AN ABSTRACT OF THE THESIS OF

Joseph R. Amann for the degree of Master of Science in Bioresource Engineering & Forest Engineering presented on April 26, 2004.

Title: Sediment Production from Forest Roads in the Upper Oak Creek Watershed of the Oregon Coast Range.

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Unpaved roads are sources of chronic sediment in forested watersheds. Bare soil on roads is exposed to erosion from rainfall and runoff. Published research on sediment production from forest roads focuses primarily on road characteristics. Since water drives the mechanics of sediment transport, hydrologic variables should correlate with sediment production. This project investigated the relationship between sediment production and runoff-producing storms.

Road and hydrologic variables were correlated with total sediment production for nine road segments in the upper Oak Creek Watershed from November 2002 through June 2003. One of the road segments was monitored intensively during four runoff-producing storms. Field data were compared with total sediment production predicted by SEDMODL2 and WEPP:Road.

Total coarse and settleable sediment produced from the nine road segments ranged from 0.025 kg (2.77×10^{-6} kg/m^2/mo) to 15.0 kg (1.04×10^{-2} kg/m^2/mo) while total

runoff volume ranged from 100 m^3 (1.11×10^{-2} m^3/m^2/mo) to 52,000 m^3 (36.1 m^3/m^2/mo). Correlation between total coarse and settleable sediment and total runoff volume for all road segments was significant ($R^2 = 0.51$, p-value = 0.004). No other variables correlated as strongly with total coarse and settleable sediment. However, while hillslope gradient and cutslope height did not yield significant correlations with total coarse and settleable sediment as individual variables, when added to total runoff volume in a multiple linear regression model, the relationship was improved.

Suspended sediment data was collected for four storms at one culvert. Results showed that suspended sediment concentration had time derivatives similar to those of culvert discharge, 1-hr rainfall intensity lagged one hour, and 2-hr rainfall intensity lagged two hours. Summed instantaneous suspended sediment concentration was correlated with cumulative rainfall.

SEDMODL2 results of predicted sediment produced from the nine road segments ranged from 0.0 to 6.7 kg (4.4×10^{-4} kg/m^2/mo). WEPP:Road results ranged from 160 kg (7.4×10^{-2} kg/m^2/mo) to 3020 kg (19.5×10^{-2} kg/m^2/mo). When compared with actual sediment data (0.025 kg to 15.0 kg), SEDMODL2 had much closer agreement. Further research is needed to quantify the total amount of *suspended* mineral sediment transported in runoff from unpaved forest roads in the upper Oak Creek Watershed.

Sediment Production from Forest Roads in the Upper Oak Creek Watershed of the Oregon Coast Range

by

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INTRODUCTION

1.1. Background

Forest roads serve many purposes that include access to and extraction of timber, fire protection, access to recreation, and access to land management. An analysis of print news media from 1994 to 1998 on public perspectives on roads in national forests showed that beliefs varied widely. Positive perceptions included recreational use and access, commodity benefits, local community benefits and fire protection. Negative perceptions included subsidy costs, ecological costs, ecological benefits of roadless areas, and roadless recreation (Bengston and Fan, 1999). The U.S. Forest Service is steward to nearly 400,000 miles of roads, which is eight times the mileage of the Interstate system. Half of the miles of road in the Forest Service road system are not maintained properly due to insufficient funds (McCullah, 2000). Changes in management objectives through the years have resulted in the network of forest roads that must be managed currently (Gilbert, 2002).

Environmental awareness in the late 1960's and early 1970's drew attention to the adverse environmental impacts of forest roads. The Federal Clean Water Act of 1972 outlined voluntary Best Professional Judgement (BPJ – today called Best Management Practices or BMPs) to minimize the adverse impacts to water quality from industrial activities including forest management (Foster and Matlock, 2001).

Since the introduction of BMPs, forest managers have made great strides to reduce adverse impacts due to forest roads, such as road-related landslides (Egan, 1999). However, based on recent publications, sediment production remains a persistent problem in roaded forested watersheds. There are ongoing efforts to understand the sediment production process and minimize sediment produced by anthropogenic causes (NCASI, 2000).

1.2. Statement of the Problem

Construction of roads in managed forests eliminates vegetation, reduces infiltration, and exposes bare soil. Soil from the road prism can be transported to surface waters and can alter aquatic ecosystems. Accurate quantification of soil that leaves the road prism (i.e. sediment production) could enable modeling of the potential for sediment production from specific road segments, thereby helping to focus efforts to reduce road erosion. Past research on quantifying sediment production from forest roads focused on the relationship between sediment quantity and 1) design of the road, 2) physical characteristics of the soil that the roadway was constructed from, and 3) the amount and type of traffic and maintenance on the road. Less research has focused on relating hydrologic variables to sediment production from forest roads. Since water drives the mechanics of sediment transport, hydrologic variables, such as rainfall and runoff, should correlate with sediment production. This project investigates the relationship between sediment production and runoff-producing storms.

1.3. Objectives

Three objectives were carried out to address the problem as stated. 1) The amount of sediment produced from forest road segments was quantified at storm and seasonal time-scales, 2) the metrics that best explain the production of sediment from road segments were determined, and 3) observed sediment quantities were compared with sediment quantities predicted by the accepted models in use today.

The overall goal of this study was to assess 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 the sediment production process on unpaved forest roads and ultimately minimize the production of anthropogenic sediment in forested watersheds.

CHAPTER 2. LITERATURE REVIEW

Sediment production from unpaved forest roads is a chronic problem that can adversely affect surface water quality. Research has focused on the relationship between sediment production and design of the road, the characteristics of the soil that the roadway was constructed from, and the amount of traffic and maintenance that occurs on the road.

Little published research exists that relates road-segment discharge and rain to sediment production from unpaved forest roads.

2.1. Sediment Production

Dietrich and Dunne (1978) constructed a sediment budget for an undisturbed forested watershed in the Oregon Coast Range and reported that soil creep in the watershed and sediment discharge out of the watershed were in rough equilibrium.

Runoff from unpaved forest roads in managed forested watersheds during storms can produce sediment that exceeds natural background levels. Excess sediment, or accelerated erosion, is the primary water pollutant associated with forest management activities (Rice et al., 1972; Beschta, 1978; Binkley and Brown, 1993).

Research on sediment production from forest roads has focused mainly on the relationship between the amount of sediment produced and road design (USDA, 1981; Boise State University, 1984; Vincent, 1985; MacDonald et al., 1997; Luce and Black, 1999), physical characteristics of the soil that the road is constructed from (Foltz and Elliott, 1997; Foltz, 1999; Luce and Black, 1999), and the amount of traffic and maintenance that occurs on the road (Reid and Dunne, 1984; Bilby et al., 1989; Foltz, 1999; Luce and Black, 1999).

A summary of the erosion process that causes sediment production from forest roads frames the impact of unpaved roads on watersheds. Erosion is initiated when rain falls on exposed soil. The impact of rain drops on bare soil exerts tremendous force on soil particles that causes detachment of the soil particles and scatters them via the raindrop splash. At the beginning of a storm, all of the rainfall infiltrates into the soil. Rainfall will continue to infiltrate into the soil until the infiltration capacity of the soil is reached. The infiltration capacity of a soil surface is a function of the density, texture, structure, and hydrophobicity characteristics of the surface.

Soils may be fine-grained such as silts or clays, which have naturally low infiltration capacities. Soils may also be coarse-grained such as sands or gravels, which have high infiltration capacities. Most surface soils are a combination of clay, silt, and sand particles. If the infiltration capacity of the soil is less than the rainfall intensity, water will pool on the soil surface until it is sufficiently deep to flow over the soil surface. Infiltration excess overland flow is referred to as Horton overland flow. Horton overland flow can also cause soil erosion. During this phase of erosion, soil is detached and transported downslope by the water.

Soils are considered either pervious or impervious based on soil texture and structure. Undisturbed forest soils of western Oregon are pervious surfaces and the infiltration capacity of the soils exceeds natural rainfall intensities (Johnson and Beschta, 1980).

Some impervious surfaces are resistant to the soil erosion that occurs with pervious surfaces. Concrete, rock, or asphalt, are not affected by raindrop splash and overland flow nor do they allow infiltration to occur. The lack of infiltration causes surface runoff to pervious surfaces, such as an unvegetated ditch or fillslope, where erosion can occur. The discharge of re-directed concentrated surface flow can affect the erodible base material that underlies impervious surfaces.

Unpaved forest roads take on the qualities of paved roads and are generally regarded to be impervious surfaces due to the compaction that occurs due to road construction and traffic. Forest roads are generally unpaved and have a coarse-graded gravel surface. Runoff from the surface of crowned roads will either discharge over the fillslope to the forest floor, or to the roadside ditch. Cross-drain culverts are installed in forest roads at a regular spacing to convey road surface and cutslope drainage from the roadside ditch to the outslope forest floor.

2.2. Why Do We Care About Excess Sediment in Forests?

Sediment from forest roads can affect local aquatic environments and downstream water users (Beschta, 1978).

2.2.1. Aquatic Environment and Habitat

Accelerated erosion in streams can be detrimental to aquatic habitat. The impacts of sediment are well-documented in the Pacific Northwest where salmon (*Oncorhynchus* spp.) are closely linked to the culture, economy, and recreation of the region. Specifically, for salmonids, deposited sediment can fill pools and reduce the flow of oxygenated water through streambed gravels, which could suffocate eggs or prevent the emergence of fingerlings (Bilby et al., 1989). Increased levels of suspended sediment can cause premature downstream migration and lowered feeding rates (Bilby et al., 1989).

Ziemer and Hubbard (1991) state that to adequately understand the impacts of forest management practices on fisheries, cumulative impacts must be understood.

The state of California's Advisory Committee on Salmon and Steelhead Trout recognized the interrelationship of forestry and fisheries in 1987. The Committee gathered a team of commercial and sportfishermen, government resource managers, university scientists, and consultants to address issues directly related to the two industries. From this meeting, two main objectives that addressed sediment were identified: 1) determine how changes in inputs of sediment and associated changes in stream channels affect aquatic habitat under varying conditions, and 2) identify and assess the cumulative effects of timber harvest on erosion, hillslope stability, streamflow, and sediment in stream channels (Ziemer and Hubbard, 1991).

Additional negative effects on aquatic resources can be attributed to excess sediment including: light attenuation, which limits primary productivity as well as visual range, smothering of invertebrate populations, and transport of sorbed contaminants (Beschta, 1978; Davies-Colley and Smith, 2001).

2.3. Hydrology

Sediment production from forest roads is an effect that results from anthropogenic disturbance of forested watersheds. How roads may affect forested environments is better understood with knowledge in physical hydrology.

2.3.1. Soils

A physical quality that makes forest soils valuable is the ability to hold and discharge water. Hursch and Fletcher (1942) illustrated that the soil profile acts like a detention facility used in stormwater design. In a more common analogy, Richardson and Siccama (2000) suggest soils act like sponges. Over time, the soil profile develops a random structure of voids and flow paths which infiltrate water to varying depths.

Many forest management practices can cause soil erosion (Croke et al., 2001). Excavation of topsoil to prepare for road construction removes organic matter, litter, ground cover, and forest canopy cover that attenuates rainfall energy. Removal of the uppermost soil horizons destroys the soil structure, collapses flow paths, and decreases infiltration.

2.3.1.1. Infiltration

Forest soils consist of macropores, channels, and burrows, that allow movement of water in all directions (Whipkey, 1965). The infiltration rate of undisturbed bare soils can be changed. Zingg (1940) suggested that pore space of bare soil surfaces can become clogged with small particles from turbid water during periods of intense rainfall. The open structure of the top layer of soil is destroyed by intense applications of water (Zingg, 1940).

Reduction in the infiltration capacity of forest roads can also occur as a result of compaction by heavy equipment (Elliot et al., 1999). Rainfall simulator measurements of infiltration capacity of forest roads in the central Oregon Coast Range were reported to range from 1.7 to 9.0 mm/hr (Marbet, 2003).

2.3.1.2. Subsurface and Surface Flow

All rainfall in undisturbed forested watersheds is conveyed down slope through the soil. Water moving through forest soils can take three flow pathways: surface flow, matrix flow, and pipeflow. Anderson et al. (1997) demonstrated with bromide injections that water can also move quickly through fractures in bedrock. If subsurface water causes soil pore pressures to exceed stability limits, hillslope failure or mass wasting can occur (Keppeler and Brown, 1998). Landslides have occurred frequently near forest roads (Megahan, 1972; Swanson and Dyrness, 1975; Swanston and Swanson, 1976; Bilby et al., 1989; Douglas, 1996; Keppeler and Brown, 1998). Ziegler and Giambelluca (1997) found unpaved roads to be critical source areas for erosion-producing overland flow. Roads in steep forested landscapes can substantially increase sediment production (Beschta, 1978)

Forest roads can intercept subsurface flow and route it to road-side ditches where it is quickly conveyed to streams (Megahan, 1972; Harr et al., 1975; Ziemer, 1981), thereby influencing the watershed discharge hydrograph (Wemple and Jones, 2003). It is believed that stream discharge can be influenced by the percentage of watershed area covered by forest roads. From a paired-watershed study in the Oregon Coast Range, Harr et al. (1975) found that peak flows increased significantly after road construction, but only when at least 12 percent of the watershed was occupied by roads.

2.3.2. Rainfall

Rainfall may possibly have the single most erosive effect on bare soil. This phenomenon was investigated by Wischmeier and Smith (1958) who found the product of the total rainfall energy of a storm and its maximum 30-minute intensity to be the best predictor of soil loss.

Reid and Dunne (1984) found that rates of sediment production were proportional to a combination of rainfall intensity, culvert discharge, and sediment concentration. Others have noted the connection between rainfall and sediment production (Vincent, 1985; Bilby et al., 1989; Luce and Black, 1999; MacDonald et al., 2001). Vincent (1985) found that road surfaces covered with snow produced little sediment, which suggests that sediment production may be minimized by covering the road surface.

Ziegler et al. (2001) found that consolidation of road surfaces makes them resistant to raindrop impact. The material and thickness of the road surface may have an effect on sediment production. Gravel in thicknesses greater than 5 cm significantly reduces sediment production from forest roads (NCASI, 2000). Ziegler et al. (2001) address road *surfaces* but the presumed relationship between rainfall and sediment production from forest roads acknowledged by other authors relates to the entire road prism.

2.3.3. Vegetation

The role of vegetation in the forest environment is noted in a study on the hydrology of subalpine forests by Troendle and Kaufmann (1987). They found that manipulation of the canopy had a noticeable impact on interception, evapotranspiration, soil water, and possibly streamflow.

2.3.3.1. Evapotranspiration

Soil moisture increases soon after clear-cutting and decreases in response to vegetation growth (Adams et al., 1991). Vegetation also affects diel patterns of streamflow as streamflow is lowest after evapotranspiration reaches a daily maximum (Bond et al., 2002) although this may not be significant during storms.

When analyzed on a relatively longer time-scale, the majority of observed increased streamflow after harvesting occurs mainly during the dormant season (Bent, 2001). Increased rates of snowmelt in clearcut areas add to stream discharge especially during rain-on-snow events (Harr, 1986; Marks et al., 1998).

The mechanism and extent of stream response to timber harvesting and roads are most notable in a literary debate amongst Jones and Grant (1996), Thomas and Megahan (1998), and Beschta et al. (2000) regarding analysis of paired watershed data from the H.J. Andrews Experimental Forest. Jones and Grant reported that harvesting and roads resulted in increased peak flows for all storms. Thomas and Megahan reported that increased peak flows did occur, but the statistical evidence of an increase for large storms was not conclusive. Beschta et al. agreed with Thomas and Megahan, but point out that different conclusions can be derived depending on the statistical methods used as well as the spatio-temporal scale of analysis.

2.3.3.2. Soil Retention/Strength/Stability

Surface cover has been observed to play a key role in the stability of soils (Elliot et al., 1999). Swanston and Swanson (1976) attribute dense vegetation, root strength, and high infiltration capacity of forest soils to protecting undisturbed forest slopes from surface and mass erosion.

Ziemer's (International Association of Hydrological Sciences - IAHS 1981) findings suggest that root systems of plants increase stability of forested slopes by three mechanisms: 1) anchoring through the soil mass into fractures in bedrock, 2) crossing zones of weakness to more stable soil, and 3) providing interlocking long fibrous binders within the weak soil mass. Ziemer (IAHS 1981) showed that soil strength is positively correlated to root biomass.

In a study of 1996 landslides in the Oregon Coast Range, Schmidt et al. (2001) found that the range of lateral root strength was greater in natural forests than industrial forests. Beschta (1978) notes that roots begin to decay once a tree is cut, thereby initiating a quick decrease in root strength and subsequent soil stability.

2.3.3.3. Rainfall Energy Attenuation

Vegetation can minimize the erosive force of rainfall impact. In a study of moist eucalypt forests in New South Wales, Australia, Cornish (2001) observed that vertical distance between soil and canopy cover affects size and energy of raindrops. Turbidity levels during regeneration in non-roaded basins were reduced from pre-harvest levels.

Observations of reduced rainfall and reduced rainfall intensity under forest canopies may also be attributed to interception (Zinke, 1967; Keim 2003). Rothacher (1963) estimated interception using throughfall measurements rather than measuring interception directly. He noted summer throughfall under a mature Douglas-fir forest at the H.J. Andrews Experimental Forest averaged 76 percent of gross summer precipitation and 86 percent during the winter.

2.3.4. Anthropogenic Sediment Production

Unpaved forest roads have been recognized as the main source of chronic sediment pollution in streams (Cornish, 2001), surface erosion and mass failure (Elliot et al., 1999), and soil compaction (Blinn et al., 1999) within managed forested watersheds. Megahan and Kidd (1972) found logging roads to increase sediment production 750 times the natural rate for a 6-year period following construction on Idaho Batholith.

In a comparative basin study, O'Loughlin et al. (1980) found that in a basin that received a comprehensive treatment of harvesting, skidding, and burning, sediment yield was eight times greater than the control basin with most sediment coming from the skid trail. Sediment production associated with skid trail construction and logging was found to be highest immediately after harvesting operations tapering off significantly after the first five years (Croke et al., 2001).

Sediment yield from road segments with freshly graded ditches can be five to seven times greater than from segments with vegetated ditches (Elliot and Tysdal, 1999; Luce and Black, 1999). Sediment production was found to be correlated to road segment length, road slope, and road surface area (Luce and Black, 1999; MacDonald et al., 2001). Cutslope height contributes some sediment, but relatively little in comparison to the rest of the road prism due to its ability to revegetate (Reid and Dunne, 1984; MacDonald et al., 2001).

In a review of 12 forest road erosion studies conducted throughout New Zealand, Fransen et al. (2001) suggest that traffic and road maintenance initially increase sediment production, but have no long-term affect on natural erosion rates in forested watersheds. Traffic and maintenance observations depend on construction techniques and surface materials used on the road (Bilby et al., 1989; Luce and Black, 1999; Swift and Burns, 1999).

2.4. Measuring Sediment from Forest Roads

Many approaches can be used to measure sediment. Luce and Black (1999) observed that hydrologic instrumentation is expensive, open to vandalism, requires frequent maintenance, and requires relatively permanent installation, thereby limiting the researcher to monitor only a few sites. Descriptions of some road sediment measurement devices follows.

Road and cutslope plot measurements in MacDonald et al.'s (2001) study on St. John, U.S. Virgin Islands, consisted of heavy, flexible, entrenched rubber strips, or "water stops", which diverted the entire sediment-laden runoff of each storm into series of 100 L plastic collection reservoirs. The contents of the 100 L plastic collection reservoirs were thoroughly agitated and then three separate replicate 1 L samples were drawn with an Imhoff cone. The sample was allowed to settle for 20 minutes at which time the volume of settleable solids was recorded. About ¾ of the samples were dried and weighed. Results of this dry weight were used to develop a regression equation which was used to convert the remaining volumetric data to dry weights. Dried sediment was combined for each storm, and particle-size distributions were determined by sieving and hydrometer analysis. The turbid water remaining in the 100 L reservoirs was decanted while measuring its volume. The residual sediment in each 100 L reservoir was dried and weighed.

Luce and Black (1999) used 1.5 m^3 storage tanks below the outlets of the crossdrains to capture sediment-laden runoff. The tanks captured 70-80% of sediment finer than silt and all of the larger fractions during a 12 mm/hr storm. The amount of sediment was determined by weighing the tank full with water and then with the captured water and sediment. Density of water was taken to be 1000 kg/ m^3 and density of sediment was estimated at 2650 kg/m^3.

In a study conducted in western New Zealand, O'Loughlin et al. (1980) used concrete-lined sediment traps behind each weir at the outlet of three study watersheds. The traps had capacities of approximately 2.5 m^3, 30 m^3, and 25 m^3 and successfully trapped sediments larger than medium sand. Automatic and manual water samplers were used to determine suspended sediment concentrations. Weight, volume, and composition of the trapped material were assessed. Suspended sediment was determined by filtration methods. These data were used to develop sediment rating curves.

Megahan and Kidd (1972) constructed eight 1/100-acre erosion plots with wooden borders and catch troughs. Material caught in the erosion plots was collected, dried, and weighed in the laboratory. Sediment dams were placed in ephemeral drainages. The accumulated sediment behind the dams was surveyed to determine its volume.

Sediment collection for Bilby et al. (1989) consisted of an H-flume fitted with a water-level recorder and located at the outfall of a cross-drain. Sediment was sampled with an automated water sampler affixed to the end of the flume. Turbidity was measured with a nephelometer and suspended sediment concentration was analyzed using vacuum filtration.

For the paired watershed study of Deer Creek, Needle Branch, and Flynn Creek, Beschta (1978) used published USGS monthly and annual suspended sediment concentrations and water discharge data. Depth-integrated samples were collected at daily or more frequent intervals during periods of high flow.

2.5. Excess Sediment Mitigation/Attenuation

Bilby et al. (1989) suggest that research on forest roads is important in order to understand how to effectively manage the land to "minimize the impact of road-surface sediment on stream biota".

In response to the relationship of road construction techniques with landslides in the late 1960's, forest managers changed forest road design standards. Although the changes increased the cost of road construction 50 to 100 percent, the adopted standards virtually eliminated newly-constructed roads as a cause of landslides and had the added benefit of reducing sediment production directly from the road surface (Kessel, 1985). Beschta (1978) noted the ability of vegetation to reduce sediment based on observations during the Alsea watershed study.

2.5.1. Modeling/Prediction

Water quality degradation associated with road-borne sediment could be minimized or eliminated if efforts were focused on problematic areas. Many studies have helped identify some physical factors affecting forest road sediment production. Models have been developed to identify probable high sediment-yielding road sections. An erosion model with proven accuracy could be used by both forest managers and regulatory agencies to assess compliance with water quality standards (Elliot et al., 1999).

Modeling of sediment prediction from unpaved forest roads can help to prioritize and account for the benefits of control and mitigation actions. Cochrane and Flanagan (1999) suggest that accurate modeling of erosion could be a very cost-effective means of monitoring sediment production in watersheds.

Modeling can be as simple as constructing equations that relate sediment production to variables based on empirical data for a specific site (Wischmeier and Smith, 1958; Luce and Black, 1999). Other models can be very complex and must be calibrated using observed data from a variety of locations. Due to the complexity of such models, software is developed to run through the calculations on a computer.

With the evolution of modern computers came the ability to model the erosion process at various spatial and temporal scales. Given appropriate values of physical variables, computer modeling allows the user to predict erosion scenarios before they occur. Erosion models use empirical data from such scenarios to calibrate a model to produce sufficiently accurate predictions for the expected range of scenarios.

Two models have been used extensively in predicting sediment production in forested watersheds: SEDMODL2, a physically-based model first developed by Boise-Cascade and later by the National Council for Air and Stream Improvement (NCASI) (SEDMODL2, 2003); and WEPP:Road (Watershed Erosion Prediction Project with forest road-specific add-on), a process-based erosion model in the public domain on the Internet (WEPP, 2003). Both are used to predict sediment production from unpaved forest roads. Empirical data gathered from many watersheds were used to calibrate these models.

In summary, models represent a potentially powerful tool for predicting road sediment loss and the benefits of mitigation measures. Models also reveal the high variability that occurs in relating sediment production with road and hydrologic variables.

