upstream stream banks collapsed into the creek. Upstream values were large, and about six times larger than downstream values. This was likely from stream bank erosion traveling as a plume towards the upstream ISCO probe; after that, it dispersed and became diluted by the time it was captured by the downstream ISCO probe.

It is likely that the increased sediment load in 2008 was due to both high flows weakening the stream bank and excavator work during the replacement. The excavator worked out of the stream channel to build the upstream rock weirs. To access this location in the stream channel, the excavator drove over part of this stream bank, which seemed the most logical access point. However, this may have weakened part of the stream bank; the part not driven over may have failed due to non-culvert replacement reasons (lack of root masses binding the soil and high flows).

Comparing sediment loads for snowmelt years with very different discharges is a challenge in hydrology research. Anderson and Potts (1987) monitored suspended sediment two years after road construction in a forested watershed in western Montana. In these Belt metasediment soils, suspended sediment appeared to decrease rapidly in the second year after logging, but the authors noted that it could be due to low water yields that year. They noted that if this second year's water yield was scaled up to equivalent water yield, the increase in suspended sediment for that year would have been four-fold (Anderson and Potts, 1987).

If spring 2008 had been a 2-year flood instead of a 4-year flood, perhaps sediment yield would have been half the amount it was. However, the rising limb of the hydrograph is missing for 2007, making it difficult to compare snowmelt years in terms of water yield. It is not clear that had water yields been as high in 2007 as in 2008 that there would have been similar suspended sediment levels.

The sediment rating curve in the next section shows a poor relationship between suspended sediment and discharge. This means that an increase in discharge does not necessarily mean a corresponding increase in suspended sediment. Increases in suspended sediment in 2008 were likely due to stochastic events of stream banks slumping rather than be caused by higher discharge. However, high flows (and possibly the excavator during the replacement) probably weakened the stream bank and parts sloughed off even when there was not an increase in flow; hence, high flows had an indirect impact on suspended sediment concentrations.

Discussion on Culvert Replacement

For the culvert replacement, suspended sediment values reached a maximum of 4,500 mg/l. Comparisons of the peak of 4,500 mg/l with peaks for other culvert removal projects in more erosive soils, suggests that this is fairly low. In Foltz et al (2008), culvert removals in highly erodible Idaho Batholith Border Zone soils, produced peak suspended sediment concentrations ranging between 2,060 and 28,400 mg/l. Brown (2002) in measuring culvert removals in headwater streams also in Idaho Batholith soils, found a range of 2.9 to 68,500 mg/l of suspended sediment.

There was a large amount of variability in the thesis data during the culvert replacement due to large pulses of sediment entering the stream during the culvert work, followed by times of inactivity where suspended sediment levels dropped. While the suspended sediment levels were sometimes high (such as 2,000 mg/l or higher), they subsided rapidly, within minutes, to 200 or 400 mg/l.

This rapid decrease of suspended sediment is consistent with the literature. In Foltz et al (2008), only three of eleven locations studied had sediment concentrations over 6,000 mg/l for more than one hour at the culvert outlets. Four of these eleven locations had sediment concentrations that exceeded 500/mg/l for three hours.

Reid and Anderson (1998) noted that during pipeline trench excavation and backfilling, while suspended sediment concentrations could exceed 2,500 mg/l, when the disturbance stopped, suspended sediment levels dropped markedly. The authors also noted that particle size helps determine the concentrations of suspended sediment, as well as how far downstream the particles traveled. Clay or silt-sized particles tend to remain suspended longer than larger particles such as gravel and coarse sand.

The results of the culvert upgrade for this thesis had similar phenomena; rapid drops of suspended sediment levels once activities ceased. While analysis was not done on particle size of the suspended sediment, they were observed to be quite fine, clearly clay or silt-sized particles. This is a result of the area being glacier-scoured, which breaks particles into fine sizes. However, unlike with Reid and Anderson (1998), these fine particles settled quickly, which seemed strange.

A concern over the time periods with elevated TSS concentrations during the thesis culvert replacement regards the impacts to aquatic life. The highest concentration of suspended sediment (4,500 mg/l) lasted for about ten minutes. There were two times when suspended sediment levels were above 2,000 mg/l for approximately an hour. Suspended sediment concentrations of 6,000 mg/l for one hour have been found to cause avoidance behavior in coho salmon (Noggle, 1978, in Foltz et al, 2008), and concentrations of 500 mg/l for three hours caused sublethal stress in adult steelhead (Redding and Shreck, 1982, in Foltz et al, 2008).

For the culvert replacement project in the thesis, fish just downstream of the crossing were electroshocked and removed prior to the replacement work and placed upstream of the crossing, behind a net, for the duration of the project. Therefore, the high suspended sediment concentration during the replacement had a lower impact on fish. However, other aquatic life may have been detrimentally affected, such as macroinvertebrates. Because the replacement was done at base flows, there was not enough flow to move the settled sediment out of the system. Therefore, a fine layer of sediment persisted on the stream bed until flows increased again, probably in early winter.

Comparing Long-Term Sediment Load with and without the Culvert Replacement

The total load expected if the culvert was left in place (the sum of downstream sediment loads from spring 2007, road surface erosion load, and the culvert fill load) was compared to the total load from doing an upgrade (the sum of the following year's downstream sediment load from snowmelt, road surface erosion, and the sum of downstream sediment loads from the upgrade). **Table 14** shows these sediment sources, and **Table 15** normalizes the data in **Table 14** by unit area in order to compare it with the literature.

Stream bank erosion is not shown in **Table 14** or **Table 15** because it was captured as suspended sediment in spring snowmelt, 2008. Therefore, the measurements of the voids as described in Section 3.b.3. to estimate how much load resulted from stream bank erosion is discussed separately from the loads in **Table 14** and **Table 15**. The estimated load from stream bank erosion was 2370 kg, and this was normalized to 0.98 kg/ha.

In **Table 15**, loads (in kg) were divided by the basin area (in hectares) above the stream crossing. Road surface erosion was also normalized by the road surface area used in the WEPP model ("plot area" in **Table 15**). This was done because the road surface erosion studies in the literature measured erosion from study plots on road segments, and presented sediment load per study plot area.

The results from **Table 14** and **Table 15** suggest that leaving the culvert in place could lead to almost 12 times as much sediment load if the culvert failed than replacing the culvert. Replacing the culvert with a bridge resulted in a 90% reduction in load. The large majority of the load from not replacing the culvert is due to culvert failure load. The majority of the load from replacing the culvert is from spring snowmelt load.

There is a huge amount of error with these results. Sources of error are discussed elsewhere, but in brief, these include: lack of complete data for both snowmelt years and the culvert upgrade, using indirect discharge measurements, possible weak stage-discharge relationships, assumptions of constant suspended sediment and discharge in between sampling intervals for snowmelt and upgrade data analysis, errors in the WEPP model, assuming the entire fill volume would be delivered to the stream if the culvert failed, and higher loads for post-upgrade snowmelt due to factors other than the upgrade.

Comparisons of Thesis Results with the Literature

This section compares sediment yields from the thesis study with the literature. None of the studies on culvert removals or replacements considered all the sources listed in **Table 14** and **Table 15**. Therefore, these components are individually compared with the appropriate literature.

Road Surface Erosion Studies: Table 16 shows the results for three road surface erosion studies, comparing them with the thesis results. Sugden and Woods (2007) measured road surface erosion in the same geographical region as the thesis study area, so there was similar geology and precipitation. The authors measured the sediment yield eroded from native surface roads in Western Montana over a three-year period. There were ten plots in Precambrian Belt geology and ten in Glacial Tills (derived from Belt geology). The mean erosion from the Belt geology plots was 5,470 kg/ha/year and from the Glacial Till geology plots, it was 5,270 kg/ha/year.

Bilby et al (1989) took place in a wetter climate (south western Washington). Over a six-month study period during the wet season, there was a 21,400 kg/ha sediment yield from the five plots. The higher sediment yields than in Sugden and Woods (2007) could be due to higher precipitation.

Megahan et al (2001) conducted a study on cutslopes on granitic road cuts on forest roads in Idaho. Erosion rates had a mean of 16,300 kg/hectares/year. The study area was much more erosive than the thesis study area, while precipitation was similar.

Comparing these studies to the thesis results in Table 16 shows that road surface erosion from the thesis stream crossing was very, very low compared with the literature even after the culvert replacement. However, it is worth noting that, at least in this thesis, the bridge did reduce road surface erosion by about 25-fold. Thus, replacing culverts with bridges may be a viable strategy for reducing road surface erosion at stream crossings. Before the replacement, the road dipped slightly to the stream crossing. After the replacement, the bridge span was slightly elevated above the crossing, serving to deliver sediment away from the crossing.

Spring Snowmelt Studies: None of the literature on culvert removal or replacement activities measured spring snowmelt before or after the removal/replacement. Therefore, studies that measure spring snowmelt for other stream-disturbance activities, such as logging and roadbuilding are examined. In addition, studies that measure spring snowmelt in undisturbed forests are compared with the pre-disturbance spring snowmelt for the thesis.

Spring snowmelt 2007 was the pre-disturbance conditions for the thesis. Upstream of the stream crossing had been logged and roaded, but not recently. While the roads above the stream crossing were not decommissioned, they were closed to public access and had some degree of vegetation cover. There was sufficient vegetation growing on clearcut hillslopes that appeared to stabilize the soil. Hence, the basin was relatively undisturbed as far as sediment yields prior to the culvert replacement, and is therefore compared with literature on undisturbed forested areas. **Table 17** summarizes the snowmelt studies in the literature.

Anderson and Potts (1987) measured suspended sediment concentrations in a watershed in Western Montana the year before and the year after disturbance by logging. The geology and climate were similar to the thesis study area. Measurements were made using continuous automated samplers throughout each year, and captured both snowmelt peak flows and base flows. Pre-disturbance annual suspended sediment yields ranged from 0.56 – 1.77 kg/ha/year. Following road building sediment yields were 13.7 kg/ha/year and a year after this, it was 3.6 kg/ha/year.

Lewis (1998) studied changes in suspended sediment concentration and sediment load with logging and road building in two drainages in northwestern California using continuous automated samplers. Precipitation in the area is about 47 inches/year. At one drainage, the undisturbed condition was approximately 340 kg/ha/year, and the increase in suspended sediment load the year after road construction commenced was 1,475 kg/ha/year.

In Lane and Sheridan (2002), sediment yield downstream of a culvert at a newly constructed road stream crossing was 32.2 kg/ha/year. The study area was in Australia, in Devonian metasediments, and the average annual rainfall is 45 inches. Suspended sediment was measured during the five high flow months.

In Fredriksen (1970), suspended sediment measurements were taken in a watershed in western Oregon prior to it being roaded and logged in the late 1950's/early 1960's. There were 455 kg/ha of sediment produced in this undisturbed forest between 1956 and 1959, or 152 kg/ha/year.

There is a huge range of values for both the undisturbed and post-disturbed sediment yields in these studies. Pre-disturbance sediment yields for the thesis (1.35 kg/ha/year) fell within the range in Anderson and Potts (1987) which is expected as they were in a similar geology and region. The other studies were extremely higher than the thesis results.

Note that the there are different time periods of snowmelt analysis: Anderson and Potts (1987), Lewis (1998), and Fredrickson (1970) measured snowmelt for a year, while Lane and Sheridan (2002) measured it only for the five high flow months. The thesis measured snowmelt for only three weeks, and included only the falling limb; the rising limb and peak flows were not measured. Therefore for pre-disturbance conditions, if the rising limb and peak flows were included, the results likely would have had higher loads than the undisturbed forest in Anderson and Potts (1987) although probably not anywhere as close as Lewis (1998, Lane and Sheridan (2002) or Fredrikson (1970).

For post-disturbance, the thesis results were considerably lower than the literature, although only slightly lower for Anderson and Potts (1987). Only a few weeks of snowmelt were measured, although the entire hydrograph was captured (except peak flows). Even if measurements were done for a year, they are likely to have been low. In sum, the spring snowmelt both before and after the culvert replacement for the thesis is very small compared with the literature, even with the fact that measurements were only done for a few weeks.

Culvert Replacement Studies: Table 18 shows four studies that measured sediment yield during culvert removal or replacement projects. The thesis results are also shown for comparison. In Foltz et al (2008), culvert removal projects were monitored in two different geographical locations to determine sediment load levels during the removal operation. The 24-hour sediment load during culvert removals in the Idaho Batholith Border Zone study area ranged between 0.002 kg/ha/24 hours to 0.10 kg/ha/24 hours. For the glacial till/volcanic ash study site, the 24-hour sediment load ranged between 0.006 and 0.01 kg/ha/24 hours.

Sediment yields from the thesis culvert replacement were higher than the results in Foltz et al (2008), which was surprising given that the thesis study area was more geologically stable. This could be attributed to how the culvert project work proceeded. Much of the sediment load in the thesis culvert replacement project resulted from excavation of the stream bed to adjust channel gradient and to create weirs.

The details on stream bed work for the NE Washington location in Foltz et al (2008) are not given, but perhaps less excavation was needed. For the Idaho site in Foltz et al (2008), an earlier paper on this removal project (Foltz and Yanosek, 2004) does give details on the removal process; there was no streambed excavation work and after each section of culvert was removed, straw and riprap were placed in the streambed. In contrast, the removal process for the thesis involved streambed excavation and there was no straw or riprap placed in the stream bed during the work. These differences in stream bed excavation and mitigation may explain why the thesis had more sediment production than the Idaho site in Foltz et al (2008).

A culvert replacement project in the Bitterroot National Forest resulted in a total sediment load of 1.09 kg/ha (Jakober, 2002). Mitigation measures (straw bales placed downstream of the stream crossing, and stream diversion) were implemented. The thesis study results were lower than Jakober (2002), perhaps due to the more erosive nature of the soils in Jakober (2002). Even so, it is interesting that the thesis project work, with no mitigation measures and involving stream excavation work, was lower than Jakober (2002).

Brown (2002) investigated sediment yield from culvert removals in headwater streams in the Clearwater National Forest in Idaho. The area was in the highly erodible Idaho Batholith. For the five stream crossings in the study, sediment yield ranged from 0.04 to 2.74 kg/ha/24 hours. The thesis results (0.17 kg/ha) fits within this range. Some of the higher ranges in the Brown study may be due to the erosive soils and excavators moving fill from the stream bed.

Table 18 has a wide range of sediment yields for culvert removal/replacement projects. The thesis exceeds some of the values but is lower than others. This is likely due to differences in stream excavation work and mitigation measures.

Stream Bank Erosion Studies: Table 19 shows stream bank erosion studies and compares them with the thesis results on stream bank erosion. Madej (2001) measured stream bank erosion several years after extensive road decommissioning in Redwood National Park, a highly erosive area. The thesis result for stream bank erosion was similar to Madej (2001), which is interesting, given the difference in erodibility between the two areas. The methods used to estimate stream bank erosion have a high degree of error (25%) (Madej, 2001), so this could be a reason for the studies having similar results.

Klein (2003) measured erosion from 18 decommissioned stream crossings in the Upper Mattole River basin in Northern California; measurements were made following the first post-decommissioning winter storm. Volume eroded from channel scour, bank slumps, and headcuts were estimated. The mean sediment delivery per crossing was 0.99 m^3/km^2. This is more than the thesis study; perhaps this is because channel scour was measured in Klein (2003) but not in the thesis study. Measurement errors could also be a factor. Comparing the thesis stream bank erosion to other sediment sources described in **Table 17** (pre-disturbance and post-roadbuilding and logging), it is extremely low.

Culvert Fill Failure Studies: The estimated culvert fill failure from the thesis was 37.1 kg/ha which is higher than both pre-disturbance and post-logging and roadbuilding in Anderson and Potts (1987) from **Table 17**; it was much higher than all the culvert replacement studies described in **Table 18**; and it was much higher than stream bank erosion studies in **Table 19**. And, the thesis results from **Table 14** and **Table 15** show that leaving the culvert in place could result in 38.5 kg/ha if it failed, while replacing it resulted in only 3.2 kg/ha; this is a 12-fold difference. Therefore, the sediment load from a culvert failure could be considered a major sediment source to the watershed.

Madej (2001) estimated that if stream crossings in Redwood National Park had not been obliterated, the volume of erosion from culvert failure would have been at least four times greater than the erosion following road obliteration. Sirucek (1999) found that a modeling scenario where a culvert was plugged produced 30-300 percent more erosion than a culvert removal scenario. These two studies support the results from the thesis, and thus it seems that replacing the culvert was worthwhile. Of all the sources of sediment involved in the culvert replacement analysis, culvert fill failure was the greatest source.

Sediment Rating Curve

In most streams and rivers, suspended sediment concentration is often strongly correlated to discharge (Thomas, 1985); as discharge increases, so does suspended sediment. Thus, discharge can be used to determine suspended sediment concentrations if there is a good fit between the two variables.

Sediment rating curves are useful for comparing changes in the suspended sediment/water discharge relationship for "before" and "after" rating curves (Thomas, 1988). Rating curves relate discharge and suspended sediment concentration, which is usually in the form of a power function (Thomas, 1985): $\mathbf{C = aQ^b}$.

Sediment rating curves were constructed for this thesis to help understand how varying discharges affect levels of suspended sediment, and how these curves were different for the two spring snowmelt years. Only the falling limbs of the hydrograph were compared for spring 2007 and 2008 snowmelts in a rating curve, as rising limb data were missing for 2007. In addition, the entire 2008 snowmelt sediment rating curve was examined.

Suspended sediment and discharge data were log transformed for the rating curve; log transforming suspended sediment and discharge data is typically done when constructing sediment rating curves (Asselman, 2000; Thomas, 1989). This makes the data points more evenly distributed and linear (Thomas, 1989), and can correct the problem of non-constant variances of the residuals (Ott and Longnecker, 2001).

Spring Snowmelt 2007, Falling Limb Only: Figure 16 and **Figure 17** show the rating curves for log transformed suspended sediment (TSS) versus log transformed discharge and the residuals plot for upstream and downstream data, respectively. The regression outputs for upstream and downstream TSS versus discharge are shown in **Appendix I**.

For the upstream sediment rating curve, the relationship between log transformed suspended sediment and log transformed discharge was very weak, with an R^2 value of 0.13, and the p-value somewhat significant ($P = 0.03$, with $\alpha = 0.05$). The relationship between log transformed suspended sediment and log transformed discharge for downstream was even weaker, with an R^2 value of 0.04, and a poor level of significance ($p = 0.26$). The residuals for both upstream and downstream data had non-constant variances, indicating either a nonlinear relationship between discharge and suspended sediment exists, or there is no association of any type. Most of the data were below detection, and thus all had identical numbers because they were all assigned a value of half the detection limit).

For values above detection, the variation in total suspended sediment concentration (TSS) levels independently of discharge is likely due to "event responses" as described by Thomas (1985). He noted that small mountain streams often rely on their suspended sediment from "event responses," which are contributions of materials from stream banks and upland areas. Such streams tend to have weaker relationships between suspended sediment and discharge than in supply unlimited streams and rivers.

"Event responses" in the thesis could be material that sloughing off stream banks or rotten logs, or even animals walking through the creek: these events are not a function of discharge. Cottonwood Creek basin does appear to be a sediment supply limited system, with a lack of sediment sources due to stable stream banks and hillslopes. Given the fact that suspended sediment concentrations (TSS) are so low in the Spring 2007 dataset, it is clear there is no association between TSS and discharge in this stream at that time.

Spring Snowmelt 2008, Falling Limb Only: Figure 18 and **Figure 19** shows the rating curve for log transformed suspended sediment versus discharge and the residuals plot for upstream and downstream spring 2008 data (falling limb only), respectively. The regression output tables for upstream and downstream are shown in **Appendix J**.

For spring snowmelt 2008 (falling limb only), for upstream data, there is no relationship between suspended sediment concentration and discharge; R^2 is 0.01. For downstream data, R^2 is 0.16, still a low value; as discharge values increase, there is a weak increase in suspended sediment concentration. Much of the TSS data is below detection.

The residuals for both upstream and downstream data exhibited non-constant variances, indicating either that there is a nonlinear relationship between discharge and suspended sediment, or that there is no association of any type. In summary, there is not a good correlation between suspended sediment concentration (TSS) and discharge for either of the snowmelt years. This is because most of the TSS values are so low.

<u>Spring 2008 Rating Curve, both Rising and Falling Limbs</u>: Figure 20 and **Figure 21** shows the rating curve for log transformed suspended sediment versus log transformed discharge for the entire spring 2008 snowmelt hydrograph and the residuals plots for upstream and downstream data, respectively. **Appendix K** shows the regression outputs for upstream and downstream rating curve analyses. Plots of the residuals showed a lack of constant variance, which suggests either a nonlinear relationship between variables, or that there is no association between these variables.

There was a low correlation between log discharge and log suspended sediment concentration for both upstream and downstream data: (R^2 of 0.13 and 0.28, respectively). There was a weak presence of hysteresis loops, which are produced by higher levels of suspended sediment on the rising limb than falling limb, at the same discharge levels (Thomas, 1985). In sum, there is a weak relationship between suspended sediment and discharge for both upstream and downstream, although at higher discharges, there was a better correlation. Factors such as bank sloughing, which are independent of discharge, seemed to play more a role in the rating curve than discharge.

In an analysis of a rating curve, Anderson and Potts (1987) found unusually high sediment concentrations in a site upstream of disturbance from logging, and suggested it was due to the collapse of undercut banks. The authors noted that stochastic factors such as bank sloughing are important in determining sediment loads for extremely supply limited streams. This explanation is likely with this thesis dataset.

<u>Turbidity</u>

Turbidity is an indirect measurement of suspended solids (such as sediment, fecal matter, and nutrients), and is commonly used by regulatory agencies to determine if state water quality standards are being met. As required by the Montana Water Quality Act, the state of Montana developed a classification system for all waters of the state that includes their present and future most beneficial uses (Administrative Rules of Montana (ARM) 17.30.607-616) and adopted standards to protect those uses (ARM 17.30.620-670) (MT DEQ, 2008). Cottonwood Creek is designated a B-1 Classification which is described below:

Classification	Designated Uses
B-1 CLASSIFICATION	Waters classified B-1 are to be maintained suitable for drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply (MT DEQ, 2008)

The maximum allowable increase in turbidity above natural levels for B-1 waters is five NTUs (MT DEQ, 2008). Upstream turbidity levels for Spring snowmelt 2007 and 2008, and during the culvert replacement (base flows) were considered the “natural levels” because these values were mostly below detection and upstream was relatively undisturbed. Thus, “natural levels” were given the value of 2.7 NTUs, the value of the below detection turbidity samples (one-half the detection limit) from upstream measurements. Therefore, under State law, the maximum allowable turbidity was 7.7 NTUs (5 NTUs plus 2.7 NTUs).

Turbidity samples were collected during spring snowmelt, 2007 and 2008, and during the culvert replacement to determine if the median of each sample met state standards. In addition, it was determined if turbidity could be used to predict suspended sediment.

Turbidity, Spring Snowmelt, 2007, (Falling Limb Only): For spring snowmelt 2007, only falling limb turbidity data was acquired. Outliers were removed if they were extreme (above 250 percent higher than the smallest value). **Table 20** shows the summary statistics for spring, 2007 turbidity data. All the samples except for one upstream sample were below the detection limit of 5.3 NTUs; these nondetects were given the value of 2.7 NTUs (one-half the detection limit). All turbidity samples were below the maximum value allowed under State law (7.7 NTUs).

Turbidity During Culvert Replacement: Table 21 shows the summary statistics for the culvert upgrade turbidity data. All the upstream samples were below detection and so were given the value of 2.7 NTUs (one-half the detection limit). The variation for downstream data was attributed to the changes in disturbance in the stream during culvert replacement. No outliers were removed.

There was a total of 31 hours of culvert upgrade work; 45 percent of that time turbidity levels exceeded the state water quality standards limit of 7.7 NTUs. As discussed in Section 3.b.7., fish were removed from just downstream of the stream crossing prior to culvert work. Therefore, fish populations were unlikely to be affected by the short-term pulses of high turbidity. However, macroinvertebrates could have been affected.

Turbidity, Spring Snowmelt 2008 (Falling Limb Only): For turbidity data collected during spring snowmelt, 2008, only falling limb data were used for statistical analysis, in order to compare with spring 2007 data. **Table 22** shows the summary statistics for this dataset. All of the data were below detection, and so were given the value of 2.7 NTUs, and thus were well below the 7.7 NTU maximum allowed level for adhering to state water quality standards.

Turbidity, Spring Snowmelt 2008 (Entire Hydrograph): For the entire hydrograph for spring snowmelt, 2008, for upstream samples, turbidity exceeded the maximum allowable value of 7.7 NTUs only two percent of the time. For downstream samples, turbidity exceeded 7.7 NTUs ten percent of the time, with the highest value at 69 NTUs; most of the values exceeding 7.7 NTUs were below 25 NTUs. **Table 23** shows the summary statistics for this dataset. No outliers were removed.

Discussion and Summary on Turbidity: Turbidities for spring snowmelt for both years were low. Spring 2007 values were all virtually below detection. For spring 2008, most of the high turbidity values were attributed to the stream bank sloughing off during peak flows. The culvert replacement increased turbidity levels to above maximum state water quality standards limits for 45 percent of the time. This could have impacted aquatic life, such as macroinvertebrates. Because the replacement was done at base flows, there was not enough flow to move the settled sediment out of the system. Therefore, a fine layer of sediment persisted on the stream bed until flows increased again, probably in early winter.

Predicting Suspended Sediment from Turbidity: Because suspended sediment analysis is time consuming, using turbidity to predict suspended sediment is convenient.

Turbidity is caused by the presence of suspended and dissolved material, such as clay, silt, organic matter, plankton, organic acids, and dyes, and air bubbles (Anderson, 2004). Thus, turbidity may or may not reflect suspended sediment levels.

To determine if there was a useful relationship between suspended sediment (TSS) and turbidity for Cottonwood Creek, a linear regression model was run using SPSS 16.0. TSS and turbidity data for spring 2007 and 2008 and the culvert upgrade were combined. Both limbs of the hydrograph were used for spring 2008. **Figure 22** shows TSS versus turbidity graphs for upstream, and its residuals graph; **Appendix L** shows the regression outputs for this dataset.

The R^2 for TSS vs turbidity for upstream data, was 0.75, indicating a moderate relationship between these variables; log transforming the variables worsened this relationship. **Figure 22** suggests that as turbidity increases, TSS also increases, but this increase is due to only a few data points; the large majority of the data are nondetects (96 percent of the turbidity data and 62% of the TSS data were nondetects)and are thus set at constant values (i.e., one-half the detection limit). With both TSS and turbidity values so low, it is impossible to determine if there is a relationship between the two variables.

Figure 23 shows TSS versus turbidity graphs for downstream, and its residuals graphs. **Appendix L** shows the regression outputs for downstream data. For downstream data, log transforming both TSS and Turbidity improved the relationship between the two variables; R^2 was 0.70, a moderate value. Although 73 percent of the turbidity data and 44% of TSS data were below detection, there was still enough data above detection to show a meaningful relationship between turbidity and TSS. So, one could use turbidity to predict TSS, although with caution as R^2 is only moderately high. Observations of the stream noted that there is a lot of suspended plant material that could influence turbidity more than suspended sediment.

Chapter Summary and Discussion

For the one stream crossing assessed in this chapter, sediment load without a culvert replacement was likely to be twelve times the sediment load with a culvert replacement. While the culvert replacement involved some periods of high suspended sediment concentrations which could detrimentally impact aquatic life, a culvert failure would be even more damaging.

It should be emphasized that most of the sediment yield occurs during the rising limb and peak of the hydrograph; both were missing for the pre-culvert replacement snowmelt year, and the peak was missing for the post-culvert replacement snowmelt year. Having the complete hydrograph for both snowmelt years could very likely change the difference between culvert removal and culvert failure in this study.

Spring snowmelt before culvert replacement was a 2-year return interval, while spring snowmelt the following year, after the replacement, was a 4-year flood. While the 4-year flood is not particularly different from the 2-year flood (compared to, say, a 10- or 25-year flood), the difference between snowmelt years was evident. In 2008 (the 4-year flood), stream bed scouring and movement of large amounts of bedload, as well as stream bank erosion, occurred at a higher degree than the previous year (a 2-year flood).

A good question to ask is: Is the sediment produced from either the culvert replacement or potential culvert failure excessive? To answer this, it is helpful to consider sediment levels in terms of what may be “normal” for Cottonwood Creek. Are excessive sediment levels from disturbances such as road surface erosion, culvert replacements, or culvert failures problematic for Cottonwood Creek?

The sediment rating curves (see Section 3.b.10.) indicate that this reach is a sediment supply limited system; increased stream discharge does not correlate well with increased suspended sediment. This suggests that there is not much sediment available to be delivered to the stream as flows increase.

This is consistent with the 2007 spring snowmelt data, which suggests that Cottonwood Creek has low sediment yields during a relatively undisturbed condition; in fact, the sediment yields collected during the falling limb of the spring snowmelt hydrograph were within that of an undisturbed forest. It should be emphasized that the rising limb and peak flow data are missing, and these generally are associated with higher sediment yields than the falling limb. But low sediment yields for this creek seem reasonable given its well-vegetated hillslopes and stream banks as well as its relatively stable Belt geology.

Because Cottonwood Creek seems to be sediment-limited, it is possible that it can accommodate occasional pulses of high levels of sediment without detrimental impacts to aquatic life. In fact, Cottonwood Creek, and other watersheds in Western Montana evolved with wildfires which caused erosion from burned areas devoid of vegetation. Therefore, the streams must have evolved with infrequent large pulses of sediment.

Fire suppression efforts eliminated these stand-replacing fires and the associated sediment pulses to the streams. Therefore, it is reasonable to argue that anthropocentric disturbances such as road surface erosion, logging, culvert failures and culvert replacements could be surrogates for sediment produced from stand-replacing fires. Could this be the case for Cottonwood Creek, a sediment-limited system? Is there evidence that excess sediment is causing problems for this creek?

Montana DEQ uses two different targets for percent surface fines: percent of substrate particles < 2 mm and percent of substrate particles < 6mm. Both are based on pebble counts done in riffles. The two size fractions are typically used in regulatory agency stream substrate assessments, and reflect the fact that some research looked at substrate particles less than 2mm while others considered particles less than 6 mm.

For example, MT DEQ (2009) used both <2 mm and <6 mm targets; the <6 mm target was based on a study that found that the greatest number of salmonid and sculpin age classes occurred when the 75th percentile of substrate particles < 6 mm was no greater than 20-30 percent. Regarding the <2 mm target, MT DEQ (2009) explained that pebble count data from various regions in western Montana found that particles <2 mm comprised less than 10% of riffle substrate. Pebble counts done before the culvert replacement (during summer low flows) determined that percent surface fines in riffles <6 mm, assessed just downstream of the stream crossing, met targets developed by Montana DEQ for the Middle Blackfoot/Nevada Creek (MBNC) TMDL, while for upstream, they were slightly above the target values . Percent surface fines in riffles <2 mm met Montana DEQ targets for both upstream and downstream of the crossing prior to the replacement (MT DEQ, 2008). **Appendix S** (**Table A)** shows these results and the target values. This information indicates that in the undisturbed condition, either the stream in this study area (i.e., the reach just upstream and downstream of the stream crossing where the culvert replacement took place) was not receiving excessive sediment or it was adequately flushing out surface fines.

Percent surface fines in riffles increased for both upstream and downstream measurement sites after the culvert replacement (measurements were taken during summer low flows), as shown in **Appendix S** (**Table A**). For fines <6 mm, maximum target levels set by MT DEQ in the MBNC TMDL were exceeded for both upstream and downstream sites (MT DEQ, 2008). For fines <2 mm, only the upstream site exceeded maximum target levels. This suggests that the stream in this study area was not able to flush out sediment deposited during the culvert replacement and post-replacement spring flows. The higher levels of fines upstream of the crossing is probably due to the stream bank collapsing just upstream of the crossing, which delivered a large amount of sediment into the creek, which settled before it was able to move downstream.

In 2004, Montana DEQ conducted surveys throughout Cottonwood Creek as part of the analyses for the Middle Blackfoot/Nevada Creek Basin TMDL. The results indicated there were excess fines (both surface and subsurface), a lack of pools, and a lack of residual pool depth (MT DEQ, 2008) throughout the creek, including the reach studied in the thesis. Percent surface fines in riffles exceeded targets for the MBNC TMDL for both <6 mm and <2 mm. In addition, there was a lack of pools and residual pool depth; both parameters failed to meet targets, indicating pools have been filled up with fine sediment (MT DEQ, 2008).

To ascertain the extent of subsurface fines, Montana DEQ conducted McNeil coresin one reach, a few miles below the stream crossing assessed in the thesis. Here, subsurface fines exceeded the maximum allowable level set by the state. Montana DEQ concluded that fine sediments were a problem in this reach, describing it as having “poor conditions with respect to excess fine sediment accumulation and residual pool depth” (MT DEQ, 2008).

