Sediment deposition below forest road drivable drain dips in Belt and glacial till parent materials of Western Montana

Brian Rawls Parker

The University of Montana

Follow this and additional works at: https://scholarworks.umt.edu/etd

Let us know how access to this document benefits you.

Recommended Citation

Parker, Brian Rawls, "Sediment deposition below forest road drivable drain dips in Belt and glacial till parent materials of Western Montana" (2005). Graduate Student Theses, Dissertations, & Professional Papers. 8288.

https://scholarworks.umt.edu/etd/8288

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
The University of Montana

Permission is granted by the author to reproduce this material in its entirety, provided that this material is used for scholarly purposes and is properly cited in published works and reports.

**Please check "Yes" or "No" and provide signature**

Yes, I grant permission

No, I do not grant permission

Author's Signature: [Signature]

Date: 5/10/05

Any copying for commercial purposes or financial gain may be undertaken only with the author's explicit consent.
SEDIMENT DEPOSITION BELOW FOREST ROAD DRIVABLE DRAIN DIPS IN BELT AND GLACIAL TILL PARENT MATERIALS OF WESTERN MONTANA

By
Brian Rawls Parker
B.A. University of Montana, 1999
B.S. University of Montana, 1999
Presented in partial fulfillment of the requirements
for the degree of
Master of Science
The University of Montana
May 2005

Approved by:

Chairperson

Dean, Graduate School

Date
Abstract

Parker, Brian Rawls, M.S., May 2005

Sediment Deposition below Forest Road Drivable Drain Dips in Belt and Glacial Till Parent Materials of Western Montana

Chairperson: Scott W. Woods

Forest roads are a primary sediment source associated with timber harvest in the western United States, and delivery of sediment from roads to streams can adversely affect water quality and fisheries. Sediment delivery to streams depends on the road erosion rate and the distance that sediment travels downslope. Many studies have quantified sediment travel distances in highly erodible parent materials such as the quartz monzonite of the Idaho Batholith, but considerably less research has been conducted in less erodible parent materials. The objectives of this study were to: i) quantify sediment travel distances below 300 drivable drain dips along logging roads in the metasedimentary Belt Series and glacial till parent materials of western Montana; and ii) develop predictive models of sediment travel distance based on site factors.

Sediment travel distance was highly variable and 32.6% of sites had a sediment travel distance of zero. The mean sediment travel distances in Belt and glacial till parent materials were 4.0 m and 3.2 m, respectively. These values are lower than those measured with a similar methodology in granitic parent material during this study, and they are also lower than values reported elsewhere from granitic sites with similar road design and drainage outfalls. Travel distances for mainline roads were up to 60% greater than for spur roads due to differences in road vegetative cover. Regression models using road segment length-slope product, hillslope roughness and road type (mainline or spur) as predictive variables explained just 23% and 11% of the variability in sediment travel distance in the Belt and till sites, respectively. The limited predictive capability of these regression models is attributed to a combination of high variability in travel distance within parent materials, highly variable climatic conditions, and limitations in the methods used to measure sediment travel distances and some of the site variables. Strong relationships between sediment travel distance and sediment plume volume were identified, and a suite of road sediment volume probability curves were developed for each parent material based on the travel distance/volume relationship. The results of this study will assist in evaluating streamside buffer widths in watersheds of similar parent material, and allow land managers to forecast road sediment yields and prioritize restoration efforts.
**Table of Contents**

Abstract ................................................................................................................................................ ii
List of Tables ........................................................................................................................................... v
List of Figures ........................................................................................................................................ vi
Acknowledgements ........................................................................................................................ vii

Introduction ........................................................................................................................................1

Study Area ..........................................................................................................................................5

Methods ................................................................................................................................................9
  Sediment Travel Distance .................................................................................................................. 9
    Sediment Travel Distance Methodology Validation ................................................................. 10
    Factors Controlling Sediment Travel Distance ........................................................................ 10
  Sediment Plume Volume .................................................................................................................. 12
  Particle Size Analysis ...................................................................................................................... 13
  Data Analysis .................................................................................................................................. 14

Results .................................................................................................................................................15
  Sediment travel distance ................................................................................................................... 15
    Sediment Travel Distance Cumulative Frequency Distribution .............................................. 17
    Sediment Travel Distance Correlation and Regression Analysis ............................................ 19
  Sediment Plume Volume .................................................................................................................. 22
    Plume Volume as a Function of Sediment Travel Distance ...................................................... 22
  Particle Size Analysis ...................................................................................................................... 26

Discussion .........................................................................................................................................28
List of Tables

Table 1. Study Township locations .........................................................................................7
Table 2. Method, precision and variables collected ..............................................................11
Table 3. Sediment travel distance data collection validation ...............................................15
Table 4. Selected descriptive statistics of collected variables .............................................16
Table 5. Summary statistics for regression analyses conducted using data from Belt Series, glacial till and combined parent materials. .................................................................20
Table 6. Regression analysis of sediment travel distance and plume volume ...................23
Table 7. Comparison of sediment travel distance and sediment plume volume by study. 29
Table 8. Sediment travel distance regression analysis comparison ....................................36
List of Figures

Figure 1. Drivable drain dip diagram .................................................................3
Figure 2. Study area location map .................................................................8
Figure 3. Sediment plume volume measurement diagram ..............................13
Figure 4. Sediment travel distance frequency distribution ..............................17
Figure 5. Cumulative frequency distribution of sediment travel distance in belt and glacial till parent materials ..................................................18
Figure 6. Mean sediment travel distance for spur and mainline roads in belt and glacial till parent materials .................................................................19
Figure 7. Sediment plume volume (m³) of Belt and glacial till parent material sample locations .................................................................22
Figure 8. Dimensionless volume and distance distribution: Belt ..................24
Figure 9. Percent volume and linear distance distribution: Belt ....................25
Figure 10. Dimensionless volume and distance distribution: glacial till .........25
Figure 11. Percent volume and linear distance distribution: glacial till ..........26
Figure 12. Percent soil texture difference between sediment plume and road tread ........27
Figure 13. Contributing road segment mean soil texture distributions ..........27
Figure 14. Sediment travel distance exceedence probability ..........................41
Figure 15. Travel distance/volume exceedence probability curves: Belt ........44
Figure 16. Travel distance/volume exceedence probability curves: glacial till ..44
Acknowledgements

I would like to take this opportunity to thank a number of people who have been instrumental in bringing this project together. First, I would like to thank Dr. Scott Woods for giving me the chance to work on the project and for fielding numerous questions and concerns regarding this project and life as a grad student. Brian Sugden, hydrologist at Plum Creek Timber Company was the force behind this project and a key component of its success. I wouldn’t have even known about this project if Paul Callahan, senior hydrologist (and now President) of Land and Water Consulting, hadn’t informed me of it. Paul has been a great boss to work for and an even better colleague with endless ideas. I appreciate the service and help of Drs. Tom DeLuca and Manny Gabet, for serving on my committee and for teaching great classes. I certainly owe my wife Erica many thanks for putting up with me for the last two years, serving as a source of encouragement and motivation and keeping me fed. Finally, all of this couldn’t have been possible if it wasn’t for the hard working guys at Tire Rama on N. Orange St. who plugged so many flat truck tires for me across two summers of driving on some of the roughest roads in Montana.

Many thanks to all of you who made this possible!
Forest roads are a primary sediment source associated with timber harvest activities in the western United States (Megahan and Ketcheson, 1996; Megahan and Kidd, 1972; Brake et al., 1997). Erosion rates are highest in the first year after road construction, when the road surface and cut and fill slopes are unvegetated and sediment availability is high (Brake et al., 1997). Erosion rates decline rapidly as sediment availability decreases and plant cover on the cut and fill slopes increases (Burroughs and King, 1989; Ketcheson and Megahan, 1996). However, erosion rates remain higher than background levels as long as roads remain in place, making them a chronic sediment source. Delivery of road-derived sediment to streams can adversely affect beneficial uses such as fisheries, water supply and recreation. Predicting sediment delivery to streams requires knowledge of the erosion rate and the sediment travel distance.