2.5.1.1. WEPP:Road

The United States Department of Agriculture (USDA) Agricultural Research Service (ARS) developed WEPP to replace the Universal Soil Loss Equation (USLE) used historically by the Natural Resource Conservation Service (NRCS) and other agencies, including the Bureau of Land Management, and the Forest Service (Foster and Lane, 1987). The model is available on the Internet and has many different versions, or add-ons such as WEPP:Road. WEPP:Road was developed to calculate the amount of road sediment that could reach adjacent streams. WEPP:Road offers fifty thousand different combinations of variables associated with sediment production (WEPP, 2003). Users select from a range of values for road variables including: distance between cross-drain culverts, road gradient, soil texture, distance from stream, and steepness of the buffer between the road and stream. ROCK:Clime is another add-on that allows the user to incorporate local or regional precipitation scenarios into the calculations. WEPP:Road is very user-friendly and yields results quickly for a wide range of conditions.

Elliot et al. (1999) acknowledge the variability of observed sediment production was 30 percent of the mean in one set of replicated experiments and suggests users of WEPP should not rely on model output for an exact amount of sediment, rather users should express the predicted amount bounded by a wide range. Elliot and Tysdal (1999) suggest their model calibration runs represent “reasonable approximations” of sediment production from forest roads in the Oregon Coast Range. In general, WEPP models seem to have a tendency toward over-prediction of soil loss under most conditions (Elliot and Tysdal, 1999; Yu and Rosewell, 2001). WEPP:Road documentation notes that the model was not validated before its release (WEPP, 2003).

2.5.1.2. SEDMODL2

SEDMODL (the first version of SEDMODL2) was intended for use in forest lands of Idaho and Washington. The structure of the model allows adaptation to similar forest lands in the Pacific Northwest (California Department of Forestry - CDF, 2003). The Boise Cascade Corporation and NCASI developed SEDMODL2 to identify the amount of sediment contributed to streams by specific road segments. It is a GIS-based model which utilizes stream, road, geology, elevation, culvert, and precipitation coverages to estimate sediment delivery based on the proximity of roads to streams. In addition to the GIS coverages, the user can choose from a range of values of associated road characteristics. SEDMODL2 calculates sediment production based on empirical modified road erosion factors from the Washington Department of Natural Resources Standard Method for Conduction Watershed Analysis surface erosion module and the Water Erosion Prediction Project (WEPP) soil erosion model.

2.5.2. Best Management Practices (BMPs)

Managers of forested watersheds are required to meet local, state, and federal water quality regulations. The amount of sediment in runoff discharged from forest roads is often controlled by water quality standards. Various Best Management Practices (BMPs) have been developed to minimize the impact of unpaved forest roads on water quality and the forest environment. Forestry BMPs are techniques that assure protection of the environment during forestry operations — from harvesting to reforestation — with a focus on preserving water quality in lakes, rivers and streams (Wisconsin Paper Council, 2003). BMPs can be either voluntary or regulatory guidelines to help landowners, loggers, and natural resource managers minimize nonpoint pollution from forest management activities (Wisconsin Department of Natural Resources - WDNR, 2003).

Forest land managers are putting conservation-oriented recommendations from scientific research into practice. In an effort to reduce road-related sediment, road management plans are developed well in advance of construction (CDF, 2003). One of the most effective BMPs incorporated into modern forest road planning is locating roads on ridgetops where the impact on water quality is significantly less than locating roads in valley bottoms immediately adjacent to streams. However, landslides and integration of channel and road networks may still occur even when forest roads are properly located (Montgomery, 1994). The advent of long span cable logging decreased the amount of sediment delivered to streams by reducing road construction approximately 75% (Megahan and Kidd, 1972).

During monitoring of logging activities managed by those taught from the BMP education and training curriculum in 1995, the Wisconsin Department of

Natural Resources noted that forest roads were one of two areas where BMPs needed the most emphasis (WDNR, 2003). Some forest road BMPs include water bars, broad-based dips, and diversion ditches. These BMPs focus on removing water quickly from the road surface before it has sufficient energy to erode the road. Although these BMPs do not directly address the reduction of sediment discharge, the quick removal of water from the road surface reduces the amount of time road sediment is subject to transport by water.

The development of Best Management Practices (BMPs) has steadily improved as understanding of forest hydrology has progressed (Swift and Burns, 1999). Although road relocation may be the best option to mitigate impacts from historic roads built before BMPs were incorporated into design, such measures are "prohibitively expensive" (Swift and Burns, 1999). BMPs can be integrated into preliminary planning and design, employed during construction activities, or, in the case of pre-existing roadways, implemented at problem locations.

2.5.2.1. Pre-Construction BMPs

The most effective BMPs are incorporated into road construction during the design phase. Elliot and Tysdal (1999) suggest the following as the most important variables in sediment production that can be controlled by proper road planning and management, in order of effectiveness: distance between the road and the nearest stream, ditch management practices, road segment length, road gradient, cutslope height, and cover.

In a study on batholith in the northern Rocky Mountains of Idaho, Burroughs et al. (1984) found that sediment production decreased significantly by surfacing roads with either dust oil, gravel, or asphalt.

2.5.2.2. Post-Construction BMPs

The goal of post-construction BMPs is to reduce or eliminate the connectivity of roads and streams and enable the managed watershed to function with a natural hydrology (Swift and Burns, 1999). It is highly recommended that BMPs be constructed or installed during dry or low-flow periods (Tornatore, 1995). Croke et al. (2001) acknowledge that most soil loss occurs within the first two years of disturbance and suggest BMPs be in place immediately after the initial disturbance. However, it is the fine sediment produced that is persistent and most difficult to manage (Croke et al., 2001).

Some methods to minimize connectivity between roads and streams on existing roads include: 1) installing more cross-drain culverts per road segment, 2) diverting runoff to sediment traps, and 3) reconstruction or complete closure of the road when not cost-prohibitive (Swift and Burns, 1999). Sediment from forest roads has also been shown to be removed efficiently by grass and gravel (Swift, 1984) as well as by the undisturbed forest floor (Swift, 1986).

Other BMPs armor the road surface (i.e. gravel), or allow for settling of sediment (i.e. brush barriers). Removing sediment from the runoff greatly reduces this primary pollutant associated with forestry activities. Another method employed to reduce sediment discharge is the construction of settling basins at the outfall of cross-drain culverts. A large pit is excavated in the hillslope into which a cross-drain culvert discharges. Water discharge infiltrates into the surrounding soil and sediment settles to the bottom of the pit. The settled sediment is later excavated by a backhoe. This method demands high costs associated with the mobilization of heavy equipment, fuel, and operator time. Excavating a large pit into the forested hillslope introduces a large disturbance in the forest environment, poses a drowning hazard to humans and forest wildlife, and has potential for mass failure on steep slopes.

Still other BMPs focus on road segments that produce the greatest amount of sediment. Some of these BMPs include “disconnecting” roadside ditches from streams, reducing historical practices of ditch “cleaning”, vegetating roadside ditches, cutslopes, and fillslopes, and placement of natural fiber mats over road surfaces during the rain season. The geotextile sock represents another BMP and is designed to trap sediment at culvert outfalls. The use of a geotextile sock on cross-drain culverts is postulated as one way sediment may be removed from runoff while avoiding extensive disturbance and unforeseen hazards. It is believed a geotextile sock can be used as a cost effective management tool for reducing sediment discharge from unpaved forest roads. Perhaps most crucial to implementing any of the aforementioned BMP methods is ensuring a forester is involved, especially during a timber sale (Egan, 1999).

CHAPTER 3. MATERIALS AND METHODS

3.1. Study Location

The upper Oak Creek Watershed is a forested headwater watershed in the eastern foothills of the Oregon Coast Range. It encompasses 824 hectares in McDonald-Dunn Research Forest, which is the school forest for the College of Forestry at Oregon State University northwest of Corvallis, Oregon (Figure 3. 1).

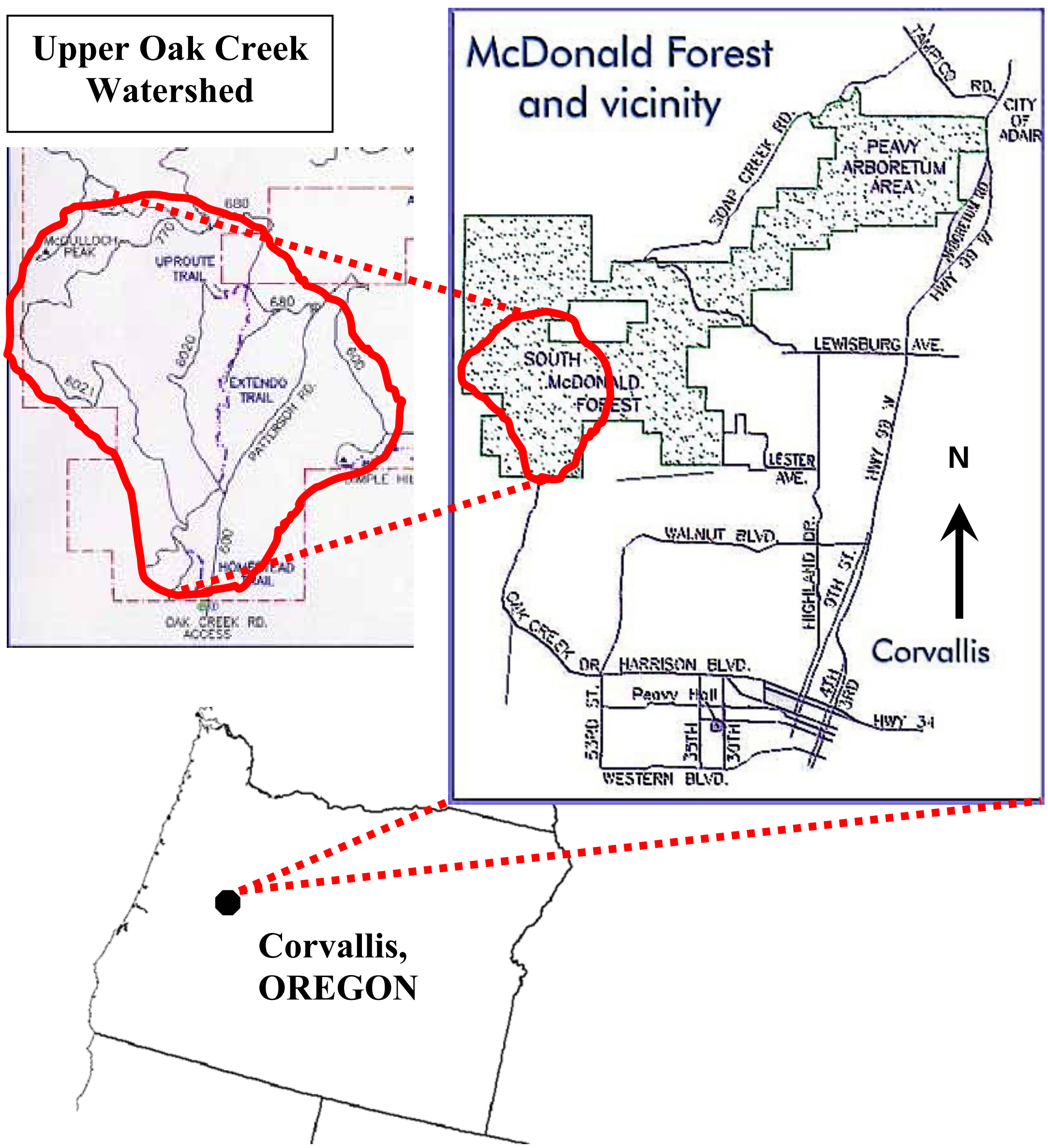


Figure 3. 1 Location of study area.

Elevations range from 140 to 600 meters and hillslope gradients range from 20 to 70 percent. Discharge from the watershed is measured at a concrete rectangular cross-section using a Tru-Track®, model WT-HR 1000 (1320 mm length), electronic automated capacitance rod for a stage-discharge relationship. The research forest is an actively managed forest. Vehicular traffic is light with most activities in the watershed mainly limited to recreation of hikers, bicyclists, horse-back riders, and pedestrians.

There are 4,880 meters of stream in the watershed for a drainage density of 5.92 m/ha. There are 4,570 meters of road for a road density of 5.55 m/ha. Most of the road system was built in the 1950's and 1960's using cut-and-fill construction methods. The average road width is five meters and most of the road surfaces are crowned with drainage ditches. All roads are gravel-surfaced with rock from the Research Forest. Upgrades of the road network including drainage have been continuously added.

The upper Oak Creek Watershed is instrumented with four tipping-bucket rain gauges, capacitance rods (i.e. automated water-level recorders) at the inlet of all culverts, and a micrometeorology station. For this particular study, sediment traps were installed at the outlet of nine cross-drain culverts.

3.2. Research Design

Nine cross-drain culverts in the upper Oak Creek watershed were instrumented to collect discharge and sediment data. Erosion prediction models, WEPP:Road and SEDMODL2, were used to predict sediment yield from the nine road segments. Data analysis and model iterations were carried out on time scales ranging from individual storm events to an entire rain season. This was a small-scale observational case study that describes processes at individual culverts in the study watershed.

Research on the hydrology of the roads in the upper Oak Creek Watershed helped to select sites for this study. Sampling sites were selected using a backward elimination system. Ellingson (2002) created a GIS database of all culverts in the watershed, which was used to locate the cross-drain culverts (Figure 3. 2). Reconnaissance of the cross-drain culverts reduced the number of potential sampling sites to those that did not involve live streams or swales. Historic peak flow data was used to reduce the number of potential study sites to fifteen culverts that had the greatest flow (Ellingson, 2002). Of these fifteen culverts, the final number of study sites was based on minimal potential for physical disturbance while setting up instrumentation at each site. This study site selection process resulted in nine study sites.

Figure 3. 2 Illustration of cross-drain culvert.

3.3. Measurement of Physical Parameters and Variables

The independent variables collected for this study include those that describe precipitation, discharge from culverts, and road and hillslope characteristics. The dependent variable was the sediment yield from each road segment.

3.3.1. Precipitation

Precipitation in upper Oak Creek was measured using four NovaLynx® tipping bucket rain gauges each mated with an Onset® HOBO event data logger. The data logger was downloaded approximately once every forty days. Three of the four rain gauges, McCullough Peak, Starker Meadow, and Dimple Hill, were located in a northwest-southeast line almost parallel to the northeast perimeter of the watershed. The McCullough Peak and Dimple Hill rain gauges were located high in elevation near rock pits. The Starker Meadow rain gauge was located in a mid-elevation clear-cut. The Oak Creek Meadow rain gauge was located in an open field at a low elevation in the south central region of the watershed. Rain gauge locations are shown in Figure 3. 3.

Data quality checks were made at the time of download. A storage rain gauge on McCullough Peak served as a data check for that tipping bucket rain gauge. Each tip of the rain gauge corresponded to 0.254 mm of precipitation, with a time stamp registered with each tip.

Two Microsoft Excel-based programs developed by Melissa Clark and Richard F. Keim were used to calculate 1-hr, 2-hr, and 24-hr rainfall intensity for individual storms and seasonal peaks.

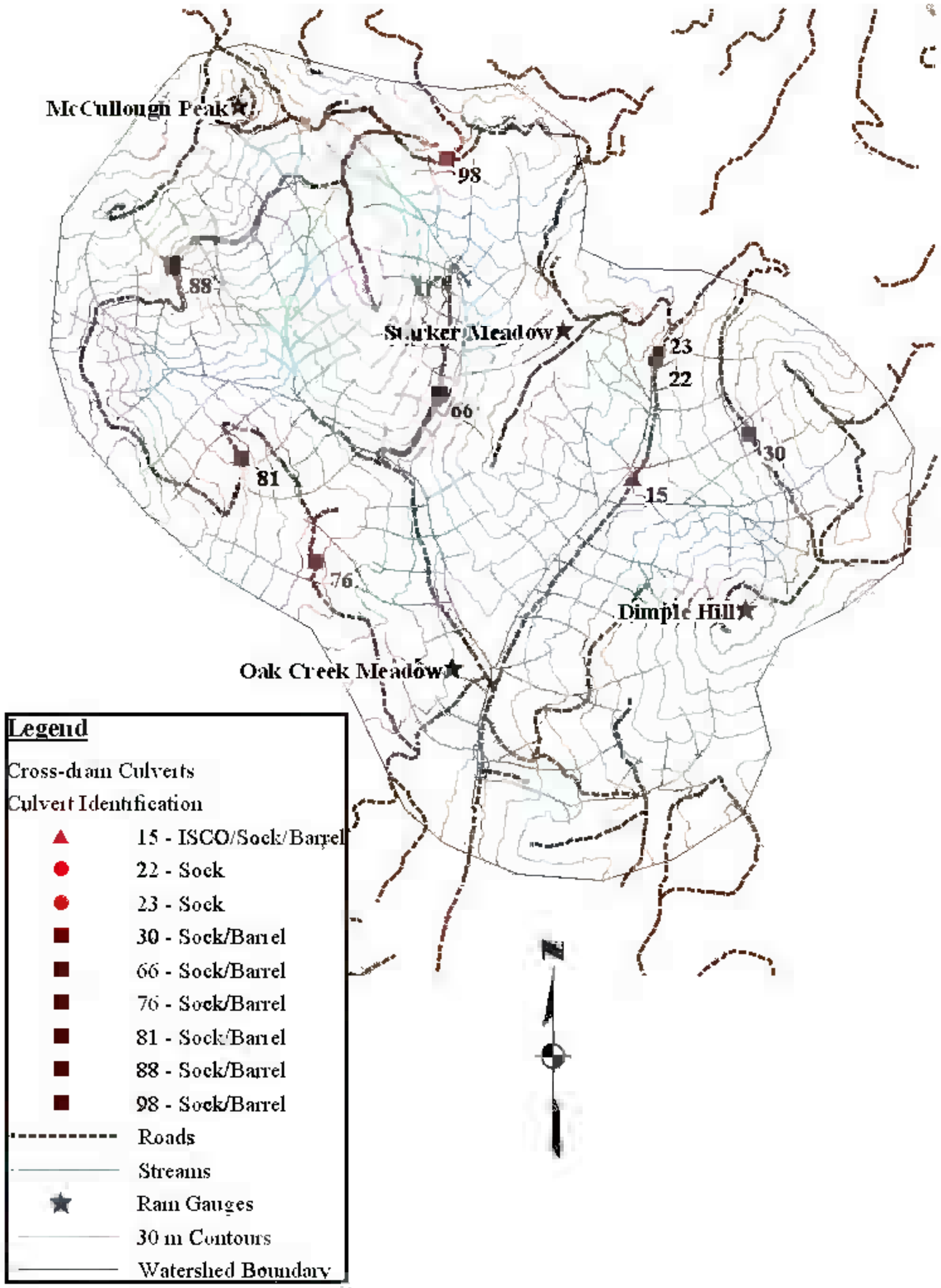


Figure 3. 3 Upper Oak Creek Watershed rain gauge and sediment sampling site locations.

3.3.2. Discharge from Cross-Drain Culverts

Tru-Track®, model WT-HR 500 (820 mm length), electronic automated capacitance rods were used to record the depth of water at each cross-drain culvert. The data collection interval was 10-minutes. Each capacitance rod was placed inside a 25 mm (1-inch) diameter PVC casing that had lateral slits cut in the bottom and holes drilled in the top to allow movement of the water column. The PVC casing was fastened to a metal fencepost at the edge of each culvert inlet with the bottom of the PVC casing just below the ground surface (Figure 3. 4).

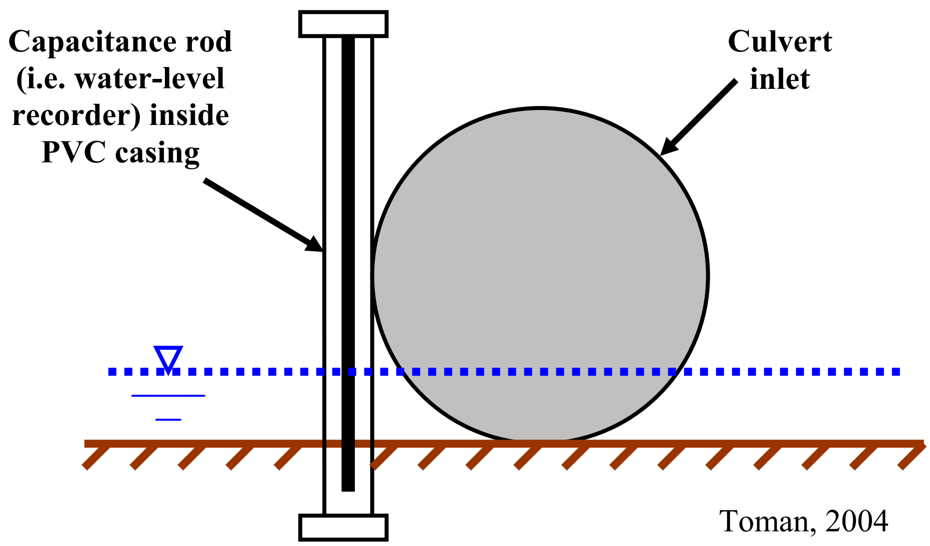


Figure 3. 4 Illustration of capacitance rod installation to measure depth of water entering culvert.

Capacitance rods were downloaded and reset approximately every 40 days. Manual measurements of water depth at the culvert inlet were taken when data was downloaded for data quality control. The capacitance rod data were used to construct hydrographs for each culvert. Corrections and adjustments to the data were made using known zero-references and manual measurements of water depth at the culvert inlet.

Stage-discharge relationships have been developed for culverts in the upper Oak Creek Watershed by comparing measured discharge with the water level at the culverts when the discharge was measured. Toman (2004) reported that the discharge equation by Henderson (1966) fit the stage-discharge relationships of the culverts in the upper Oak Creek Watershed the best (Equation 3.1).

Equation 3.1 Culvert discharge (Henderson, 1966)

$$Q = 0.432\sqrt{g}\left(h - z\right)^{1.9} d^{0.6}$$

where,

Q = discharge (m^3/s),
g = acceleration of gravity (m/s^2),
h = water surface elevation above a datum (m),
z = culvert entrance elevation minus the datum elevation (m), and
d = culvert diameter (m)

Henderson's (1966) discharge equation was used to calculate water discharge from each culvert using the water-levels recorded by the capacitance rods. Water level was collected at 10-minute intervals and converted to discharge. The total volume of runoff from each culvert was the sum of the discharge values over the time of interest.

The primary error associated with the capacitance rods was a consistent determination of a water depth corresponding to zero flow. When a capacitance rod was returned to the PVC casing after downloading data, the potential for sediment to fill in the PVC casing existed, which resulted in a new position for the capacitance rod. Correction of the data was carried out manually where differences in water level were noticed before and after downloading.

Water level values were not recorded for culverts 30 through 88 until early January 2003. Culverts that were close by were used as surrogates for the missing values, although temporal variations were observed between adjacent culverts that were lost during these periods.

3.3.3. Sediment

Three types of sediment traps were used in this study. They corresponded to sediment size: coarse, settleable, and suspended. The fabric sock trapped the coarse fraction (≥ 0.425 mm or #40 U.S. Sieve) of sediment and organic debris; the barrel trapped the settleable size fraction that was too small to be trapped by the fabric sock but large enough to settle out in the barrel; the water sampler grabbed representative portions of suspended sediment flowing out of the barrel.

3.3.3.1. Coarse Sediment/Geotextile Sock

The coarse sediment trap was constructed by wrapping a 1 m long, 2 mm thick vinyl membrane around 0.5 m of the outfall of a cross-drain culvert and extending it another 0.5 m past the outfall. A Dandy Pipe Sock®, or "geotextile sock" with the appropriate diameter was slid over the vinyl membrane on the culvert outfall. The drawstring of the geotextile sock was tied tightly around the culvert securing it in place. A 3 m section of smooth-bore, corrugated plastic culvert, or "culvert extension" with the same diameter was placed over the geotextile sock and fastened to the cross-drain culvert outlet with a culvert collar of an appropriate size (Figure 3. 5). The vinyl membrane acted like a water-tight seal between the culvert outfall and the culvert extension. The vinyl membrane also ensured that all the water and sediment discharged from the culvert would be directed into the geotextile sock.

