AN ABSTRACT OF THE DISSERTATION OF

Christopher G. Surfleet for the degree of Doctor of Philosophy in Forest Engineering presented July 24, 2008.

Title: Uncertainty in Forest Road Hydrologic Modeling and Catchment Scale Assessment of Forest Road Sediment Yield

Abstract approved:

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Arne E. Skaugset III

The goal of this study was to advance methods for assessment of forest road hydrologic response and sediment yield at a catchment scale. This research looked at the effect of soil depth estimation on the Distributive Hydrology Soil Vegetation Model (DHSVM), assessed the uncertainty and accuracy of hydrologic modeling of forest roads by DHSVM, and evaluated the use of road runoff and sediment sampling for catchment scale road sediment estimates. The influence of soil depth estimation on DHSVM varied by spatial scale and hydrologic process modeled. Soil depth measurement improved DHSVM simulated streamflow and road ditchflow for the rising limb of the hydrograph with no improvements during baseflow. For site specific or small scale modeling a deterministic soil depth model fit to field measurements was best. For larger scale simulations of streamflow mean soil depth provided as good or better estimates.

Considerable uncertainty in estimates of road hydrologic response was observed from DHSVM. DHSVM over predicted individual road discharges. As the spatial scale and temporal scale was increased the uncertainty in DHSVM results decreased. This suggests that model structures chosen for DHSVM would be better determined with internal catchment data, at smaller scales. The GLUE assessment showed that change detection analysis with DHSVM will be limited to sites or scales of the catchment that behavioral model structures can be identified. From this research it was determined that only the catchment scale simulations and a few individual road locations could be used for change detection.

The storm runoff volumes and peak flows from road ditchflow had linear relationships with storm sediment load. These relationships had to be developed by classes of road locations and types in an intensively managed forest due to variability in road design, hydrologic response, and road use. Sediment from roads estimated from field measurements used with SEDMODL2 or WARSEM provided substantially lower estimates than without field measured adjustments. The use of road runoff for sediment estimation provided even lower catchment scale sediment results. DHSVM simulated road runoff for sediment estimation provided catchment scale results similar to the sediment yield estimated from observed road runoff.

Uncertainty in Forest Road Hydrologic Modeling and Catchment Scale Assessment of Forest Road Sediment Yield

by

Christopher G. Surfleet

A DISSERTATION

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APPROVED:

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Christopher G. Surfleet, Author

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CONTRIBUTION OF AUTHORS

Arne E. Skaugset and Jeffrey McDonnell assisted in the writing of Chapter 2.

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UNCERTAINTY IN FOREST ROAD HYDROLOGIC MODELING AND CATCHMENT SCALE ASSESSMENT OF FOREST ROAD SEDIMENT YIELD

CHAPTER 1: INTRODUCTION

Background

The effect of forest roads on catchment hydrology and sediment production are increasingly the focus of regulatory and scientific concern. This requires that land managers and owners become more sophisticated in the assessment of the impacts of their practices. Forest roads generate overland flow from compacted surfaces (Harr et al 1975, King and Tennyson 1984), intercept sub-surface flow at road cuts (Burroughs et al 1972, Megahan 1972, Wemple 1998) and affect hillslope hydrologic processes. Forest roads can re-distribute water on hillslopes and change the timing of stream flow, sub-surface flow, or the distribution of soil moisture (Megahan 1972, Wigmosta and Perkins 2001), extend stream channel networks through gullies (Wimple et al 1996), or alter peak flows at stream crossings (Toman 2004).

Research on the effects of forest roads on hillslope and watershed hydrology has concentrated primarily on individual locations along roads or isolated segments of roads with a few observations from paired watershed studies or hydrologic modeling. These observations have not produced consistent results. Studies that developed strong relationships between roads and hydrologic processes in some watersheds often do not find the same relationships in other watersheds. Observations at a local scale, i.e. road segments, do not necessarily scale up to a catchment scale. Models such as the Distributive Hydrology Soil Vegetation Model (DHSVM)(Wigmosta et al., 1994) allow a conceptual understanding of the hydrologic interactions of roads and hillslopes to be included in a hydrologic model. This increases the opportunity to understand and study the hydrologic interactions of forest roads and hillslopes beyond a road segment up to a watershed scale. Understanding the limitations and uncertainty of these models is important to appropriately interpret their results.

A large amount of the sediment caused from timber harvest activities is attributed to roads and road building (i.e. Reid, 1981; Ketcheson and Megahan, 1996, California Department of Forestry, 2002; Surfleet, 2004; Gucinski et al., 2001). The increase in sediment production from timber harvest activities, which includes forest roads, can degrade water quality and aquatic habitat (e.g. Gucinski et al., 2001; Spence et al., 1996; Haskell, 2000). Concerns regarding the impacts of sediment due to timber harvest have resulted in regulations that require landowners to repair sediment sources, use improved harvesting practices, and monitor reductions in sediment production. The implementation of policies such as Total Maximum Daily Loads (TMDL), the Endangered Species Act, and State Water Quality Regulations requires that landowners accurately monitor reductions in sediment production and the subsequent improvement of aquatic habitat over time.

A common difficulty when monitoring sediment is separating natural sources of sediment from the sediment produced from land management, for example forest roads. This is a complex problem given the high variability in sediment production in space and time caused by the many influences on sediment production, transport, and storage. The problem becomes more complex when an attempt is made to isolate the different sources of sediment production at a watershed scale. In addition to the challenge of isolating the production of sediment from roads at a watershed scale is the need to accurately and cost effectively measure sediment production from roads.

Contributions

This research made four contributions to the study of the hydrology of forest roads, the hydrology of roaded watersheds, the measurement of sediment production from forest roads, and the prediction of these processes using DHSVM, WARSEM, and SEDMODL2. The first contribution, described in Chapter 2, investigated the effect of soil depth on DHSVM output and evaluated several approaches to estimate soil depth across a catchment. For the Oak Creek watershed, simple empirical methods to estimate soil depth did not accurately estimate soil depth. Field measurements of soil depth used as input to DHSVM resulted in improved model performance when compared to methods to estimate soil depth that did not use field measurements. Using the average depth of the soil as measured in the field gave the best results at the catchments scale. A physically based soil depth model fit to the field measurements of soil depth resulted in the best simulations of streamflow and road ditchflow at small spatial scales.

The second contribution is described in Chapter 3. In this chapter the model DHSVM is evaluated for its ability to simulate the hydrology of individual forest roads and roads collectively at a watershed scale. Further, model uncertainty in estimating the hydrologic response is evaluated by carrying out a Generalized Likelihood Uncertainty Estimation (GLUE) analysis of DHSVM. DHSVM modeled reasonable simulations of the hydrology of roaded watersheds at the catchment scale but not at the scale of individual roads. This suggests model structures chosen for DHSVM would be better determined with internal catchment data applied at smaller scales. The uncertainty assessment of DHSVM allows future users of the model to understand the uncertainty in the simulations. The uncertainty assessment also demonstrated that soil porosity and the exponent of decay of soil hydraulic conductivity with depth were sensitive parameters for the model.

The third and fourth contributions are described in Chapter 4. This research showed that road sediment models overestimated actual sediment production from roads. The performance of the models can be improved if measurements of road runoff and sediment sampled from the catchment are used in conjunction with road erosion models or hydrologic models. The production of sediment from forest roads can be estimated at the road segment or catchment scale with simple and low cost sampling methods that were developed and described in this chapter.

Research Goals

The goals of this research were to investigate methods to assess the impact of forest roads on hydrology and sediment yield at a catchment scale. This research looked at the effect of the estimation of soil depth on the results of a distributive hydrologic model, DHSVM. Four techniques of soil depth estimation were analyzed for their effect on the hydrologic output from DHSVM at three spatial scales. Next this research assessed the uncertainty and accuracy of hydrologic modeling of forest roads using DHSVM. A Generalized Likelihood Uncertainty Estimation (GLUE) assessment was carried out using DHSVM that compared model results with a comprehensive data set of road runoff observations from Oak Creek, Oregon. Change detection and model accuracy at predicting hydrologic response was investigated. Finally this research evaluated the use of road runoff and sediment sampling to make catchment scale estimates of road sediment production. Road erosion models and runoff observations were used for spatial extrapolation to the catchment scale. How road runoff and its associated sediment production should be sampled was another key question of the research.

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CHAPTER 2: EFFECTS OF SOIL DEPTH ESTIMATION ON STREAMFLOW AND ROAD RUNOFF PREDICTIONS USING THE DISTRIBUTIVE HYDROLOGY SOIL VEGETATION MODEL (DHSVM)

Christopher G. Surfleet

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Jeffrey McDonnell

INTRODUCTION

Soil depth is a key control on hillslope hydrologic response to storm rainfall and solute transfer (e.g. Hewlett and Hibbert, 1967; Weiler and McDonnell, 2004). Knowledge of soil depth is a key element in modeling land surface atmosphere exchange processes (Miller and White, 1998). Consequently, soil depth is an influential parameter for many distributed rainfall-runoff models, especially for application to steep catchments where subsurface stormflow is the dominant runoff response mechanism. Soil depth controls the conversion of vertical water movement to lateral subsurface flow during events and the spatial distribution of water in the soil column available for evapotranspiration (Tromp van Meerveld and McDonnell, 2006).

The Distributive Hydrology Soil Vegetation Model (DHSVM), developed by Wigmosta et al. (1994) is a popular distributed rainfall-runoff model for evaluating the effects of forest management in maritime climates. The model has been applied in many environments in a variety of applications, from modeling snowmelt related to forest harvesting (i.e. Whitaker et al, 2002; Schnorbus and Alila, 2004), modeling the effects of road construction on catchment hydrology (Bowling and Lettenmaier, 2001), modeling preferential flow in hillslopes (Beckers and Alila, 2004), or modeling response of climate change (i.e. Lueng and Wigmosta, 1999). Estimation of soil depth for DHSVM, like other distributed hydrologic models, have used soil depths assigned by soil texture in soil surveys (i.e. Bowling and Lettenmaier, 2001; Thyer et al, 2004), a mix of field observations and estimates (i.e. Whitaker et al, 2003), an assumed uniform soil depth (i.e. Wigmosta and Perkins, 2001) or a deterministic-stochastic prediction of average soil depths for three different ecotypes in a catchment (Beckers and Alila, 2004).

While variable soil depth has been incorporated into some DHSVM model applications, few studies have examined how important inclusion of variability in soil depth is in modeling hydrologic response for different scales within a catchment. Field observations have shown that patterns of subsurface flow are controlled by the pattern of soil depth and topographic relief of the soil-bedrock interface (Allen and Roulet, 1994; Freer et. al., 2002; Spence and Woo, 2002; Tromp-van Meerfeld and McDonnell, 2006; Frisbee et al. 2007). An assumption of DHSVM, like most distributed models, is that the bedrock beneath the soil is impermeable or significantly less permeable than the soil matrix. This makes the depth of the soil used in calculations of sub-surface flow influential to model results. Soil depth is so influential that it has been used in one study as one of the primary model parameters adjusted to calibrate the response of DHSVM to observed streamflow and road runoff (e.g. Bowling and Lettenmaier, 2001).

The high variability in soil depth within and between watersheds creates uncertainty in the estimation of soil depth. Digital terrain models have provided an inexpensive way to estimate soil depth based on topography. For example, Dietrich et. al. (1995) used digital elevation data to develop a model for soil formation and depth in colluvial soils. Digital terrain models based on topographic index (Beven and Kirkby, 1979) or downslope drainage efficiency (Hjerdt et al 2004) have been used to estimate soil depth at the catchment scale. All of these techniques rely on field measurements or regionalization of point measurements of soil depth. Measurement of soil depth is difficult and involves subjective interpretations of the soil profile or often, as in this study, a determination of resistance from a drive probe. While more sophisticated techniques to determine soil depth exist (e.g. ground penetrating radar or gravimetry), these approaches are costly to apply at the watershed scale and difficult to implement in steep mountainous terrain.

Although soil depth is influential on hydrologic responses in mountain catchments, little work has explored the effect of soil depth and soil depth estimates on output from distributed hydrologic models. This study attempted to study the hydrologic model response by first determining a reasonable technique for estimating the measured soil depths within our research catchment. We then developed four different estimates of soil depths for the research catchment for use in DHSVM. The four techniques for soil depth estimation were:

1) The chosen soil depth estimation technique fit to field measurements.
2) The chosen soil depth estimation technique but used without the benefit of field measurements.
3) The chosen soil depth estimation technique fit to field measurements but also incorporating a spatial estimate of the error to the predictions.
4) The mean soil depth from field measurements.

