Sediment Travel Distances below Drivable Drain Dips in Western Montana*

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Abstract
Sediment delivery to streams from unpaved forest roads consists of direct delivery from road segments leading into stream crossings and indirect delivery below drainage outfalls. The indirect component of sediment delivery depends on the distance that sediment travels downslope as well as the road erosion rate. Several studies have quantified sediment travel distances in highly erodible parent materials such as the quartz monzonite of the Idaho Batholith, but less research has been conducted in other parent materials. We investigated sediment travel distances below drivable drain dips along unpaved roads in the metasedimentary Belt Series and glacial till parent materials of western Montana. In the Belt parent materials, sediment travel distances ranged from 0 to 58.2 m (n = 139, mean = 4.0 m), but 78% of the sites had a travel distance of < 5m and 24% had a travel distance of zero. Similarly, in glacial till parent materials, travel distances ranged from 0 to 33.4 m (n = 148, mean = 3.2 m) while 76% of sites had a travel distance of < 5m and 40% had no detectable sediment below the dip. These travel distances are lower than those measured in granitic parent material, both in this and other comparable studies. Due to the limited sediment travel distances, most drainage outfalls in these parent materials do not contribute sediment to streams. Indirect sediment delivery is most likely to occur at drainage outfalls near to stream crossings or if the road erosion rate is unusually high. Sediment delivery from existing roads can be effectively reduced by: 1) positioning the first drivable dip such that the sum of direct and indirect delivery is minimized, 2) installing slash filter windrows below drainage outfalls, 3) closing unused roads, and 4) grading road segments near stream crossings only as necessary to avoid the formation of ruts.

1. INTRODUCTION

Unpaved roads are a primary sediment source in forested watersheds in the western United States (Megahan and Ketcheson, 1996; Megahan and Kidd, 1972; Brake et al., 1997). Sediment delivery to streams from unpaved forest roads consist of a direct component, which is the sediment delivered from road segments leading into stream crossings, and an indirect component which is the sediment delivered at constructed drainage outfalls and where road surface runoff flows off the road tread before reaching a ditch or drain. Improved knowledge of the direct and indirect components of sediment delivery can be used to reduce the impact of roads on streams and other aquatic habitat through improved road system planning and better management and maintenance of existing roads.

The sediment delivery ratio from road segments leading into stream crossings is close to 100%, so that the direct component of sediment delivery depends almost entirely on the road

erosion rate. Road erosion rates vary with road age, road design and maintenance, parent material characteristics, and the intensity and timing of road use (Sugden and Woods, *in press*; Packer, 1967; Reid and Dunne, 1984). 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), but decline rapidly as sediment availability decreases and vegetation cover on the cut and fill slopes increases (Burroughs and King, 1989; Ketcheson and Megahan, 1996). Higher erosion rates occur on steeper, longer road segments due to the greater stream power associated with overland flow on the road tread. Roads in highly erodible parent materials, such as feldspar-rich granitic rocks, can have erosion rates that are many times higher than in less erodible parent material. 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). Active hauling on roads during wet periods results in particularly high erosion rates.

The delivery ratio for indirect sediment delivery is less than 100% because a portion of the sediment eroded from the road is stored on the hillslope as a plume of sediment that lies on top of the natural soil profile. Since indirect sediment delivery only occurs if the sediment plume intersects a stream channel, the delivery rate depends on the distance that sediment travels downslope. 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). The higher sediment volume fills up storage elements on the hillslope, 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).

Sediment delivery to streams from existing road networks is managed through voluntary Best Management Practices (BMPs) and designation of streamside management zones (SMZs). BMPs 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. For example, drivable drain dips divert run-off from the road tread onto the hillslope below the road, so reducing overland flow distances and the resultant erosion (Logan, 2001). Drivable dips are popular because they are relatively inexpensive to install, and because they can be retro-fitted to existing roads. However, these and other road BMPs such as ditch relief culverts, open top culverts, and flapper water bars are only effective if they are located so that the sediment travel distance below the drainage outfall is less than the distance to the nearest stream. Similarly SMZs, which act as a vegetative filter strip that reduces runoff and sediment delivery to streams from the adjacent upland, are only effective in reducing sediment delivery if the sediment travel distance is less than the SMZ width. Selection and location of appropriate road BMPs and designation of adequate SMZ widths requires knowledge of sediment travel distances in a range of environments.
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 and Kidd, 1972, Megahan et al., 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. Given the current state of watershed assessments, TMDL load allocations, and road system planning and management, there is a need for more precise, parent material specific sediment travel distance data. 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 recommendations for more effective BMP implementation and road system management to reduce sediment delivery. 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.