Road erosion rates depend on precipitation, parent material characteristics, road design, and the intensity and timing of road use (Packer, 1967; Reid and Dunne, 1984). Insloped, ditched roads often have a higher erosion rates than outsloped roads because ditch erosion provides an additional sediment source. Higher erosion rates occur on steeper, longer road segments due to the greater stream power associated with overland flow on the road tread. Roads that receive more use, such as mainline haul roads, have higher erosion rates because vegetation establishment on the road tread is limited and periodic grading to maintain the road surface increases sediment availability (Brake et al., 1997).

Studies conducted in granitic parent material have shown that the sediment travel distance varies with the road erosion rate, the transport capacity of road runoff, and the
amount of storage available on the hillslope (Megahan and Ketcheson, 1996). Road segments with a high erosion rate tend to have longer travel distances because of the greater volume of sediment delivered to the hillslope (Megahan and Ketcheson, 1996). Sediment fills up storage elements on hillslopes, leading to a greater cumulative travel distance. Insloped roads have higher sediment travel distances because road surface runoff is concentrated in the ditch and at drainage outfalls, providing greater transport capacity for eroded sediment (Megahan and Ketcheson, 1996). Similarly, longer, steeper road segments have longer travel distances because of the increased flow depth of the surface runoff. Hillslope roughness is an important control on sediment travel distances because of the greater amount of sediment storage available in depressions and behind rocks, branches and logs (Haupt, 1959).

Various approaches have been used to minimize the delivery of sediment from forest roads to streams. These procedures and practices are collectively referred to as Best Management Practices (BMPs) - “voluntary preferred ways to manage forest land that go beyond legally mandated Streamside Management Zones” (Logan, 2001). BMPs are intended to either reduce the basic erosion rate and the extent to which runoff is concentrated at drainage outfalls, route sediment onto hillslopes where it is more likely to be held in long term storage, or act as a physical barrier to the downslope movement of sediment. The drivable drain dip (Figure 1) is a BMP used extensively throughout western Montana to divert run-off from the road tread onto the adjacent hillslope below the road. A drain dip (Figure 1) consists of “a gentle roll in the road surface sloped to carry water from inside to outside, onto natural ground” (Logan, 2001). Drivable dips are popular because they are relatively inexpensive to install, and because they can be retro-
fitted to existing roads. Drivable dips and other road BMPs such as ditch relief culverts, open top culverts, and flapper water bars are only effective if they are located appropriately. Specifically, the sediment travel distance below the drainage outfall from the structure must be less than the distance to the nearest stream channel.

**Figure 1. Drivable drain dip diagram.**

In addition to voluntary BMPs, Montana state law requires the implementation of Streamside Management Zones (SMZs), which restrict management activities within 50 to 100 feet (depending on adjacent hillslope gradient) from "the ordinary high water mark" of the stream (*Logan, R.*, 2001). The SMZ acts as a vegetative filter strip that reduces runoff and sediment delivery to streams from the adjacent upland. However, an SMZ is only effective in reducing sediment delivery from roads if the sediment travel distance is less than the width of the SMZ. Designation of adequate SMZ widths is
therefore dependent on knowledge of sediment travel distances in a range of environments.

Similarly, federal lands within the interior Colombia River basin are subject to the Inland Native Fish Strategy (INFISH). The INFISH “calls for long-term management direction to protect habitat and populations of resident native fishes outside anadromous fish habitat” (ICBEMP, 2000). A strategy within INFISH is the use of Riparian Habitat Conservation Areas (RHCAs). RHCAs mandate a wider management exclusion zone adjacent to streams on federal lands than state based SMZ laws. RHCAs are categorized from one to four depending on the stream type and fisheries residence. Category one, the most conservative designation, is applicable to perennial fish-bearing streams and mandates a RHCA width of 300 feet. Categories two and three designate RHCA widths of 150 feet for perennial non-fish-bearing streams, and for ponds, lakes and reservoirs greater than one acre (Brassfield, 2004).

Extensive research has been conducted on road erosion and sediment travel distances in highly erodible parent materials such as the granitics of the Idaho batholith (Megahan et al. 1972, 1996, 2001; Burroughs and King, 1989), and the high precipitation and landslide prone climate of Oregon’s Coast Range (Wemple et al. 1996, 2001; Luce et al. 1999, 2001; Brake, et al. 1997). However, there has been much less comparable research in less erodible parent materials such as the Belt Series and glacial tills of western Montana. The only previous study from Montana that has been documented in the literature was by Packer (1967), who investigated road related sediment production across the Northern Rockies and developed regression equations to predict maximum road segment and travel distances for six parent materials in the region. Packer’s (1967)
identification of parameters related to erosion and sediment travel is appropriate for a coarse analysis of road sediment delivery in the Northern Rockies. However, given the current state of watershed assessments, TMDL load allocations, and environmental impact statement exercises, more precise, parent material specific sediment travel distance and volume data are needed.

The objectives of this study were to: 1) quantify sediment travel distance and plume volume below drivable drain dips along roads in Belt and glacial till parent materials in western Montana; and 2) develop regression models to predict sediment travel distance based on easily measured site physical factors. The data and analysis reported in this study should assist land managers to more accurately assess, identify, and mitigate sediment impacts from forest roads in the northern Rockies.

**Study Area**

Approximately 75% of western Montana (31.5 million km²) is underlain by rocks of the Belt Supergroup, which is primarily composed of quartzites, argillites, and limestones (Ross, 1963). These rocks are the product of low-grade metamorphism of Precambrian age deposits of sands, silts, clays, and carbonate. In the northern portion of the state the dominant parent materials are tills, outwash and lacustrine deposits left by Quaternary continental and alpine glaciers (Johns, 1970).

The study was conducted on roads in Belt and glacial till parent materials within Plum Creek Timber Company’s (PCTC) land ownership in western Montana. PCTC has an ongoing road erosion study in 17 Townships in Belt and glacial till parent materials within their Montana ownership (Brian Sugden, pers. comm., 2004). In an effort to
integrate the PCTC study with the current project, and to increase data collection efficiency, six of these Townships, three per parent material, were randomly selected for use in the present study (Figure 2, Table 1).

The vast majority of roads in the PCTC road network have a native surface, and are gently outsloped. Because of the relatively dry climate, there is typically no interior ditch and broad-based (rolling) dips are used to route overland flow from the road tread. Most of the road system is at least ten years old and the cutslopes and fillslopes are generally well vegetated. The frequency of maintenance operations varies depending on the level of use for log hauling and other forest management activities (B. Sugden, pers. comm.).

The three study Townships in the Belt Series parent material lie in the Sapphire, Garnet, and Bitterroot mountain ranges of west-central Montana (Figure 2). The three Townships range in elevation from 3300 to 6800 ft. and they are primarily within the Douglas-fir (Pseudotusga menziesii) and lodgepole pine (Pinus contorta) forest types. Parent materials in all three townships are primarily quartzite and argillite beds belonging to the Missoula Group of the Belt Supergroup (Winston, 1986). The majority of the soils within the Belt study townships are in the Winkler series, and comprise loamy-skeletal, mixed, frigid Udic Ustepts (USDA, 1995).

The area of Montana that includes the three Belt Series townships has a modified continental climate. Precipitation varies considerably with elevation; the mean annual precipitation at Missoula (elevation 3250 ft) is 13.5 inches, while at the N. Fork of Elk Creek SNOTEL site (elevation 6250 ft) located slightly north of the Belt study townships, mean annual precipitation is 28.9 inches.
<table>
<thead>
<tr>
<th>Geology</th>
<th>Location</th>
<th>Township</th>
<th>County</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt</td>
<td>Garnet</td>
<td>13N, 17W</td>
<td>Missoula</td>
</tr>
<tr>
<td>Belt</td>
<td>Sapphire</td>
<td>12N, 18W</td>
<td>Missoula</td>
</tr>
<tr>
<td>Belt</td>
<td>N. Bitterroots</td>
<td>14N, 21W</td>
<td>Missoula</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>S. Swan</td>
<td>17N, 16W</td>
<td>Missoula</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>N. Swan</td>
<td>24N, 18W</td>
<td>Lake</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>Dayton North</td>
<td>25N, 21W</td>
<td>Lake</td>
</tr>
<tr>
<td>Granitic</td>
<td>Lolo Hot Springs</td>
<td>11N, 23W</td>
<td>Missoula</td>
</tr>
</tbody>
</table>

The three Townships with glacial till parent material are located within 100 miles north of Missoula, Montana. Two of them are located on the eastern flanks of the Mission Mountains, while the third lies approximately 5 miles north of Dayton, Montana (Figure 2). Soils in the three townships are largely in the Waldbillig series, and comprise loamy-skeletal, mixed Andic Cryepts. These soils formed from glacial till deposited by the Pinedale glacial episode (glacial maximum occurred 15,000 years ago), and many of them have an ash cap resulting from volcanic activity in the Pacific Northwest (USDA, 1995).