The four different estimates of soil depths for the catchment were tested with DHSVM simulations of surface runoff at the watershed scale and internally within measured road crossings. Specifically, we address the following questions:

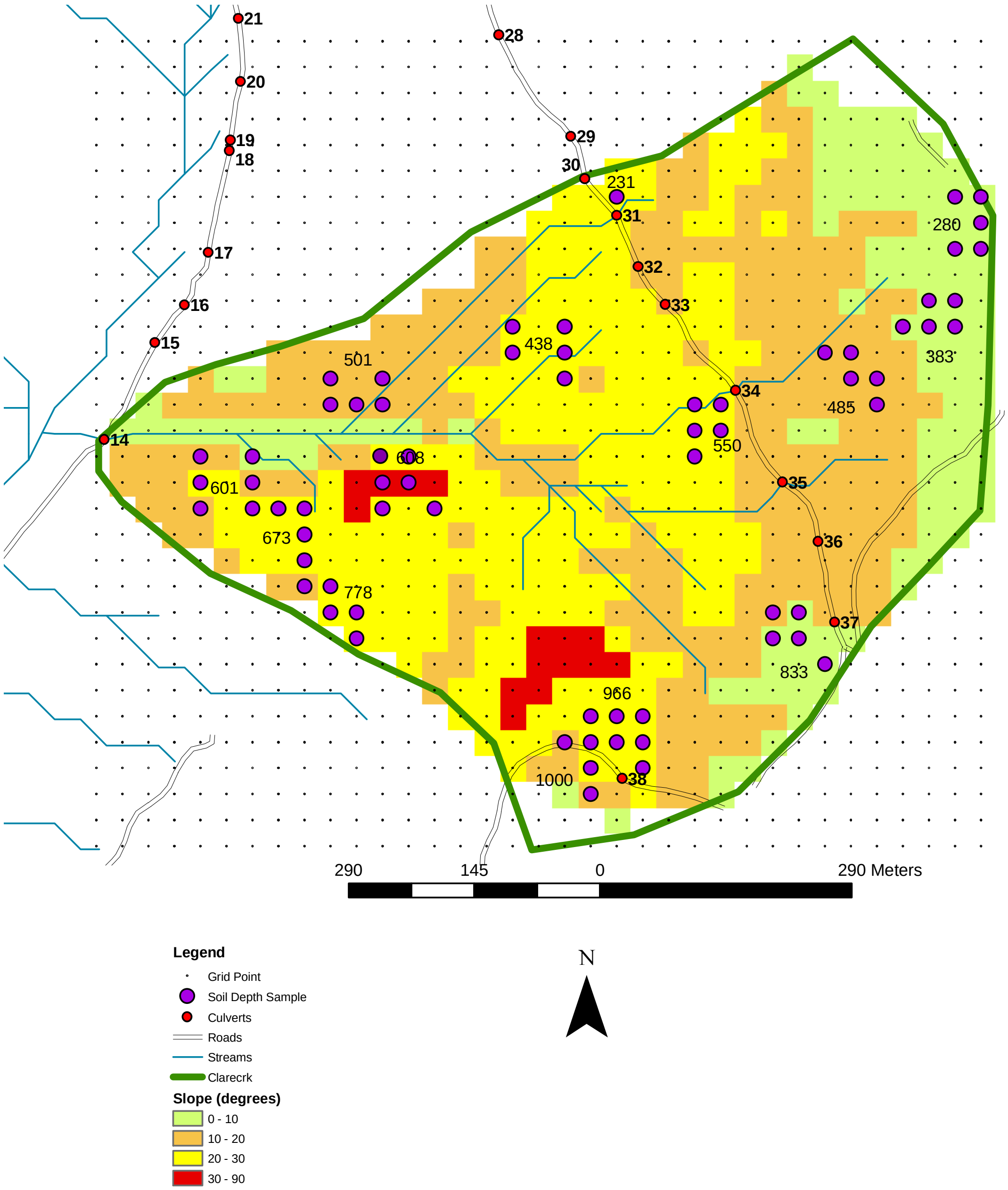
- Which of the following methods of estimating soil depth provided the best fit to measured soil depths: topographic index, downslope topographic index, multiple regression of topographic descriptors, or the soil depth model provided with DHSVM (Westrick, 1999)?
- What influence do four soil depth estimation techniques have on separate model output for run-off response to direct precipitation, hillslope drainage following precipitation, and baseflow?
- What effect does the soil depth estimation technique have on spatial scale modeled by DHSVM?
- Which of the four soil depth estimation techniques provide the best results for peak flow predictions by DHSVM?

STUDY AREA

The study was done at Claire Creek, a 55 ha watershed in western Oregon USA (Figure 2.1). Elevations within the catchment range from 200 to 470 meters and hillslope gradients range from 0 to 45 degrees. The annual precipitation for Claire Creek during the 2006 water year was 930 mm. The bedrock underlying the watershed is the Siletz River Volcanics, a basalt formation (Knezevich 1975). Soils in the watershed are classified as silty clay loam; some areas of silty loam are present (Knezevich 1975). The catchment is forested with forest vegetation predominately Douglas-fir (*Pseudotsuga minziesii*), with minor components of other conifers and hardwoods.

The Claire Creek watershed has 1.5 km of logging road with 8 road drainage locations (culverts), comprised of 3 stream crossing culverts and 5 drainage relief culverts (Figure 2.1). The road drainage structures were instrumented with capacitance rods recording at 10 minute intervals or crest gages measured monthly for calculation of runoff or peak flows respectively. The three stream crossings (culverts 14, 34, and 35; Figure 2.1) and two of the ditch relief culverts (culverts 31 and 32; Figure 2.1) had capacitance rods installed at the invert of the stream crossing culverts to continuously measure stage. Trapezoidal flumes were installed in the adjoining road ditches for two of the stream crossing culverts (culverts 34 and 35); capacitance rods measured stage in the flumes. Stage values measured at the inlet of Culvert 14 were used to calculate streamflow for the Claire Creek catchment.

A meteorological station was located 0.8 km from the outlet of the Claire Creek catchment; meteorological observations were collected during the 2006 water year. This meteorological station provided continuous measurements of air temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation. Three additional precipitation gages were located within 2 km of the Claire Creek catchment. The meteorological station and precipitation gages were used for inputs to DHSVM for modeling streamflow and road ditchflow for the Claire Creek catchment.



<u>Figure 2. 1</u>. The Locations of Soil Depth Measurements for Claire Creek, a 55 Hectare Catchment near Corvallis, Oregon, USA. (Cluster locations are identified by number within 34 x 30 grid; 1 is in upper left corner with numbers increasing left to right.

METHODS

Soil Depth Sample Design

A 30 m grid was established in Claire Creek in a North/South and East/West direction; the grid points corresponded to the center of each 30 meter pixel of the digital elevation model (DEM). The DEM for Claire Creek was developed from 6 m lidar elevation data. The grid points were used as the sampling frame for soil depth measurements in Claire Creek (Figure 2.1). We used a two stage cluster sample design. In the first stage of the sample design, 13 sample locations were selected based on a balanced sample of slope and area classes as produced from the DEM. The soil depth measurement sites were randomly selected within each unique class of slope and area. The second stage of the sample design randomly chose five pixels from the cluster of nine pixels around each of the 13 sample locations. The five pixels selected from each of the 13 sample locations were where soil depth was measured (Figure 2.1) for a total of 65 measurements of soil depth in Claire Creek. The number of measurements of soil depth was slightly more than a 10% sample of the 30 meter pixels from the Claire Creek DEM.

The soil depth measurement locations were located in the field with a Geographic Positioning System (GPS). Soil depth was measured at the center of each 30 m pixel selected in the sample. When trees or vegetation made the measurement of soil depth impossible, the location of the soil depth measurement was adjusted, but by no more than 15 meters to keep the measurement within the selected 30 meter pixel. If a road was encountered at the pixel center the soil depth measurement was adjusted to a location within 15 meters of the pixel center to a place no longer affected by the road. If a soil depth measurement was moved off of the pixel center, care was taken that the measurement was representative of the slope and terrain characteristics of the pixel center.

Soil depth was measured with a Drive Probe (Williamson, 1994). The Drive Probe consisted of a 1.36 cm diameter (1/2 inch) galvanized metal pipe that was driven into the ground using a 5 kg hammer. The maximum possible depth we could measure with this type of Drive Probe was 3.5 meters. The force of the hammer blow was determined by dropping the 5 kg hammer a distance of 1 meter (Figure 2.2). The soil depth was determined by driving the Drive Probe to 'refusal,' which was defined as the depth when 10 blows from the hammer could no longer drive the probe 1 cm vertically into the ground. Previous "trial" measurements of soil depth in the area varied between 1 and 2 meters. If the Drive Probe stopped at a soil depth less than 1 meter, the probe was moved and another measurement was taken to ensure that the probe had not hit a rock or root in the soil and that the shallow depth was correct. If a soil depth less than 1 meter was repeated for a second or third attempt, the deepest measurement was used.

While we have defined soil depth to be the depth at which refusal was found with a Drive Probe; this may not be the true depth of the soil. The depth of the soil where there is a transition between soil and weathered rock will always be a subjective decision; even when interpreted in a soil pit by a soil scientist. A definition of soil depth that describes the point in the soil where significant resistance was found with a Drive Probe seems a reasonable estimate for the point where sub-surface properties change affecting water movement.

Figure 2. 2. Measuring Soil Depth using a Drive Probe.

Determining the Best Technique for Estimating Soil Depths for Claire Creek

Several different techniques were evaluated for estimating soil depth where soil depth had been measured. These methods were the topographic index, downslope topographic index, multiple regression using topographic descriptors, or a physically based soil depth model provided with DHSVM (Westrick, 1999). Linear regression was used to compare each of the different technique's estimated soil depths to the corresponding measured soil depths. The linear regression produced with the lowest p value and adjusted r^2 value was considered the best soil depth estimation technique.

The topographic indices evaluated were the natural log of area per unit contour by Beven and Kirkby (1979) and the downslope topographic index developed by Hjerdt et.

al. (2004). Each index calculated the soil depth for each 30 meter pixel of Claire Creek using the Geasy software developed by Seibert (2004). Within Geasy the contributing area is calculated following the specifications discussed in Seibert and McGlynn (2007).

A multiple linear regression model was attempted to estimate soil depth using the dependent variables of slope, elevation, area, log of area, the "Topmodel" topographic index, and downslope topographic index. A best subsets approach was used to determine the best regression model. The model with the lowest "Cp" statistic was chosen and correlated with the measured soil depth.

A physically based soil depth model (Westrick, 1999) provided with the DHSVM source code was used to estimate soil depth. This model has been used by many DHSVM users, though it was not peer reviewed with DHSVM (Bowling personal communication 2006). This model calculates soil depth from the slope, upslope contributing area, and elevation for each pixel from the DEM. The user has the ability to assign weights to slope, area, and elevation. The weights were required to be between zero and one and they must add up to one. The slope, area, and elevation variables are further adjusted by an exponent. The model requires a maximum elevation, area, and slope value. These maximum values were the largest coefficients where each of the model variables were assumed to no longer have an influence on the soil depth. In Claire Creek the maximum values were a slope of 30 degrees, an area of 1000 pixels (900 square meters per pixel), and an elevation of 600 meters. The soil depth model was "fit" to the 65 field measurements of soil depth. The weights and exponents for the deterministic model were adjusted to minimize the sum of square errors and the mean square errors.

The equation for the model is:

$$\text{mindepth} + (\text{maxdepth} - \text{mindepth}) * (\text{Wt.slope}) * (1 - \text{local.slope}/\text{max.slope})^{\text{slope.power}}$$
$$+ (\text{maxdepth} - \text{mindepth}) * (\text{Wt.area}) * (1 - \text{local.area}/\text{max.area})^{\text{area.power}}$$
$$+ (\text{maxdepth} - \text{mindepth}) * (\text{Wt.elev}) * (1 - \text{local.elev}/\text{max.elev})^{\text{elev.power}}$$

Where:

mindepth = minimum depth to bedrock in catchment.

maxdepth = maximum depth to bedrock in catchment.

Wt.slope = weight of slope component for depth estimate (between 0 and 1).

local.slope = slope at DEM pixel.

max.slope = maximum slope for depth to bedrock calculations (above this slope no slope component used in equation).

slope.power = exponent between 0 and 1.

Wt.area = weight of area component for depth estimate (between 0 and 1).

local.area = flow accumulation area at DEM pixel (number of contributing pixels).

max.area = maximum area for depth to bedrock calculations (above this area no area component used in equation).

Wt.elev = weight of elevation component for depth estimate (between 0 and 1).

local.elev = elevation at DEM pixel.

max.elev = maximum elevation for depth to bedrock calculations (above this elevation no elevation component used in equation).

The mean soil depth was calculated by dividing the sum of the soil depth measurements by the number of measurements.

Soil Depth Estimation Technique Combined with Model Error to Estimate Soil Depth

The soil depth technique that provided the best estimates of the field measured soil depths was combined with a spatial extrapolation of the estimated soil depth's error. The error was the residuals between the measured and estimated soil depths. A variogram model was developed for the residuals then spatially extrapolated by kriging. The soil depth estimates and errors were added together to produce an estimate of soil depths for Claire Creek.

DHSVM

DHSVM is a physically based, hydrologic model that explicitly solves water and energy balances for each model grid cell (Bowling and Lettenmaier, 2001). DHSVM was originally developed by Wigmosta et al (1994) for use in forested, mountainous terrain and extended for use in maritime climates by Storck et al (1995). The model and road interception component of the model is described in detail elsewhere (Wigmosta et al, 1994; Storck et al, 1995; Storck et al, 1997; Wigmosta and Perkins, 2001) so only a brief description of the model is provided here. This description follows the general description of DHSVM and the road interception component of DHSVM from Storck et al (1998) and Wigmosta and Perkins (2001).

DHSVM calculates the spatial distribution of soil moisture, snow, evapotranspiration, and runoff at hourly or longer time steps for individual grid cells or pixels based on the digital elevation model (DEM) of the catchment. Meteorological inputs required for each time step of the model are precipitation, relative humidity, air temperature, wind speed, shortwave radiation, and longwave radiation. A one-dimensional water balance is calculated for each grid point based on effects from vegetation, climate, soil hydraulic properties, and topography. The model uses a two-layer canopy representation for calculation of interception and evapotranspiration of vegetation, a two-layer energy balance model for snow accumulation and melt, a multi-layer unsaturated soil model based on Darcy's Law, and a saturated subsurface flow model. Once the water balance calculations are completed each grid cell exchanges water with adjacent grid cells, resulting in a three dimensional redistribution of surface and sub-surface water across the catchment.

