Cedar River Watershed Road Sediment Study

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Summary

The Cedar River Municipal Watershed (CRMW) has a legacy road network that includes nearly 600 miles of unpaved forest roads. Erosion from these roads has the potential to deliver sediment to streams, lakes, and wetlands within the watershed, potentially degrading aquatic habitat and water quality. Because it is very time-consuming to measure actual sediment production from roads, the Washington Road Surface Erosion Model (WARSEM) was used to estimate both erosion and delivery of sediment from the road network. Recent studies of road surface erosion models have shown that while the models predict relative differences in roads with different conditions well (e.g., traffic, surfacing, gradient) and are therefore useful for predicting changes in erosion resulting from road management activities, calibration with locally-measured erosion rates is needed if the models are to predict actual amounts of eroded sediment from a particular road segment.

In order to test the WARSEM predictions of road surface erosion and delivery in the CRMW, sediment eroded from 16 road segments covering a variety of traffic, gradient, and surfacing conditions was measured annually between 2008-2011. In addition, sediment was collected at 12 silt fences located 10, 25, 50, or 100 feet from roads to help understand how far road sediment is transported across the forest floor.

Average coarse sediment production rates for the three years of study from the 16 plots ranged from 6 to 382 pounds/year which was the equivalent of 30 tons/square mile/year to 821 tons/square mile/year from the road surface. Trap efficiency of the settling tanks was estimated to be 45% for a road with fine-grained surfacing and 90% for a road with coarse-grained surfacing. In other studies, roads with higher traffic levels were found to have higher sediment production rates. However, the road segments measured in this study did not follow that trend, most likely because roads in this study with less traffic had much higher gradients than roads with heavy traffic.

The study shows that WARSEM over-estimates sediment production in the CRWM by an average of 5,700 % to 8,900 %. A calibration factor of 0.02 on coarse-grained surface and 0.04 on fine-grained surface roads can be applied to WARSEM results to more closely estimate actual road surface erosion rates in the watershed.

Additionally, the study found that delivery to the aquatic system from road was greatly over estimated with only 27% of the sediment generated reaching 10 feet from the road; 15% reaching 25 feet from the road; 5% reaching 50 feet from the road and 0% reaching 100 feet from the road. It is recommended that the WARSEM model delivery categories for the CRMW be adjusted to None – 0%, Direct – 100%, Direct via gully – 100%, 1 to 100 feet – 25%, 101 to 200 feet – 0%.

Based on the data collected as part of this study, the most effective way to reduce delivery of sediment to waterways in the CRMW is to disconnect road segments from the stream network,

particularly those that drain roads with steep gradients or fine-grained surfacing. Roads/culverts/ditchlines that deliver sediment within 25 feet of a stream could be disconnected from the stream by installing drivable dips (on low use roads) or cross drains (on higher use roads where drivable dips are less desirable) that deliver runoff/sediment to the undisturbed forest floor more than 50 feet away from the stream. Additional cross drains or drivable dips should be added uphill of drainage points that were determined to be connected to streams via a gully. Gully formation downhill from culverts is likely due to excess runoff from either long/steep road segments, or cutslope seepage. Added drainage points should be placed so that they drain to the forest floor more than 50 feet away from a stream.

1 Introduction

Constructed when commercial timber harvesting was widely practiced in the watershed, the Cedar River Municipal Watershed (CRMW) road network consisted of approximately 650 miles of unpaved forest roads, 36 bridges, and over 3,000 culverts prior to road decommissioning efforts in recent years. Today the watershed no longer supports commercial timber harvesting so most of these logging roads are no longer needed for watershed management activities. Sediment delivery from the road network is problematic for Seattle Public Utility (SPU) for three primary reasons: 1) it diminishes water quality, particularly during major storm events, affecting SPU's ability to deliver drinking water, 2) it degrades aquatic and riparian ecosystems, and 3) it violates the provisions of the Washington Forest Practices Act that limit sediment delivery to streams from forest roads. In recent years, delivery of sediment to streams during large storm events has resulted in shutting down the diversion of Cedar River water into the City's supply until sediment settled out to acceptable levels. The absence of filtration facilities in the Cedar water supply system underscores the potential impact the road system can have on water supply.

An important asset used to track, monitor, and prioritize road work within the CRMW includes a comprehensive road inventory originally conducted in 2004 and updated in 2007 and 2012. Using the inventory, which includes field observations of key characteristics such as widths, surfacing, drainage patterns, and delivery on roughly 88% of the CRMW roads, estimates of annual sediment production from the road network have been made using the Washington Road Surface Erosion Model (WARSEM). The inventory covered 99% of drivable roads in the watershed and a sub-sample (82%) of overgrown roads. Model estimates of annual sediment production from the road network delivering to surface water further aid in prioritizing road abandonment and road improvement work and predicting improvements to water quality and aquatic habitat within the CRMW associated with SPU road work. While an important monitoring tool for documenting if stated objectives within the Habitat Conservation Plan are being met, the accuracy of these predictions has not been assessed, resulting in a significant source of uncertainty as to the effectiveness of our roads program at achieving a fundamental objective.

In order to assess the accuracy of WARSEM predictions as well as the effectiveness of road improvements at reducing the delivery of road-generated sediment to streams, a road erosion study was implemented. This report summarizes findings on sediment production as well as sediment transport distances along the forest floor from a small stratified subset of watershed roads. These results also facilitate an assessment of the accuracy of WARSEM predictions of annual sediment production. In the final section of the report, potential management implications and existing knowledge gaps are discussed.

1.1 Physical Setting

Within the densely forested CRW there is a wide diversity of landforms, ranging from steep mountainous basins formed by alpine glaciers to gently sloping lowlands formed by advances of the continental ice sheets. Elevation range in the watershed is from approximately 500 feet to over 5,000 feet. The watershed can be divided into two geologic regions based on its geomorphic history. The area east of Cedar Falls, referred to as the Upper Watershed, consists of steep mountainous terrain. The stream network varies from steep headwaters formed by alpine glaciers to u-shaped alluvial valley bottoms at the lower reaches of the basin. Chester Morse Lake (formerly called Cedar Lake) is located in an historic lake basin at the lower end of the Upper Watershed. The area west of Cedar Falls (including the Taylor Creek drainage), referred to as the Lower Watershed, consists of thick deposits of recessional outwash and ice-contact deposits at lower elevations, and unglaciated sedimentary or volcanic geology at higher elevations. Thick deposits of recessional outwash and ice-contact deposits create gently sloping terraces in this area.

On undisturbed forest slopes within the CRMW, a thick layer of duff typically protects the soil from surface erosion, and most rainfall and snowmelt infiltrates into the soil. However, construction of forest roads has occurred within most of our steep, mountainous terrain, leading to high rates of surface erosion due to: 1) removal of all vegetative cover and surface protection; 2) the construction of cut and fill slopes that are steeper than the original hillslope to provide a relatively level driving surface; 3) greatly increased potential for overland water flow due to soil compaction and concentration of runoff; and 4) interception of groundwater by the cut slope. Characteristics which contribute to the erosion and transport of sediment from CRMW roads include compacted road surfaces, long lengths of roads without cross drains, areas with heavy rainfall, and soils prone to gully formation. Of course, road erosion does not pose a threat to water quality unless the eroded sediment is transported to a stream where it could degrade water quality or aquatic habitat. Delivery of road sediment to a stream is most likely to occur when the road is close to a stream, there is a steep slope between the road and the stream, and there are few obstructions to slow down or trap the sediment. Sediment is likely to be trapped (deposited) before it enters a stream if it is produced from roads far from a stream, or from roads with a vegetative buffer or topographic low between the road and the stream.

1.2 Existing Information

A comprehensive inventory of roads within the CRMW was conducted in 2004 during which 4,885 individual road segments with a median length of 450 feet, ranging in length from 30 to 13,000 feet, were identified and assessed. Approximately 48% or 2,359 of all road segments potentially deliver road generated fine sediment to surface water. Fine sediment delivery was assumed to be direct (e.g., 100 percent of the sediment is delivered to the stream) where ditches drained directly into streams and where gullies were observed below cross drain culverts such that water-borne sediments were not deposited prior to entering downslope tributaries. Where culverts drained onto the forest floor, or where gullies were observed to grade into the hillslope, no delivery was assumed if the road was farther than 200 feet from a stream. Road segments within 101 and 200 feet and within 1 to 100 feet of streams were delineated as indirect delivery segments. A portion of the sediment from these indirect delivery segments was assumed to be delivered to streams based on established relationships between distance and percent fine sediment delivery from roads.

Road inventory data for each segment included length, width, age, surfacing, traffic, gradient, cutslope height and cover, and distance from a stream. Using this data as well as other spatially-derived GIS data, the WARSEM was used to estimate the long-term average annual tons of sediment per year delivering to a stream or wetland from each road segment. We know from measurements of road surface erosion that the amount of sediment delivered to streams from roads is influenced by a number of factors including the physical setting, the proximity of the road to a stream, the condition of the road, the amount and intensity of rainfall and the amount and type of traffic. The actual quantity of sediment eroded from a particular road segment varies greatly from year to year as a result of differences in precipitation, traffic, and maintenance activities. Our ability to measure or predict all of these factors precisely at each location is limited. However, it is useful to predict where roads have the potential to produce relatively high amounts of sediment based on our current understanding of road erosion processes and typical conditions of each road segment. The model output, in average annual tons of sediment per year, allows road managers to identify road segments that are most likely to produce larger amounts of sediment, and to determine the relative sediment savings from a variety of management practices. Therefore only long-term average sediment delivery was calculated.

Road surface erosion is controlled by the characteristics of the road itself as well as the climate, traffic use, and underlying geology. Measurements of forest road surface erosion and the influence of different road characteristics on erosion and delivery have been undertaken throughout the United States since the 1960's (a comprehensive discussion of previous work is available in Appendices A and C of the WARSEM manual, Dubé et. al 2004). WARSEM estimates road erosion and delivery based on road length, width, age, surfacing, traffic, gradient, cutslope height and cover, rainfall, geology, and distance from a stream. The influence of several of these factors on erosion is fairly well constrained by available research (e.g., road gradient, cutslope cover, road age). Other variables either show differing responses between studies, or have fewer measurements (e.g., traffic, geology, climate, surfacing, delivery). Based on the confidence in each of the factors, as well as specific data needs in the CRMW, critical questions were formulated for this study.

1.3 Study Questions

A number of critical questions were developed to help guide the selection and quantity of road sampling locations. A summary of samples used to support answers to these questions is included in Table 1.

Note that the categories listed in Table 1 (as well as data in Figures 1, 2, and 3) are based on road inventory data collected in 2005. Road improvements such as changes to surfacing and addition of drainage structures have taken place on approximately 185 miles (28%) of roads since that time.

Erosion: Critical Question 1: How accurate are the WARSEM estimates of road surface erosion in the Cedar River Municipal Watershed?

Justification: The WARSEM model results are being used to estimate road surface erosion from the road network in the Cedar River Municipal Watershed. The model is an empirical model, based on road erosion research from watersheds across the United States (Dubé et. al 2004). Road surface erosion estimates using WARSEM have been shown to both under- and over-estimate measured road surface erosion, and calibration of the model to local conditions is recommended if accurate predictions are needed (Dubé et. al 2011). Since model predictions are an important tool for tracking progress and gauging success in reducing sediment loads from the road network, calibration of these estimates will enable SPU management to more confidently evaluate the overall benefit of this expensive work on water quality.