The 2004 Montana DEQ assessments differed from the 2007 thesis results for the same reach. This discrepancy could be explained by differences in substrate analysis locations, variations in methodologies, and operator error. Variations in stream substrate in riffles within a reach could be possible due to localized variations in flow (caused by boulders and vegetation) and areas where sediment is added to the stream from sources such as unstable stream banks. There are also likely differences in sampling methologies: the thesis study used a gravelometer and a sample size of over 300 particles (see Appendix S). The pebble count methodology used in the MBNC TMDL was not described, from personal experience, agencies frequently use a sample size of 100 particles measured with a ruler. With different methodologies and operators, error is added (Bunte and Abt, 2001).

These results suggest that a recent trend of low-flow years is responsible for the accumulation of sediment in this system that normally is supply-limited. Even a moderately high flow would probably flush out these fines. Therefore, in the long term, Cottonwood Creek is still a sediment supply limited stream. However, if low flows persist in the future because of climate change, “normal” levels of sediment may have detrimental impacts if they cannot be flushed out properly.

CHAPTER 4: RESEARCH OBJECTIVE #2, RISK ASSESSMENT OF COTTONWOOD CREEK STREAM CROSSINGS

Chapter 3 focused on one stream crossing in the Cottonwood Creek watershed. What about the rest of the watershed? Are there other stream crossings at high risk of fill failure or road surface erosion that could be replaced to improve conditions at those crossings?

This research objective assesses how much sediment is potentially deliverable to streams at various stream crossings in the Cottonwood Creek watershed from culvert failures and/or chronic surface erosion from the roads crossing the streams. Several stream crossings were field assessed throughout the Cottonwood Creek watershed to determine the risk of culvert failure or/and road surface erosion. If there was a high risk of these events, then the amount of sediment load deliverable to the stream was calculated. As with Research Objective #1, two scenarios were compared; one with a culvert replacement, and one without. Sediment loads from each scenario were compared to see if a culvert replacement resulted in a lower net sediment yield. The results from this research objective were compared with those in Chapter 3 and the literature to judge whether replacing high risk culverts with bridges may result in a net decrease of sediment yield.

Methods

Field Sampling Methods

There are over 100 stream crossings in the Cottonwood Creek watershed. Rather than visit all of them, only those at high risk of culvert failure or/and road surface erosion were selected for analysis. Risk factors were determined to be geology, soil type, and slope steepness (Wemple et al, 2001; Anderson and Potts, 1987; Sugden and Woods, 2007; Packer, 1967; Burroughs and King, 1989; Best et al, 1995).

The geology types were examined using GIS layers from Montana Natural Resources Information System (MT NRIS, 2009a) and found to be Belt series, alluvium, and glacial outwash. Belt series are generally stable and lie in the upper reaches of the watershed, which coincide with steeper slopes. Glacial outwash can be unstable, but lies in the lower part of the basin, where slopes are mild. **Appendix D** shows the geology. The literature review and Geology sections go into more detail about these geologic types.

To determine which soil types were at risk for erosion and landslides, soil surveys were examined (USDA NRCS, 1995 and USDA NRCS, 2003). The soil type corresponding with every stream crossing in the Cottonwood Creek watershed was examined to identify its hazard rating. The risk category examined in the soil surveys was called “Hazard of erosion and suitability of roads on forestland” (USDA NRCS, 1995; and USDA NRCS, 2003). The risk issues were “Severe Slope and Erodibility” (USDA NRCS, 1995; and USDA NRCS, 2003). Therefore slope was a factor in soil stability.

Because soil types had more specific information regarding which areas were unstable than the geology information, high risk stream crossings were chosen for field visits based on soil type criteria. **Appendix M** shows a map of these high risk soils.

The northern part of the Cottonwood Creek basin has not been surveyed by USDA soils survey agencies. However, these were very steep areas, so it was assumed they were at high risk for culvert failures and road surface erosion; all stream crossings in these areas were visited. In addition, a few sites were visited that were classified as low risk soils, but high risk features were identified, such as old clearcuts.

Thirty four stream crossings were visited in the summer and fall, 2008. **Appendix M** shows the locations of these crossings. To determine culvert failure risk, culvert fill dimensions (height, length, and width) and culvert diameter and length were measured. For road surface erosion, road length and width, gradient, and fill length and gradient were measured.

Data Analysis

Culvert Failure Risk: Regional regression equations for each return interval (2-year, 5-year, 10-year, 25-year, 50-year, and 100-year floods) using Omang’s (1992) methods were used to determine the peak flows at each stream crossing. The regression equations for the study area’s hydrologic region (West Region) used basin area and precipitation as the explanatory variables, and peak flow for a given return flood as the dependent variable. **Appendix B** shows these regression equations and their standard errors of prediction. The same methods were used as for the Hydrology section for Cottonwood Creek (Section 2.2.3.).

ArcGIS 9.3 measuring and analysis tools were used to measure the basin area (in square miles) above each stream crossing. Precipitation information was acquired through

PRISM (MT NRIS, 2009) for the Cottonwood Creek watershed; annual precipitation ranged between 24-60 annual inches of precipitation per year. The average of this was 42 annual inches of precipitation, which was used in the regression equations.

To determine if a culvert had the capacity to handle each return interval, the Hw:D for the culvert was examined at each stream crossing. The Hw:D is the headwater depth above the inlet of the culvert, and is used to see if the culvert has the capacity to handle a flood of a given return interval (US DOT, 2005). A nomograph was used to line up a given culvert's diameter with a Hw:D of 1.4 (a Hw:D of 1.4 is typically used in the literature) to find the corresponding stream discharge. This is the maximum discharge that the culvert had the capacity for, and was compared with each predicted return flood (from the regression equations) to see if it was above the return flow. Section 2.3.3. describes how the one standard error was derived.

For example, the predicted capacity of the culvert at site 17 was 44 cfs. Of all the return floods, it could only handle a Q2 flood (19 cfs), a Q5 flood (31 cfs), and a Q10 flood (41 cfs). For Q25 and greater return intervals, its capacity was not greater than those flood events. Where a culvert's capacity failed to exceed a given return flood, it was assumed the culvert would fail at that return flood, as well as any greater ones (USDA Forest Service, 1998).

To determine the annual load from culvert fill failure, the methods in U.S. Forest Service (1998) were used. Here, the chance that the capacity of a given culvert will be equaled or exceeded during *n* years was calculated. USDA Forest Service (1998) argues that exceeding capacity means culvert failure. The probability that a given return interval is equaled or exceeded at least once in the next *n* years was calculated according to the following formula. This formula is the sum of the probabilities of occurrence for each year until the nth year:

$$p_n = 1 - \left[\frac{T_r - 1}{T_r}\right]^n$$

A 20-year time period was chosen for this assessment; 20 years is a reasonably long enough time period to encompass the return intervals. In a 20-year period, what is the probability of a Q2, Q5, Q10, Q25, Q50, or Q100 flood occurring? Which of the culverts found to lack a capacity for one or more return flow would likely fail in this 20-year period?

An assumption made in this thesis is if the culvert failed, the entire amount of fill would enter the stream. For each stream crossing with a culvert that could fail at a given return interval, the load from its fill volume was calculated based on geometric measurements of the culvert fill volume made during field visits. To find this, the culvert void volume (m^3) was subtracted from the fill and culvert volume (m^3) to obtain just the fill volume. This was multiplied by the bulk density of the soil in that area. Soil bulk density values were obtained from the Natural Resources Conservation Service's (NRCS) Soil Data Mart website (USDA NRCS, 2009a; USDA NRCS, 2009b).

Road Surface Erosion: The Water Erosion Prediction Project (WEPP) model was used to estimate chronic surface erosion from the road at the stream crossing for 31 stream crossings visited (this is less than the 34 crossings assessed for culvert fill failure because three crossings were so completely overgrown and had no road gradient that it was unlikely there was any road surface erosion) (USDA Forest Service, 2008). Measurements included road gradient and width, fill length and gradient, and road surface material, and were taken prior to and after the culvert upgrade to determine if there was a difference. Road surface erosion was modeled for a ten-year time period, which was arbitrarily chosen. The WEPP model has a large amount of error; Elliot (2008) says the predicted erosion is usually within plus or minus 50% of the true value. The same parameters were used in the model as described in Section 3.a.1.4.

Sources of Error: Stream crossings were not selected on the basis of representativeness of other stream crossings in the watershed; i.e., the goal was to assess all high risk stream crossings, not a random sample. Therefore, no statistical tests were done on the level of precision or accuracy. At each stream crossing, only one measurement was done for culvert failure potential, and one for road surface erosion potential; measurement replicates were not done.

A limitation of regression equations is if the values of any of the explanatory variables lie outside the range of values used to develop the equations. The range of values used to develop the equations for the basin area explanatory variable is between 0.86 and 2,354 square miles and for precipitation, it ranges between 19-79 inches per year (Omang, 1992). Out of the 34 sites visited in Cottonwood Creek, 22 were below the range for basin area; for precipitation, all sites were within the range. Therefore, the results of the regression equations for these 22 small basin sites may not be valid (Omang, 1992).

For the regression equations, the standard error of prediction used in the Omang (1992) literature was used, which was plus or minus one standard error. For the road surface erosion modeling, the plus or minus 50 percent error stated by Elliot (2008) was used to determine the level of error in the WEPP model runs.

Results and Discussion

Culvert Capacity Analysis

Using the regression models from Omang (1992), the Q2, Q5, Q10, Q25, Q50, and Q100 predicted return floods were calculated for each of the 34 stream crossings. **Appendix N** shows these values. In addition, for each return interval, there is one standard error above and below the predicted return interval given. This is based on the standard error of prediction (%) for each return flood (Omang, 1992) as described in Section 2.3.3.

Thirty four stream crossings were visited during the fall of 2008, and measurements were taken for culvert failure analysis as described in Section 4.a.1. Culvert sizes varied due to differences in stream size: the range of sizes was 18 to 67 inches in diameter. Basin areas above the crossings ranged from 0.07 to 13 square miles. Sixteen of the 34 sites visited had culverts with capacities that failed to meet one or more return interval (50% of total sites visited).

Table 24 shows the number of culverts predicted to fail at each of the six return intervals. Approximately one-quarter of the culverts lacked the capacity to accommodate a 2-year flood or more; over 47% were predicted to fail at a 50-year flood or higher.

The probabilities of various return flows occurring during the next 20 years were calculated using methods from Section 4.a.2.1. During this time period, there is a 99% chance that the 2-year and 5-year floods will be equaled or exceeded; an 88% chance of a ten-year flood or greater; a 56% probability of a 25-year flood or higher, and a 33% and 18% chance for a 50-year and 100-year flood, respectively. To be conservative, only the 2-year, 5-year and 10-year floods were considered as highly likely to occur during the 20-year period.

Of the 16 culverts that could fail at one or more flood intervals, ten had capacities below the Q2, Q5, and Q10 floods, so there is a 63 percent culvert failure rate for these intervals. Annually, there is a 3 percent failure rate (63 percent divided by 20 years). **Appendix O** shows these ten sites along with their corresponding culvert fill volumes and sediment load. The total load for these crossings was 428,500 kg (470 tons) with an average of 42,850 kg (50 tons) per crossing, and a range of 2,540 (3 tons) to 194,340 kg (213 tons). The fill volume for the ten sites ranged from 1.7 m^3 to 129.6 m^3.

The total load of 428,500 kg was normalized by basin area for each crossing, which resulted in 39 kg/ha, or 4 kg per crossing. Therefore, over the 20-year period, there is a high probability (over 88%) that there will be 428,500 kg (39 kg/ha) of sediment delivered to the Cottonwood Creek basin from these ten failed culverts. Multiplying the total load of 428,500 kg by the 3 percent annual failure rate results in 12,900 kg per year, and normalizing by total basin area for the ten culverts produces 2 kg/ha/year load. **Appendix O** shows the total basin area for these ten crossings, and **Appendix P** shows their locations.

If the ten culverts were replaced by bridges, how might that affect the sediment load for the 20-year period? As with Research Objective #1, two scenarios were compared: one where the ten culverts were not replaced and one where they were replaced. Spring snowmelt loads from the 24 culverts that were not predicted to fail were also considered in each scenario. Because road erosion results were negligible, these are not used in this analysis. The scenarios are described below:

<u>Scenario where Culverts are not Replaced</u>: Here, ten out of the 34 culverts assessed were predicted to fail over the 20-year period, while the remaining 24 culverts were not expected to fail. For convenience in estimations, it was assumed that there would be one culvert failure per year, starting with the first year of the 20-year period. Thus, for the first year, one culvert would fail and 33 would not. For the second year, another culvert fails, and the remaining 32 do not, and so on until the tenth year, at which the last of the ten culverts fail. **Table 25** shows this sequence. The load for each failed culvert is obtained from **Appendix O**.

This analysis includes sediment loads from spring snowmelt runoff for the culverts that do not fail. The pre-culvert replacement snowmelt load of 3,300 kg from Research

Objective #1 (see **Table 14**) was used to estimate the annual spring snowmelt load for each culvert that did not fail during the 20-year period. For example, for the first year, the 33 culverts that do not fail each have an estimated spring snowmelt load of 3,300 kg. The total load for this year for these 33 culverts is 108,900 kg. **Table 25** shows the spring snowmelt loads for culverts not predicted to fail for each of the 20 years.

After the tenth year, all ten culverts will have failed. However, the 24 non-failed culverts remain, producing annual loads from spring snowmelt. As **Table 25** depicts, from the 11th through 20th year, there are 24 culverts that each produce 3,300 kg of sediment from spring snowmelt annually, for a total of 79,200 kg/year.

The total load for all failed and non-failed culverts over the 20-year period is 2,161,000 kg and the annual rate for the 20-year period is 108,100 kg. Normalizing by the total basin area (obtained from **Appendix N**) for the 34 culverts (13,730 hectares), produces 160 kg/ha total for the 20 years, and eight kg/ha annually. These numbers are very rough estimates as there are variations in stream size, fill volume and other factors that would influence the amount of sediment yield produced during spring snowmelt and a culvert replacement.

Scenario where Culverts are Replaced: In this scenario, the ten culverts are replaced by bridges at the beginning of the 20-year period. Each of these ten culverts produces sediment loads from both the replacement event and spring snowmelt during the post-replacement years. In addition, the other 24 non-replaced culverts produce spring snowmelt loads for each of the 20 years, as with the first scenario. Sediment yields from Research Objective #1 (see **Table 14**) were used to estimate the sediment loads for non-failed culverts (3,300 kg/culvert), for the culvert replacement (420 kg/culvert), and the post-replacement snowmelt load (7,400 kg/culvert for the first two years; 3,300 kg/culvert for the next 18 years) in this scenario.

Post-replacement spring snowmelt loads were expected to decline each year after the replacement; after two years, they were estimated to return to approximately pre-disturbance levels. This estimate was based on Anderson and Potts (1987), where suspended sediment yields were measured for two years after road building in Belt metasediments. In this study, spring snowmelt loads the first year after road building were approximately seven times that of pre-disturbance loads. The second year after road building, loads decreased to twice that of undisturbed conditions. Based on these results, it is reasonable to expect that sediment yields for the third year after road building would be close to undisturbed levels.

Based on the results from this study, in this scenario, spring snowmelt loads the first two years after the culvert replacement for the ten culverts were estimated at 7,400 kg/replaced culvert, and the next 18 years at 3,300 kg/replaced culvert. Thus the total load for all failed and non-failed culverts over the 20-year period is 2,330,200 kg and the annual rate for the 20-year period is 116,500 kg. As with the first scenario, this scenario is a very rough estimate that does not consider variations between streams, and makes assumptions on post-culvert replacement loads that may not be accurate. **Table 26** shows the results for this scenario.

<u>Discussion on Scenarios</u>: Table 25 and **Table 26** show that the scenario where the ten culverts are not replaced produces a slightly lower net sediment yield than the scenario where the culverts are replaced. Not replacing the culverts produced a total load of 2,161,000 kg (160 kg/ha), which is an annual load of 108,100 kg (8 kg/ha) for the 20-year period. Replacing the ten culverts resulted in 2,330,200 kg (170 kg/ha) of sediment, which is 116,500 kg (8.5 kg/ha) per year, over the 20-year time frame. Replacing the culverts resulted in a six percent higher sediment load than not replacing the culverts; it is therefore not beneficial to replace them.

However, there is considerable error in this analysis; using sediment loads from Research Objective #1 probably overestimates sediment yield from both these scenarios. Most of the culverts for Research Objective #2 were smaller than the one from the first objective: the mean culvert fill load and culvert diameter for the ten culverts was 42,850 kg and 24 inches, respectively. The culvert fill load and diameter for the culvert replaced in Research Objective #1 was 90,000 kg and 55 inches, respectively. Therefore, the estimates used for each scenario in the second objective are based on a culvert that was larger and contained more fill than most of the ten culverts assessed in each scenario. Although there is considerable error in these estimates, they still suggest there is no great advantage to replacing culverts..

Road Surface Erosion Modeling

There were 31 stream crossings modeled using WEPP, which gave estimated values, in pounds, for road prism erosion and the amount of sediment leaving the buffer between the road and stream. Road prism erosion includes road surface and fill. **Appendix Q** shows the parameters chosen to run the model, and **Appendix R** is a spreadsheet of the WEPP output runs, modeled for a ten-year period, and gives annual erosion rates.

There is very high variability in these measurements, likely due to the +/- 50% error in the model. Erosion from the road prism was summed for all stream crossings to determine the total pounds of sediment entering the watershed from the road prism and from the buffers. There were 1,000 kg of sediment eroding from the road prism (road surface and fill) from all the crossings assessed, and 2,350 kg from the buffers. This is a total of 3.8 tons, or 3,350 kg/year, (modeled over a ten-year period). There is an average of 105 kg/crossing, the range is 0 to 940 kg/year and the standard deviation of the modeled sediment for each crossing was 232 kg, which is very large (twice as much as the mean). Seven out of the 31 crossings (23%) produced over 100 kg per crossing.

This high level of variability and large range of values reflects the large differences between stream crossings. These differences include steepness of the road surface, which allows more sediment delivery than less steep areas. Longer road sections leading to a stream crossing also deliver more sediment than shorter sections. In addition, steep areas require more fill so there is more fill length and width, plus a steeper fill gradient; such areas could have higher erosion rates than areas with less fill volume and gentler fill gradients. Level of vehicle use of a road affects erosion rates; vehicle use on roads grinds surfacing material and creates loose, erodible material available for transport. Normalizing the total sediment load for all the 31 stream crossings (3,350 kg) to basin area for Cottonwood Creek (17,900 hectares) resulted in 0.19 kg/ha/year. **Table 27** gives a summary of the WEPP results.

A critique of the WEPP model is that it is only run on an annual basis; as Sugden and Woods (2007) pointed out, while annual precipitation in Western Montana is not as high as, say, Western Oregon, there are episodes of high intensity rainfall in summer months. These summer storms over a period of four months produce the majority of annual rainfall erosivity (Renard et al, 1997, in Sugden and Woods, 2007). This is not reflected in the WEPP annual modeling-it is an average of all precipitation, including snowmelt, which does not detach particles near to the extent that heavy rainfall does. Thus, 3,350 kg/year may be low, but during summer months when there are episodes of heavy rain, surface erosion may be higher than is reflected in the 3,350 kg/year annual average number.

Comparing Culvert Failure and Road Surface Erosion Results to the Literature

Culvert Fill Failure: The 2 kg/ha/year estimated load from culvert fill failure from the ten stream crossings is extremely low; in fact, it is only very slightly above the range for an undisturbed forest in Anderson and Potts (1987). For the replacing/not replacing culvert scenarios, both yielded similar results (8 kg/ha/year for the non-replacement scenario and 8 kg/ha/year for the replacement scenario). These values are lower than the spring snowmelt loads the first year after road building, but higher than spring snowmelt loads the second year after road building in Anderson and Potts (1987) (13.7 kg/ha/year and 3.6 kg/ha/year, respectively, in that study). Averaged over a 20-year period, it seems excessive that annual loads for either scenario exceed that for the second year after road building in Anderson and Potts (1987). Perhaps annual sediment loads will become reduced over a longer time period than 20 years.

Road Surface Erosion: There was a 0.19 kg/ha/year estimated sediment yield from road surface erosion for the 10 stream crossings. Upgrading a culvert to a bridge for the one stream crossing described in Chapter 3 resulted in a 97% drop in sediment yield from road surface erosion. There are no studies in the literature regarding road surface erosion changes by a culvert-to-bridge replacement. However, the road surface erosion is so very low for the ten crossings that it seems irrelevant to be even concerned about this. It is, in fact, well below the undisturbed forest range in Anderson and Potts (1987) by three-fold.

However, while for a basin-wide analysis the values are low, there could be local impacts on aquatic life downstream of an eroding stream crossing. Chronic road surface erosion is cumulative; it can settle in pools, thus reducing pool volume and also settles in stream substrate (Espinosa et al, 2007).

Cottonwood Creek and other creeks in the MBNC do have important fish habitat just downstream or road crossings. Seven out of the 31 crossings (23%) produced over 100 kg per crossing. While these are averaged out when considering load per unit area, these high sediment-producing stream crossings still could have problematic local effects on aquatic habitat.

Summary of Chapter 4

Sediment yields from culvert fill failures for the ten culverts assessed over a 20-year period was very low compared to the literature, even for undisturbed forests. Therefore, replacing them is not necessary in the context of reducing load to Cottonwood Creek basin. However, the impacts locally to aquatic life can be significant (Redding and Shreck, 1982, in Foltz et al, 2008; Espinosa et al, 2007). Therefore, the analysis broadened to considering the possible benefits of replacing these culverts.

There was no difference in sediment yield between replacing and not replacing the ten culverts over the 20-year period of analysis. These results were low compared with the literature values for post-road building spring snowmelt. However, there is considerable error in the sediment yield estimates from each scenario due to overinflated load estimates based on the one culvert replacement from Research Objective #1. It should be emphasized that this analysis models culvert failure only for a 20-year period, so does not include culverts that could fail at Q25 return floods and greater. Because it is questionable whether replacing the ten high-risk culverts would have any benefit, it would be best to replace only those that have large loads from culvert fill.

It should also be emphasized that all culverts, even low-risk ones, will eventually fail. The thesis analysis looked only at the ability of culverts to accommodate floods at different intervals. There are other factors besides culvert capacity that affect culvert failure, such as abrasion, corrosion and debris that becomes caught in the culvert. The length of time culverts last given the threats of abrasion and corrosion depends on their material, the amount of bedload moving through, and the pH and level of corrosive salts in the surrounding soil (USDOT, 2005). Debris obstructions can occur at any time in a culvert’s life, and can result in culvert failure due to water diverting around the plugged up culvert.

CHAPTER 5: RESEARCH OBJECTIVE #3, CRITIQUE OF MIDDLE BLACKFOOT/NEVADA CREEK TMDL, FOCUSING ON SEDIMENT-RELATED ISSUES

Background

Chapter 5 describes Montana DEQ's modeling efforts for the Middle Blackfoot-Nevada Creek basin, the larger watershed that encompasses Cottonwood Cr. The results from Chapter 4 are compared with these efforts, as well as compared with other TMDLs in the region.

The final Middle Blackfoot-Nevada Creek TMDL/Water Quality Improvement Plan (MBNC TMDL/WQIP) was approved on September 22, 2008 by the U.S. EPA (MT DEQ, 2008). The Middle Blackfoot and Nevada Creek basins lie in the middle area of the Blackfoot watershed. The MBNC TMDL/WQIP was produced by Montana Department of Environmental Quality (MT DEQ) as required by the Clean Water Act. This research objective critiques the sediment portion of the MBNC TMDL/WQIP, focusing on the Middle Blackfoot Basin (the watershed in which Cottonwood Creek lies). This critique will be based on lessons learned from the first two research objectives, as well as information from the literature.

Under Section 303 (d) of the Clean Water Act (CWA), each state is required to identify any of their water bodies that fail to meet water quality standards. Montana DEQ produces a document that identifies threatened and impaired water bodies and describes methods used to determine impairment/threatened status (MT DEQ, 2008). This document is called the 303(d) list, and fulfills the CWA requirement to identify water bodies that fail to meet standards (MT DEQ, 2008).

A water body (or stream segment) that is classified as "impaired" is failing to comply with applicable water quality standards. A "threatened" water body (or stream segment) is fully supporting its designated uses but is threatened for one of those uses (MT DEQ, 2008). Section 303 of the CWA requires states to develop TMDLs for impaired and threatened water bodies (or stream segments).

The Total Maximum Daily Load (TMDL) is the maximum amount of a pollutant that a water body can take without exceeding relevant standards (MT DEQ, 2008). The study to determine this amount, sources, and solution is also called a TMDL. The pollutant load is the mass of a pollutant that enters a water body per unit of time (MT DEQ, 2008). Because there is uncertainty in estimating pollutant loads, TMDLs include a margin of safety. The MBNC TMDL/WQIP document includes the TMDL component as well as a watershed-wide water quality restoration plan (MT DEQ, 2008).

As required by the Montana Water Quality Act, the state of Montana developed a classification system for all waters of the state that includes their present and future most important beneficial uses (also known as designated uses) and adopted standards to protect those uses (MT DEQ, 2008). All water bodies within the Middle Blackfoot-Nevada Creek Planning Areas are designated a B-1 Classification, as described below:

Classification	Designated Uses
B-1 CLASSIFICATION	Waters classified B-1 are to be maintained suitable for drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.

Besides the Designated/Beneficial Use standards, there are also numeric and narrative standards, and a nondegradation policy, as part of Montana water quality laws (MT DEQ, 2008). Numeric standards are used for pollutants, such as heavy metals, that have been determined to be toxic, carcinogenic, or harmful. (MT DEQ, 2008). Narrative standards apply to pollutants that lack adequate information to develop specific numeric standards, such as sediment (MT DEQ, 2008). These standards prohibit increases of sediment above natural levels if this would result in adverse effects (MT DEQ, 2008).

To determine if narrative water quality standards are being met, MT DEQ uses the reference condition methodology. The reference condition is defined as: “the condition of a water body capable of supporting its present and future beneficial uses when all reasonable land, soil, and water conservation practices have been applied” (MT DEQ, 2008). To determine what reference conditions are for a particular water body, minimally impaired water bodies from a nearby watershed or in the same ecoregion, with similar characteristics to the one in question, are considered (MT DEQ, 2008).

In general, the major pollutant categories in the Middle Blackfoot /Nevada Creek Planning Area waters are excess sediment, nutrients, trace metals, and elevated stream temperatures (MT DEQ, 2008). Only sediment-related issues are discussed in this thesis.

The beneficial uses for Cottonwood Creek are: aquatic life, coldwater fisheries, drinking water, primary contact recreation, agriculture, and industry (MT DEQ, 2008). Sediment is a pollutant of concern in Cottonwood Creek; the ten mile reach upstream from its mouth on the Blackfoot River was listed as impaired in 1996 because it was only partially supporting aquatic life and cold water fisheries due to flow and habitat alterations, as well as excessive siltation. The causes of these problems were due to stream bank trampling by livestock (MT DEQ, 2008).

In the late 1990's, BMPs and restoration efforts were implemented to improve instream flows, riparian areas, and fish passage. In 1999, Montana DEQ re-assessed Cottonwood Creek and concluded that although there was still moderate habitat impairment, the chemical and biological evidence indicated minor impairment and full use support. Thus, the stream was listed as fully supporting from 1996 to 2006 (MT DEQ, 2008).

As a side note, in a study of seven tributaries of the Blackfoot River in 1995, a composite score of macroinvertebrate metrics ranked Cottonwood Creek the third highest in aquatic biointegrity (Rothrock et al, 1998). The study site on Cottonwood Creek was just downstream of the Blackfoot-Clearwater Wildlife Management Area, a grassland-dominated habitat a few miles north of the junction of Cottonwood Creek with the Blackfoot River. This is within the reach listed in 1996 by Montana DEQ as impaired due to an inability to fully support aquatic life and fisheries; the 1995 study appears to contradict this listing as far as macroinvertebrate quality.

However, data collected as part of the MBNC TMDL/WIQR assessments in 2004 found that the Cottonwood Creek's fisheries potential was not being met and therefore the 1996 impairment listings were still warranted. Specifically, none of the reaches met all of the targets for habitat and substrate quality. One reach had excess fine sediment accumulation in pools and minimal pool depth (MT DEQ, 2008). Other reaches had high levels of fines in the substrates and low concentrations of woody debris. Therefore, MT DEQ decided the original 1996 303(d) listing based on flow, habitat, and siltation issues was still warranted. The causes of degradation included excess sediment production, removal of stream bank vegetation, and flow alterations. MT DEQ identified four sources of sediment: stream bank erosion, road surface erosion, culvert fill failure, and hillslope erosion.

The TMDL process for the Middle Blackfoot and Nevada Creek Planning Areas began in June 2003 where existing data were compiled and reviewed. In 2004, Montana DEQ collected a comprehensive suite of base parameter data for the TMDL analysis. This included field measurements of stream channel morphology, stream habitat, vegetation composition, and land use characteristics near water bodies (MT DEQ, 2008). These data were used to help develop TMDLs for excess sediment, habitat alterations, temperature, and nutrients, and to develop statistical norms for the parameters.

Stream Bank Erosion Inventory: Methods and Results

Eroding stream banks were inventoried during the base parameter assessments in 2004 to determine how much sediment they were contributing to the overall load in the MBNC Planning Areas (MT DEQ, 2008). Two bank erodibility estimation tools were used, a stream bank erodibility index (Bank Erosion Hazard Index, or BEHI), and Near Bank Stress (NBS), both Rosgen methods .

Seven streambank characteristics are used to develop the BEHI index (Rosgen, 2001). These are: 1) ratio of streambank height to bankfull width, 2) ratio of riparian vegetation rooting depth to streambank height, 3) degree of rooting density, 4) composition of streambank, 5) streambank angle, 6) stratigraphy of stream bank and presence of soil lenses, and 7) protection of streambank by debris (Jessup, 2004).

Streambank erosion is also influenced by the flow near the streambank, which can cause “near-bank stress”(Jessup, 2004). The “near-bank” area is the one-third part of the channel cross-section closest to the stream bank (Rosgen, 2001). Near Bank Stress (NBS) is estimated using criteria such as channel pattern, ratio of pool slope to average water surface slope, ratio of near-bank maximum depth to bankfull mean depth, and several other parameters (Jessup, 2004).

Worksheets are used to enter information concerning the eroding stream bank, and an index system of stream bank erosion severity (from very low to extreme) is determined based on the BEHI and NBS attributes (U.S. EPA, 2009). The relationship of BEHI and NBS risk ratings is then graphed to predict the annual stream bank erosion in feet/year. This erosion rate is multiplied by the stream bank height times the bank length associated with a given BEHI and NBS. This gives an estimate of cubic yards of sediment eroded per year (U.S. EPA, 2009).

For the MBNC TMDL/WQIP, the BEHI and NBS index methods described above were used to determine the severity of stream bank erosion (MT DEQ, 2008). To quantify bank erosion rate, the literature was perused for appropriate stream bank annual retreat rates (lateral recession rates), and the ones developed for the Palisades TMDL in Southeast Idaho (Zaroban and Sharp, 2001) were the most applicable (MT DEQ, 2008).

The NRCS stream bank erosion inventory is a field method that was used in the Palisades TMDL to estimate streambank/channel stability, length of active eroding banks, and bank geometry. These measurements were used to estimate the long-term lateral recession rate of the stream banks (Zaroban and Sharp, 2001).

These stream bank retreat rates were matched to the BEHI rates, according to level of severity. To calculate the annual stream bank erosion rate, bank retreat rate was multiplied by stream bank height times length. The result was multiplied by the bulk density of the soils in the area to obtain a yearly volume of sediment in tons/mile/year (MT DEQ, 2008).

Total stream bank erosion measurements were divided into controllable and background components. The TMDL defines “background” as the condition in an environment without human disturbances (non-anthropogenic), while “controllable” is the condition that is impacted by anthropogenic activities, and constitutes the amount of stream bank erosion that can be controlled.

To determine the background erosion rate, MT DEQ reviewed land uses, vegetation conditions, and bank stability ratings, as well as field notes documenting bank and reach conditions (MT DEQ, 2008).

Seven reaches in Cottonwood Creek were measured and modeled for streambank erosion using the methods described above. The cumulative total bank erosion estimate for the seven reaches was 296 tons/year. This value included both background and controllable loads. The cumulative controllable reach load was estimated at 106 tons/year, and the cumulative background load was estimated to be 190 tons/year (MT DEQ, 2008). **Table 28** shows these quantities in terms of sediment yield per unit area.