Soil Depth within DHSVM

Four different estimates of soil depth were used for DHSVM simulations of hydrologic response within Claire Creek. The four estimates are described in the introduction and are referred in the remainder of this chapter by the following titles:

Fitted Soil Depths - The chosen soil depth estimation technique fit to field measurements.

Non-fitted Soil Depths - chosen soil depth estimation technique but used without the benefit of field measurements.

Soil Depths Considering Spatial Errors - the chosen soil depth estimation technique fit to field measurements but also incorporating a spatial estimate of the error to the estimates.

Mean Soil Depth - the mean soil depth from field measurements.

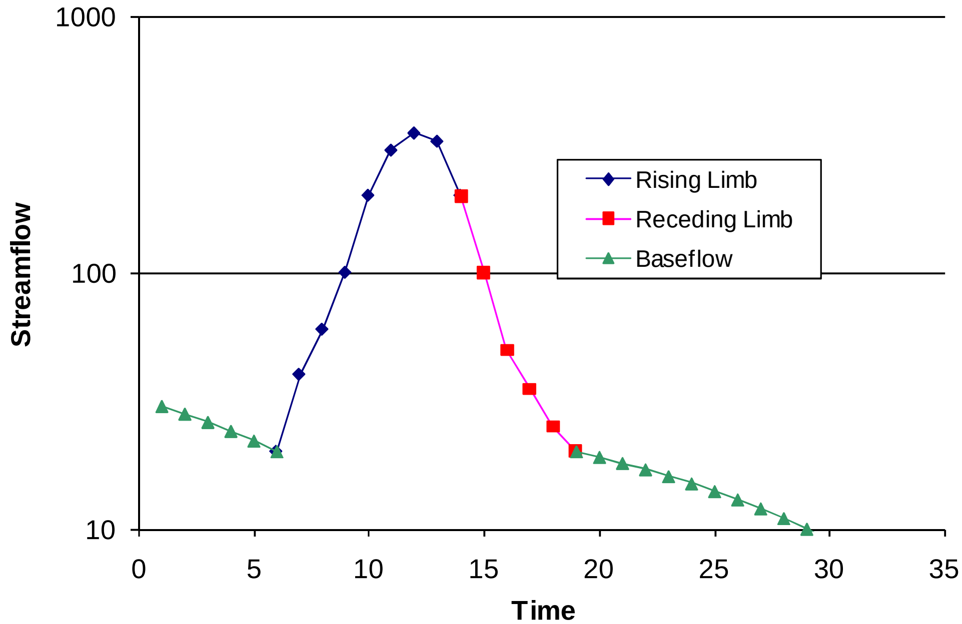
DHSVM Set-Up

DHSVM version 2.0.1 was used with a 30 meter DEM as the topographic basis for simulation. DHSVM is limited in the grid sized used by the width of roads and stream channels of the catchment; 30 meters was the smallest scale grid that could accomplish this in Claire Creek. The DHSVM application used a 3-hour time step for calculations. DHSVM was calibrated to streamflow and road ditchflow for three spatial scales in Claire Creek for the same time period used for evaluation of DHSVM by the four soil depth estimates; December, 2005 thru February, 2006 encompassing seven precipitation events. This period of time had the largest storms and the greatest range in stream flows during the five year data record for the catchment. DHSVM was calibrated using a systematic manual calibration technique similar to Whitaker et al (2003). The model was fit to stream hydrographs quantitatively by: 1) volume error for predicted versus observed run-off; 2) model efficiency (Nash and Sutcliffe, 1970) and 3) coefficient of determination (Whitaker et al, 2003). Fit of the model was also evaluated qualitatively for agreement between predicted and observed streamflow. A qualitative approach was also necessary because it was impossible to achieve good quantitative fits for modeled road ditchflow.

Comparison of Simulated and Observed Streamflow and Road Ditchflow

Streamflow was modeled using DHSVM for each of the four estimates of soil depth. Each of the four simulations used the same set of model parameters and timeframe, to allow comparison among the different estimates of soil depth. Simulated streamflow was compared to observed streamflow at the outlet of Claire Creek (55 hectares in area) and above stream crossing culvert 35 (5 hectares in area). The streamflow above culvert 35 was calculated by subtracting the road ditchflow entering culvert 35 from the streamflow measured at the culvert inlet. Simulated ditchflow was compared to observed ditchflow at the four culvert locations in Claire Creek that had continuous ditchflow measurements (culverts 31, 32, 34, and 35) (Figure 2.1).

Observed streamflow and ditchflow was compared with predicted streamflow and ditchflow for three components of the hydrograph after Boyle et al (2000)(Figure 2.3): 1) rising limb; 2) receding limb; and 3) baseflow. This approach is based on the premise that these 3 components of the hydrograph represent different hydrologic processes. The behavior of runoff driven by precipitation represented by the rising limb of the hydrograph would be different than runoff without direct precipitation. Periods immediately following the cessation of precipitation, the receding limb of the hydrograph, dominated by subsurface flow can be distinguished from periods of baseflow (Boyle et. al., 2000).



<u>Figure 2. 3</u>. Partition of hydrograph for comparison of simulated and observed streamflow and ditchflow (adapted from Boyle et. al., 2000)

The fit of the streamflow and ditchflow simulated with DHSVM to observed streamflow and ditchflow was evaluated for each of the three hydrograph components using the root mean square error (RMSE). Simulated and observed peak flows were compared for each of the four techniques used to estimate soil depth based on the slope of their linear relationship compared to a 1:1 line.

RESULTS

Estimation Techniques for Soil Depths for Claire Creek

The best estimate of measured soil depths was from the soil depth model provided with DHSVM (Westrick, 1999) fit to field measurements. The best fit was found with weights used for slope, area, and elevation variables of 0.3, 0.2, and 0.5, respectively. The slope, area, and elevation power exponents were 2.0, 0.25, and 0.2, respectively. The linear regression model between the soil depths estimated from the soil depth model and the measured soil depths was statistically significant (p value = 0.04), however the model only explained 6.3% of the variability of the observations (adjusted $r^2 = 0.063$).

The linear regression model of estimates of soil depth from Beven and Kirkby's (1979) topographic index and measured soil depth did not have a statistically significant relationship at the 95% confidence level (p value = 0.96) with an adjusted $r^2 = 0.00004$. The downslope topographic index (Tan α_d) also did not have a statistically relationship with measured soil depth at the 95% confidence level (p value = 0.25) with an adjusted r^2 of 0.036.

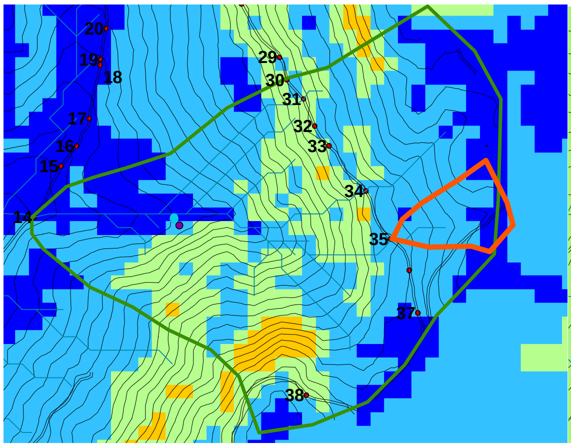
Using a best subsets approach to model selection for multiple linear regression, the best regression model to predict soil depth in Claire Creek used only slope as an explanatory variable. However, the relationship with measured soil depth was not statically significant at 95% confidence (p value = 0.14). An attempt was made to fit a multiple linear regression model to the same explanatory variables of slope, elevation, and area as the soil depth model that accompanies DHSVM (although the model that accompanies DHSVM does not use a linear relationship). The resulting multiple regression model was not statistically significant at 95% confidence (p value = 0.35).

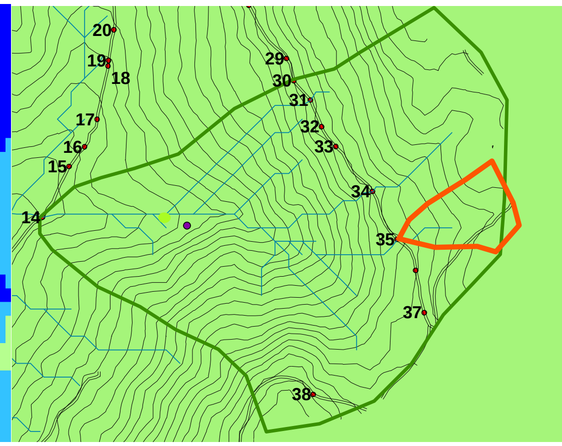
The mean soil depth in Claire Creek was 1.21 meters with a 95% confidence interval of 0.52 and 1.91 meters and a standard deviation of 1.28 meters. Individual observations of soil depth ranged from 0.4 to 3.05 meters; the observation of 3.05 meters was unusually deep. When the 3.05 meter observation was removed, individual observation of soil depth ranged from 0.4 to 1.95 meters.

The analysis of effects of soil depth estimates on DHSVM output used an estimate of soil depths that were not based on field measurements. Since the best predictor of the measured soil depths was from the soil depth model provided with DHSVM (Westrick, 1999) estimates of soil depths for Claire Creek without the use of field measurements to fit the model were created; the Non-Fitted Soil Depth estimate. The weights and exponents of the soil depth model were assigned based on the judgment and experience of the modeler prior to field measurements of soil depth. A range of 0.5 to 2.0 meters was used to represent the range of values for soil depth in the model. The weights used for slope, area, and elevation components of the equation were 0.5, 0.3, and 0.2, respectively. The slope, area, and elevation power exponents were 0.75, 0.25, and 0.75, respectively.

Soil Depth Effects on DHSVM Output

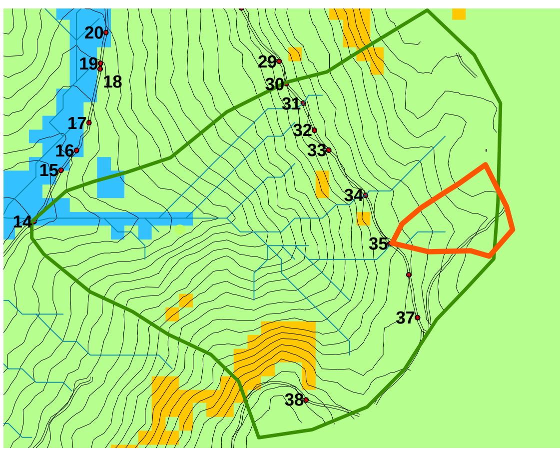
The maps of estimated soil depths for Claire Creek catchment are shown in Figure 2.4. The three representations of soil depths that used field measurements in their measurements (Fitted Soil Depths, Soil Depths Considering Spatial Error, and Mean Soil Depth) had similar mean values (1.21-1.31 meters) and standard deviations (0.11-0.12 m). The soil depth estimate for the Non-Fitted Soil Depths resulted in a higher mean soil depth and standard deviation estimated, 1.6 m and 0.22 m respectively.

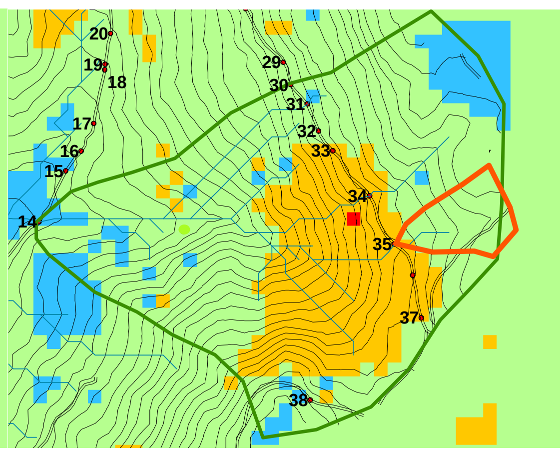




Non-Fitted Soil Depths
Mean = 1.60 m St. Dev. = 0.22 m

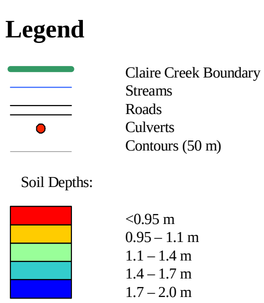
Mean Soil Depth (1.21 meters)





Fitted Soil Depths
Mean = 1.31 m St. Dev. = 0.11 m

Soil Depth Considering Spatial Errors
Mean = 1.31 m St. Dev. = 0.12 m



<u>Figure 2. 4</u>. Four Soil Depth Estimates for Claire Creek

The differences in the observed and simulated streamflow or each of the different estimates of soil depth are shown (Figures 2.5 and 2.6). The Claire Creek simulated streamflow had similar hydrograph shapes for each of the four estimates of soil depths (Figure 2.5). For the most part the simulations based on different estimates of soil depths tracked each other throughout the hydrographs. There were slight variations in simulations at the peak flow of the hydrographs, with the estimates of soil depths based on field measurements producing predicted peak flows closer to observed values. All of the estimates of soil depths produced slight over-predictions of the receding limb of the hydrograph and under-predictions of the baseflow between runoff events. Similar results are observed in the hydrographs for the streamflow above road point 35 (Figure 2.6). The simulated streamflow appears to fit the observed streamflow much better at road point 35 than the Claire Creek streamflow. The receding limbs for the simulated streamflow hydrographs are still an over-predicted but the simulated baseflow is not under-predicted like Claire Creek streamflow, rather it is slightly over-predicted.