Scope of Study: The primary road attributes that control sediment production are: traffic/grading (disturbance); surfacing/ditch condition (available material); road area (length/width); and gradient (energy). It was decided to hold road length as constant as possible since segment length has been shown to affect erosion rates (study segments were similar lengths; 200-300 feet based on the average length of direct delivery segments in the watershed) and sample erosion from roads with the following characteristics (see Table 1 and Figures 1, 2 and 3):

- Traffic – occasional, light, moderate, moderately high
- Surfacing – Crushed rock, Borrow, Native blocky-coarse, Native blocky medium-fine, Native fine
- Gradient – 2-3%, 5-7%, 10-12%

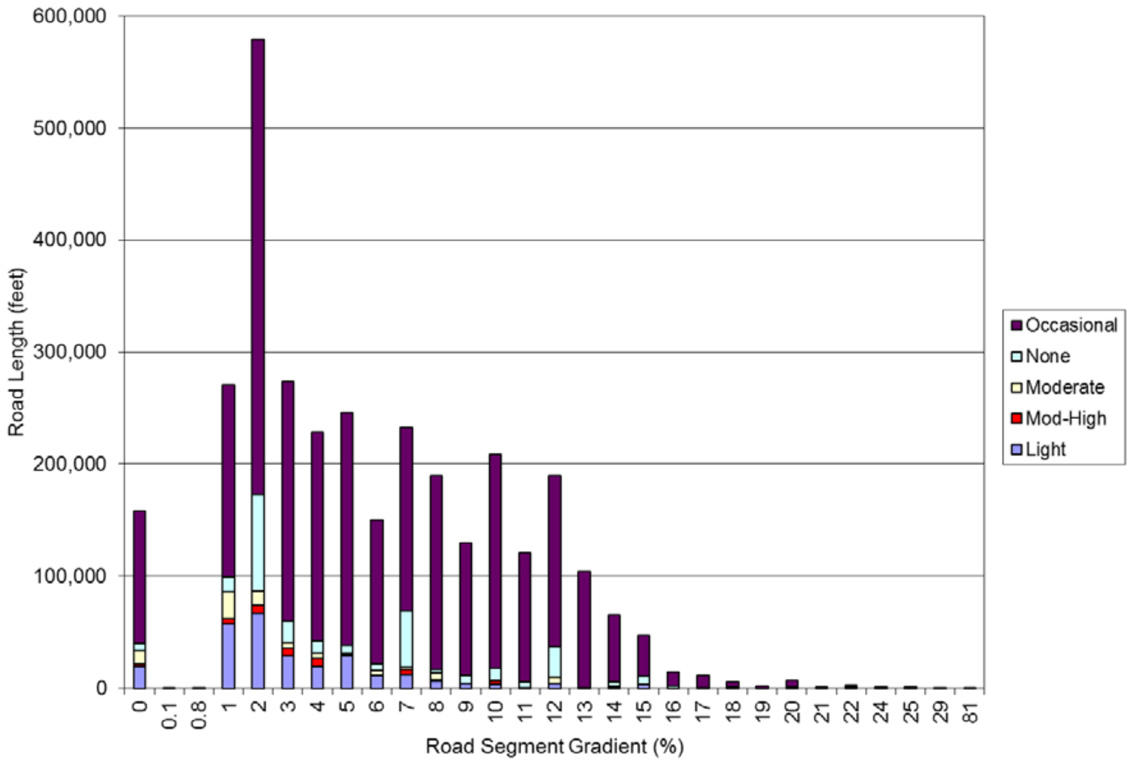
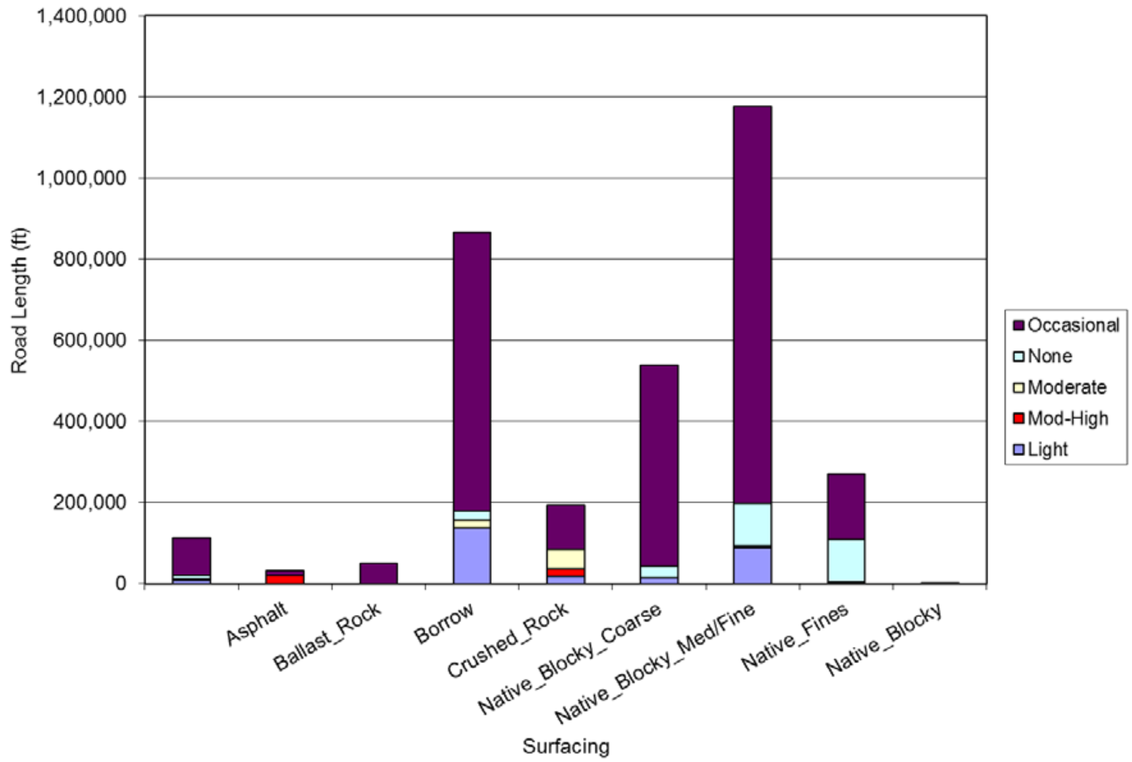


Figure 1. Total length (ft) of roads in Cedar River Municipal Watershed by traffic and road gradient (%).



(Note: based on 2005 inventory; 100/200 roads – light native Med/Fine blocky – are now crushed surfacing)

Figure 2. Total length of roads in Cedar River Municipal Watershed by traffic and surfacing

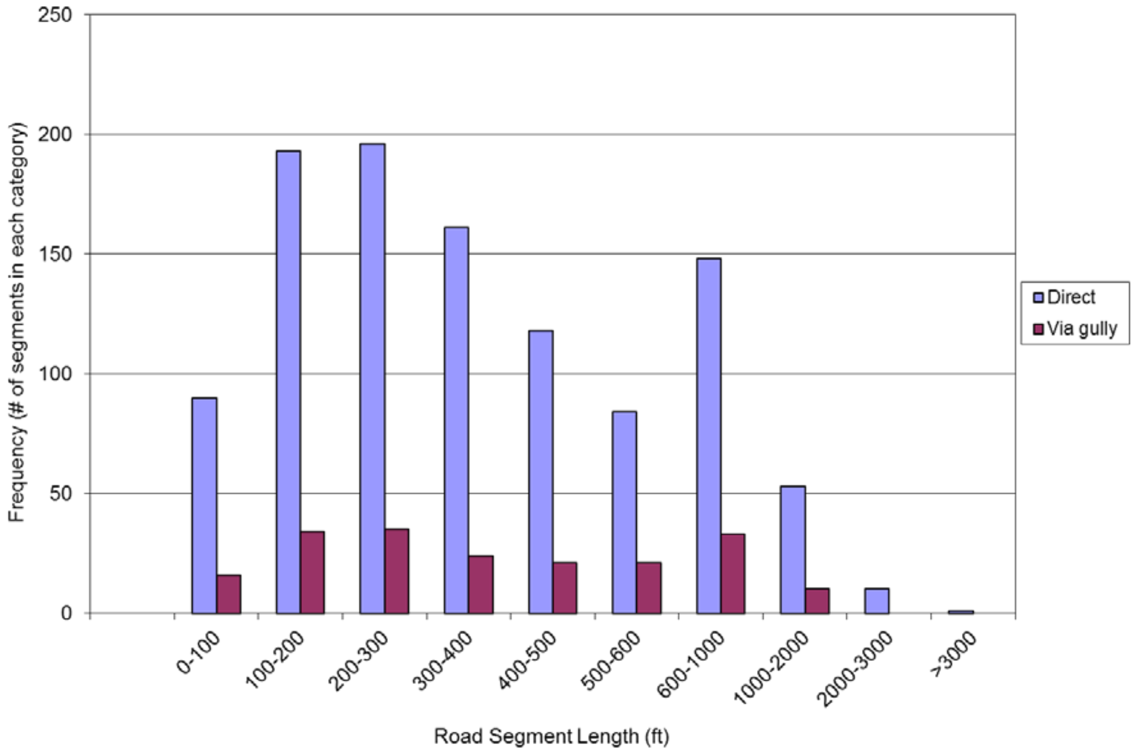


Figure 3. Frequency of road segment lengths of direct delivery and direct via gully road segments in Cedar River Municipal Watershed.

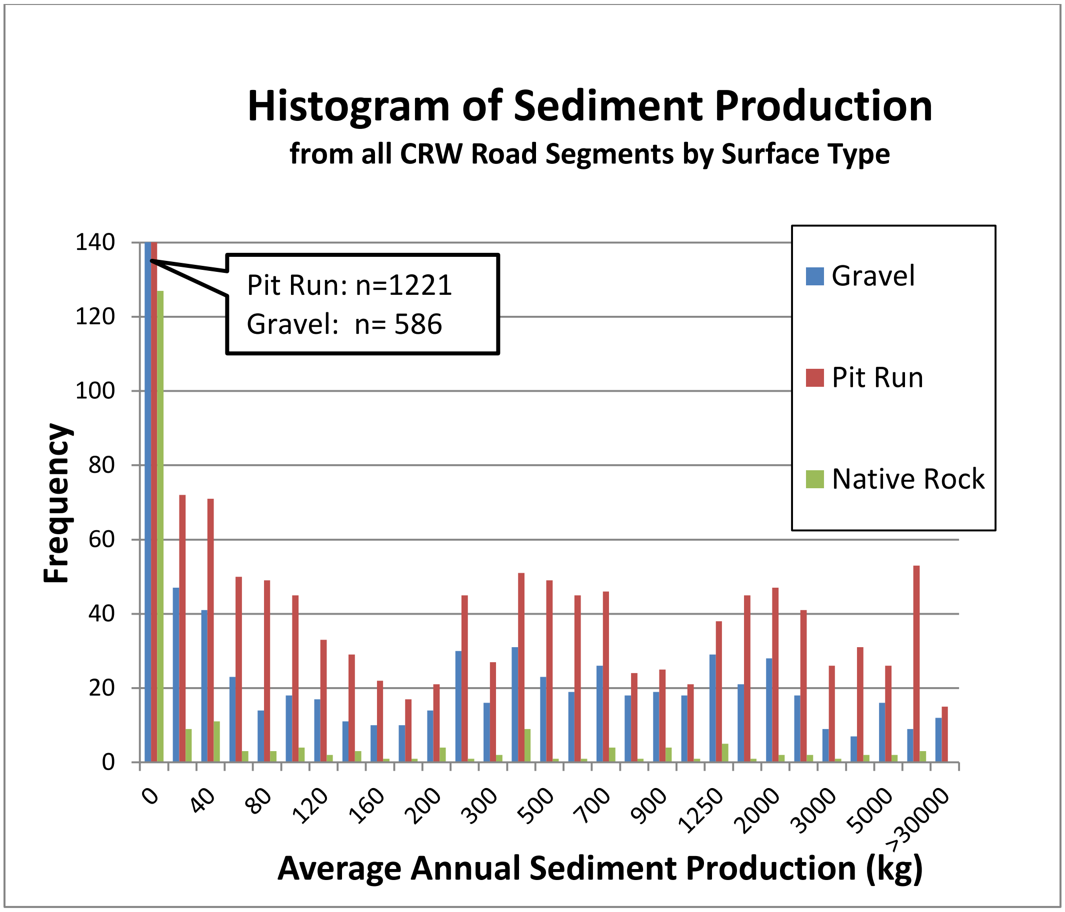


Figure 4. Estimated average annual sediment production from road segments in Cedar River Municipal Watershed (Based on WARSEM modeling).

Delivery: Critical Question 2: How accurate are the WARSEM predictions of delivery of eroded sediments in the Cedar River Municipal Watershed?

Justification: The WARSEM model uses data from a road research study in Idaho to estimate the distance sediment can be transported from the outlet of a culvert (Ketcheson and Megahan 1996). The Idaho study site conditions were different than those in the Cedar Watershed (Idaho – sandy soil, Cedar – finer-grained soil, different precipitation patterns and intensities). Improving our understanding of the distances and associated site characteristics where sediment delivery across the forest floor occurs will greatly improve our confidence in sediment predictions and the implementation of future road improvements designed to reduce sediment delivery to streams.

Scope of Study: The proposed study method included installing filter fabric structures (similar to silt fences) to catch runoff at varying distances below culvert outfalls and at dispersed runoff sites. A total of 12 sample sites were monitored over 3 years (10, 25, 50, 100 ft from culvert outfalls and 10 and 20 ft from dispersed sites).

Traffic: Critical Question 3: How much sediment is produced from low traffic roads in the CRMW.

Justification: One important objective of road decommissioning work in the CRMW is the reduction of sediment delivering from nonessential roads. Understanding the amount of road surface erosion produced from these roads will inform our prioritization, enabling us to more confidently identify and prioritize roads where significant sediment delivery to streams and wetlands is occurring.