Montana DEQ next determined how much stream bank erosion could be reduced, and this is called the “achievable reduction,” which is the amount of the controllable load that could be reduced by using BMPs. Montana DEQ estimated the achievable reduction by assessing land use, vegetation, bank stability ratings, and other criteria of the measured stream banks (MT DEQ, 2008). For Cottonwood Creek, the achievable reduction to the human-caused component of stream bank erosion for the reaches assessed was estimated at 68%, or 72 tons/year. BMPS to control stream bank erosion are discussed later in this chapter.

Critique of Stream Bank Erosion Methods

Dr. David Rosgen developed the BEHI/NBS model on only two rivers; one in the Lamar Basin in Yellowstone National Park and the other in Colorado’s Front Range (Rosgen, 2001). There were only two channel types in the study reaches: A and B channel types. This is a concern because the TMDL uses this model outside the range for which it was developed. For example, there are differences in geology between the Middle Blackfoot/Nevada Creek (MBNC) area and Lamar Basin/Front Range; the latter two areas have igneous influences, while the MBNC is composed of sedimentary rocks.

As a parallel argument, in assessing peak flow regression curves for various return intervals, the literature warned against using the curves for regions outside of the regions for which they had been developed (Parrett and Johnson, 2004). Perhaps that argument is valid for the Rosgen methodology? Certainly, Dr. Rosgen does not talk about limitations of his methods regarding their use outside the regions for which they have been developed. As far as using this model in different regions from where it was developed, Rosgen (2001) simply stated that field practitioners would need to establish local regression curves relating BEHI to NBS. However, as described below, researchers using this model in different channel types than those used in its development have run into problems.

The Rosgen methodology does not discuss any measurement of error. This is in stark contrast to other water quality/quantity measurement and prediction tools that were assessed in this thesis. The regression curves for peak flow estimates contained standard errors of prediction for each return interval equation (Omang, 1992). For calculating the headwater depth to determine culvert capacity to handle peak flows, percent error was estimated

(USDOT, 2005). The WEPP model also had an estimate of error (Elliot, 2008). Given that these other models have estimates of error, the question is asked: why does the Rosgen stream bank prediction model lack estimates of error?

The literature is mixed as far as how well the Rosgen methods predicted streambank erosion compared with actual measurements using erosion pins or other survey methods. Van Eps et al (2004) used BEHI, NBS and erosion pins measurements on the West Fork White River in Arkansas to develop a model to predict streambank erosion rates based on relationships between these three measurements. This model was compared with the Rosgen model and another BEHI/NBS model that was used in North Carolina, and found to have different results. The authors speculated that differences between models may have been due to variation in watershed size or characteristics such as soils and precipitation (Van Eps et al, 2004).

Harmel et al (1999) tested the ability of the BEHI and NBS models to predict short-term streambank erosion rates in the Illinois River in the Ozarks. BEHI, NBS, and erosion pins measurements were taken on stream types classified as mainly C4 and F4. The relationship of BEHI and NBS had a poor correlation in this study. In Dr. Rosgen's studies in the Lamar Valley and Colorado Front, bank erosion rate increased as both BEHI and NBS increased. Harmel et al (1999), on the other hand, there was an inconsistent relationship between these three variables. Therefore, the authors concluded that BEHI and NBS were poor predictors of bank erosion for these channel types.

Regarding methods used in the MBNC TMDL/WQIP to estimate stream bank erosion, the use of the stream bank retreat rates from the Palisades TMDL described in Section 5.2 seem suspect. This TMDL concerns water quality issues in Southeastern Idaho (Zaroban and Sharp, 2001), an area that is very different from Western Montana in terms of soils, geology, and vegetation.

The MBNC TMDL/WQIP does not divulge what the other choices were for stream bank retreat rate, simply stating that the ones developed for the Palisades TMDL were most applicable. It would have been helpful to have a margin of error for the use of these stream bank retreat rates. There was no such information found in the Palisades TMDL.

Roads Assessment: Measurements and Estimates of Sediment Produced from Road Surface Erosion and Culvert Failures, and Critique of these Methods

The *Quality Assurance Project Plan and Sampling and Analysis Plan* (QAPP/SAP) and the *Field-Updated Implementation Report and Data Analysis and Results Summary* (Implementation Report) are two comprehensive documents that detail the objectives, methods and results of road surveys done for the Middle Blackfoot-Nevada Creek TMDL/WQIP (River Design Group, Inc., 2006). These road surveys were a collaborative effort between Montana DEQ, the River Design Group, Inc., Blackfoot Challenge, and several land management agencies and land owners; they will be collectively referred to as Montana DEQ, the entity that provided oversight to the road survey project. The road surveys assessed road surface erosion loading and the amount of road fill at risk from culvert failure, as well as documenting culvert impacts on fish passage and road impacts on Large Woody Debris. The results from these surveys were further analyzed in the MBNC TMDL/WIQR document.

These road surveys included existing surveys conducted by land management agencies and private landowners, as well as surveys specifically done for the MBNC TMDL/WQIP, which were conducted in the summer of 2005 by staff members of various local agencies. The Implementation Report explained how training and calibration for the 2005 surveys were done so that staff conducted measurements in a similar manner (River Design Group, Inc., 2006). This was an important part of the field data collection and the report did well explaining the complex methods used to assure representativeness, reduce bias, and have adequate comparability.

Regarding site selection, the QAPP/SAP explained that a five percent sub-sample was needed of the total number of stream crossings in each of the Middle Blackfoot and Nevada Creek Planning Areas, but doesn’t explain why five percent was chosen (River Design Group, Inc., 2005). Is this sample large enough to acquire a representative distribution of sampling of crossings?

The QAPP/SAP discussed how sampling stratification would occur, in order to ensure the range of conditions and the variability of environmental and management characteristics across the Middle Blackfoot and Nevada Creek Planning Areas were represented for road surface erosion and culvert fill failure assessments. Stratification was based on ownership (public vs private), precipitation zone, and geology (River Design Group, Inc., 2005).

These seem like reasonable stratification criteria, although soil risk types might have been a good stratification category because soil types vary throughout the Middle Blackfoot-Nevada Creek area and some soils are more erodible than others. Other suggested levels of stratification are: stream order/size, road surface slope, and level of road use. Regarding stream order or size, larger streams would have more culvert fill at the crossing that could influence the amount of erosion and fill at risk of failure. For road surface slope, steeper roads could have more surface erosion than less steep roads, as well as more fill at the stream crossings. Higher use roads would have more road surface erosion that those that are little used from wear and tear on the road.

The distribution of crossings was also weighted by the percent distribution of area by the particular land ownership, precipitation zone, and geology. For example, thirteen percent of the Middle Blackfoot Planning Area is in the 34 inch precipitation zone, so the total number of crossings (1,818) was multiplied by thirteen percent, and this was multiplied by five percent to obtain 12 sites to survey in this category.

This stratification technique seems reasonable; it helped increase representativeness of the sampling by both stratifying the Planning Areas and weighting the strata categories to ensure the random sampling will more likely capture samples in a representative fashion. However, it can reduce sample power when categories have only a few samples because they are less well-represented. It is a tradeoff; there is increased sample power with fewer categories but a larger sample size, or more categories but smaller sample sizes. Some discussion explaining the pros and cons of these tradeoffs would be beneficial.

Road Surface Erosion

Existing surveys previously done by Plum Creek Timber Company (PCTC) were included in the road surface erosion analysis in order to reduce new data collection and to guide sampling methods (River Design Group, Inc., 2005). These existing surveys were stratified as mentioned in the previous section, and for each land owner, precipitation zone, and geological type, it was determined how many additional surveys needed to be done in 2005 to assure representativeness in each stratifying group (River Design Group, Inc., 2006).

Montana DEQ used the Washington Forest Practices Board method ("Washington Method") for collecting road surface erosion data, which included parameters such as road tread length and width, road grade, surface type, cutslope length and width, and fillslope length and width (River Design Group, Inc., 2005; River Design Group, Inc., 2006). The Implementation Report did not explain how much error is in this model; in contrast, the WEPP road surface erosion model does give a measurement of error (plus or minus 50%). The amount of error in a model is important for judging how close measured values may be to the "true" values. However, such information was absent in the MBNC TMDL/WQIP.

For the Middle Blackfoot TMDL Planning Area, there were approximately 1,818 stream crossings identified by MT DEQ; it is not clear how many were actually surveyed as there is a discrepancy between the Implementation Report and MBNC TMDL/WIQR. According to the Implementation Report, 227 stream crossings were surveyed for road surface erosion; the MBNC TMDL/WIQR says there were 323 surveyed. The MBNC TMDL/WIQR does not explain the discrepancy. The number of streams surveyed come to more than a five percent sample; some of the existing data were not available at the time that the surveys were implemented, and therefore were not included in determining the sample size (River Design Group, Inc., 2006).

The Implementation Report does not explain if the existing surveys done by Plum Creek Timber Company (PCTC) were randomly selected (the 2005 surveys done by Montana DEQ were randomly chosen). This is a concern, because the PCTC surveys were combined with the 2005 surveys to extrapolate to unsurveyed crossings. If the PCTC surveys were not randomly conducted, there may be bias towards certain types of crossings.

However, because the PCTC surveys were stratified according to land ownership, precipitation zone, and geology, as described in the previous section, this could help to reduce the bias from non-random surveys. However, there is still bias if the PCTC sites were selected based on factors other than randomness. Some discussion on this in the TMDL would be helpful.

For the Middle Blackfoot Planning Area, there were either 249 or 299 tons/year road surface erosion sediment load from surveyed crossings; there was a discrepancy between the Implementation Report and MBNC TMDL/WIQR document. The Implementation Report stated that out of 227 crossings surveyed, there was 249 tons/year load, while in the MBNC

TMDL/WIQR, out of 323 crossings surveyed, there was 299 tons/year load. There is no explanation in these documents regarding this discrepancy.

Montana DEQ extrapolated the road surface erosion results from surveyed crossings (both PCTC and 2005 surveys) to the non-surveyed stream crossings based on stratified group combinations. As described earlier, there were three stratified groups: land ownership, precipitation, and geology. The Implementation Report generated all possible combinations of these groups. For example, one combination was: BLM ownership group, 17-26 inches/year precipitation group, and Alluvium-Glacial-Volcanics geology group. The Implementation Report showed the number of surveyed and non-surveyed crossings, and the mean of sediment yield loads for each combination (River Design Group, Inc., 2006).

The mean sediment yield for a particular stratified group was multiplied by the number of possible stream crossings in that group minus the number actually surveyed. However, the number of stream crossings in each stratified group combination was not given in either the Implementation Report or MBNC TMDL. These two documents gave a table for each subbasin in the MBNC with the total number of stream crossings, number of surveyed crossings, road surface erosion sediment yield from the surveyed crossings, and the total extrapolated road surface erosion yield. However, the numbers cannot be checked because information on how many stream crossings in each stratified group combination is missing.

For Cottonwood Creek, there were 177 possible stream crossings, based on assessing GIS layers of streams and roads intersections (MT DEQ, 2008). There were 27 crossings surveyed, for a total of 20 tons/year estimated road surface erosion load from all 27 crossings (MT DEQ, 2008). Extrapolating to the non-surveyed crossings resulted in 183 tons/year road surface erosion load estimated for both surveyed and extrapolated crossings (MT DEQ, 2008). As described in the above paragraph, this 183 tons/year road surface erosion load cannot be verified. **Table 30** summarizes this information and normalizes sediment yield by basin area.

The amount of sediment that could be reduced from each subbasin was determined by assuming that there could be a 30% reduction in loads by implementing BMPs that minimize road surface erosion (MT DEQ, 2008). This reduction estimate is based on Forest Service and Plum Creek Timber Company analyses on roads after implementing BMPs (MT DEQ, 2008). **Table 29** gives the numbers described above, gives the 30% possible estimated load reduction by implementing BMPs, and normalizes sediment yield by basin area. Sediment load in the entire Middle Blackfoot Planning Area could be reduced by 500 tons/year by implementing appropriate BMPs. For Cottonwood Creek, the controllable load was 55 tons/year, as shown in **Table 30** (MT DEQ, 2008).

The Implementation Report noted that at most stream crossings in the Middle Blackfoot-Nevada Creek Planning Areas, BMPs were lacking or not well-implemented, and it included a list of recommendations for BMP improvements. Low-cost BMPs include increasing vegetation on cut and fill slopes, while more costly endeavors are graveling road surfaces or decommissioning old roads (River Design Group, Inc., 2006). The strategy of improving BMP use seems a reasonable one, although the reader wonders why the BMPs were lacking or not well-implemented? How can one be assured that they will be sufficient and well-implemented in the future?

Road Surface Erosion: TMDL vs Thesis Project Results

This thesis estimated a total of 3.4 tons/year (3,350 kg/year or 0.19 kg/ha/year) from road surface erosion (modeled as the annual average for a ten-year period) from the 31 crossings measured. This is 50-fold lower than the 183 tons/year (165,981 kg/year, or 9.3 kg/ha/year) road surface erosion load estimated in the TMDL analysis, which is due to several reasons. First, the TMDL assumed all stream crossings produced road surface erosion, while the thesis assumed only high risk sites produced erosion. The thesis only considered stream crossings with culverts while the TMDL looked at all stream crossings, including those with bridges. There are also differences between stream crossings that result in variation in modeling results. And finally, different methods likely produce different results: for the TMDL, the Washington Method was used, while WEPP was the modeling method for the thesis.

The TMDL also extrapolated surveyed crossing results to non-surveyed stream crossings; the thesis did not do this because crossings selected to sample were not randomly selected, but rather, were selected on the basis of risk. Extrapolation to other stream crossings could only be done if crossings selected to sample were randomly selected. Extrapolating the surveyed results to unsurveyed crossings for the thesis project was also not valid as it would be extrapolating high risk results to low risk crossings.

For the thesis study, high risk sites were chosen and all crossings at high risk sites were field visited. However, in truth, all stream crossings likely produce some level of erosion. Therefore, some information was left out of the thesis project by omitting low-risk crossings, so a possible reason for lower loads than the TMDL.

In addition, there are differences between the Washington Method and WEPP in estimating road surface erosion. For the thesis, WEPP estimated 108 kg of road surface erosion per stream crossing, while for the TMDL, the Washington Method's estimates were 938 kg/crossing; this is a nine-fold difference. This discrepancy can be attributed in part to variations in survey methodologies and also to differences in how surveying crews conducted the assessments.

Road Fill-Culvert Failure Assessments: Entire Middle Blackfoot Planning Area

Montana DEQ assessed 73 stream crossings in the Middle Blackfoot Planning Area to determine the risk of culvert fill failure and the total sediment load produced should a culvert fail (River Design Group, Inc., 2006). At each of these stream crossings, they measured the constriction ratio and culvert fill volume (River Design Group, Inc., 2006). The constriction ratio is the ratio of culvert diameter to bankfull channel width; risk of culvert failure is highest when this ratio is less than one (MT DEQ, 2008). To determine the volume of fill that could enter a stream should a culvert fail at a given modeled discharge, the fill volume minus the volume of culvert void space was calculated (River Design Group, Inc., 2006).

A critique of using the constriction ratio method is that there is no measurement of error given for this method. In contrast, discharge-based culvert failure analysis methods (using regression equations to determine peak flows at various return intervals, and determining if a culvert has the capacity for each return interval flood) have associated measurements of error.

Based on the constriction ratio method, Montana DEQ found that 38 out of the 73 crossings assessed were at risk from culvert failure, which represented a total of 4,393 tons of fill (River Design Group, Inc., 2006). To estimate sediment load for unsurveyed crossings, they took the mean value of 115.6 tons per crossing (4,393 tons divided by 38 sites) in the Middle Blackfoot and extrapolated that value to the unsurveyed crossings. The amount of fill at risk in the Middle Blackfoot Planning Area as a whole (for both surveyed and non-surveyed crossings) was thus estimated to be 210,165 tons of fill (115.6 tons/site times 1818 crossings) (River Design Group, Inc., 2006).

Montana DEQ estimated the annual load from culvert failure as 2,102 tons/year, which is 1% of the 210,165 tons of fill; they assumed there is a one percent annual failure rate (MT DEQ, 2008). This appears to be based on a Q-100 flood, as is elaborated on below. This annual load value of 2,102 tons/year assumes that the failed culverts would be replaced with culverts of the same size (MT DEQ, 2008b).

To calculate how much annual loadings from culvert failures could be reduced, Montana DEQ created a scenario in which failed culverts were upgraded to larger ones that could pass the Q100 peak flow (MT DEQ, 2008). This strategy is based on guidelines from USFS INFISH recommendations which call for culverts to be able to pass the Q100 flood (MT DEQ, 2008). Montana DEQ stated that upgrading culverts to larger ones implemented all reasonable conservation practices that addressed culvert failure (MT DEQ, 2008). This seems to be a reasonable strategy for reducing the potential for sediment load from culvert fill failure. For the Middle Blackfoot Planning Area, upgrading culverts at risk of failure to ones that can pass the Q100 flood reduced the estimated annual sediment load ("controllable load") by 1,618 tons/year, leaving an annual load of 483 tons/year. This 483 tons/year is the estimated load after replacing "failed" culverts with Q100-sized culverts.

One flaw in this exercise is that there were no considerations of the short-term impacts of upgrading undersized culverts to larger ones. While it is true that MT DEQ is estimating loads from failed culverts on an annual basis (i.e.,for the "long-term"), there should still be at least a rough estimate of the short-term impacts from replacing these culverts. There are estimates from the literature that could guide these estimates: Madej, 2001; and Klein, 2003 are examples.

Table 31 shows the loadings for culvert fill failure for the entire MBNC Planning Area, along with the estimated load by replacing undersized culverts with those that can pass the Q100 flood.

Road Fill-Culvert Failure Assessments: Cottonwood Creek

The Implementation Report divided the 1,818 crossings from the entire Middle Blackfoot Planning Area into the sub-watershed level. For Cottonwood Creek, ten sites out of 27 visited (37%) during the 2005 TMDL surveys were determined to be at risk of failure (as determined by the constriction ratio being less than one), which represented a total of 744 tons of fill (River Design Group, Inc., 2006).

Montana DEQ extrapolated surveyed crossings to unsurveyed crossings in Cottonwood Creek by using the culvert fill load estimated from the Middle Blackfoot Planning Area (as explained in Section 5.3.b.1.), rather than using the ten surveyed sites in Cottonwood Creek to extrapolate to unsurveyed crossings. There were an estimated 177 stream crossings in the Cottonwood Creek watershed based on GIS road/stream crossings (MT DEQ, 2008b). The amount estimated to be delivered from failed culverts was derived from multiplying 115.6 (the mean value of sediment load for the 38 crossings in the Middle Blackfoot Planning Area) times all 177 crossings to obtain a total of 20,401 tons at risk of failure. Assuming a one percent culvert failure rate per year, there is an estimated 205 tons per year from failed culverts (MT DEQ, 2008b). By replacing undersized culverts with ones that can pass the Q100 flood, annual load drops to 47 tons per year. **Table 32** shows this information, along with normalized data by basin area.

A confusing part in the MBNC TMDL/QIQR concerned why Montana DEQ used the average load per stream crossing of the Middle Blackfoot Planning Area to extrapolate to unsurveyed crossings in Cottonwood Creek, rather than using the average load per stream crossing from surveyed sites in Cottonwood Creek. It seems that using Cottonwood Creek data, rather than data averaged from the entire Middle Blackfoot Planning area, would be more site-specific, and thus give more accurate results.

The answer to this quandary was found in a letter from Plum Creek Timber Company reviewing the Implementation Report (Sugden, 2005). Here, Mr. Sugden suggested using the average delivery per stream crossing for the entire watershed and apply this to the sub-watershed level. Using load for surveyed crossings at the sub-watershed level was not recommended, argued Mr. Sugden, because of a lower sample power at that level. Because five percent of roads in the Middle Blackfoot Planning Area as a whole were sampled, estimating total loads for individual sub-watersheds would likely have more error due to the lower sample power.

This explanation by Mr. Sugden seems reasonable, as some of the sub-watersheds did have very few crossings surveyed, which would have a lower sample power than using the data from the entire Middle Blackfoot Planning Area. It would have been greatly helpful to explain Mr. Sugden's analysis in the MBNC TMDL/WIQR report or the Implementation Report, otherwise, it is confusing to the reader as to why Montana DEQ chose to extrapolate data from the entire Middle Blackfoot Planning Area, rather than from sub-watersheds.

Road Fill-Culvert Failure Assessments: TMDL vs Thesis Project Results

This thesis has very different results from the TMDL, with annual loads of 2 kg/ha (for a 20-year period) for the thesis vs 10.4 kg/ha for the TMDL (for a 100-year period). This can be explained by a couple of reasons; for one, the thesis considered culvert fill failures over a period of 20 years only, and looked at the return intervals with the highest probability of failure during that time period, which were the Q2, Q5, and Q10. The TMDL looked at culverts that could not pass the Q100 flood. Therefore, there is a discrepancy, but 20 years seemed a more realistic time period to consider than 100 years.

Another difference between the thesis and TMDL is that the TMDL randomly selected crossings to survey and so did not select crossings based on any criteria. It then extrapolated surveyed crossing results to non-surveyed stream crossings.

The thesis did not extrapolate surveyed estimates to unsurveyed sites: for the thesis, unsurveyed sites were considered to be at low risk for culvert failure. In fact, many of the estimated 177 crossings are bridges, have no crossing structures, or had the culverts removed as part of road closure efforts. The low risk sites with culverts were in flat areas, or in areas where there was no longer a functioning stream channel. Because only high risk crossings were selected to survey, crossings were not randomly selected, and thus extrapolation to other crossings could not be done. Therefore, the loadings from the crossings for the thesis are lower than those for the TMDL, which considered all crossings. For culvert fill failure, it seems reasonable to only consider high risk crossings as low-risk crossings are unlikely to fail. Therefore, it seems the TMDL over-inflated the sediment loads from culvert fill failure.

However, it should be noted that while the low-risk crossings may have the capacity to handle a 100-year flood, there are other factors besides culvert capacity that affect culvert failure, such as abrasion, corrosion and debris that becomes caught in the culvert. Thus, even a properly sized culvert will eventually fail from these other factors. However, this thesis focused only on culverts that did not have the capacity for certain flood return intervals.

How would the thesis results compare with the TMDL results over a 100-year period, rather than a 20-year period? If all sixteen culverts from the thesis were to fail (for a 100-year flood), there would be a total load of 870,200 kg (900 tons). Normalizing by the total basin area for the 16 crossings (12,170 ha) results in 72 kg/ha sediment yield. There was a 100 percent failure rate for these culverts and annually, a five percent failure rate (100 percent divided by 20 years). Multiplying the total load by the five percent failure rate per year results in 43,510 kg/year (4 kg/ha/year). This is a little closer to the 10.4 kg/ha/year sediment load from the TMDL estimates for Cottonwood Creek, but still lower due to the reasons explained above.

Hillslope Erosion and the SWAT Model Hillslope Processes

Background on the SWAT Model

For the MBNC TMDL, the SWAT (Soil and Water Assessment Tool) model was used to estimate sediment loading from hillslope erosion (MT DEQ, 2008). SWAT is a watershed scale model that was developed to predict the impact of land management activities on water, sediment, and agricultural chemical yields in large, complex basins with varying land use, soil types, and management conditions over long time periods (Neitsch et al, 2002).

In order to accomplish such complex tasks, the model is physically based. This means it requires specific information about climate, soil properties, topography, vegetation, and land use. Using these input data, physical processes associated with water and sediment movement are directly modeled by SWAT (Neitsch et al, 2002). SWAT is a continuous time model, meaning it is to be used for long-term yields, rather than a single-event flood (Neitsch et al, 2002).

In SWAT, water balance is the driving force of all activities in the watershed; to accurately model the movement of variables such as sediment, the hydrologic cycle must be accurately portrayed. There are two main parts of the model: the land phase, which controls the amount of sediment, water, nutrients, or pesticide loading to the main channel in each subbasin, and the routing (water) phase, which is the movement of water, sediment, etc., through the channel to the outlet (Neitsch et al, 2002).

For use in the model, a watershed is partitioned into subbasins; each subbasin is assumed to be homogeneous in terms of climate, groundwater, ponds/wetlands, and the main channel in the subbasin. Subbasins are further subdivided on the basis of soil types, land cover, and management activities into hydrologic response units (HRUs) (Neitsch et al, 2002).

Parameters are then chosen for predicting water quantity and water quality characteristics. One parameter that was important in the MBNC TMDL analysis was snow cover. The snow cover component of SWAT allows modeling of a non-uniform snow cover (non-uniform conditions are influenced by shading, drifting, topography, and land cover) rather than simply a uniform snow cover (Neitsch et al, 2000). The model also allows subbasins to be divided into up to ten elevation bands, where snow cover and melt can be simulated separately for each band. This allows SWAT to evaluate the differences in snow cover and melt caused by orographic variations in precipitation and temperature (Neitsch et al, 2000).

Once the parameters are chosen, the model is calibrated and validated. The literature highly recommends calibration to be done at not just the annual and monthly scale, but also at the daily scale, because the model simulations will be producing daily stream discharges and sediment loadings (Sudheer et al, 2007).

Calibration is an iterative process that evaluates and refines the parameters by comparing simulated and observed values (Donigian, 2002). Validation analyzes model performance, which provides an independent check on the robustness of the parameter estimates (Ahl, 2007). During the validation process, model results derived over the calibration period are compared to those generated when SWAT is used with an independent dataset (Ahl, 2007).

Once calibration and validation are complete and satisfactory, model simulations can be done. Here, the relationship between streamflow (or sediment, nutrients, or chemicals) estimated by SWAT during validation and measured streamflow (or sediment, etc.) for corresponding periods is evaluated. A simple linear regression model is used where simulated values predict the actual values for each given time period (Ahl, 2007).

Application of the SWAT Model to the MBNC TMDL

For the MBNC TMDL, the SWAT version used for predicting hillslope erosion was AVSWAT 2003 (Arc View Soil and Water Assessment Tool), which has an ArcView GIS interface (MT DEQ, 2008). The MBNC was partitioned into 65 subbasins which were further delineated into 633 Hydrologic Response Units (HRUs) based on factors such as land cover types (MT DEQ, 2008).

Fourteen parameters that controlled hydrologic processes were grouped into three categories: surface, subsurface, and basin response parameters (MT DEQ, 2008). There were 15 parameters governing sediment and nutrient response (nutrients won't be examined in this thesis). These parameters were then calibrated and validated based on available climate and discharge data for the MBNC watershed. Calibration was done for a period of record from 2002 to 2004 at six stream gauging stations, at the monthly and daily scale (MT DEQ, 2008).

It was not discussed in the MBNC documents how the parameters were chosen; it appears as if the default standard parameters used in the SWAT model were chosen (MT DEQ, 2008). However, the literature suggests conducting a sensitivity analysis to choose which parameters influence model outputs most strongly (Sudheer et al, 2007). There are so many parameters that it is difficult and unnecessary to have to independently calibrate all of them if only a few are relevant (Ahl, 2007).

Comparison of measured versus simulated daily discharges for three sites in the Middle Blackfoot basin were in good agreement for the calibration process. Validation was done using monthly discharges, and there was very good agreement between measured versus simulated results for the sites chosen for this process (MT DEQ, 2008). Validation was also done using average monthly measured versus simulated hydrographs, and showed that SWAT tended to underestimate discharge during winter and late fall months for two of the sites. The authors did not know why this was so (MT DEQ, 2008).

Following calibration and validation, brief testing of SWAT showed that improvements in streamflow predictions for the SWAT model could be accomplished in at least two ways: (1) a single set of parameters had been used to describe snow accumulation and melt processes throughout the basin (MT DEQ, 2008). A better option would be to use locally-based calibration parameters for these processes, which would do a better job representing the spatial and temporal variations across the watershed (MT DEQ, 2008). (2) The hydrologic calibration did not include water loss associated with irrigation of farmlands in the watershed (MT DEQ, 2008). Appendix I of the TMDL/WIQR does not divulge if these improvements were implemented; if they were not, why not? Later in the document, it is mentioned that future monitoring will include improving the SWAT model, so perhaps these two improvements will be included in that.

The authors of the SWAT model component of the MBNC TMDL noted that there were insufficient data available for calibrating water quality parameters; only 5-16 measured instantaneous values were used for calibration at three sites on the Middle Blackfoot basin (MT DEQ, 2008). Calibration was done by comparing graphical results of measured versus simulated sediment, and these were quite different. The authors admitted that calibration of sediment loading with SWAT "proved to be a very daunting task for the Blackfoot Watershed." (MT DEQ, 2008).

The authors tried adjusting the four parameters that control sediment transport and bank erosion in the model, but consistent results did not occur, when compared with measured data (MT DEQ, 2008). They suggested two improvements: 1) add a slope steepness component as a GIS component, and 2) use regional sets for the sediment re-entrainment functions. (MT DEQ, 2008). It is not clear if these improvements were implemented; the TMDL does not say one way or another. Perhaps they will be implemented in future SWAT work in the watershed.

After calibrating, model simulations were performed for discharge and water quality conditions in the Middle Blackfoot watershed, providing sediment and nutrient loading estimates for each of the subbasins (MT DEQ, 2008). This was done for a baseline period between 1996 and 2004 (MT DEQ, 2008).

The SWAT model output included tons of hillslope sediment delivered annually from each of the 65 planning area subbasins (MT DEQ, 2008). One problem with estimating hillslope erosion was that there were huge differences between land surface slope and stream channel slope between each subbasin (MT DEQ, 2008). This made it impossible to calibrate land surface sediment delivery with channel sediment transport. Montana DEQ stated that high average subbasin slopes inflated sediment yield estimates. Therefore, SWAT estimates were adjusted downward to better reflect the amount of sediment likely to be delivered to the stream channels (MT DEQ, 2008).

Another adjustment was changing how sediment transported as overland sheet flow was modeled. Sheet flow generally occurs over a distance less than 400 feet and slopes greater than three percent; these criteria were built into the model to adjust SWAT subbasin sediment yields (MT DEQ, 2008). These adjusted sheet flow values were then allocated into naturally occurring and controllable components.

The naturally occurring component was the load that was expected to move through adequate vegetative filters to a stream channel. Montana DEQ assumed that vegetation buffers would filter 75% of the hillslope sediment yield. This 75% value is the controllable load; it can be controlled by management activities, while the other 25% is the naturally occurring load (MT DEQ, 2008). The naturally occurring load is composed of both background and anthropogenic-related sources where all reasonable land, soil and water conservation practices are used (MT DEQ, 2008).

Estimates of the sediment loading for Cottonwood Creek were: initial SWAT sediment loading estimates were 2,950 tons/year. The portion of that number that is due to overland sheet flow is 1,325 tons/year; of that, 331 tons/year are naturally occurring and 994 tons/year are the cumulative controllable load (MT DEQ, 2008). These are shown in **Table 33**.

MT DEQ also analyzed the filtering ability of vegetation for the cumulative controllable load. If there was no human influence in Cottonwood Creek, they argued, vegetation buffers would filter 994 tons/year from entering streams. However, with human influence, only a portion of that load was prevented from reaching streams.

Using aerial photography and ground photos fror each stream, Montana DEQ made site-specific estimates of the sediment filtering ability of vegetation (MT DEQ, 2008). For Cottonwood Creek, MT DEQ estimated the filtering ability was 0.70. This is the percentage of the controllable (994 tons/year) that is prevented from reaching the stream by vegetative buffers. Therefore, 30 percent of the controllable load (298 tons/year) was reaching the stream (MT DEQ, 2008). The TMDL did not give a total load that moved through the buffers; that would be the sum of the naturally occurring load (331 tons/year) and the 30 percent portion of the controllable load (298 tons/year), which is 630 tons/year. **Table 30** shows these adjusted values.

Problems and Concerns with SWAT Model

Some of the concerns are described in the above section. It should be noted that the SWAT model has been used for 30 years for non-point source modeling (Neitsch et al, 2000); however, it has been used mainly in agricultural and rangeland areas, and rarely in forested, mountainous, snowmelt-driven watersheds (Ahl, 2007). Therefore, it is still relatively new for snowmelt-driven, forested watersheds, and errors can be expected.

While SWAT has the ability to simulate snowmelt dynamics, these have only been evaluated in Minnesota with little relief and mixed landcover, a very different ecosystem than in Montana (Ahl, 2007). Therefore there is a lack of actual use of this model in snowmelt-driven systems. An exception is Ahl, 2007, where AVSWAT 2005 (an Arc View interface for SWAT version 2005) was calibrated at the Tenderfoot Creek Experimental Forest research watershed in central Montana, which has a high elevation lodgepole pine forest community type (Ahl, 2007).

SWAT tended to underestimate discharge during winter and late fall months for two of the Middle Blackfoot sites during calibration/validation, and it was not determined why this occurred (MT DEQ, 2008). Ahl (2007) found similar problems; in his research (using SWAT 2005), SWAT consistently underestimated water yield from January through June, but it overestimated the water yield from July through November. Most of the water in the basin comes from snowmelt, so a component of the model that improves its ability to store and transmit groundwater could help with these baseflow issues (Ahl, 2007).