Road ditch flow was represented graphically by a hydrograph from only one culvert, culvert 31 (Figure 2.7). The hydrographs in Figure 2.7 show that the simulated ditchflow using the Fitted Soil Depths resulted in a hydrograph that most closely tracked the observed ditchflow; although with a lot of variability. The other three estimates of soil depths produced ditchflow simulations that under-predicted the observed ditchflow for all portions of the hydrograph. The simulated ditchflow using the Fitted Soil Depth under-predicted the baseflow portion of the hydrograph and varied between under or over-predictions of the peak flows and receding limbs for varying runoff events.

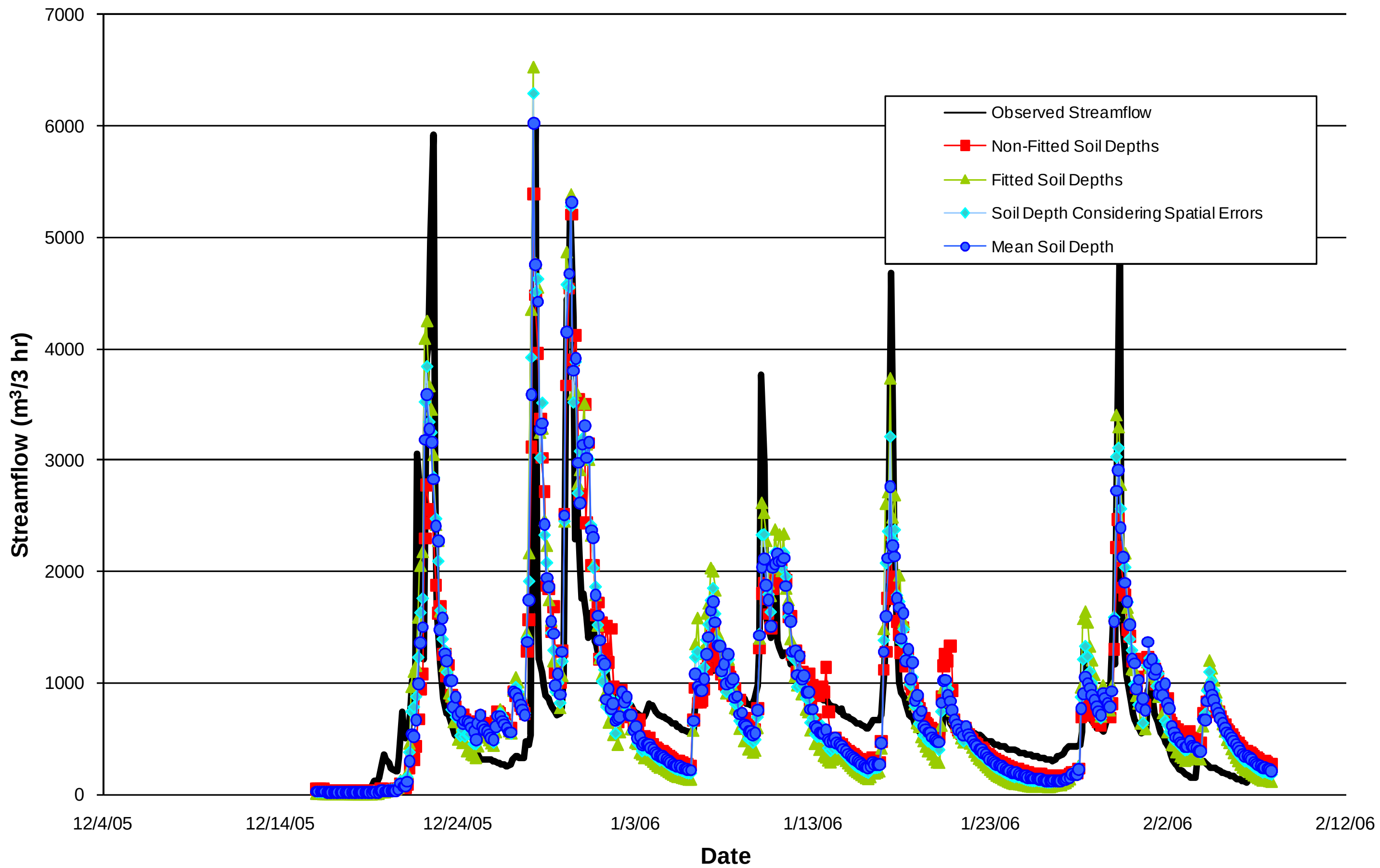


Figure 2. 5. **Claire Creek Observed versus DHSVM Simulated Streamflow using Four Techniques to Estimate Soil depth; Winter 2005 and 2006.**

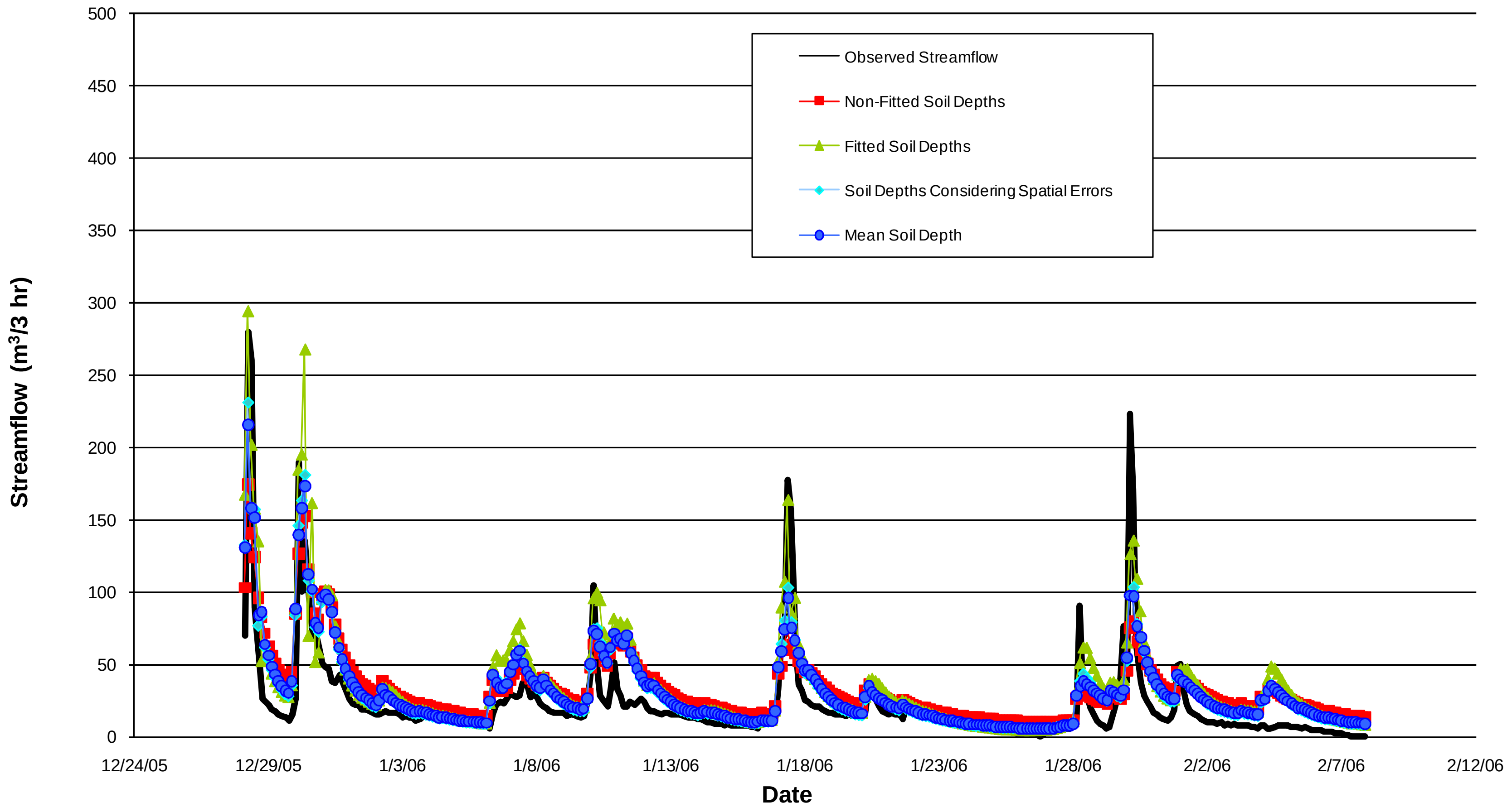
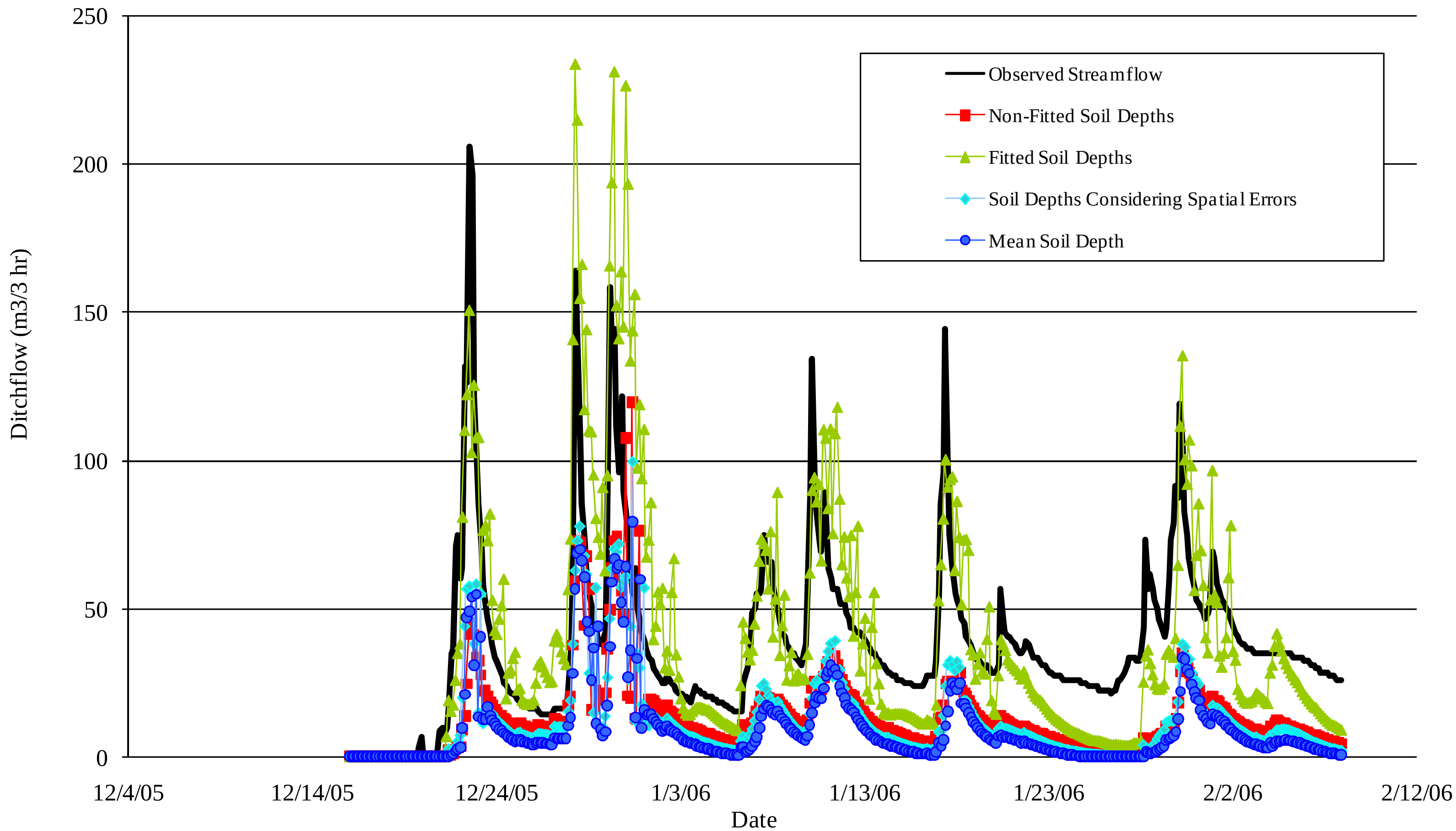


Figure 2. 6. Above Road Point 35 Observed versus DHSVM Simulated Streamflow using Four Techniques to Estimates Soil depth; Winter 2005-2006.



<u>Figure 2. 7</u>. Road Point 31 Observed versus DHSVM Simulated Road Ditchflow using Four Techniques to Estimate Soil depth; Winter 2005-2006.

