PREDICTING SEDIMENT DISCHARGE FROM FOREST ROADS: THE ROLE OF SURFACE RUNOFF AND RAINFALL INTENSITY

Joseph R. Amann, Hydraulic Engineer, WEST Consultants, Inc., Bellevue, Washington; email: jamann@westconsultants.com; Dr. Arne Skaugset, Associate Professor, Department of Forest Engineering, Oregon State University, Corvallis, Oregon; email: arne.skaugset@oregonstate.edu

Abstract: Unpaved roads can be sources of chronic sediment to streams in forested watersheds. The bare soil on forest roads is subjected to rainfall and overland flow, which lead to surface erosion. Published research on sediment production from forest roads focuses primarily on road and hillslope characteristics. Water drives the mechanics of sediment transport; therefore, hydrologic variables should correlate with sediment production from roads. This project investigated the relationship between parameters representing storms that produced runoff on individual road segments in a forested watershed and the sediment production from those road segments. Rainfall parameters were correlated with sediment production for nine road segments in the upper Oak Creek Watershed in western Oregon near Corvallis from November 2002 through June 2003.

INTRODUCTION

Most running surfaces of roads in managed forests are a mixture of aggregate and soil that has low infiltration capacities. The soil from the road can be transported to streams and can degrade aquatic habitat and water quality. Accurate prediction of the potential of road segments to produce sediment could help focus efforts to reduce erosion from roads. Existing tools that quantify sediment production from roads focus on 1) road design, 2) physical characteristics of the road, 3) the amount and type of traffic on the road, and 4) road maintenance. There are fewer research results available that relate sediment production from roads to hydrologic variables. Since water drives sediment transport mechanics, hydrologic variables, such as rainfall amount as well as intensity and runoff amount, should be good predictors of sediment production from roads. This project assessed sediment production from unpaved roads in a small forested watershed in the Oregon Coast Range. The results of this study are part of ongoing research to understand sediment production from aggregate surfaced forest roads and to minimize the production of this sediment.

Site Description: Upper Oak Creek is an actively managed forested watershed in the eastern foothills of the Oregon Coast Range. It encompasses 824 hectares in McDonald-Dunn Research Forest, the school forest for the College of Forestry at Oregon State University, northwest of Corvallis, Oregon (Figure 1).

The elevation of the watershed ranges from 140 to 600 meters and hillslope gradients range from 20 to 70 percent. Discharge from the watershed is measured at the boundary of the Research Forest. Traffic is light and consists mainly of vehicles involved in research or teaching on the school forest. Other activities in the watershed include hiking, bicycling, and horse-back riding. There are 4,880 meters of stream in the watershed resulting in a drainage density of 5.92 m/ha and there are 4,570 meters of road in the watershed resulting in a road density of 5.55 m/ha. The average width of the roads is five meters. They are crowned with drainage ditches and all are aggregate-surfaced. Most of the road system was built in the 1950's and 1960's using cut-and-fill construction methods.

The watershed is instrumented with four tipping-bucket rain gauges, a micrometeorology station, and capacitance rods (automated water-level recorders) were installed at the inlet of all culverts. Sediment traps were installed at the outlet of nine cross-drain culverts. Data were analyzed on time scales that ranged from individual storms to the complete winter. This was a small-scale, observational case study that describes processes at individual road segments.

METHODS

Sampling sites were selected using a backward elimination process. The process began by using the GIS database developed by Ellingson (2002) to locate the population of cross-drain culverts within the Oak Creek Watershed. The flow data from these culverts from past winters were used to identify fifteen culverts that had experienced the highest flow. Of these fifteen culverts, nine were chosen based on the ease of installing the sampling equipment.