One of the major problems in calibrating SWAT in the Tenderfoot Creek watershed was correctly matching the simulated baseflow component of the hydrograph to actual measured baseflows. Ahl (2007) adjusted different parameters during calibration to slow the response to recharge to obtain more reasonable baseflow rates.

Ahl (2007) found that setting the snow parameters to their default values caused the snowmelt driven runoff peak to occur 75-80 days earlier than the calibrated and observed peaks, and extended the falling limb also by about 75-80 days. Adjusting snow parameters therefore changed the runoff peak flows between late May and early June.

Ahl (2007) also discussed problems with the automated calibration procedures used in the AVSWAT interface (version 2005). The author states that this automated calibration algorithm cannot be used effectively in watersheds with snowmelt dominated hydrology with a strongly seasonal, unimodal hydrograph (Ahl, 2007). The reason for this is that this algorithm does not simultaneously calibrate the model for both high and low flows. Ahl (2007) recommends improvement in this algorithm.

The above issues in Ahl (2007) show problems with the SWAT model and possible reasons for these problems. These problems are similar to those with the MBNC modeling. Perhaps the revelations from the Ahl (2007) work could be applicable to the problems with the SWAT model used in the MBNC TMDL/WIQR.

A key issue discovered in Ahl (2007) was the assumption in the model that streamflow was mainly routed to the stream as surface runoff, rather than via infiltration. This was discovered during assessments of calibration results. Infiltration, not surface (overland) runoff, is the primary method of snowmelt movement in forested areas, especially pristine ones. Even when the soil is frozen, argues Ahl (2007), infiltration occurs. This is therefore a major flaw in the SWAT model. Ahl (2007) suggested that this flaw is due to SWAT assuming an infiltration rate of zero in frozen soils, and he adjusted SWAT to correct this problem. Ahl (2007) felt that modifying SWAT for future use to allow infiltration into frozen forest soils would improve model performance and better representation of runoff processes in forested basins. Allowing more infiltration should reduce peak flows and increase base flows, but that could then exacerbate the problem noted earlier of SWAT underestimating water yield from January to June and overestimating water yield from July to November.

The problem with SWAT discussed in the above paragraph apparently remained with the MBNC TMDL analysis. Overland sheet flow erosion was modeled as 1,325 tons/year, which was six times that of road surface erosion or culvert fill failure load. That seems incredibly high for a relatively undisturbed forest with a high degree of vegetative cover and organic debris; in these areas, precipitation is mainly infiltrated into the soil, with sheet flow minimized. Where infiltration is the dominant method of snowmelt and precipitation movement, there is little soil erosion compared with areas where overland flow predominates. Clearly, the SWAT model is assuming an unreasonably high amount of overland flow. This is probably due to the problem identified in Ahl (2007), where the model assumed that when the soil was frozen, there was no infiltration. This assumption is incorrect; there is still infiltration when the soils are frozen (Ahl, 2007). Thus, the 1,325 tons/year yield is likely over-estimated due to SWAT over-estimating overland sheet flow erosion. Therefore, the SWAT model fails to adequately model runoff processes in snow dominated systems.

The description of the SWAT model simulations in the MBNC TMDL/WIQR omitted any mention of residuals testing for ensuring an underlying normal distribution (MT DEQ, 2008). The literature stresses that the linear regression models used in the model simulations must meet the assumptions of normality and independence (Ahl, 2007; Sudheer et al, 2007). Because linear regression models are parametric, using datasets that lack a normal distribution can result in flawed results. To ensure underlying normality, residuals must be tested to ensure they have constant variances (homoscedasticity), a zero mean, and are mutually uncorrelated (Ott and Longnecker, 2001).

Sudheer et al (2007) notes the flaw in many studies where information on residuals testing is not shown; rather, just the R^2 of the regression is displayed, and it is not clear to the reader if residuals testing was even done. Sudheer et al (2007) found in their own study using SWAT that there was a strong R^2 which suggested a good relationship between variables, but upon examination of the residuals, heteroscedasticity was found, where the residuals' variability increased with increasing runoff.

Summary of Sediment Loadings from TMDL Analysis

Table 35 summarizes the different methods used to estimate each sediment source in the MBNC TMDL. For Cottonwood Creek, the TMDL analysis estimated the total annual sediment loadings from stream bank erosion, road surface erosion, culvert fill failure, and hillslope erosion at 2,009 tons/year (MT DEQ, 2008). Upland areas produced the most sediment; hillslope erosion produced an estimated total load of 2,950 tons/year, with 1,325 tons as sheetflow, with an estimated 994 tons of controllable sediment annually. Logging in the upper reaches was believed to be the main source of hillslope erosion. Grazing and hay production in the valley areas contributed 35% of hillslope sediment loads (MT DEQ, 2008).

Stream bank erosion was thought to be the second largest cause of sediment, with 296 tons per year produced; 106 tons/year of this considered controllable (MT DEQ, 2008).

Removal of vegetation in the riparian areas from logging is believed to be the cause of bank erosion in the upper reaches (MT DEQ, 2008). While the stream bank erosion levels decline downstream, there still is erosion, likely due to livestock grazing. Another source of erosion was the 183 total tons of annual sediment from road surface erosion, of which 55 tons/year is controllable.

Comparison of MBNC TMDL Results with the Literature

How do the results from the TMDL analysis of sediment yields from various sources for Cottonwood Creek compare with results from other subbasins in the area, and with other sources of sediment? **Table 34** shows some of the many subbasins analyzed in the MBNC TMDL along with modeled estimates of sediment yield from different sediment-producing sources. These subbasins were randomly chosen from the fifteen subbasins analyzed in the TMDL. **Table 34** includes Cottonwood Creek.

Cottonwood Creek’s road surface erosion is towards the upper end of values for some of the other subbasins in the MBNC Planning Area. Culvert fill failure sediment yield is higher than the other subbasins in **Table 34**. The total sediment yield for Cottonwood Creek (102 kg/ha/year) is the second largest value in the table. Differences in values in sediment yield are due to a number of factors. There are differences in natural loadings; for example, the North Fork Blackfoot River has very high stream bank erosion due to highly erodible stream banks in one reach. There are also variations in land use patterns between subbasins, and variations in topography, such as slope.

How does the MBNC TMDL results for Cottonwood Creek compare to other TMDLs in other areas with different precipitation and geology? **Table 36** shows results from TMDLs and other assessments in Montana.

The Yaak River TMDL addresses an area with a wetter climate than the MBNC Planning Area, and the Bitterroot Headwaters Planning Area TMDL assesses a region with less stable geology than the MBNC Planning area. These two TMDLs conducted quantitative analysis only on road surface erosion and hillslope erosion.

Road surface erosion for Cottonwood creek (9.3 kg/ha/year) was greater than road surface erosion in the Yaak TMDL, but fell within the range for the Bitterroot Headwaters TMDL.

It was expected that the Yaak River watersheds, which have higher precipitation than the MBNC Planning Area would have higher levels of road surface erosion than Cottonwood Creek. It was also expected that the Bitterroot Headwaters Planning Area would have higher sediment yields as its geology is less stable than the geology in the MBNC Planning Area. Two out of three watersheds in the Bitterroot Headwaters area were indeed higher than Cottonwood Creek, while one was not.

Cottonwood Creek's sediment yield from hillslope erosion (67.1 kg/ha/year) was higher than both the Yaak and Bitterroot Headwaters TMDLs. This was unexpected as lower as it has lower precipitation and more stable geology than those other two TMDLs. These unexpected results in these comparisons could be due to differences in modeling methods, steepness in the area, and variations in land use patterns.

The MBNC TMDL results for Cottonwood Creek are also compared with the same literature as in **Table 17** in Chapter 4 of this thesis. The total load from stream bank erosion, hillslope erosion, road surface erosion, and culvert fill failure from the TMDL was 102 kg/ha/year. The studies in **Table 17** for undisturbed forested basins ranged from 0.56 to 455 kg/ha/year, and for a one-to-two year period after road building or/and logging, the studies ranged between 13.7 to 1,475 kg/ha/year. Cottonwood Creek falls at the low end of these ranges, although its total loads were higher than the post-road building and logging sediment yields from a study done in a similar region.

This shows that while there could be site-specific impacts to aquatic ecology from road surface erosion, culvert fill failure, hillslope erosion, or stream bank erosion, as a whole, the basin receives a very low amount of sediment from these sources compared with other forested drainages and other regions.

TMDL Targets and Needed Reductions in Annual Loadings

To develop a TMDL, quantitative water quality goals (targets) must be developed. The MBNC TMDL/WIQR set TMDL targets for various parameters; to do this, it was necessary to know what the beneficial uses were, and the sources of excess sediment loads causing degradation and departure from beneficial uses. Good target parameters are based on the least impacted reference systems nearby (MT DEQ, 2008).

TMDL targets must represent the water quality standards for which they were developed. These targets quantify parameters that describe channel substrate composition, channel morphology, and aquatic habitat quality (MT DEQ, 2008). Parameter examples are: pool frequency, percent fines <2mm in riffles, percent fines <6mm in riffles, width:depth ratio, and woody debris. For each parameter, target values were set according to Rosgen stream channel type (i.e., B, C, E, etc).

The MBNC TMDL/WIQR explained the rationale for each target: these explanations appeared reasonable and based on science. Measured site values were then compared with target values, for each major stream within the Middle Blackfoot-Nevada Creek Planning Areas, noting if there was a departure from the target condition and if there so, how much. If the stream did not fully support its beneficial uses, it was considered to be impaired.

As described earlier in this Chapter, there are three broad sources of sediment to Cottonwood Creek: hillslope, stream bank, and road erosion (MT DEQ, 2008). Based on the analysis for these sediment loading sources and amounts, TMDLs and load allocations were done for individual basins in the MBNC Planning areas that were listed as impaired by sediment; this section focuses only on Cottonwood Creek.

The TMDLs show the amount of needed reductions in current sediment loading from the various sources (MT DEQ, 2008). Sediment load reductions were developed from the literature, agency and industry documentation of BMP effectiveness, field evaluation, and interpretation of geographic information such as aerial photos. For Cottonwood Creek, MT DEQ set the total amount of needed annual load reductions at 583 tons/year (MT DEQ, 2008). This number was allocated to different land uses in the basin, which was determined by landcover type. For example, in the rangeland landcover type, grazing was assumed to be the dominant land use; load reduction allocations for grazing were thus proportional to the modeled loading values from rangeland landcover types.

Specific allocations of load reductions were: livestock grazing: 286 tons/year, hay production: 7 tons/year, silviculture: 241 tons/year, road crossings: 213 tons/year (MT DEQ, 2008). To reduce road surface erosion and culvert failure to the desired levels, the MBNC TMDL/WIQR suggested implementing appropriate BMPs (MT DEQ, 2008). **Table 37** summarizes these load reductions and allocations.

Margin of safety (MOS) measures were added to address the inherent uncertainty in load estimates. One MOS was using a conservatively large estimated size of sediment contributing area in the hillslope analysis for each stream. Another MOS was using a higher base erosion rate for estimating road surface erosion (MT DEQ, 2008). More general margin of safety actions given were continuous evaluations through the adaptive management process, such as: continuous refinement of sediment loading models, improved land cover characterization, and refinement of land use impacts on hillslope and bank erosion (MT DEQ, 2008).

BMPs and Restoration, and Implementation and Monitoring Efforts

The TMDL does not discuss which subbasins should be prioritized for BMPs and restoration efforts. A list of subbasins or/and reaches within these subbasins with high priority restoration needs would be helpful.

Implementing appropriate BMPs can help reduce sediment impacts in the watershed. There are six types of BMPs identified in the MBNC TMDL/WIQR to accomplish sediment load reductions, which are listed in **Table 38** for each sediment source.

The BMPs in **Table 38** are described in detail in Appendix H of the MBNC TMDL/WIQR. For example, Upland BMPs include establishing and maintaining permanent vegetative cover to reduce erosion, and to provide filter strips of vegetation between streams/riparian areas and areas of disturbance, such as cropland, grazing areas, and disturbed forest land. Forestry BMPs include prohibiting timber harvest within 50 feet of any water body and minimizing road construction within this buffer. Riparian BMPs include stabilization of stream banks to reduce erosion (MT DEQ, 2008).

Roads BMPs referenced in the MBNC TMDL/WIQR are vague, but in other literature sources, such as the Montana State University Extension Service, they include: maintaining culvert function by cleaning out debris from culverts, cleaning out cross drains and ditches, vegetating cut and fill surfaces, installing energy dissipators (rock, wood, etc) at culvert outlets to reduce erosion, road closures, and upgrading culverts to larger ones or bridges (Logan, 2001). Planned water quality restoration projects in Cottonwood Creek include stream channel and riparian area restoration; these projects are currently (as of fall, 2008) under development (MT DEQ, 2008).

Methods for implementing restoration efforts and achievement of water quality targets were discussed in the final part of the MBNC TMDL/WIQR. These methods include working in partnerships between agencies and land owners, incorporating water quality restoration objectives into comprehensive management plans, and selecting conservation practices on a site-specific basis (MT DEQ, 2008).

Funding opportunities were also described; a vital component of the TMDL, as without funding, no restoration or monitoring can be done! A list of funding opportunities, the funding cycle, and what projects can be funded was given (MT DEQ, 2008).

The TMDL concluded with stating that a program for measuring success was necessary in order to determine if the causes and sources of water quality problems were correctly identified, whether the water quality restoration targets were being achieved, and if adjustments to water quality restoration plans were needed. This includes tracking completed projects and monitoring (MT DEQ, 2008).

The MBNC TMDL/WIQR details a monitoring strategy to accomplish tasks such as a better understanding of the connection between groundwater and surface waters and compilation of enough data so that the SWAT model can be calibrated and improved. This is a good goal, and noteworthy that the MBNC TMDL/WIQR acknowledges the problems with SWAT and wishes to improve it.

To judge the effectiveness of restoration projects, site-specific monitoring will be done. Various monitoring parameters based on biological, physical, and chemical criteria were suggested, such as: macroinvertebrate sampling, habitat and riparian area assessments, suspended sediment sampling, and percent fine sediment assessments (MT DEQ, 2008).

The strategy for success outlined in this part of the MBNC TMDL/WIQR seems sound, with good methods described for ensuring that restoration efforts are implemented. One key element that can drive the success is the partnerships that Montana DEQ has with organizations such as the Blackfoot Challenge and Trout Unlimited. These partners have already been involved in restoration efforts in the Blackfoot watershed and can help guide future efforts and oversight to ensure projects are implemented and monitored. As part of oversight for these efforts, the MBNC TMDL/WIQR states that Montana DEQ will evaluate the watershed restoration plan five years after the TMDL development and work with its partners on this five-year evaluation.

The TMDL also proposes a system for tracking completed restoration projects and monitoring in order to evaluate how well these projects influence water quality. A tracking system has not been developed yet. The TMDL noted that the Blackfoot Challenge (one of the stakeholders in the MBNC basin) does have a small database of completed projects and monitoring, and will pursue development of a watershed project database. This is vague; is this watershed project database the same as a comprehensive tracking system that the TMDL proposes? When will this tracking system be created and by whom?

The restoration effectiveness monitoring is equally as vague: it mentions that the Blackfoot Challenge has been involved in monitoring site specific restoration projects where it is a partner, and tracks data collection for effectiveness of these projects. However, the TMDL adds that other partners often collect site specific restoration data, and this data "should be viewed collectively when evaluating the project effectiveness" (MT DEQ, 2008). This is vague; who is in charge for developing and tracking projects in the entire MBNC Planning Area? When will such a tracking system occur? The document does not explain that this will happen, rather, that it "should" happen. There is a sense of hopefulness that it will "happen." This is not good enough to ensure follow-through of the MBNC TMDL.

The Status and Trends monitoring part of the TMDL did a better job assuring the reader that monitoring and tracking will be implemented. In 2004, partners in the MBNC created and implemented the Blackfoot Watershed Status and Trends Water Quality Monitoring Program. This develops monitoring stations to evaluate and describe water quality conditions, spatial patterns, and time trends in the MBNC. Twelve stations have been implemented so far, with monitoring conducted in 2004 and 2005, and this is expected to continue every few years (costs prohibit annual monitoring). The TMDL does admit that implementation of the plan "will ultimately depend on the ability, willingness, and priorities of landowners and land managers" (MT DEQ, 2008).

Measurable targets for success were not discussed as part of the implementation and monitoring part of the TMDL. It appears measurable targets for success would be the needed reductions described in Section 5.7. Tying in these needed reductions with implementation and monitoring would be helpful as they are quantitative targets that can be used to judge the effectiveness of implementation and monitoring efforts.

CHAPTER 6: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

This thesis examined sediment inputs and sediment reducing activities at three spatial scales: at a single stream crossing, at the third-order watershed scale (both concerning Cottonwood Creek), and at the entire basin level (the Middle Blackfoot/Nevada Creek basin, which encompasses Cottonwood Creek). The objective for the single stream crossing study was to consider whether there was a net benefit in replacing a culvert with a bridge in terms of sediment inputs. The total load expected if the culvert was left in place (the sum of downstream sediment loads from spring 2007, road surface erosion load, and the culvert fill load once the culvert failed) was compared to the total load from doing a culvert replacement (the following year's downstream sediment load from snowmelt, road surface erosion, and the sum of downstream sediment loads from the upgrade). **Table 14** shows these results.

The results suggest that leaving the culvert in place could lead to almost 12 times as much sediment load when the culvert failed than replacing the culvert. The large majority of the hypothetical load for the non-replacement scenario was due to culvert failure load. There was a large amount of error with the results; a major one was lacking the rising limb of the hydrograph for spring 2007 snowmelt. In addition, spring snowmelt 2008 was approximately a four-year return flood, while spring 2007 was approximately a two-year return flood. Therefore, it is not known how much of the higher load from spring 2008 was due to the culvert replacement disturbance from the previous fall vs the higher discharges.

For the third-order watershed scale of analysis, the objective was to assess other stream crossings in the Cottonwood Creek basin for risk of culvert failure and to estimate sediment load from culvert failure and road surface erosion. Would replacing culverts at risk of failure with bridges result in a net decrease in sediment yield? To answer this research question, stream crossings that lay in highly erodible soil types were selected to field survey; these were considered to be at high risk for culvert failure and/or road surface erosion.

Out of 34 sites visited, 16 culverts were predicted to fail at one or more return intervals. **Table 24** shows the number and percent of culverts, out of 34 stream crossings, that are likely to fail at a given return interval. Twenty-four percent were likely to fail at a 2-year and higher flood event.

For a 20-year period, the probabilities of different return flows were calculated, and the Q2, Q5, and Q10 return intervals had high probabilities (over 88%) of occurring during that time period. Of the 16 culverts that could fail at one or more flood intervals, ten had capacities below the Q2, Q5, and Q10 floods, so there is a 63 percent culvert failure rate for these intervals. Annually, there is a 3 percent failure rate (63 percent divided by 20 years).

Over the 20-year period, there is a high probability (over 88%) that there will be 428,500 kg of sediment delivered to the Cottonwood Creek basin from failed culverts; translating that to an annual basis, 12,900 kg/year of sediment, or 2 kg/ha/year, is expected to be delivered to the watershed each year. These loads are very low compared with the literature; in fact, they are just slightly above the range for an undisturbed forest in the same ecoregion. **Appendix P** shows the locations of these ten stream crossings.

Two scenarios were compared: one where all ten culverts were replaced, and one where they were not replaced. There was no difference in sediment yields between these scenarios. **Table 25** and **Table 26** show the results for each scenario. Using the WEPP model, 34,000 kg of sediment was estimated to erode from the road prism annually, modeled over a ten-year period.

At the entire basin level, the objective was to critique a comprehensive TMDL/Water Quality Improvement Plan (WQIP) for the Middle Blackfoot/Nevada Creek basin, focusing on Cottonwood Creek and various sediment issues. This critique considered whether the TMDL/WIQR used sound methods for sediment analysis and adequately analyzed methods for reducing sediment inputs in Cottonwood Creek. In addition, the critique compared the TMDL sediment load estimates to the thesis and other literature sources.

The stream bank erosion methods were questionable as to whether they were appropriate for the Middle Blackfoot basin; the Rosgen methods used in this analysis were developed in different ecoregions than the Middle Blackfoot/Nevada Creek (MBNC) area. In addition, they were developed for A and B channel types, but were used in C, D, and other channel types for the MBNC area.

To determine road surface erosion in Cottonwood Creek, MT DEQ used the Washington Forest Practices Board method for the MBNC TMDL analysis. Twenty seven crossings were surveyed, and the results were extrapolated to all 177 stream crossings in the basin, for a basin sediment yield of 183 tons/year (165,981 kg/year, or 9.3 kg/ha/year) from road surface erosion for both surveyed and extrapolated crossings. This is much higher than the 3.4 tons/year (3,350 kg/year or 0.19 kg/ha/year) estimated from the WEPP model for the thesis road crossing surveys. The most likely reason is that the thesis surveys focused only on crossings that were at high risk for erosion, while the TMDL assumed that all crossings would produce erosion.

In retrospect, for the thesis, focusing only on stream crossings that were at the highest risk for surface erosion was not the best choice; it is likely that all stream crossings contribute some level of road surface erosion. Therefore, the true quantity of road surface erosion is likely higher than the thesis estimates, but not likely as high as the TMDL estimates. When normalized by stream crossing, the Washington Method, used in the TMDL estimates for road surface erosion, was nine times higher than the WEPP model used in the thesis.

For determining the load from culvert fill failure in Cottonwood Creek for the TMDL, ten sites out of 27 surveyed (37%) were determined to be at risk of failure, which represented a total of 744 tons of fill. The TMDL/WIQR extrapolated sediment load from culvert fill failure to unsurveyed stream crossings in Cottonwood Creek to obtain 20,461 tons. Assuming a one percent culvert failure rate per year, there is an estimated 205 tons per year from failed culverts in Cottonwood Creek.

Extrapolation to unsurveyed sites in Cottonwood Creek for the thesis surveys was not done because the unsurveyed sites are at low risk for culvert failure. In fact, many of the estimated 177 crossings are bridges, have no crossing structures, are clearly at very low risk of failure, or do not exist. Therefore, the thesis estimates for culvert failure load appear to be better than the TMDL estimates.

The differences between the TMDL and thesis regarding culvert fill failure estimates are likely due to the different methods used. The thesis looked at a 20-year period for culvert failures, while the TMDL considered a 100-year period. In addition, while the TMDL randomly selected stream crossings to survey, the thesis only looked at crossings at high risk of failure.

Conclusions and Recommendations

While on a basin-wide consideration, loadings are low for Cottonwood Creek, there may be site-specific issues. The sediment yield from a failed culvert may be small when considered on a basin-wide basis, but it could be devastating to sensitive fish and macroinvertebrate habitat downstream of a crossing. Likewise, chronic road surface erosion may average out to miniscule amounts when considered in terms of sediment yield by basin; but it can fill up pools and cover spawning gravels. Cottonwood Creek has reaches that are not attaining its potential for adequate number of pools. It is also home to both westslope cutthroat trout and bull trout in Cottonwood Creek, and is a core habitat area for bull trout.

That said, improving stream crossings is expensive, and budgets for stream restoration work are small. Therefore, thought should be given to which stream crossings should be improved. The ten most at-risk culverts discussed in the second objective might be good choices. However, another consideration in choosing which culverts to replace should be whether there is sensitive fish and macroinvertebrate habitat downstream of the crossing, and the amount of fill. While the ten most at-risk culverts represent the most immediate need for being replaced because they are likely to fail in the near future, the other culverts identified as being at risk of failure in the next 30-100 years should also be considered for replacement if they are located in sensitive stream habitat. In addition, culverts with a large volume of fill would have a higher degree of impact than those with little fill.

Regarding the TMDL analysis, it is recommended that Montana DEQ prioritize culvert replacements for the at-risk culverts they identified in their field surveys based on the factors described in the above paragraph. For road surface erosion, the highest sediment-producing stream crossings should be addressed, and replacing them with bridges to reduce erosion should be considered.

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Table 1 - Peak flows (cfs) for various return floods for entire Cottonwood Creek basin (using regression equations from Appendix B)

Site	**Basin Area (A) (sq miles)**	**Annual Precip (P) (in)**	**minus 1 SE**	**Q2**	**plus 1 SE**	**minus 1 SE**	**Q5**	**plus 1 SE**	**minus 1 SE**	**Q10**	**plus 1 SE**
entire basin	69	42	363	757	1150	570	1075	1580	758	1378	1999

Site	**Basin Area (A) (sq miles)**	**Annual Precip (P) (in)**	**minus 1 SE**	**Q25**	**plus 1 SE**	**minus 1 SE**	**Q50**	**plus 1 SE**	**minus 1 SE**	**Q100**	**plus 1 SE**
entire basin	69	42	893	1624	2354	1018	1885	2752	1078	2074	3069

Table 2 - Sampling time periods for each time frame

Spring 2007: May 11 – June 4, 2007

Culvert Upgrade: September 27-29, 2007

Spring 2008: May 6, 2008 – June 27, 2008

Table 3 - Summary statistics for TSS, Cottonwood Creek, Spring 2007, (before culvert replacement) (falling limb only; 17 sampling days)

		TSS, upstream, spring 2007 (mg/l) BD = below detection	**TSS, downstream, spring 2007 (mg/l) BD = below detection**
N = 39			
Mean		**4 (BD)**	**4 (BD)**
Std. Error of Mean		0.4	0.3
Conf Interval Mean		**(3, 5) (BD)**	**(3, 5) (BD)**
Median		**3 (BD)**	**3 (BD)**
Conf Interval Median		**(3, 3) (BD)**	**(3, 3) (BD)**
Std. Deviation		3	2
Skewness		3	2
Sum		150	150
Minimum		**3 (BD)**	**3 (BD)**
Maximum		15	11
IQR		0	0
Percentiles	25	3	3
	50	3	3
	75	3	3

Table 4 - Summary statistics for Cottonwood Creek sediment load during spring snowmelt 2007, (before culvert replacement) (falling limb only; 17 sampling days)

		Sediment load, upstream, spring 2007 (kg)	**Sediment load, downstream, spring 2007 (kg)**
N =39			
Mean		91	84
Std. Error of Mean		38	29
Conf Interval Mean		(17, 160)	(27, 140)
Median		20	25
Conf Interval Median		(16, 25)	(16, 30)
Std. Deviation		230	180
Sum		3600	3300
Minimum		15	12
Maximum		1300	800
IQR		12	42
Percentiles	25	16	15
	50	20	25
	75	28	58

Table 5 - Summary statistics for Cottonwood Creek TSS during spring snowmelt 2008, (after culvert replacement), falling limb only (17 days)

		TSS, upstream, spring,08 (mg/l)	**TSS, downstream, spring,08 (mg/l)**
N = 71			
Mean		8	6
Std. Error of Mean		2	1
Conf Interval Mean		(4, 13)	(4, 9)
Median		**3 (BD)**	**3 (BD)**
Conf Interval Median		**(3, 3) (BD)**	**(3, 3) (BD)**
Std. Deviation		19	11
Sum		580	450
Minimum		**3 (BD)**	**3 (BD)**
Maximum		140	88
IQR		4	4
Percentiles	25	3	3
	50	3	3
	75	7	7

Table 6 - Summary statistics for Cottonwood Creek sediment load, spring snowmelt 2008, (after culvert replacement) falling limb only (17 sampling days)

		Sediment load (kg), upstream, falling limb only spring 08	**Sediment load (kg), downstream, falling limb only, spring 08**
N = 71			
Mean		220	100
Std. Error of Mean		100	24
Conf Interval of Mean		(15, 420)	(56, 150)
Median		38	38
Conf Interval Median		(36, 50)	(36, 52)
Std. Deviation		880	210
Sum		15500	7400
Minimum		31	31
Maximum		6800	1100
IQR		52	48
Percentiles	25	35	35
	50	37	38
	75	88	8

Table 7 - Wilcoxon Signed Ranks test for sediment load, falling limb only, spring 2008

	SedLoad upstream Spring, 08 – SedLoad downstream, Spring_08
Z	**-.4**[a]
Asymp. Sig. (2-tailed)	**.7**

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table 8 - Sediment load, upstream, spring 2007 (before culvert replacement) vs spring 2008 (after culvert replacement)

	SedLoad, upstream, spring 2008 – SedLoad, upstream, spring 2007
Z	**-2.4**[a]
Asymp. Sig. (2-tailed)	**.02**

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table 9 - Sediment load, downstream, spring 2007 (before culvert replacement) vs spring 2008 (after culvert replacement)

	SedLoad, downstream, spring 2008 – SedLoad, downstream, spring 2007
Z	**-2.4**[a]
Asymp. Sig. (2-tailed)	**.02**

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table 10 - Cottonwood Creek TSS during culvert replacement, fall 2007

		TSS (mg/l), upstream BD = below detection	**TSS (mg/l), downstream BD = below detection**
N = 53			
Mean		3 (**BD)**	1040
Std. Error of Mean		0	184
Conf Interval Mean		**(**3, 3) **(BD)**	(683, 141)
Median		3 **(BD)**	323
Conf Interval Median		**(**3, 3) **(BD)**	(213, 657)
Std. Deviation		0	1340
Sum		153	55,300
Minimum		3 **(BD)**	3 **(BD)**
Maximum		3 **(BD)**	4500
IQR		0	1860
Percentiles	25	3	128
	50	3	323
	75	3	1990

Table 11 – Summary statistics for sediment load during culvert replacement

		Sediment load, upstream, upgrade (kg)	**Sediment load, downstream, upgrade (kg)**
N = 53			
Mean		0.06	7.80
Std. Error of Mean		0.03	1.30
Conf Interval Mean		(0, 0.12)	(5.20, 10.40)
Median		0.03	3.50
Conf Interval Median		(0.02, 0.03)	(1.90, 5.10)
Std. Deviation		0.22	9.70
Sum		3.10	415
Minimum		0.02	0.03
Maximum		1.70	36
IQR		0.02	11
Percentiles	25	1.20	1.20
	50	3.50	3.50
	75	12	12

Table 12 - Wilcoxon Signed Ranks Test results for culvert replacement

	SedLoad, downstream, upgrade – SedLoad, upstream, upgrade
Z	-6.1[a]
Asymp. Sig. (2-tailed)	.00

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table 13 - Return flows for upgrade crossing and culvert capacity for these flows

Site	**Basin Area (A) (sq miles)**	**Annual Precip (P) (in)**	minus 1 SE	Q2	plus 1 SE	minus 1 SE	Q5	plus 1 SE	minus 1 SE	Q10	plus 1 SE	minus 1 SE	Q25	plus 1 SE
upgrade xing	9.37	42	43	90	137	74	140	206	101	184	267	125	227	329

Site	**Basin Area (A) (sq miles)**	**Annual Precip (P) (in)**	minus 1 SE	Q50	plus 1 SE	minus 1 SE	Q100	plus 1 SE	**Culvert Diam (in)**	**Predicted Capacity (cfs)**	**Return flows culvert fails at**
upgrade xing	9.37	42	145	269	393	158	303	449	55	130	Q50 and Q100

NOTE: Basin Area above the stream crossing is 6,000 acres.