2. STUDY AREA

Study sites were located within seven townships in western Montana where Plum Creek Timber Company (PCTC) is the primary landowner. PCTC owned roads within the six townships have a native surface and due to the general absence of subsurface flow interception they typically do not have an interior ditch and drivable dips are used to route overland flow from the roadbed. Most of the PCTC road system is at least ten years old and the cutsslopes and fillsslopes are generally well vegetated. The frequency of maintenance operations varies depending on the level of use for log hauling and other forest management activities.

Parent materials in three of the townships are primarily quartzite and argillite beds belonging to the Missoula Group of the Belt Supergroup (Winston, 1986). Rocks of the Belt Supergroup underlie approximately 75% (31.5 million km$^2$) of western Montana (Ross, 1963). Soils within the three Belt townships comprise primarily loamy-skeletal, mixed, frigid Udic Ustepts of the Winkler Series (USDA, 1995). In another three of the townships, the soils are formed from glacial till deposited by the Pinedale glacial episode. Tills, outwash and glacio-lacustrine sediments deposited by Quaternary continental and alpine glaciers are the dominant parent material in much of the northern part of Montana (Johns, 1970). Soils in the three glacial till townships comprise loamy-skeletal, mixed Andic Cryepts of the Waldbillig Series. The seventh township lies in the upper Lolo Creek watershed near the Montana – Idaho border, and is underlain by quartz-monzonite granitic rocks. Data from the seventh township were collected to validate the study methodology and to provide a comparison with similar studies conducted elsewhere in granitic terrain (e.g. Ketcheson and Megahan, 1996).

Western Montana has a continental-maritime climate in which topography is the primary control on precipitation and temperature. Mean annual precipitation in the vicinity of the six study townships ranges from 600 mm to 1000 mm per year (USDA Soil Conservation Service, 1981), and as much as 70% of this precipitation can fall as snow. Approximately 95 percent of the annual rainfall erosivity is due to convective storms that occur between May and September (Renard et al., 1997). Summers are warm, and maximum daily temperatures above 35 °C are not
uncommon. The coldest month of the year is January, when much of western Montana experiences sub-zero daily maximum temperatures.

3. METHODS

3.1 Sediment Travel Distance

Sediment travel distances were measured at 139 drivable drain dips in the Belt Series townships, 148 in the glacial till townships and 50 in the granitic township. Drain dips were randomly selected from the population of all dips on PCTC roads within each township. A GIS was used to randomly select 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 and fifteen years prior to this study. 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 road sediment deposited above a buried O or A horizon was no longer visible.

3.2 Factors Controlling Sediment Travel Distance

Eight independent variables were measured at each sample site to determine the factors controlling the sediment travel distance (D, m): road type (ROAD, mainline or spur), elevation (E, m), road vegetation cover (V, %), segment length (L, m) and gradient (S %), road shape (SHAPE, %), hillslope gradient (HILLSLOPE, %), and hillslope roughness index (R, dimensionless). R was defined in accordance with (Morgan, et al. 1993) as:

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

where M = ground microtopographic distance along plume axis (m)
S = straight line distance along plume axis (m)

The ground microtopographic distance 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.

3.3 Sediment Plume Volume

Sediment plume volume was measured at five Belt Series sites and four glacial till sites using a simplified version of the procedure described by Ketcheson and Megahan (1996). The objective was to determine the plume geometry as a function of distance downslope, and to relate plume volume to the sediment travel distance. At each site, the sediment plume was divided along its longitudinal axis into ten slices, and each slice was divided into six “cells”, aligned
parallel to the plume long axis. At the center of each cell the depth of the deposited road sediment was measured and recorded. Total plume volume estimates were calculated by summing the individual cell volumes.

3.4 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).