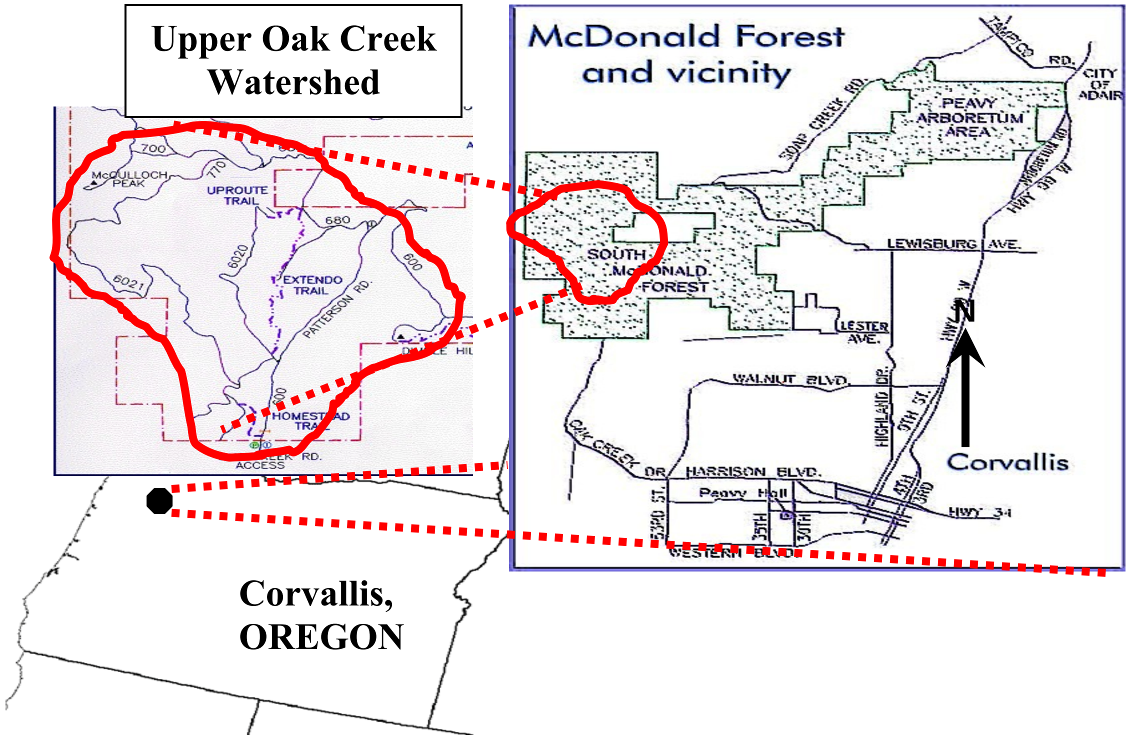

Figure 1 Location of study site.

Hydrology: Precipitation in the upper Oak Creek watershed was measured using four NovaLynx® tipping bucket rain gauges each mated with an Onset® HOBO event data logger. Culvert discharge was measured using depth/discharge relationships. Depth of water at each cross-drain culvert was measured using Tru-Track®, model WT-HR 500 (820 mm length) electronic automated capacitance rods. The location of the rain gauges and culverts is shown in Figure 2.

Sediment: Three types of sediment traps were used to capture sediment during this study. Each type of sediment trap corresponded to a specific size class of sediment observed: coarse, settleable, and suspended. A geotextile sock was attached to the outlet of each study culvert that trapped the coarse fraction (≥ 0.425 mm or #40 U.S. Sieve) of sediment and organic debris. A barrel was installed at the outlet of the geotextile sock that trapped the settleable size fraction that was too small to be trapped by the geotextile sock but large enough to settle out in the barrel. Finally, an ISCO water sampler was used to sample the suspended sediment size fraction that flowed out of the barrel.

RESULTS AND DISCUSSION

Hydrology: During the period of study, November 17, 2002 through June 18, 2003, precipitation was slightly below average for the region. Monthly precipitation during the study period is summarized in Table 1.

Table 1 Monthly 2002 - 2003 total precipitation in upper Oak Creek watershed and Hyslop weather station Corvallis, Oregon. Values are in millimeters of precipitation. Note: "N/A" indicates rain gauge malfunction.