Table 14 - Comparison of culvert replacement to non-culvert replacement loads

Culvert Replaced?	**Spring Snowmelt Load (kg)**	**Road Surface erosion (kg)**	**Culvert Removal Load (kg)**	**Culvert Failure Load (kg)**	**Total (kg)**
No	3,280 (2007 snowmelt); falling limb	77	N/A	90,000	93,000
Yes	7,380 (2008 snowmelt); falling limb	3	415	N/A	7800

Table 15 - Table 14 in kg/hectares (2,428 hectares of basin area above stream crossing)

Culvert Replaced ?	**Spring Snowmelt Load (kg/ha)**	**Road Surface erosion (kg/ha)**	**Culvert Removal Load (kg/ha)**	**Culvert Failure Load (kg/ha)**	**Total (kg/ha)**
No	3,280 kg/2,428 hectares, 1.35 kg/ha	*By plot area*: 77 kg/0.025 hectare road surface & fill, 3,100 kg/ha/year --------------------- *By basin area*: 77 kg/2428 ha, 0.03 kg/ha/year	N/A	90,000 kg/2,428 ha, 37.10 kg/ha	**38.5 kg/ha/3 weeks**
Yes	7,380 kg/2,428 ha, 3.04 kg/ha	*By plot area*: 3 kg/0.025 ha rd surface & fill, 120 kg/ha/year --------------------- *By basin area*: 3 kg/2428 ha, 0.001 kg/ha/year	415 kg/2,428 ha, 0.17 kg/ha	N/A	**3.2 kg/ha/3 weeks**

Table 16 - Comparing thesis results on road surface erosion at culvert upgrade site to the literature

Authors	Region	Geology &Annual Precipitation	Sediment Yield
Sugden &Woods (2007)	W. Montana	Belts, Glacial Tills 24-39 inches/year	Belts: Mean:5,470 kg/ha/year Glacial Tills: Mean: 5,270 kg/ha/year
Bilby et al (1989)	SW Washington	Volcanic ash 50 inches/year	21,400 kg/ha sediment yield/six months
Megahan et al (2001)	S Idaho	Granitic 35 inches/year	Mean: 16,300 kg/hectares/year
Shapiro Thesis	W. Montana	Belts, Glacial Tills 14-50 inches/year	Before culvert replacement: 3,100 kg/ha/year After culvert replacement: 120 kg/ha/year

Table 17 - Comparing thesis results on TSS measured during spring high flows to the literature

Authors	Region	Geology &Annual Precipitation	Pre-Disturbance Sediment Yield	Post-disturbance Sediment Yield
Anderson & Potts (1987)	W. MT	Belts, 27-35 inches/year	0.56 – 1.77 kg/ha/year	1st year after road building: 13.7 kg/ha/year 2nd year after road building: 3.6kg/ha/year
Lewis (1998)	NW CA	Franciscan shales & sandstones, 47 inches/year	340 kg/ha/year	1,475 kg/ha/year
Lane & Sheridan (2002)	Australia	Devonian metasediments, 45 inches/year	N/A	32.2 kg/ha /five high flow months
Fredriksen (1970)	W OR	Volcanic ash deposits, 90 inches.year	455 kg/ha/year	420 kg/ha/year
Shapiro Thesis	W MT	Belts, Glacial Tills 14-50 inches/year	1.35 kg/ha/3 weeks	3.04 kg/ha/3 weeks

Table 18 - Comparing thesis results on culvert replacement to the literature

Authors	Region	Geology &Annual Precipitation	Sediment Yield During Replacement
Foltz et al (2008)	Central ID	Idaho Batholith Border Zone, 46 inches/year	Range: 0.002 kg/ha/24 hours to 0.10 kg/ha/24 hours
Foltz et al (2008)	NE WA	glacial till/volcanic ash, 45-57 inches/year	Range: 0.006 and 0.01 kg/ha/24 hours
Jakober (2002)	W MT	Idaho Batholith and metasediments intruded by granite, 30-50 inches/year	1.09 kg/ha/26 hours
Brown (2002)	Central ID	Idaho Batholith, 48 inches/year	0.04 to 2.74 kg/ha/24 hours
Shapiro Thesis	W MT	Belts, Glacial Tills 14-50 inches/year	0.17 kg/ha/36 hours (normalized to 0.11 kg/ha/24 hours)

Table 19 - Comparing thesis results on stream bank erosion to the literature

Authors	Region	Geology &Annual Precipitation	Stream bank erosion volume
Madej (2001)	N CA	Franciscan Assemblage (sandstones, mudstones), 79 inches/year	0.07 m^3/km^2
Klein (2003)	N CA	Shale, mudstone, sandstone, 68 inches/year	0.99 m^3/km^2
Shapiro Thesis	W MT	Belts, Glacial Tills 14-50 inches/year	0.08 m^3/km^2

Table 20 - Cottonwood Creek turbidity spring snowmelt, 2007, falling limb only, before culvert replacement

	Turbidity Upstream (NTUs) **BD =below detection**	Turbidity Downstream (NTUs) **BD =below detection**
N = 39		
Mean	2.8 **(BD)**	2.7 **(BD)**
Std. Error of Mean	0.07	0.00
Conf Interval Mean	(2.7, 2.9)	(2.7, 2.7)
Median	2.7 **(BD)**	2.7 **(BD)**
Conf Interval Median	(2.7, 2.7) **(BD)**	(2.7, 2.7) **(BD)**
Std. Deviation	0.45	0.00

Table 21 - Cottonwood Creek turbidity, during culvert replacement

	Turbidity Upstream (NTUs) **BD = below detection**	Turbidity Downstream (NTUs) **BD = below detection**
N = 53		
Mean	2.7 **(BD)**	2000
Conf Interval Mean	(2.7, 2.7) **(BD)**	(880, 3100)
Std. Error of Mean	0.00	580
Median	2.7 **(BD)**	340
Conf Interval Median	(2.7, 2.7) **(BD)**	(170, 870)
Std. Deviation	0	4200

Table 22 - Cottonwood Creek turbidity, spring snowmelt, 2008, falling limb only

	Turbidity Upstream (NTUs) **BD = below detection**	Turbidity Downstream (NTUs) **BD = below detection**
N = 71		
Mean	2.7 **(BD)**	2.7 **(BD)**
Conf Interval Mean	(2.7, 2.7) **(BD)**	(2.7, 2.7) **(BD)**
Std. Error of Mean	0.00	0.00
Median	2.7 **(BD)**	2.7 **(BD)**
Conf Interval Median	(2.7, 2.7)	(2.7, 2.7)
Std. Deviation	0.00	0.00

Table 23 - Cottonwood Creek turbidity, spring snowmelt, 2008, entire hydrograph

	Turbidity Upstream (NTUs) **BD = below detection**	Turbidity Downstream (NTUs) **BD = below detection**
N = 206		
Mean	3.5 **(BD)**	4.1 **(BD)**
Conf Interval Mean	(2.8, 4.2) **(BD)**	(3.4, 4.8) **(BD)**
Std. Error of Mean	0.38	0.34
Median	2.7 **(BD)**	2.7 **(BD)**
Conf Interval Median	(2.7, 2.7) **(BD)**	(2.7, 2.7) **(BD)**
Std. Deviation	5.4	4.9

Table 24 - WEPP model results for road surface erosion

Total from road prism	Total from buffers	Total from road prism & buffers	Average per crossing	Range of xing values	Std Deviation of xing values	Normalized by basin area
1,000 kg/yr	2,350 kg/yr	3,350 kg/yr	105 kg	0-940 kg/year	232 kg	0.19 kg/ha/year

Table 25 - Stream bank erosion in Cottonwood Creek from the MBNC TMDL, & achievable reduction

Cottonwood Creek basin area	Cumulative Total (anthropogenic + background	Cumulative Controllable (anthropogenic)	Cumulative Background (natural)	Achievable reduction
17,900 hectares	296 tons/year (15.0 kg/ha/year)	106 tons/year (5.4 kg/ha/year)	190 tons/year (9.6 kg/ha/year)	72 tons/year

Table 26 - Road surface erosion tonnage for entire MBNC and normalized by basin area

No. of stream crossings	Total stream crossings surveyed	Road surface erosion load from surveyed crossings	Total road surface erosion load from surveyed & unsurveyed crossings	Possible load reduction
1,818	Either 230 or 320	Either 250 tons/year or 300 tons/year (12.6 kg/ha/year or 15.2 kg/ha/year)	Either 1,820 or 1,680 tons/year (92.3 k/ha/year or 85.3 kg/ha/year)	By 500 tons (By 26 kg/ha)

Table 27 - Road surface erosion tonnage for Cottonwood Cr

No. of stream crossings	Total stream crossings surveyed	Road surface erosion load from surveyed xings	Total road surface erosion load from surveyed & unsurveyed xings	Possible load reduction
177	27	20 tons/year (1.0 kg/ha/year)	183 tons/year (9.3 kg/ha/year)	By 55 tons (2.8 kg/ha)

Table 28 - Road-fill Culvert Failure tonnage for entire MBNC

No. Crossings assessed	No xings at risk of failure (surveyed xings)	Load at risk from surveyed xings	Unsurveyed xings	Total amount of fill at risk of failure for both surveyed & unsurveyed xings	Annual load from culvert failure	Load by replacing culverts with Q100-sized ones
73	38	4,393 tons of fill	From surveyed xings, mean value of 115.6 tons/xing (4,393 tons divided by 38 sites) is extrapolated to unsurveyed xings	210, 161 tons (115.6 tons/site x 1,818 xings)	2,102 tons/year	483 tons/year

Table 29 - Road-fill Culvert Failure tonnage for Cottonwood Cr, and normalized by basin

No. xings in basin	No. Crossings assessed	No xings at risk of failure (surveyed xings)	Total amount of fill at risk of failure for both surveyed & unsurveyed xings	Annual load from culvert failure (1% failure rate)	Load by replacing culverts with Q100-sized ones
177	27	10	20,460 tons (185,620 kg/ha)	205 tons/year (10.4 kg/ha/year)	47 tons/year (23.8 kg/ha/year)

Table 30 - Hillslope Loadings for Cottonwood Creek from the TMDL

Total overland sheet flow	Naturally occurring part of total sheet flow	Cumulative controllable load part of total sheet flow	Sediment removal efficiency	Portion of controllable load that gets through vegetative buffers	Total load that gets through buffers
1,325 tons/year (67.14 kg/ha/year)	331 tons/year (16.8 kg/ha/year)	994 tons/year (50.4 kg/ha/year)	0.70	298 tons/year (15.1 kg/ha/year)	630 tons/year (32 kg/ha/year)

Table 31 - Comparing modeled results for different stream disturbances in the MBNC TMDL to the thesis stream crossing survey results

Watershed	Basin area (hectares)	Road surface erosion (kg/ha/year)	Culvert Fill Failure (kg/ha/year)	Stream Bank Erosion (kg/ha/year)[1]	Hillslope Erosion[2] kg/ha/year	Total kg/ha/year
Cottonwood Cr	17,900	9.3	10.4	15	67.1	102
Yourname Cr	5,000	12.6	6.9	50.2	11.4	81
Rock Cr	9,000	2.02	3.4	23	59.4	88
North Fork Blackfoot R	32,500	3.3	2.5	183.1	100.1	289
Monture Cr	39,700	3.9	3.2	17.6	2.7	27
Blanchard Cr	15,900	6.3	6.4	3.4	0.7	17

[1] Stream bank erosion includes both anthropogenic and non-anthropogenic loads

[2] Hillslope erosion is the 25% of overland erosion that moves through protective buffers. In this context, it includes both natural and anthropogenic sources.

Table 32 - Other Montana TMDLs in different geologies and precipitation and their sediment sources

Assessment & Area	Watershed	Geology & Annual Precipitation	Road surface erosion (kg/ha/year)*	Culvert Fill Failure (kg/ha/year)	Natural Upland/Hillslope Erosion[1]
Yaak River TMDL, Kootenei NF	17-mile Cr	Belt Supergroup, 36-70 inches/year	1.4 kg/ha/year	Not done	24.9 kg/ha/year[2]
Yaak River TMDL, Kootenei NF	SF Yaak R	Belt Supergroup, 36-70 inches/year	1.1 kg/ha/year	Not done	24.9 kg/ha/year[2]
Kootenei NF WATSED Assessment, Kootenei NF	Quartz Cr	Belt Supergroup, 36-70 inches/year	N/A	N/A	28.4 kg/ha/year
Kootenei NF WATSED Assessment, Kootenei NF	Lamoka Cr	Belt Supergroup, 36-70 inches/year	N/A	N/A	48.3 kg/ha/year
Bitterroot Headwaters Planning Area TMDL, Bitterroot NF	EF Bitterroot	Granitics, 20-60 inches/year	13.6 kg/ha/year	Not done	62.3 kg/ha/year[3]
Bitterroot Headwaters Planning Area TMDL, Bitterroot NF	Meadow Cr	Granitics, 20-60 inches/year	18.1 kg/ha/year	Not done	56.1 kg/ha/year[3]
Bitterroot Headwaters Planning Area TMDL, Bitterroot NF	Moose Cr	Granitics, 20-60 inches/year	4.5 kg/ha/year	Not done	57.9 kh/ha/year[3]

*Surveyed road crossings extrapolated to non-surveyed crossings

[1] Non-anthropogenic sources

[2] Based on regression curves for modeled basins; modeling and validation of modeling results were not conducted at a watershed scale for 17-mile Creek and South Fork Yaak River

[3] Described in the TMDL as “natural background sources” but not defined; appears to mean non-anthropogenic sources, and excludes stream bank erosion, so appears to be hillslope-related

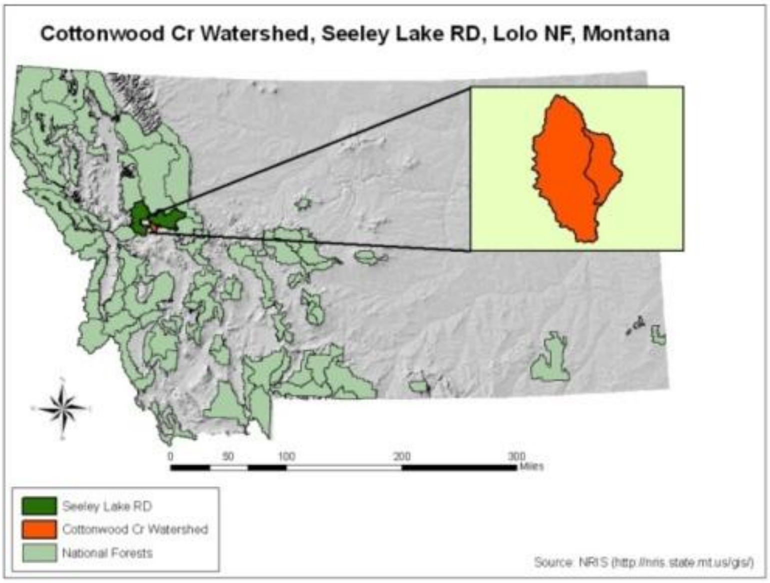
Table 33 - Allocations of load reductions in Cottonwood Creek

Total needed annual load reductions	Livestock grazing	Hay production	Silviculture	Road crossings
583 tons/year	286 tons/year	7 tons/year	241 tons/year	213 tons/year

Table 34 - Suspected sources and applicable treatments of excess fine sediments in Cottonwood Creek

Suspected Sources	Applicable Treatments
Stream bank sediment (106 tons/yr)	Riparian Area BMPs Grazing BMPs Water Conservation BMPs Forestry BMPs
Road sediment (55 tons/yr)	Roads BMPs
Hill slope sediment (994 tons/yr)	Riparian Area BMPs Grazing BMPs Upland BMPs Forestry BMPs

Figure 1 - Location of Cottonwood Creek basin



Source: NRIS (http://nris.state.mt.us/gis/)

Figure 2 - Normalized Regional flow duration curve for the hydrologic region that includes Cottonwood Creek, in Western Montana

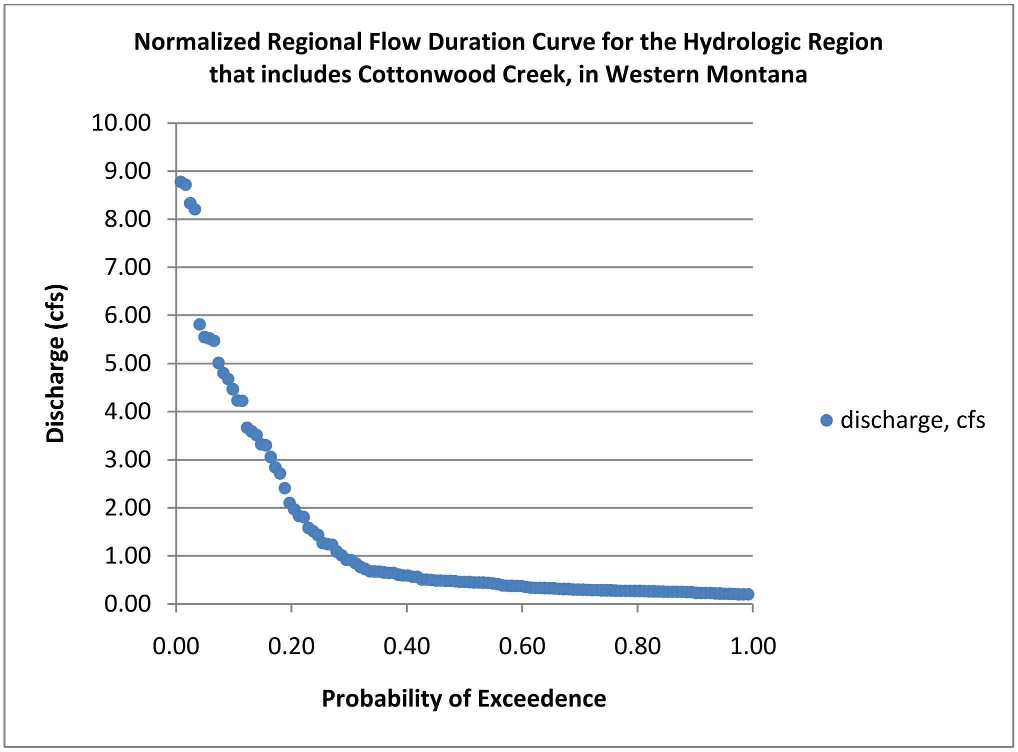


Figure 3 - Cottonwood Creek snowmelt hydrograph

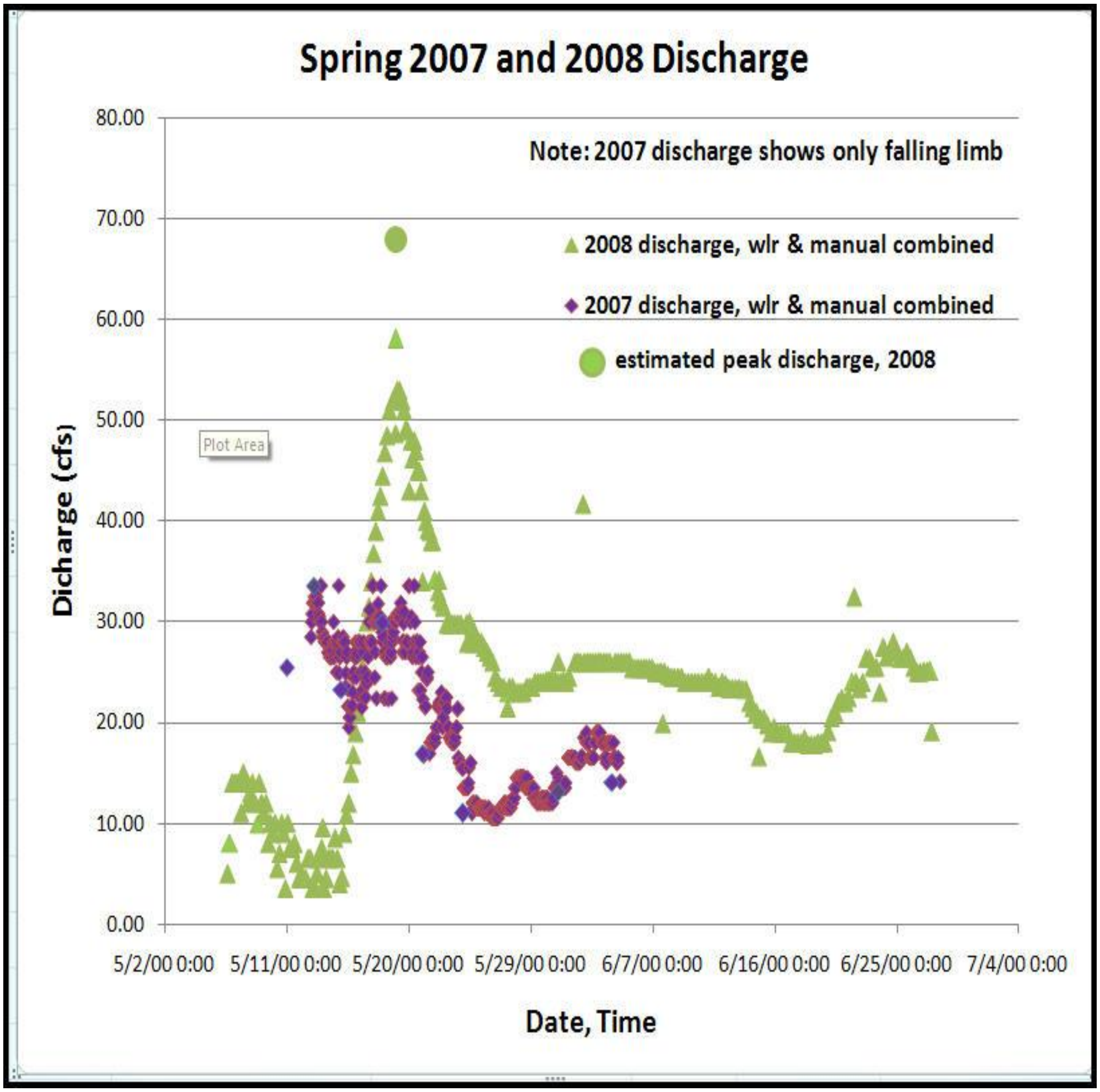


Figure 4 - TSS (mg/l) upstream and downstream, respectively, Cottonwood Cr, spring 2007 (before culvert replacement)

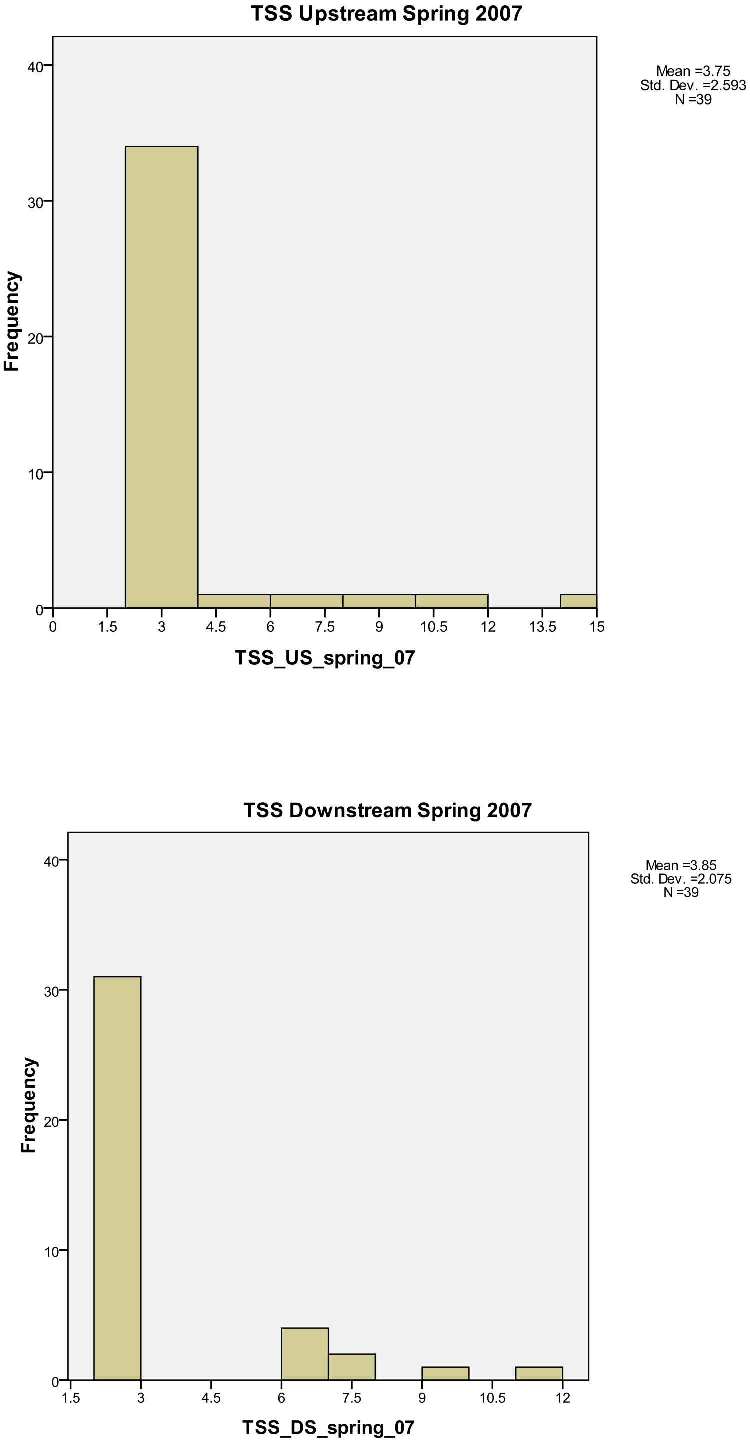


Figure 5 - Boxplots for upstream & downstream TSS (mg/l), Cottonwood Creek, spring 2007, falling limb only (before culvert replacement)

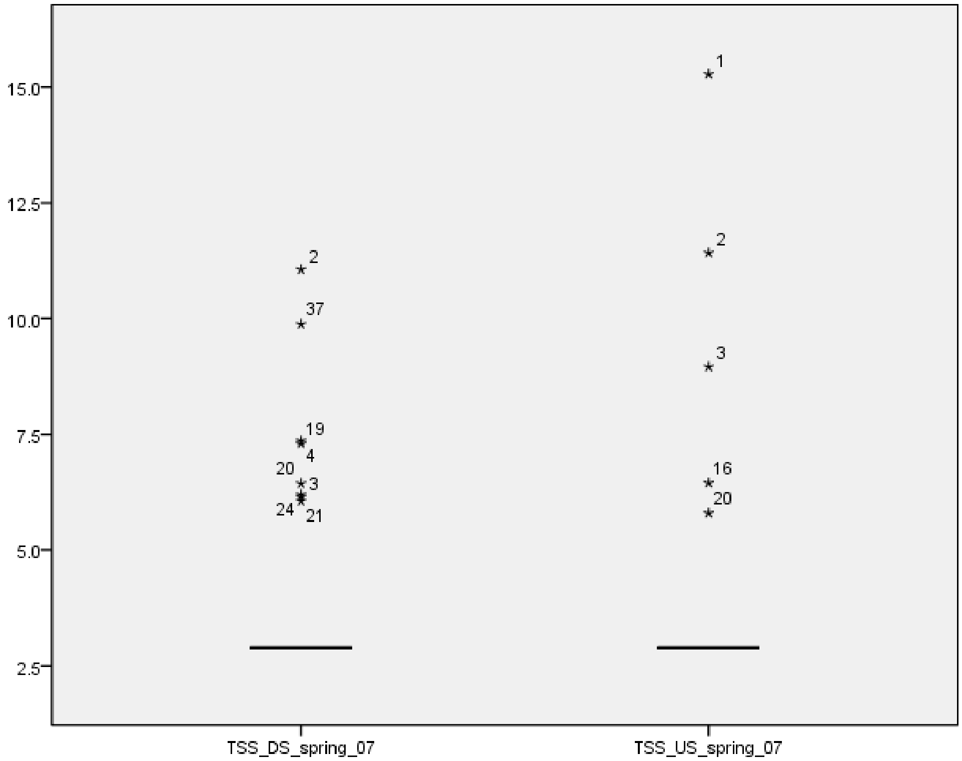
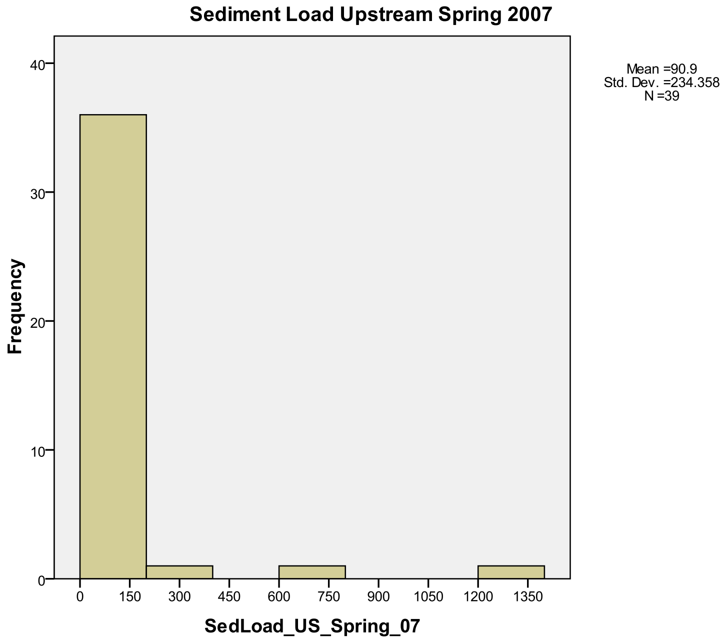


Figure 6 - Sediment load (kg) upstream and downstream, respectively, Cottonwood Creek, spring 2007 (before culvert replacement)



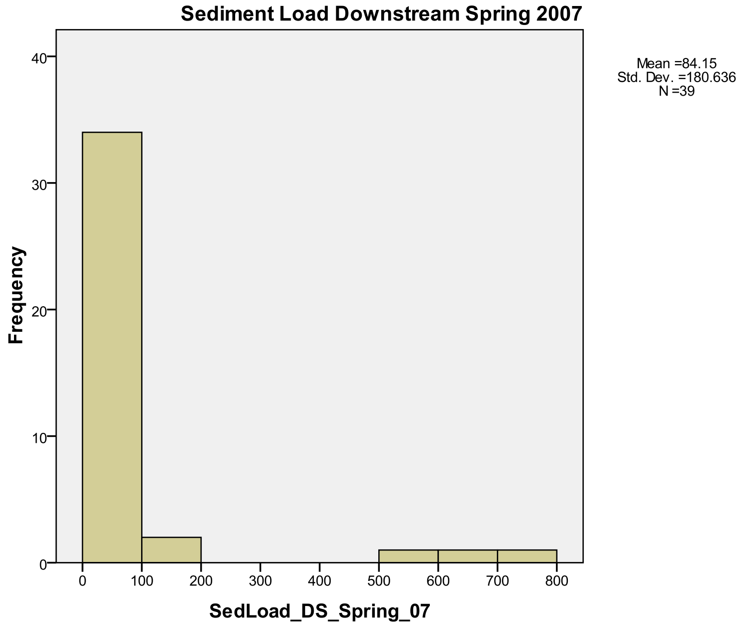


Figure 7 - Boxplots for upstream & downstream sediment load (kg), Cottonwood Creek, spring 2007, (before culvert replacement), falling limb only

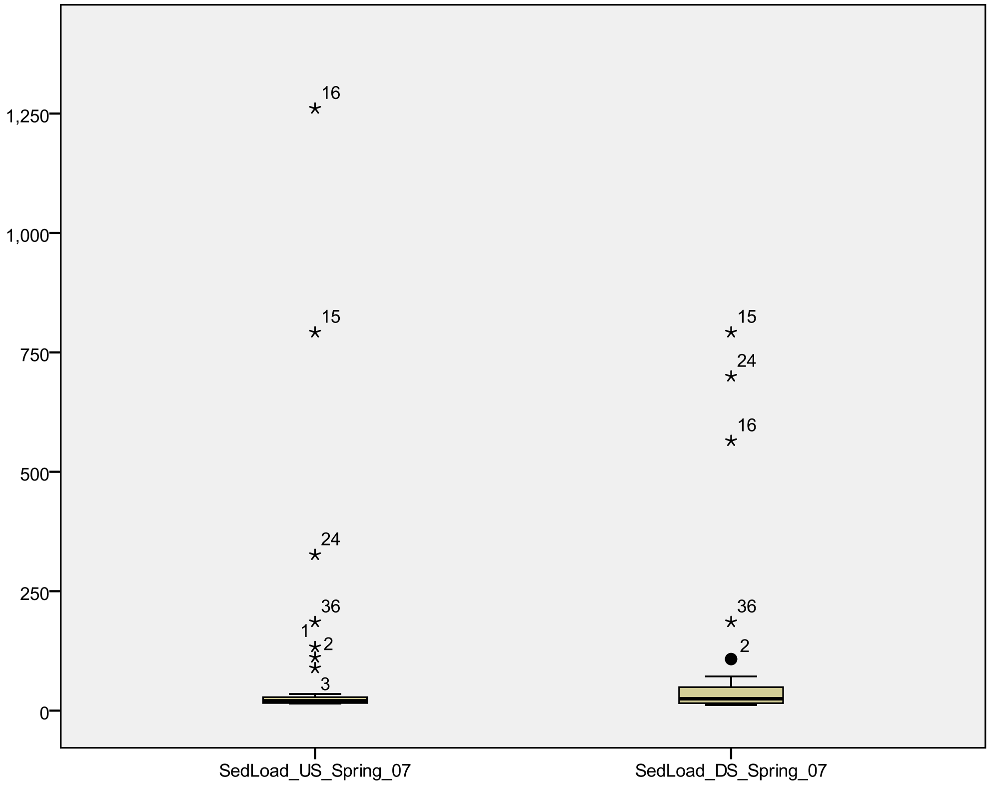
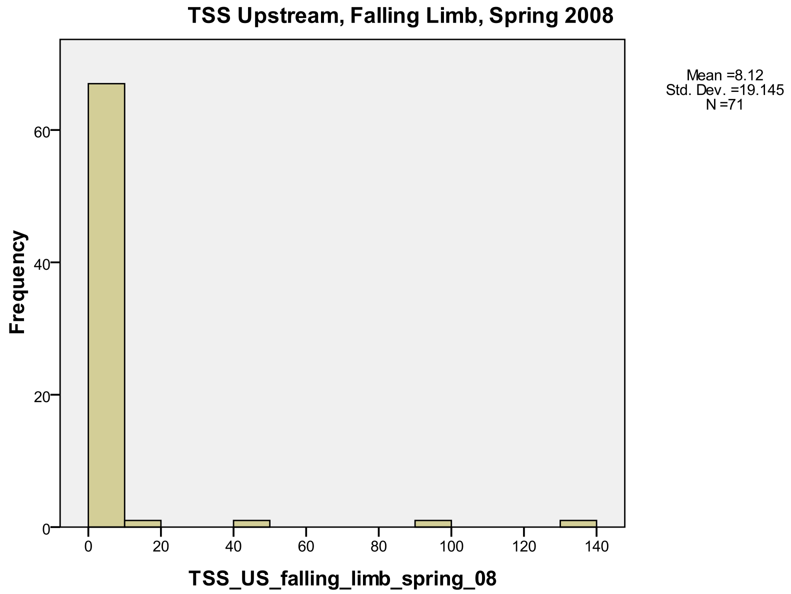