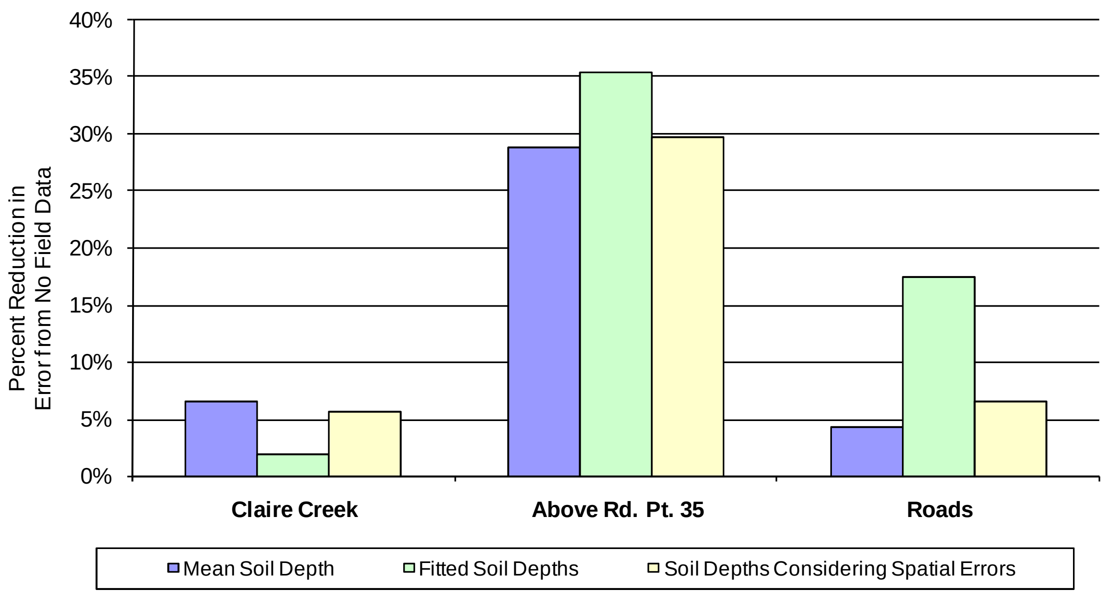
The three estimates of soil depths developed from field measurements reduced the RMSE for simulated streamflow and ditchflow compared to Non-Fitted Soil Depths for the rising limb and instantaneous peak flows. The lowest RMSE were from the simulated streamflow and road ditchflow using the Fitted Soil Depths for the rising limb of the hydrograph, except for streamflow at the outlet of Claire Creek (Figure 2.8).

The streamflow above road point 35 and ditchflow locations showed a substantial reduction in the RMSE for the rising limb of the hydrograph for DHSVM simulations using Fitted Soil Depths (Figure 2.8). For the Claire Creek simulated streamflow there was only a small reduction in RMSE for the rising limb of the hydrograph. The use of the Mean Soil Depth provided the greatest reductions in RMSE for the rising limb of Claire Creek. Mean Soil Depth provided similar reductions in the RMSE for the rising and receding limbs for simulated streamflow above road point 35 compared to the Fitted Soil Depths.

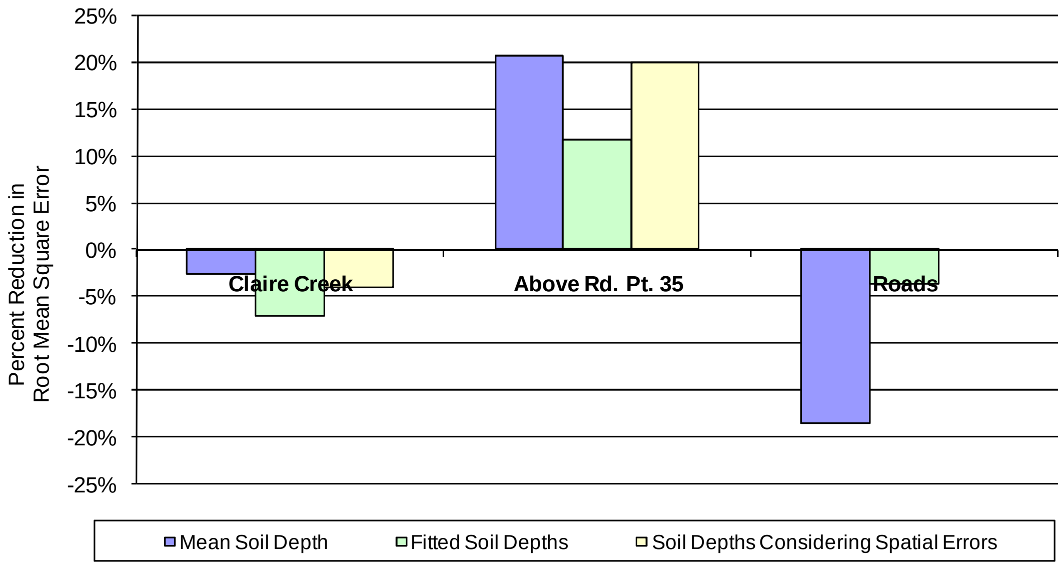
Estimates of soil depths using field measurements gave mixed results for DHSVM output for the receding limb or baseflow portion of the hydrograph compared to Non-Fitted Soil Depths (Figure 2.9 and Figure 2.10). Only the simulations using soil depths based on field measurements at road point 35 improved model output over the use of Non-Fitted Soil Depths and only the Fitted Soil Depths improved the simulations for baseflow (Figure 2.9). The DSHVM simulations of baseflow using the Fitted Soil Depths improve with a decrease in the size of the watershed that is modeled (Figure 2.10). RMSE was reduced 8% for the smallest catchment area the road ditch, it was reduced 6% at the scale of the 5 hectare catchment (above road point 35) and showed no improvement at the 55 hectare catchment (Claire Creek).

The RMSE for the rising limb of the hydrograph was not reduced by the simulations using Soil Depths Considering Spatial Errors compared to Non-Fitted Soil Depths except for Claire Creek streamflow (the largest catchment area modeled)(Figure 2.8).

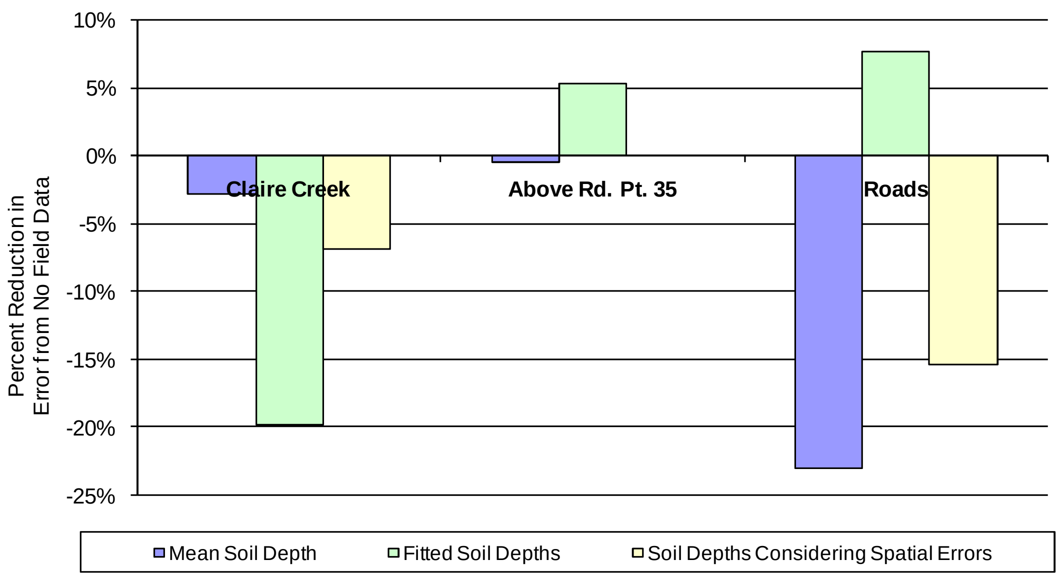
However, the difference in the reduction of the RMSE for Claire Creek streamflow was slight and the use of Mean Soil Depth yielded a similar reduction. The RMSE for the receding limb and baseflow portions of the hydrograph were not reduced using the Soil Depths Considering Spatial Errors to estimate soil depth compared with using estimates of soil depth without field measurements. The exception to this was for the streamflow above culvert 35 during the recession limb of the hydrograph (Figures 2.9 – 2.10) but Mean Soil Depth provided a slightly greater reduction in the RMSE.



<u>Figure 2. 8.</u> Reduction in RMSE for the Rising Limb of Hydrographs for the Three Estimates of Soil Depths using Field Measurements Compared to the Non-Fitted Soil Depths; Claire Creek, Oregon.



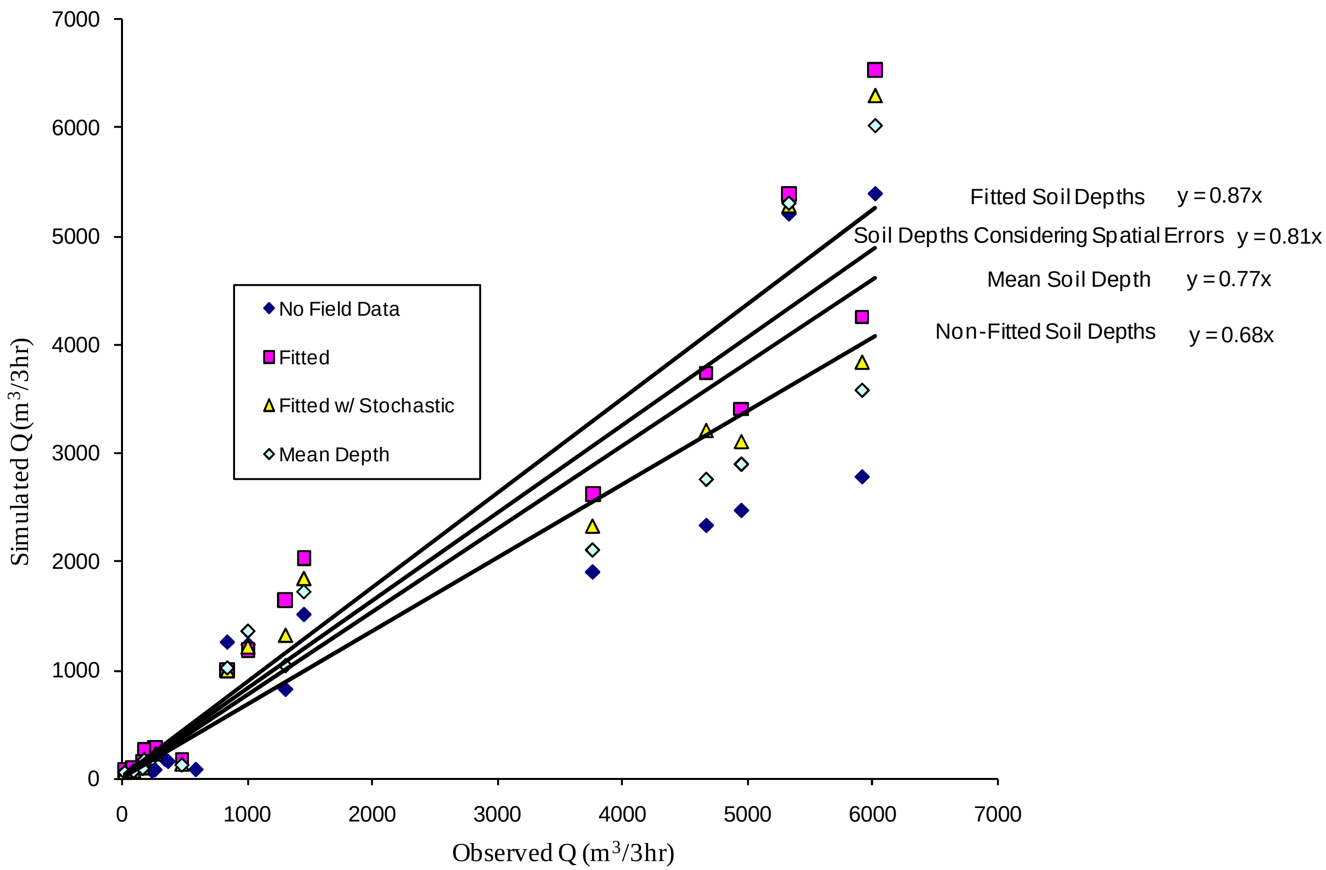
<u>Figure 2. 9</u>. Reduction in RMSE for the Receding Limb of Hydrographs for the Three Estimates of Soil Depths using Field Measurements Compared to the Non-Fitted Soil Depths; Claire Creek, Oregon.