3.5 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 and between sites on mainline haul roads and spur roads. Sediment travel distance was normalized using a log_{10} transformation. Multiple regression was used to assess the effect of the eight independent variables and two generated variables (LS, the road length-slope product, and LS^2, the length-slope squared product) on the sediment travel distance in each parent material. Previous studies have indicated that LS and LS^2 can be a more significant predictor of sediment travel distance than length or slope alone (Luce and Black, 1999). ROAD was defined as a categorical variable where a value of 1 represents a mainline road and 2 represents a spur road. Values for R, L and LS were log transformed prior to analysis to improve the normality of the data. Pearson correlation analysis was used to identify the variables that were significantly correlated with sediment travel distance and with each other. Only the most significant variable in a group of correlated variables was included in the regression modeling. A step-wise approach was used to develop the most appropriate regression model using these variables.

4. RESULTS

4.1 Sediment Travel Distance

Sediment travel distances at the Belt Series sites ranged from zero to 58.2 m, with a mean of 4.0 m. All except one of the sites had a travel distance of less than 24 m, 78% had a travel distance of less than 5 m and 24% of the sites had no detectable sediment below the outfall (Figure 1). In the glacial till sites, travel distances ranged from zero to 33.4 m with a mean of 3.2 m. Seventy six percent of till sites had a travel distance of less than 5 m and 40% had a travel distance of zero. Sediment travel distances measured in the granitic parent material ranged from zero to 28.7 m, with a mean of 5.4 m. Ketcheson and Megahan (1996) obtained mean values of 3.8 m and 8.7 m for sediment travel distances below fillslopes and rock drains, respectively in granitic terrain, indicating that the methodology used for the present study is valid and that comparisons with studies conducted elsewhere are appropriate.

Mean sediment travel distances in the Belt and glacial till parent materials were not significantly different (P>0.05). However, mainline roads had a significantly higher mean sediment travel distance than spur roads in both parent materials (P < 0.05). This is likely due
primarily to greater vegetation cover on the spur roads and the resultant reduction in the road erosion rate. Spur roads had almost five times and more than three times the average road tread vegetation cover than mainline roads in Belt and glacial till sites, respectively, and the differences were statistically significant in both cases. In the glacial till sites, spur roads were also significantly less steep than mainline roads (P < 0.01) and this may have contributed to the lower sediment travel distance.

Figure 1. Percent exceedance probability for sediment travel distances below drivable dips on roads in the Belt Supergroup and glacial till soils of western Montana.

4.2 Sediment Travel Distance Correlation and Regression Analysis

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), LS$^2$ (P = 0.003) and log LS (P = 0.019) were all significantly correlated with the logarithm of sediment travel distance ($\log_{10} D$). 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:

$$\log_{10}(D) = 0.977 + 0.226 \times 10^{-4} (LS) - 0.174 (ROAD) - 0.289 \log RI$$

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

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 used in the regression analysis for till sites were road type and log LS. The resulting model:
log_{10}(D) = 1.013 – 0.282 (ROAD)

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

4.3 Sediment Plume Volume

Sediment plume volumes were generally small, with 6 of the 9 plumes containing less than 0.5 m$^3$ of road sediment. In the Belt Series sites plume volume ranged from 0.07 to 6.2 m$^3$ with a mean of 1.4 m$^3$. The largest plume volume in the Belt sites was an outlier, and occurred at a site which had one of the longer sediment travel distances, 7.6m. In the till sites the plume volume ranged from 0.12 to 0.56 m$^3$ with a mean of 0.4 m$^3$.

![Figure 2. Cumulative percent plume volume versus cumulative percent of total travel distance for sediment plumes below drivable dips in the Belt Supergroup and glacial till soils of western Montana](image)

Sediment plume volume rapidly diminished with increasing distance from the fillslope toe such that, on average, 80% and 75% of the plume volume occurred in the upper half of the plume in the Belt Series ($R^2 = 0.98$, std. error = 4.83) and glacial till sites ($R^2 = 0.82$, std. error = 15.0), respectively (Figure 2). These results are consistent with work conducted in granitic sites in central Idaho, where 84% of the plume volume occurred in the upper half of the plume (Ketcheson and Megahan, 1996). Plume volume was highly correlated with sediment travel distance in both parent materials ($R^2 = 0.90$, std. error = 0.1, Figure 3), indicating that the road erosion rate largely determines the sediment travel distance.
4.4 Particle Size Analysis

Particle size analysis indicated that there was less clay in the plume sediment sample relative to the road tread sample in four of the five Belt series sites, and the mean clay content in plume and roadbed samples from the Belt Series was significantly different (P < 0.05). 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.