Rain Gauge Location	Elevation (m)	NOV 2002	DEC 2002	JAN 2003	FEB 2003	MAR 2003	APR 2003	MAY 2003	JUN 2003
Dimple Hill	440	146	338	224	N/A	N/A	161	N/A	N/A
McCullough Peak	592	152	367	254	110	248	N/A	N/A	N/A
Oak Creek Meadow	163	141	320	204	99	210	N/A	N/A	N/A
Starker Meadow	324	159	385	247	114	264	182	N/A	N/A
Hyslop	70	137	318	183	91	191	165	34	9
Average (not including Hyslop)		149	353	232	108	241	171	N/A	N/A

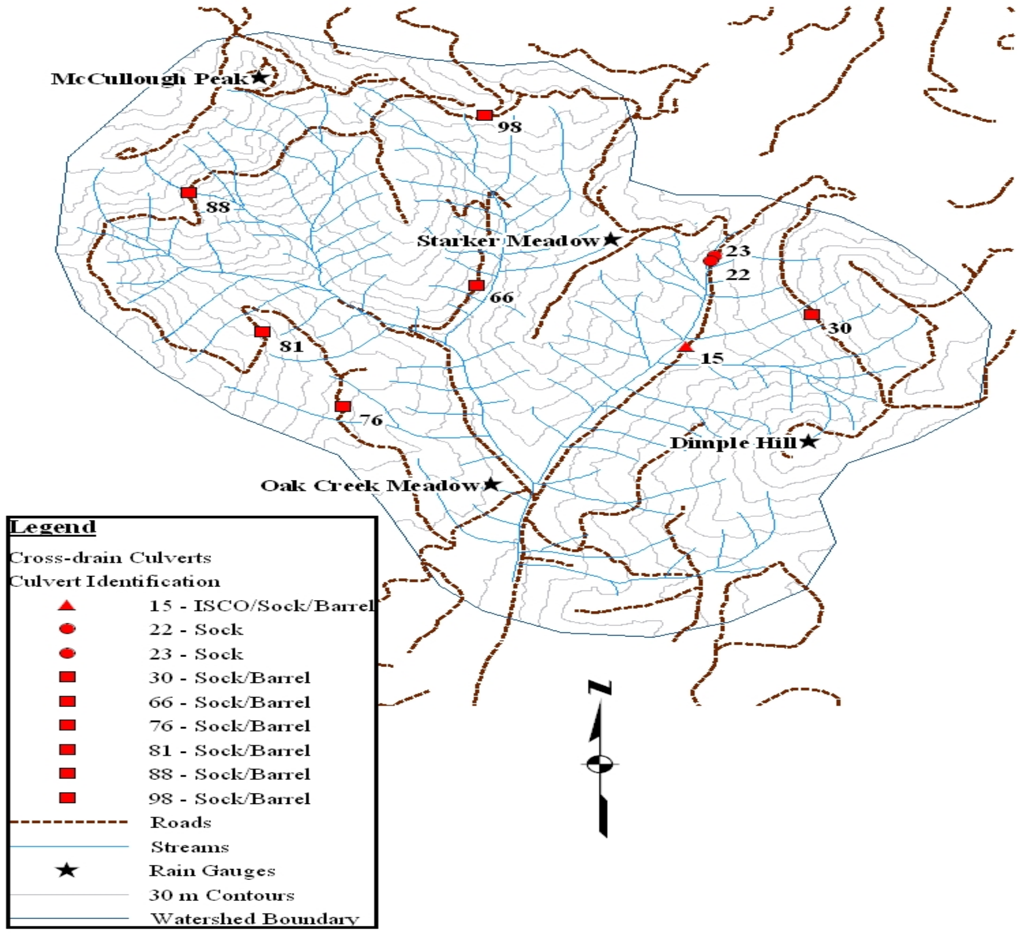

Figure 2 Upper Oak Creek Watershed rain gauge and sediment sampling site locations.

Analysis was carried out for four storms. A storm was defined as any 24-hour period when at least 12.7mm (0.5 inch) of precipitation was recorded. Storms occurred March 5-9, April 11-15, April 23-27, and May 3-5, 2003. Storm attributes are summarized in Table 2.

Table 2 Summarized precipitation and discharge data used for storm analysis. Discharge data is from culvert 15.