Elevation in the three glacial till Townships range from 3400 to 6400 feet. The two Townships in the Mission/Swan area have a modified maritime influenced climate, whereas the Dayton site has a modified continental climate typical of west-central Montana. Annual average precipitation in these areas range from 15.0 inches at Polson to 28.6 inches at Swan Lake. The forest types in the Townships reflect their contrasting
climate. The Mission/Swan Townships have a spruce-fir (*Picea* and *Abies* series) forest type, with lush understory vegetation while the Dayton site is comprised predominately of Douglas-fir forest types.

**Figure 2. Study area location map.**

Summers for all of the study townships are typically hot and dry with occasional convective storms. Winters are typically cold, though not extreme, with average maximum January temperatures near 29 degrees Fahrenheit (-2° C). Streamflow is largely snowmelt dominated. The annual maximum snow water equivalent occurs in
April, and annual peak flows occur during snowmelt in May or June. Smaller peak flows can occur in response to convective and frontal storms during the summer and fall.

**Methods**

**Sediment Travel Distance**

Sediment travel distances were measured at 50 drivable drain dips within each Township, for a total of 300 measurement locations. Drain dips were randomly selected from the population of all dips on PCTC roads within each township. A GIS was used to randomly select sixty road segments in each township, ranging in length from less than 10 meters to hundreds of meters. Road segments were visited in the order designated by the random selection process, and a maximum of five drain dips was surveyed in each road segment. If a road segment contained more than five dips, the first five dips encountered traveling upslope were surveyed. The majority of drain dips in the study area were installed between five (1998) and fifteen (1988) years prior to this study. Drain dips sampled for sediment travel distance were visited during the summer months of 2003 and 2004.

Sediment travel distance below each dip was defined as the straight-line distance from the toe of the road fillslope to the lower limit of observable sediment deposition. The lower limit of deposition was defined by excavating with a hand trowel along the axis of the plume until alluvial deposits of road sediment above a buried O or A horizon were no longer visible.
Sediment Travel Distance Methodology Validation

Similar studies of sediment travel distances have focused on granitic parent materials of the Idaho batholith in central Idaho. Data comparison with these previous studies was used to validate the sample methodology of the present research. An additional township within the Idaho batholith was sampled using methods analogous to those described for the Belt and glacial till sites to determine if the methodology used in the present study provided similar results to those obtained in previous studies (specifically, Ketcheson and Megahan (1996)). The measurements were obtained from 50 rolling dips along the roads in a township (11N, 23W, Missoula Co. 4400-4900 ft.) in the upper Lolo Creek watershed near the Montana – Idaho border. This location has similar habitat-type structure to that described by Ketcheson and Megahan (1996) though Lolo Pass SNOTEL (5600 ft.) indicates elevated annual precipitation amounts (48 inches) relative to those reported in central Idaho (35 inches).

Factors Controlling Sediment Travel Distance

Eight independent variables were measured at each sample site to determine the factors controlling the sediment travel distance (Table 2).
Hillslope roughness (R) was defined in accordance with (Morgan, et al. 1993) as:

$$R = \left( \frac{M - S}{M} \right) \times 100$$

M = ground microtopographic distance (m)

S = straight line distance (m)

The ground microtopographic distance (M) was measured along the axis of the plume and included rocks, sticks, and logs that were in contact with the ground surface. Low growing bunch grasses were included in the measurement but live woody-stemmed understory vegetation was not included due to its minimal effect on sediment storage and overland flow.
Sediment Plume Volume

Sediment plume volume, as a function of distance along the sediment plume, was measured at ten sample sites within the study townships. Measurements capture sediment plume volume since the time of dip installation. The sediment plume volume was determined using a simplified version of the process described by Ketcheson and Megahan (1996). At each sample location, the sediment plume length was measured with a tape to the nearest 0.1m. The sediment plume length was then divided equally along its longitudinal axis into ten lateral sub-groups or “slices”, thus slice width was determined (Figure 3). Both ends of each slice were determined and delineated in a manner analogous to the determination of sediment travel distance. Slice length, measured orthogonally to the longitudinal axis of the plume, was correspondingly determined. Each of the ten plume slices was then equally divided into six “cells”, divided parallel to the plume long axis. At the center of each cell the depth of deposited road sediment was measured and recorded. Measurements (cm) were made from the plume surface to the top of the buried O or A horizon in a 1.75 cm diameter soil core. Total plume volume estimates were calculated by the summation of intra-slice cell volumes.
Particle Size Analysis

Sediment samples from the contributing road surface and the corresponding sediment plume were collected at the ten sediment plume volume sample locations to ascertain the change in sediment particle size distribution between road tread and sediment plume. These data were used to evaluate the percentage of fines transported beyond the measured plume length. Particle size analysis was conducted using the modified hydrometer method (Gee and Bauder 1986).
Data Analysis

Sampling locations were stratified by parent material and by road type and an analysis of variance (ANOVA) was used to determine whether there were significant differences in sediment travel distance between sites in the Belt Series and glacial till or between sites on mainline haul roads and spur roads. Sediment travel distance was normalized using a log_{10} transformation. Normality was defined as skewness and kurtosis values between – 1.1 and 1.1.

Multiple-regression was used to assess the effect of the eight independent variables (Table 2) and two generated variables: 1) the contributing road length-slope product (LS) and 2) length-slope squared (LS^2) -- on the sediment travel distance in each parent material. These variables were included in the analysis because previous studies (Luce and Black, 1999) have indicated that they can be a more significant predictor of sediment travel distance than length or slope alone.

Variable selection for multiple regression analysis was based on a two step process. First, Pearson correlation analysis was used to identify the variables that were significantly correlated with sediment travel distance. Only significant variables (P < 0.05) were included in the second step of the selection process, in which variables that were correlated with each other were identified. Only the most significant variable in a group of correlated variables was included in the model. The variables identified from this two-step procedure were then incorporated into the multiple regression modeling, which used a step-wise approach.
Results

Sediment travel distance

Sediment travel distances measured in the granitic parent material ranged from zero to 28.7 m with a mean of 5.36 m. These values are similar to those obtained in previous studies (Table 3) indicating that the methodology used for the present study is valid, and that comparisons with studies conducted elsewhere are appropriate.

Table 3. Sediment travel distance data collection validation.

<table>
<thead>
<tr>
<th>Study</th>
<th>Geology</th>
<th>Variable</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Study</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>0 – 28.7</td>
<td>5.36</td>
<td>6.33</td>
</tr>
<tr>
<td>Ketcheson &amp; Megahan, 1996 (fills)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>0.4 – 66.1</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Ketcheson &amp; Megahan, 1996 (rock drains)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>1.2 – 33.9</td>
<td>8.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Sediment travel distances in Belt and glacial till parent materials were highly variable and were log normally distributed due to a high proportion of sites where the sediment travel distance was zero (Figure 4). Sixty six percent of the Belt Series sites had a travel distance of zero, and the maximum travel distance was 58.2 m. All but one of the sites had a travel distance of less than 24 m. In the glacial till sites, 58 % had a travel distance of zero, and the maximum travel distance was 33.4 m. Due to the high number of sites with a travel distance of zero, the mean sediment travel distances are relatively small: 4.0 m for the Belt Series and 3.2 m for the glacial till sites (Table 4). These mean values were less than the mean for the granitic sites in the present study, and they were
also less than the mean sediment travel distance reported for rock drains in granitic terrain by Ketcheson and Megahan (1996).