Figure 8 - TSS (mg/l), upstream and downstream, respectively, Cottonwood Creek, spring 2008 (after culvert replacement)



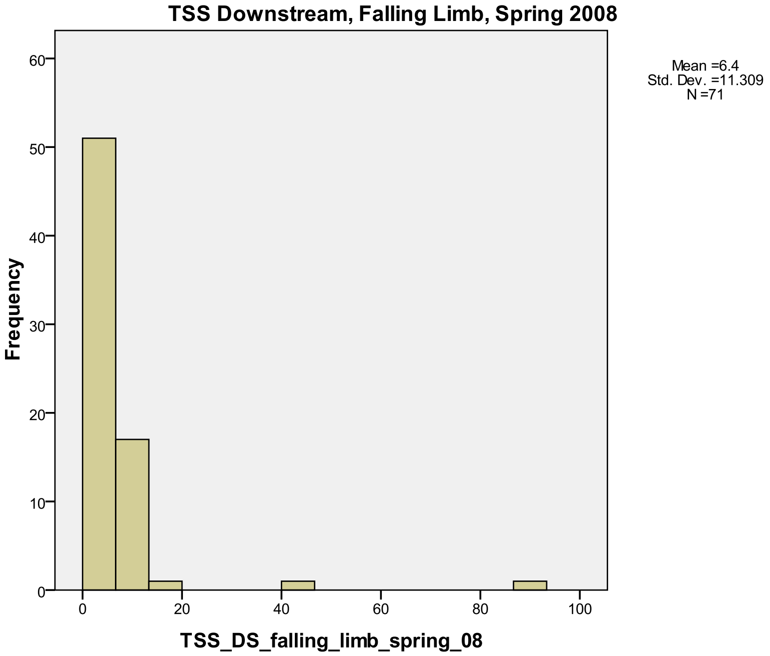


Figure 9 - Boxplots for upstream & downstream TSS (mg/l), Cottonwood Creek, falling limb only, spring 2008 (after culvert replacement)

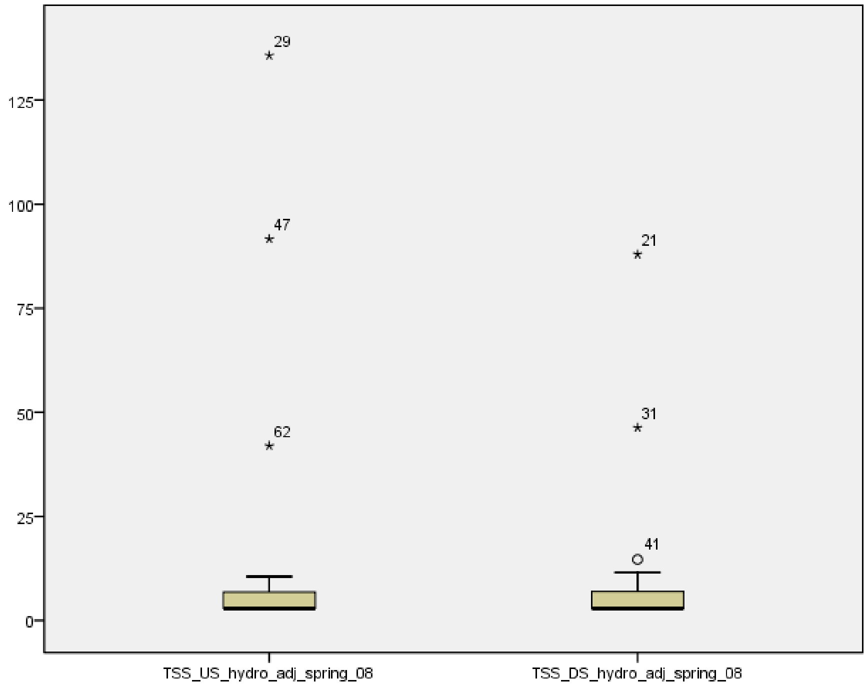
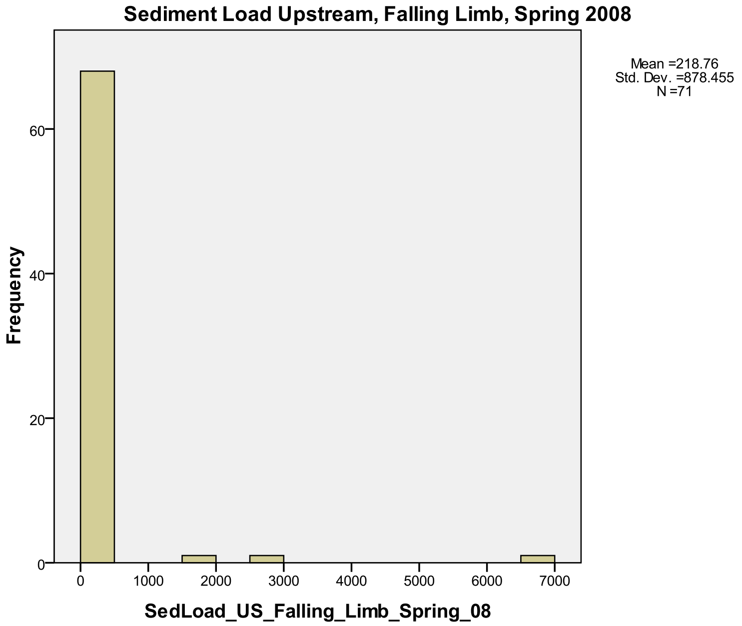


Figure 10 - Sediment load (kg), upstream and downstream, respectively, Cottonwood Cr, falling limb only, spring 2008, (after culvert replacement)



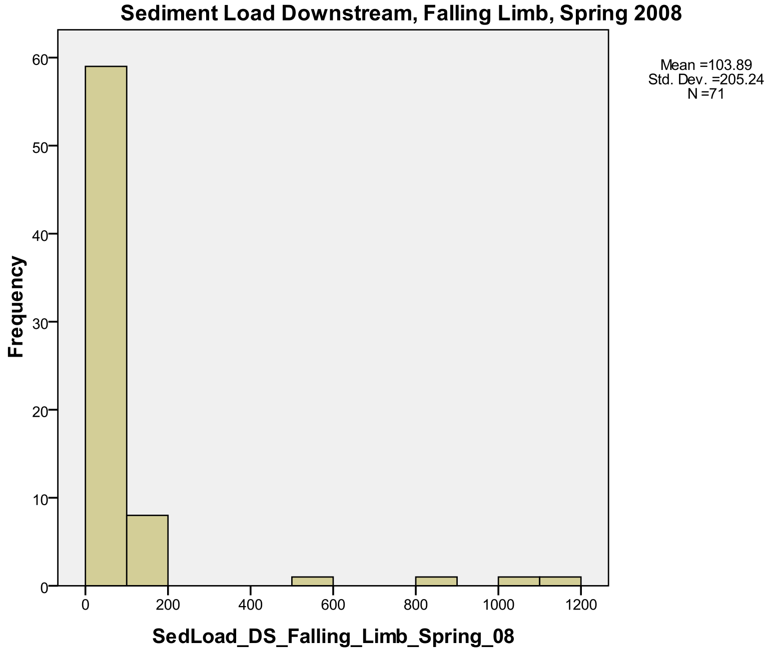


Figure 11 - Boxplot of Cottonwood Creek sediment load (kg), upstream and downstream, spring 2008, (after culvert replacement), falling limb only

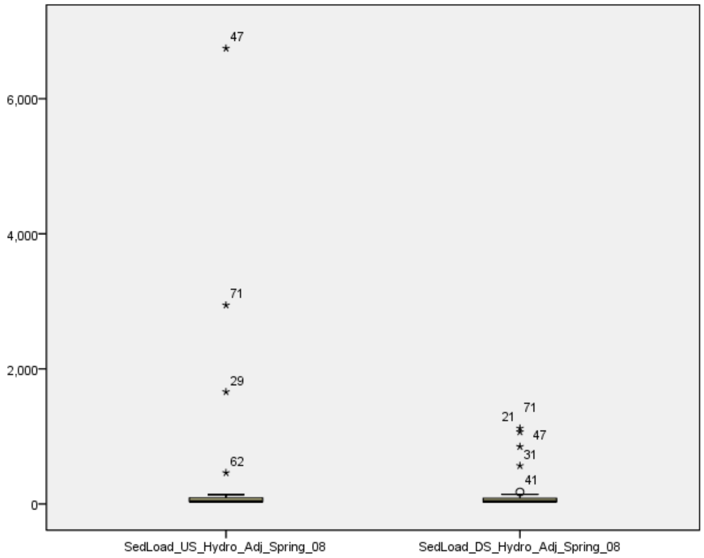


Figure 12 - Cottonwood Creek TSS (mg/l), downstream, during culvert replacement

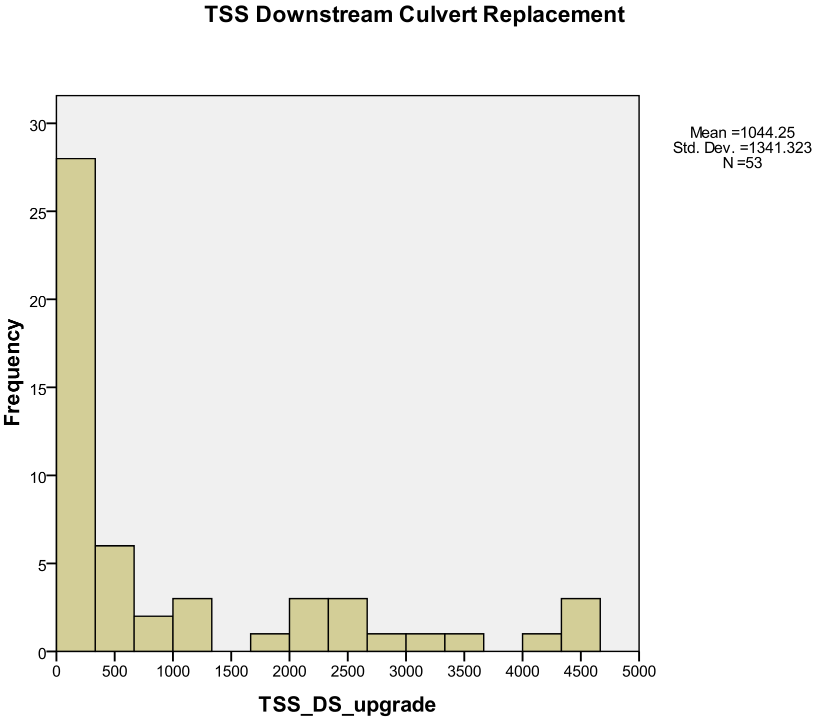


Figure 13 - Cottonwood Creek TSS (mg/l), downstream, during culvert replacement

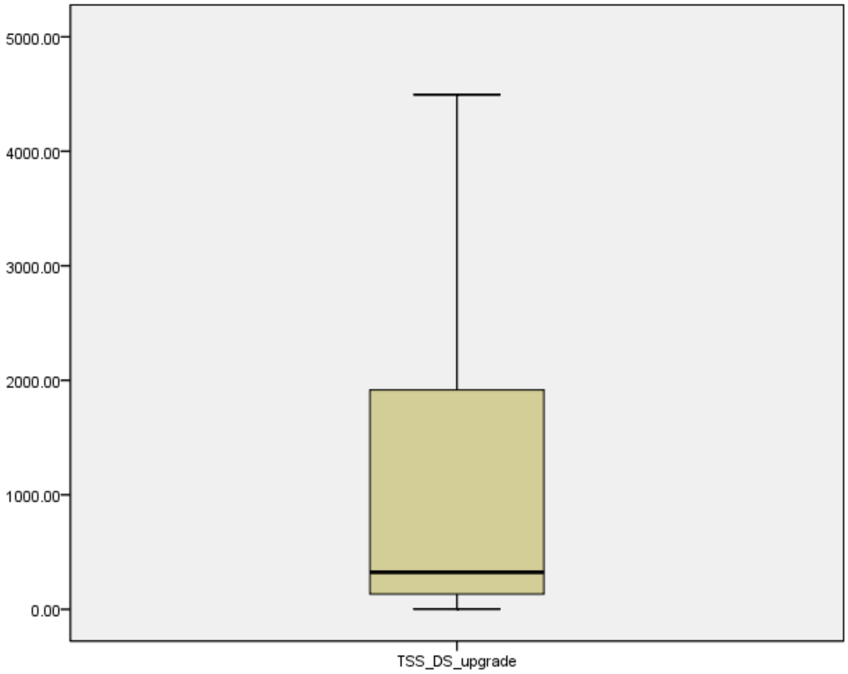
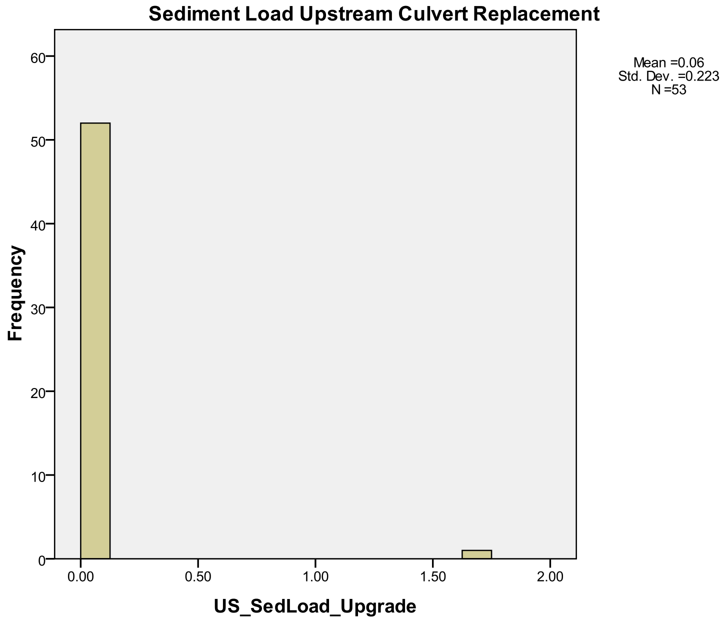


Figure 14 - Cottonwood Creek sediment load (kg), upstream and downstream, respectively, during culvert replacement



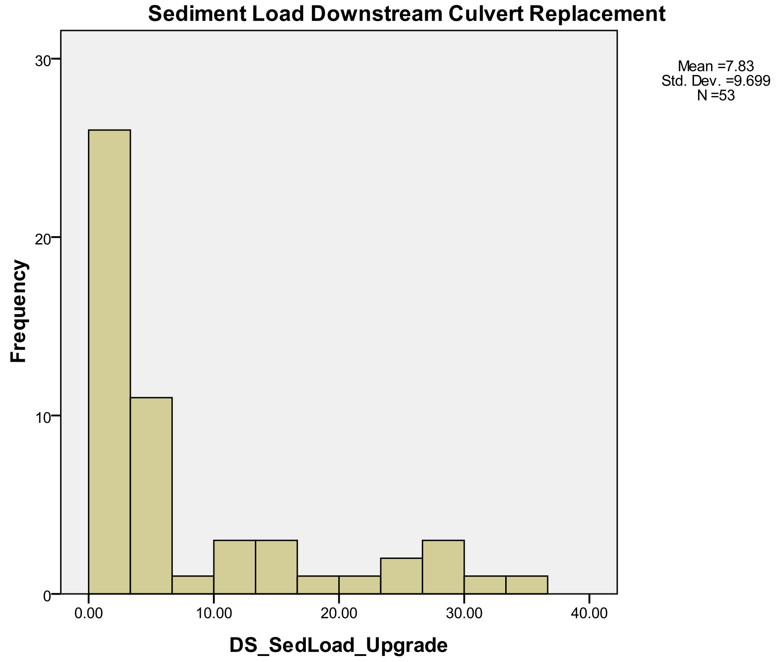


Figure 15 - Cottonwood Creek upstream and downstream sediment load (kg) during culvert replacement

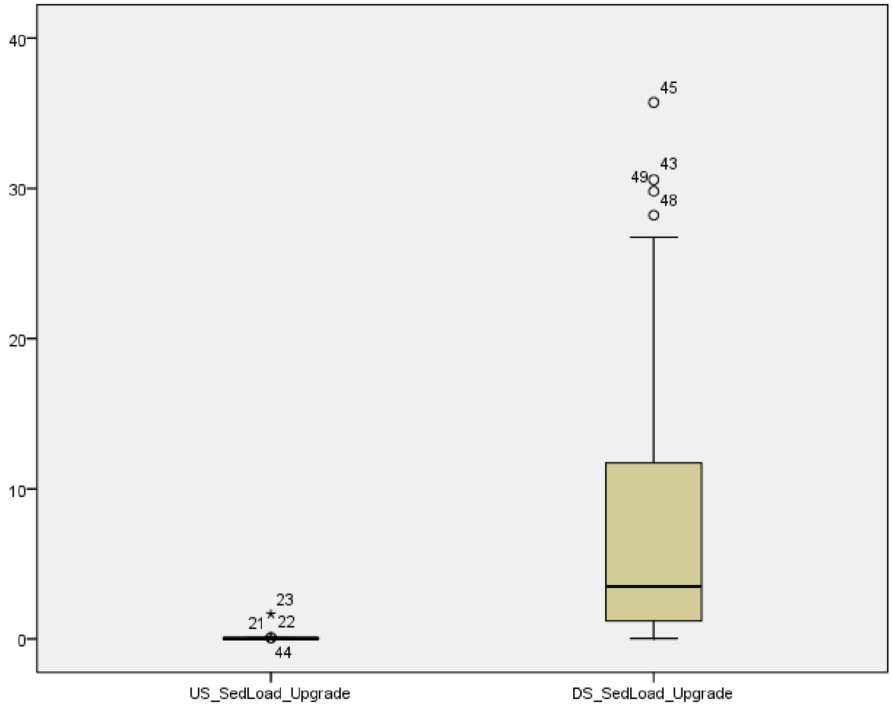
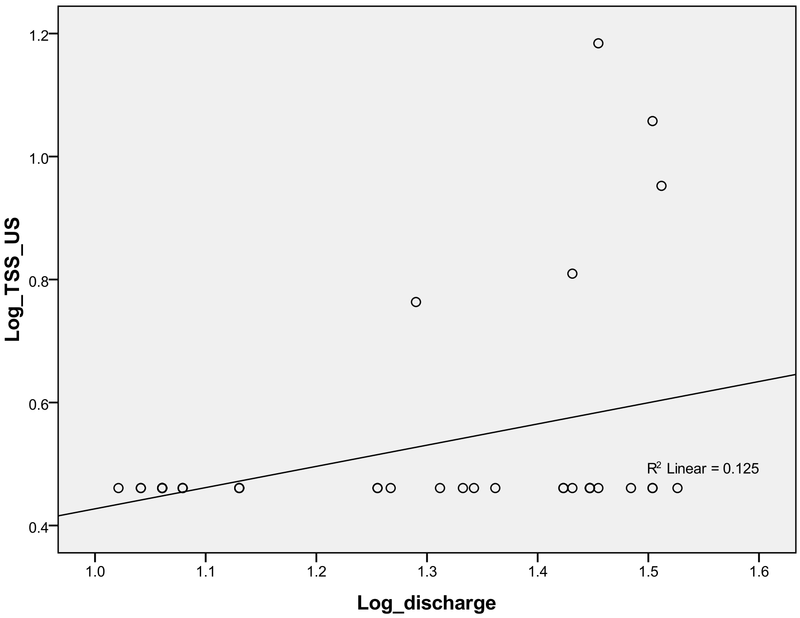


Figure 16 - Log transformed TSS (mg/l) versus log transformed discharge for Cottonwood Creek upstream, spring snowmelt 2007, falling limb only, and residuals plot

Log TSS Upstream vs Log Discharge, Spring 2007 falling limb only



Residuals, Log TSS Upstream vs Log Discharge, Spring 2007 falling limb only

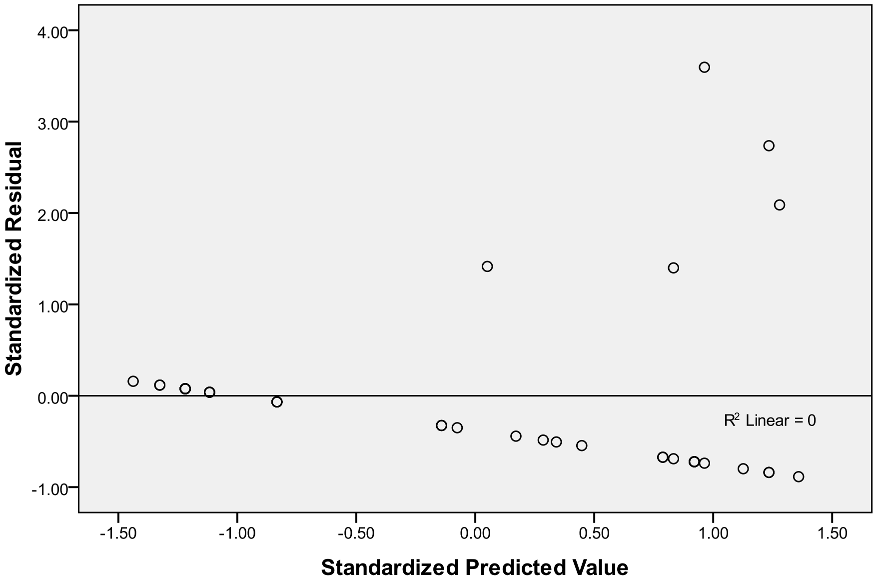
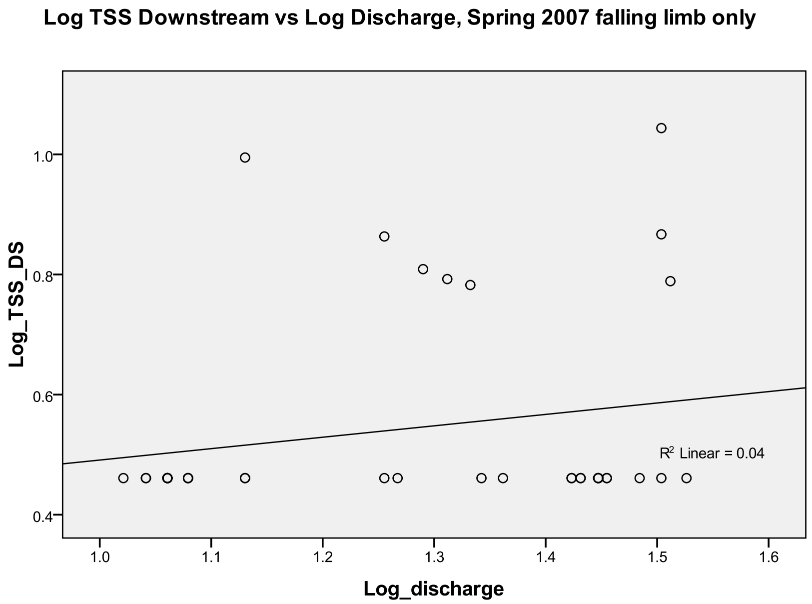


Figure 17 - Log transformed TSS (mg/l)versus log transformed discharge for Cottonwood Creek, downstream, spring snowmelt 2007, falling limb only, and residuals plot



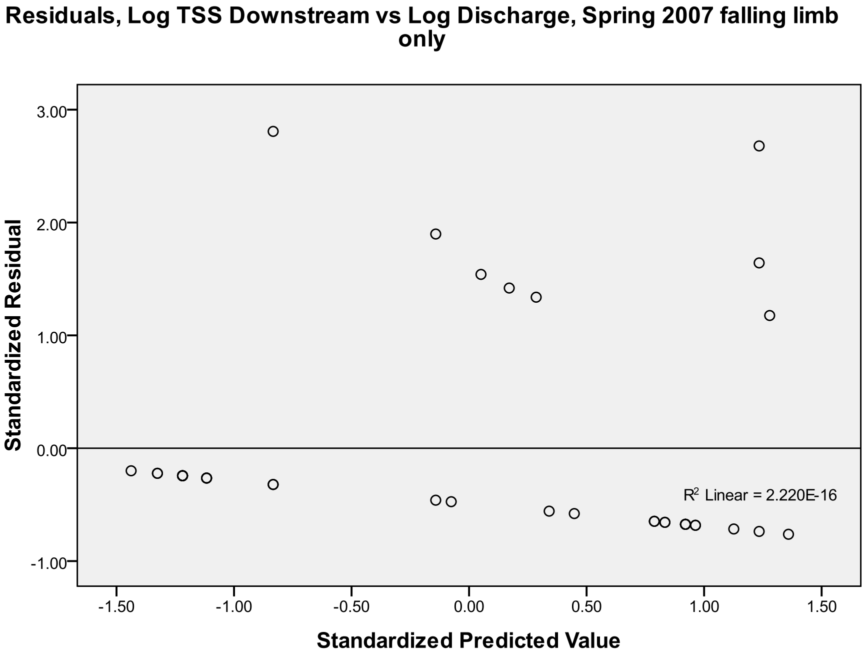
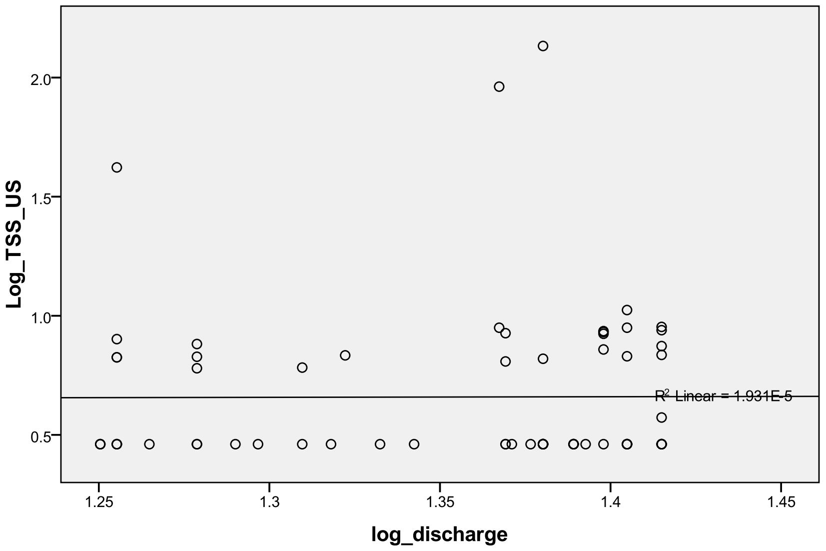


Figure 18 - Log transformed TSS (mg/l) versus log transformed discharge for Cottonwood Creek upstream, spring snowmelt 2008, falling limb only, and residuals plot


Log TSS Upstream vs Log Discharge, Spring 2008 falling limb only

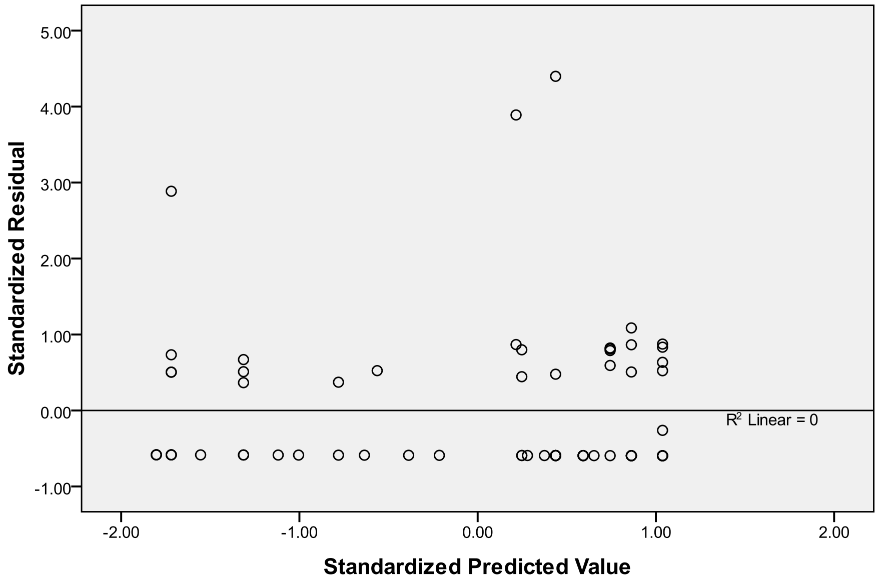
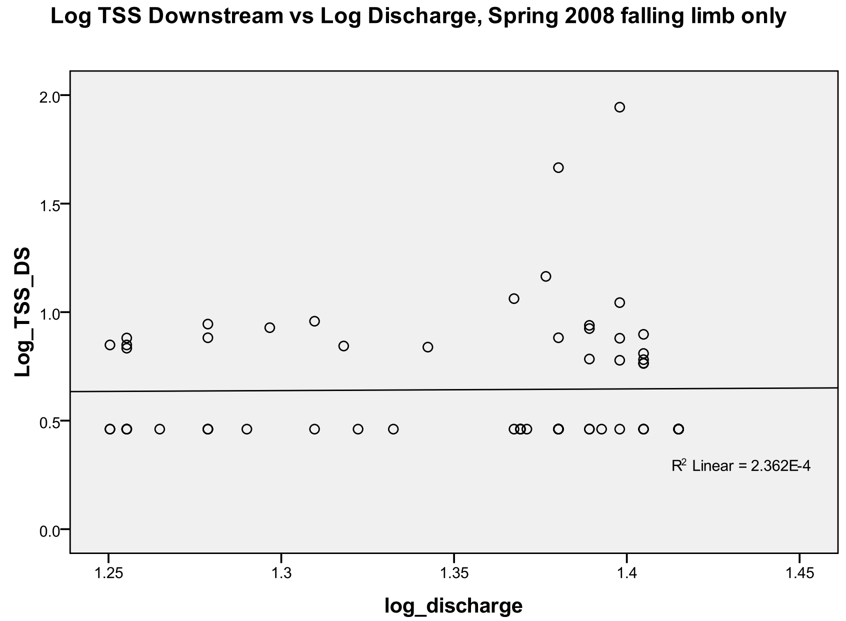

Residuals, Log TSS Upstream vs Log Discharge, Spring 2008 falling limb only

Figure 19 - Log transformed TSS (mg/l) versus log transformed discharge for Cottonwood Creek downstream, spring snowmelt 2008, falling limb only, and residuals