Storm Attributes	Storm 1	Storm 2	Storm 3	Storm 4
Date	March 5-9	April 11-15	April 23-27	May 3-5
Duration (hr:min)	97:25	96:24	83:02	31:25
Total Precipitation (mm)	82	28	43	16
1-hr intensity (mm/hr)	5.2	6.1	1.8	2.0
2-hr intensity (mm/hr)	3.2	3.7	1.4	1.7
24-hr intensity (mm/hr)	1.6	0.9	1.4	0.6
Cumulative Discharge (m^3)	33	25	86	24
Depth of runoff from culvert (mm)	63	47	163	46
Average runoff rate (mm/hr)	0.65	0.49	1.96	1.46
Runoff Ratio	3.0	6.7	15.1	11.3
Peak Discharge (L/s)	0.27	0.39	0.43	0.25
Date & Time of peak	3/8/03 2:58	4/12/03 22:22	4/25/03 17:22	5/4/03 6:02

The 1-hour, 2-hour, and 24-hour rainfall intensities from these four storms varied. All storms that occurred during water year (WY) 2003 at Oak Creek had a recurrence interval of less than 1-year (Toman, 2004). The March 5-9 storm had a 24-hour intensity of 1.6 mm/hr and a total storm precipitation of 82 mm. The storm that occurred April 11-15 had the greatest 1-hour intensity of 6.1 mm/hr. These were some of the highest values recorded in Oak Creek during the 2003 WY.

Average discharge for each of the nine culverts during the study period ranged from 0.01 l/s at culvert 81 to 5.96 l/s at culvert 23. A runoff ratio was calculated for each road segment to determine the proportion of the total runoff from the road segment that came from the road surface (Marbet, 2003). The road segment that drained to culvert 81 was the only one where runoff came mainly from the road running surface. Runoff at culvert 23 was, most likely, from the contributing hillslope. These values are summarized for each culvert in Table 3.

Table 3 Summary of discharge data for all culverts.

Culvert Number	Time Span of Record	Average Discharge (L/s)	Total Runoff Volume (m^3)	Cont. Area (m^2)	Runoff Ratio	Peak Q (L/s)	Sediment (g)
15	11/17/02 - 06/18/03	0.05	945	825	5.7	1.2	3550
22	03/10/03 - 06/18/03	0.22	1870	25	16.5	2.3	400
23	03/10/03 - 06/18/03	5.96	52000	31600	173.0	355	15000
30	11/17/02 - 06/18/03	0.05	920	225	5.5	0.9	650
66	11/17/02 - 06/18/03	0.17	2600	150	16.6	1.7	1020
76	11/17/02 - 06/18/03	0.06	960	250	4.0	1.6	570
81	11/17/02 - 06/18/03	0.01	100	75	0.1	4.9	25
88	11/17/02 - 06/18/03	0.26	3960	400	21.8	3.9	80
98	01/11/03 - 06/18/03	0.39	5960	350	7.4	11.6	2510

Culvert 15 was chosen to be monitored intensively during the four storms. The runoff ratio for this road segment for the four storms was not constant. Storm 1 had the most precipitation (82 mm) and 33 m^3 of runoff. Storm 3 had roughly half the precipitation (43 mm) but 2.6 times more runoff (86 m^3). Discharge at culvert 15 for the four storms is shown in Table 4.

Table 4 Summarized discharge values during automated water sampling at culvert 15.

	Storm 1	Storm 2	Storm 3	Storm 4
Cumulative Discharge (m^3)	33	25	86	24
Depth of runoff from culvert (mm)	63	47	163	46
Average runoff rate (mm/hr)	0.65	0.49	1.96	1.46
Runoff Ratio	3.0	6.7	15.1	11.3
Peak Discharge (L/s)	0.27	0.39	0.43	0.25
Date & Time of peak	3/8/03 2:58	4/12/03 22:22	4/25/03 17:22	5/4/03 6:02

Sediment: The sum of coarse and settleable sediment trapped by geotextile socks and barrels was also highly variable and ranged from 25 g at culvert 81 to 15,000 g at culvert 23.