Table 4. Summary statistics for sediment travel distance, contributing segment length and segment slope for sites in granitic, Belt Series and glacial till parent materials.

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Mean</th>
<th>Sample Variance</th>
<th>n</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till Total sediment travel distance (m)</td>
<td>0 - 33.4</td>
<td>3.19</td>
<td>25.65</td>
<td>147</td>
<td>5.06</td>
<td>0.42</td>
</tr>
<tr>
<td>Belt Total sediment travel distance (m)</td>
<td>0 - 58.2</td>
<td>3.97</td>
<td>39.62</td>
<td>138</td>
<td>6.29</td>
<td>0.53</td>
</tr>
<tr>
<td>Granitic sediment travel distance (m)</td>
<td>0-28.7</td>
<td>5.36</td>
<td>40.1</td>
<td>50</td>
<td>6.33</td>
<td>0.98</td>
</tr>
<tr>
<td>Till Contributing segment length (m)</td>
<td>10.0 - 254.4</td>
<td>72.48</td>
<td>1741.84</td>
<td>147</td>
<td>41.74</td>
<td>3.44</td>
</tr>
<tr>
<td>Belt Contributing segment length (m)</td>
<td>19.6 - 416.4</td>
<td>126.7</td>
<td>6329.95</td>
<td>138</td>
<td>79.56</td>
<td>6.8</td>
</tr>
<tr>
<td>Till Combined segment slope (%)</td>
<td>1 - 16</td>
<td>5.8</td>
<td>9.87</td>
<td>147</td>
<td>3.14</td>
<td>0.26</td>
</tr>
<tr>
<td>Belt Combined Segment Slope (%)</td>
<td>1 - 15</td>
<td>6.32</td>
<td>12.78</td>
<td>138</td>
<td>3.57</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Due to the variability in sediment travel distance data, a cumulative frequency distribution plot is a more useful planning tool than the mean sediment travel distance (Burroughs and King, 1989). Presentation of the data in this format shows that the majority of the sample population in both parent materials is confined to a minority of the surveyed sediment travel distance range (Figure 5). Specifically, 80% of drain dips had sediment travel distances of less than 5 m and 95% of drain dips had sediment travel distances of less than 10 m.
Sediment travel distances in the two parent materials were not significantly different (P>0.05). However, spur roads had a significantly (P < 0.05) lower mean sediment travel distance than mainline roads in both parent materials (Figure 6). Spur roads in Belts had almost five times the average road tread vegetation cover when compared to mainline roads. In glacial tills, spur roads had over three times the mean vegetative cover. Road tread vegetation cover is the only variable (in addition to sediment travel distance) that is significantly (P < 0.01) different between mainline and spur roads in Belts (Table A3). In the glacial till sites, road tread vegetation cover and road segment slope (in addition to sediment travel distance) are significantly different (P < 0.01) between mainline and spur roads (Table A4).
Sediment Travel Distance Correlation and Regression Analysis

A log-10 transformation was used to normalize sediment travel distance values. The log-transformation of sediment travel distance was not entirely normalized, but the absence of multi-collinearity (VIF = 1.03, 1.15, and 1.02 tolerance = 0.98, 0.85, and 0.94 for Belts, tills, and combined datasets respectively) (Table 5), as well as the satisfactory behavior of the residuals (Figures A1, A2) justifies the log transformation.

The continuous independent variables included in the correlation and regression analyses were elevation (E meters), vegetation cover (V %), segment length (L meters), segment slope (S %), road shape (SHAPE), fillslope slope (FILL %), roughness index
(RI), the length slope product (LS meters), the length-slope squared product (LS² meters) and the log-10 transformations of RI (log RI), L (log L) and LS (log LS). Road type (ROAD) was included as a categorical variable where a value of 1 represents a mainline road and 2 represents a spur road.

In the Belt Series sites, the variables E (P = 0.027), V (P = 0.038), L (P = 0.005), log L (P = 0.003), S (P=0.047), SHAPE ( P = 0.001), log RI (P = 0.008), LS (P=0.002), LS² (P = 0.003) and log LS (P = 0.019) were all significantly correlated with the logarithm of sediment travel distance. Most of the independent variables representing road length and slope were correlated with one another, so that only LS was used in the step-wise regression modeling. The resulting model:

\[ \log_{10}(STD) = 0.977 + 0.226 \times 10^{-4} (LS) - 0.174 \text{ (ROAD)} - 0.289 \log RI \]

is significant (P < 0.001) and explains 23 % of the variance in sediment travel distance (Table 5).

<table>
<thead>
<tr>
<th></th>
<th>R²</th>
<th>Adj R²</th>
<th>N</th>
<th>Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt</td>
<td>0.31</td>
<td>0.26</td>
<td>140</td>
<td>0.309</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>0.13</td>
<td>0.11</td>
<td>148</td>
<td>0.343</td>
</tr>
<tr>
<td>Combined</td>
<td>0.18</td>
<td>0.16</td>
<td>288</td>
<td>0.330</td>
</tr>
</tbody>
</table>

The site variables obtained from the till sites had considerably less predictive capability than those in the Belt Series sites. Only S (P = 0.037) and log LS (P = 0.045) were significantly correlated with the logarithm of sediment travel distance. Segment
slope (S) was omitted from the multiple regression model because it was significantly correlated with LS and was a less significant predictor of sediment travel distance. Consequently, the only variables included in the regression analysis for till sites were road type and log LS. The resulting model

\[
\log_{10}(\text{STD}) = 1.013 - 0.282 \text{ (ROAD)}
\]

is significant (P = 0.001) but it explains just 11% of the variability in sediment travel distance.

Due to the low predictive capability of the regression model for the till sites, and the fact that sediment travel distances in the Belt and till sites were not significantly different, the data from both parent materials were combined into a single data set for additional regression analysis. Correlation analysis for this data set indicated that E (P = 0.057), V (P = 0.020), L (P = 0.020), log L (P = 0.025), S (P = 0.004), SHAPE (P = 0.001), LS (P = 0.005), LS^2 (P = 0.005) and log LS (P = 0.003) were all significantly correlated with sediment travel distance. The transformed variables representing segment length and slope were mostly correlated with one another so that only log LS was included in step wise regression modeling. The resulting model:

\[
\log_{10}(\text{STD}) = 1.009 - 0.196 \text{ (ROAD)} + 1.500 \log \text{LS} - 0.285 \log \text{RI}
\]

is significant (P < 0.001) and explains 16% of the variability in sediment travel distance.
Sediment Plume Volume

Sediment plume volumes were generally small, with 70% of the plumes containing less than 0.5 m$^3$ of road derived sediment; the mean volumes were 1.4 m$^3$ for Belts and 0.4 m$^3$ for glacial tills (Figure 7). The higher mean Belt value was largely due to the effect of one site, which had a measured plume volume of 6.2 m$^3$. The higher plume volume at this site was apparently related to the road segment being insloped with a 90° curve. This road segment behaved similarly to a road with a ditch relief culvert configuration and caused run-off to concentrate and erode the large volume of sediment. This site also had one of the longest sediment travel distance values, ___ m.

Figure 7. Sediment plume volume (m$^3$) of Belt and glacial till parent material sample locations.

Plume Volume as a Function of Sediment Travel Distance

Normalized cumulative plume volume was significantly correlated with normalized cumulative sediment travel distance for sites in both parent materials (Table
6). Similarly strong correlations were also obtained when actual cumulative plume volume was plotted against actual sediment travel distance. Although all of the correlations were significant, the relationships were stronger for the Belt series sites than in the glacial till sites.