The outfall of culverts 22 and 23 was nearly level with the ground surface, which eliminated the ability to use a barrel and automated water sampler, thus only coarse sediment was captured. Samples of coarse sediment were a composite taken over several months. One geotextile sock

Figure 3. 5 The author preparing site for installation of sediment trap. The vinyl membrane is not pictured. Roadway is left of the picture.

remained on cross-drain culverts 22 and 23 from March 10 through June 18, 2003.Sediment trapped by the geotextile sock was collected from the two cross-drain culverts after four months. When the geotextile socks were removed on June 18, they were transferred to a plastic bag that was labeled with the date and time that the geotextile sock was in place and the number of the culvert.

In the laboratory, the plastic bags that contained the geotextile socks were opened and placed in a fume hood so as much water as possible could evaporate. When the contents were air-dried, they were transferred to a pre-weighed and numbered drying pan and placed in an oven at 105^{o}C until the contents were oven-dried but not less than 24 hours. The oven-dried weight was used as the total sediment weight for each sock.

After the total sediment weight was determined, the procedure for determining organic matter content using incineration (following Clesceri et al., 1998 Method 2540D, see Appendix A-2) was followed on a sub-sample of the total sediment sample to determine the total mineral sediment weight. Mineral sediment served to normalize sediment weight and account for large variances in organic debris among the geotextile socks.

3.3.3.2. Settleable Sediment/Barrel

The settleable sediment was trapped using a 208 L barrel that was placed at the outfall of the culvert extension such that the culvert extension was supported by the barrel (Figure 3. 6). This type of sediment trap will

Figure 3. 6 Barrel + sock sediment trap as used at culverts 30, 66, 76, 81, 88, and 98. Geotextile sock is extended inside barrel but not in view in this picture.

be called “barrel + sock”. Barrel + sock samples were also a composite of several months. One geotextile sock and one barrel remained on cross-drain culverts 66, 76, 81, 88, and 98 from November 17, 2002 to June 18, 2003. Sediment trapped by the geotextile sock and the barrel was collected from five cross-drain culverts after seven months.

The sediment trap at culvert 30 was installed the same way, however, the gravel pad underneath the barrel eroded and caused the barrel to fall over and spill its contents. The barrel at culvert 30 was reestablished on February 3, 2003 and remained until June 18, 2003. At culvert 30, the geotextile sock trapped sediment for 7 months but the barrel trapped sediment for only 4.5 months.

By June 18, 2003 all solids in the barrels had settled, which permitted disposal of the water. The barrels were decanted using two 19 mm diameter vacuum pressure hoses as siphons. The barrels were labeled with the corresponding culvert number and transferred to the laboratory. Contents in both the geotextile socks and barrels from these culverts were handled in the same fashion as described previously for culverts 22 and 23 to determine mineral sediment weight.

3.3.3.3. Suspended Sediment

The sediment trap for culvert 15 was set up similar to the barrel + sock sediment traps described previously. However, two ISCO®, model 1200, automated water samplers, or “automated water samplers”, were used to sample suspended sediment during four (4) storms that occurred March 5-9, April 11-15, April 23-27, and May 3-5, 2003. This sediment trap is called “complete”.

For culvert 15 at the beginning of each storm, the existing geotextile sock was removed and transferred to a plastic bag and handled like the other geotextile socks. A new geotextile sock was installed on the culvert along with the culvert extension. The barrel was moved to the side and covered. A clean barrel was placed under the culvert extension outfall and remained for the duration of the storm (Figure 3. 7).

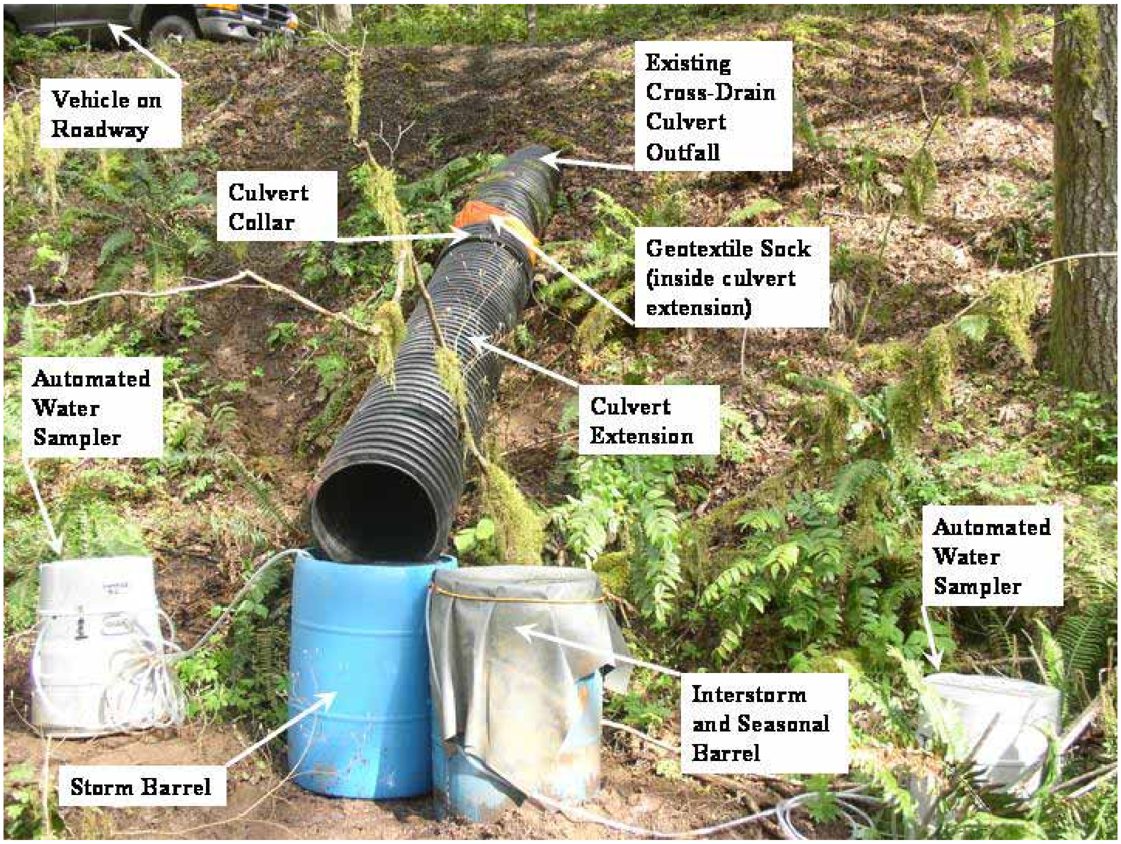


Figure 3. 7 Complete sediment trap used at culvert 15.

The automated water samplers collected samples from the new barrel approximately 150 mm (6-inches) below the rim of the barrel. They were programmed to take 1000 mL samples at 2-hour time intervals that spanned the predicted storm duration.

Sediment trapped by a geotextile sock, barrel, and automated water samplers was collected from cross-drain culvert 15 using a frequency that matched the occurrence of the four storms.

After each storm the geotextile sock was removed and transferred to a plastic bag and handled like the other geotextile socks. A new geotextile sock was installed on the culvert followed by the culvert extension. The storm barrel was moved to the side and covered. The previous barrel was moved back under the culvert extension outfall to continue collecting seasonal and inter-storm sediment.

After four days, all sediment in the storm barrel had settled. The water was decanted in the same manner as the barrels from the other culverts. The contents of the storm barrel were transferred to a 54-gallon Rubbermaid® plastic bin, covered for transport, and labeled with the date and time that the barrel was in place. The contents of the bin and geotextile sock were handled like the other barrels and geotextile socks. The 1000 mL water samples from the automated water samplers were labeled, capped, and placed in a 14^{o} C refrigerator until they could be analyzed. Suspended sediment concentration of the 1000 mL water samples was determined using vacuum filtration (following Clesceri et al., 1998 Method 2540D, see Appendix A-1). The amount of organic matter remaining on the filters was also determined (following Clesceri et al., 1998 Method 2540D, see Appendix A-2).

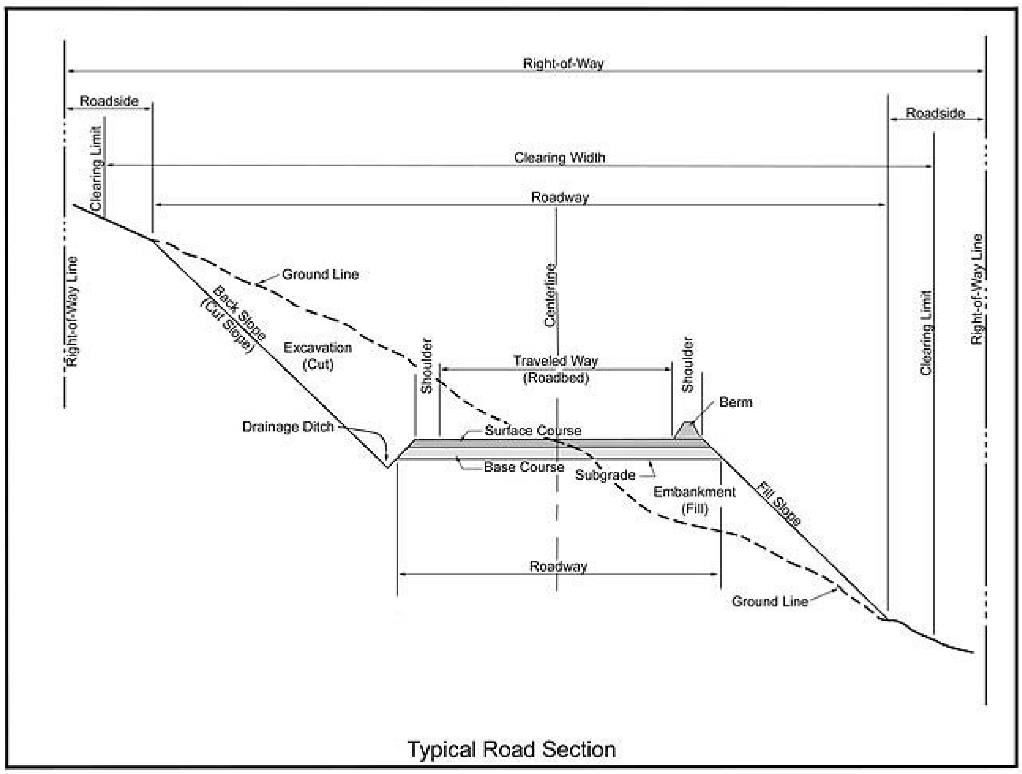
The storm barrel used for the first sampled storm (March 5-9, 2003) had a leak. The amount of sediment lost due to the leak is unknown. The sediment remaining in the barrel was processed and analyzed without adjustment for the loss.

The beginning of storms 1 and 3 (March 5-9 and April 23-27, 2003) were missed. The two storms that were sampled from beginning to end (April 11-15, 2003 and May 3-5, 2003) yielded stronger correlations as shown in Chapter 4.

3.3.4. Other Watershed/Road Variables

Values for culvert elevation, soil type and depth, and watershed contributing area were from Ellingson’s (2002) GIS database. Reconnaissance was used to verify the following road characteristics from Ellingson’s (2002) GIS database: road cutslope height, road gradient, road length between culverts, and hillslope gradient.

Cutslope height was taken as the average height from the ditch to the top of the cutslope along the length of road between culverts (Figure 3. 8). Road gradient was measured using a clinometer. Road length between culverts was the lineal distance between the cross drain culverts. Hillslope gradient was measured with a Suunto® clinometer from the centerline of the road upslope a distance not less than 15 meters. Statistical relationships were investigated among these variables.



http://www.wildlifecrossings.info/media/Typical%20Road%20Sectionsmall%20dwg.jpg

Figure 3. 8 Definitions for terminology used to describe typical forest road section.

3.4. Sediment Prediction Models

Two sediment prediction models were used to compare empirical model results with actual field results from this study. The two models chosen were WEPP:Road and SEDMODL2. These models are considered the standard used by the forest management community today. Variable values from the study sites were used in both models.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Road Segment and Culvert Site Characteristics

The independent variables that were quantified for each culvert location included culvert type, culvert diameter, elevation, distance between culverts, average road grade, watershed contributing area, average hillslope gradient, average soil depth, average cutslope height, soil type, roadway maintenance, hydrologic regime (ephemeral or intermittent), and peak culvert discharge. Figure 4. 1 illustrates these terms in a plan view of a typical forest road section.

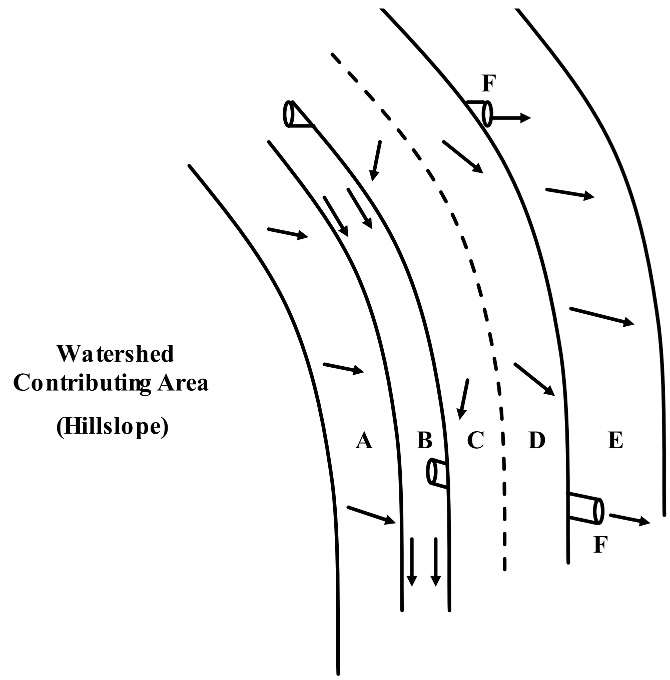


Figure 4. 1 Plan view of a study road segment with associated terminology (adapted from Marbet, 2003). Arrows indicate direction of surface runoff.

A. Cutslope.
B. Ditch, carries intercepted subsurface flow from cutslope as well as overland flow and surface runoff from the road.
C. Cutslope side of the road, drains to ditch.
D. Fillslope side of the road, drains from road to fillslope and/or forest floor.
E. Fillslope.
F. Cross-drain culvert, drains water from ditch underneath road to fillslope and/or forest floor.

The characteristics of each culvert location are summarized in Table 4.1. Culverts were either 18 or 15 inches (450 mm or 375 mm) in diameter and were either corrugated plastic pipe (CPP), corrugated metal pipe (CMP), or smooth-bore plastic pipe (SPP). Elevations of the culvert locations ranged from 216 to 501 meters above sea level. Road and ditch length that contributed to each culvert was 96 meters or less for all culverts except culvert 81, which was 258 meters, and culvert 98, which was 256 meters. The average road grade ranged from 1 to 13 percent. The watershed area above each culvert, including the contributing area of the road surface and ditch, ranged from 25 to 31,600 m^2. Average hillslope gradient ranged from 20 to 68 percent. Average soil depth for the vicinity of each culvert was 0.8 meters for four culvert locations, 1.3 meters for two culvert locations, and 1.5 meters for two culvert locations (NRCS 2004). For the hillslope at culvert 88, the average soil depth was 0.4 meters (NRCS 2004).

Four soil series are present on the hillslopes associated with the culvert locations. At culverts 22 and 23, the soils are comprised mainly of the Abiqua (AB) soil series. This soil was formed in alluvium on flood plains, terraces and fans with slopes from 0 to 5 percent. It is well-drained and has an average depth of 1.5 m (NRCS, 2004). The most common soil series is the Dixonville (DN) that is associated with culverts 30, 66, 76, and 98. This soil series was formed in fine textured colluvium and residuum weathered from basalt on hills with slopes from 3 to 60 percent. It is also well-drained and has an average depth of 0.8 m (NRCS, 2004). The hillslopes associated with culverts 15 and 81 are comprised of the Price (PR) soil series that formed in fine textured colluvium derived from basalt on side slopes of hills and mountains with slopes from 30 to 90 percent. It is well-drained and has an average depth of 1.3 m (NRCS, 2004). The Witzel soil series is in the vicinity of culvert 88, and was formed in colluvium weathered from basalt on broad ridgetops and side slopes of hills and mountains with slopes from 3 to 75 percent. It is well-drained and has an average depth of 0.4 m (NRCS, 2004).

The roads and ditches associated with the contributing area of each culvert were scheduled to be graded except for the segment contributing to culvert 66.

However, only the roads associated with culverts 15, 22, 23, and 30 received this treatment. This routine maintenance occurred about one month before this study commenced.

Table 4.1 Site characteristics of the nine culverts. Culvert Type: CPP = corrugated plastic pipe; SPP = smooth-bore plastic pipe; CMP = corrugated metal pipe. Soil Type: AB = Abiqua; DN = Dixonville; PR = Price; WL = Witzel.

Culvert Number	Culvert Type	Diameter (mm)	Elevation (m)	Distance Between Culverts (m)	Average Road Grade (%)	Watershed Contributing Area (m^2)	Average Hillslope Gradient (%)	Average Soil Depth (m)	Average Cutslope Height (m)	Soil Type	Roadway Maintenance	Hydrologic Regime (E = Ephemeral; I = Intermittent)	Runoff Ratio	Peak Discharge (L/s) Date and Time	Total Runoff Volume During Study Period (m^3)	Total Mineral Sediment Trapped During Study Period (g)
15	CPP	450	216	53	7	825	25	1.3	2.0	PR	Graded	I	5.70	1.2 3/22/03 6:45	945	3550
22	CPP	450	264	36	4	25	20	1.5	0.5	AB	Graded	I	16.5	2.3 4/29/03 18:17	1870	400
23	SPP	450	265	96	2	31600	20	1.5	0.5	AB	Graded	I	173	355 3/22/03 7:38	52000	15000
30	SPP	450	359	53	10	225	45	0.8	4.3	DN	Graded	I	5.50	0.9 3/22/03 6:52	920	650
66	CMP	375	262	50	7	150	37	0.8	1.0	DN	None	I	16.6	1.7 3/22/03 6:55	2600	1020
76	CPP	375	287	76	3	250	37	0.8	1.0	DN	None	E	4.00	1.6 3/22/03 7:13	960	570
81	CPP	375	388	258	13	75	38	1.3	1.3	PR	None	E	0.10	4.9 4/12/03 22:49	100	25
88	CPP	375	501	58	1	400	68	0.4	2.0	WL	None	I	21.8	3.9 3/22/03 0:36	3960	80
98	CMP	375	442	256	6	350	27	0.8	1.1	DN	None	E	7.40	11.6 3/22/03 6:57	5960	2510

4.2. Precipitation

During the period of study, November 17, 2002 through June 18, 2003, precipitation was slightly below average for the region. From mid-November 2002 through April 2003, 1254 mm of precipitation fell in the upper Oak Creek watershed. The highest monthly precipitation, 318 mm, fell in December and most of that fell in the latter half of the month. The City of Corvallis set a record with 347 mm of precipitation in March and April 2003 (Taylor and Jenson, 2003). Monthly precipitation during the study period is summarized in Table 4.2. The "Hyslop" rain gauge was included as a long-term reference site in the Corvallis area.

Table 4.2 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" is indicated when the tipping bucket rain gauge malfunctioned.

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

Four storms were chosen for intensive analysis. A storm was defined as a 24-hour period when at least 12.7mm (0.5 inch) of precipitation fell. The storms occurred on March 5-9, April 11-15, April 23-27, and May 3-5, 2003. Storm attributes are summarized in Table 4.3.

Table 4.3 Summarized precipitation data during automated water sampling at Culvert 15.

Storm Attributes	Storm 1	Storm 2	Storm 3	Storm 4
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

The 1-hour, 2-hour, and 24-hour rainfall intensities from these four storms were variable. All storms that occurred during water year (WY) 2003 at Oak Creek had a recurrence interval 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. These were some of the highest rainfall values in Oak Creek during the 2003 WY. The storm that occurred April 11-15 had a 1-hour intensity of 6.1 mm/hr, which was also one of the highest values in Oak Creek for the water year.

4.3. Discharge

Beginning on December 12, culverts 15, 22, 23, 30, 66, and 88 began intermittent flow (i.e. continuous conveyance) that lasted until May 2003. Culverts 76, 81, and 98 had ephemeral flow (i.e. discontinuous conveyance) for the whole study. As shown in Table 4.1, peak discharge from the culverts ranged from 0.9 L/s at culvert 30 to 355 L/s at culvert 23. The next highest peak discharge is 11.64 L/s at culvert 98. The peak discharge for all culverts occurred on March 22, 2003 at approximately 07:00 on March 22, 2003, except for culvert 88, when it occurred at approximately 00:30 the same day, culvert 81 when it occurred at approximately 23:00 on April 12, 2003, and culvert 22 when it occurred at 18:00 on April 29, 2003.

A runoff ratio (RR) was calculated for each road segment to determine the proportion of water that fell on the road surface that actually occurred as runoff in the ditch (Marbet, 2003). Runoff ratio was defined as the ratio of total culvert discharge to the product of one-half the road surface area (given: crowned road) and precipitation, or

Equation 4.1

$$\text{Runoff Ratio (RR)} = \frac{\text{Total Culvert Discharge } (m^3)}{0.5 * \text{Road Surface Area } (m^2) * \text{Precipitation } (m)}$$

A runoff ratio greater than one (i.e. RR > 1) indicates that the road runoff must come from sources other than just the road surface. A runoff ratio less than one (i.e. < 1) indicates that the road runoff is most likely dominated by Hortonian flow from the road surface. Road segments were crowned so nominally half of the area of the road surface drained to the ditch and the other half of the road surface drained to the fillslope. All of the road segments had runoff ratios greater than one except for the road segment for culvert 81, which had a runoff ratio of 0.1. The runoff ratios for the rest of the road segments ranged from 4 to 173. These data are summarized in Table 4.1.

The aforementioned high peak discharge value at culvert 23 should be viewed with caution because there was evidence of culvert surcharge (i.e. filled beyond capacity). When the geotextile sock was removed, dried detritus was present on the inner circumference of the culvert. Also, the peak water level recorded by the capacitance rod was greater than the diameter of the culvert. This happened on March 22 and April 6, 2003. If, in fact, culvert 23 surcharged, it was likely caused by the tremendous amount of debris trapped within the geotextile sock that would have acted like a plug. However, if the debris was acting like a plug or a dam, the culvert hydrograph should have shown evidence of this by long falling limbs after storms or possibly an increased depth in culvert discharge. The hydrograph suggested no such plugging or damming (Figure 4. 2), therefore culvert 23 discharge and sediment data were kept in the statistical analysis. The high values for both discharge and sediment were consistent with the theory of the physical processes involved in sediment production from forest roads (i.e. more water transports more sediment). It is reasonable to assume that culvert 23 conveys a large amount of water because the watershed contributing area was the largest of the nine culverts at 31,600 m^2 and the runoff ratio was the highest at 173.