Scope of Study: A measure of sediment production from low use roads is included in Critical Question 1.

High use roads Critical Question 4: How much sediment is produced and delivered from high use roads adjacent to key water features?

Justification: Traffic use, particularly during wet weather, has been shown to greatly increase sediment production from road surfaces. Several high use roads are located adjacent to waterways in the Cedar River Municipal Watershed with a high likelihood of delivery of the sediment to water bodies. A measure of the amount of sediment produced by these roads would provide information on the importance of controlling sediment from these roads.

Scope of Study: A measure of sediment production from high use roads is included in Critical Question 1. Delivery is included in Critical Question 2.

Table 1. Sample site characteristics and sample size for road monitoring project.

Traffic	Surfacing	Gradient	Number of Monitoring Locations	Road Segments/ Comments
Critical Questions 1, 3, and 4				
Occasional	Borrow	5-7%	3	18, 22, 21
	Native blocky/coarse	5-7%	2	810, 800
	Native Medium/fine	5-7%	3	200, 210, 800
	Native fine	5-7% or 10-12%	0	
Light	Borrow	5-7%	3	10, 61, 70
	Crushed	2-3%	2	50, 100
	Blocky Medium		1	100-300
Moderate	Borrow	2-3%	2	
	Crushed	2-3%		50, 101a
Moderately High	Crushed	2-3%, 7%	0	
Critical Question 2				
Silt fence monitoring sites			12	Various segments

2 Methods

Road surface erosion has been collected using a variety of methods by researches through the years. The data collection methodologies used in the current study were:

- Road surface erosion sampling using a settling tank based on Black and Luce (2007)
- Sediment delivery distance sampling using silt fence traps set at pre-determined distances downslope of selected road segments (Robichaud and Brown 2002).

2.1 Road Surface Erosion Sampling

Road surface erosion sampling measured the amount of sediment produced from road segments. Black and Luce (2007 Draft) developed a cost-effective method for measuring surface erosion using a bordered road erosion plot, a settling tank, and an optional tipping bucket/flow sampling device. The advantages to this methodology are that it is comparatively low cost, requires only periodic checking (annually if only the settling tank is used; monthly data downloads for the tipping bucket device), and collected data is comparable to other data that is being collected in the Pacific Northwest using the same equipment.

Road segments to be measured were isolated from other portions of the road network by the use of constructed wood/rubber waterbars at the top and bottom of the segment. Segment lengths were relatively consistent among monitoring sites to minimize variability caused by differences in length. The rubber waterbar at the top of the segment prevented water and sediment from upslope road segments from entering the measurement segment. The rubber waterbar at the bottom of the segment directed runoff from the measured road segment into the ditchline. A ditch diversion structure directed the runoff into a 6 inch corrugated plastic pipe that carried water under the road and flowed into a steel settling tank on the downslope side of the road (Figure 5; alternatively, an existing culvert was used to divert water under road). The coarse sediment (and some fraction of the fine-grained silt and clay) settled and remained in the tank. During the dry summer months, any water remaining in each tank was decanted and sediment accumulated at the bottom of the tank was removed, dried, and weighed.

Figure 5. Sediment tank and tread diverter setup.

Settling tanks were installed at 12 road segments that included a variety of surfacing, traffic use, and gradients (Table 2, Figures 6 and 7). The Road Plot Designation includes a reference to traffic use (first character, O-Occasional/L-Light/M-Moderate), surfacing (second characters, Bw-Borrow, BC-Native Coarse Blocky, BM-Native Medium Fine, CR-Crushed Gravel), and site number (last character, 1, 2, etc.). Sites in figures 6 and 7 beginning with DD characters are sites used to determine delivery distances and are discussed in Section 2.2 below.

Table 2. Road segment characteristics at sediment sampling sites.

Road Plot Designation	Road Number	Segment Length (ft)	Tread Width (ft)	Ditch Width (ft)	Surfacing	Traffic Use	Road Gradient (%)
OBw1	21	253	11	4	Borrow	Occasional	13
OBw2	21	300	12	0	Borrow	Occasional	5
OBw3	18	291	8	0	Borrow	Occasional	8
OBC1	810	450	12	0	Native Coarse Blocky	Occasional	11
OBC2	800	507	12	5	Native Coarse Blocky	Occasional	11
OBM1	200	365	12	4	Native Medium Fine	Occasional	5
OBM2	210	245	14	0	Native Medium Fine	Occasional	6
OBM3	800	180	10	0	Native Medium Fine	Occasional	4
LBw1	10	1000	14	2	Borrow	Light	5
LBw2	61	345	17	2	Borrow	Light	8
LBw3	70	291	13	3	Borrow	Light	5
LBM1	100-300	385	14	4	Native Medium Fine	Light	4
LCr1	50	341	13	2	Crushed Gravel	Light	7
LCr2	100	450	9	4	Crushed Gravel	Light	2
MCr1	100	623	18	4	Crushed Gravel	Moderate	7
MCr2	70	271	11	3	Native Medium Fine	Moderate	6

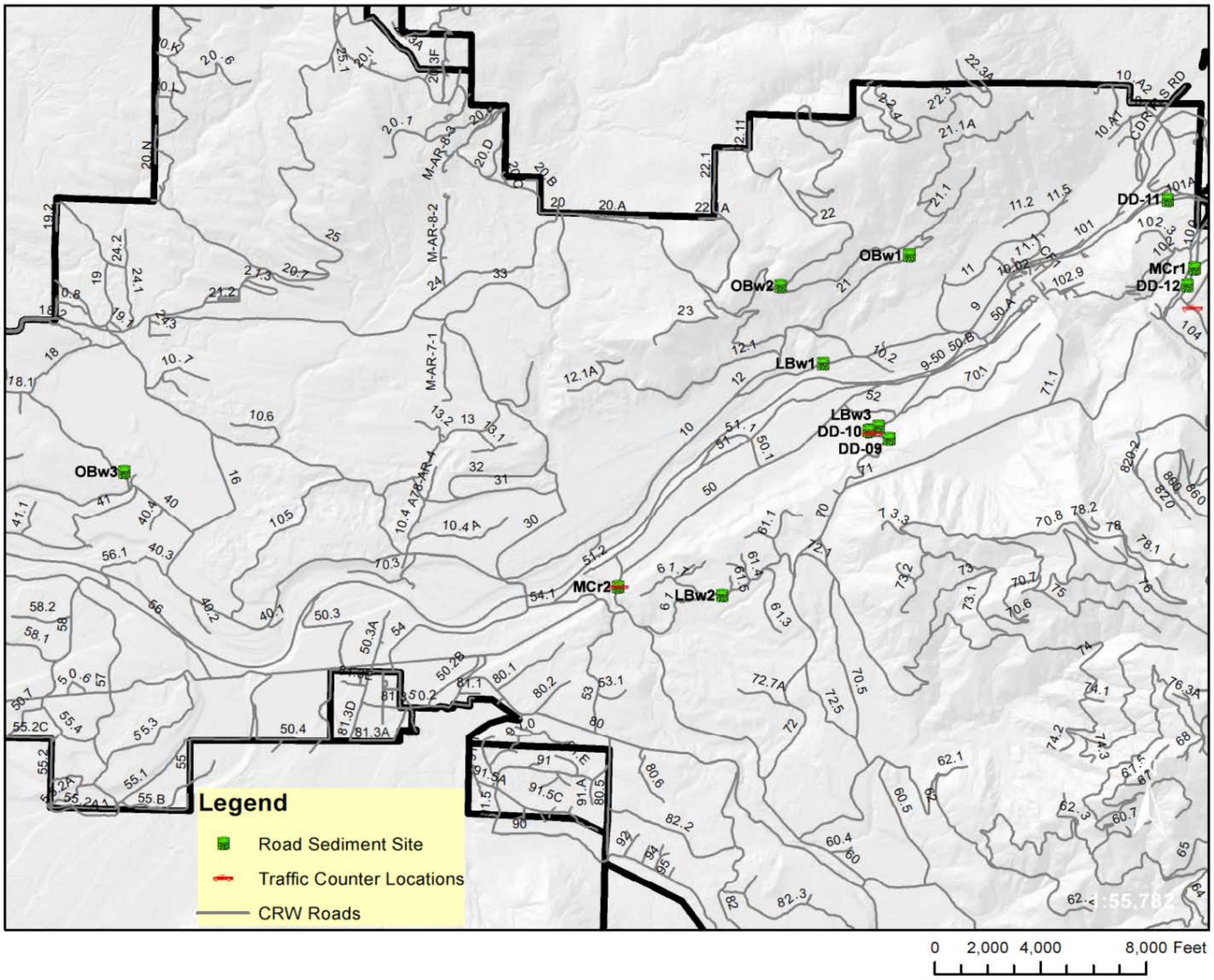


Figure 6. Lower Cedar River Watershed sediment and traffic monitoring sites.

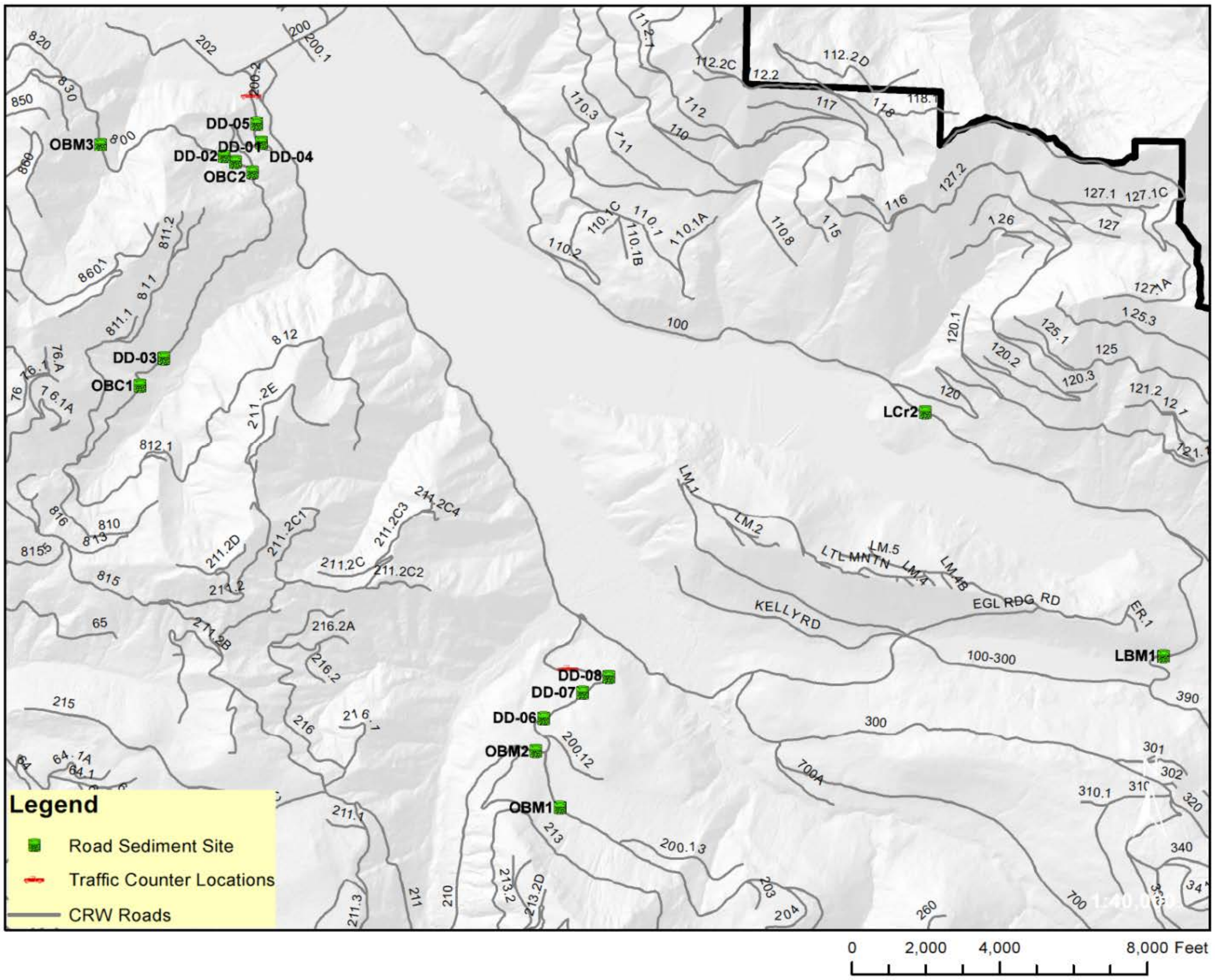


Figure 7. Upper Cedar River Watershed sediment and traffic monitoring sites.