Table 6. Regression analysis of sediment travel distance and plume volume.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>r²</th>
<th>sig.</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt Dimensionless distance (forced fit)</td>
<td>0.98</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
<tr>
<td>Belt Dimensionless distance</td>
<td>0.97</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
<tr>
<td>Belt Linear Travel distance</td>
<td>0.998</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
<tr>
<td>Till Dimensionless distance (forced fit)</td>
<td>0.84</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
<tr>
<td>Till Dimensionless distance</td>
<td>0.74</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
<tr>
<td>Till Linear travel distance</td>
<td>0.99</td>
<td>P &lt; 0.001</td>
<td>5</td>
</tr>
</tbody>
</table>

Sediment plume volume rapidly diminished with increasing distance from the fillslope toe. Plots of the normalized cumulative sediment volume versus normalized cumulative plume distance show that the majority of the plume volume occurs in the upper half of the plume. Figures 8 and 10 illustrate that the majority of eroded road sediment is deposited and stored on the hillslope, a short distance (relative to total plume length) below the fillslope toe. The trendlines of figures 9 and 11 are very similar. The Belt has a slightly steeper slope indicating a small increase in sediment storage per unit length of sediment plume in Belt materials. Granitics data (Ketcheson and Megahan, 1996) from the central Idaho batholith have a steeper slope than in the Belt, suggesting increased sediment deposition per length of sediment plume. For example, in the Belts sites, 80% of the sediment plume volume was deposited in the first 50% of plume length,
whereas in the glacial till sites, 75% of the sediment plume was deposited in the first 50% of plume length; in granitics approximately 84% of the plume volume was deposited in the first 50% of plume length. Possible explanations for the diversity of curves include differences in sediment particle density and/or differences in hillslope roughness elements. Soil textural analysis of the sediment plume volume sites indicate a higher mean proportion of silt and clay size particles within the glacial till sites (Figure 14), though no significant differences were found using independent sample t-test ($P > 0.05$).

**Figure 8. Dimensionless belt sediment volume and distance distribution.**
Figure 9. Percent Belt volume and linear distance distribution.

Figure 10. Dimensionless glacial till volume and distance distribution.
Particle Size Analysis

Particle size distributions differed between the plume and the road tread in both parent materials (Figure 13). In four of the five Belt series sites, there was an overall decrease in the proportion of clay in the plume sediment sample relative to the road tread sample, while there was no change in the fifth sample. The proportion of clay in samples from the plume in Belt Series sites was significantly less than the samples from the road tread ($P<0.05$, Table A2). Three of the five samples taken from the glacial till sediment plumes contained less clay than the road tread sample, but the overall means were not significantly different. The reduction in clay content of the plume samples relative to the road tread in seven of the ten samples collected suggests that fine sediment is being carried beyond the visible extent of the plume.
Figure 12. Percent soil texture difference between sediment plume and road tread.

*Positive values note an increase of this percent of textural class in plume relative to related road tread.

Figure 13. Contributing road segment mean soil texture distributions.
Discussion

Sediment Travel Distance

Previous studies have reported sediment travel distances ranging from zero to almost 200 meters, and mean travel distances of between 3.8 and 19.2 meters (Table 7). The sediment travel distances measured in the present study are at the lower end of this range, with mean values in the Belt, till and granite sites of 4.0, 3.2 and 5.4 meters respectively. Differences between the mean sediment travel distances obtained in this study and those observed elsewhere can be attributed to differences in the parent material characteristics, climate, the type of road drainage structure evaluated, and the age and usage level of the roads in the study area.
Table 7. Comparison of sediment travel distance and sediment plume volume by study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Geology</th>
<th>Variable</th>
<th>Range</th>
<th>Mean</th>
<th>Sample Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Study</td>
<td>Belt</td>
<td>STD (m)</td>
<td>0 - 58.2</td>
<td>3.97</td>
<td>0.53</td>
<td>6.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume (m³)</td>
<td>0.07-6.21</td>
<td>1.42</td>
<td>7.19</td>
<td>2.68</td>
</tr>
<tr>
<td>Current Study</td>
<td>Till</td>
<td>STD (m)</td>
<td>0 - 33.4</td>
<td>3.19</td>
<td>25.65</td>
<td>5.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume (m³)</td>
<td>0.12-0.56</td>
<td>0.039</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>Current Study</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>0 – 28.7</td>
<td>5.36</td>
<td>40.1</td>
<td>6.33</td>
</tr>
<tr>
<td>Haupt, 1959 (cross ditch)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>1-112.5</td>
<td>19.27</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Burroughs &amp; King, 1989 (culverts)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>0 - 194.8</td>
<td>38.7</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ketcheson &amp; Megahan, 1996 (fills)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>0.4 – 66.1</td>
<td>3.8</td>
<td>N/A</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume (m³)</td>
<td>0.003-30.7</td>
<td>0.2</td>
<td>N/A</td>
<td>5.9</td>
</tr>
<tr>
<td>Ketcheson &amp; Megahan, 1996 (rock drains)</td>
<td>Granitic</td>
<td>STD (m)</td>
<td>1.2 - 33.9</td>
<td>8.7</td>
<td>N/A</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume (m³)</td>
<td>0.03-3.4</td>
<td>0.3</td>
<td>N/A</td>
<td>3.8</td>
</tr>
<tr>
<td>Brake et al., 1997 (culverts)</td>
<td>Sand / Siltstone</td>
<td>STD (m)</td>
<td>0 - 23.2</td>
<td>5.09</td>
<td>20.04</td>
<td>4.48</td>
</tr>
<tr>
<td>(rd &gt; 5yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brake et al., 1997 (culverts)</td>
<td>Sand / Siltstone</td>
<td>STD (m)</td>
<td>1 - 40.1</td>
<td>9.33</td>
<td>129.36</td>
<td>11.37</td>
</tr>
<tr>
<td>(rd &lt; 5yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Effect of Parent Material Characteristics**

Contrary to expectations, sediment travel distances in the Belt and glacial till parent materials were not significantly different. Previous studies have shown that under similar climatic conditions, erosion rates in glacial till are higher than in metasedimentary rocks, and this would be expected to translate into a similar contrast in sediment travel distances. The similarity in travel distances in the two parent materials in this study may be partly due to the similar particle size distributions in the road tread materials (Figure 14). Belt series road treads contained more sand than glacial till treads, and the tills had a
higher composition of silts and clays, but the only significant difference was in clay content.

The mean travel distances in Belt series and glacial till parent materials were less than the mean travel distance in the granitic parent material township and less than comparable previous studies of sediment travel distances in granitics (Table 7). This difference likely reflects lower erosion rates in the Belt series and glacial till parent materials of western Montana compared to granitics in this region and elsewhere in the Pacific Northwest. Both Belt and glacial till soils in western Montana contain a high proportion of coarse fragments and this reduces the erodibility of the road surface by creating a natural armoring effect (B. Sugden, unpublished data). In contrast, granitic parent materials are highly erodible and weather to form sandy soils that are inherently vulnerable to erosion.

Differences in climate may further explain the low erosion rates obtained in this study relative to other areas. In western Montana, the relative lack of summer rainfall along with the fact that as much as 70 % of the precipitation falls as snow, means that annual erosivity is relatively low, and this has the effect of lowering the erosion rate and the sediment travel distance from roads in all parent materials. For example, roads in glacial till in western Montana produced an average of 4.7 Mg ha\(^{-1}\) y\(^{-1}\) of sediment (B. Sugden, unpublished data) while roads in glacial outwash in rain-dominated southwest Washington, which receives over 50 inches of rain per year, produced 55-60 Mg ha\(^{-1}\) y\(^{-1}\).
Effect of Road Drainage Structure Characteristics

This study focused on sediment travel distances below rolling dips, which are widely used throughout western Montana as an effective road drainage structure. However, other road drainage systems are often used depending on the local climate and geology, and individual agency and private landowner BMP requirements. The effect of differences in the road drainage structure on sediment travel distance can be assessed by comparing studies of sediment travel distances in granitic parent materials. The mean sediment travel distance obtained for granitic parent material in the present study (5.4 meters) is considerably less than the values obtained for sediment plumes below drainage culverts in granitic terrain by Ketcheson and Megahan (1996) and Burroughs and King (1989). The increased sediment travel distance below ditch relief culverts can be attributed to increased stream power and velocity of road runoff when runoff is confined to the road-side ditch and culvert due to reduced roughness and increased hydraulic radius. Additionally, ditch relief culvert outlets, if properly installed, will be placed at the fillslope toe which effectively increases “channel” slope, and hence velocity. Increased velocity at the culvert outlet, generated by increased slope and hydraulic radius, leads to increased travel distance of suspended road sediment. In contrast, runoff routed to a drain dip is typically impeded by vegetation and debris on the road shoulder and fillslope. These impediments effectively increase surface roughness and reduce the velocity, leading to deposition before the run-off reaches the hillside below the fillslope.