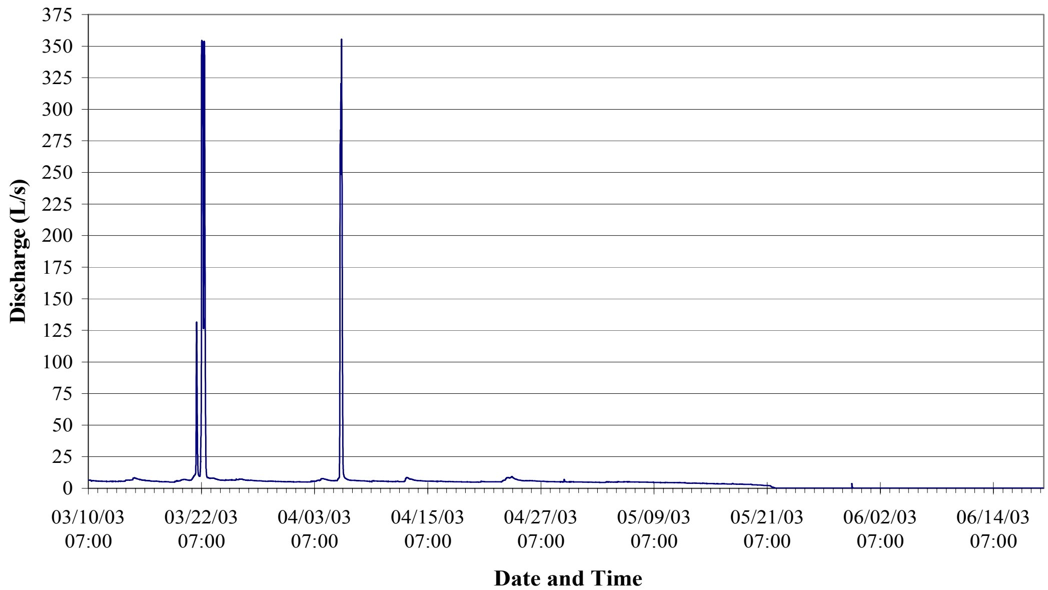


Figure 4. 2 Culvert 23 hydrograph from 03/10/03 through 06/19/03 with peak discharges occurring on 03/22 and 04/06. Note the absence of extended falling limbs as well as the absence of elevated discharge depth after the peak discharges.

Average discharge for each of the nine culverts for the duration of the study period ranged from 0.01 L/s at culvert 81 to 5.96 L/s at culvert 23. These values are summarized in Table 4.4.

Table 4.4 Summary of discharge data for all culverts. Blocked, shaded sections correspond to partitioned analysis of culvert. (See Appendix A-3 for complete table).

n	Culvert Number	Time Span of Record	Average Discharge (L/s)	Total Runoff Volume (m^3)
1	15	11/17/02 - 06/18/03	0.05	945
2	22	03/10/03 - 06/18/03	0.22	1870
3	23	03/10/03 - 06/18/03	5.96	52000
4	30	11/17/02 - 06/18/03	0.05	920
5	66	11/17/02 - 06/18/03	0.17	2600
6	76	11/17/02 - 06/18/03	0.06	960
7	81	11/17/02 - 06/18/03	0.01	100
8	88	11/17/02 - 06/18/03	0.26	3960
9	98	01/11/03 - 06/18/03	0.39	5960

The runoff at culvert 15 as measured for the four storms in the spring that were analyzed intensively and the results are listed in Table 4.5. 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). The variability of the runoff ratio among these storms ranged from 3.0 to 15.1. The runoff ratios illustrate that the runoff from the road segment that contributes to culvert 15 is affected by factors besides the road surface. The antecedent soil moisture of the watershed is believed to be largely responsible for the variability in the runoff ratio.

Table 4.5 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

4.4. Sediment

The sum of coarse and settleable sediment as trapped by geotextile socks and barrels, respectively, varied from 25 g at culvert 81 to 15,000 g at culvert 23. Suspended sediment collected only at culvert 15 was not added to the total amount of sediment for that road segment. All reported values of sediment are expressed in terms of mineral sediment as the organic matter was ashed (following Clesceri et al., 1998 Method 2540D, see Appendix A-2).

4.4.1. Coarse and Settleable Sediment

Culverts 22 and 23 only had geotextile socks. The geotextile socks at culverts 15 for storm 4, 66, 76, and 98 trapped more sediment than the barrels. The barrels at culverts 15 for storms 1-3, 30, 81, and 88 collected more sediment than the socks (Figure 4.3).

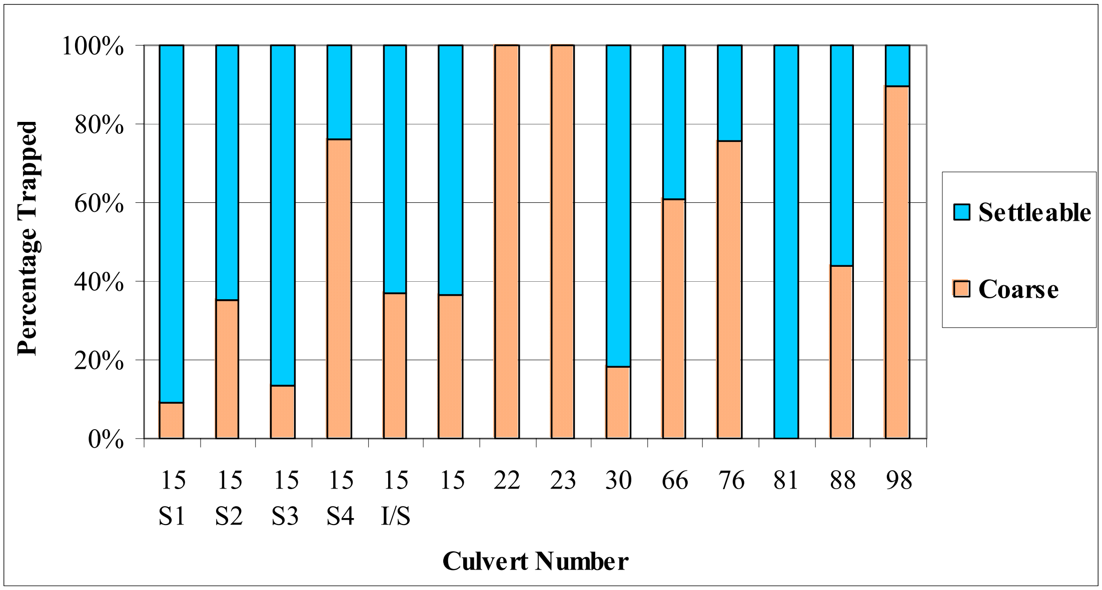


Figure 4.3 Percentage of trapped sediment partitioned by geotextile sock (coarse) and barrel (settleable). Note: culverts 22 and 23 only had geotextile socks.

The most sediment trapped, 15,000 g, was at culvert 23 (Table 4.6 and Figure 4. 4). This culvert would undoubtedly have trapped even more sediment if a geotextile sock had been installed during the whole study and a barrel had been installed to capture settleable sediment. Culvert 23 also had the largest watershed contributing area (3.16 ha), total runoff volume (52,000 m^3), and runoff ratio (173, Table 4.1).

The least amount of sediment (25 g) was trapped at culvert 81 and all of it was trapped in the barrel (Table 4.6 and Figure 4. 4). Culvert 81 had the longest distance between culverts (258 m), the second smallest watershed contributing area (75 m^2), the smallest runoff ratio (0.1) and total runoff volume (100 m^3). The peak discharge at culvert 81 (4.9 L/s) occurred during storm 2 (Table 4.1).

Table 4.6 Summary of coarse and settleable sediment data for all culverts. Note: Blocked, shaded sections correspond to partitioned analysis of culvert. (See Appendix A-3 for complete table).

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

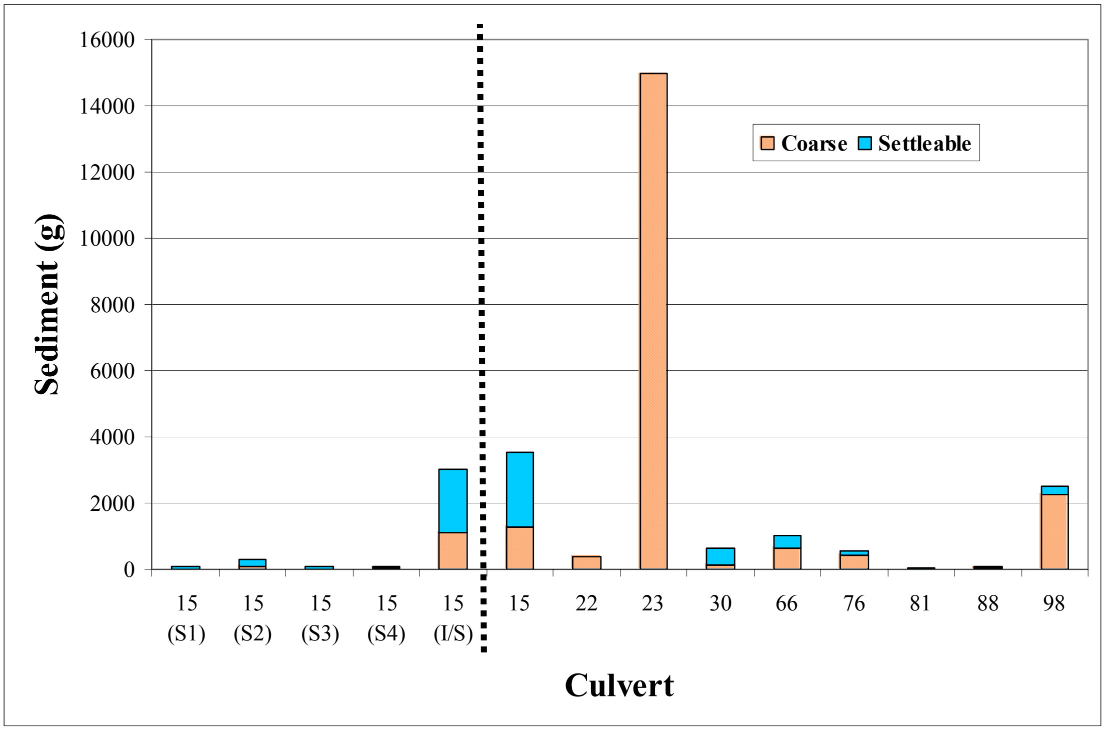


Figure 4. 4 Amount of sediment trapped by geotextile sock (coarse) and barrel (settleable) at each culvert. Note: Dashed vertical line separates storms and interstorm values from total for culvert 15. (S1) - (S4) signifies storms 1-4; (I/S) signifies interstorm.

Determination of the relationship between total sediment and total runoff volume was an objective of this research. A log-transformation of the data was done before analysis. Total coarse sediment (geotextile sock) and coarse and settleable sediment (geotextile sock + 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; Figure 4. 5 and Figure 4.6).

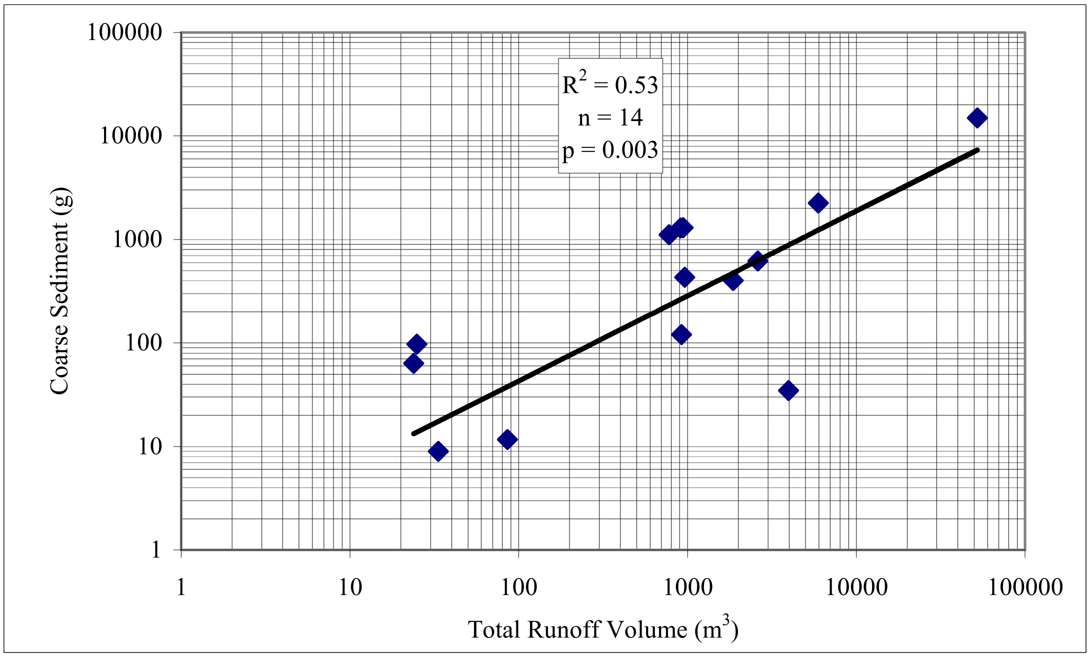


Figure 4. 5 Regression of coarse sediment from geotextile sock on total runoff volume for all culverts.

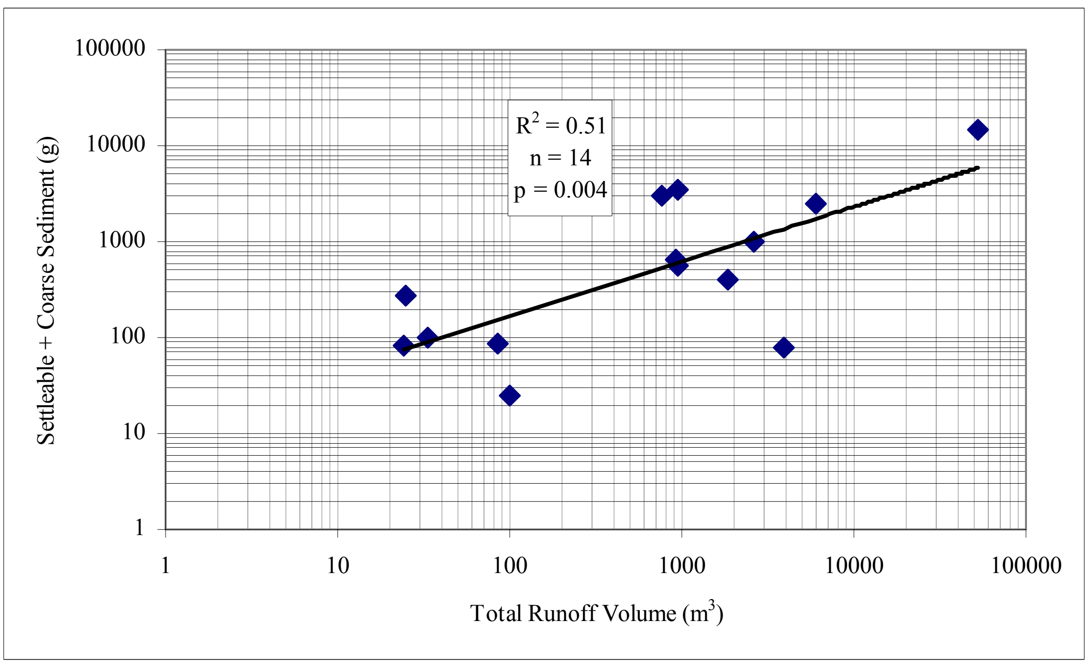


Figure 4.6 Regression of coarse sediment from geotextile sock and settleable sediment from barrels on total runoff volume for all culverts.

All of the numerical variables in Table 4.1 were regressed linearly against total sediment. Models developed using stepwise regression revealed that ln(runoff) had the strongest relationship of any individual variable and explained 51 percent of the variability of ln(sediment) (p-value = 0.004). The model, ln(runoff) + hillslope gradient, explained 74 percent of the variability of ln(sediment) (p-value < 0.001), while another model, ln(runoff) + hillslope gradient + cutslope height, explained 84 percent of the variability of ln(sediment) (p-value < 0.001). These models, their R-squared values, and their p-values are listed in Table 4.7.

Table 4.7 Statistics of selected models regressed on sediment data.

Model	R^2	p-value
ln(sediment) = ln(runoff)	0.51	4.2E-03
ln(sediment) = ln(runoff) + hillslope gradient	0.74	5.5E-04
ln(sediment) = ln(runoff) + hillslope gradient + cutslope height	0.84	3.2E-04

4.4.2. Suspended Sediment

Suspended sediment concentration (SSC) was sampled only at culvert 15 at 2-hr intervals. Rainfall was recorded according to intensity and discharge was recorded at 10-minute intervals. Summed instantaneous SSC (ΣSSC) was determined as the additive SSC of the number of samples collected (n) during a storm, or

Equation 4.2

$$\text{Summed Instantaneous SSC,}\left(\frac{\text{mg}}{\text{L}}\right) = \sum_{n}^{1} \text{SSC}\left(\frac{\text{mg}}{\text{L}}\right)$$

Summed instantaneous SSC and maximum SSC for each of the four storms are listed in Table 4. 8. Storm 1 had the highest ΣSSC (1982 mg/L) and storm 2 registered the highest maximum SSC (796 mg/L). Storm 3 had the lowest maximum SSC (121 mg/L). Storm 4 had the lowest ΣSSC (532 mg/L).

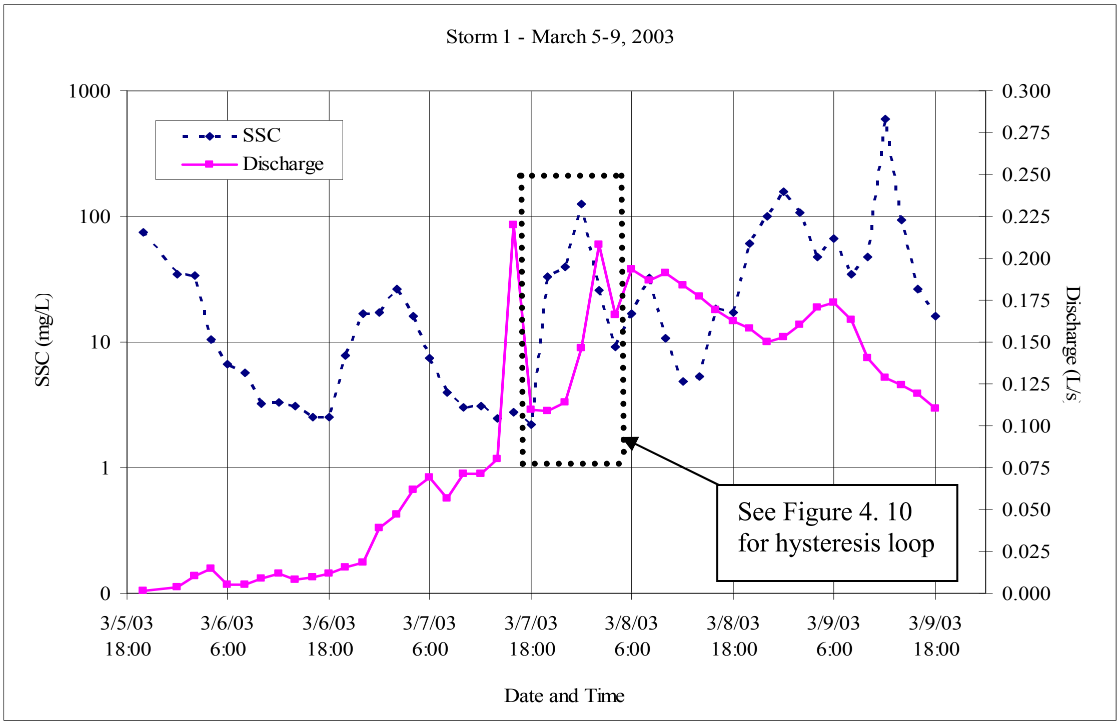
Table 4. 8 Summarized suspended sediment data during automated water sampling at culvert 15.

	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

Hydrographs for the individual storms and graphs of SSC at culvert 15 are shown in Figure 4. 7 and Figure 4. 8. The variability of the hydrographs is illustrated and the rising and falling limbs of several storms and their associated SSC are shown.

A single discharge does not consistently yield a predictable value of SSC. There is no minimum threshold of discharge that initiates suspended sediment production. This means that the variability in SSC is not adequately explained by discharge as the single independent variable. A sediment rating curve for culvert 15 is shown in Figure 4.9 for SSC data from the four storms that further illustrates the lack of predictability of discharge with respect to SSC. When the individual data points (n = 166) for all four storms are combined, the R-squared value is 0.0095. This reflects the fact that discharge is not a good predictor of SSC.

Hysteresis loops of SSC were developed by plotting SSC against discharge for selected data from culvert 15 for the four storms. Hysteresis occurs during a storm when SSC for a given discharge on the rising limb of the storm hydrograph is higher than SSC for the same discharge on the falling limb of the storm hydrograph. The lack of a clear and identifiable hysteresis effect over the course of an entire storm is undoubtedly due in part to the lack of a single identifiable hydrograph. Each storm was characterized by a series of small peak flows with several rising and falling limbs. However, hysteresis loops were indeed evident in storms 1 and 3. The hysteresis loops are shown in Figure 4. 10 and Figure 4. 11. The data were plotted in this manner to



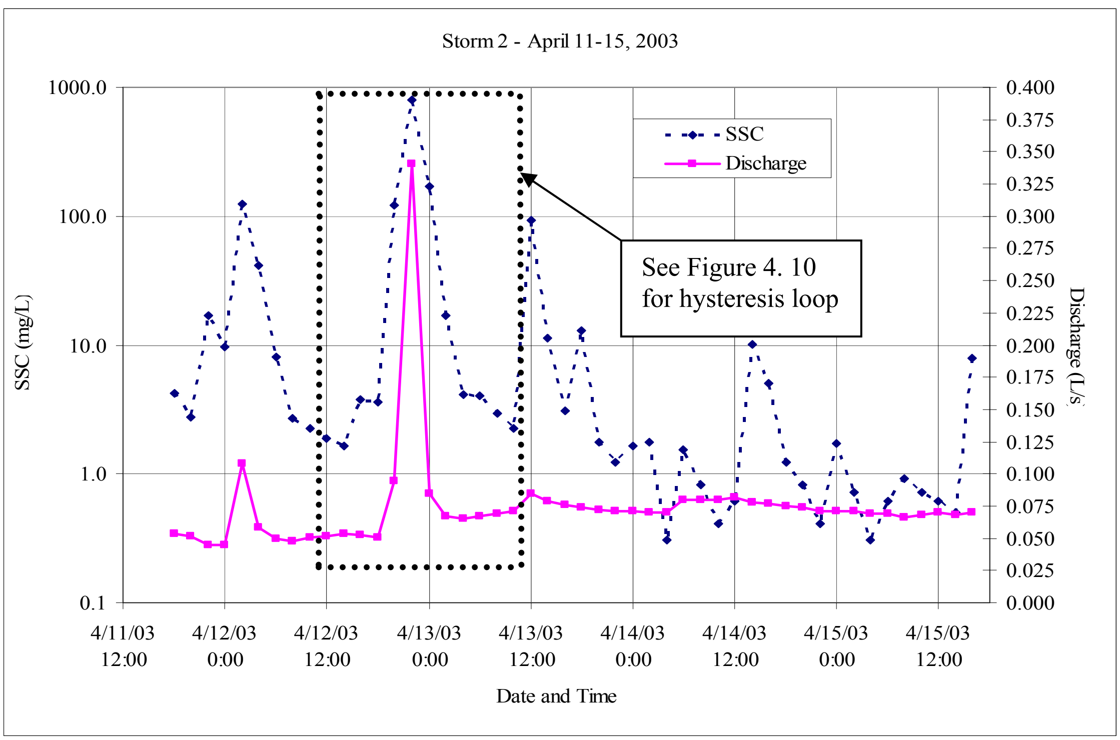
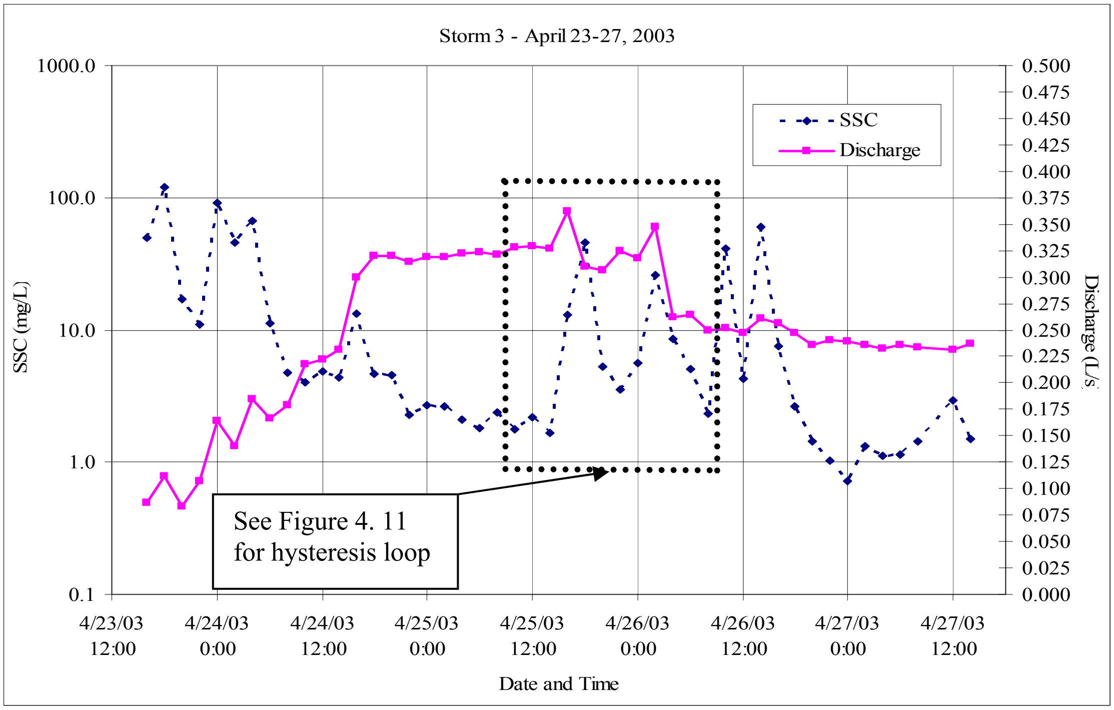


Figure 4. 7 Discharge hydrographs and suspended sediment concentration at culvert #15 for storms 1(top) and 2 (bottom). Dashed boxes indicate sequences of SSC and discharge used to develop the hysteresis plots shown in Figure 4. 10. Note: SSC is on log-scale.