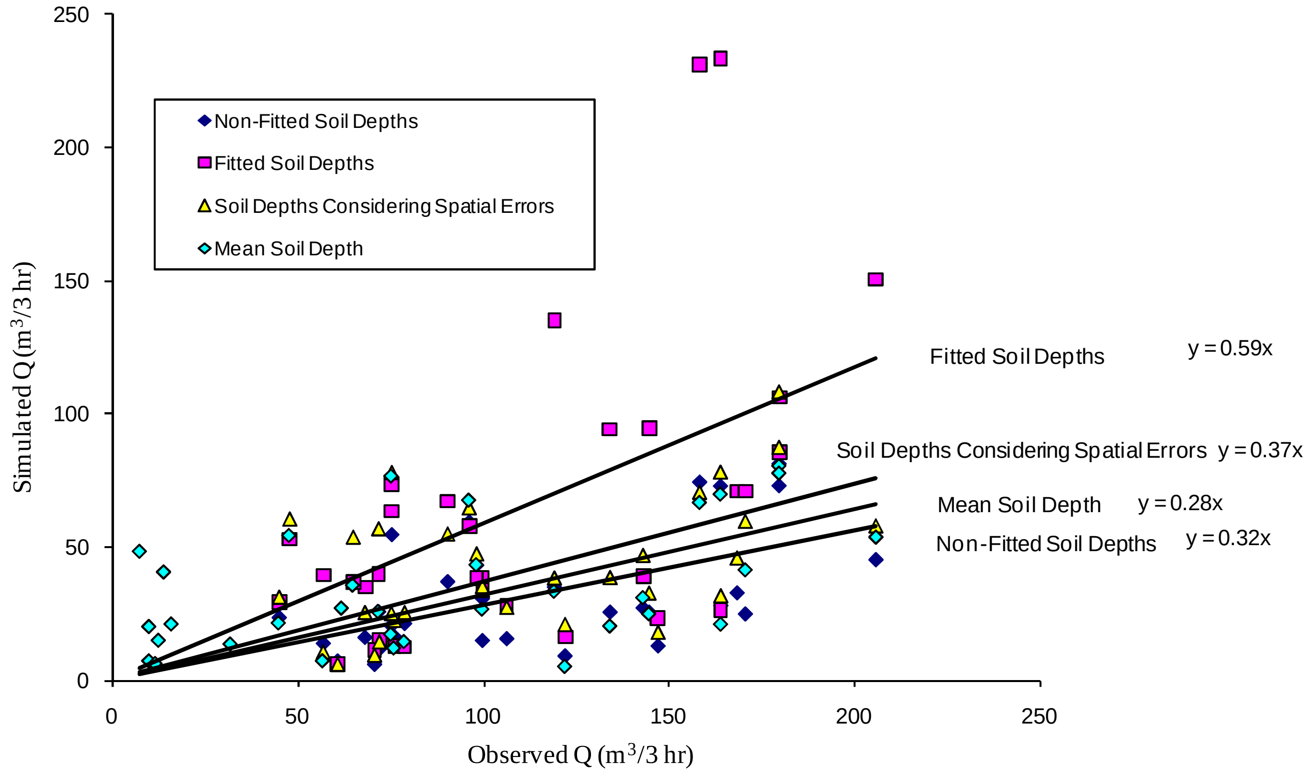
<u>Figure 2. 10</u>. Reduction in RMSE for Baseflow for the Three Estimates of Soil Depths using Field Measurements Compared to the Non-Fitted Soil Depths; Claire Creek, Oregon.

Effect of Soil depth Estimates on Instantaneous Peak Flow Predictions

The instantaneous peak flows simulated by DHSVM using soil depths estimated from field measurements resulted in regression lines closer to a 1:1 ling of observed and simulated peak flows compared to estimates of soil depth without field measurement (Figures 2.11 and 2.12). Use of the Fitted Soil Depths resulted in simulations of the peak flows that were closest to observed peak flows (regression line slope of 0.87). The Soil Depths Considering Spatial Errors resulted in estimates of peak flow that were the second closest to observed values (regression line slope of 0.81). These results were consistent for streamflow at Claire Creek, road point 35 (Figure 2.11), and ditchflow (Figure 2.12). However, the estimates of peak flow for road ditchflow had greater departure from the target 1:1 line than predictions of peak flow for the streams. Using the mean soil depth in DHSVM yielded almost as good an estimate of the peak flows as the use of other estimates of soil depth for streamflow locations but not for ditchflow. The slope of the regression line correlating observed versus estimated peak flows for streamflow was 10 % lower when mean soil depth was used in DHSVM compared to Fitted Soil Depths. However, for ditchflow the peak flows that were estimated using mean soil depth were the least accurate. For ditchflow, peak flows that were estimated using a fitted model for soil depth were the best; however, they were approximately 42% lower than observed peak flows (regression line slope of 0.58).



<u>Figure 2. 11</u>. Comparison of DHSVM Simulated and Observed Instantaneous Peak Flows for Streamflow of Claire Creek and Above Road Point 35; Winter 2005-2006.



<u>Figure 2. 12</u>. Comparison of DHSVM Simulated and Observed Instantaneous Peak Flows for Ditchflow of Claire Creek; Winter 2005-2006.

DISCUSSION

Physically Based Estimates of Soil Depth

Soil formation processes are complex and soil mass wasting processes affect the depth of the soil and soil development from the weathered basalt geology of Claire Creek. The physically based approaches to estimate soil depth used in this study were simple and used only a few general variables. This may in part explain why the topographic index and physically based approaches resulted in low to no correlation to observed soil depths. The topographic index (Beven and Kirkby, 1979), downslope drainage index (Hjerdt et al 2004), best subset linear regression, or multiple linear regression based on slope, area, and elevation did not correlate with soil depth. A physically based soil depth model (Westrick, 1999) fit to field measurements provided only weak correlation with measured soil depths.

The soil depth model when fit to field measurements provided the best estimate of soil depth in this study. Using the Soil Depths Considering Spatial Errors theoretically should have provided a better estimate of soil depths than the model alone. However, this approach did not produce a greater reduction in simulation error than the Fitted Soil Depths. This demonstrated that there was no spatial correlation for the errors between the Fitted Soil Depths and field measured soil depths. If there was a spatial relationship for estimation of soil depths than we would expect a spatial relationship for the error from the soil depth estimates. This suggests that the soil depth model used did not accurately capture the soil depths of Claire Creek and that some other approach for soil depth estimation needs to be discovered if more accurate representations of soil depth is needed.

Another factor in the problems with physically based models of soil depth could be that the field measurements of soil depth were represented at the smallest spatial scale the

DHSVM could be used for this application, 30 meters. This scale appears too coarse to characterize the variability of soil depth across terrain of the Claire Creek catchment. This conclusion was problematic as the scale of DHSVM modeling for Claire Creek was constrained by the width of the road prism.

Soil Depth Estimation and the Hydrologic Process Modeled

The influence of the soil depth estimate on the results from DHSVM varied for the 3 partitions of the storm hydrograph. Estimates of soil depth based on field measurements improved the results from DHSVM during periods of precipitation as evidenced by the reduced RMSE for the rising limbs of storm hydrographs. Drainage of sub-surface water that follows precipitation, represented by the receding limb of the hydrograph, only reduced the RMSE for the small scale streamflow site (above road point 35). During baseflow only soil depth estimated with the fitted deterministic model for road ditchflow and the small scale streamflow site reduced the RMSE. This suggests that model parameters other than soil depth are having a greater influence on the distributed hydrologic model results for the receding limb and baseflow periods of run-off. These results agree with the suggestion that distributive hydrologic model results can be improved if calibrated with separate parameter sets for each portion of the hydrograph (Boyle et al, 2000).

Soil Depth Estimates for Different Spatial Scales

The influence on DHSVM results by the different estimates of soil depth varied by the spatial scale being modeled. The estimates of Fitted Soil Depths had the greatest reductions in the RMSE for the small scale streamflow and road ditchflow locations; while Mean Soil Depth provided better results at the catchment scale of Claire Creek. Mean Soil Depth provided reduced RMSEs for DHSVM simulations for Claire Creek (55 hectares, largest scale modeled) and for the small scale streamflow site (above road

35; 5 hectares). The influence of spatial scale for the Fitted Soil Depths and Mean Soil Depth was observed in the linear regression of simulated versus observed peak flows. The mean soil depth had a slope close to the 1:1 line for streamflow but a slope far from the 1:1 line for ditchflow.

A physically based estimate of soil depths attempts to represent the variations in soil depth based on physical influences, while a mean soil depth only provides a uniform depth. The improvement in DHSVM results at small scales based on Fitted Soil Depths demonstrates the sensitivity of the hydrologic model to soil depth variations when modeling runoff from small spatial areas. As the size of the catchment modeled increased the need to capture variations in soil depth was not as important. This suggests the type of soil depth estimate a modeler chooses could be based on the objective of the modeling. If small area or site specific hydrologic observations are the objective than soil depth estimates that attempts to represent the local soil depth variations would be best. For large scale hydrologic modeling a mean soil depth estimate appears sufficient. For accurate peak flow predictions the use of Fitted Soil Depths gave the closest relationship (slope of 0.87) to the 1:1 line of observed to simulated peak flows. However, if a modeler is willing to sacrifice some accuracy then the mean soil depth provided reasonable results for streamflow associated peak flows as well (slope of 0.77).

Mean Soil Depth was based on many field measurements of soil depth providing an accurate assessment of the mean. It would be expected that inaccurate estimates of the mean soil depth would have adverse effects increasing uncertainty for hydrologic modeling results. Indeed field measurements appeared to be necessary for our catchment. For example, if a modeler used the mean soil depth provided in the soil survey for the area, approximately 1 meter (Knezevich 1975), the depth estimate would be 20% shallower than measured in the catchment. This 20% difference in soil depth would increase uncertainty in model results.

The sampling needed to provide a reasonable estimate of mean soil depth across a catchment could be approached differently than a sampling design that needs to identify the spatial variations in soil depth. A sample design attempting to calculate the mean soil depth could rely on a sample that gives adequate spatial coverage of a catchment. A spatially balanced sample as described by Stevens and Olsen (2004) would likely meet the needs of this type of sample design, provided a sufficient sample size was used. While a sampling design to determine soil depth estimates for site specific or deterministic approach might require a spatially stratified sampling approach potentially increasing the sample size and complexity of the field observations.

CONCLUSIONS

Our study showed that the way soil depth is estimated influences distributed hydrologic model results in mountainous terrain. In Claire Creek, Oregon the influence of different soil depth estimation techniques varied by the spatial scale and the hydrologic process modeled as observed from 3 separate partitions of storm hydrographs. Within Claire Creek attempts to predict soil depth with physically based approaches ranged from low to no correlation with observed soil depths. Even with this lack of predictive capacity a soil depth model fit to field measurements gave the best DHSVM results for ditchflow and streamflow associated with the rising limb and peak flow of storm hydrographs. However, mean soil depth was as good as or better than using a deterministic soil depth estimate for our streamflow locations of 55 and 5 hectares in size. The measurement of soil depth in the field was important to improving our distributed hydrologic model results; however, this comes at a cost to the modeler. This study demonstrated that different strategies for making field measurements can be considered with the modeler weighing the cost of reduced uncertainty to their modeling objectives.

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CHAPTER 3: UNCERTAINTY ASSESSMENT OF FOREST ROAD MODELING WITH THE DISTRIBUTIVE HYDROLOGY SOIL VEGETATION MODEL (DHSVM)

INTRODUCTION

The effect of forest roads on catchment hydrology and sediment production are increasingly the focus of regulatory and scientific concern. This requires that land managers and owners become more sophisticated in the assessment of the impacts of their practices. Forest roads generate overland flow from compacted surfaces (Harr et al 1975; King and Tennyson 1984), intercept sub-surface flow at road cuts (Burroughs et al 1972; Megahan 1972; Wemple 1998) and affect hillslope hydrologic processes. Forest roads can re-distribute water on hillslopes and change the timing of stream flow, sub-surface flow, or the distribution of soil moisture (Megahan 1972; Wigmosta and Perkins 2001), extend stream channel networks through gullies (Wimple et al 1996; Montgomery, 1994), or alter peak flows at stream crossings (Toman 2004).

We have the ability to measure hydrologic response for individual road segments. The small flumes and continuous stage recording devices available today are inexpensive and accurate. Road culverts provide locations where runoff can be rated with stage at the culvert inlet (Toman, 2004). These measurement techniques are sensitive enough to accurately measure even very small amounts of runoff from road surfaces or ditches. However, hydrologic responses from roads are highly variable and it is not cost effective to measure the hydrologic response at all road runoff locations.

Attempts have been made to associate physical measurements of the topography, soils, and road to provide a prediction of the road's hydrologic response. Wemple and Jones (2003) reported that hillslope length, soil depth, and cutslope height explained much of the variability in the amount of subsurface flow intercepted by cutslopes at the H.J. Andrews Research Forest in the western Cascades. La Marche and Lettenmaier (2001) found no relationship between peak runoff and cutslope height of adjoining road segments in the Deschutes River watershed in Washington. Gilbert (2002) found no relationship between spatial variability of subsurface interception and topographic indicators in the Oregon Coast Range. Ellingson (2002) found that road length and elevation (surrogate for orographic precipitation effects) correlated with the peak discharge from roads for one storm analyzed in the Oak Creek watershed in the Oregon Coast Range. However, no relationship was found for topographic or physical properties and total storm runoff volume from roads. I repeated Ellingson's analysis for 5 storms in 2003 and found the log of elevation and hillslope gradient provided the best model for predicting the log of the peak flow (p value <0.0001). However, the model did not predict much of the response variability (adj. $r^2 = 0.12$). Elevation in this case can be considered a surrogate for general differences in precipitation rates in the Oak Creek watershed; hillslope gradient would generally be related to road cutslope height. I also found that log of road surface area, log upslope contributing area to road, and the hillslope gradient provided the best predictors for the response of log of total road run-off volume (p value = 0.0009) but the model predicted little of the response variability (adj. $r^2 = 0.09$). Neither slope nor road drainage areas were statistically significant in determining the occurrence of gullies from road drainage in a study of the Deschutes River, Washington (La Marche and Lettenmaier, 2001). This result may indicate that the presence of macropore or pipe flow is more important than hillslope steepness in determining the amount of subsurface flow intercepted by a road segment, and hence the propensity for gullies to form below the culverts (La Marche and Lettenmaier, 2001).