Coarse and Settleable Sediment: The most sediment trapped, 15,000 g, was at culvert 23 (Tables 3 and 5). This culvert may have trapped more sediment had sampling equipment been in place earlier. Culvert 23 also had the greatest total runoff volume and runoff ratio.

Total coarse sediment (geotextile sock) and coarse and settleable sediment (geotextile sock with barrel) were regressed against total runoff. These relationships had comparable R^2-values (0.53 and 0.51, respectively) and p-values (0.003 and 0.004, respectively).

Suspended Sediment: Suspended sediment concentration (SSC) was sampled at culvert 15 at 2-hr intervals. The occurrence of rainfall was recorded for each 0.254 mm (0.01 inches) of rain and discharge was recorded at 10-minute intervals. The sum of the instantaneous suspended sediment concentration (SSC), or ΣSSC, was determined using Equation 1. Storm 1 had the highest ΣSSC (1982 mg/L, Table 6) and storm 2 had the highest maximum SSC (796 mg/L) in a sample.

$$\left(\frac{mg}{l}\right) = \sum_{n}^{1} SSC\left(\frac{mg}{l}\right) \tag{1}$$

Table 5 Summary of coarse and settleable sediment for all culverts. Note: Blocked, shaded sections correspond to partitioned analysis of culvert. Suspended sediment collected only at culvert 15 was not added to the total amount of sediment for that road segment.

n	Culvert Number	Time Span of Sampling	Oven-dried Weight of Mineral Sediment (g)		
			COARSE (Geotextile Sock)	SETTLEABLE (Barrel)	TOTAL
1	15 Storm 1	03/05/03 - 03/09/03	9	90	99
2	15 Storm 2	04/11/03 - 04/15/03	97	180	277
3	15 Storm 3	04/23/03 - 04/27/03	12	75	87
4	15 Storm 4	05/03/03 - 05/05/03	63	20	83
5	15 I/S	Beg. & End of Season + Interstorm	1110	1900	3010
6	15 Total	11/17/02 - 06/18/03	1290	2260	3550
7	22	03/10/03 - 06/18/03	400	N/A	400
8	23	03/10/03 - 06/18/03	15000	N/A	15000
9	30	11/17/02 - 06/18/03	120	N/A	N/A
10	30	02/03/03 - 06/18/03	N/A	530	650
11	66	11/17/02 - 06/18/03	620	400	1020
12	76	11/17/02 - 06/18/03	430	140	570
13	81	11/17/02 - 06/18/03	0	25	25
14	88	11/17/02 - 06/18/03	35	45	80
15	98	01/11/03 - 06/18/03	2250	260	2510

Table 6 Summarized suspended sediment data during automated water sampling at culvert 15.

	Storm 1	Storm 2	Storm 3	Storm 4
ΣSSC, (mg/L)	1982	1506	717	532
Max. SSC, (mg/L)	598	796	121	189
Date & Time of Max.	3/9/03 12:00	4/12/03 22:00	4/23/03 18:00	5/4/03 6:00

For culvert 15, storm 3 was selected to illustrate some of the findings from this study. Similar results from the three other storms studied can be found in Amann, (2004). A hydrograph for the storm and a graph of SSC are shown in Figure 3. The graph shows that a given value for discharge does not yield a unique value of SSC. There was no minimum threshold of discharge that initiated the production of suspended sediment. The variability in SSC is not explained by discharge as the independent variable.