2.2 Delivery Distance

In addition to sediment production, road models estimate the percent of eroded sediment that is delivered to a stream or water body based on the distance between the road runoff point (e.g., culvert outfall) and the stream. The WARSEM model assumes that 35% of the sediment produced from a road segment located between 1-100 feet from a stream is delivered to a stream, and 10% of the sediment is delivered from segments located between 101-200 feet from a stream. These estimates are based on research in the Idaho batholith (sandy soils, sparse vegetation) and likely overestimate delivery in the Cedar watershed with its dense vegetation that helps trap sediment traveling across the forest floor.

Silt fence sediment traps on hillsides downslope of road segments were used to measure how far road sediment is transported from a road. Silt fence methodologies are described in Robichaud and Brown (2002). In order to measure sediment transport distances, silt fence traps were installed 10, 25, 50, and 100 ft downslope from culvert outfalls, and 10 and 20 ft downslope from dispersed sites (e.g., outsloped road segments). A total of 12 silt fences were installed

(Table 3, Figures 6 and 7, above). Silt fence locations were visited twice per year to determine if any sediment was collecting at them (Figure 8). If sediment was present, the sediment was collected and weighed to determine quantity reach the silt fence.

Table 3. Delivery distance sampling site characteristics.

Silt Fence Site	Road	Delivery Distance (ft)	Traffic	Surfacing	Relative Erodibility of Underlying Geology	Road Gradient
DD-01	800	25	Occasional	Gravel	High	>10%
DD-02	800	100	Occasional	Gravel	High	>10%
DD-03	810	10	Occasional	Gravel	High	>10%
DD-04	800	50	Occasional	Gravel	Medium	>10%
DD-05	800	50	Occasional	Gravel	Medium	>10%
DD-06	200	10	Occasional	Gravel	Medium	>10%
DD-07	200	25	Occasional	Pit Run	Medium	5-10%
DD-08	200	100	Occasional	Pit Run	Medium	5-10%
DD-09	70	100	Light	Pit Run	Medium	>10%
DD-10	70	50	Light	Gravel	Medium	5-10%
DD-11	101A	25	Moderate	Gravel	Medium	5-10%
DD-12	100	10	Moderate	Gravel	Medium	<5%

Figure 8. Typical silt fence site before and after collecting sediment for measurement.

2.3 WARSEM Calculations

The Washington Road Surface Erosion Model (WARSEM) calculates the average annual amount of road surface erosion that is delivered to a stream from each road segment entered into the model. The erosion calculations are based on a set of empirical relationships that have been developed from research on road erosion. The model uses a base erosion rate that is dependent upon the type of soil (geology) the road is built on. The base erosion rate is multiplied by a series of factors that either increase or decrease the amount of erosion, depending upon the characteristics of the road tread, ditch, and cutslope, and how much of the eroded sediment is predicted to reach a stream. The model uses the following formulas, using factors derived from data in the road inventory database, to calculate road surface erosion for each road segment:

- Total Sediment Delivered to a Stream from each Road Segment (in tons/year) = (Tread & Ditch Sediment + Cutslope Sediment) x Road Age Factor
- Tread & Ditch Sediment= Geologic Erosion Factor x Tread Surfacing Factor x Traffic Factor x Segment Length x Road (Tread + Ditch) Width x Road Gradient Factor x Rainfall Factor x Delivery Factor
- Cutslope Sediment= Geologic Erosion Factor x Cutslope Cover Factor x Segment Length x Cutslope Height x Rainfall Factor x Delivery Factor

The WARSEM model was applied to each of the road test segment using appropriate characteristics from each segment – road area, surfacing, traffic, gradient, etc. The model results were used for comparison with measured sediment production.

3 Results

3.1 Rainfall

Rainfall amount and intensity are related to both erosion and delivery of eroded sediment; higher or more intense rainfall results in greater runoff and therefore great energy to erode sediment and transport it off the road prism. An analysis of daily rainfall data during Water Years 1983 to 2010, collected at the Masonry Dam in the Cedar River Municipal Watershed (Figure 9) indicates that 2008 tracked closely with annual averages while mid-winter storm totals in 2009 were below average and 2010 had above average precipitation. The majority of precipitation falls between October and June. The snow level in the CRMW varies throughout the winter, but at least some of the winter precipitation falls as snow even on the lower elevations roads during most years and higher elevations have snow during much of the winter. Snowfall does not result in erosion or transport of sediment until the snowmelt season. Roads that remain covered in snow for many months do not experience erosion/runoff during those months, but if snowmelt is rapid, they may experience rapid erosion during the snowmelt season.

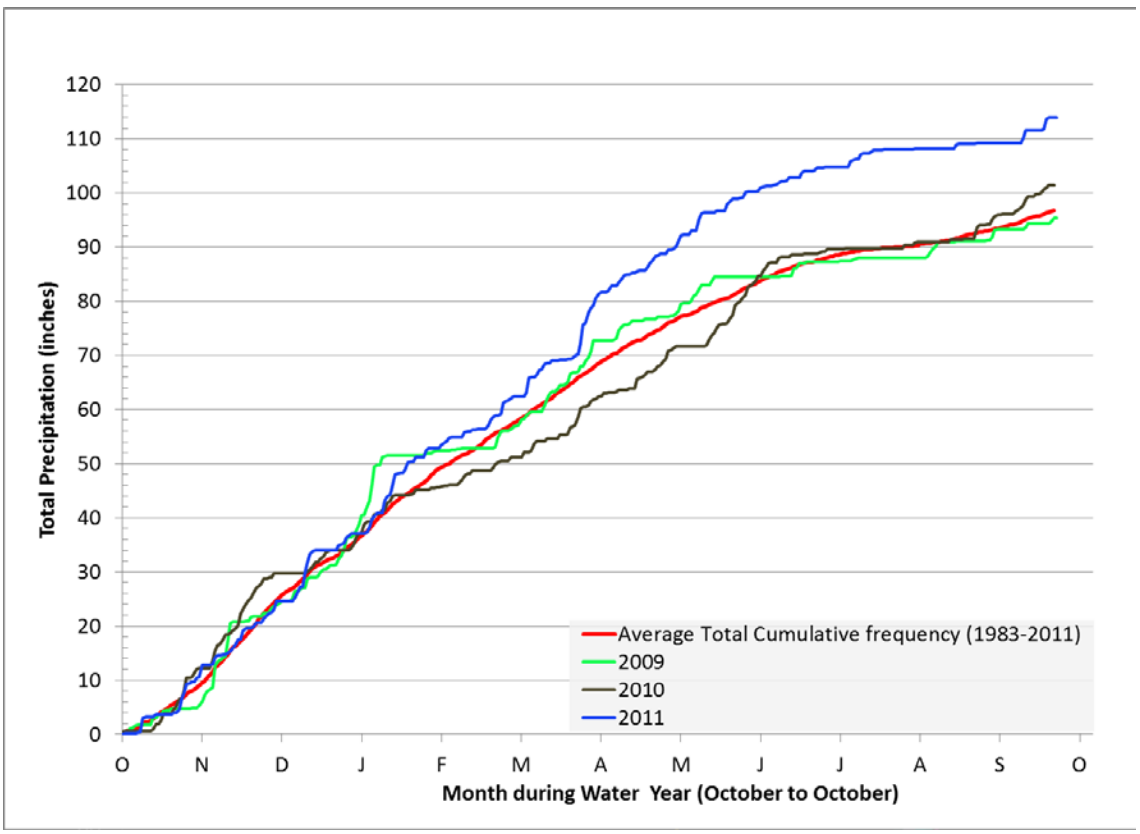


Figure 9. Cumulative average precipitation at the Masonry Dam; 1983 to 2010 and cumulative annual precipitation over three monitoring years (2009-2011).

3.2 Traffic

Traffic counters were installed on five of the roads in the watershed during portions of the period 2009-2012. Total traffic counts were divided by number of days of record to obtain an average number of vehicles/day on each road (Table 4). Because of difficulties with the traffic counters, the data were fairly intermittent and were used primarily to provide an estimate of average traffic on some of the measured road segments. Higher traffic levels have been shown to correlate with higher sediment production in other watersheds.

Table 4. Measured traffic 2009-2012.

Road	**100 Road**	**200 Road**	**800 Road**	**70 Road**	**50 Road**
Period of Record	7/2 to 8/28/09; 9/29/11 to 10/25/12	9/29/2011 to 11/29/11	9/29/11 to 11/29/11; 2/17/12 to 3/21/12	7/2 to 9/11/09; 10/04/11 to 10/27/11; 12/2/11 to 7/26/12	7/2 to 10/13/09; 12/1/11 to 12/22/12
No. of Days	391	60	65	312	123
Total Traffic Count	11,860	59	306	1,006	2,314
Average Vehicles per day	**30**	**0.9**	**4.7**	**3.2**	**19**

3.3 Measured Sediment Production

Sediment from the settling tank at each measured road section was collected and weighed annually for three years (Table 5 and Figure 10). The settling tanks collected all of the coarse sediment (sand and coarser material) and some portion of the finer-grained silt and clay material (see discussion in Section 3.3.1). The measured sediment varied considerably between road segments and between years. While the total sediment collected in the higher rainfall 2010-2011 period was more than in previous years, this trend was not consistent at all segments.

Table 5. Measured coarse sediment production.

Road Segment	Measured Sediment Production (pounds)			Average Production		
	November 2008 - September 2009	October 2009 - September 2010	October 2010 - September 2011	Pounds/ year	Tons/year	Tons/mi^2/ year
OBw1	3	4	299	102	0.05	374
OBw2	n/a	14.5	346	180	0.09	698
OBw3	41	9	100	50	0.03	299
OBC1	448	418.5	88	318	0.16	821
OBC2	579	299	267	382	0.19	617
OBM1	34	15	90	46	0.02	111
OBM2	n/a	51	83	67	0.03	272
OBM3	4	6	7	6	0.00	44
LBw1	172	74.5	37	95	0.05	82
LBw2	5	10.5	57	24	0.01	51
LBw3	87	87	177	117	0.06	350
LBM1	138	36	22	65	0.03	131
LCr1	21	19	14	18	0.01	49
LCr2	11	5	22	13	0.01	30
MCr1	294	172.5	619	362	0.18	368
MCr2	26	18.5	22	22	0.01	81
Total Collected	1,863	1,240	2,250			

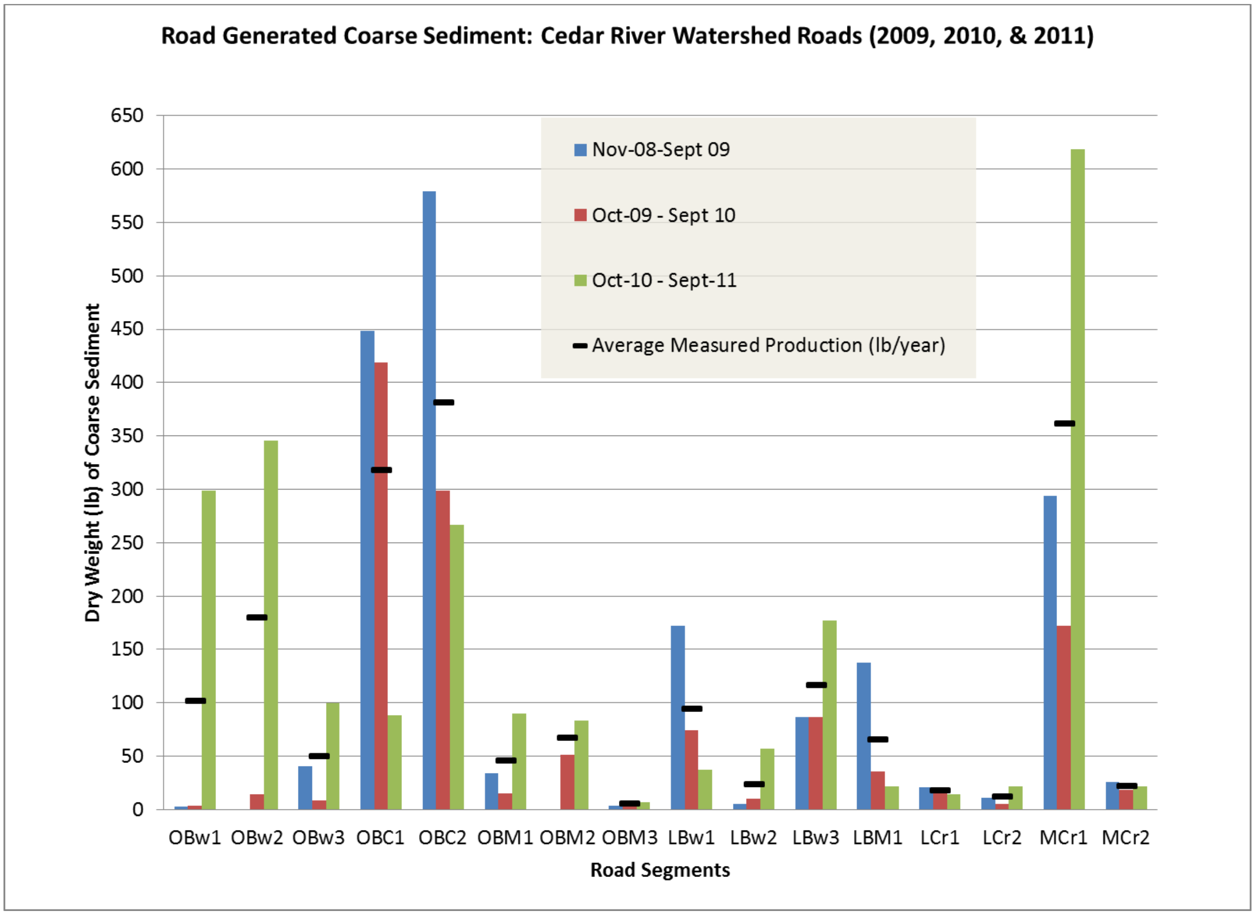


Figure 10. Measured coarse sediment production for years 2008, 2009, and 2010.