5. DISCUSSION

Previous studies have reported sediment travel distances ranging from zero to almost 200 m, and mean travel distances of between 3.8 and 19.2 m (Table 1). The sediment travel distances measured in the present study are at the lower end of this range, and this is likely due to differences in the parent material characteristics, climate and the type of road drainage structure.

5.1 Effect of Parent Material

The lower mean travel distances in Belt series and glacial till parent materials relative to those in the granitic parent material township and in other comparable studies of sediment travel distances in granitics reflects, in part, the low erodibility of Belt series and glacial till soils in
western Montana. These soils contain a high proportion of coarse fragments and this reduces the erodibility of the road surface by creating a natural armoring effect (Sugden and Woods, *in press*). In contrast, granitic parent materials form sandy soils that are inherently vulnerable to erosion.

5.2 Effect of Climate

The relative lack of summer rainfall in western Montana 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 further 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 5.3 Mg ha\(^{-1}\) y\(^{-1}\) of sediment over a 3-year period that included both wet and dry years (Sugden and Woods, *in press*). In contrast, 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\(^{-1}\) (Bilby *et al.*, 1989).

Table 1. Range, mean and standard deviation of sediment travel distances reported in this and previously published studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Geology</th>
<th>Location</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Study</td>
<td>Belt Drivable dip</td>
<td>0 - 58.2</td>
<td>3.97</td>
<td>6.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Till Drivable dip</td>
<td>0 - 33.4</td>
<td>3.19</td>
<td>5.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Granitic</td>
<td>0 – 28.7</td>
<td>5.36</td>
<td>6.33</td>
<td></td>
</tr>
<tr>
<td>Haupt, 1959</td>
<td>Granitic Cross ditch</td>
<td>1-112.5</td>
<td>19.2</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Burroughs &amp; King, 1989</td>
<td>Granitic Culvert</td>
<td>0 - 194.8</td>
<td>38.7</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Ketcheson &amp; Megahan, 1996</td>
<td>Granitic</td>
<td>Fillslope</td>
<td>0.4 – 66.1</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Rock drain</td>
<td>1.2 – 33.9</td>
<td>8.7</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Brake et al., 1997</td>
<td>Sandstone / Siltstone</td>
<td>Culvert, road &gt; 5 yr old</td>
<td>0 - 23.2</td>
<td>5.09</td>
<td>4.48</td>
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<tr>
<td></td>
<td></td>
<td>Culvert, road &lt; 5 yr old</td>
<td>1 - 40.1</td>
<td>9.33</td>
<td>11.37</td>
</tr>
</tbody>
</table>

5.3 Effect of Road Drainage Structure Characteristics

The effect of road drainage structures on sediment travel distance can be assessed by comparing the data obtained from granitic sites in this and other studies. The sediment travel distances observed below drivable drain dips in granitic terrain in the present study are comparable to those obtained for fillslopes by Ketcheson and Megahan (1996) (Table 1).
However they are considerably less than those obtained for rock drains by the same authors, and for culverts by Burroughs and King (1989). Runoff routed to a fillslope or a drainage dip is slowed by vegetation and other hillslope roughness elements. These impediments effectively increase surface roughness and reduce the velocity, leading to deposition before the run-off reaches the fillslope. In addition, the roads included in our study were almost entirely outsloped roads, which distribute flow over a larger area, thus reducing the flow depth and increasing surface roughness and 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. In contrast with fillslope outfalls and drivable dips, ditch relief culverts concentrate flow, first in the roadside ditch and then at the outflow point. 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.

5.4 Regression Modeling

The only variable to appear in both of the regression models was the road type, reflecting the fact that mainline roads had significantly higher sediment travel distances than spur roads in both parent materials. The higher sediment travel distances along mainline roads are largely due to higher traffic levels and more frequent grading, both of which result in less vegetation cover on the road surface. Vegetation cover 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 velocity, discharge and, hence, stream power. Infiltration capacity also increases as plant roots penetrate the road surface. Finally, given enough vegetative cover and sufficient time, the accumulation of soil organic matter increases the soil water holding capacity so reducing the probability of overland flow during precipitation events.

The length-slope product was identified as a significant predictive variable for sites in the Belt Series. Increasing the road segment length or slope increases the velocity, competence, and stream power of overland flow, leading to an increase in erosion and sediment transport. Brake et al. (1997) also found LS to be a significant predictive variable for sediment transport distance. Luce and Black (1999) found that $LS^2$ was a better predictor of erosion rates than LS, reflecting the fact that slope has a greater effect on road erosion than segment length.