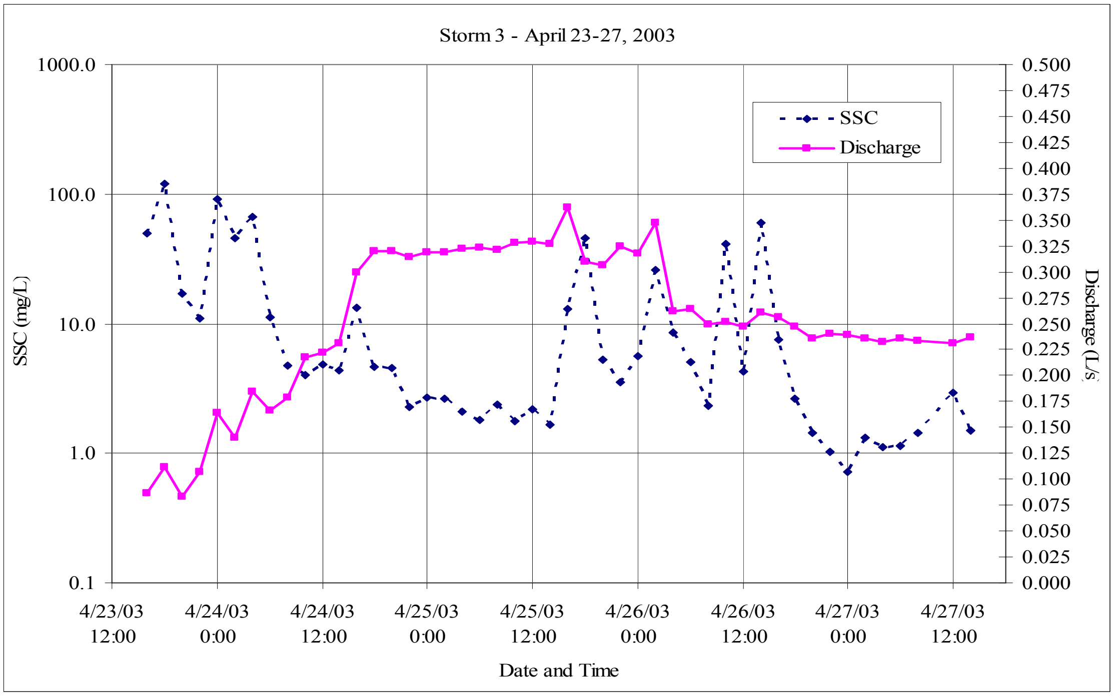

Figure 3 The hydrograph and suspended sediment concentrations at culvert 15 for storm 3. Note: SSC is on log-scale.

Cumulative discharge and ΣSSC were plotted against time to further observe how suspended sediment might be affected by discharge (Figure 4). Discharge accumulated slowly before a linear slope was achieved. However, SSC accumulated over many steps with occasional periods of production. At culvert 15, storm 3 yielded the most discharge and the third most suspended sediment.

Plots of 1-hr and 2-hr rainfall intensities and SSC at culvert 15 showed that changes in SSC are correlated with changes in rainfall intensity. In the upper Oak Creek watershed for the storms that were studied, rainfall intensity is a better predictor of SSC than culvert discharge at culvert 15. Peak 1-hr and peak 2-hr rainfall intensities for all four storms were significantly correlated with peak SSC at culvert 15 (Figure 5), which also demonstrates the close relationship between rainfall intensity and SSC. The quantity of rainfall was also related to suspended sediment (Figure 6). As rainfall accumulated, suspended sediment accumulated proportionally.

CONCLUSIONS

The amount of sediment collected from the nine segments of unpaved forest road in the upper Oak Creek Watershed was variable and ranged from as little as 0.025 kg to as much as 15.0 kg over seven months during the winter of 2002-2003. The volume of runoff measured at cross-drain culverts from the same road segments ranged from 100 m^3 to 52,000 m^3. Total runoff volume was the single most important variable that explained the variability in sediment ($R^2 = 0.51$, $p = 0.004$).

Summed instantaneous SSC (ΣSSC) was correlated with cumulative rainfall during storms 2, 3, and 4. The implications of such data suggest that sediment production from unpaved roads may be minimized if the erosive force from raindrop impact can be attenuated. The ability to predict sediment is an important step toward managing it.

The relationship between sediment production, runoff, and rainfall suggests that the erosion processes from forest roads in the upper Oak Creek Watershed is energy-limited. Rainfall energy detaches soil particles and runoff energy transports them. Without runoff, soil particles detached by rainfall would be transported only as far as the raindrop splash. Without rainfall, runoff energy would be limited to transporting only soil particles that could not withstand the shear forces of overland flow.