3.3.1 Estimate of Fine Sediment Loss from Settling Tanks

The settling tanks capture all of the sand and coarser material from the road segments, but some portion of the finer-grained silt and clay remains in suspension and is lost as water overflows the settling tanks. Black and Luce (2007) estimated a trap efficiency of 21-68% for settling tanks with roads on silty clay loam soils, depending on the fraction of sand that was transported through the ditch. The trap efficiency of two of the settling tanks in the CRMW was tested during one storm event on October 31, 2012. Grab samples of inflow and outflow from one settling tank on the 100 road and one tank on the 800 road were collected and analyzed for sediment concentration of various particles sizes. The overall trap efficiency for the finer-grained sediment produced by the crushed gravel on the 100 road was 45% and the trap efficiency for the coarser-grained surfacing on the 800 road was 90% (Table 6). Trap efficiency for the coarser sediment was higher than for the silt and clay fractions. These results, while not a complete analysis of trap efficiency, suggest that the measured sediment production values listed in Table 5 underestimate the total erosion from roads with surfacing that includes a substantial amount of silt and clay material (e.g., Crushed Gravel, Borrow and likely Native Medium Fine). Actual sediment from these roads could be as much as twice that listed in Table 5.

Table 6. Sediment concentration and trap efficiency by size fraction in 100 and 800 road settling tanks, October 31, 2012 storm.

Sample	**Concentration (mg/L) or Percent**				
Size Fraction	**Medium sand**	**Fine sand**	**Silt**	**Clay**	**Total sample**
Particle Size Range	**> 500 µm**	**500-62.5 µm**	**62.5-3.9 µm**	**<3.9 µm**	
100 Road (crushed surfacing, breaks down to fine grained material)					
Percent in Source Area	18%	17%	44%	21%	
Percent in Inflow	1%	2%	58%	39%	
100 Road tank inflow concentration	5.29	6.91	235.84	158.54	406.58
100 road tank outflow concentration	0.35	3.04	115.36	105.63	224.38
Concentration Retained	4.94	3.87	120.48	52.91	182.2
Percent Retained	93%	56%	51%	33%	45%
800 Road (Native surfacing, coarser grained)					
Percent in Source Area	51%	25%	21%	3%	
Percent in Inflow	14%	14%	45%	27%	
800 road tank inflow concentration	156.75	162.39	518.51	314.18	1151.83
800 road tank outflow concentration	2.77	2.05	78.93	36.13	119.88
Concentration Retained	153.98	160.34	439.58	278.05	1031.95
Percent Retained	98%	99%	85%	89%	90%

3.3.2 Factors Influencing Sediment Production

Previous researchers have also found that sediment production varies considerably between segments and between years on the same segment, so this result is not surprising in the CRMW road data (see summary in Dubé et al. 2011). Factors that result in variations in sediment production include those that were measured (e.g., segment length, width, gradient, surfacing, average traffic use) as well as factors that were not measured (e.g., interception of cutslope water, micro-drainage patterns on the road tread that concentrate flow, and traffic use during intense rainstorms).

While there are many factors that influence sediment production on a road, plots of the relative influence of surfacing, traffic, gradient, and geology (soil erodibility) are shown in Figure 11. There was little difference in measured sediment production among the borrow, crushed gravel, or native medium fine surfacing segments. The two native coarse blocky surfacing segments had higher sediment production. This was likely related, at least in part, to the higher trap efficiency for the coarser surfacing. However, these two segments were higher gradient (11%) than most of the other segments which may have also influenced the results (see discussion on gradient below).

Traffic also seems to have an influence on sediment production, with light traffic roads producing less sediment than moderate traffic roads, and occasional use roads producing the most sediment. Based on previous research, occasional use roads should produce less sediment than the higher traffic light or moderate use roads. Some of the difference may be the result of the low trap efficiency for the crushed surfacing on moderate use roads, or a higher contribution of sediment from the ditch on higher gradient occasional use roads. This result also suggests additional research may be needed regarding traffic and sediment production or additional review of maintenance activities is needed on occasional use roads.

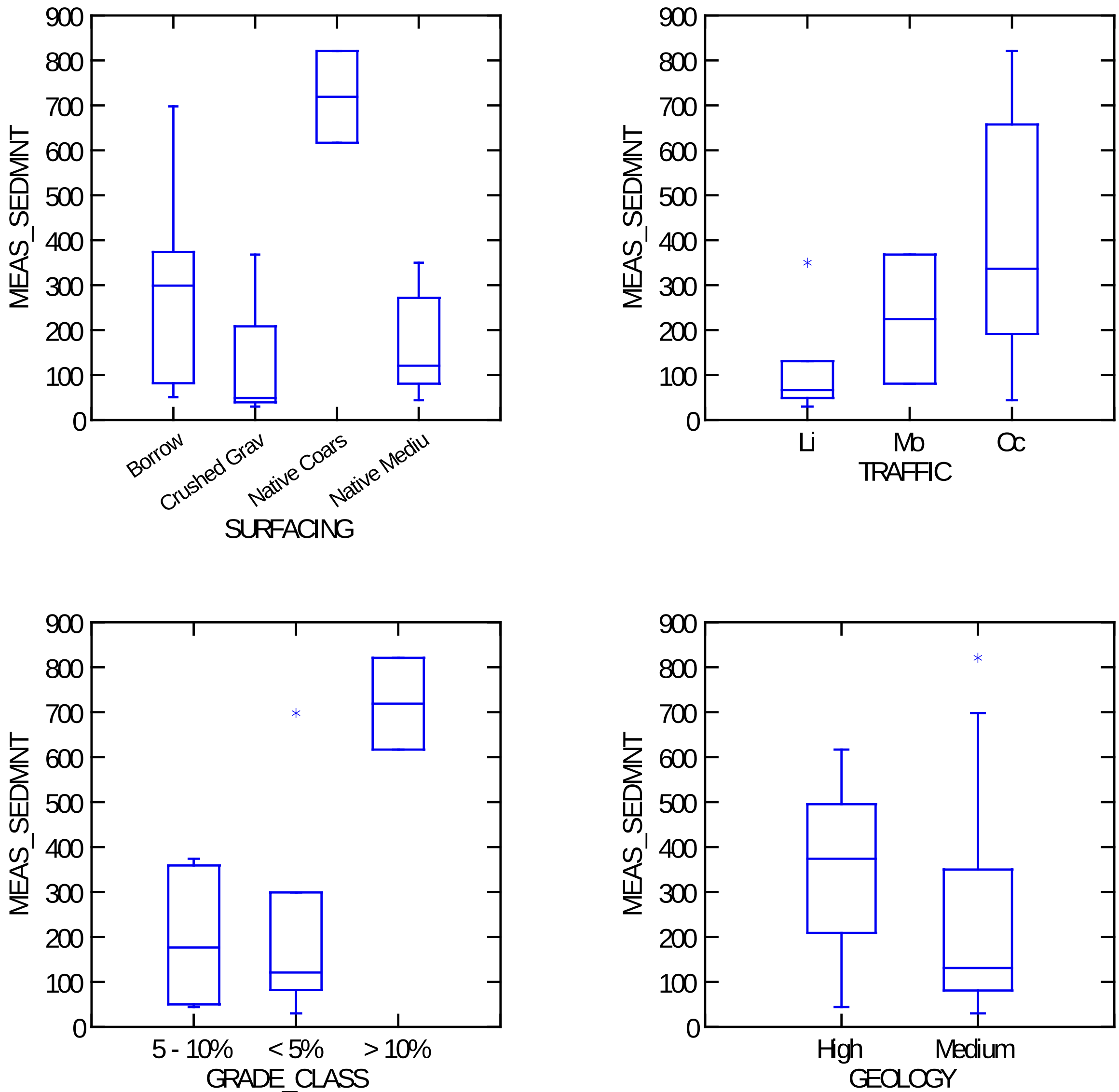


Figure 11. Influence of surfacing, traffic, gradient, and geology on sediment production.
Note: MEAS_SEDMNT is measured sediment production in tons/sq mi/yr. Box plots show average, 25%, 75%, and maximum and minimum values of sediment production for each classification.

Road segment length and gradient have been shown in studies from other areas to have an influence on sediment production; runoff from longer road segments and higher gradient segments has more energy to entrain and carry sediment off the road surface or along the ditch (Luce and Black 1999b). The measured results in the Cedar River Municipal Watershed are consistent with other studies; higher gradient segments had higher measured erosion. Luce and Black (1999b) found that sediment production was linearly related to segment length times segment gradient squared (L x S^2). Data from the CRMW were plotted to determine if this relationship was similar (Figure12). The measured road data have a general trend of increasing sediment production as segment length and gradient increase, but there are obviously other factors influencing sediment production from each segment such as surfacing and traffic, as discussed in previous sections.

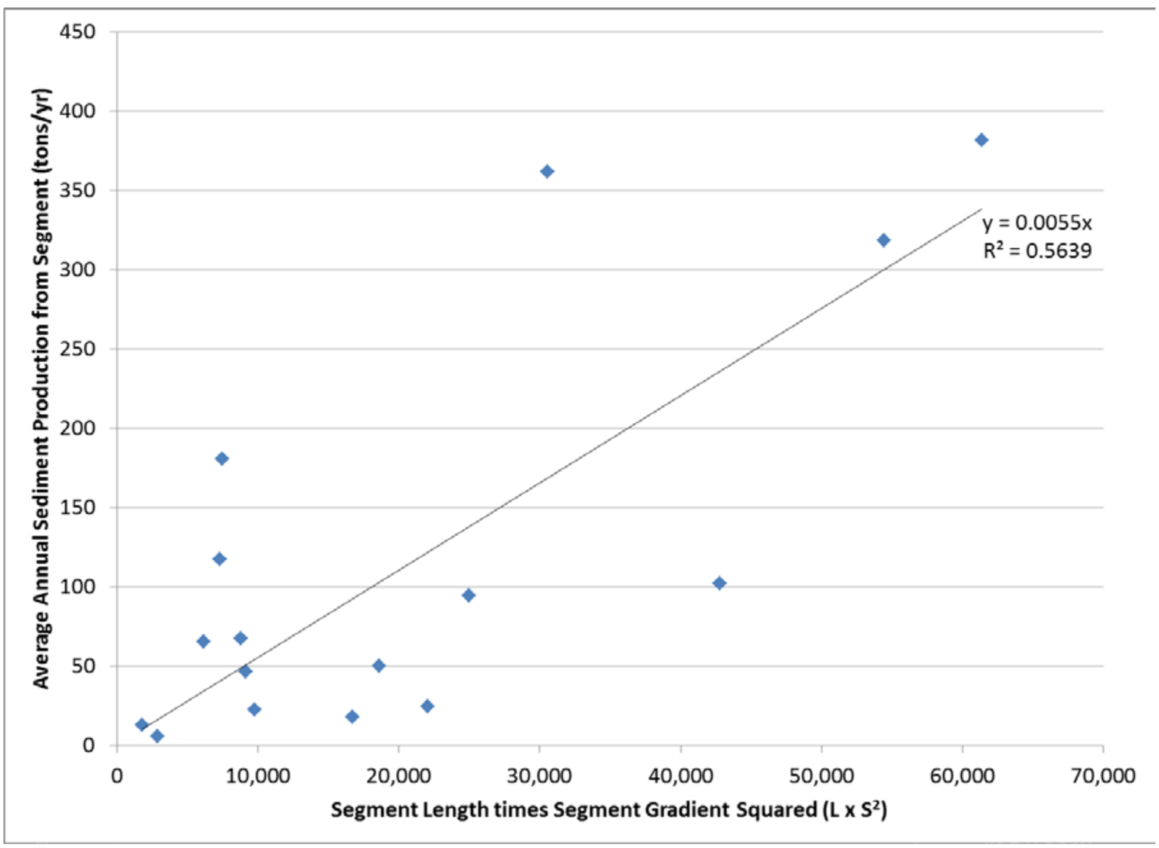


Figure 12. Sediment production versus segment length/slope variable.