In addition, the roads included in our study were almost entirely outsloped roads, which distribute flow over a larger area thus reducing flow depth and effectively increases surface roughness, reduces velocity and shear stress due to a reduced hydraulic
radius, and increased boundary resistance. While isolated areas of “confined” flow occur in the form of minor road tread rilling and/or rutting from vehicular passage, these locations are diffuse across the study area. Additionally, the contributing area to these “channels” is significantly less than the entire road tread as in the insloped road design. The net effect is a reduction in sediment travel distance below drain dips compared to a culvert outfall in the same geologic and climatic setting. Fill slope outfalls are generally similar to rolling dips in that they do not experience the concentration of flow that occurs below culvert outfalls.

Effect of Road Type and Usage Level

Mainline roads had significantly higher sediment travel distances than spur roads in both parent materials, and the variable representing road type appears in the regression models for both Belt and till sites. The significance of road type reflects differences in road usage level which lead to differences in the amount of vegetation cover on the road tread, and the frequency of grading. Vegetation cover on the road surface serves a number of functions that assist in erosion reduction, principally to reduce raindrop energy and associated soil particle displacement (Wischmeier and Smith, 1958). Vegetation also provides increased surface roughness, which reduces flow velocities. Velocity reductions diminish discharge (Q) and correspondingly stream power (Ω) by the relationship $\Omega = \gamma Qs$ (where $\gamma$ = the specific weight of water, $Q$ = discharge, and $s$ = slope), and this reduces erosivity and competence of a runoff event. Infiltration capacity also likely increases as plants expand rooting zones that serve to aerate and de-compact the road surface. Finally, given enough vegetative cover and sufficient time, soil organic matter
development may occur and correspondingly increase soil water holding capacity, which will reduce the probability of overland flow for a precipitation event of a given magnitude (Horton, 1945).

Since spur roads are usually not entered extensively between harvest cycles, vegetative cover establishes on the road tread. In contrast, mainline roads are traveled frequently in order to access spur roads that are being used for current harvest activities, and vegetation cover is reduced. In this study, spur roads in Belts had almost five times the average road tread vegetation cover when compared to mainline roads. In glacial tills, spur roads had over three times the mean vegetative cover. Vegetation cover was the only site variable that was significantly different between road types in the two parent materials, suggesting that it is the primary reason for the contrasting sediment travel distances.

Another factor related to road type and usage levels is the frequency of grading. More frequent grading is required on more heavily used roads to maintain the travelway and avoid the formation of ruts. Road grading essentially returns the road tread to a condition similar to that following construction. These situations are characterized by minimal vegetation and a disturbed road tread, which breaks up the compacted road surface, reducing shear strength of the road based soil particles, thus promoting particle entrainment and erosion at reduced shear stresses. Grading frequency was not included as a variable in the present study. However, grading removes the vegetation cover on the road surface, so the amount of vegetation cover is an appropriate surrogate for grading frequency. The difference in vegetation cover between mainline and spur roads, and the
corresponding difference in sediment travel distances is likely due in part to more frequent grading of mainline roads.

Regression Analysis

Significant independent variables in the regression models for Belt and till series parent materials were the length-slope product (LS), hillslope roughness, and road type. The effects of road type were discussed previously, and the effect of the other significant variables is discussed below.

The influence of the length-slope product on sediment travel distance is grounded in the previously described relationships of increased velocity, competence, and stream power with increasing slope and length. This positive relationship leads to increasing erosion and sediment transport with increasing bead (road tread) length and slope. Brake et al. (1997) also found LS to be a significant predictive variable. Luce and Black (1999), tested LS, but found LS² to produce a model of superior strength, reflecting the fact that slope generally has a greater effect on road erosion and sediment travel distances than segment length.

Hillslope roughness was significantly correlated with sediment travel distance for roads in the Belt Series soils, and has been found to be an important predictor of sediment travel distances in several previous studies (Haupt, 1959; Packer (1967; Ketcheson and Megahan (1996; Brake et al., 1997). Roughness elements in contact with the ground surface, be they slash, bunch-grass, regenerative vegetation, etc., serve to impede flow, resulting in run-off ponding, reduced flow velocities, and sediment aggradation, and this leads to reduced sediment travel distances. The relationship and importance of these
factors can be assessed in relating Manning’s equation to the sixth power law of flow competence. According to Manning’s equation:

$$V = k \left( R^{2/3} s^{1/2} / n \right)$$

where $R =$ hydraulic radius; $s =$ slope; $n =$ Manning’s roughness

velocity decreases with increasing roughness ($n$). The sixth power law of flow competence:

$$c = xv^6$$

where $c =$ flow competence; $x =$ constant; $v =$ flow velocity, shows that a reduction in velocity exponentially decreases the transportable maximum particle size. A reduction in flow velocity due to increased roughness will lead to increased sediment deposition, all other factors being equal.

The regression coefficients obtained for the models in this study (23% in Belt Series, 11% in glacial tills, and 16% in the combined dataset) are considerably less than those reported in similar studies (Table 8), and this may be due in part to differences in study design and the methods used in data analysis. The model developed by Ketcheson and Megahan (1996) had the highest predictive power of any previous studies, largely because it included plume volume as a predictive variable. Our study found that plume volume was highly correlated with sediment travel distance, and inclusion of this variable in our regression model would have increased the predictive capability. However, the goal of our study was to develop models that can be used by foresters and land managers to predict sediment travel distances based on relatively easily measured site metrics. The use of plume volume as a predictive variable would be inconsistent with this goal because
it is difficult to measure and because it requires the a priori existence of a plume at the study location.

Table 8. Sediment travel distance regression analysis comparison.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fills</td>
<td>Rock Drains</td>
<td>Old Roads</td>
<td>New Roads</td>
<td></td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.26</td>
<td>0.11</td>
<td>0.52</td>
<td>0.70</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The study conducted by Packer (1967) included 25 variables in the regression model. One of the characteristics of the regression method is that the strength of the correlation may be artificially inflated by including a larger number of variables in the model than is appropriate, and this may have been the case with the Packer study. Brake et al., (1997) used a stepwise approach that reduces the potential for overparameterization of the regression model, and achieved regression coefficients approximately more than twice as high as those achieved in the present study. Brake et al (1997) used a stratified sampling approach where study sites were replicated within each of three aspects (north, south and east-west), two soil textures (coarse and fine), two USLE length slope coefficients (low and high) and two hillslope gradients (low and high). Such an approach has the advantage of ensuring that all possible combinations of site variables occur in the data set, thus improving the predictive capability.

*Unexplained Variability in Sediment Travel Distances*

Potential explanations of the low explanatory power of the models obtained from the present study include variability in erosion rates within parent materials, variable
climatic conditions among study sites, the effect of unmeasured variables such as traffic volume, and limitations in the study methodology.

This study initially used parent material as a stratification mechanism for measuring sediment travel distance in the hope that results could be applied to a large land base. However, analysis of variance of sediment travel distance of the two parent materials suggested that there is no significant difference between the two parent materials. Inter-parent material variability was investigated, but coincidently all Belt sample locations fell within the Missoula Group of the Belt Series, and correspondingly the Winkler soil series. No further soil type stratification occurred for two reasons. 1) Increasing stratification ultimately diminishes applicable utility of research findings. 2) Due to typically severe hillslope gradients of most sample locations and the corresponding height of road cut slopes, stratification finer than soil series level seemed futile. That is, at most sample locations the hillslope gradient required a large volume of material to be displaced for road construction, which resulted in the road tread being established well into the regolith, if not blasted from the bedrock. This observation ultimately devalues the influence of soil type in explaining sample variability. Regolith and soil within a specific soil series is not a homogeneous media, hence the potential for variance introduction is great. This factor combined with those described below may help explain the model weakness.