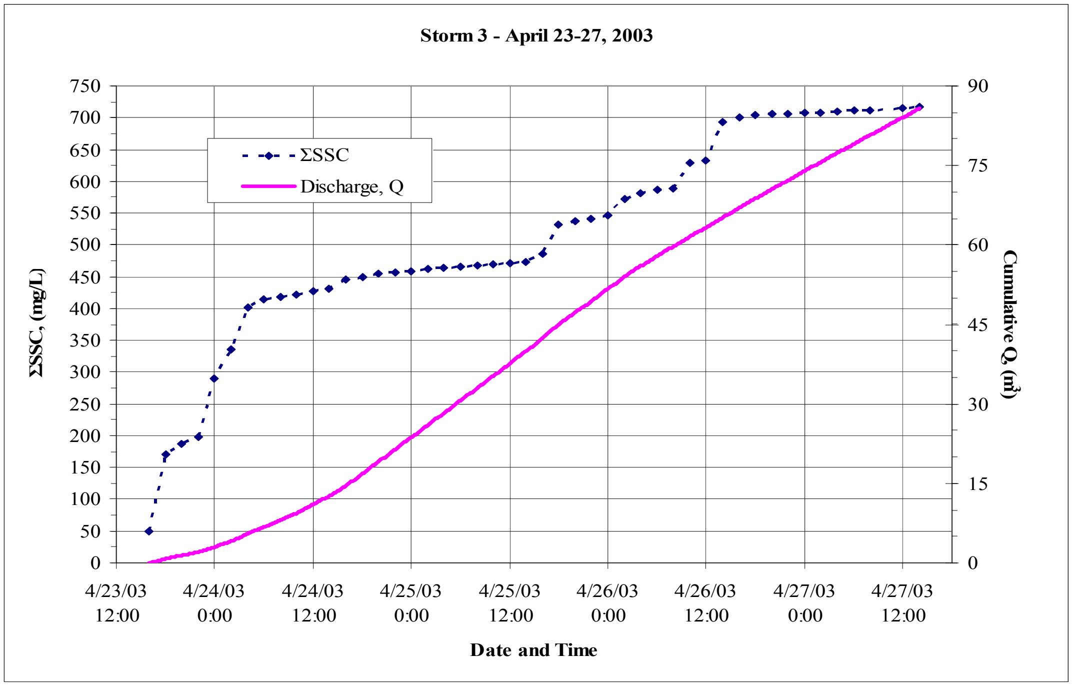

Figure 4 ΣSSC and cumulative discharge at culvert 15 during storm 3.