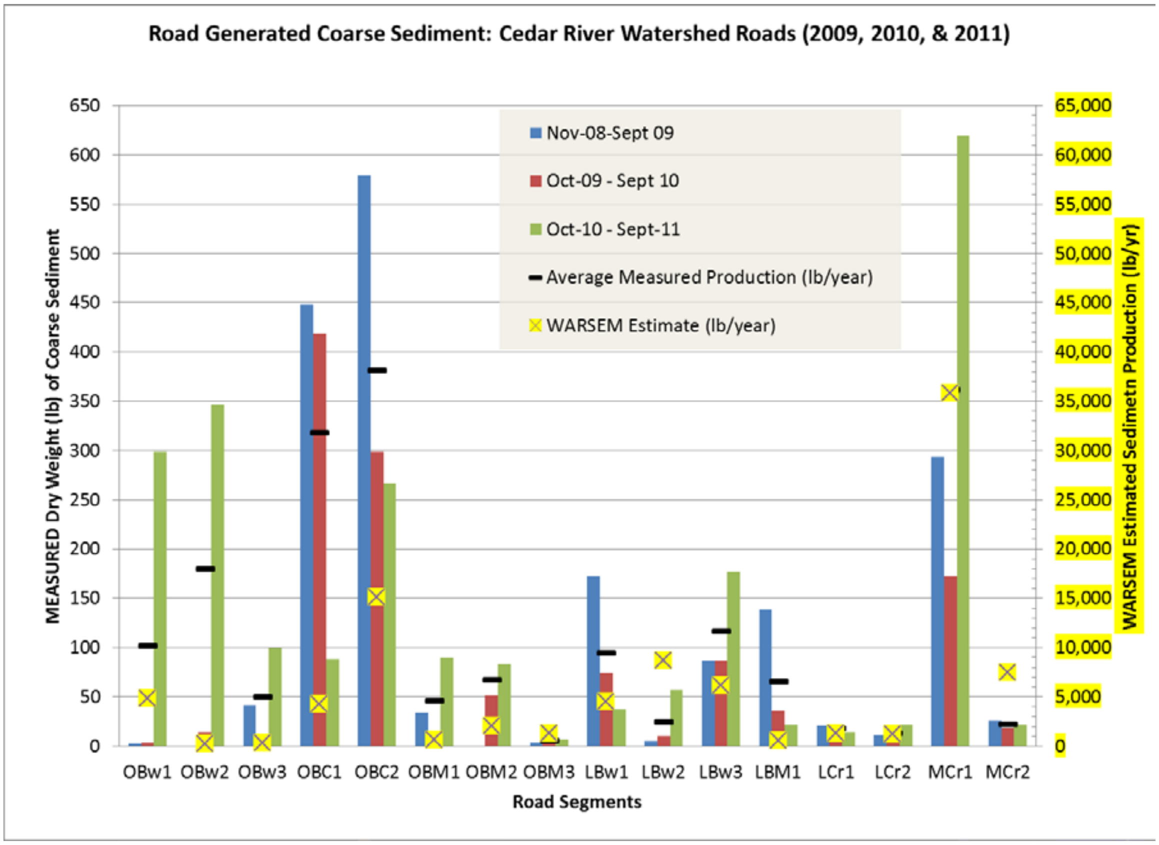
3.4 Comparison of Measured and Modeled Sediment Production

One of the objectives of the road sediment study was to determine how well the WARSEM model predicts erosion from roads in the Cedar River Municipal Watershed (Erosion Critical Question 1). The average annual measured road erosion coarse sediment data were compared to WARSEM model predictions for each road segment using traffic, surfacing, and geologic erosion factors based on WARSEM manual recommendations (Table 7, Figure 13). Using the recommended factors in the manual to represent the traffic, surfacing, and grading activities on the monitored CRMW road segments, WARSEM substantially over-predicted sediment production from the road segments, by an average of 8,900% (890 times measured values) using the assumption that the sediment captured in the tanks represents total road erosion. If a trap efficiency of 50% is assumed for fine-grained segments (borrow, crushed gravel), WARSEM over-predicts sediment production by an average of 5,700%.

Table 7. Measured vs. WARSEM predicted sediment production.

Road Segment	Average Measured Production (lb/year)	Estimated Total Average Measured Production (lb/year)*	WARSEM Estimate (lb/year)	Percent Over-prediction
OBw1	102	204	4,837	2,271% - 4,642%
OBw2	180	360	248	-31% - 38%
OBw3	50	100	321	221% - 542%
OBC1	318	318	4,260	1,240%
OBC2	382	382	15,121	3,858%
OBM1	46	46	674	1,365%
OBM2	67	67	2,045	2,952%
OBM3	6	6	1,281	21,250%
LBw1	95	190	4,515	2,276% - 4,653%
LBw2	24	48	8,689	18,002% - 36,104%
LBw3	117	234	6,172	2,538% - 5,175%
LBM1	65	65	595	815%
LCr1	18	36	1,290	3,483% - 7,067%
LCr2	13	26	1,205	4,535% - 9,169%
MCr1	362	724	35,864	4,854% – 9,807%
MCr2	22	44	7,444	16,818% - 33,736%

* Numbers include the projected contribution of fine-grained sediments that were lost from the settling tanks.



*NOTE: The vertical scale for WARSEM estimated sediment production is 100 times the measured production scale.

Figure 13. Measured and predicted road sediment yield at road segments.

Due to the large variation in road erosion rates found in sites across the country, Dubé et al (2011) recommend using local measured road sediment data to calibrate any road erosion model to local conditions. Confounding factors in developing a local approach to compare measured sediment with predicted sediment are road segment differences in surfacing, slope, traffic factor, etc. Most researchers agree that slope is a fairly consistent variable. The average of the 3 years of measured erosion rates in the Cedar River Municipal Watershed were standardized (tons/sq mi/yr) by the gradient formula in WARSEM (measured slope ÷ 7.5%)^2 to provide a reference base erosion rate for the watershed (Table 8).

Table 8. Slope standardized base erosion rate calculation.

Road Segment	3-Year Average Measured Erosion (tons/sq mi/year)	Road Segment Slope %	Slope Factor	Standardized Base Erosion Rate (tons/sq mi/yr)
OBw1	374	13	3.00	125
OBw2	698	5	0.44	1,570
OBw3	299	8	1.14	263
OBC1	821	11	2.15	382
OBC2	617	11	2.15	287
OBM1	111	5	0.44	249
OBM2	272	6	0.64	425
OBM3	44	4	0.28	154
LBw1	82	5	0.44	185
LBw2	51	8	1.14	45
LBw3	350	5	0.44	788
LBM1	131	4	0.28	462
LCr1	49	7	0.87	56
LCr2	30	2	0.07	424
MCr1	368	7	0.87	422
MCr2	81	6	0.64	127
Average	**274**			**373**

The WARSEM base road erosion rate for the watershed (19,264 tons/square mile/year) was computed using the factors in the WARSEM program for a road in the watershed with native surfacing[1], then adjusted to the standardized base erosion rate from measured segments (373 tons/square mile/year) to provide a Cedar-Watershed specific calibration factor (0.0194) for the WARSEM calculations. The calibrated WARSEM erosion values tracked much more closely with measured values (Figure 14). It is recommended that a calibration factor be applied to the WARSEM model results in the future. Note that the 0.0194 calibration factor is based on the coarse-grained sediment production only; if it is assumed that the settling basins had a 50% trap efficiency (Section 3.3.1), the total sediment production (fine and coarse sediment) could be twice the measured amount (746 tons/square mile/year) and the calibration factor would be 0.04.

[1] The base WARSEM erosion rate was calculated using the following formula: Tread & Ditch Sediment= Geologic Erosion Factor (2 tons/acre/yr) x Tread Surfacing Factor (1) x Traffic Factor(1) x Road Area (1 square mile = 640 acres) x Road Gradient Factor (1) x Rainfall Factor $[0.016*(96 \text{ inches/yr})^{1.5}]$ x Delivery Factor (100%)

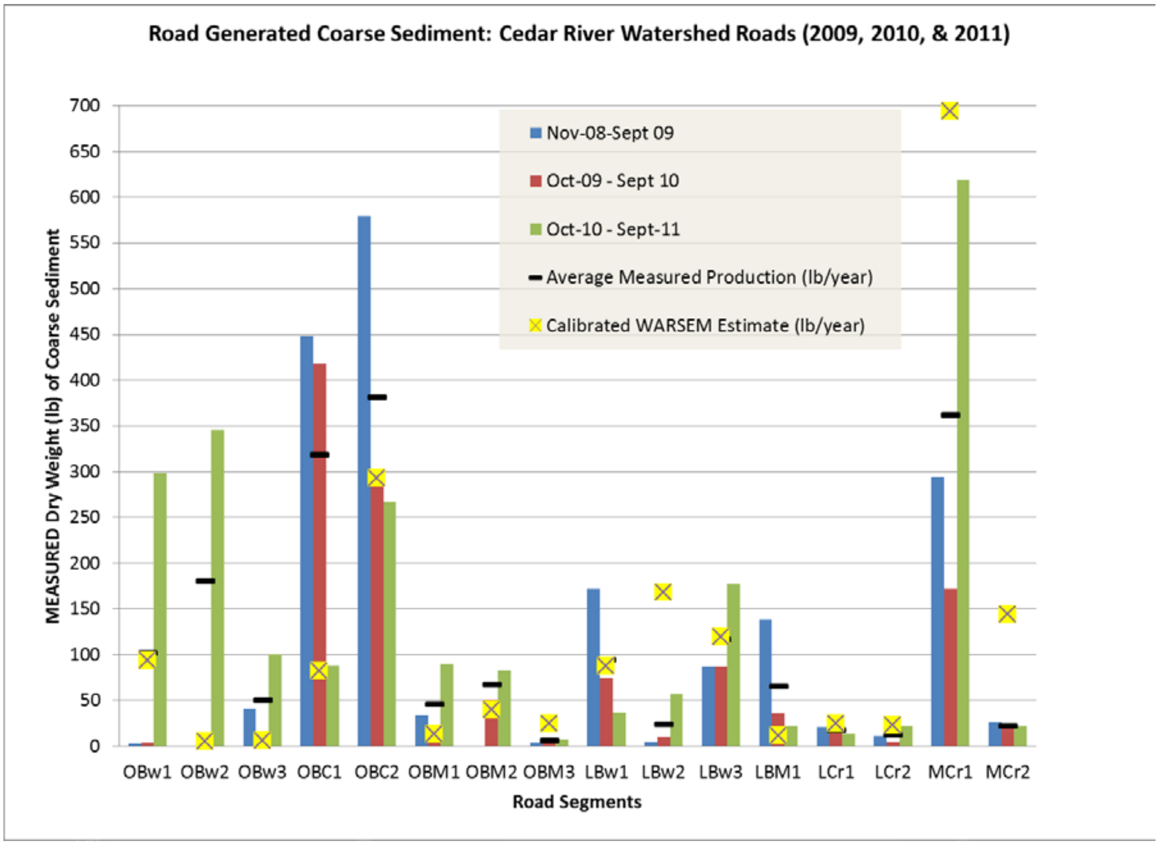


Figure 14. Measured and calibrated predicted road sediment yield at road plots.

3.5 Sediment Delivery Distance

In order for sediment produced on a road to have an effect on aquatic resources or water quality, the sediment has to be transported from the road surface to a stream or wetland. In some cases, road runoff flows directly into a stream, for example where the road ditch drains directly to a stream, but in other cases the road ditch drains to a relief culvert with an outlet on a forested slope, or the road is outsloped and the tread runoff drains to the forest floor. The distance eroded sediment can be transported across a forested hillslope depends on a variety of site-specific conditions, including volume of water and sediment being transported, gradient of the hillslope, infiltration capacity of the soil, and the number of obstructions (e.g., twigs, leaves, branches, vegetation, soil depressions) on the slope. The WARSEM model bases the percent delivery of eroded sediment on three delivery distance categories: direct connection to stream via ditch or gully (100% delivery); outlet 1-100 feet from a stream (35% delivery); and outlet 101-200 feet from a stream (10% delivery). In the present study, silt fences on forested hillslopes were used to determine the amount of sediment captured at 10, 25, 50, and 100 feet from a road/culvert outlet.