Hillslope roughness appeared in the predictive equation for sediment travel distances in the Belt Series sites, and has been found to be an important predictor of sediment travel distances in other 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.

5.5 Unexplained Variability in Sediment Transport Distances

The regression coefficients obtained for the models in this study are considerably less than those reported in similar studies, and this may be due in part to differences in the study design and the methods used in data analysis. The regression models developed by Ketcheson
and Megahan (1996) explained 70% and 88% of the variability in sediment travel distance below fills and rock drains, respectively, and plume volume was the primary predictive variable. Our study also found that plume volume was highly correlated with sediment travel distance, but it was not measured at all of the sites due to logistical constraints. Inclusion of this variable in our regression model would have substantially increased the model predictive capability. Packer’s (1967) model explained 52% of the variability in sediment travel distances. However, one of the characteristics of the regression method is that the strength of the correlation may be artificially inflated by including a large number of variables in the model. This may have been the case with the Packer study, which included 25 variables in the predictive model. Brake et al., (1997) used a stepwise approach that reduces the potential for overparameterization of the regression model, and achieved regression coefficients 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.

Other factors that may have contributed to the low predictive capability of the models 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. The Belt Series includes a wide range of lithologies with corresponding variability in soil texture. In western Montana, most road erosion occurs during spatially isolated but locally intense summer convective storms (Vincent, 1985). Due to the spatially distributed nature of the sampling sites, analogously configured road segments may have been exposed to significantly different precipitation events, resulting in corresponding differences in the sediment travel distance. Variability in travel distances due to different climatic history may be further exacerbated by differences in traffic volume between sites, and by interactions between the timing of vehicle traffic and the occurrence of large storms.

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.

5.6 Sediment Plume Volume – Distance Relationship

The positive relationship between sediment plume volume and sediment travel distance is logical and was previously described by Megahan and Ketcheson (1996). Sediment diverted from the road surface and onto a hillslope will travel downhill until it is either trapped behind a log, rock or other hillslope roughness element, or until the stream power is reduced sufficiently that the flowing water can no longer convey the sediment load. Downhill extension of the sediment plume over time reflects both the progressive filling-up of hillslope storage and the associated reduction in hillslope roughness along the plume, which leads to a reduction in the rate that stream power decreases below the road. Higher erosion rates lead to more sediment...
volume on the hillslope, more rapid filling of hillslope storage, reduced hillslope roughness, and longer sediment travel distances. The broader implication is that the road erosion rate is a very important determinant of the sediment travel distance. Road segments with high erosion rates are also likely to have longer sediment travel distances and will thus deliver more sediment to streams, both by direct and indirect flowpaths.

5.7 Management Implications

The generally low sediment travel distances observed in this study indicate that most drivable dips along unpaved roads in western Montana do not deliver sediment to streams. For example, the 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 just 5%. Viewed another way, the vast majority of the sediment introduced to streams comes from just a few drainage outfalls. 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 sediment. These outfalls are most likely to occur in the vicinity of stream crossings, where the road crosses into and through the SMZ and the drainage outfall lies just a short distance from the stream. Our study suggests that there is an optimal location for the drainage outfall nearest a stream crossing that minimizes both the direct and indirect sediment inputs to the stream channel. This optimal location may be identified by combining the sediment travel distance probability and plume length – volume relationships presented here with calculated or estimated road erosion rates.

The results of the regression analysis indicate that sediment travel distances may be reduced by increasing hillslope roughness and road vegetative cover and reducing road segment length and slope. On existing roads, hillslope roughness may be increased by installing slash filter windrows or other obstructions below drain dip outflows and ensuring that these objects are in contact with the ground surface. Road vegetative cover can be increased by temporarily or permanently closing roads when they are not being used. Road system designers should avoid constructing long, steep road segments that lead to increased flow velocities and stream power. Since plume length and volume are highly correlated, any activity that increases the road erosion rate will also increase the sediment travel distance. In an associated study, Sugden and Woods (in press) identified the road segment slope, time since grading, roadbed gravel content and mean annual precipitation as significant predictors of road erosion rates in Belt Series and glacial till sites. Of these, time since grading is the only variable that can be altered by managers dealing with existing road networks. By grading roads only as needed to eliminate ruts, particularly along road segments near to streams, managers can further reduce sediment delivery and the resultant impact on aquatic resources.

6. LITERATURE CITED