Most road erosion occurs during summer convective storms (Vincent, 1985). The combination of a large sample area within each parent material, and the isolated nature of most convective storms responsible for erosion events introduce the potential influence of climatic variation. Typically, these strong summer thunder storms produce
geographically isolated, high energy precipitation events, which generate localized particle displacement and transport. The large sample area, and sample size, may have introduced this source of variation into the dataset. Specifically, analogously configured road segments may have been exposed to significantly different precipitation events, and correspondingly, associated sediment travel distances would be equally variable. Ultimately, this type of geographically induced climatic variation may have exacerbated inherent sample variation.

Traffic volumes, influence sediment travel distance both directly and indirectly. Dataset variability may be partially explained by an inability to detect travel frequencies at an appropriate scale, or as an interaction term, to reduce or stratify this variability. For example, perhaps it is necessary to capture an interaction between travel frequency and climatic data, such as a rainfall event greater than a certain intensity in order to reduce dataset variation. This type of data can not be extrapolated from the existing dataset and would require the deployment of significant quantities of specialized equipment.

Various factors may have affected the representativeness of the sediment transport distance measurements. Sediment travel distance was measured from the toe of the fillslope so that only sediment plumes that extended beyond the road prism were included in the dataset. The disadvantage of this approach in an environment with steep slopes is that fill slopes can be a significant proportion of the total plume length extending from the edge of the road. In addition, plumes that do not extend beyond the edge of the fillslope are shown as “zero” sediment transport distances in the data set when there is in fact transport of sediment beyond the edge of the road tread.
Another factor that may have affected the measurement representativeness was that in many cases a substantial proportion of the eroded sediment remains on the road in the bottom of the rolling dip. This is especially likely to occur if the slope of the dip towards the road edge is very low, and if road grading has created a berm at the road margin. The potential for storage of sediment on the road is specific to each individual dip outfall, and cannot be predicted from the variables included in this study.

Hillslope roughness is often an important predictor of erosion rates but it had limited predictive capability in our study. The measurement of roughness variables differs between studies, each technique having individual positive and negative qualities. The roughness measure of the current research was dependent on the existence of a sediment plume. This aspect of the utilized technique is a potential vulnerability, particularly in situations with significant numbers of sample sites having travel distances of zero (no observable sediment plume). A better alternative would be to measure the distance from the toe of the fillslope to the first obstruction greater than a prescribed dimension. Using this technique, a roughness measure could be generated in situations where the sediment travel distance is zero, potentially increasing the predictive power of this variable. This approach was used successfully by Brake et al. (1997) in a similar study of road sediment travel distances.

*Comparison with SMZ and RHCA set-aside widths*

The exceedance probability curve for sediment travel distance (figure 15) provides a potentially powerful tool for examining the likelihood of sediment delivery to streams in Belt and glacial till parent materials. For example, Figure 15 shows that the
exceedence probability of sediment from drain dips in Belt Series or glacial till parent materials traveling a distance greater than the Montana SMZ width of 15 m (50 ft) is 0.05. In steeper terrain where Montana SMZ width increases to 30 m (100 ft), the probability that this distance will be exceeded is 0.02 in glacial tills and less than 0.01 in Belts. Probabilities that road sediment will travel distances greater than RHCA set aside widths of 45 m (150 feet) and 90 m (300 feet) (depending on category) are less than 0.01 in both Belt and glacial till parent materials. Since the majority of drain dips lie a considerable distance from a stream, and only a fraction of the plume volume travels the full length of the plume, the implication is that very few dips will introduce sediment to a stream. This means that it should be possible to substantially reduce sediment delivery from roads to streams by identifying and treating the relatively small number of drainage outfalls in a watershed that contribute the majority of the sediment. However, this refers to configurations where the road is parallel stream rather than a stream crossing. Road stream crossings typically have minimal buffer capacity between the road prism and the stream. Additionally, drain dips are frequently constructed near stream crossings to minimize direct sediment loading at the crossing. At these locations, roads enter and cross through SMZs and RHCAAs reducing the active buffer width and increasing the probability of sediment delivery to streams. The application of the probabilities discussed above would be inappropriate for these road configurations.
The probability/travel distance relationships of the present study were similar to those found in fills by Ketcheson and Megahan (1996), but notably lower than values reported for situations involving ditch relief culverts. Burroughs and King (1989) report that “over half of the relief culverts had sediment transport distances exceeding about 75 ft.” in gneiss and schist parent materials, while Ketcheson and Megahan (1996) report a travel distance of 4m from fills and 50 m from cross drains at the 0.5 exceedence probability; and a near zero probability of sediment traveling greater than 200 feet below fills, berm drains and rock drains in granitics of the Idaho batholith (Belt, et. al., 1992). The relationship of these values illustrates the increased velocity associated with ditch relief culvert configurations and the subsequent increase in sediment travel distance. Conversely, the similarity in values between this study and those reported for fills by...
Ketcheson and Megahan (1996) show that hillslope roughness or obstructions exert comparable reductions in flow velocity and competence.

**Sediment Plume Volume**

Sediment plume volume was positively correlated with sediment travel distance. This relationship is logical and is analogous to what Megahan and Ketcheson (1996) describe. As sediment laden runoff is diverted from the road bed, increased hillslope roughness is encountered thus reducing flow velocity and competence ultimately leading to sediment aggradation. In a situation of continual road use it would be logical to expect sediment plume length to grow. This is due to the filling effect behind roughness elements, which ultimately reduces overall roughness thus promoting increased sediment travel and plume volume. Conversely, in a situation where routine travel is not occurring, e.g., a spur road, sediment plume volume may remain static until that road segment is intensively re-entered.

**Plume Volume Exceedence Probability**

The culmination of the collected and subsequently generated data, based on the strong relationship of sediment plume volume and sediment travel distance (Figures 8 and 10), was the generation of a suite of exceedence probability curves for given sediment travel distances and sediment plume volume interactions (Figures 15 and 16). These two groups of curves provide a strong planning tool because they integrate exceedence probability of sediment travel distance and sediment plume volume. The relationship of the curves allows planners to assess the risk of various percentages of
sediment volume traveling a range of distances below the fillslope toe. For example, if a drain dip is located three meters (~10 ft) from a streambank in Belt parent material, a planner can quickly determine that there is an exceedence probability of 0.3 (a 30% chance) that 10% of the total sediment plume volume will enter the stream. Given the road configuration and level of use, the planner can reference Figure 8 to establish a relevant sediment plume volume. If the mean volume value is chosen, the planner can deduce that 0.14 m$^3$ will enter the stream at this point. It is then up to the planner to determine if this risk is acceptable given the stream, habitat, and watershed characteristics.

Sediment volume does not have a temporal component. Volume measurements assessed the accumulated sediment volume below a drain dip since time of construction of that dip, which may or may not coincide with the age of the road. PCTC is currently conducting a road sediment mass analysis study on different road configurations within Belt and glacial till parent materials. The publication of the PCTC study will provide data such as mass per unit area of road per unit time and mass of total eroded sediment. The integration of that data-set with the sediment volume-distance probability curves should allow users to establish probabilities of sediment mass loading to fluvial systems.
Figure 15. Belt travel distance/volume exceedence probability curves.

Figure 16. Glacial till travel distance/volume exceedence probability curves.
Conclusions

The thousands of miles of forest roads currently on the landscape throughout the United States serve as a reservoir of sediment that is slowly being transferred to adjacent streams, negatively impacting aquatic habitat and stream morphology. The research presented here demonstrates that in Belt and glacial till parent materials sediment travel distances and volumes are not as great as in more erodible parent materials. However, any chronic increase in sediment production or delivery is arguably too much; yet most forest roads will remain in place for the foreseeable future. Therefore, land managers should strive to implement practices that diminish sediment delivery from roads.

Management decisions can affect three factors that lead to increased sediment travel distance, and correspondingly volume; hillslope roughness, road vegetative cover and road segment length and slope. These concepts are not new, but this study helps confirm the importance of these factors and differences management can make. Efforts should be made to 1) increase the use of hillslope roughness elements, particularly slash filter windrows or other obstructions placed below drain dip outflows and insure that these objects are in contact with the ground surface; 2) avoid constructing long, steep road segments that lead to increased flow velocities and stream power; and 3) close or avoid entry to roads when not in use to promote road tread vegetative cover. While the subject of road closures is a sensitive political issue throughout the Northern Rockies, findings from this study illustrate the importance of vegetation re-establishment in reducing road based sedimentation. Finally, based on findings of this study and similar studies, the use of outsloped roads segments serviced by driveable drain dips will produce shorter sediment travel distances and smaller plume volumes than analogous road
configurations serviced by ditch relief culverts. Outsloped roads are not the proper management strategy in every situation, but in a “typical” road configuration in western Montana, they are suggested.