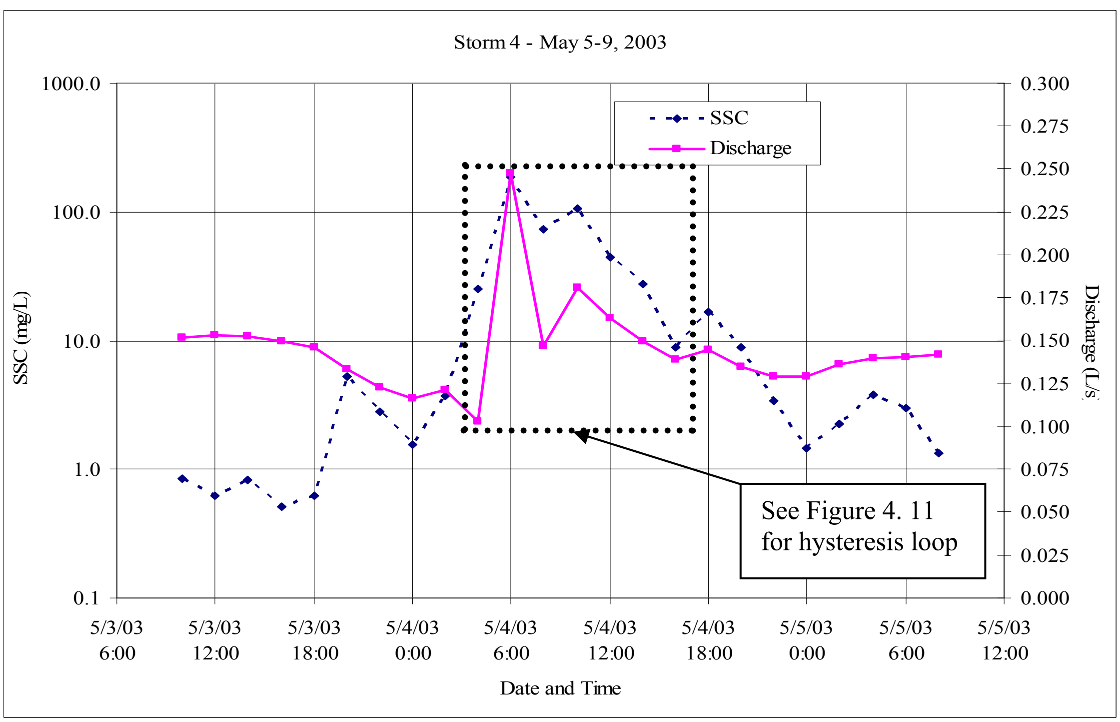


Figure 4. 8 Discharge hydrographs and suspended sediment concentration at culvert #15 for storms 3 (top) and 4 (bottom). Dashed boxes indicate sequences of SSC and discharge used to develop the hysteresis plots shown in Figure 4. 11. Note: SSC is on log-scale.

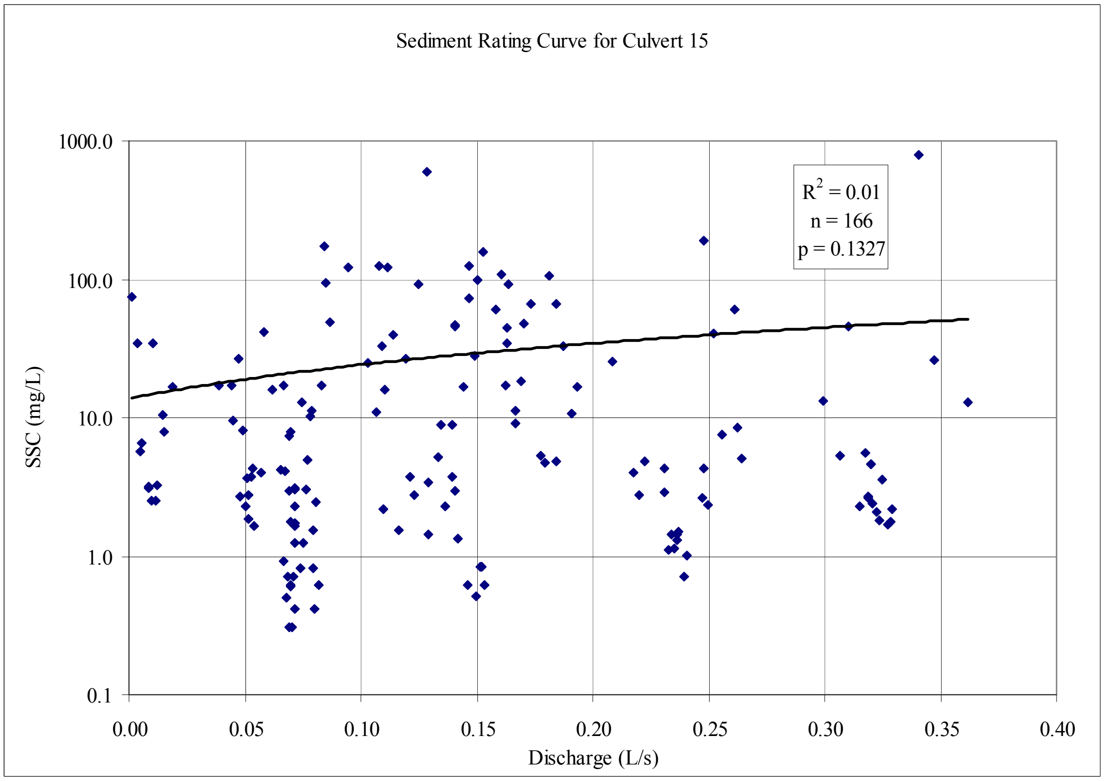
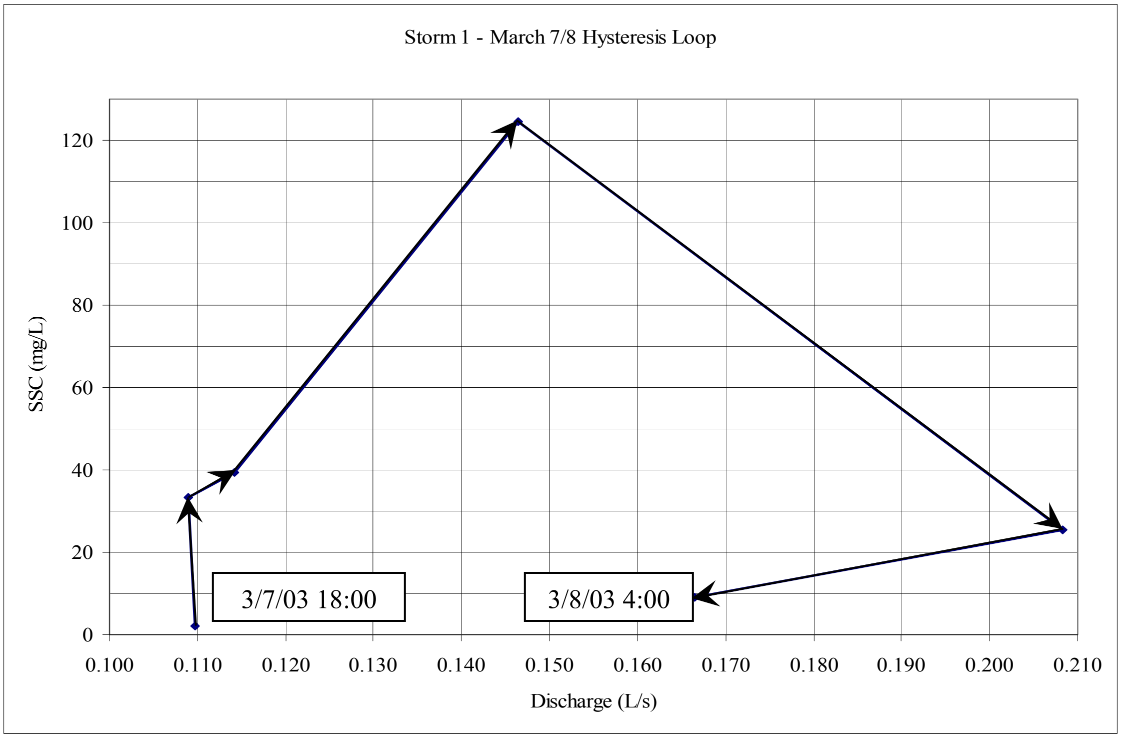


Figure 4.9 Sediment rating curve for culvert 15. Data points from storms 1-4.

investigate if hysteresis loops similar to those observed by Paustian and Beschta (1979) for the suspended sediment regime of Oak Creek were present in the SSC data from the road at culvert 15. Hysteresis loops indicate a "flushing" of sediment from the ditch and the road surface. This mechanism has been observed for streams but is not widely reported for roads. The existence of sediment hysteresis loops for roads indicates whether sediment supply or energy dominates this relationship.

Discharge and SSC follow similar patterns during storms 2 and 4. This pattern was further investigated by comparing the first derivative (i.e. rate of change) of both variables over the course of each storm. The similarity in both proportion and timing of the changes in SSC and discharge is noteworthy in storm 2 and storm 4 (Figure 4.12). Storms 1 and 3 did not exhibit these patterns.



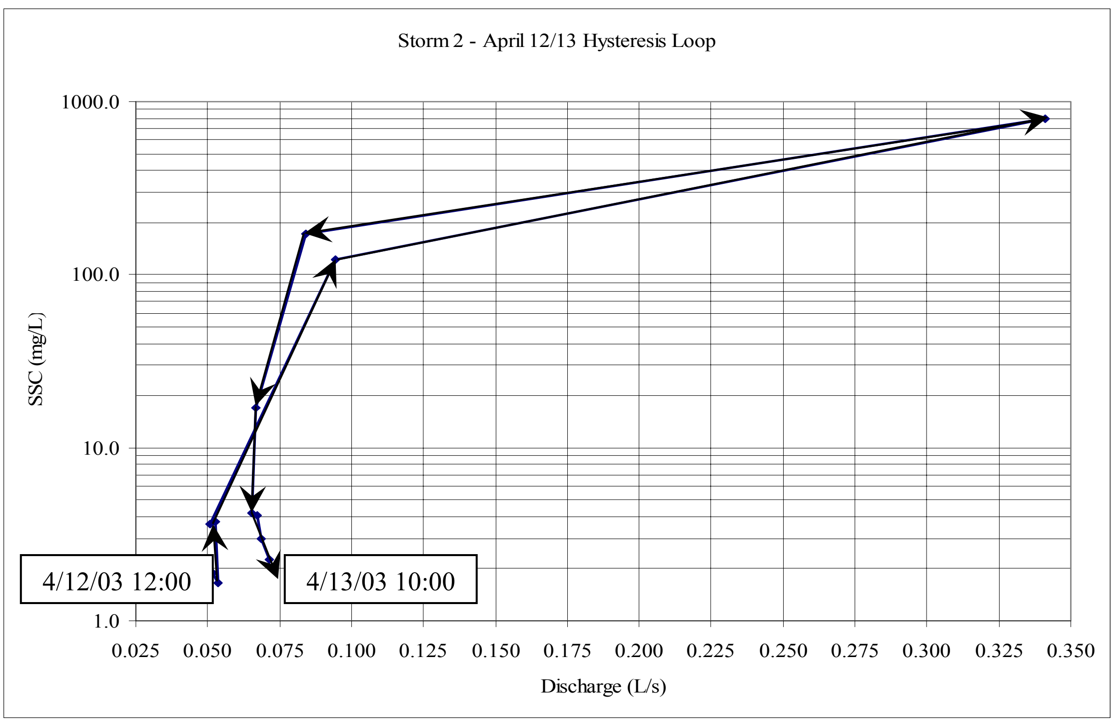
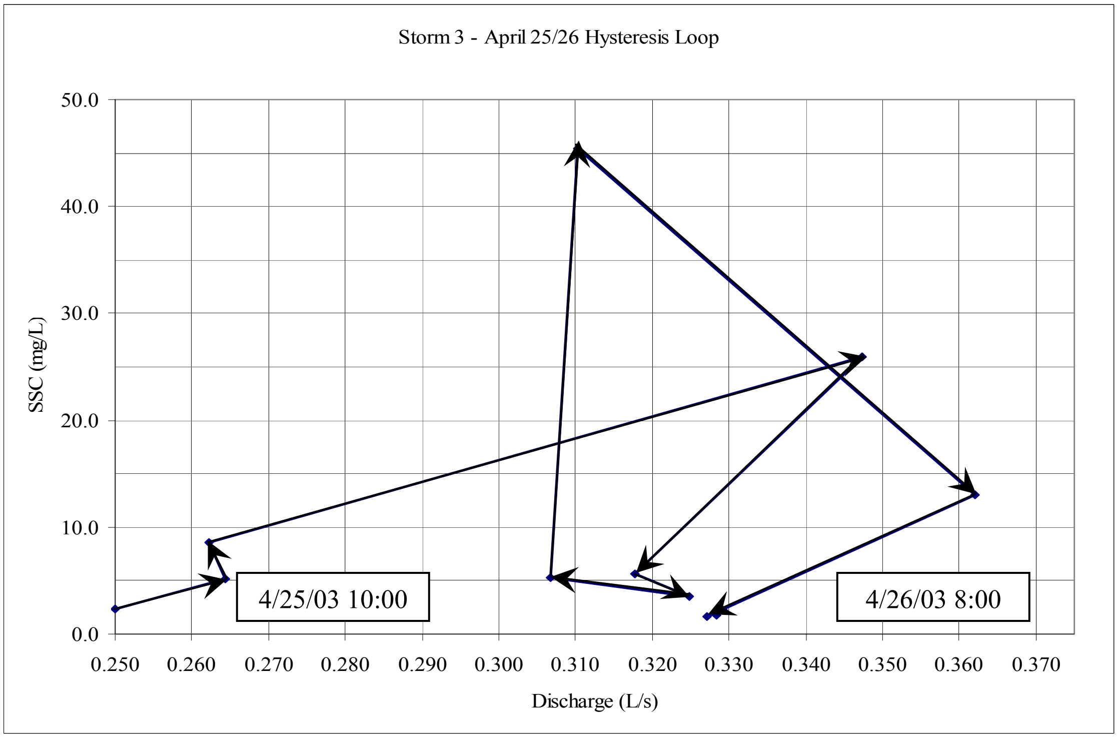


Figure 4. 10 Hysteresis loops for select phases of hydrograph for storms 1 (top) and 2 (bottom) at culvert 15. Arrows indicate progression through time. Boxes containing date and time indicate start and finish of hysteresis loop.



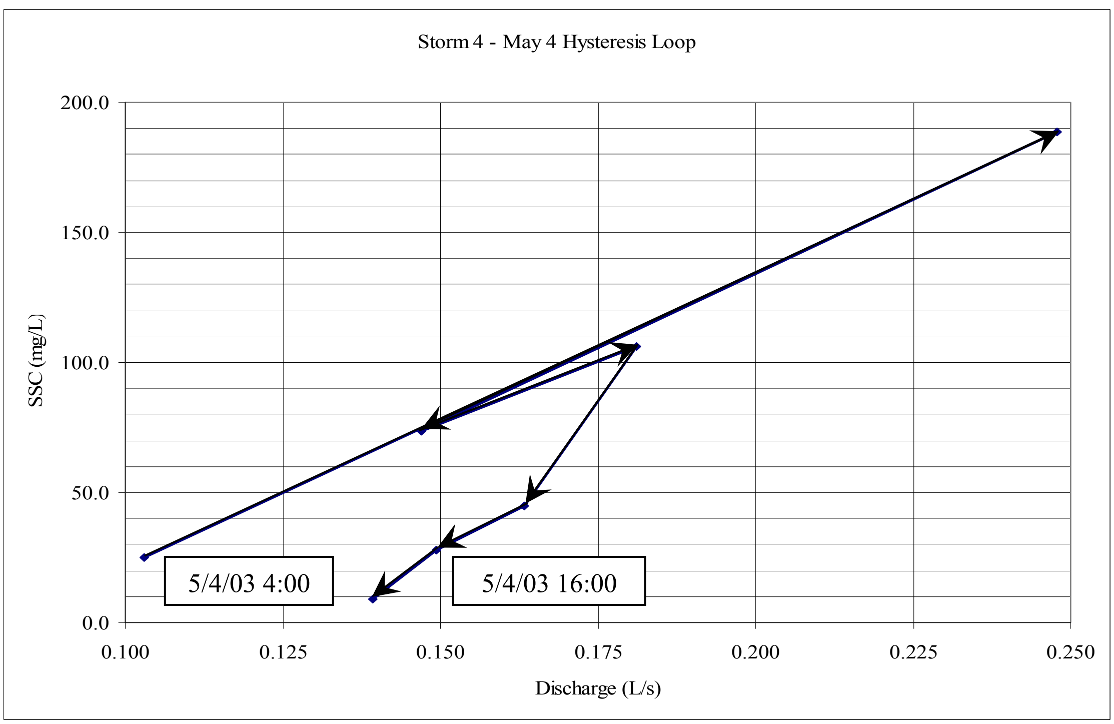
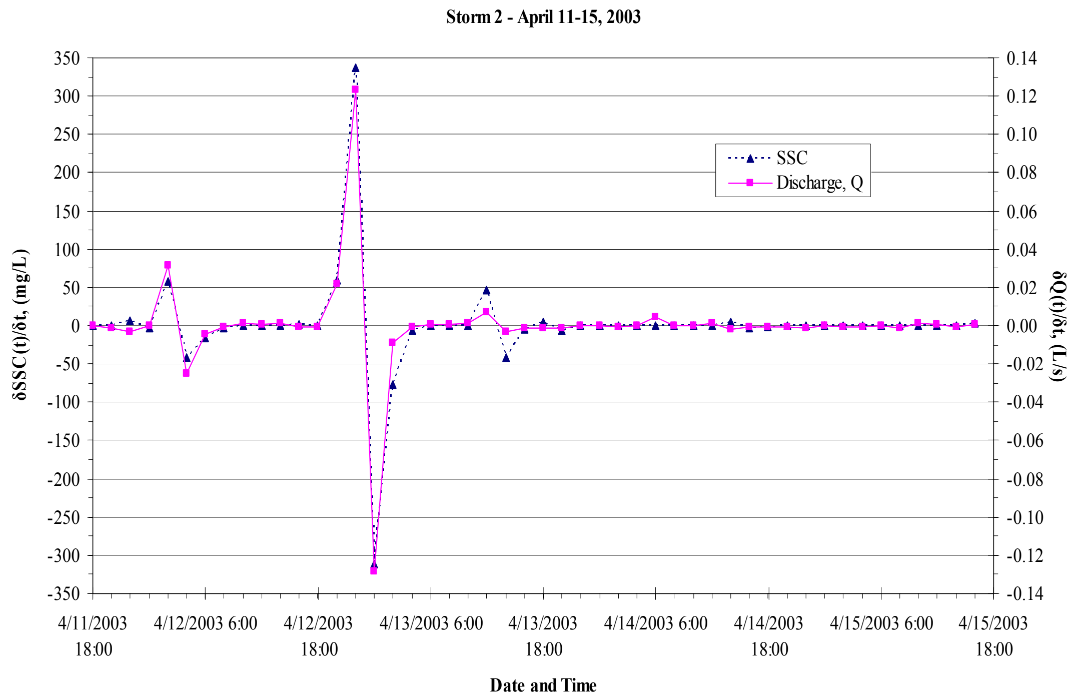


Figure 4. 11 Hysteresis loops for select phases of hydrograph for storms 3 (top) and 4 (bottom) at culvert 15. Arrows indicate progression through time. Boxes containing date and time indicate start and finish of hysteresis loop.



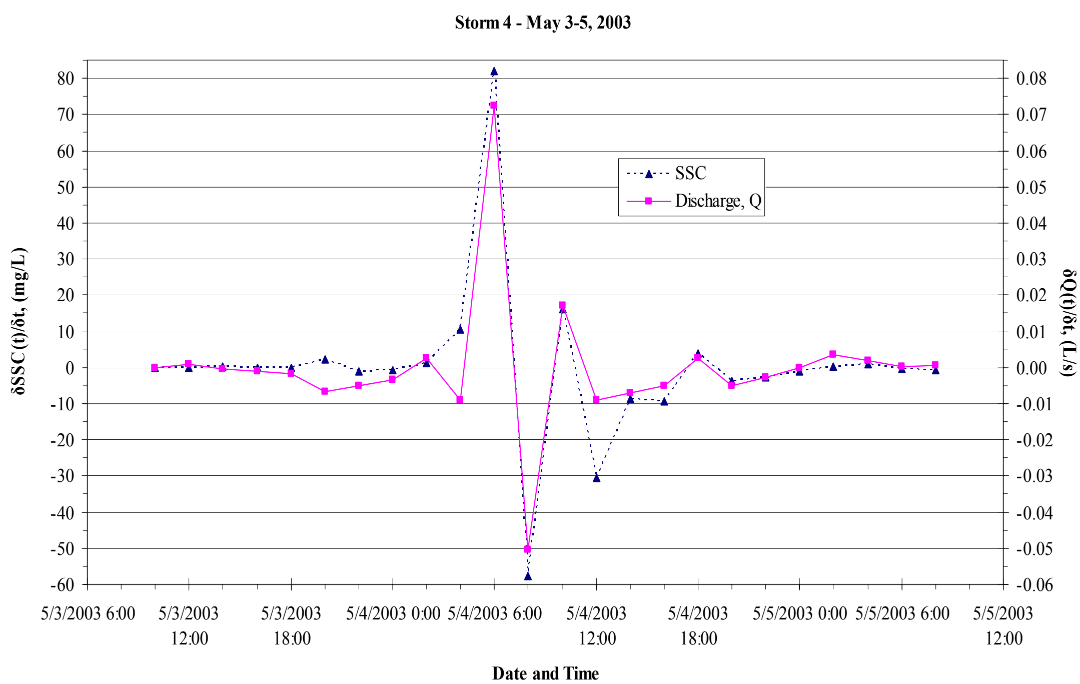
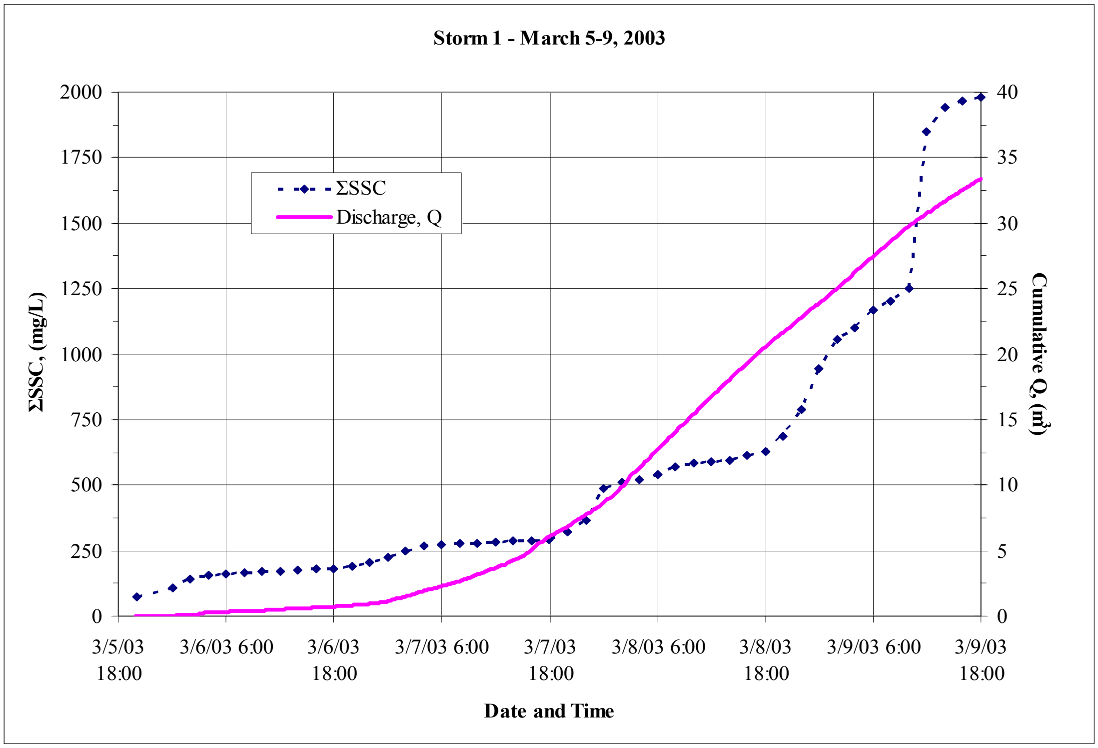


Figure 4.12 First derivatives (i.e. rates of change) of SSC and discharge at culvert 15 for storms 2 and 4.