The amount of sediment trapped on the silt fences were measured over three years and generally decreased with increasing distance from the road/culvert; very little sediment was transported to the silt fences farther than 50 feet from the road prism (Table 9, Figure 15).

Table 9. Measured sediment trapped on silt fences.

Silt Fence Site	Distance from Road (ft)	Measured Sediment Trapped at Fence (lbs)			
		Nov-08-Sept 09	Oct-09 - Sept 10	Oct 10- Sept 11	3-Year Average
DD-03	10	558	510	131	400
DD-06	10	65	42	58	55
DD-12	10	5	7	7	6
DD-01	25	3	4	68	25
DD-07	25	185	10	147	114
DD-11	25	59	4	7	23
DD-04	50	5	5	5	5
DD-05	50	2	8	6	5
DD-10	50	2	2	3	2
DD-02	100	5	1	9	5
DD-08	100	2	1.5	4	3
DD-09	100	6	2	5	4

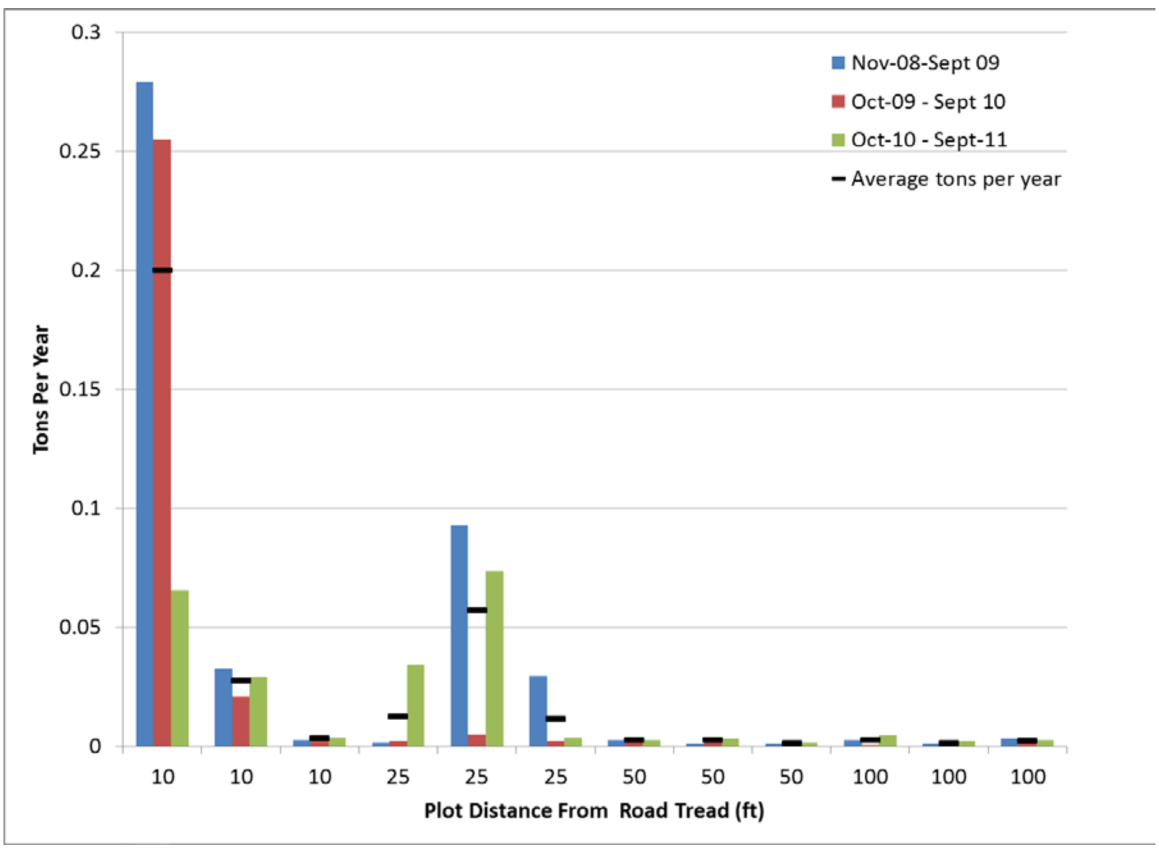


Figure 15. Amount of sediment trapped on silt fences.

The amount of sediment trapped on each silt fence was compared to the WARSEM estimated production from the associated road segment to calculate percent of the total eroded sediment that was delivered to the silt fence. These data were plotted against distance of the silt fence from the road to evaluate the distance versus percent delivery relationship for the CRMW (Figure 16). Delivery distances were found to be less than those used in the WARSEM model, which were developed based on data from Idaho where climate, soil, and ground cover conditions facilitate greater delivery distances. Delivery in the Cedar River Municipal Watershed was calculated to be (based on a logarithmic relationship with distance from the road prism): 27% at 10 feet from road; 15% at 25 feet from road; 5% at 50 feet from road and 0% at 100 feet from road.

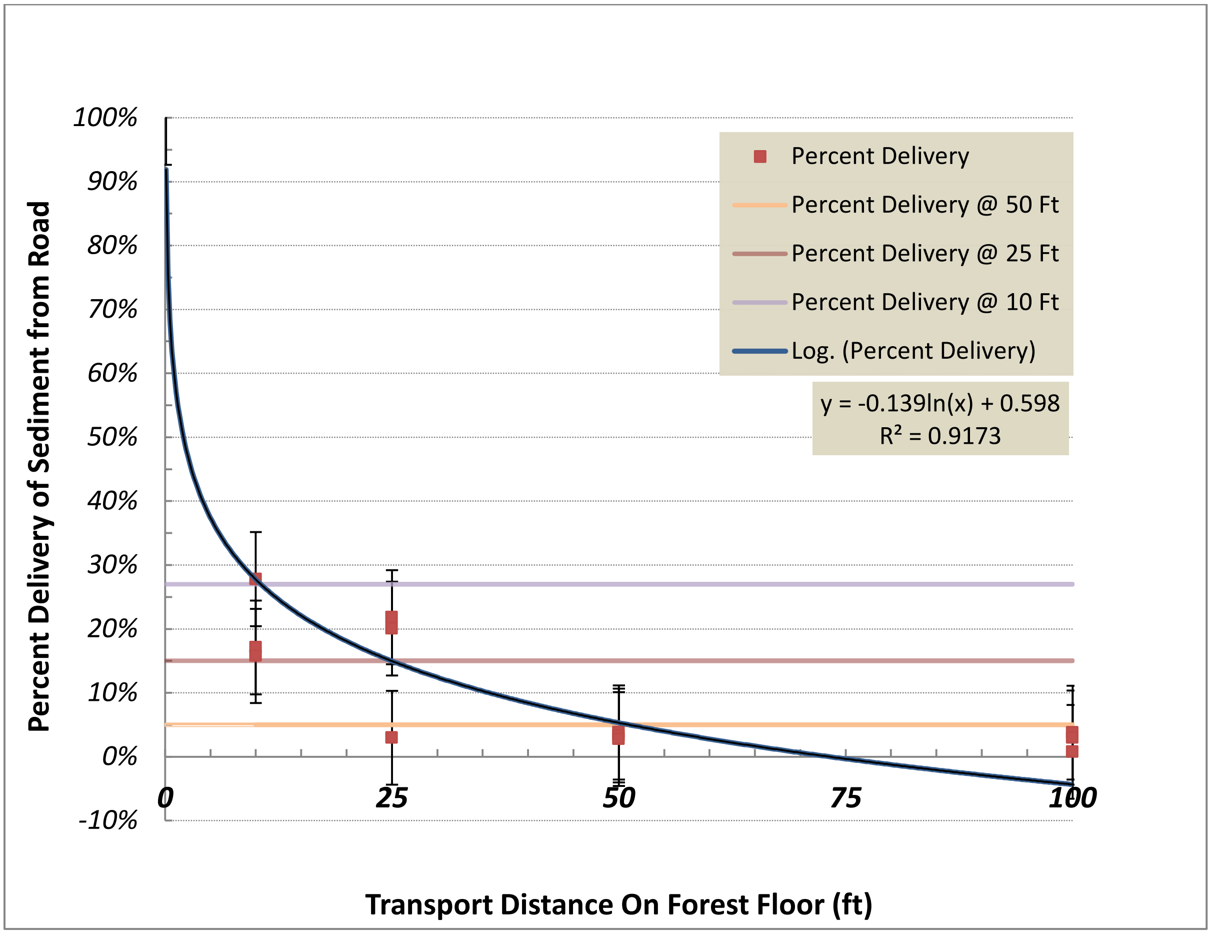


Figure 16. Percent sediment transport vs. distance from road prism.

While the logarithmic regression shows a decline between 50 and 100 feet from the road, the silt fence data for these two distances show similar, very low levels of sediment/debris accumulation at both distances. It is possible that either: 1) since the material collected on the 50 and 100-foot silt fences was primarily organic matter, this material could have been part of the normal downslope-movement of leaf and needle litter and not related to road erosion, so little sediment moved past 50 feet from the road; or 2) if some of the material is road-related, then there is some small amount of sediment that moved beyond 100 feet from the road prism which should be included in future modeling of transport distances. Due to the high infiltration capacity of undisturbed forest soils in the CRMW, the deep litter mat, and the numerous obstructions on the ground, it is most likely that little road-related sediment is transported past 50 to 100 feet from the road surface unless the road runoff is concentrated enough to form a gully (a gully was seen upslope of at least one of the silt fences and resulted in substantial sediment delivery downslope). Brake et al. 1997 monitored road sediment transport distances in the Oregon Coast Range and found that little sediment was transported farther than 25 feet from the road prism. The CRMW data are consistent with the short transport distances found in the Brake study.

4 Summary and Management Implications

The Cedar River Watershed has a legacy road network that includes nearly 600 miles of unpaved forest roads. Erosion from these roads has the potential to deliver sediment to streams, lakes, and wetlands within the watershed, potentially degrading aquatic habitat and water quality. An inventory of all the roads in the watershed was undertaken in 2004 and updated in 2007 and 2012 following road work to help reduce the amount of sediment produced and delivered from the road network. Because it is very time-consuming to measure actual sediment production from roads, the Washington Road Surface Erosion Model (WARSEM) was used to estimate both erosion and delivery from the road network. Recent studies of road surface erosion models have shown that while the models predict relative differences in roads with different conditions well (e.g., traffic, surfacing, gradient) and are therefore useful for predicting changes in erosion resulting from road management activities, calibration with locally-measured erosion rates is needed if the models are to predict actual amounts of eroded sediment from a particular road segment (Dubé et al. 2011).

In order to test the WARSEM predictions of road surface erosion and delivery in the Cedar Municipal River Watershed, sediment eroded from 16 road segments covering a variety of traffic, gradient, and surfacing conditions was measured annually between 2008-2011. In addition, sediment was collected at 12 silt fences located 10, 25, 50, or 100 feet from roads to help understand how far road sediment is transported across the forest floor. These data were collected to help address the following critical questions:

Erosion Critical Question 1: How accurate are the WARSEM estimates of road surface erosion in the Cedar River Municipal Watershed?

> The measured erosion rates were standardized for road gradient and compared to the WARSEM estimates of erosion from roads with similar characteristics for each measured segment. Measured rates were found to be substantially lower than the WARSEM predicted rates for all road segments; a calibration factor was derived to adjust WARSEM estimated erosion rates to more realistically portray actual road surface erosion rates in the watershed. The adjustment factor depends on whether road surface is fine-grained or coarse-grained as follows:

- Coarser-grained surfacing (Native Coarse Blocky, Native Medium Fine) – multiply WARSEM results by 0.02 to obtain more realistic measure of erosion.
- Finer-grained surfacing (Borrow, Crushed Gravel) - multiply WARSEM results by 0.04 to obtain more realistic measure of erosion.

It is recommended that the calibration factor be applied to future WARSEM model results. Section 4.1 provides updated WARSEM values for existing road conditions.

Delivery Critical Question 2: How accurate are the WARSEM predictions of delivery of eroded sediments in the Cedar River Municipal Watershed?