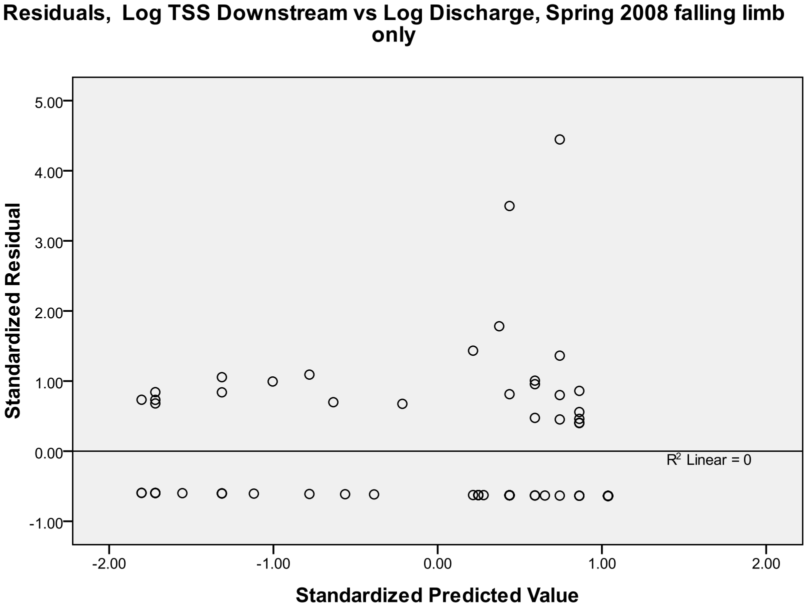
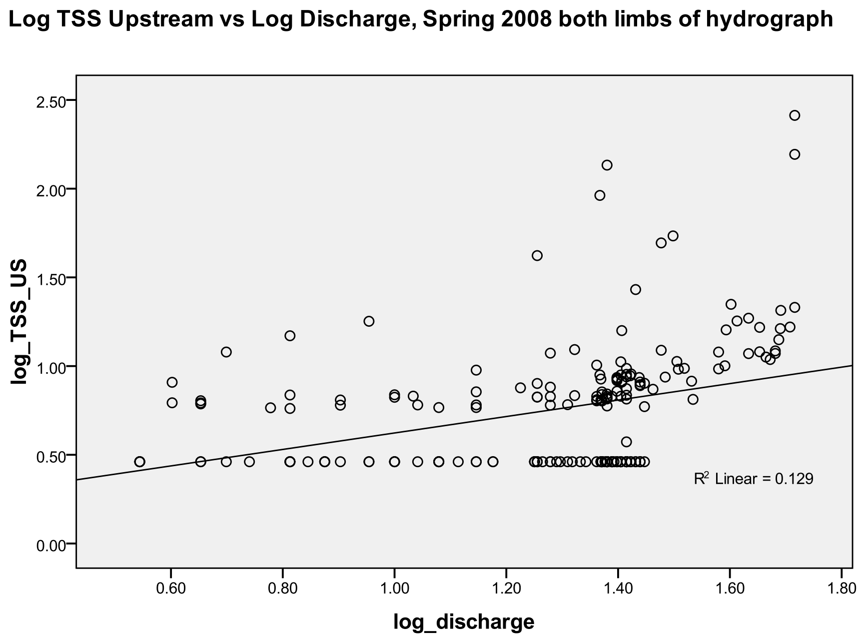


Figure 20 - Log transformed TSS versus log transformed discharge for Cottonwood Creek upstream, spring snowmelt 2008, entire hydrograph, and residuals plot



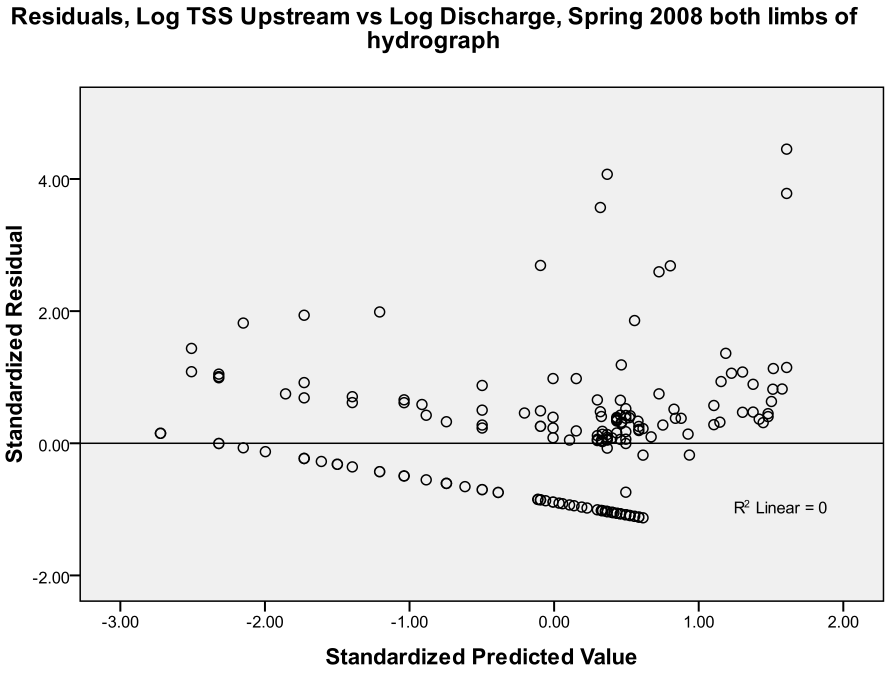
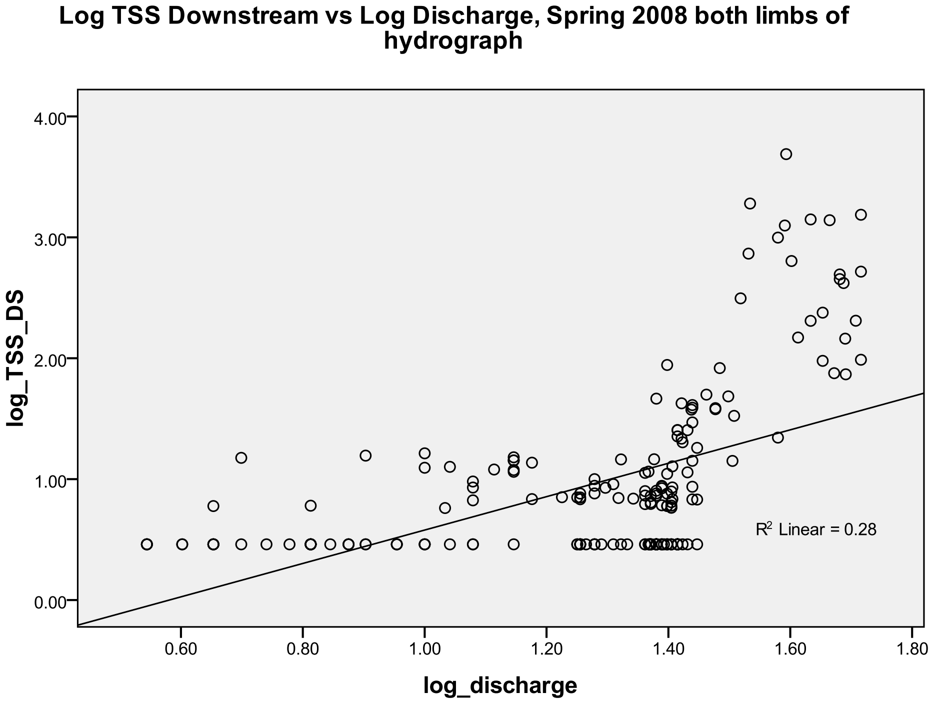


Figure 21 - Log transformed TSS versus log transformed discharge for Cottonwood Creek downstream, spring snowmelt 2008, entire hydrograph, and residuals plot



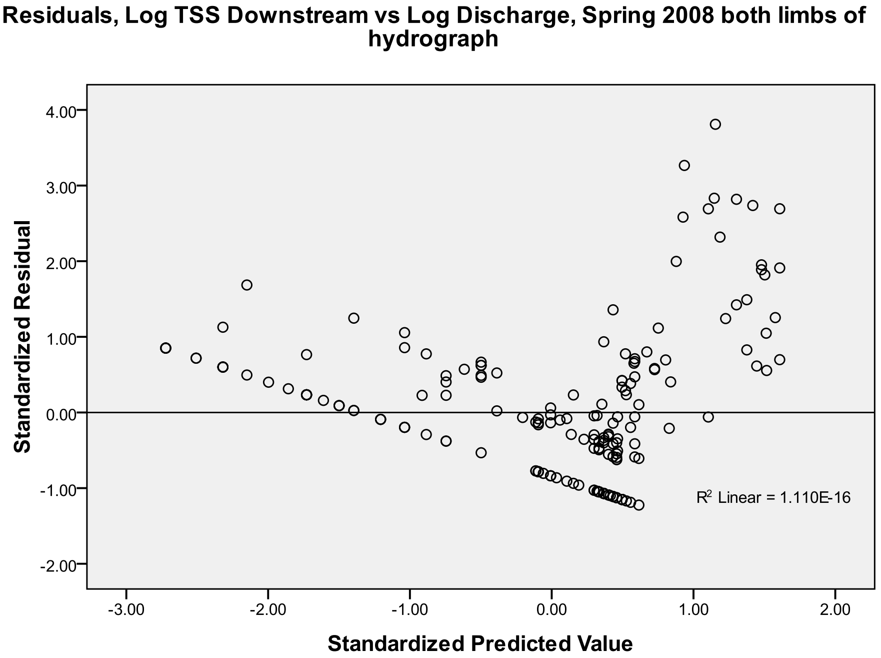
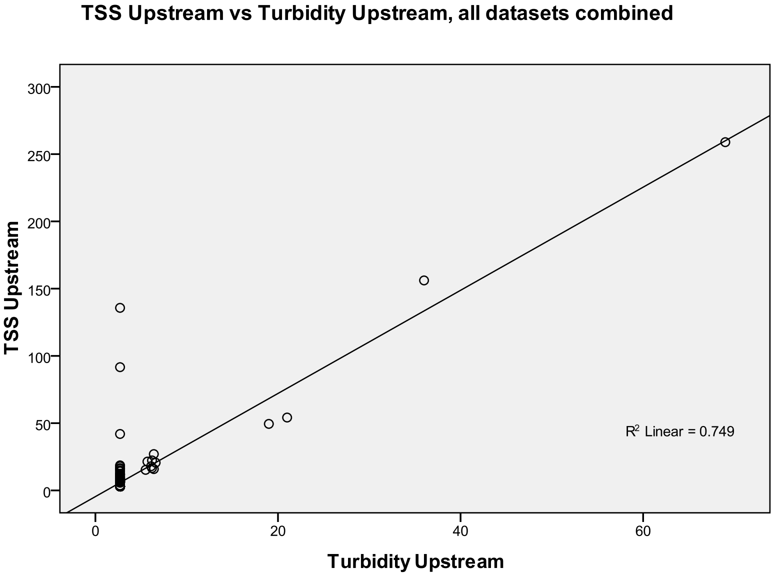


Figure 22 - TSS vs Turbidity, Cottonwood Creek upstream, both limbs of hydrograph, all datasets combined, with residuals plot



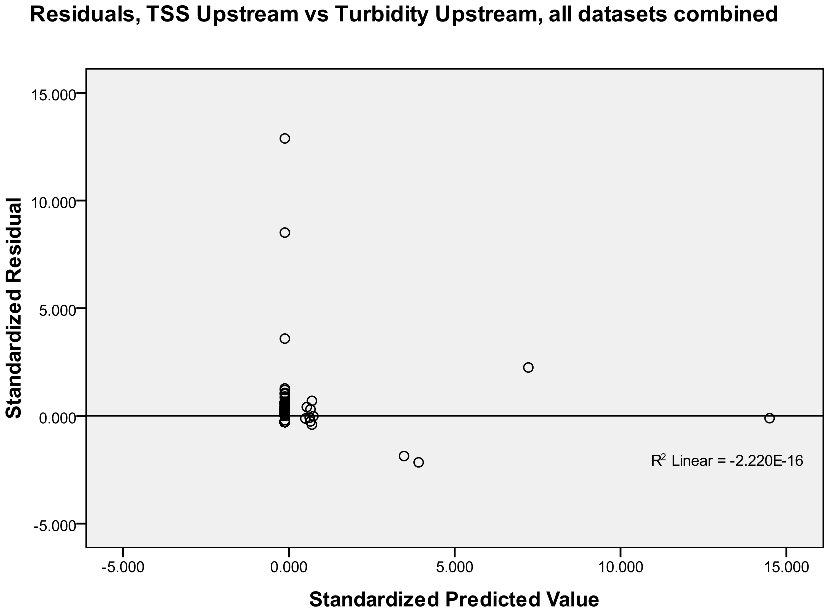
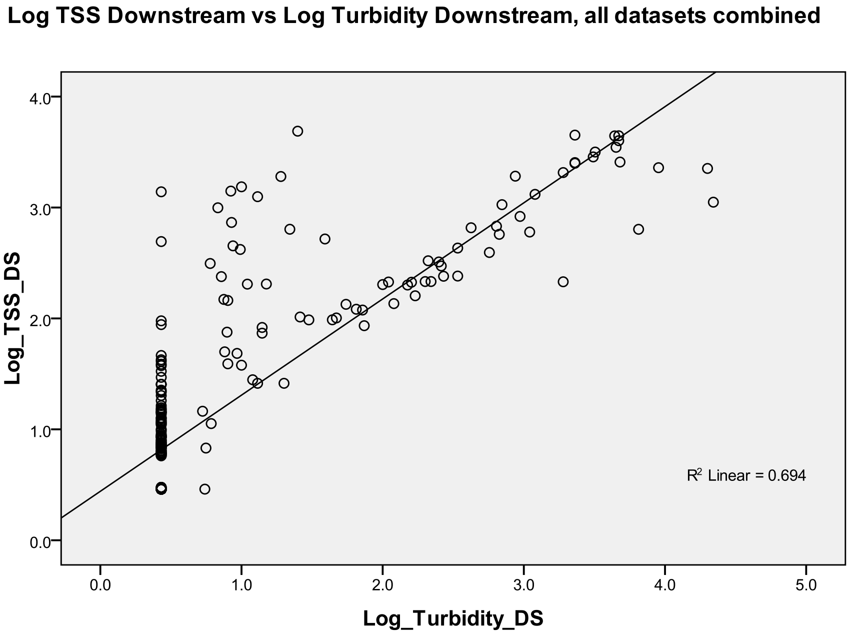
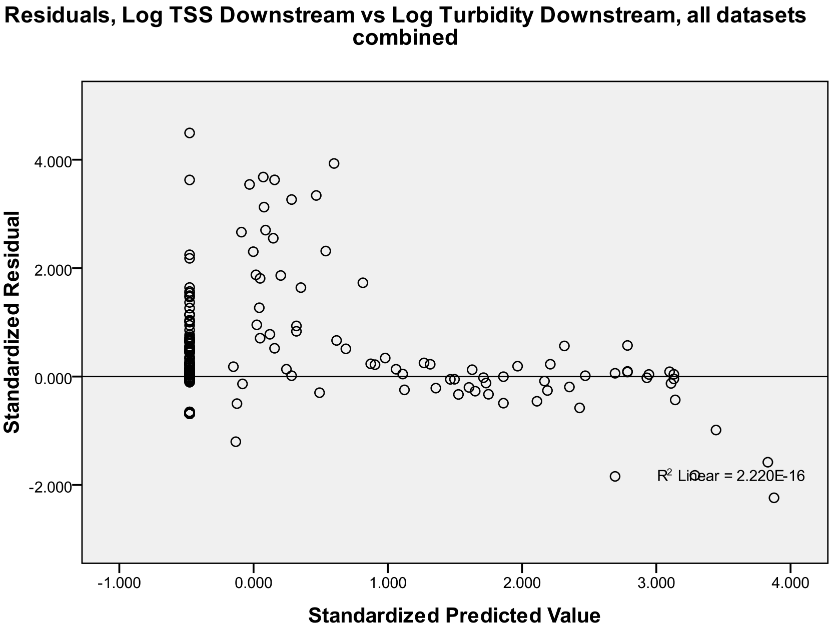


Figure 23 - TSS vs Turbidity, Cottonwood Creek downstream, both limbs of hydrograph, all datasets combined, with residuals plot





APPENDICES

Appendix A- Monthly Climate Summary Data

Seeley Lake Ranger Station Climate Station, Montana

Period of Record Monthly Climate Summary

Period of Record: 10/16/1936 to 12/31/2008

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	30.1	37.5	44.3	54.0	63.9	71.3	82.0	81.5	70.7	57.3	39.9	31.1	55.3
Average Min. Temperature (F)	9.0	12.8	18.6	26.9	34.4	40.7	43.5	41.8	35.5	29.6	21.7	13.2	27.3
Average Total Precipitation (in.)	2.56	1.77	1.43	1.25	1.87	2.31	1.08	1.12	1.40	1.40	2.26	2.48	20.93
Average Total SnowFall (in.)	32.4	19.0	15.0	3.3	0.8	0.1	0.0	0.0	0.0	1.8	17.0	30.7	120.1
Average Snow Depth (in.)	18	22	17	3	0	0	0	0	0	0	3	10	6

Percent of possible observations for period of record:
Max. Temp.: 99.2%, Min. Temp.: 99.2%, Precipitation: 98.7%, Snowfall: 98.6%, Snow Depth: 96.8%.

Ovando 9 SSE Station Climate Station, Montana
Period of Record Monthly Climate Summary

Period of Record: 8/15/1976 to 6/30/2009

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Avg Max. Temp (F)	29	34	44	55	63	71	80	80	69	56	39	29	54
Avg Min. Temp (F)	6	9	19	25	32	39	42	40	31	23	15	6	24
AvgTotal Precip (in.)	0.8	0.6	0.6	0.8	1.8	1.8	1.1	1.1	1.1	0.8	1.0	0.9	12
AvgTotal SnowFall (in.)	8.5	5.3	4.2	1.4	0.3	0.1	0	0.1	0.4	1.6	5.5	9	36
AvgSnow Depth (in.)	5	5	1	0	0	0	0	0	0	0	1	3	1

Percent of possible observations for period of record:
Max. Temp.: 98.7%, Min. Temp.: 98.5%, Precipitation: 98.1%, Snowfall: 94%, Snow Depth: 86.4%.

Appendix B - Regional flood frequency equations for West Region, MT (Omang 1992)

Regression equation	Standard error of prediction (%)
$Q_2 = 0.042A^{0.94}p^{1.49}$	52
$Q_5 = 0.140A^{0.90}p^{1.31}$	47
$Q_{10} = 0.235A^{0.89}p^{1.25}$	45
$Q_{25} = 0.379A^{0.87}p^{1.19}$	45
$Q_{50} = 0.496A^{0.86}p^{1.17}$	46
$Q_{100} = 0.615A^{0.85}p^{1.15}$	48

A = basin area in square miles
P = annual precipitation, in inches

Appendix C – Peak Streamflow Data for NF Blackfoot River above Dry Gulch, near Ovando, MT

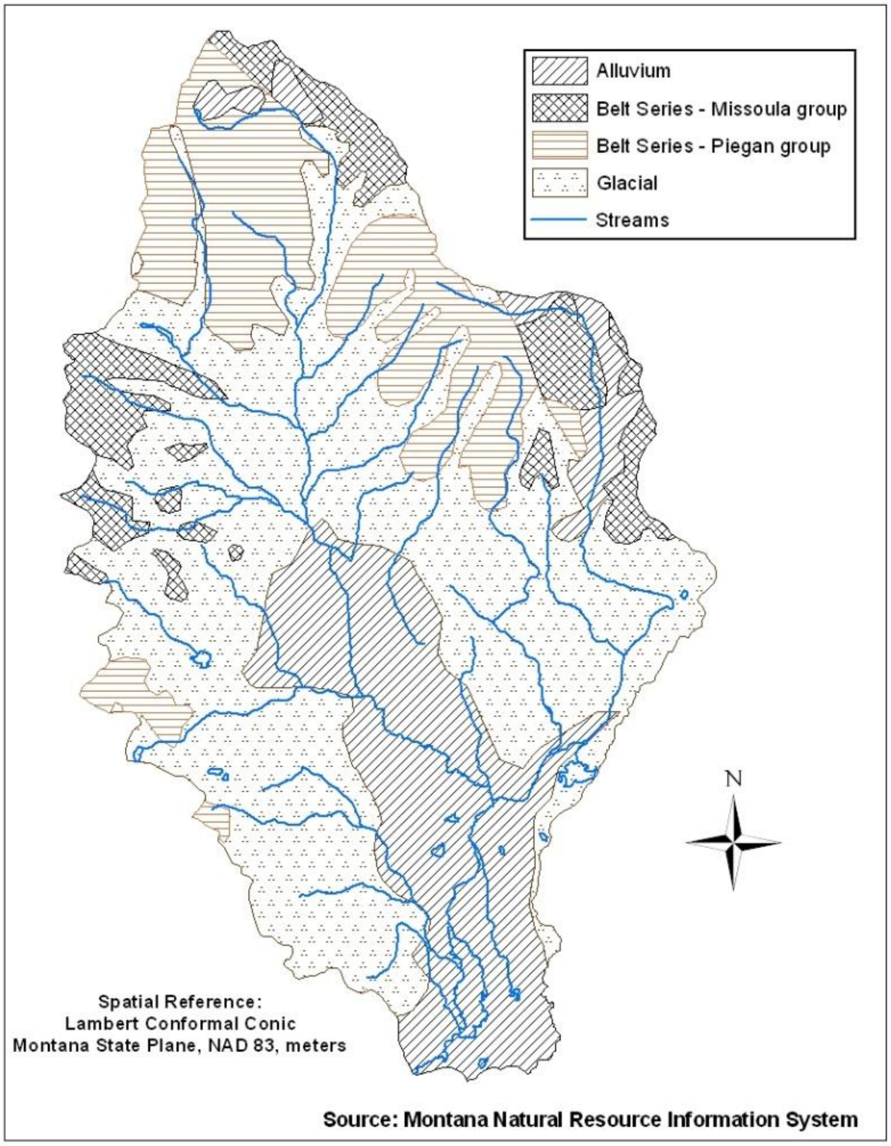
Peak Date	**Streamflow (cfs)**	**Rank**	**Recurrence Interval**
5/26/1999	4280	1	12
5/20/2002	4020	2	6
5/19/2008	**3870**	**3**	**4**
5/30/2003	3770	4	3
5/21/2006	3240	5	2.4
5/3/2007	**2370**	**6**	**2**
6/20/1998	2260	7	1.7
5/17/2005	1950	8	1.5
5/8/2004	1860	9	1.3
5/15/2001	1670	10	1.2
5/4/2000	1590	11	1.1

n = 11

$$\textbf{Recurrence Interval (T)} = \frac{\textbf{Number of events (n) + 1}}{\textbf{Rank (m)}}$$

Source: USGS, no date (a) and Dunne and Leopold (1978)

Appendix D - Geology of the Cottonwood Creek Watershed



Source: Montana Natural Resource Information System

Appendix E - How ISCO Probes were Located

The best locations for automated sampler probes are just above the downstream end of a pool, where the stream flows over the crest to the riffle below the pool. The crest provides a control area with relatively uniform sediment and discharge (Thomas, 1985). While there were appropriate locations downstream, there were no pools in the corresponding upstream area due to aggradation creating a low gradient riffle area. Therefore, a riffle was chosen for the downstream probe to match the upstream probe location.

One ISCO sampler probe was placed approximately 50 feet upstream, and one 50 feet downstream of the stream crossing. A consideration in ISCO sampler probe location was the mixing zone for the downstream sampler probe. Based on guidelines from the Montana Department of Environmental Quality (Montana DEQ), the mixing zone was estimated to be 40 feet downstream of the culvert (MT DEQ, 2007). The sampler probes were located 50 feet upstream and downstream of the culvert, a balance between the mixing zone and appropriate stream channel location criteria. The probes were located in similar areas of the stream for both snowmelt years.

Appendix F - How the Detection Limits for Suspended Sediment and Turbidity were Determined

There are various methods for determining the detection limit for water quality samples, and the methods described in the U.S. EPA (1986), were chosen because they are referenced frequently in other agency literature, such as the Wisconsin Department of Natural Resources laboratory certification program (Wisconsin DNR, 1996) and the U.S. Geological Survey (Oblinger-Childress et al, 1999). Therefore, the methods from U.S. EPA (1986) were used for determining detection limits for suspended sediment and turbidity.

A detection level is the smallest amount that can be detected above the noise in a procedure that is within a certain confidence level (APHA, 1998). Data below the detection level are called “nondetects” or “censored data” (Helsel, 2005). The Method Detection Limit (MDL) is described as: “the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero and is determined from analysis of a sample in a given matrix containing the analyte” (U.S.EPA, 1986).

To find the MDL, first, a laboratory standard is prepared which is within the same concentration range as the estimated detection limit. This is recommended to be between one to five times this estimated detection limit (U.S.EPA, 1986). A standard solution of low concentration is used rather than a blank solution because it is generally impractical to measure noise in repetitive blank samples (Oblinger-Childress et al, 1999). A minimum of seven aliquots of the sample are taken to calculate the MDL and are processed through the complete analytical process.

To compute the MDL, the standard deviation of the replicate measurements is then calculated. Then the student's t value for a 99% confidence interval level and a standard deviation estimate with n-1 degrees of freedom is found by consulting a student's t value table (U.S.EPA, 1986):

MDL = $t(n-1, 1-\alpha=0.99)$ x (Standard Deviation)
where:
MDL = the method detection limit
$t(n-1, 1-\alpha=.99)$= the students' t value for a 99% confidence level with standard deviation estimate of n-1 degrees of freedom.

An assumption of the MDL is that the data has a normal distribution. Another assumption is that the frequency distribution of successively lower concentration replicates (and thus the standard deviation of the replicates) will become constant at some level of low concentration and will remain constant down to zero concentration (Oblinger-Childress et al, 1999).

These assumptions do not always hold (Oblinger-Childress et al, 1999). In addition, a sample with a true concentration equal to the MDL has a 50% chance of being a false negative (Oblinger-Childress et al, 1999). Therefore, due to the limitations of the MDL method, many laboratories set quantification limits at concentrations greater than the MDLs, which add a little more confidence in the detection limit (Oblinger-Childress et al, 1999).

There is more than one way to set this quantitation limit. Practical Quantitation Limits (PQL) are five to ten times the MDL (Oblinger-Childress et al, 1999). The Limit of Quantitation is ten times the standard deviation of the results of a series of replicates used to determine the MDL (Wisconsin DNR, 1996). For this thesis, the LOQ will be used as the detection limit.

Suspended Sediment LOQ

Because suspended sediment samples are so variable, it is not possible to acquire a known laboratory standard as is done with other water quality pollutants, such as phosphorus or nitrates. Therefore, two of the actual suspended sediment samples containing very low levels of sediment were chosen as a “standard” for the purposes of calculating the MDL. Once these samples were filtered onto a filter, they were dried and weighed ten consecutive times to determine their standard deviation.

The MDL was calculated as the product of the standard deviation multiplied by the Student t-value based on a sample size of ten and a 99% confidence interval. The MDL was 0.002 grams/liter. The LOQ was determined by multiplying the standard deviation by ten, which was 0.006 gram. Each sample’s suspended sediment weight was compared with this LOQ value of 0.006 gram to see if they were below or above the detection limit. Samples below 0.006 were given the value of 0.003 (one-half the LOQ).

Turbidity LOQ

The LOQ for turbidity was not determined during turbidity analysis due to operator error; the LOQ determination was done later, at which time there were no longer any turbidity samples available from the culvert upgrade site. Instead, a one liter bottle was used to collect water from the Clark Fork River in Missoula during fall baseflows. Turbidity was run on a subsample of this sample using the methods described in Section 3.a.2. of the thesis. A subsample was taken from the larger one liter sample and ran in the turbidimeter ten times, gently inverting the subsample in between runs. The same subsample was used in each of the ten runs, rather than replacing it in the one liter bottle and taking a new sample. This was done in order to measure the variability of the turbidimeter readings for a particular sample, rather than measuring the variability of different subsamples of a larger sample.

Four different turbidity analyses were done at varying dilutions of the subsamples in order to capture a variety of low turbidities (one sample ranged between 8.8 and 13.4 NTUs, the second ranged between 7.1 and 8.8 NTUs, the third ranged from 1.0 to 1.8 NTUs, and the fourth sample ranged between 0.9 and 1.1 NTUs).

The MDL was calculated as the product of the standard deviation multiplied by the Student t-value based on a sample size of ten and a 99% confidence interval. The average of the four samples was 2.1 NTUs. The LOQ was determined by multiplying the standard deviation by ten; this was done for each of the four samples, and the average of these taken, which was 5.3 NTUs. Each turbidity sample, for each of the snowmelt years and the upgrade, were compared with this LOQ value of 5.3 NTUs to see if they were below or above the detection limit. Those below 5.3 NTUs were given the value of 2.7 NTUs (one-half the LOQ).

Appendix G - Determining if there is a Difference between Upstream and Downstream Sediment Loads, Spring 2007, using Wilcoxon Sign Rank Test Methods for N < 50

First, the difference between upstream and downstream pairs was calculated and all zero values were deleted. N was the number of nonzero values. The absolute values of the differences were ranked in increasing order. The sign of the difference (positive or negative) was applied to each rank, and the positive and negative ranks were each summed. The test statistic was the sum of the negative ranks. This value was compared to a critical value in a Critical values for the Wilcoxon signed-rank test table in Ott and Longnecker (2001), based on the number of nonzero values and the alpha value for a one-tailed test. Ho was rejected if the value of the test statistic was less than or equal to the critical value. The table below shows the results:

Wilcoxon Sign Rank Results for Sediment Load, Spring Snowmelt 2007

DS	US	Difference	Rank of Absolute Difference	Sign	sum of positives (T+)	sum of negs (T-)
25	133	-108	16.0	neg		16.0
108	111	-4	1.0	neg		1.0
61	89	-28	10.0	neg		10.0
72	28	44	14.5	pos	14.5	
28	28	0	none			
27	27	0	none			
30	30	0	none			
25	25	0	none			
25	25	0	none			
25	25	0	none			
24	24	0	none			
23	23	0	none			
23	23	0	none			
25	25	0	none			
25	25	0	none			
24	53	-29	11.0	neg		11.0
24	16	8	4.5	pos	4.5	

DS	US	Difference	Rank of Absolute Difference	Sign	sum of positives (T+)	sum of negs (T-)
25	16	8	4.5	pos	4.5	
60	16	44	14.5	pos	14.5	
58	35	23	8.5	pos	8.5	
60	19	41	13.0	pos	13.0	
29	19	10	6.5	pos	6.5	
30	20	10	6.5	pos	6.5	
58	18	40	12.0	pos	12.0	
16	16	0	none		none	
16	16	0	none		none	
16	16	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
15	15	0	none		none	
14	14	0	none		none	
41	18	23	8.5	pos	8.5	
12	18	-6	2.5	neg		2.5
12	18	-6	2.5	neg		2.5
			SUM		93.0	43.0

N = 16 (the number of non-zero differences)

Test statistic is the sum of negative values = 43

This is a one-sided test with alpha = .05

Critical value statistic = 35

Reject Ho if T- is less than or equal to 35

43 is not less than or equal to 35, so fail to reject Ho

Appendix H-Annual WEPP Model Runs for Stream Crossing Replaced with a Bridge; Modeled for a Ten-Year Period for both Pre- and Post- Replacement

Pre- or Post- rep	**Road slope**	**Road length & width**	**Fill slope & length**	**Buffer slope & length**	**Rainfall runoff (in)**	**Snowmelt runoff (in)**	**Road prism erosion (lbs)**	**Buffer erosion (lbs)**	**Road prism + buffer erosion (lbs)**	**Road prism + buffer erosion (kg)**
Pre	2%	142 ft & 18 ft	40% & 10 ft	0.30% & 1 ft	0.6 in	0.6 in	99 lb	70 lb	169 lbs	77 kg
Post	2%	12 ft & 18 ft	0.3% & 1 ft	0.30% & 1 ft	0.08 in	0.08 in	7 lb	0.4 lb	7 lbs	3 kg

These parameters are the same for each scenario:

Climate Station, Soil, % Rock in Road Surface, Road Surface & Traffic, Road Design, & Precipitation.