Cumulative discharge and ΣSSC were plotted along a time scale to further observe how suspended sediment might be affected by discharge (Figure 4. 13 and Figure 4. 14). Discharge accumulates linearly in storms 2 and 4. During storms 1 and 3, discharge accumulates slowly before a linear slope is achieved similar to that of storms 2 and 4. The runoff ratios for the four storms were all greater than one (>1; Table 4.5). This suggests that runoff at culvert 15 came from sources other than the road surface and that it occurred nearly at a constant rate during storms 2-4.

Storms 1 and 3 produced suspended sediment over many “steps” with occasional distinct periods of quick production. Storms 2 and 4 had one period of increased suspended sediment production with very gradual production at the beginning and end. Storm 1 produced the most suspended sediment and the second most discharge. Storm 3 yielded the most discharge and the third most suspended sediment.



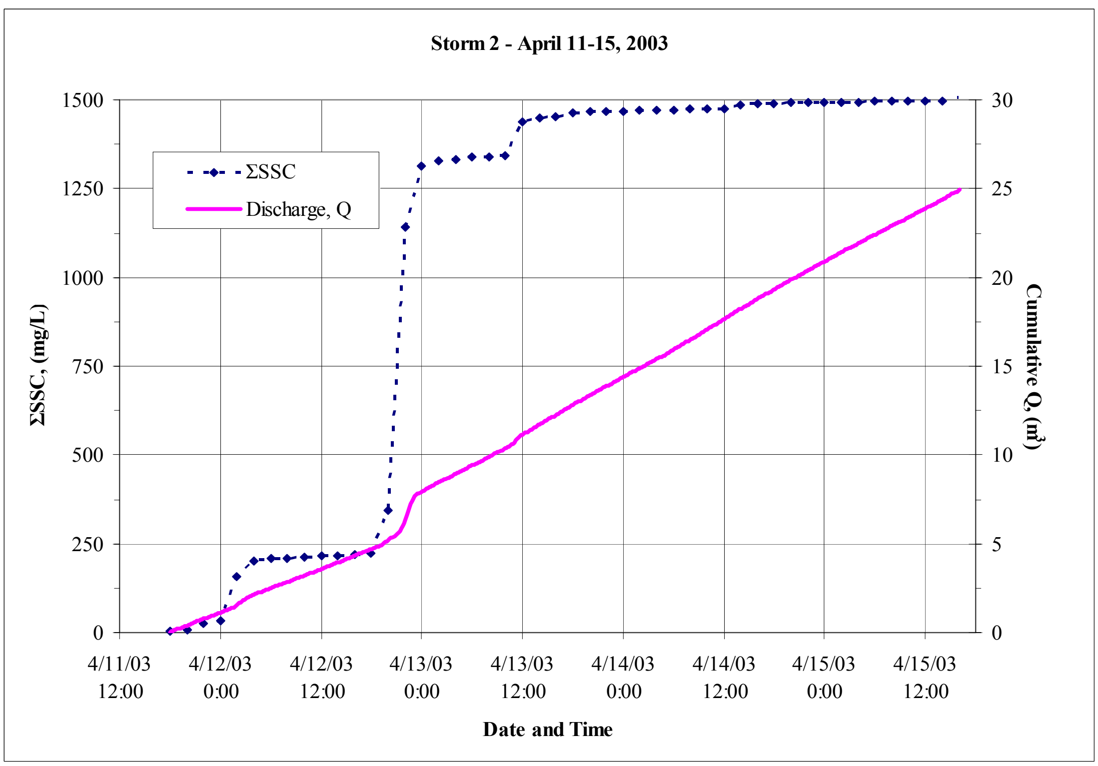
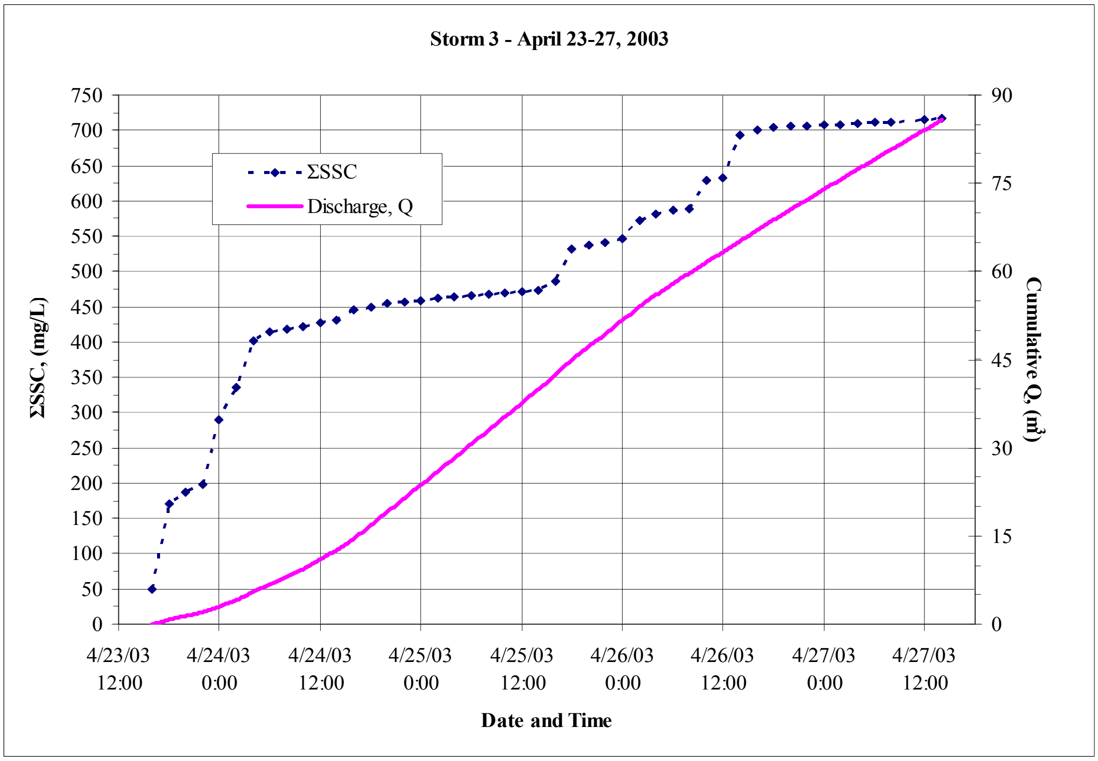


Figure 4. 13 ΣSSC and cumulative discharge at culvert 15 during storms 1 (top) and 2 (bottom).



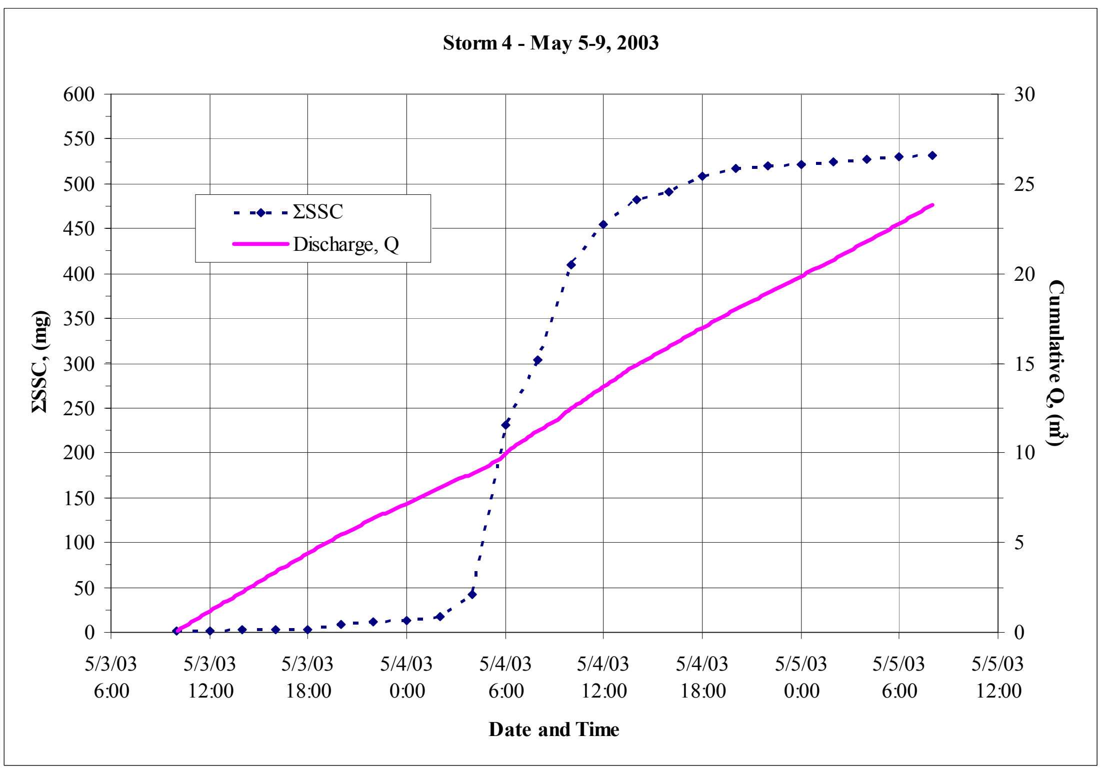
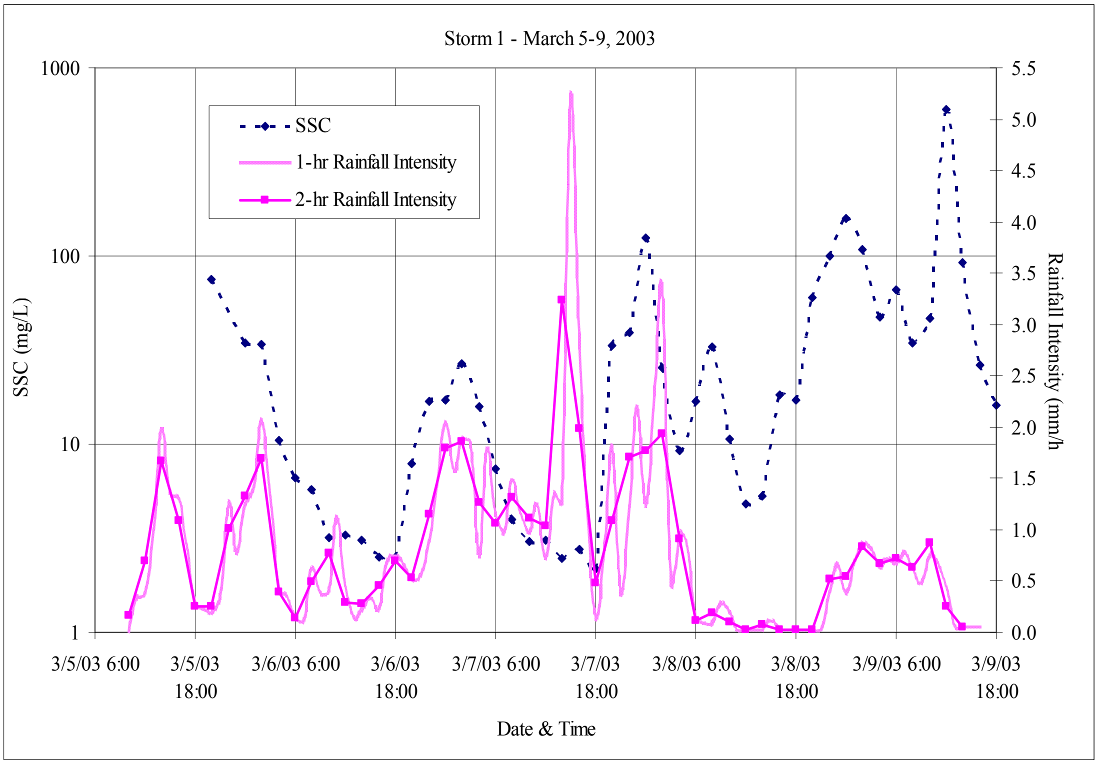


Figure 4. 14 ΣSSC and cumulative discharge at culvert 15 during storms 3 (top) and 4 (bottom).

Plots of 1-hr and 2-hr rainfall intensities and SSC at culvert 15 during the four storms are shown in Figure 4. 15 and Figure 4. 16. There is a time lag between rainfall intensity and SSC. Rainfall intensity increased before SSC. This time lag is logical because rainfall detaches soil particles from the road surface before the particles are transported through the ditch and culvert to where they are sampled. Non-lagged rainfall intensities were analyzed, but both 1-hr rainfall intensity lagged one hour and 2-hr rainfall intensity lagged two hours had the best correlation with SSC and were used in the development of suspended sediment rating curves based on rainfall intensity (Figure 4.17 and Figure 4.18). These sediment rating curves based on rainfall intensity had better correlations ($R^2 = 0.22$, $p<<0.001$) than the sediment rating curve based on culvert discharge ($R^2 = 0.01$, $p = 0.1327$, Figure 4.9). Also, sediment rating curves based on non-lagged rainfall intensities had better correlation than the sediment rating curve based on culvert discharge. Within the upper Oak Creek watershed, rainfall intensity is a better predictor of SSC than culvert discharge at culvert 15, particularly when time lag is accounted for.

Lagged rainfall intensities and SSC follow similar patterns during storms 2 and 3. This pattern was further investigated by comparing the time derivative of both variables over the course of each storm. The similarity in both proportion and timing of the changes in SSC and 1-hr rainfall intensity lagged one hour is noteworthy in storm 2 (Figure 4.19). This similarity existed between 2-hr rainfall intensity lagged two hours during Storm 3 (Figure 4.20). Storms 1 and 4 did not exhibit these patterns.



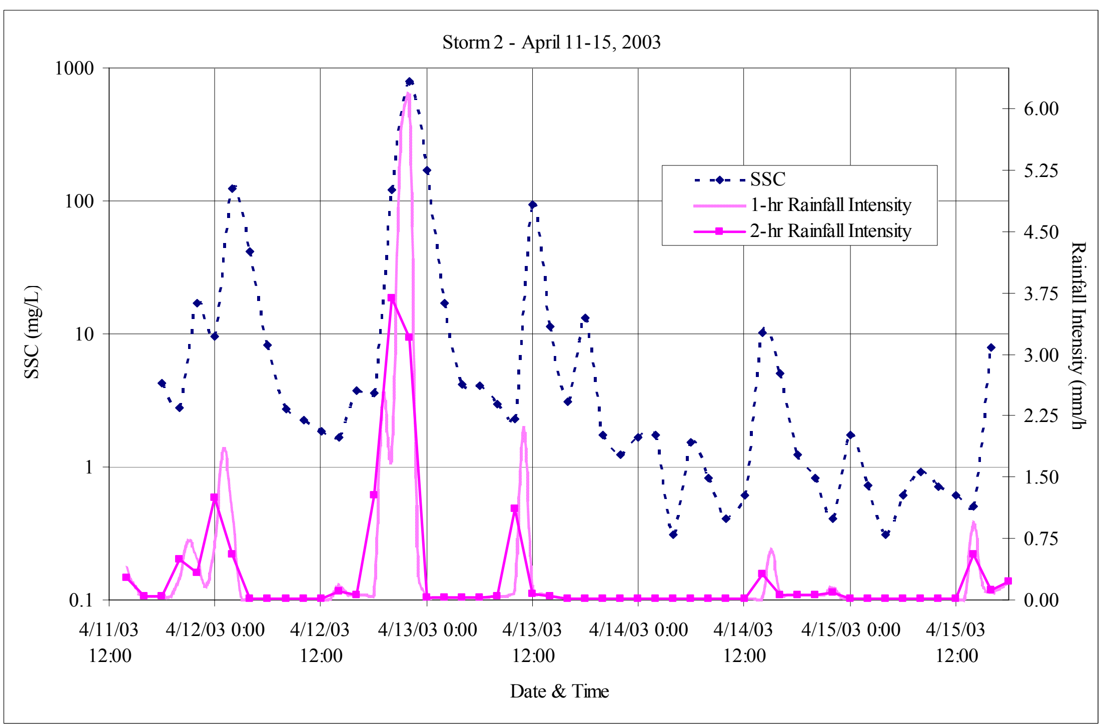
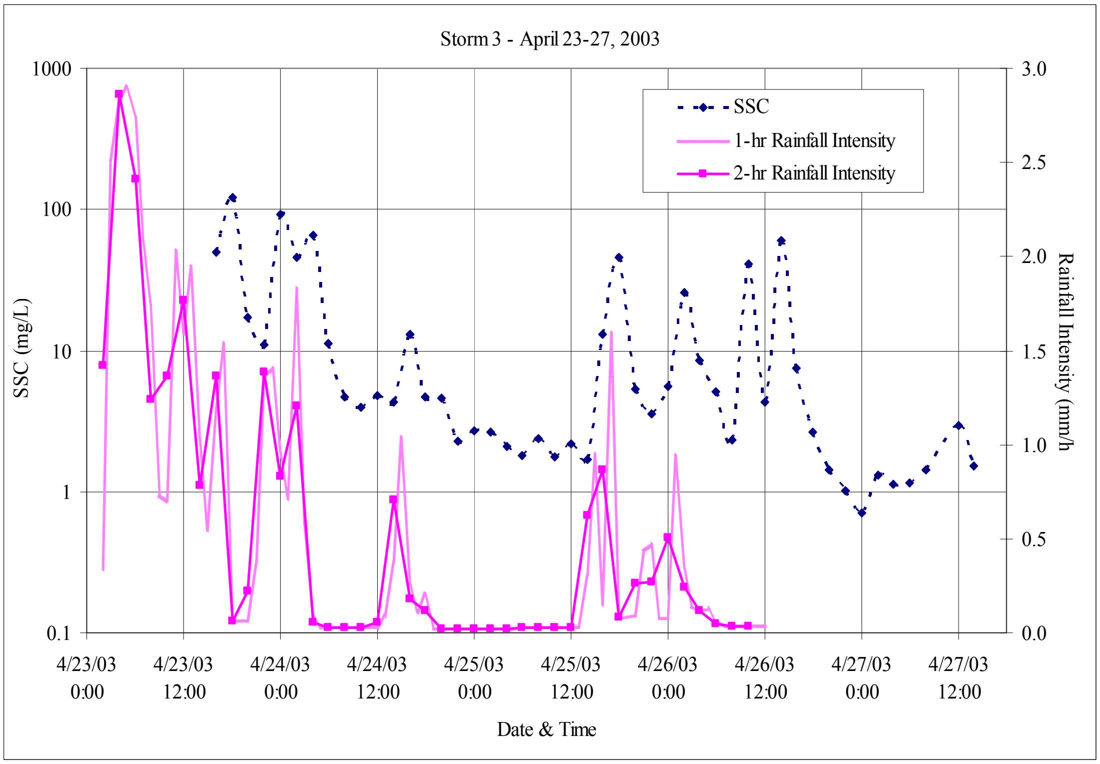


Figure 4. 15 SSC and 1- and 2-hr rainfall intensity at culvert 15 during storms 1 (top) and 2 (bottom). Note: SSC is on log-scale.



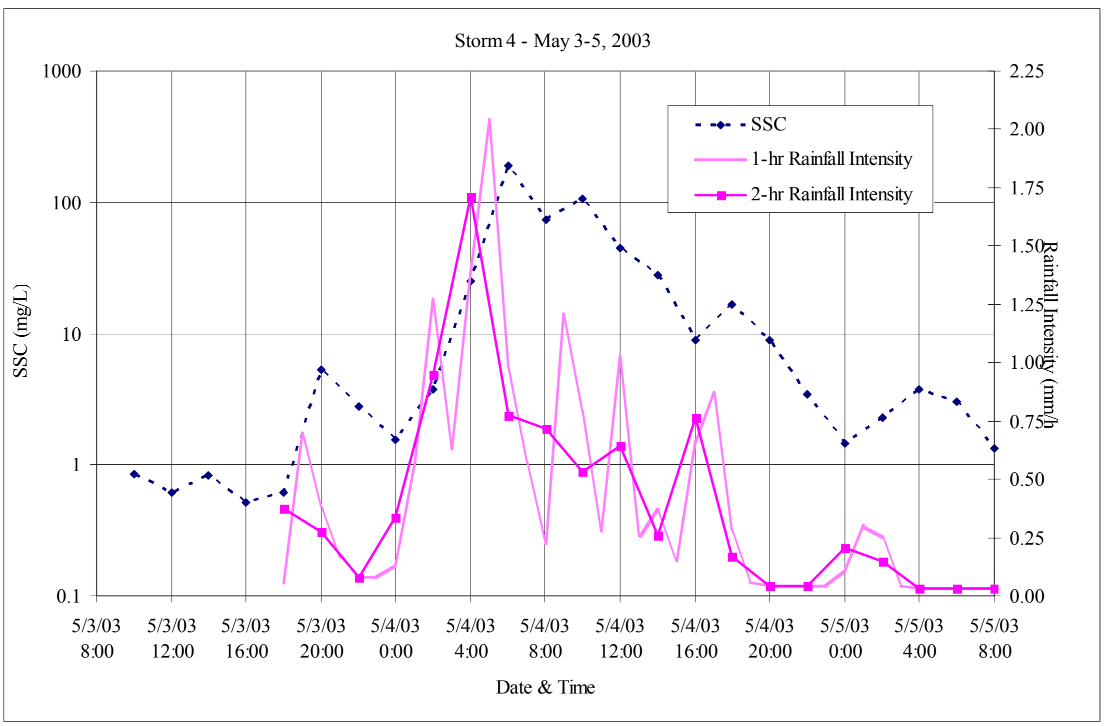


Figure 4. 16 SSC and 1- and 2-hr rainfall intensity at culvert 15 during storms 3 (top) and 4 (bottom). Note: SSC is on log-scale.