The standard WARSEM predicted delivery rates were compared to those obtained from the CRMW:

WARSEM	Cedar River Municipal Watershed
Direct connection - 100%	Not measured, but assumed 100%
1-100 feet – 35%	10 feet – 27%
	25 feet – 15%
	50 feet – 5%
101-200 feet – 10%	Over 100 feet – 0%

Delivery distances in the Cedar River Municipal Watershed are less than those used in the WARSEM model. The CRMW road erosion inventory categorized culverts into five different delivery categories. It is recommended that the following factors be applied to future WARSEM model delivery results:

Inventory Delivery	Adjusted WARSEM Delivery Percent
None	0%
Direct	100%
Direct via gully	100%
1-100 feet	25%
101-200 feet	0%

These adjusted WARSEM delivery percentages were developed to apply to the existing road inventory categories which differentiated between culverts in the following distance bins: 0-100 feet and 101-200 feet. If future inventory or site-specific road analysis is conducted, the delivery percentages listed for the CRMW based on 0-10 feet, 11-25 feet, and 26-50 feet (above) could be applied based on actual site conditions for specific culverts. It is not recommended to adjust existing culvert delivery categories based on the proximity of culverts to streams using the current GIS layers due to the fact that some roads and streams are not depicted accurately enough for this level of analysis in GIS shapefiles.

The implications of the measured delivery rates for management activities in the CRMW are that roads/culverts with outfalls farther than 50-100 feet from a stream likely do not delivery appreciable amounts of sediment to streams unless there is a gully below the culvert. This provides an opportunity to disconnect the road system from the stream at stream crossing by installing relief culverts with outfalls that have 50 or more feet of vegetated/undisturbed forest floor between the outfall and the edge of the stream.

Traffic Critical Question 3: How much sediment is produced from low traffic roads in the CRMW?

The amount of sediment produced from low traffic (Occasional use) roads varied between segments, but on average was considerably more than segments with higher traffic levels. One factor contributing to the higher sediment production levels from Occasional use roads could be that many of these roads are steeper than roads with higher traffic levels, or the data could be showing higher erosion due to the better trapping of the coarser-grained surfacing on these roads in the sediment tanks. Erosion has been shown to vary with the road gradient squared, so steeper roads can produce greater amounts of sediment even if they have less traffic. The data collected on roads with low (Occasional) traffic use in the watershed suggest that these roads have the ability to produce a considerable amount of sediment, particularly from long, steep segments. It is recommended that placing additional culverts 50 feet or greater away from streams would help disconnect these roads from the aquatic system. Additional research may be needed regarding traffic and sediment production or additional review of maintenance activities and ditch condition/sediment trapping is needed on occasional use roads, particularly those with gradients over about 8% where rilling or gullying of the tread or ditch can occur.

Critical Question 4: How much sediment is produced and delivered from high use roads adjacent to key water features?

Two higher use road segments were sampled, one segment on the 70 road and another on the 100 road. The 70 road segment (MCr2) had less sediment (and much less traffic according to the traffic counter data) than the 100 road segment. The measured data do not completely answer Critical Question 6 due to the wide variation in sediment production between the two high use segments measured. Additional data collection on other high use road segments that include methods to measure fine-grained sediment that do not collect in settling tanks would be needed to completely answer this question.

4.1 Adjusted WARSEM Results

In 2005, road surface erosion was calculated using WARSEM for road conditions measured during an inventory of roads in the watershed in 2004. Since 2005, road maintenance, upgrades, and decommissioning has taken place. Re-inventories of roads that had maintenance or upgrades took place in 2007 and 2012. The WARSEM estimates of the most recent road conditions (2012 inventory) were computed and then adjusted based on surfacing and delivery type following the recommendations above (Critical Questions 1 and 2). The results are shown by sub-basin in Table 10, which lists miles of delivering roads, estimated average tons of sediment delivered from surface erosion, and the Washington DNR Forest and Fish Report targets/metrics for each sub-basin.

Sub-basin values for three targets assessing either amount of sediment delivered to streams or length of road delivering runoff/sediment to streams were compiled, and the sub-basins were ranked for each target from highest to lowest. The ranks were summed; Table 10 lists the sub-basins in order from most affected (highest relative sediment delivery and/or hydrologic connectivity) to least affected.

Table 10. Estimated road length delivering, sediment delivery, and road sediment targets by sub-basin.

Sub-basins	Sub-basin Area (mi^2)	Total Stream Length (miles)	Miles of Road which Deliver to Surface Water	Average tons of Sediment Delivered (tons/yr)	Target 1: Road Surface Erosion (*WARSEM Prediction*) (Tons/yr/mi^2)	Sub-basin Rank: Target 1	Target 2: Road Length Delivering: Total Stream Length (mi./mi.)	Sub-basin Rank: Target 2	Target 3: Road Sediment production: Total Stream Length (t/yr/mi.)	Sub-basin Rank: Target 3	Total Rank (Sum of Targets 1-3)
Cabin Ck	0.56	1.4	0.70	0.89	1.59	2	0.50	3	0.82	2	7
Green Pt Ck	0.96	4.1	1.42	1.73	1.80	1	0.35	7	0.83	1	9
Walsh Ditch	4.35	11.6	4.21	4.87	1.12	5	0.36	6	0.49	4	15
Seattle Ck	3.79	16.1	8.90	2.68	0.71	8	0.55	1	0.33	9	18
Steele Ck	1.07	3.3	0.97	1.37	1.28	3	0.29	10	0.46	7	20
Middle Fk Taylor	6.09	24.3	5.87	6.15	1.01	6	0.24	12	0.47	5	23
Williams Ck	2.44	6.6	1.56	3.06	1.25	4	0.24	13	0.46	6	23
Lindsey Ck	3.85	14.4	6.98	1.91	0.50	11	0.48	4	0.26	12	27
Rex River	12.08	42	12.52	6.12	0.51	10	0.30	9	0.28	10	29
Rack Ck	2.25	9.8	2.22	2.09	0.93	7	0.23	15	0.42	8	30
Cedar below Williams	7.89	7.8	4.11	1.02	0.13	26	0.53	2	0.71	3	31
McClellan Ck	1.51	6.1	1.34	0.80	0.53	9	0.22	16	0.23	13	38
South Fk Cedar	7.06	22.2	9.88	2.00	0.28	20	0.45	5	0.18	15	40
South Fk Taylor	2.05	9.7	3.27	0.81	0.40	15	0.34	8	0.11	21	44
Boulder Ck	4.73	21.4	4.12	2.04	0.43	13	0.19	20	0.19	14	47
Chester Morse Lk	11.23	25.7	3.60	4.01	0.36	18	0.14	21	0.27	11	50

Sub-basins	Sub-basin Area (mi^2)	Total Stream Length (miles)	Miles of Road which Deliver to Surface Water	Average tons of Sediment Delivered (tons/yr)	Target 1: Road Surface Erosion (*WARSEM Prediction*) (Tons/yr/mi^2)	Sub-basin Rank: Target 1	Target 2: Road Length Delivering: Total Stream Length (mi./mi.)	Sub-basin Rank: Target 2	Target 3: Road Sediment production: Total Stream Length (t/yr/mi.)	Sub-basin Rank: Target 3	Total Rank (Sum of Targets 1-3)
Taylor Ck	4.7	12.4	1.37	1.87	0.40	14	0.11	25	0.15	16	55
Pine Ck	1.6	5.7	1.34	0.39	0.24	23	0.23	14	0.13	18	55
Cedar bw Falls and Williams	9.78	26	6.46	3.66	0.37	17	0.25	11	0.04	28	56
Upper Cedar	10.54	32.4	6.39	2.59	0.25	22	0.20	19	0.14	17	58
Bear Ck	3.05	9.8	2.11	0.93	0.31	19	0.22	17	0.10	22	58
Rock Ck	4.52	13.9	1.66	1.76	0.39	16	0.12	24	0.13	19	59
North Fk Taylor	4.27	20.8	0.72	1.95	0.46	12	0.03	28	0.12	20	60
Goat Ck	2.06	7.4	1.55	0.57	0.28	21	0.21	18	0.07	24	63
Roaring Ck	1.09	4.5	0.49	0.20	0.18	24	0.11	26	0.09	23	73
Findley Ck	2	7.5	0.97	0.25	0.13	27	0.13	23	0.07	25	75
North Fk Cedar	9.99	33.9	4.59	1.00	0.10	28	0.14	22	0.06	27	77
Eagle Ridge Ck	1.32	2.8	0.00	0.18	0.14	25	0.00	29	0.07	26	80
Otter Ck	0.69	2.6	0.17	0.03	0.04	30	0.06	27	0.02	29	86
Damburat Ck	0.51	1.8	0.00	0.04	0.07	29	0.00	30	0.02	30	89
Shotgun Ck	0.88	3.4	0.00	0.02	0.02	31	0.00	31	0.01	31	93

Yellow highlight indicates sub-basin exceedance of proposed FFR performance target – Target 2 for western Washington is 0.25 miles/mile

4.2 Knowledge Gaps

Three of the critical questions originally included in the study plan for the road erosion monitoring study were not specifically addressed in the current study due to budget and time constraints, although data collected for this study provide some insights into these questions:

> **Sediment Reduction: Critical Question A:** What is the actual reduction of road surface erosion due to road work in the Cedar River Municipal Watershed?
>
> **Road Use: Critical Question B:** How much sediment is produced from road use/alterations associated with temporary, project-related effects (e.g., thinning operations)?
>
> **WARSEM Modeling: Critical Question C:** Do the road segments WARSEM predicted to be the highest sediment producers actually produce large quantities of sediment?

Sediment Reduction: Critical Question A: What is the actual reduction of road surface erosion due to road work in the Cedar River Municipal Watershed?

Justification: A great deal of effort has and continues to be expended to reduce sediment input from roads in the watershed. A measure of the success of this effort is important to help determine the cost effectiveness of these actions. Common expensive measures used to address this issue include surfacing (gravel), grading, ditching/cleaning, armoring ditches, addition of culverts, vegetation management, and installation of silt fencing.

Scope of Study: Sampling the effectiveness of BMPs requires either a paired segment study (one segment without BMP, another similar one with the BMP) or monitoring of a single segment without the BMP for several years, adding the BMP, and monitoring the segment with the BMP for several years. Recommended BMPs to measure are:

- Adding gravel
- Grading
- Ditching/cleaning
- Armoring ditches

Due to budget constraints, this question was not tested in the current study, but the data collected shows the differences between different road surfacing (e.g., native surfacing vs. crushed rock or borrow) which is one method used to reduce surface erosion in the watershed. Another BMP, disconnecting the road and stream network by installation of cross drains or drivable dips farther than 50 feet from a stream, was shown to be effective in the delivery distance (silt fence) testing. In order to completely answer the question, additional monitoring of paired segments from different BMP measures (as discussed above) would be needed.

Road Use: Critical Question B: How much sediment is produced from road use/alterations associated with temporary, project-related effects (e.g., thinning operations)

Justification: Temporary changes in traffic patterns and road maintenance and reconstruction are associated with special projects such as thinning operations in the watershed. Disturbance associated with special projects generally last less than one year and will continue at various locations in the future. These temporary changes likely result in a temporary increase in sediment production from the affected areas. Research in other locations suggests the temporary increases from only changes in traffic use return to normal levels in a short period of time (days to weeks; Reid 1981), but increases from road reconstruction take 2-3 years to return to pre-disturbance levels (Ketcheson et. al 1999, Luce and Black 1999a, Grace 1999, Swift 1984, Dryness 1975, Megahan 1974, Megahan and Kidd 1972).

Scope of Study: This critical question was not included in the current study. Additional monitoring, as described above, would be needed to completely answer this question

WARSEM Modeling: Critical Question C: Do the road segments WARSEM predicted to be the highest sediment producers actually produce large quantities of sediment?

Justification: The top 20 WARSEM-predicted road segments have the following characteristics: direct/direct via gully delivery, long segment lengths (500-2,500 feet), native surfacing (all but 2), high gradient (7-20%), and varying traffic rates.

Scope of Study: Directly sampling the predicted high sediment producers is a great goal. However, the long lengths (most over 800 feet long) would preclude them from being part of the "constant length" pool of study segments discussed in Critical Question 1. This critical question was not included in the current study, and would require monitoring of high sediment producing segments.

There was considerable variability in the measured road erosion rates, as has been found in studies in other parts of the country. The variability highlights the fact that many site-specific conditions that are difficult to assess can influence road surface erosion rates. Additional monitoring of road surface erosion, particularly collection of fine-grained sediment that was not trapped in the sediment tanks, would provide higher confidence in the results, particularly for roads with finer-grained surfacing.

The collected data do provide a range of erosion rates that can be used to assess current and future road surface erosion and appropriate methods to reduce delivery of sediment to streams and lakes in the watershed to protect aquatic resources and water quality. Based on the data collected as part of this study, the most effective way to reduce delivery of sediment to waterways in the CRMW is to disconnect road segments from the stream network, particularly those that drain roads with steep gradients or fine-grained surfacing. Roads/culverts/ditchlines that deliver sediment within 25 feet of a stream could be disconnected from the stream by installing drivable dips (on low use roads) or cross drains (on higher use roads where drivable dips are less desirable) that deliver runoff/sediment to the undisturbed forest floor more than 50 feet away from the stream.

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