Data presented here on sediment travel distance and sediment plume volume provide scientists and land managers throughout western Montana additional planning tools to more efficiently and effectively manage the regions natural resources. The prediction equations and probability curves provided by this research should assist in establishing restoration priorities and more precisely evaluating cumulative effects from forest road sediment. The utility of this data is based in part on the fact that the study surveyed roads of various age, and thus the results can be extrapolated to roads that have been on the landscape, as well as roads recently constructed.
Literature Cited


Sugden, B. 2004. Plum Creek Timber Company, Hydrologist. Personal communication


Appendix A

Table A1. Interaction of road type and parent material STD ANOVA results.

<table>
<thead>
<tr>
<th>(I) GEOLOGY/ROAD TYPE</th>
<th>(J) GEOLOGY/ROAD TYPE</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt Main</td>
<td>Belt spur</td>
<td>.2372 *</td>
<td>8.543E-02</td>
<td>.028</td>
</tr>
<tr>
<td>Belt Main</td>
<td>Till Main</td>
<td>2.716E-03</td>
<td>9.830E-02</td>
<td>1.000</td>
</tr>
<tr>
<td>Belt Main</td>
<td>Till spur</td>
<td>.2848 *</td>
<td>9.009E-02</td>
<td>.009</td>
</tr>
<tr>
<td>Till Main</td>
<td>Belt Main</td>
<td>-.2372 *</td>
<td>8.543E-02</td>
<td>.028</td>
</tr>
<tr>
<td>Till Main</td>
<td>Till Main</td>
<td>-.2345 *</td>
<td>7.325E-02</td>
<td>.007</td>
</tr>
<tr>
<td>Till Main</td>
<td>Till spur</td>
<td>4.753E-02</td>
<td>6.180E-02</td>
<td>.868</td>
</tr>
<tr>
<td>Till spur</td>
<td>Belt Main</td>
<td>-.21559E-03</td>
<td>9.830E-02</td>
<td>1.000</td>
</tr>
<tr>
<td>Till spur</td>
<td>Belt spur</td>
<td>.2345 *</td>
<td>7.325E-02</td>
<td>.007</td>
</tr>
<tr>
<td>Till spur</td>
<td>Till spur</td>
<td>.2821 *</td>
<td>7.864E-02</td>
<td>.002</td>
</tr>
<tr>
<td>Till Main</td>
<td>Till spur</td>
<td>-.2848 *</td>
<td>9.009E-02</td>
<td>.009</td>
</tr>
<tr>
<td>Belt spur</td>
<td>Belt Main</td>
<td>-4.753E-02</td>
<td>6.180E-02</td>
<td>.868</td>
</tr>
<tr>
<td>Belt spur</td>
<td>Till Main</td>
<td>-4.7534E-02</td>
<td>7.864E-02</td>
<td>.002</td>
</tr>
<tr>
<td>Belt spur</td>
<td>Till Main</td>
<td>-4.7534E-02</td>
<td>7.864E-02</td>
<td>.002</td>
</tr>
</tbody>
</table>

* The mean difference is significant at the .05 level.

Table A2. Belt road type ANOVA results.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Vegetation</td>
<td>9.873</td>
<td>.002</td>
</tr>
<tr>
<td>Road Segment Length</td>
<td>3.853</td>
<td>.052</td>
</tr>
<tr>
<td>Road Segment Slope</td>
<td>.450</td>
<td>.504</td>
</tr>
<tr>
<td>Hillslope Gradient</td>
<td>.016</td>
<td>.898</td>
</tr>
<tr>
<td>Sediment Travel Distance</td>
<td>14.381</td>
<td>.000</td>
</tr>
<tr>
<td>Hillslope Roughness</td>
<td>1.811</td>
<td>.181</td>
</tr>
</tbody>
</table>

Table A3. Glacial till road type ANOVA results.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Vegetation</td>
<td>44.979</td>
<td>.000</td>
</tr>
<tr>
<td>Road Segment Length</td>
<td>.083</td>
<td>.773</td>
</tr>
<tr>
<td>Road Segment Slope</td>
<td>20.170</td>
<td>.000</td>
</tr>
<tr>
<td>Hillslope Gradient</td>
<td>.103</td>
<td>.749</td>
</tr>
<tr>
<td>Sediment Travel Distance</td>
<td>17.707</td>
<td>.000</td>
</tr>
<tr>
<td>Hillslope Roughness</td>
<td>1.621</td>
<td>.205</td>
</tr>
</tbody>
</table>
Table A4. Particle size distribution (by geology) paired sample t-test.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Paired Differences</th>
<th></th>
<th></th>
<th></th>
<th>t</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Std. Error</td>
<td>Mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair 2 BELT ROAD SILT - BELT PLUME SILT</td>
<td>4.8000</td>
<td>5.1672</td>
<td>2.3108</td>
<td>2.077</td>
<td>.106</td>
<td></td>
</tr>
<tr>
<td>Pair 3 BELT ROAD CLAY - BELT PLUME CLAY</td>
<td>2.4000</td>
<td>1.6733</td>
<td>.7483</td>
<td>3.207</td>
<td>.033</td>
<td></td>
</tr>
<tr>
<td>Pair 4 TILL ROAD SAND - TILL PLUME SAND</td>
<td>4.8000</td>
<td>8.4971</td>
<td>3.8000</td>
<td>1.263</td>
<td>.275</td>
<td></td>
</tr>
<tr>
<td>Pair 5 TILL ROAD SILT - TILL PLUME SILT</td>
<td>-6.8000</td>
<td>9.6021</td>
<td>4.2942</td>
<td>-1.584</td>
<td>.188</td>
<td></td>
</tr>
<tr>
<td>Pair 6 TILL ROAD CLAY - TILL PLUME CLAY</td>
<td>2.0000</td>
<td>5.0990</td>
<td>2.2804</td>
<td>.877</td>
<td>.430</td>
<td></td>
</tr>
</tbody>
</table>

Figure A1. Regression standardized residuals normal P-P plots for Belt Series parent materials.
Figure A2. Regression standardized residuals normal P-P plots for glacial till parent material.
Appendix B

Table B1. Mean values of Belt Series and glacial till variables by road type.

<table>
<thead>
<tr>
<th>Geology</th>
<th>Road Type</th>
<th>Road Vegetation Cover (%)</th>
<th>Road Segment Length (m)</th>
<th>Road Segment Slope (%)</th>
<th>Rd Shape</th>
<th>Hill Slope Grade (%)</th>
<th>Sediment Travel Distance (m)</th>
<th>Micro Topographic Distance</th>
<th>Roughness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt Series</td>
<td>Main</td>
<td>9.00</td>
<td>149.84</td>
<td>5.20</td>
<td>56.50</td>
<td>44.11</td>
<td>6.61</td>
<td>7.47</td>
<td>10.64</td>
</tr>
<tr>
<td></td>
<td>Spur</td>
<td>43.67</td>
<td>114.89</td>
<td>6.88</td>
<td>28.35</td>
<td>43.22</td>
<td>2.64</td>
<td>3.06</td>
<td>9.89</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>32.03</td>
<td>126.54</td>
<td>6.32</td>
<td>37.58</td>
<td>43.51</td>
<td>3.95</td>
<td>4.52</td>
<td>10.14</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>Mainline</td>
<td>16.79</td>
<td>71.02</td>
<td>7.38</td>
<td>39.77</td>
<td>30.77</td>
<td>5.61</td>
<td>6.14</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>Spur</td>
<td>90.00</td>
<td>60.50</td>
<td>4.00</td>
<td>5.00</td>
<td>28.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>42.90</td>
<td>72.48</td>
<td>5.78</td>
<td>24.37</td>
<td>30.08</td>
<td>3.19</td>
<td>3.51</td>
<td>4.64</td>
</tr>
</tbody>
</table>