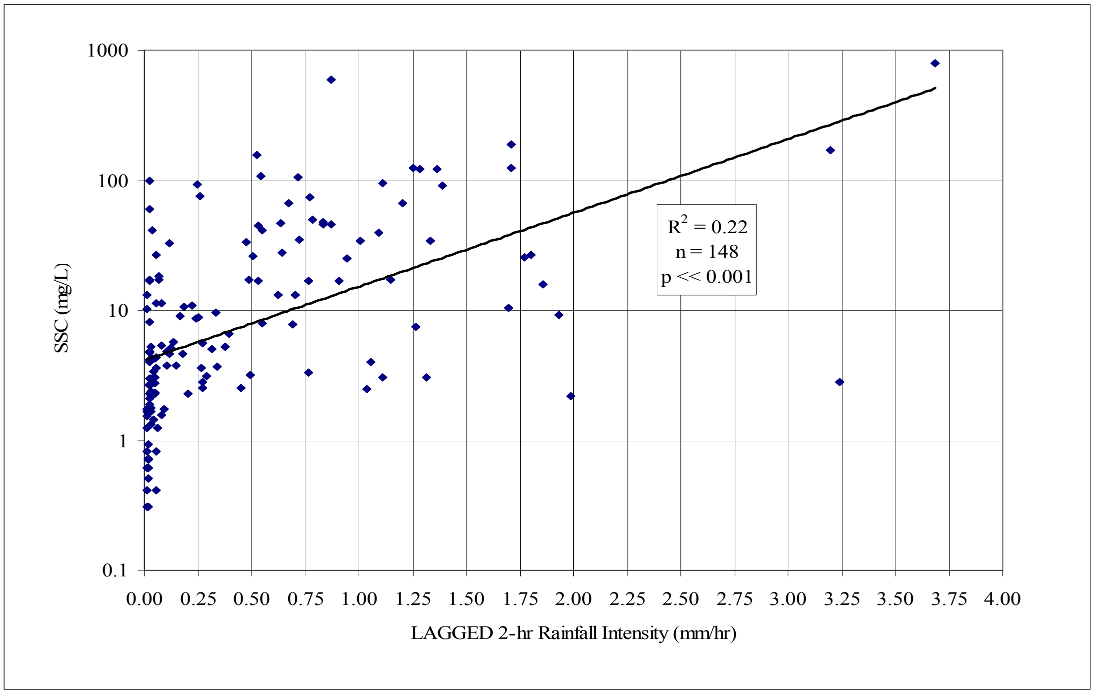


Figure 4.17 Suspended sediment rating curve based on 2-hr rainfall intensity lagged two hours at culvert 15 for storms 1-4. Note: SSC is on log-scale.

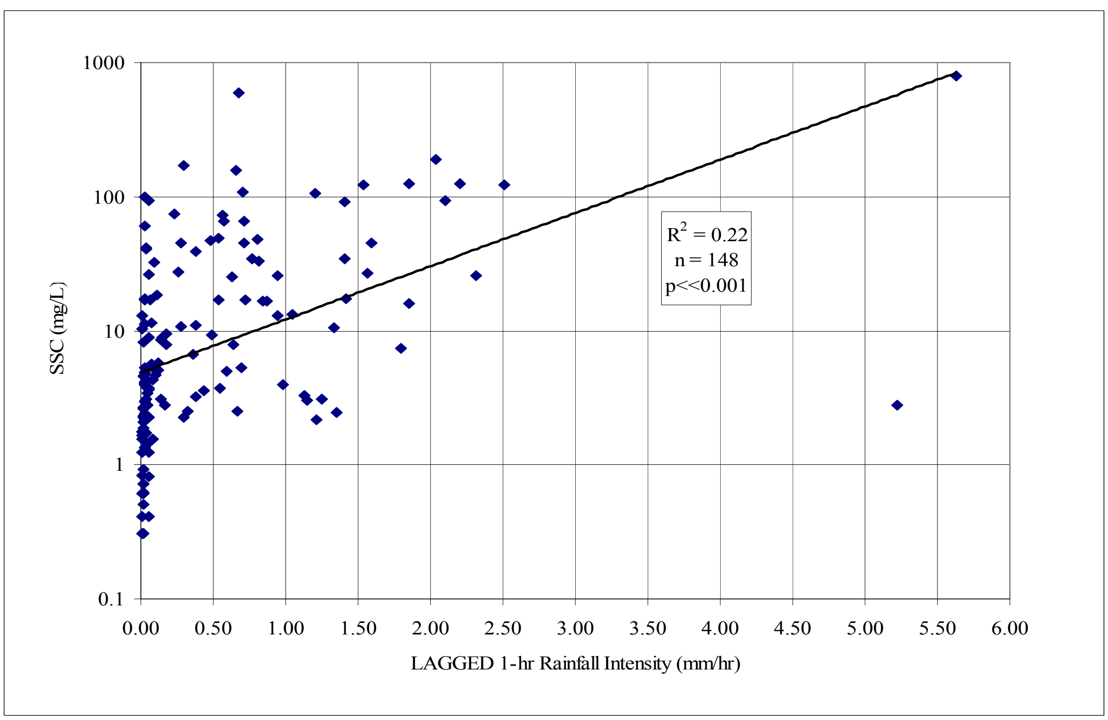


Figure 4.18 Suspended sediment rating curve based on 1-hr rainfall intensity lagged one hour at culvert 15 for storms 1-4. Note: SSC is on log-scale.

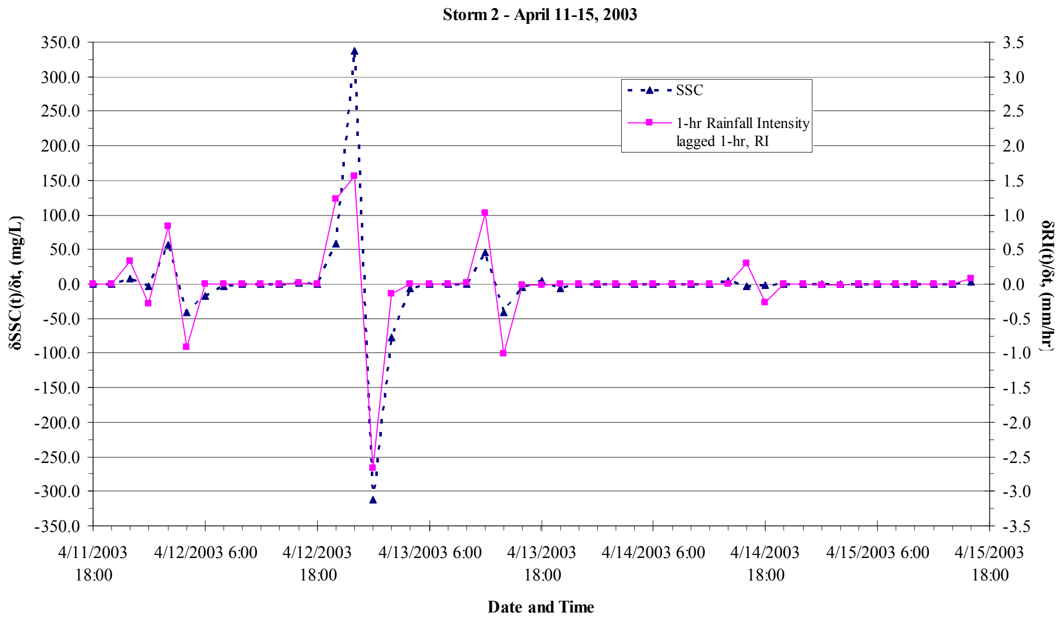


Figure 4.19 First derivatives (i.e. rates of change) of SSC and 1-hr rainfall intensity lagged one hour at culvert 15 for storm 2.

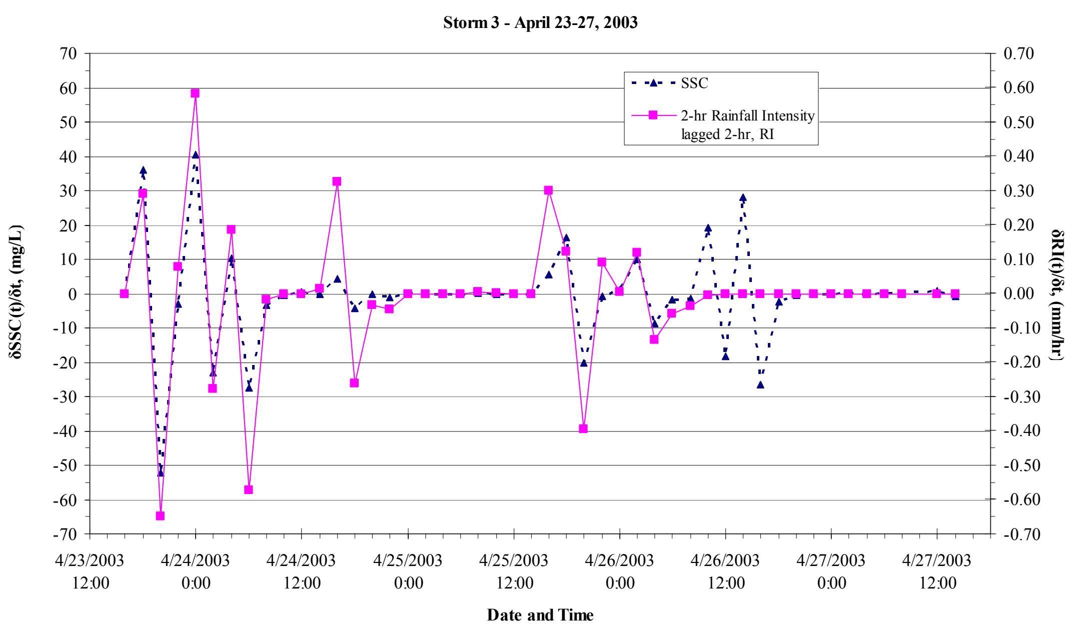


Figure 4.20 First derivatives (i.e. rates of change) of SSC and 2-hr rainfall intensity lagged two hours at culvert 15 for storm 3.

Peak 1-hr and peak 2-hr rainfall intensities for the four storms were significantly correlated with peak SSC at culvert 15 (Figure 4.21), further showing rainfall intensity as a predictor of SSC. The peak 1-hr rainfall intensity occurred at the same time as the peak SSC during Storm 2.

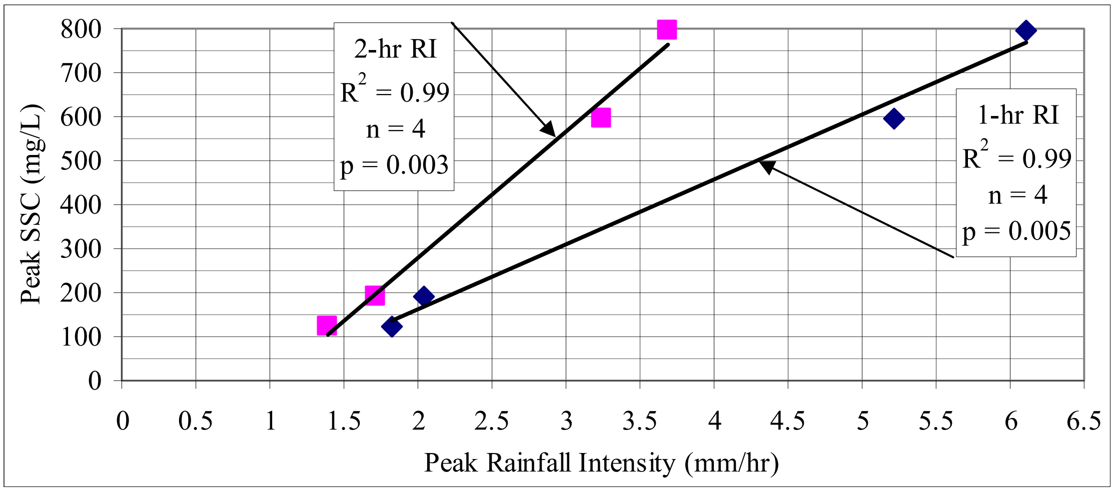
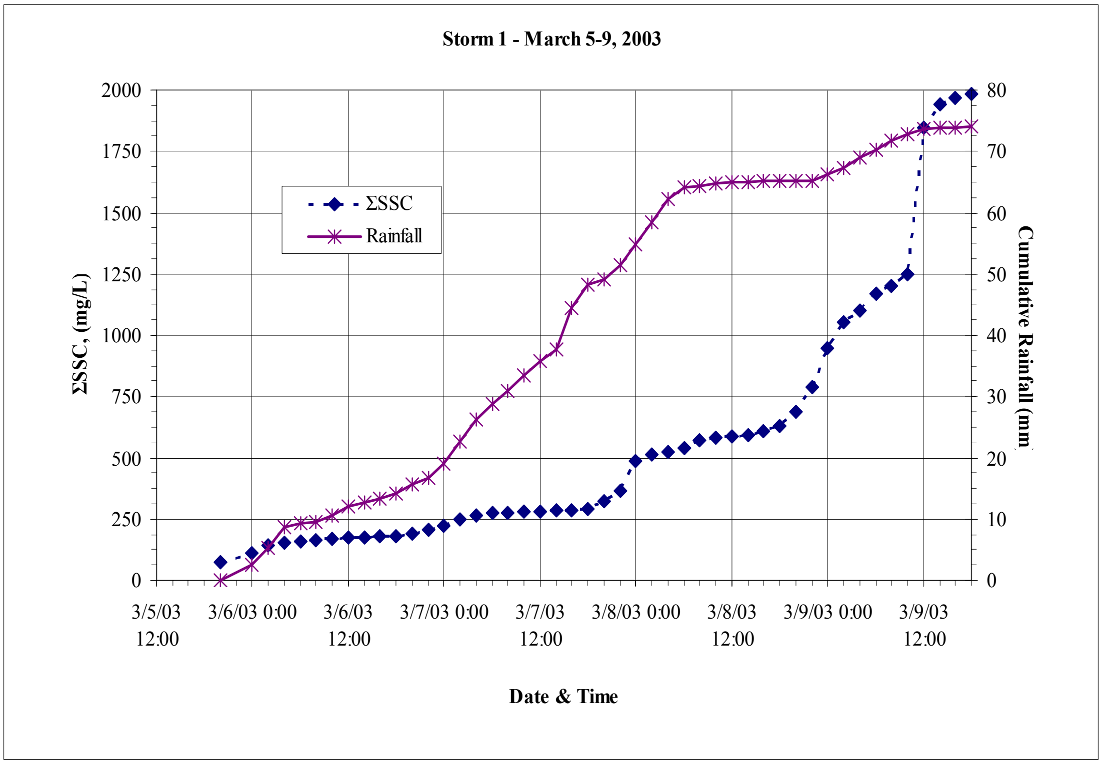


Figure 4.21 Regression of peak suspended sediment concentration on peak 1- and 2-hr rainfall intensity for Storms 1-4 at culvert 15.

The quantity of rainfall was also related to suspended sediment (Figure 4. 22 and Figure 4. 23). Storm 2 had the closest relationship between ΣSSC and cumulative rainfall. Storms 3 and 4 had noteworthy relationships between these parameters and storm 1 had the weakest relationship. However, storm 1 produced the most ΣSSC (1982 mg/L) and the most rainfall (74 mm). Storm 4 yielded the least ΣSSC (532 mg/L) and the least rainfall (16 mm).



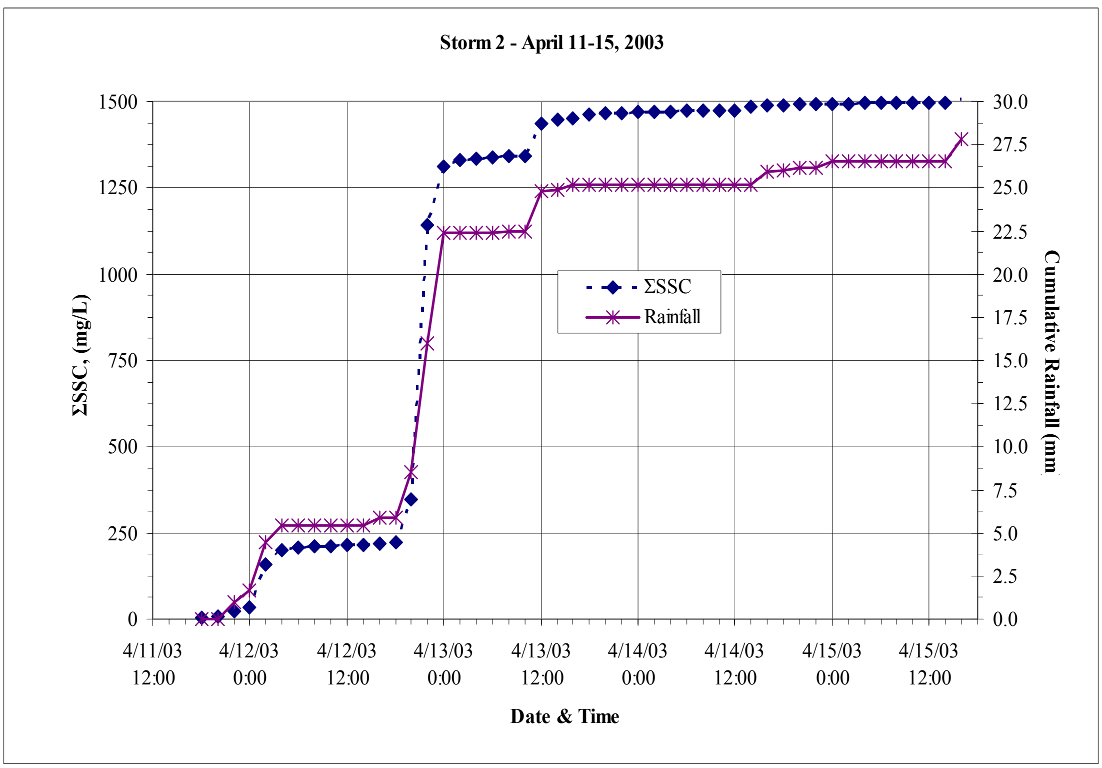
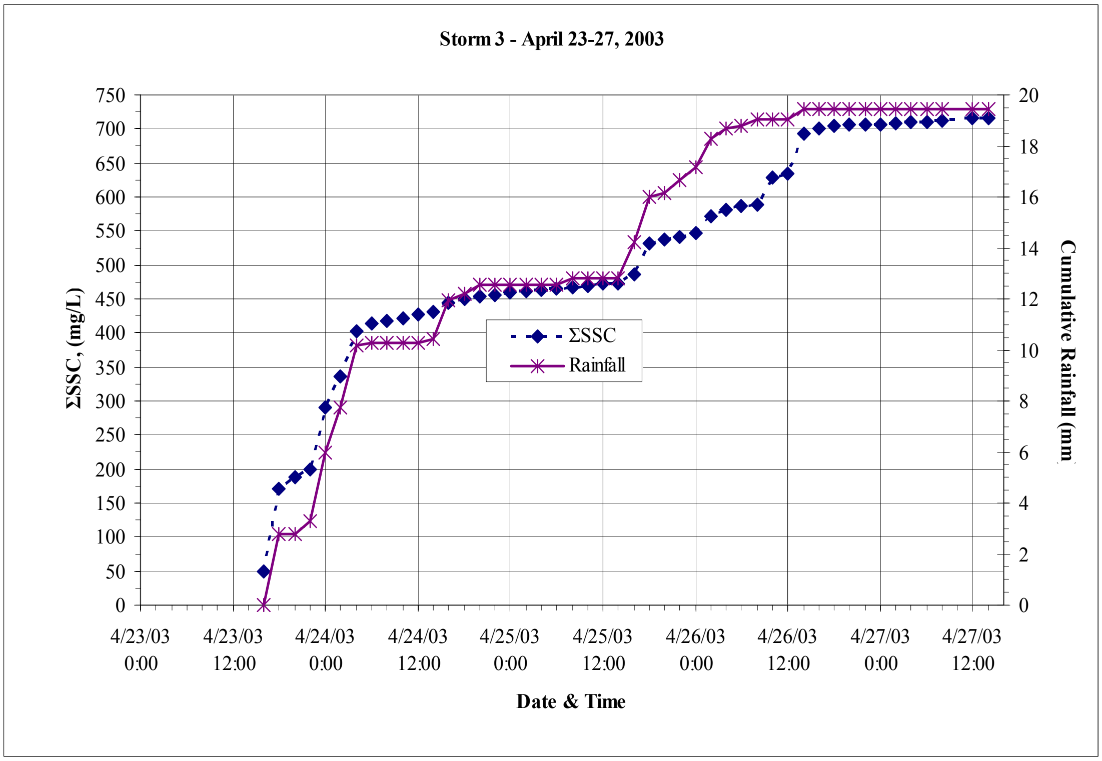


Figure 4. 22 ΣSSC and cumulative rainfall at culvert 15 for storms 1 (top) and 2 (bottom).



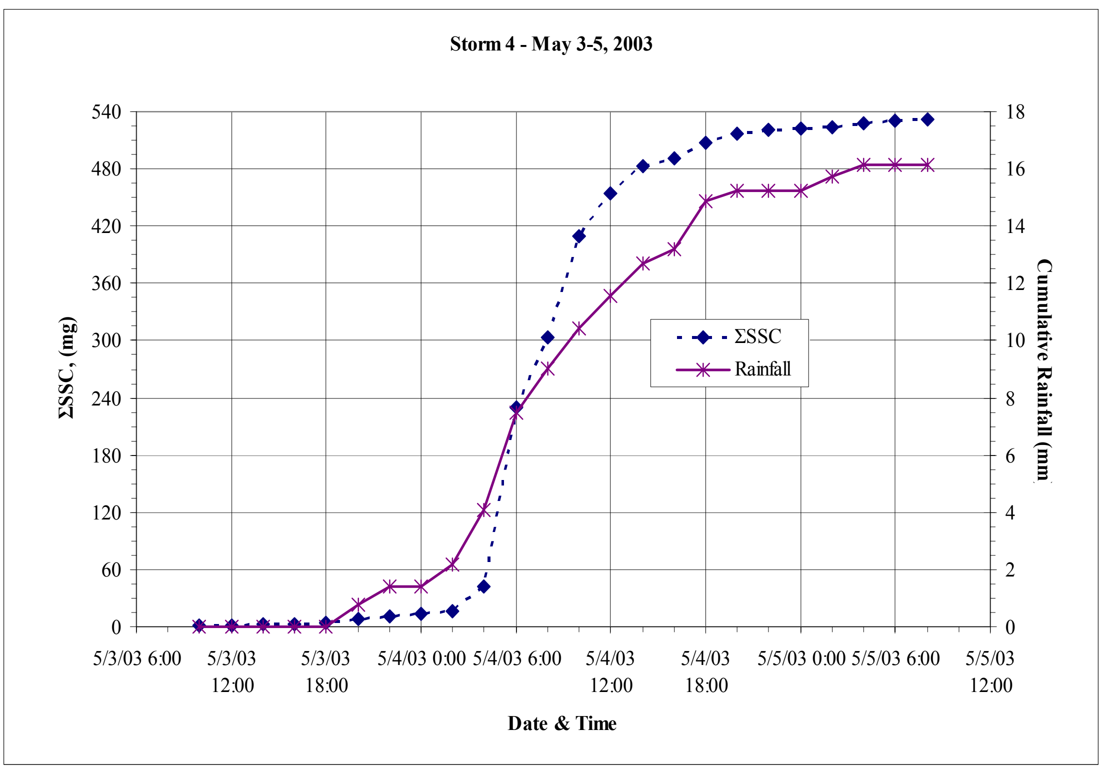


Figure 4. 23 ΣSSC and cumulative rainfall at culvert 15 for storms 3 (top) and 4 (bottom).

4.4.3. Sediment Production Models

Sediment estimates from WEPP:Road and observed sediment values are summarized in Table 4.9. WEPP:Road output was calculated over an entire year (minimum allowed by the model). Observed sediment was collected over 7 months at culverts 15, 30, 66, 76, 81, 88, and 98 and over 3 months at culverts 22 and 23. WEPP:Road calculated sediment yield from the entire range of soil particle distribution (WEPP, 2003), but field data was only comprised of settleable and coarse sediment. Extrapolation of SS at culvert 15 for storms 2-4 increased total sediment production at the culvert by a factor of ten (see Appendix A-3). Increasing observed total sediment at culvert 15 by a factor of ten yielded 36 kg, which was still much less than the WEPP:Road estimate of 279 kg. It should be noted that WEPP:Road estimated sediment production from culverts 22, 30, and 66 despite showing no runoff.