Climate Station: SEELEY LAKE RS MT 22.55 +
Soil: Silt Loam
% Rock: 20%
Road Surface & Traffic: Native & High
Road Design: Insloped, Vegetated
Precipitation: 23 inches annually

Appendix I - Regression Outputs for Log Transformed TSS versus Discharge, Upstream and Downstream, Spring Snowmelt 2007

Upstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.35[a]	.13	.10	.17

a. Predictors: (Constant), logdischarge (2007 snowmelt)

b. Dependent Variable: logTSS_US (2007 snowmelt)

Upstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.08	.19		.42	.67
	Log_discharge	.35	.15	.35	2.30	.03

a. Dependent Variable: logTSS_US, 2007 snowmelt)

Downstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.20[a]	.04	.01	.17

a. Predictors: (Constant), Discharge (spring 2007)

b. Dependent Variable: logTSS_DS

Downstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.30	.20		1.52	.14
	Log_discharge	.19	.15	.20	1.24	.22

a. Dependent Variable: logTSS_DS (spring 2007)

Appendix J- Regression Outputs for Log Transformed TSS versus Log Transformed Discharge, Upstream and Downstream, Spring Snowmelt 2008 (Falling Limb Only)

Upstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.00[a]	.00	-.01	.33

a. Predictors: (Constant), logDischarge (spring 2008)

b. Dependent Variable: log_US_TSS

Upstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.63	.94		.67	.51
	logDischarge	.03	.69	.00	.04	.97

a. Dependent Variable: log_US_TSS (spring 2008)

Downstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.02[a]	.00	-.01	.29

a. Predictors: (Constant), logDischarge (spring 2008)

b. Dependent Variable: log_DS_TSS

Upstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.54	.82		.66	.51
	logDischarge	.08	.60	.02	.13	.90

a. Dependent Variable: log_DS_TSS

Appendix K- Regression Outputs for Log Transformed TSS vs Log Transformed Discharge, Upstream and Downstream, Entire Hydrograph, Spring Snowmelt 2008

Upstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.36[a]	.13	.12	.33

a. Predictors: (Constant), logdischarge

b. Dependent Variable: logTSS_US_08_both

Upstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.16	.11		1.44	.15
	logdischarge	.46	.09	.36	5.49	.00

a. Dependent Variable: logTSS_US_08_both

Downstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.53[a]	.28	.28	.60

a. Predictors: (Constant), logdischarge

b. Dependent Variable: logTSS_DS_08_both

Downstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.80	.20		-3.95	.00
	logdischarge	1.38	.16	.53	8.91	.00

a. Dependent Variable: logTSS_DS_08_both

Appendix L - Regression Outputs for TSS vs Turbidity, All Time Frames Combined

Upstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.87[a]	.75	.75	10.08

a. Predictors: (Constant), Turbidity Upstream

b. Dependent Variable: TSS Upstream

Upstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4.60	.72		-6.40	.00
	Turbidity Upstream	3.83	.13	.87	29.71	.00

a. Dependent Variable: TSS Upstream

Downstream Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.83[a]	.69	.69	.52

a. Predictors: (Constant), Log_Turbidity_DS

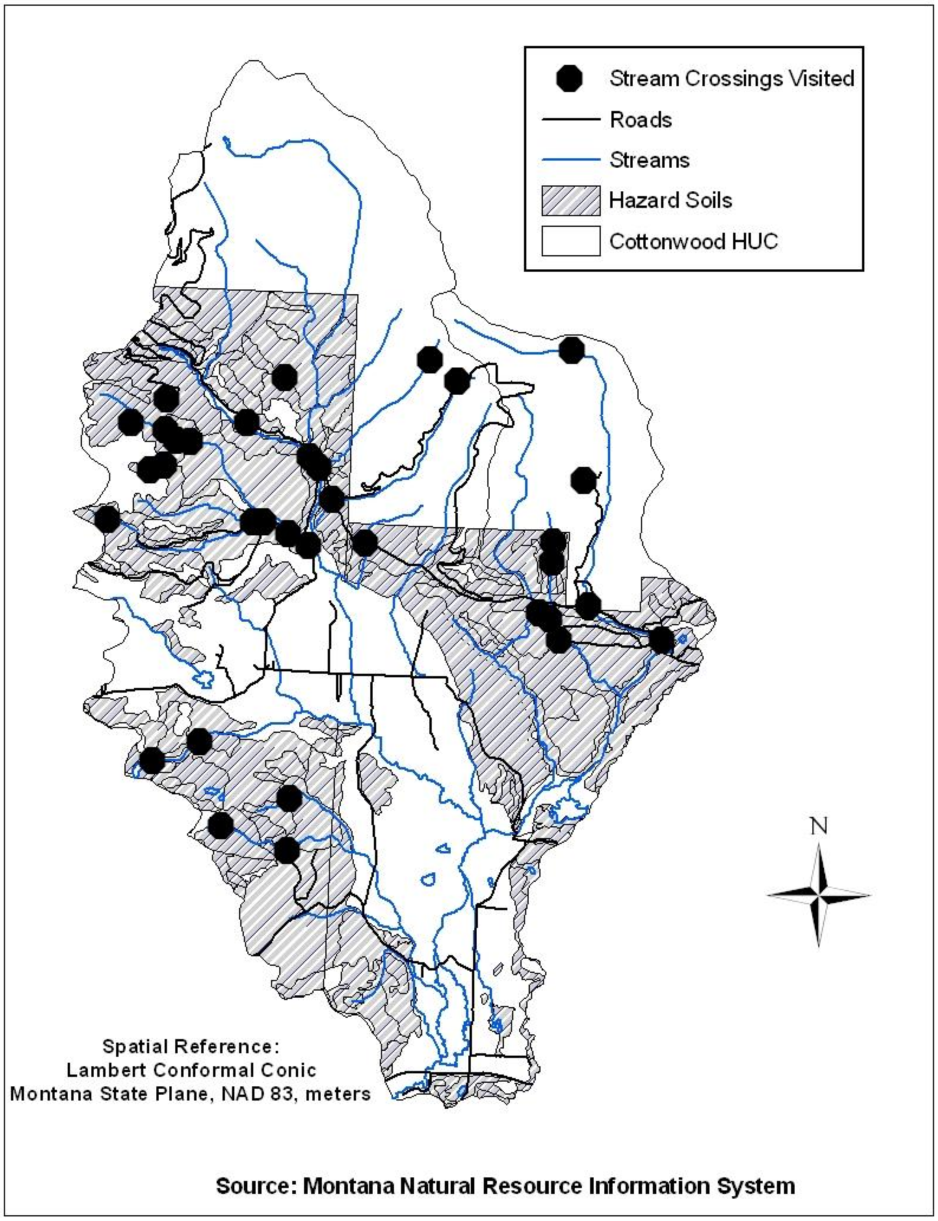
b. Dependent Variable: Log_TSS_DS

Downstream Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.44	.04		10.63	.00
	Log_Turbidity_DS	.87	.03	.83	25.93	.00

a. Dependent Variable: Log_TSS_DS

Appendix M-Map of High Risk Soils and Stream Crossings Field Visited



Source: Montana Natural Resource Information System

Note: The northern boundary of the hazard soils is the northernmost boundary of the soils surveys conducted by USDA agencies in Cottonwood Creek; wilderness areas lie north of this soils survey periphery, which have not been surveyed.

Appendix N - Regression Equation Results for Peak Flows at Various Return Intervals (Omang, 1992)

Site	Basin Area (sq miles)	-1 SE	Q2	+1 SE	-1 SE	Q5	+1 SE	-1 SE	Q10	+1 SE	-1 SE	Q25	+1 SE	-1 SE	Q50	+1 SE	-1 SE	Q100	+1 SE	Culvert Diam (in)	Predicted Capacity (cfs)	Culvert capacity>peak flow?	Return flows culvert fails at
AA	0.15	1	2	3	2	3	5	3	5	7	3	6	9	4	8	11	5	9	13	24	16	yes	
BB	0.10	1	1	2	1	2	3	2	3	5	2	4	6	3	5	8	3	6	9	36	44	yes	
CC	0.18	1	2	3	2	4	6	3	5	8	4	7	11	5	9	13	5	11	16	36	44	yes	
DD	0.19	1	2	4	2	4	6	3	6	8	4	8	11	5	9	14	6	11	16	24	16	yes	
EE	0.51	3	6	9	5	10	15	8	14	20	10	18	26	12	22	32	13	26	38	24	16	no	Q25 & up
FF	1.65	8	18	27	16	29	43	22	39	57	28	50	73	33	60	88	36	69	103	36	44	no	Q25 & up
GG	0.87	5	10	15	9	17	24	12	22	32	16	29	42	19	35	51	21	40	59	24	16	no	Q5 & up
HH	0.13	1	2	2	2	3	4	2	4	6	3	5	8	4	7	10	4	8	12	24	16	yes	
II	0.59	3	7	10	6	12	17	9	16	23	11	20	30	13	25	36	15	29	43	24	16	no	Q10 & up
JJ	0.19	1	2	4	2	4	6	3	6	8	4	8	11	5	9	14	6	11	16	24	16	yes	
KK	0.22	1	3	4	3	5	7	4	7	9	5	9	13	6	11	16	6	12	18	24	16	yes	
LL	0.07	0	1	1	1	2	3	1	2	3	2	3	5	2	4	6	2	5	7	24	16	yes	
MM	0.09	1	1	2	1	2	3	2	3	4	2	4	6	3	5	7	3	6	9	24	16	yes	
NN	1.93	10	20	31	18	34	50	25	45	65	32	57	83	37	69	101	41	79	117	24	16	no	Q2 & up
2	0.19	1	2	4	2	4	6	3	6	8	4	8	11	5	9	14	6	11	16	18	7	no	Q25 & up
4	13.44	61	127	192	103	194	285	140	254	368	171	310	450	198	367	536	214	412	610	20	10	no	Q2 & up
1	0.27	2	3	5	3	6	8	4	8	11	6	10	15	7	13	19	8	15	22	18	7	no	Q10 & up
12	0.81	4	9	14	8	15	23	11	21	30	15	27	39	18	33	48	20	38	56	18	7	no	Q2 & up
13	0.26	1	3	5	3	6	8	4	8	11	6	10	15	7	12	18	7	14	21	20	10	no	Q50 & up
14	4.63	22	47	71	39	74	109	54	98	143	68	123	178	79	147	215	87	166	246	24	16	no	Q2 & up
15	5.20	25	52	79	44	83	121	60	109	158	75	136	197	88	162	237	96	184	272	24	16	no	Q2 & up
16	1.18	6	13	20	12	22	32	16	29	42	21	37	54	24	45	66	27	52	77	55	130	yes	

Site	Basin Area (sq miles)	-1 SE	Q2	+1 SE	-1 SE	Q5	+1 SE	-1 SE	Q10	+1 SE	-1 SE	Q25	+1 SE	-1 SE	Q50	+1 SE	-1 SE	Q100	+1 SE	Culvert Diam (in)	Predicted Capacity (cfs)	Culvert capacity>peak flow?	Return flows culvert fails at
17	1.74	9	19	28	16	31	45	23	41	60	29	52	76	34	63	92	38	72	107	36	44	no	Q25 & up
18	0.32	2	4	6	4	7	10	5	9	13	7	12	17	8	15	22	9	17	25	37	49	yes	
20	4.91	24	49	75	42	78	115	57	104	150	71	129	187	83	155	226	91	175	259	24	16	no	Q2 & up
21	4.70	23	47	72	40	75	111	55	100	144	68	124	180	80	149	217	88	169	250	24	16	no	Q2 & up
22	5.29	25	53	80	44	84	123	61	111	160	76	138	200	89	165	241	97	186	276	35	44	no	Q2 & up
A1	0.04	0	1	1	1	1	2	1	1	2	1	2	3	1	2	4	2	3	4	24	16	yes	
A2	0.14	1	2	3	2	3	5	2	4	6	3	6	8	4	7	11	4	9	13	31	30	yes	
A3	0.16	1	2	3	2	4	5	3	5	7	4	7	10	4	8	12	5	10	14	35	44	yes	
A4	0.61	3	7	11	6	12	18	9	16	23	12	21	31	14	26	38	15	30	44	43	72	yes	
A5	0.18	1	2	3	2	4	6	3	5	8	4	7	11	5	9	13	5	11	16	39	52	yes	
9	1.07	6	12	18	11	20	29	15	27	39	19	34	50	23	42	61	25	48	71	45	74	yes	
10	0.53	3	6	9	6	11	16	8	14	21	10	19	27	12	23	33	14	26	39	67	200	yes	

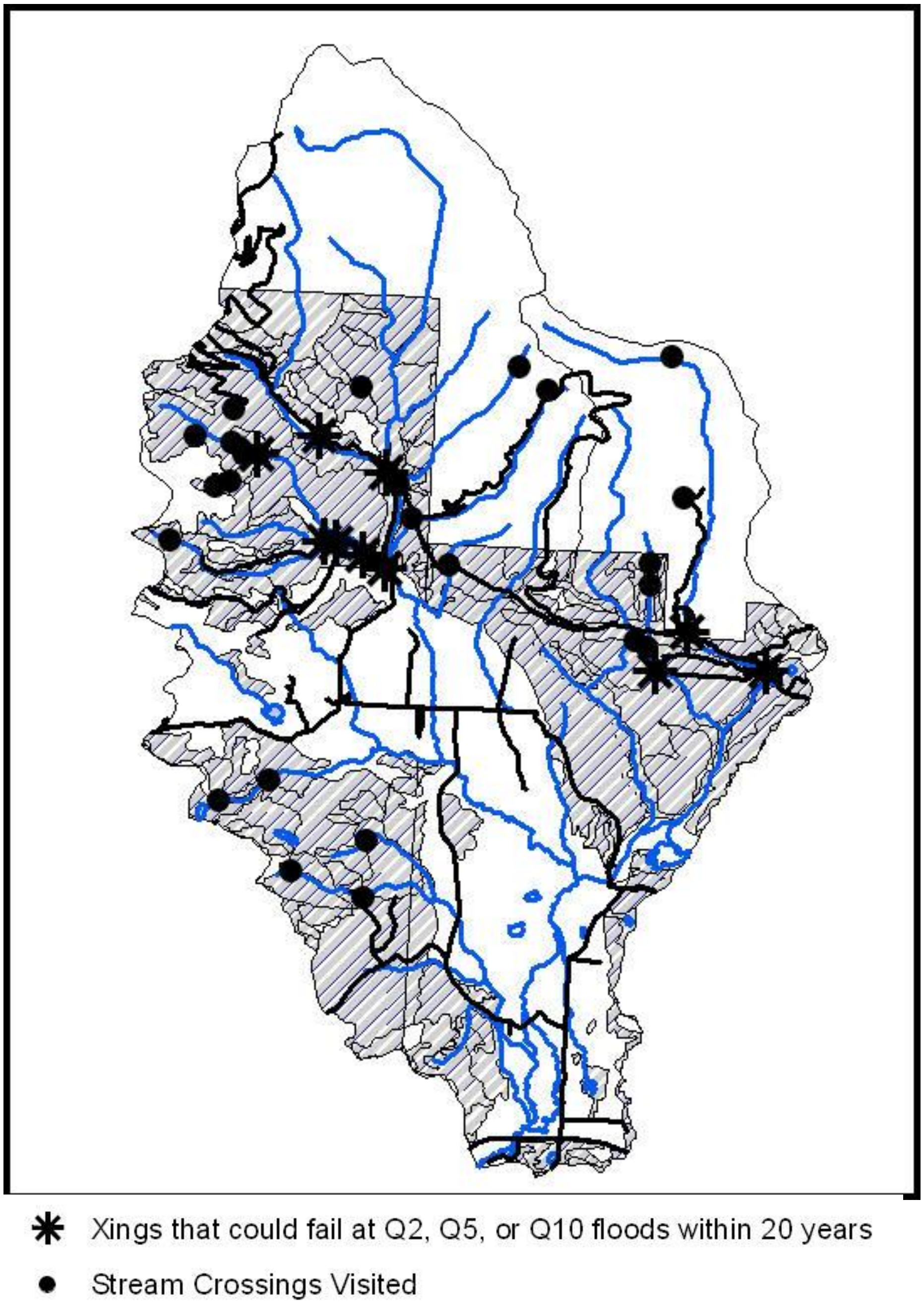
22 out of 34 sites were below the range for basin area; basin area parameters were developed for basins that were larger than most of the ones in this study.
Annual Precipitation for all sites was 42 inches.

Appendix O- Load Calculations from Crossings where Culvert Capacity is less than Q2,Q5, and Q10 over the Next 20 Years

Site	**Total fill volume (m^3)**	**Bulk density (kg/m^3)**	**Load from fill (kg)***	**Basin area (ha)**
GG	6.84	1500	10,260	225
NN	1.69	1500	2,535	500
4	54.15	1500	81,225	3481
1	17.83	1400	24,962	70
12	15.01	1500	22,515	210
14	8.05	1500	12,075	1199
15	18.51	1500	27,765	1347
20	16.19	1500	24,285	1272
21	20.4	1400	28,560	1217
22	129.56	1500	194,340	1370
		TOTAL	**428,500 kg (470 tons)**	**10,900 ha**

***Total fill volume x Bulk density = Load from fill**

Appendix P-Map of Stream crossings Surveyed as part of the Thesis with a High Probability of Failure in the Next 20 Years*



***** The northern boundary of the hazard soils is the northernmost boundary of the soils surveys conducted by USDA agencies in Cottonwood Creek; wilderness areas lie north of this soils survey periphery, which have not been surveyed.

Appendix Q-WEPP Parameters used in WEPP Model

Climate: the Seeley Lake climate station at the Seeley Lake Ranger Station was selected.
Soil Texture: the Silt Loam option was selected.
Road Design: “Insloped, vegetated or rocked ditch,” or “Outsloped, unrutted” were the two options chosen, depending on the stream crossing.
Rock Percent: 20% was chosen.
Road Surface: “Native” was selected.
Traffic Level: High, low, or none was chosen.
Seven choices concerning road, fill, and buffer gradient and length, and road width: the choices were: Road gradient, Road Length, Road width, fill gradient, fill length, buffer gradient, and buffer length. The developer of the WEPP model recommended setting buffer gradient and length to the minimum possible because the buffer is generally negligible (Elliot, 2008).
Years to simulate: The model was run for ten years.

Appendix R-Annual WEPP Model Runs for each Stream Crossing Assessed (Modeled for a Ten Year Period)

Erosion results are annual rates

Site	**Surface & traffic**	**Design**	**Road gradient**	**Road length**	**Road width**	**Fill gradient (%)**	**Fill length (ft)**	**Buffer gradient (%)**	**Buffer length (ft)**	**Precip (inch)**	**Runoff from rainfall (in)**	**Runoff from snowmelt (in)**	**Road prism erosion (lbs)**	**Sediment leaving buffer (lbs)**	**Road prism + buffer erosion (lbs)**	**Road prism + buffer erosion (kg)**
Site AA	native low	outsloped unrutted	3%	328 ft	11 ft	95%	15 ft	0.30%	1 ft	23.15 in	0.06 in	2.59 in	41.37	11.81	53.18	23.93
Site BB	native low	outsloped unrutted	5%	328 ft	11 ft	95%	24 ft	0.30%	1 ft	23.15 in	0.07 in	2.39 in	45.02	20.79	65.81	29.61
Site CC	native low	outsloped unrutted	3.50%	328 ft	19 ft	110%	40 ft	0.30%	1 ft	23.15 in	0.08 in	2.29 in	71.25	79.28	150.53	67.74
Site CC	native none	outsloped unrutted	3.50%	328 ft	19 ft	100%	39 ft	0.30%	1 ft	23.15 in	0.03 in	1.91 in	85.46	16.09	101.55	45.70
Site DD	native none	outsloped unrutted	3.50%	240 ft	11 ft	100%	8 ft	0.30%	1 ft	23.15 in	0.06 in	3.10 in	35.65	5.1	40.75	18.34
Site HH	native low	insloped vegetated	4%	36 ft	12 ft	110%	15 ft	0.30%	1 ft	23.15 in	0.18 in	3.58 in	5.27	2.89	8.16	3.67
Site II	native low	insloped vegetated	4.80%	115 ft	13 ft	100%	22 ft	0.30%	1 ft	23.15 in	0.51 in	4.56 in	27.85	25.72	53.57	24.11
Site JJ	native low	insloped vegetated	1%	59 ft	16 ft	100%	26 ft	0.30%	1 ft	23.15 in	0.19 in	3.54 in	7.16	9.2	16.36	7.36
Site KK	native low	insloped vegetated	0.30%	3 ft	1 ft	110%	15 ft	0.30%	1 ft	23.15 in	0.00 in	1.51 in	0	0	0	0.00
Site LL	native low	insloped vegetated	0.30%	3 ft	1 ft	100%	52 ft	0.30%	1 ft	23.15 in	0.03 in	1.42 in	0	0	0	0.00

Site	Surface & traffic	Design	Road gradient	Road length	Road width	Fill gradient (%)	Fill length (ft)	Buffer gradient (%)	Buffer length (ft)	Precip (inch)	Runoff from rainfall (in)	Runoff from snowmelt (in)	Road prism erosion (lbs)	Sediment leaving buffer (lbs)	Road prism + buffer erosion (lbs)	Road prism + buffer erosion (kg)
Site MM	native high	insloped vegetated	0.75%	180 ft	13 ft	50%	19 ft	0.30%	1 ft	23.15 in	0.82 in	5.03 in	53.64	34.27	87.91	39.56
Site NN	native none	insloped vegetated	0.30%	3 ft	1 ft	50%	6 ft	0.30%	1 ft	23.15 in	0.00 in	1.82 in	0	0	0	0.00
Site 2	native none	insloped vegetated	1.50%	315 ft	12 ft	75%	8 ft	0.30%	1 ft	23.15 in	1.44 in	5.77 in	32.54	17.41	49.95	22.48
Site 4	native high	insloped vegetated	2.50%	513 ft	14 ft	120%	12 ft	0.30%	1 ft	23.15 in	1.62 in	5.92 in	181.05	313.84	494.89	222.70
Site 12	native low	insloped vegetated	0.30%	3 ft	1 ft	40%	6 ft	0.30%	1 ft	23.15 in	0.00 in	1.86 in	0	0	0	0.00
Site 13	native low	insloped vegetated	0.30%	3 ft	1 ft	50%	10 ft	0.30%	1 ft	23.15 in	0.00 in	1.72 in	0	0	0	0.00
Site 14	native low	outsloped unrutted	10%	407 ft	11 ft	90%	12 ft	0.30%	1 ft	23.15 in	0.19 in	3.65 in	81.54	26.81	108.35	48.76
Site 15	native low	outsloped unrutted	4%	66 ft	17 ft	100%	14 ft	0.30%	1 ft	23.15 in	0.12 in	3.24 in	14.48	8.22	22.7	10.22
Site 16	native high	insloped vegetated	2%	344 ft	20 ft	105%	11 ft	0.30%	1 ft	23.15 in	1.46 in	5.78 in	162.15	208.35	370.5	166.73
Site 17	native high	insloped vegetated	3%	420 ft	20 ft	100%	62 ft	0.30%	1 ft	23.15 in	0.68 in	4.87 in	222.09	898.36	1120.45	504.20
Site 18	native high	insloped vegetated	4%	900 ft	23 ft	90%	19 ft	0.30%	1 ft	23.15 in	1.72 in	5.99 in	729.18	1361.44	2090.62	940.78
Site 9	native low	insloped vegetated	2%	555 ft	26 ft	100%	72 ft	0.30%	1 ft	23.15 in	0.75 in	4.98 in	91.56	1844.61	1936.17	871.28

Site	Surface & traffic	Design	Road gradient	Road length	Road width	Fill gradient (%)	Fill length (ft)	Buffer gradient (%)	Buffer length (ft)	Precip (inch)	Runoff from rainfall (in)	Runoff from snowmelt (in)	Road prism erosion (lbs)	Sediment leaving buffer (lbs)	Road prism + buffer erosion (lbs)	Road prism + buffer erosion (kg)
Site 10	native high	insloped vegetated	1%	30 ft	24 ft	105%	12 ft	0.30%	1 ft	23.15 in	0.17 in	3.61 in	18.88	5.86	24.74	11.13
Site 20	native low	outsloped unrutted	1%	114 ft	15 ft	105%	13 ft	0.30%	1 ft	23.15 in	0.07 in	2.81 in	17.5	6.02	23.52	10.58
Site 21	native high	insloped vegetated	2%	300 ft	21 ft	98%	11 ft	0.30%	1 ft	23.15 in	1.39 in	5.73 in	153.53	172.18	325.71	146.57
Site 22	native high	insloped vegetated	0.30%	60 ft	25 ft	105%	19 ft	0.30%	1 ft	23.15 in	0.31 in	4.23 in	0.61	4.65	5.26	2.37
Site 1	native high	insloped vegetated	2%	270 ft	17 ft	110%	12 ft	0.30%	1 ft	23.15 in	1.31 in	5.64 in	113.72	138.8	252.52	113.63
Site A1	native low	outsloped unrutted	0.30%	3 ft	1 ft	75%	12 ft	0.30%	1 ft	23.15 in	0.00 in	1.28 in	0.03	0	0.03	0.01
Site A2	native low	outsloped unrutted	3%	135 ft	1 ft	75%	13 ft	0.30%	1 ft	23.15 in	0.00 in	1.29 in	1.52	0.07	1.59	0.72
Site A3	native low	outsloped unrutted	1%	180 ft	9 ft	100%	12 ft	0.30%	1 ft	23.15 in	0.04 in	2.41 in	16.54	3.29	19.83	8.92
Site A4	native low	outsloped unrutted	1%	150 ft	9 ft	55%	355 ft	0.30%	1 ft	23.15 in	0.04 in	1.24 in	13.79	1.08	14.87	6.69
Site A5	native high	insloped vegetated	0.30%	3 ft	1 ft	75%	17 ft	0.30%	1 ft	23.15 in	0.01 in	1.59 in	0.01	0	0.01	0.00
												TOTAL	**2,223 lbs**	**5,216 lbs**	**7440 lbs**	**3348 kg**
													1000 kg	**2350 kg**		

Note: The parameters Climate, Soil, and % Rock in Road Surface were constant for all sites.

Climate: SEELEY LAKE RS MT 22.55 +

Soil: Silt Loam **% Rock: 20%**

Average per xing in kg: 105 kg/xing

Std deviation of results (in kg): 232 kg
Range: 0-941 kg

Appendix S - Substrate and Stream Morphology Assessments

(1) Pebble Counts

Using the methods from Bundt and Abt (2001), pebble counts were conducted at the Cottonwood culvert upgrade crossing. Pebble counts were done in July, 2007 (before the upgrade) and in August, 2008 (after the upgrade). A pilot study was first done, as recommended by Bundt and Abt (2001), to determine an appropriate sample size. The pilot study was done in July, 2007, using the heel-to-toe method, with a sample size of 100 counts, and conducted just upstream and downstream of the stream crossing. An appropriate sample size reflects the amount of variation in the stream substrate; the more variation, the larger the sample size. Using methods from Bundt and Abt (2001), the sample size was calculated to be 494 pebble counts for upstream, and 386 for downstream.

For both pre-and post-upgrade pebble counts, a gravelometer was used, and the heel-toe method was used to randomly select a particle along a pre-defined transect beginning just up- and downstream of the crossing and working away from the crossing until enough particles were selected. A particle was picked up and pushed through different holes in the gravelometer until a hole was found that was too small. This “larger than” method records the largest hole size that is smaller than the particle’s diameter.

Figures A and B show the Cumulative Frequency Diagrams for upstream and downstream particle sizes, for pre- and post-upgrade data. Table A shows the D16, D50, and D84 cumulative frequencies for the data. For example, for upstream, pre-upgrade substrate, 16 percent of the particles are below 6 mm.

Figure A: Cumulative frequency particle sizes, upstream

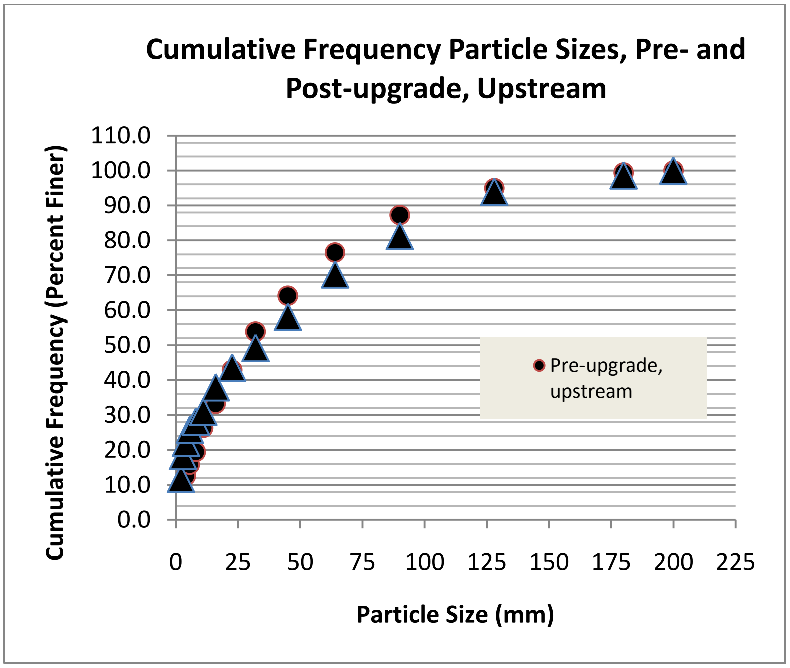


Figure B: Cumulative frequency particle sizes, downstream

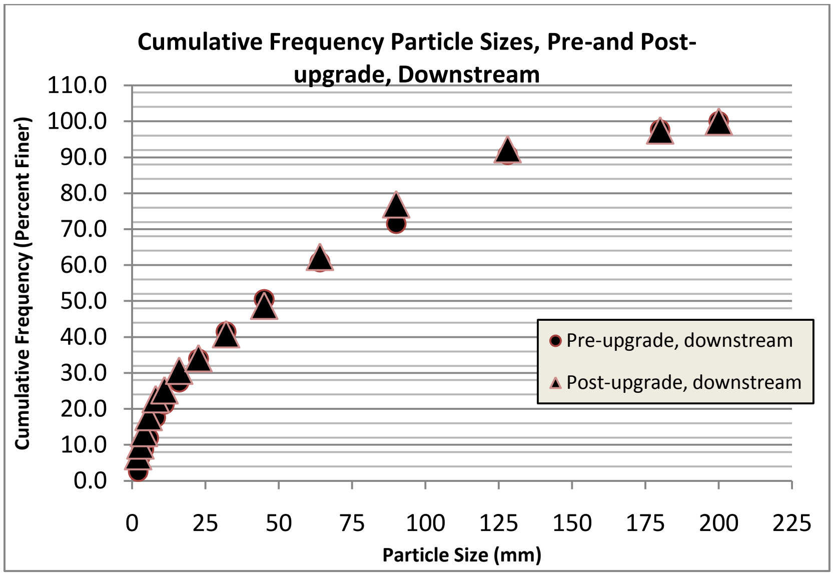


Table A: D16, D50, & D84 cumulative frequencies of particles, & percent surface fines

				Percent Surface Fines in Riffle		
Measurement Period	D16 (mm)	D50 (mm)	D84 (mm)	% <2mm[*]	% <6 mm[t]	
Upstream, pre-upgrade	6	28	87	6	16	
Upstream, post-upgrade	3	32	95	12	26	
Downstream, pre-upgrade	7	44	112	3	12	
Downstream, post-upgrade	5	47	109	7	18	

[*] Montana DEQ targets in the MBNC TMDL are ≤11 mm (MT DEQ, 2008)
[t] Montana DEQ targets in the MBNC TMDL are ≤15 mm (MT DEQ, 2008)

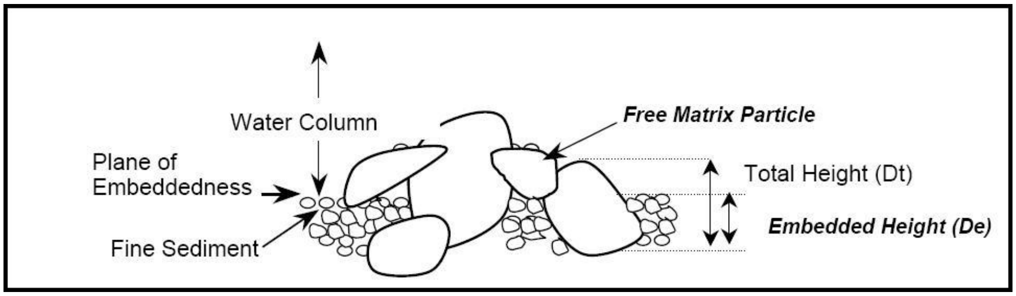
(2) Rosgen Classification

The Rosgen methodology was used to determine the stream classification at the culvert upgrade site. Measurements were taken just below and above the stream crossing, in both the summer before and after the culvert upgrade project. This area was classified as a B4 type; there was no change in classification after the culvert upgrade.

(3) Cobble Embeddedness

Cobble embeddedness measures the degree to which fine sediments surround coarse substrates on the streambed surface (Sylte and Fischenich, 2002). Cobble embeddedness measurements were done both upstream and downstream of the Cottonwood stream crossing at which the culvert upgrade was performed. Measurements were done during the summer preceding the upgrade, and the summer after the upgrade, using the Burns methodology (Sylte and Fischenich, 2002; Rowe, et al, 2003). A 60 cm hoop was randomly tossed in a riffle area in which the water velocity was between 24 and 67 cm/s, and depth between 15 and 45 cm. Within the hoop, 100 particles were randomly selected; extra hoop tosses were done if not enough particles were found in the first hoop toss.

There were two measurements taken for each particle; the total height of each particle and the depth of the particle below the plane of embeddedness were measured. Percent embeddedness for each particle was calculated as the embedded depth divided by the total height for the particle. The average of the percent embeddedness was taken to determine the overall percent embeddedness for the sample.



Sylte and Fischenich, 2002

Pre-upgrade cobble embeddedness for upstream and downstream of the crossing was 24 and 32 percent, respectively. Post-upgrade embeddedness was 32 and 29 percent for upstream and downstream, respectively. Upstream cobble embeddedness levels increased more than for downstream, the year following the culvert upgrade. This may be due to the same reasons as for the increases in pebble counts in the upstream site the year after the upgrade; bank erosion during low flows may have been a factor in increased particle fines and embeddedness.

There are few guidelines for acceptable levels of cobble embeddedness. None were found in Montana gravel-cobble streams; in fact, for several TMDL reports for Montana watersheds, no cobble embeddedness studies were done (MT DEQ website). On the Payette National Forest in Idaho, cobble embeddedness criteria were set at a five year mean below 32 percent, with no individual year above 37 percent (Idaho DEQ, 2002).