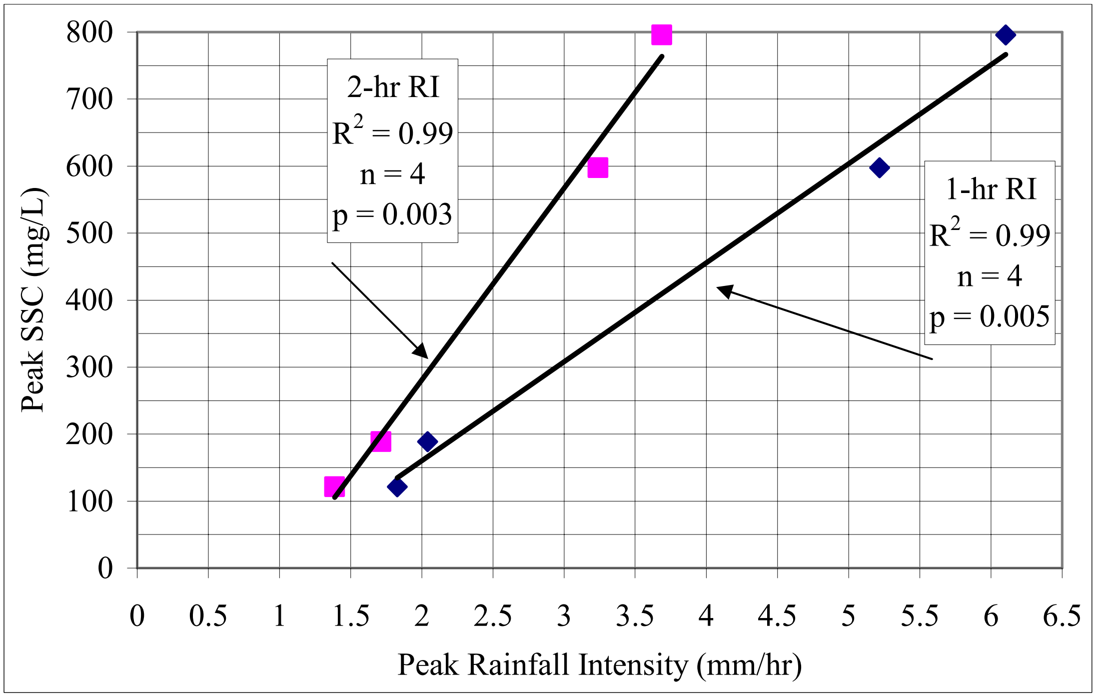

Figure 5 Regression of peak suspended sediment concentration on peak 1- and 2-hr rainfall intensity for storms 1-4 at culvert 15.

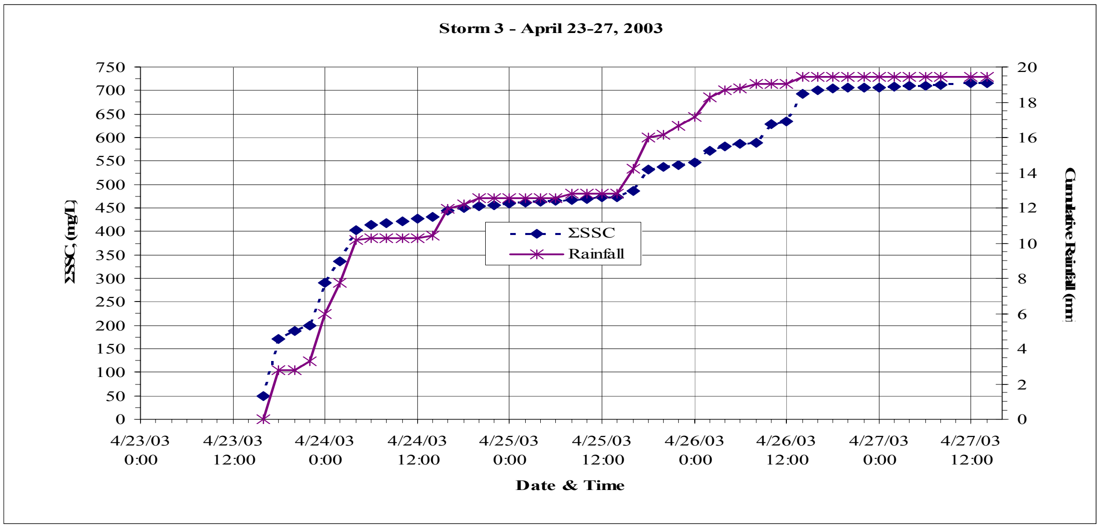

Figure 6 ΣSSC and cumulative rainfall at Culvert 15 for storm 3.

REFERENCES

Amann, J. R. 2004. Sediment production from forest roads in the Upper Oak Creek Watershed of the Oregon Coast Range. M.S. thesis. Forest Engineering Department, Oregon State University. Corvallis, Oregon. 90 pp.

Ellingson, K. 2002. Road surface runoff for the Oak Creek Watershed: the influence of hillslope and road characteristics. M.F. thesis. Forest Engineering Department, Oregon State University. Corvallis, Oregon. 63 pp.

Marbet, C. E. 2003. Hydrology of Five Forest Roads in the Oregon Coast Range. M.S. thesis. Forest Engineering Department, Oregon State University. Corvallis, Oregon. 94 pp.

Toman, E. T. 2004. Forest road hydrology: the influence of forest roads on stream flow at stream crossings. M.S. thesis. Forest Engineering Department, Oregon State University. Corvallis, Oregon. 78 pp.