The highly varied response of road runoff and lack of simple matrices to predict a road's hydrologic response makes road hydrologic effects at the catchment scale difficult and costly to study. As a result assessments of hydrologic effects by forest roads increasingly rely on attempts to simulate the complex processes using hydrologic models, like the Distributive Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al, 1994; Wigmosta and Perkins, 2001). DHSVM is a physically based distributed parameter hydrologic model that allows the simulation of runoff processes in forested and mountainous watersheds (Wigmosta et al, 1994). A brief description of DHSVM is provided in Chapter 2 of this dissertation. A more thorough explanation can be found elsewhere (Wigmosta et al, 1994; Storck et al, 1995; Storck et al, 1997; Wigmosta and Perkins, 2001). DHSVM contains a road interception component that models the interception of hillslope water at road cutslopes (Storck et al., 1998; Wigmosta and Perkins, 2001). The fraction of the permeable soil occupied by the road cut becomes a controlling factor in the amount of interception (Wigmosta and Perkins, 2001). DHSVM then routes the intercepted water along the road ditch to a drainage location; which enables estimates of road hydrologic effects for individual sites or cumulatively for catchment scale effects.

The conceptual model within DHSVM for road hydrologic effect has interception of hillslope water occurring when a seasonally high water table flowing over an impermeable base (e.g. bedrock) becomes deep enough to intersect the road ditch. Thus the fraction of the permeable soil occupied by the road cut becomes a controlling factor in the amount of interception. The published record on road hillslope water interception has demonstrated the complexity of the subject and suggests substantial variability (Luce, 2002). Various researchers have observed that cutslope contributions can be much smaller than, equal to, or much greater than road surface contributions; unfortunately, the dependencies are not clear (Luce, 2002). On forest roads in Idaho and Oregon a substantial portion of the road runoff came from subsurface flow intercepted by the cutslope (Burroughs et al., 1972; Megahan, 1972; Wemple, 1998; Marbet, 2003). In catchments in the Oregon Coast Range the dominant mechanism for road runoff was variable throughout the catchments. Some road segments have runoff dominated by road interception of hillslope water while other road segments by overland flow from the road tread (Marbet, 2003; Toman, 2004).

Wigmosta and Perkins (2001) demonstrated the utility of the road network component of DHSVM in Carnation Creek for showing changes in peak flows and routing of water along road networks. Bowling and Lettenmaier (2001) tested DHSVM on 12 culverts within Hard and Ware Creeks and found the model generally simulated outlet peaks well, and culvert peaks approximately. Their DHSVM results predicted peak flow changes within the catchment from the road network. DHSVM was also used to simulate road influence on road runoff, peak flows, water table, and forest harvest related changes within the Deschutes River watershed (La Marche and Lettenmaier, 2001). Though the applicability of DHSVM road modeling has been shown the authors stated that in order to better understand the effects that forest roads have on hydrologic processes more research needs to be done (Wigmosta and Perkins, 2001; Bowling and Lettenmaier, 2001).

Physically based distributed models, like DHSVM, are demanding in their input requirements. Considerable uncertainty can be represented from the inputs to the model and the calculations within the model used to simulate the response. Uncertainty and output error come from a variety of sources. For instance the precipitation inputs to a rainfall runoff model, like DHSVM, are highly influential in the model simulations. The measurement of precipitation has been shown to have considerable spatial variability (Larson and Peck, 1974; Morissey et al., 1995) and accuracy errors associated with its measurement (Peck, 1972; Robinson and Rodda,1969; Chou, 1968; Green and Helliwelt, 1972; Habib, 2001). Parameter values of DHSVM such as hydraulic conductivity are represented as a single value depending on the soil texture while the measurement of this value has been shown to range as much as 150% (Warrick and Nielson, 1980). Model structure errors account for a significant proportion of uncertainty in predictions that generally increases with model complexity and reflects the constraints of our scientific understanding of the processes at work (Brazier et al., 2000). Finally, the observations of road ditchflow and streamflow that are used for comparison and evaluation of model output have error adding uncertainty to our model assessment.

Increasingly hydrologic modeling is embracing the need to quantify the predictive uncertainty associated with the model (e.g. Beven, 1993; Beven and Binley, 1992). One approach to assessing this predictive uncertainty is the The Generalized Likelihood Uncertainty Estimation (GLUE) Methodology (Beven and Binley, 1992; Beven, 2001a). In this approach the model simulations are attempting to achieve equifinality. Equifinality for a model is the basis of the GLUE procedure. Equifinality is the idea that many model structures or parameter sets used in a model can provide acceptable simulators of catchment hydrologic behavior (Beven, 2000). Statistical parameter inference is predicated on the implicit assumption that the "true" model is available, the rejection of that possibility in favor of a concept of equifinality means that some new approaches are needed. Equifinality shows that many model structures will give an acceptable simulation and that all of these acceptable model structures need to be considered in a modeled analysis.

GLUE is one approach that can be used to evaluate equifinality in models, however only for models or applications where it is computationally feasible to apply. It was used for distributed and semi-distributed models over limited domains but there are still some problems with distributed models where the parameter dimensionality and computational times make a full Monte Carlo analysis infeasible (Beven, 2001b). To date, efforts that use DHSVM have used manual calibration. A manual calibration relies on systematic altering of the most sensitive or influential parameters of the model through a sequence of model runs. This approach has been used primarily because of the long run times required for DHSVM (i.e. Whitaker et al, 2003) making multiple calibration runs very time consuming and often DHSVM users lack the computer resources to do the multiple model iterations necessary for GLUE. An additional challenge is that because GLUE has not been used with DHSVM, no software or programming has been created to enable automatic GLUE assessment of DHSVM. Thus to use the GLUE procedure for DHSVM the tools have to be created.

The applications of DHSVM modeling road hydrologic effects have relied on one set of calibrated model parameters for its predictions (La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001; Wigmosta and Perkins, 2001; Cuo et al, 2003). In fact in all of the published accounts of DHSVM; hydrologic simulations have relied on the model being calibrated to one model structure (e.g. Lueng and Wigmosta, 1999; Whitaker et al, 2003; Beckers and Alila, 2004; Schnorbus and Alila, 2004).

The varied hydrologic responses from roads shown in the literature suggest there is considerable uncertainty associated with assuming a simple conceptual model of road interception, like used in DHSVM, can accurately predict road hydrologic effects. To date there is not an assessment of equifinality or uncertainty of DHSVM. This chapter shows an assessment of uncertainty, equifinality, and DHSVM accuracy in predicting the hydrologic effects of forest roads for the Oak Creek watershed, in the Oregon Coast Range. The goal is to provide insights on the hydrologic processes associated with forest roads by interpreting the uncertainty and output of different parameters and spatial scales of DHSVM output. This work also provides users of DHSVM information on predictive uncertainty of model results and application.

The objectives of this chapter are:

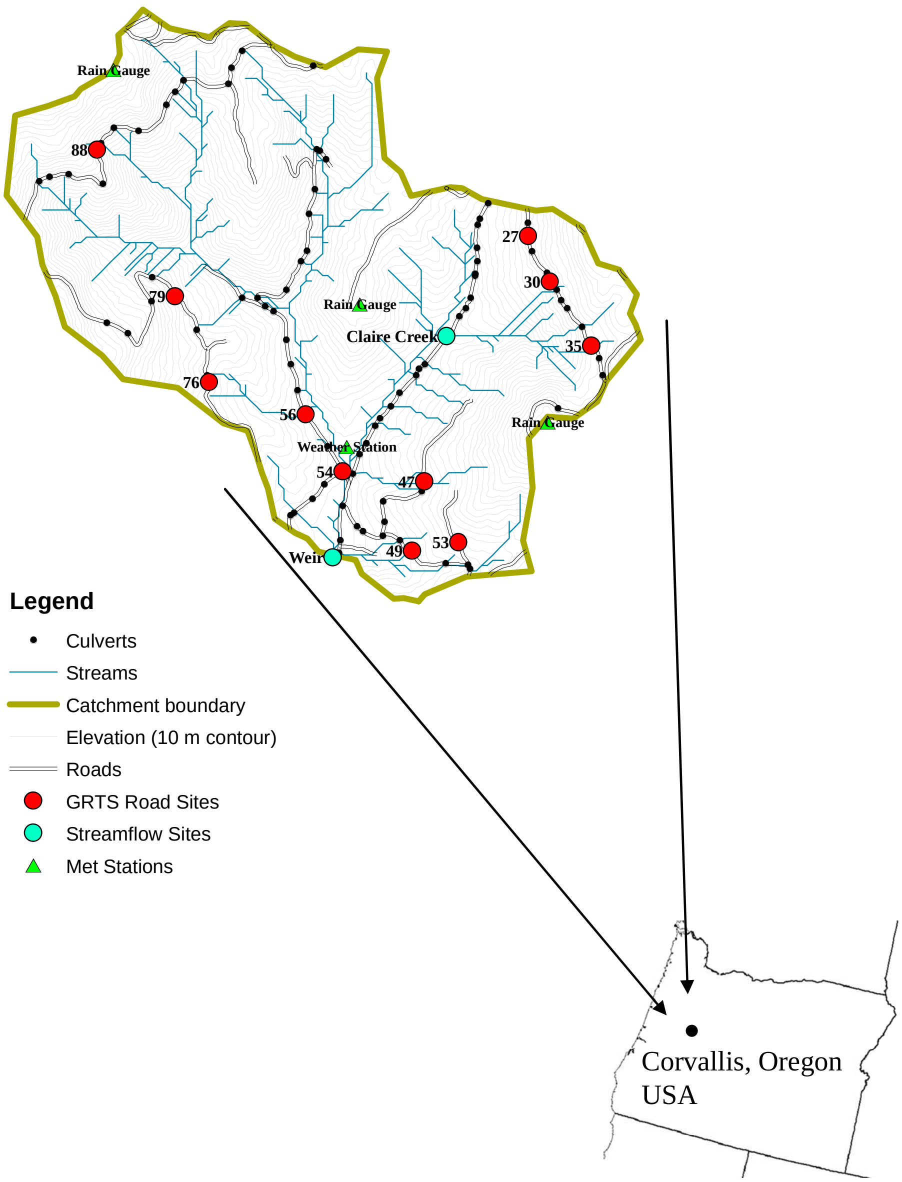
- To provide an uncertainty assessment of DHSVM streamflow and road ditchflow for four influential soil hydraulic parameters of the model using the GLUE procedure.
- To test and contrast the road interception component of DHSVM to observed road hydrologic response within Oak Creek.
- To perform a case study of effect of roads in the Oak Creek watershed on peak flow and changes in storm runoff.

METHODS

Study Area

This study was conducted in the upper Oak Creek catchment, within McDonald/Dunn Forest, owned and managed by the College of Forestry, Oregon State University. The study catchment area is 630 hectares; measured to the Oak Creek stream gage (Figure 3.1). Elevations within the research catchment ranged from 140 to over 600 meters (Toman, 2004). The average annual precipitation for the Oak Creek catchment for 2003 thru 2006 water years was 97 cm per year, with a range of 83 to 111 cm. Precipitation comes predominately as rain, with an annual snowfall depth of approximately 11 cm (Oregon Climate Service, 2005). The bedrock underlying the watershed is the Siletz River Volcanics, a basalt formation (Knezevich 1975). Soils in the watershed are classified as silty clay loam; some areas of silty loam are present. The forest type is predominately Douglas-fir, with minor components of other conifer, hardwood species, and grass meadows.

The drainage density is 24 m/ha based on the stream channels created with the “createstreamnetwork.aml” that accompanies DHSVM. The road density is 5.55 m/ha (Toman, 2004). The roads were, on average, five meters wide, had rocked surfaces, crowned tread design with roadside ditches. There were 97 culverts within the study catchment for the time period of this study (Figure 3.1). Of these structures, 23 were stream crossing culverts and the remaining 74 were drainage relief culverts. A stream crossing culvert was defined as a culvert that ran surface water at least part of the year and was directly connected to the stream channel as evidenced by a defined channel for at least 10 meters upslope of the culvert invert and a defined channel below the culvert outlet that converged with another stream channel (Toman, 2004).



<u>Figure 3. 1</u>. Upper Oak Creek Study Catchment and Study Sites, Corvallis, Oregon.

Each of the 97 culverts was instrumented to collect water stage for calculations of storm run-off. Most of these instruments were in place since 2001 and continually maintained by the Department of Forest Engineering, Oregon State University. The 23 stream crossings have capacitance rods installed at the invert of the stream crossing culverts to continuously measure stage. Trapezoidal flumes were installed in the ditches of the stream crossing culverts; capacitance rods measure water stage at the flumes. Stage was measured for the 74 cross-drain culverts, culverts that drained water under the road from a road ditch, with capacitance rods or crest gages. Capacitance rods were installed at the inlet of 45 of the cross drain culverts the remaining 29 cross drain culverts have crest gages installed to measure the peak stage. Crest gages were randomly distributed among the cross drain culverts. Stage and turbidity were continuously measured at the outlet of Oak Creek since 2001 and 2003, respectively. Stage was measured at a small tributary stream, Claire Creek (55 hectares) since 2003. Flow rating curves at both the outlet of Oak Creek and Claire Creek were developed and used to predict streamflow.

A meteorological station was operated near the outlet of the study catchment; meteorological observations were collected since 2003. This meteorological station provided continuous air temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation. In addition three additional rain gages were located throughout the catchment; locations varied by elevation and aspect.