Initial results from SEDMODL2 estimated that the road segments discharging to the study culverts produced minimal sediment in comparison with non-study segments (Figure 4.24). The sediment production predicted by SEDMODL2 at the study culverts ranged from 0.0 to 6.7 kg. Road sections greater than this range were eliminated, which provided a graphical output specific to the needs of this study as shown in Figure 4.25.

Table 4.9 WEPP:Road input and output for each culvert. Last column (shaded) lists the observed amount of sediment. Additional WEPP:Road input parameters that were the same for every road segment include: "1-year" analysis; Rock:Clime generated "Corvallis St. Col. OR" for local climate, which gave an estimate of 1177 mm of annual precipitation; "silt loam" soil; "graveled none" surface and traffic; "insloped vegetated" design; and "5 m" road width.

	WEPP:Road Input						WEPP:Road Output				Observed
Culvert	Road Gradient (%)	Road Length (m)	Fillslope Gradient (%)	Fillslope Length (m)	Buffer Gradient (%)	Buffer Length (m)	Rain Runoff (mm)	Snow Runoff (mm)	Sed profile (kg)	Sediment from Road (kg)	Sediment from Road (kg)
15	7	53	50	6	30	3	32	15	98	279	3.6
22	4	36	20	1	30	10	0	0	0	160	0.40
23	2	96	20	1	30	10	7	11	31	319	15.0
30	10	53	50	10	50	75	0	0	0	332	0.65
66	7	50	50	2	30	30	0	0	0	262	1.0
76	3	76	40	1	30	30	1	1	126	287	0.60
81	13	258	40	2	30	30	19	14	2136	3019	0.02
88	1	58	50	1	50	30	1	1	126	187	0.08
98	6	256	30	2	50	30	14	14	902	1111	2.5

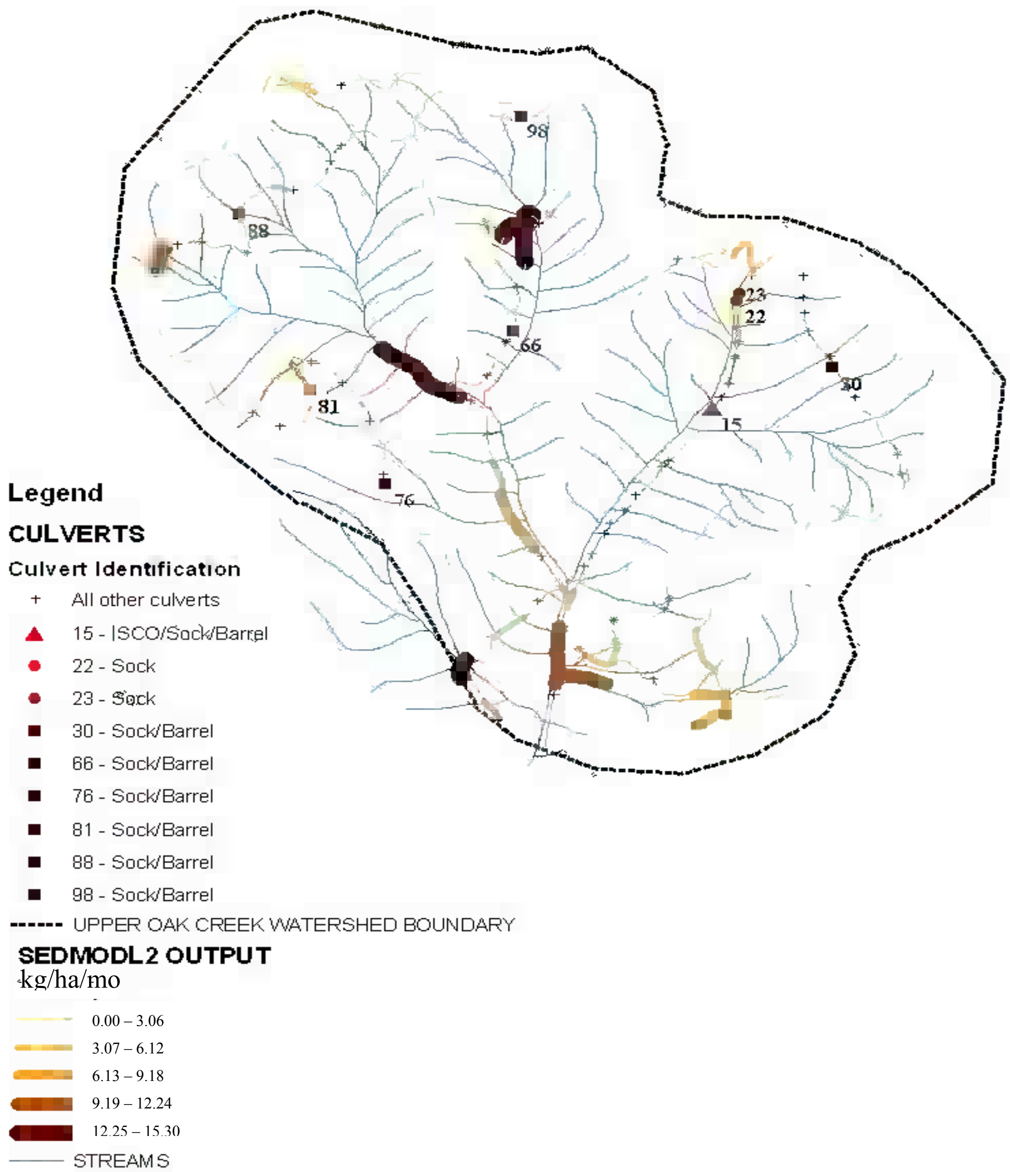


Figure 4.24 Initial SEDMODL2 graphical output.

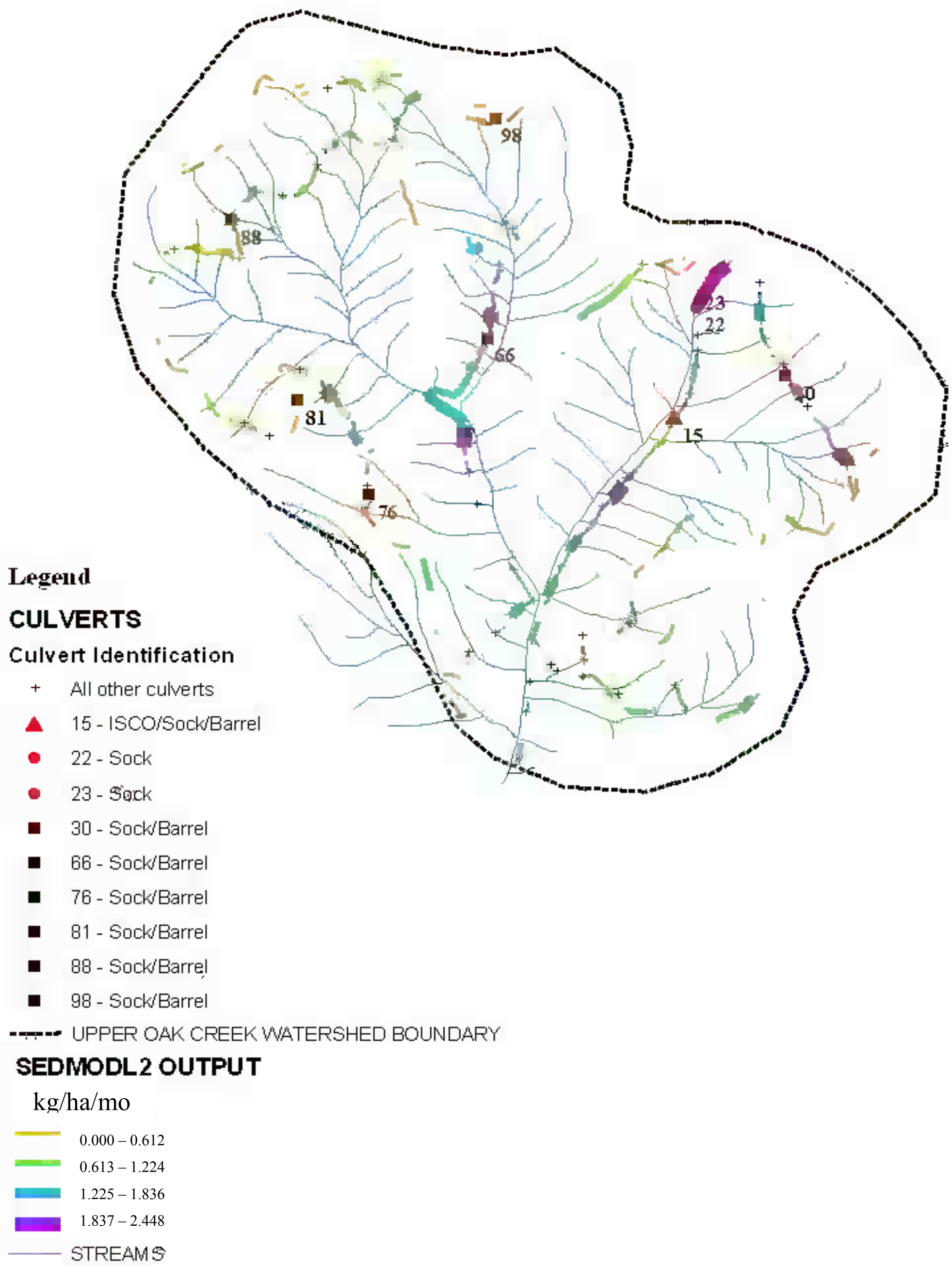


Figure 4.25 Refined SEDMODL2 graphical output with focus on monitored road segments.

Sediment production was ranked with respect to each model, which allowed nonparametric comparison of predicted sediment to observed sediment (Table 4.10). The values predicted by SEDMODL2 were significantly closer to the actual values than were the values predicted by WEPP:Road. Culverts 22 and 23 were not included because they collected sediment for only 3 months. WEPP:Road ranked culvert 98 second for most sediment, which was the same rank for observed sediment. WEPP:Road estimated culvert 81 to yield the most sediment (rank = 1) but it had the least observed sediment (rank = 7). This suggests that WEPP:Road is heavily based on road segment length as the road segment length for culvert 81 was the longest at 258 m. SEDMODL2 predicted culvert 81 produced no sediment and ranked it last, which is in agreement with actual data. Both models ranked the road segments above culverts 15 and 66 fifth and sixth, respectively. However, culvert 15 was ranked highest (rank =1) in terms of observed sediment.

Table 4.10 Values and corresponding rank of model-predicted sediment production values at each culvert. Culverts 22 and 23 were not included since they collected sediment for only three months. SEDMODL2 and WEPP:Road calculate sediment production on an annual basis, whereas sediment collected at the remaining culverts was trapped over the course of seven months.

	SEDMODL2		WEPP:Road		Observed	
Culvert	**Sediment**	**Rank**	**Sediment**	**Rank**	**Coarse and Settleable Sediment**	**Rank**
15	0.000 - 0.688 kg	5	278.51 kg	5	3.56 kg	1
22	0.600 - 0.800 kg	n/a	159.66 kg	n/a	0.40 kg	n/a
23	1.620 - 2.160 kg	n/a	318.72 kg	n/a	14.96 kg	n/a
30	1.376 - 2.064 kg	2	332.29 kg	3	0.65 kg	4
66	0.000 - 0.656 kg	6	261.75 kg	6	1.02 kg	3
76	0.000 - 0.994 kg	3	286.52 kg	4	0.57 kg	5
81	0 kg	7	3018.60 kg	1	0.02 kg	7
88	0.000 - 0.762 kg	4	187.34 kg	7	0.08 kg	6
98	3.344 - 6.688 kg	1	1111.04 kg	2	2.51 kg	2

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Total trapped sediment from nine segments of unpaved forest road in the upper Oak Creek Watershed was highly 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. Total volume of runoff measured at cross-drain culverts from the same road segments ranged from 100 m^3 to 52,000 m^3 and most of the runoff came from sources other than the road surface. Total runoff volume was the single most important variable that explained the variability in total trapped sediment ($R^2 = 0.51$, $p = 0.004$). Hillslope gradient, and cutslope height helped improve the relationship between total runoff volume and coarse and settleable sediment production. These observations suggest that non-suspended sediment production in the upper Oak Creek Watershed can be predicted using total runoff volume and a combination of field measurements.

Hysteresis loops were observed during four intensively sampled storms suggesting that a “flushing” mechanism exists on forest roads as has commonly been noticed in streams. Correlation was observed between the time derivatives of culvert discharge and suspended sediment concentration (SSC) during storms 2 and 4. Correlation was also observed between the time derivatives of SSC and 1-hr rainfall intensity lagged one hour during storm 2 and 2-hr rainfall intensity lagged two hours during storm 3. Sediment rating curves based on rainfall intensity predicted SSC better than sediment rating curves based on culvert discharge. Summed instantaneous SSC (ΣSSC) was correlated with cumulative rainfall during storms 2, 3, and 4. The relationship between rainfall intensity and sediment production has been reported previously (Reid and Dunne 1984, Vincent 1985, Bilby et al. 1989, Luce and Black 1999, MacDonald et al. 2001). 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. Croke et al. (2001) suggested that it is the fine sediment produced that is persistent and most difficult to manage. The ability to predict suspended sediment could be the first step toward managing it.

The relationship between sediment production, runoff, and rainfall suggests that the forest road erosion process in the upper Oak Creek Watershed is an energy-limited system dependent on these two hydrologic variables working in concert. Rainfall energy detaches soil particles and runoff energy transports them. Without runoff, soil particles detached by rainfall energy 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.

Sediment production models SEDMODL2 and WEPP:Road provide a means of estimating forest road erosion. For the upper Oak Creek Watershed, SEDMODL2 made a closer approximation of actual coarse and settleable sediment production than WEPP:Road, which overestimated the values. This could be due in part to the validation of SEDMODL2 and the lack of validation of WEPP:Road. The user-friendliness and Internet-availability of WEPP:Road make it accessible, quick, and intuitive, but the accuracy of SEDMODL2 made it a better choice for estimation in this case. Neither model consistently ranked sediment production according to actual amounts collected.

5.2. Recommendations

More research is needed to determine whether these observations hold under different conditions in different regions. Replicating this study on more culverts in the upper Oak Creek Watershed would help to contribute more data points, thereby improving the statistical analysis. In future studies, more culverts should be equipped with automated water samplers and on-site tipping-bucket rain gauges to further investigate suspended sediment rating curves based on rainfall intensity. A different method for sampling suspended sediment should be used. This study cast doubt on the accuracy and consistency of sampling from barrels. Also, research involving applications that control rainfall intensity and runoff would help determine how these two variables relate to subsequent sediment production.

Sediment production may be minimized by attenuating rainfall energy with various coverings on the road surface, ditch, and cutslope. Check dams could be used in the ditch to slow runoff and allow sediment to settle out of the water. Dispersal methods, such as more frequent spacing of cross-drain culverts, would serve to minimize the erosive force of concentrated runoff.

SEDMODL2 provided accurate estimates of sediment production, but is not user-friendly. WEPP:Road is user-friendly, but did not provide accurate estimates of sediment production. WEPP:Road should be developed to minimize its dependence on road length. SEDMODL2 should be developed to accommodate users not adept at ARCInfo. Both models could benefit from more observations for calibration.

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APPENDICES

APPENDIX A-1

DETERMINATION OF SUSPENDED SEDIMENT CONCENTRATION USING VACUUM FILTRATION

Materials:

Wash bottles with DI (deionized) water
Vacuum filtration manifold with Buchner funnels
Vacuum pressure hose/rubber stopper/glass tube assembly for carboy and vacuum line
Large carboy for filtrate
Desiccator cabinet and jar
Forceps/tweezers
1.5 µm glass fiber filter paper (Whatman 934-AH) sized to fit Buchner funnels – **ALWAYS** HANDLE GLASS FIBER FILTER PAPERS WITH FORCEPS/TWEEZERS
Oven at 105^{o} C
Numbered aluminum weighing tins that will fit in appropriate analytical balance – **ALWAYS** HANDLE ALUMINUM WEIGHING TINS WITH FORCEPS/TWEEZERS
Analytical balance accurate to 0.0001 gram
Analytical balance able to handle load of one sample bottle filled with sediment and water

Procedure:

1. Place many (25-50) glass fiber filters and aluminum weighing tins (**ALWAYS** HANDLE PAPERS AND TINS WITH FORCEPS/TWEEZERS) in oven at 105^{o} C for 24 hours.
2. Weigh each bottle of sediment/water (container + sample).
3. Weigh filter paper for each sample, place in pre-numbered tin.
4. Be sure at least two (2) lines of the manifold are open/on, then turn on the vacuum line.
5. Be sure to keep track of filter paper and its corresponding pre-numbered tin. Place filter paper in funnel and wet it down with DI water. This will create a seal and prevent floating of the filter paper when a during sample filtration. Use the other manifold line to throttle the flow of air through the funnel being used for filtration.
6. Shake the bottle with fluid in it. Pour the fluid into the funnel **slowly**, taking care that suction is continuously maintained – not too much; not too little. If the water has too much sediment, just filter what you can on the first filter and filter the remainder with another filter and combine the weights. Watch the

APPENDIX A-1 (CONTINUED)

carboy to make sure it isn't too full to pull water through the lines; empty the carboy as needed.

7. Wash all sediment out of empty sample bottle onto filter paper with DI water. Weigh empty/washed sample bottle and cap.
8. When the sample has been completely filtered and the paper appears to no longer be saturated, release the vacuum suction from the funnel, and remove the filter paper with sediment from the funnel using blunt tweezers. Place on the corresponding pre-weighed tin – the filter can be folded to fit in tin, but only by using forceps/tweezers. Dry at 105^{o}C for 24 hours. Note: the filter papers will most likely stick to the drying tins in the oven – be aware of this for future calculation of weight beyond the scope of measuring suspended sediment concentration.
9. After 24 hours, remove the tin from the oven and place in the desiccator cabinet or jar immediately and allow to cool to room temperature. Then weigh tin + filter.
10. At least one (1) blank filter paper per every ten (10) water samples should be run using only DI water. Note: blanks will typically lose weight; this represents loss of filter fibers during filtration. The mean fiber loss should be added back into sample weights.
11. Clean funnels with DI water and Kimwipes after use.
12. Calculation:

suspended sediment concentration, SSC (mg/L) = $\dfrac{(A-B)\times 100}{SampleVolume(mL)}$

Where: A= weight of filter + dried residue (mg)
B = weight of filter (mg)

***Note**: Total suspended solids (TSS) involves using an aliquot of a sample.Suspended sediment concentration (SSC) involves using the entire sample.

(Sources: http://www.epa.gov/etv/sitedocs/meetings/wqp/sum_111301.pdf and http://water.usgs.gov/osw/pubs/ASCEGlysson.pdf)

Adapted from Method 2540D in:

Clesceri, L.S., A.E. Greenberg and A.D. Eaton, eds. 1998. Standard Methods for the Examination of Water and Wastewater. 20th ed. American Public Health Association, Washington, DC.

APPENDIX A-1 (CONTINUED)

Figure A-1. 1 Vacuum filtration manifold with 8-55mm Buchner funnels.

Figure A-1. 2 Vacuum filtration manifold with 4-110mm Buchner funnels.

APPENDIX A-2

DETERMINATION OF ORGANIC MATTER CONTENT USING INCINERATION

Materials:

Desiccator cabinet and jar
Forceps/tweezers
Crucible tongs
Eight (8) pencil-numbered small porcelain crucibles (ALWAYS HANDLE CRUCIBLES WITH CRUCIBLE TONGS)
High-temperature oven mitts with long forearm protection
Muffle furnace at 550^{o} C (ALWAYS WEAR OVEN MITTS WHEN INSERTING/REMOVING ANYTHING FROM MUFFLE FURNACE)
Small soil spatula and/or sample spoon
Analytical balance accurate to 0.0001 gram

Procedure:

1. Place 8 small crucibles in muffle furnace at 550^{o} C for 1 hour. Be sure samples have been properly oven-dried and place in desiccator to prevent moisture from adding weight.
2. After 1 hour, place the same 8 crucibles in desiccator cabinet and allow to cool to room temperature.
3. Remove one crucible from desiccator cabinet and place sample in crucible (use forceps/tweezers if handling glass-fiber filter paper samples, or small soil spatula/sample spoon if handling loose soil samples). Weigh crucible containing sample and record being sure to note the appropriate crucible number. Also record the sample weight alone as this will be used in the calculation of Step 7 below. Then place crucible and sample back in the desiccator cabinet. Repeat this step for remaining 7 crucibles in set.
4. After 8 crucibles with samples have been weighed, remove them from the desiccator cabinet and insert into muffle furnace at 550^{o} C.
5. After approximately 1 hour, remove crucibles with samples from muffle furnace, place in desiccator cabinet, and allow to cool to room temperature. Weigh the incinerated crucibles and samples and record. Repeat Steps 4 and 5, until incinerated weight does not change.
6. Discard or preserve incinerated samples. Clean crucibles with water, dry, number, and repeat Steps 1-6 with additional samples.

APPENDIX A-2 (CONTINUED)

7. Calculation:

$$\text{organic matter content, OMC (\%)} = \frac{(A - B) \times 100}{Oven - dried\ Sample\,(mg)}$$

Where: A = weight of crucible + oven-dried sample (mg)
B = weight of crucible + incinerated sample (mg)

Adapted from Method 2540D in:

Clesceri, L.S., A.E. Greenberg and A.D. Eaton, eds. 1998. Standard Methods for the Examination of Water and Wastewater. 20th ed. American Public Health Association, Washington, DC.

APPENDIX A-3

Table A-3. 1 Water and sediment data for all culverts.

n	Culvert ID	Span of Record	Elapsed Time	WATER: AVERAGE DISCHARGE, Q	WATER: VOLUME, ∀	SEDIMENT: ISCO (Suspended)		SEDIMENT: BARREL (Fine;Settleable)		SEDIMENT: GEOTEXTILE SOCK (Coarse)		SEDIMENT: TOTAL				
						SSC [extrapolated] (g)	Average %VSS	oven-dried weight of *mineral* sediment (g)	Average %VSS	oven-dried weight of *mineral* sediment (g)	Average %VSS	oven-dried weight of sediment [w/extrapolated SSC values] (g)	oven-dried weight of sediment [w/out extrapolated SSC values] (g)	Average %VSS [w/extrapolated SSC values]	oven-dried weight of *mineral* sediment (g)	oven-dried weight of *mineral* sediment [w/out extrapolated SSC values] (g)
			s	(L/s)	m^3											
1	15 S1	03/05/03-03/09/03	3.4E+05	0.10	33	1801	9	88	15	9	46	1921	120	10	1734	97
2	15 S2	04/11/03-04/15/03	3.4E+05	0.07	25	2383	10	178	14	97	30	2729	346	11	2422	275
3	15 S3	04/23/03-04/27/03	3.4E+05	0.25	86	1028	19	75	15	12	40	1135	108	19	921	87
4	15 S4	05/03/03-05/05/03	1.7E+05	0.14	24	719	17	18	17	63	32	834	114	19	679	81
5	15 I/S	Beg. & End of Season + Interstorm	1.7E+07	0.04	776			1903	13	1114	26	3693	3693	18	3017	3017
6	15 TOTAL	11/17/02-06/18/03	1.9E+07	0.05	944			2262	14	1295	27	10311	4381	15	8773	3557
7	22	03/10/03-06/18/03	8.7E+06	0.22	1867					403	24	531		24	403	
8	23	03/10/03-06/18/03	8.7E+06	5.96	52082					14960	14	17461		14	14960	
9	30	sock 11/17/02-06/18/03	1.8E+07	0.05	920					121	41	205		41	121	
10	30	barrel 02/03/03-06/18/03	1.2E+07	0.05	644			529	14			614		14	529	
11	66	11/17/02-06/18/03	1.5E+07	0.17	2602			402	14	622	23	1278		20	1024	
12	76	11/17/02-06/18/03	1.6E+07	0.06	961			141	8	432	18	681		16	573	
13	81	11/17/02-06/18/03	1.6E+07	0.01	100			23	23	1	64	33		26	24	
14	88	11/17/02-06/18/03	1.6E+07	0.26	3957			46	15	35	68	163		50	81	
15	98	01/11/03-06/18/03	1.5E+07	0.39	5955			263	10	2246	21	3142		20	2509	