Site Selection for Study

The GLUE evaluation for DHSVM within the Oak Creek catchment used 2 stream flow locations and 11 road drainage culverts (see Figure 3.1). The streamflow locations were Oak Creek, representing the outlet of the catchment (630 hectares), and Claire Creek, a smaller tributary (55 hectares). The streamflow locations were the largest catchment areas with streamflow measurements. The 11 road drainage sites were selected using the Generalized Random Tessellation Stratified design (Stevens and Olsen, 2004). This sampling approach is a spatially balanced sample, selecting its sample by balancing the sampled locations across the area studied. The sampling frame was road sites with continuous electronic observations (no crest gages sites were in the sample frame) and at least 2 winters of hydrologic data; 35 of the 97 road culverts met these criteria.

DHSVM Inputs

DHSVM requires spatial information on the catchment in the form of binary grids created from ArcInfo coverages of elevation, soil type, soil depth, and vegetation type. DHSVM required connecting arcs (spatially aligned lines) for the stream network and road network. Meteorological information was required for each time step of the duration modeled. The following describes the process that was used to generate these inputs. For greater detail on how these inputs were generated see Appendices A and B.

Oak Creek Spatial Data

The digital elevation model (DEM) for the Oak Creek catchment was created from 6 meter laser altimetry topography data using light detection and ranging technology (LIDAR) collected by the College of Forestry, Oregon State University. A 30 meter DEM for Oak Creek was projected from this LIDAR data and used for DHSVM. A pixel size of 30 meters was chosen because it was large enough to encompass the stream channel and road widths found in Oak Creek (a constraint of DHSVM) and it represented a pixel size commonly used in topographic analysis.

The soil types for Oak Creek came from the Benton County Soil Survey (Knezevich 1975) in a GIS layer provided by the College Forests (Oregon State University). This GIS layer was projected to correspond with the 30 meter DEM created for Oak Creek. The parameters of DHSVM that were varied for uncertainty analysis were physical variables associated with water movement in the soil. To facilitate the Monte Carlo analysis associated with the GLUE procedure only one soil type was designated across the Oak Creek catchment; silty clay loam. This soil type was the starting point for random soil parameter selection for the GLUE analysis.

The vegetation for Oak Creek is mainly Douglas fir (*Pseudotsuga menziesii*), with stand ages varying from 40 to greater than 120 years in age. A vegetation layer specifying one vegetation type (coastal forest type) was projected to correspond with the 30 meter DEM for Oak Creek for this Douglas fir forest. There are minor components of Oak, Alder, and grass meadows within Oak Creek however these areas are very small and assumed not large enough to be influential; therefore they were not designated for use for DHSVM vegetation inputs.

Soil depths were estimated by a soil depth model (Westrick, 1999) fit to field measurements of soil depth in Claire Creek (see Chapter 2 for details). The stream network for Oak Creek was generated by the "createstreamnetwork" Arcinfo script provided with DHSVM. The road GIS layer for Oak Creek from the College of Foresty, Oregon State University was used to represent the road network. This road network was spatially accurate, with culverts on the road mapped to within 1 meter accuracy. Road dimensions of cutslope depth, road width, ditch width, road type (crowned, outsloped, insloped), and road ditch depth were from field observations.

The meteorological inputs for DHSVM were primarily from the weather station within Oak Creek. Meteorological data from the United States Bureau of Reclamation Agrimet climate station in Corvallis, Oregon was used to develop relationships with Oak Creek meteorological data to fill missing time periods (see Appendix A).

GLUE Analysis

The Generalized Likelihood Uncertainty Estimation (GLUE) Methodology (Beven and Binley, 1992; Beven, 2001a) is an extension of the Generalized Sensitivity Analysis of

Hornberger, Spear and Young (Hornberger and Spear, 1981; Spear *et al*., 1994) in which Monte Carlo simulation is done with randomly chosen model parameter sets; a likelihood measure is used to reject some models (model structure/parameter set combinations) as nonbehavioral while all those models which meet the likelihood measure are considered as behavioral and are retained in prediction.

Number of Model Iterations and Parameters

The initial step in the GLUE procedure was a Monte Carlo based simulation using randomly selected parameter variables sampled over a uniform or previously known distribution. For this study 10,000 model simulations were performed based on randomly selected soil variables of lateral hydraulic conductivity, the exponent of decay by depth of the hydraulic conductivity, the porosity of the soil matrix, and the vertical hydraulic conductivity. These 4 parameters and range from which variables were selected were based on preliminary model trials that demonstrated competence at achieving model fit to observed data. The ranges of variables randomly sampled are shown in Table 3.1. Because 3 of the parameter ranges sampled were from tenths to hundred thousandths of unit values a lognormal distribution was used for random sampling. This provided equal probability for a low value (hundred thousandth of a unit) to be sampled as a high value (1 or 10 units). Sampling from a uniform distribution would have been too heavily weighted toward higher parameter values.

Table 3. 1. Range of Parameter Variables Randomly Sampled for GLUE

Parameter	Range of Variable Values
Lateral Hydraulic Conductivity	0.00001 – 1.0 m/s
Exponent of Hydraulic Conductivity Decrease by Depth	0.01 – 10.0
Vertical Hydraulic Conductivity	0.00001 – 1.0 m/s
Porosity	0.4 – 0.55

A limitation of the GLUE assessment is the dependence on Monte Carlo simulation (Beven, 1998). For complex models that require a lot of computer time for a single run, such as DHSVM, it was not possible to fully explore all parameter interactions. The analysis was limited by the computer resources available, which resulted in only 10,000 simulations that varied only four model parameters. However, it is suggested that the upper limit of model performance is often well defined by a limited number of model realisations and that prediction intervals are reasonable in comparison with observations (Beven, 1998).

Likelihood Function (Goodness of Fit)

The Nash and Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) was used as the likelihood function for the GLUE procedure of DHSVM. It should be pointed out that the term "likelihood" takes a broader definition in the GLUE analysis than proposed in classical statistical techniques (Binley and Beven, 1991). The Nash and Sutcliffe Efficiency was chosen because it provides a reasonable test of the magnitude and timing between observed and simulated time series points. The NSE was also chosen because it was successfully implemented with GLUE (i.e. McMichael et. al., 2006) and was a goodness of fit measure in other DHSVM applications (i.e. Whitaker et al, 2003).

$$NSE = \left[1 - \frac{\sum_{i=1}^{n} \left(Qobs_i - Qsim_i \right)^2}{\sum_{i=1}^{n} \left(Qobs_i - \overline{Qobs} \right)^2} \right]$$

Where: $Qobs_i$ = stream or road flow observation at the ith time.

$Qsim_i$ = stream or road flow DHSVM simulation at the ith time.

$\overline{Qobs}$ = mean observed stream or road flow for entire time series.

The ith time of the NSE was each three hour time step used in the DHSVM simulations. Nash and Sutcliffe Efficiency (NSE) values that approach 1 represent the best fit, while values less than 0 suggest that the observed mean observation provides a better representation of the observed values than the simulated time series. The DHSVM simulated time series for the Oak Creek and Claire Creek streamflow that equaled or exceeded a NSE of 0.5 were used for the GLUE analysis. NSE values exceeding 0.5 suggest a reasonable fit to the observed time series. The fit of the time series of road ditchflow to observed ditchflow was not as good as streamflow. In order to provide greater simulations for GLUE analysis, road ditchflow simulations that equaled or exceeded a NSE of 0.3 were used for the GLUE analysis. Road run-off is highly variable and can be highly influenced by local precipitation intensity, which makes it difficult to match simulated and observed data by time periods. The use of a NSE of 0.3 attempted to compensate for these discrepancies and provide a conservative threshold value for evaluation of uncertainty in model results. The literature reports higher values of NSE with application of hydrologic modeling with DHSVM (McMichael et al, 2006; Whitaker et al, 2003). However, to ensure that behavioral model structures were not excluded due to drawbacks in the use of NSE, the 0.5 NSE for streamflow and 0.3 NSE for road ditchflow was used in this analysis.

Dotty Plots

One measure of the sensitivity and interaction of parameters provided from the GLUE analysis are dotty plots. Dotty plots are plots of the likelihood measure, in this case the NSE, against the value of each individual parameter used for the corresponding time series. One dot was plotted for each Monte Carlo run that meets the specified NSE threshold of 0.5 for streamflow and 0.3 for road ditchflow. The Dotty Plots are projections of all the Monte Carlo samples onto single parameter axes (Beven, 1998). Therefore the interpretation of dotty plots must consider that the plot is only a one-dimensional representation of one parameter in relation to all other parameters used in the model run.

Sensitivity Plots

Sensitivity of parameters can be interpreted from plots of the cumulative distributions of parameter values grouped according ranking by their likelihood measure. Sensitivity plots were compiled for each of the 4 parameters evaluated for each road ditchflow and each streamflow location in Oak Creek. Differences between the cumulative distributions for a given likelihood measure or variable indicates sensitivity to that parameter. Distributions plotting close together indicate a lack of sensitivity.

Calculation of Uncertainty Bounds

The GLUE analysis allows uncertainty assessment for simulated time series. In this case a 95% uncertainty bound as derived from the Monte Carlo simulation was used. The uncertainty bounds depict prediction errors from model structure, effective parameterization, and hydrologic processes as calculated by DHSVM. The uncertainty bounds apply for the entire time series and individual time steps. It should be stressed that these predictive uncertainty bounds define the upper and lower prediction limits associated with the behavioural parameter sets, and do not represent probabilistic uncertainty intervals or objective probabilities (McMichael et al, 2006).

For each ditchflow and streamflow site used in the GLUE analysis the modeled time series that exceeded the NSE threshold were sorted low to high for each time step. The time series at the 2.5% and 97.5% level of sorted model time steps were extracted and used to represent a 95% uncertainty bound. Statistics from the uncertainty bounds were generated to show the percentage of observed peak flows and storm runoff volumes that were within the uncertainty bounds of model simulations. The percentage of model runs from the Monte Carlo simulations that meet the NSE threshold values of 0.5 and 0.3 for streamflow and road ditchflow respectively were calculated as well.

Assessment of DHSVM Estimation for Road Discharge

Peak Flow and Storm Runoff Volume Estimation

Ditchflow from the roads during storms was designated for all road discharge locations (culverts) monitored in the Oak Creek catchment for the 2006 and 2007 water years. The storm designation for 2006 and 2007 water years was determined from the streamflow record at the outlet of Oak Creek. For consistency in storm designation the start and end times for storms designated from the Oak Creek gaging station were used as the starting point for designating storms. For each road discharge location, with continuous ditchflow observations, the initial storm start and stop time from the outlet was adjusted based on interpretation of individual site hydrographs. Generally, storms for the road locations stayed within the time frame designated for storms at the outlet of Oak Creek. The exception was road locations with small catchment areas that had storm start times sooner than the outlet. For each storm, the total volume and peak discharge was calculated for each road culvert with continuous ditchflow observations.

All of the discharge points for road ditches (culverts) within Oak Creek were monitored for runoff. Approximately half of the culverts had continuous ditchflow recorded with capacitance rods and the remaining half had crest gages. For the road sites with crest gages, only the highest stage is recorded (the peak flow). The highest stage was collected approximately once per month throughout the winter when maintenance and data downloads occurred in the catchment. This provided the peak flow for the location and time period. When more than 1 storm occurred between observations of the crest gage, the peak flow was assigned to the storm with the highest peak flow at the outlet of Oak Creek that occurred since the previous observation for the crest gage.

DHSVM was run for the Oak Creek catchment for the 2005 through 2007 water years. The 2005 water year information was used as a "spin-up" period for DHSVM to ensure that model streamflow and groundwater levels had equilibrated to the catchment's meteorological data. The model was calibrated to 2003-2006 water year observations. Fit of the model to stream hydrographs was evaluated quantitatively by: 1) volume error for predicted versus observed run-off; 2) model efficiency (Nash and Sutcliffe, 1970) and 3) coefficient of determination (see Whitaker et al, 2003). Fit of the model was also evaluated qualitatively for general fit of model observations to observed values. This was necessary because it was impossible to get good quantitative fits for the model output at the wide variety of scales used for the calibration, particularly the road locations. The resulting calibrated model used only one parameter set for this analysis. The DHSVM simulated streamflow and road ditchflow was separated into storms that corresponded to the same times of observed streamflow and ditchflow storm designations. For each storm the total runoff volume and peak flow was calculated.

There were 12 storms designated for the 2006 water year and 20 storms designated for the 2007 water year. Storm volumes were designated from 49 road locations with continuous ditchflow. Peak flows were designated for 92 of the 96 culverts from a combination of capacitance rod and crest gage locations. The storm volumes and peak flows were paired with the corresponding runoff volumes and peak flows simulated by DHSVM. Linear regression was used to determine the relationship between simulated and observed storm volumes and peak flows. This linear regression analysis was done for all ditchflow sites, intermittent road ditchflow sites, and ephemeral road ditchflow sites. Intermittent ditchflow at a culvert was defined as ditchflow with a volume greater than precipitation volume occurring on the road. Ephemeral ditchflow at a culvert was defined as having ditchflow volume less than precipitation volume.

Total Road Runoff Volume

DHSVM was evaluated for simulation of total annual runoff from roads in Oak Creek. Six roads were designated in Oak Creek that represented aggregate road segments from the upper, middle, and lower portion of hillslopes (Figure 3.2). For each of the road segments the total volume of runoff was calculated for the 2006 and 2007 water years by summing ditchflow volume from all road culverts of the road segments. This was done for observed and DHSVM simulations. The total simulated and observed runoff from roads was also calculated for all roads in Oak Creek.

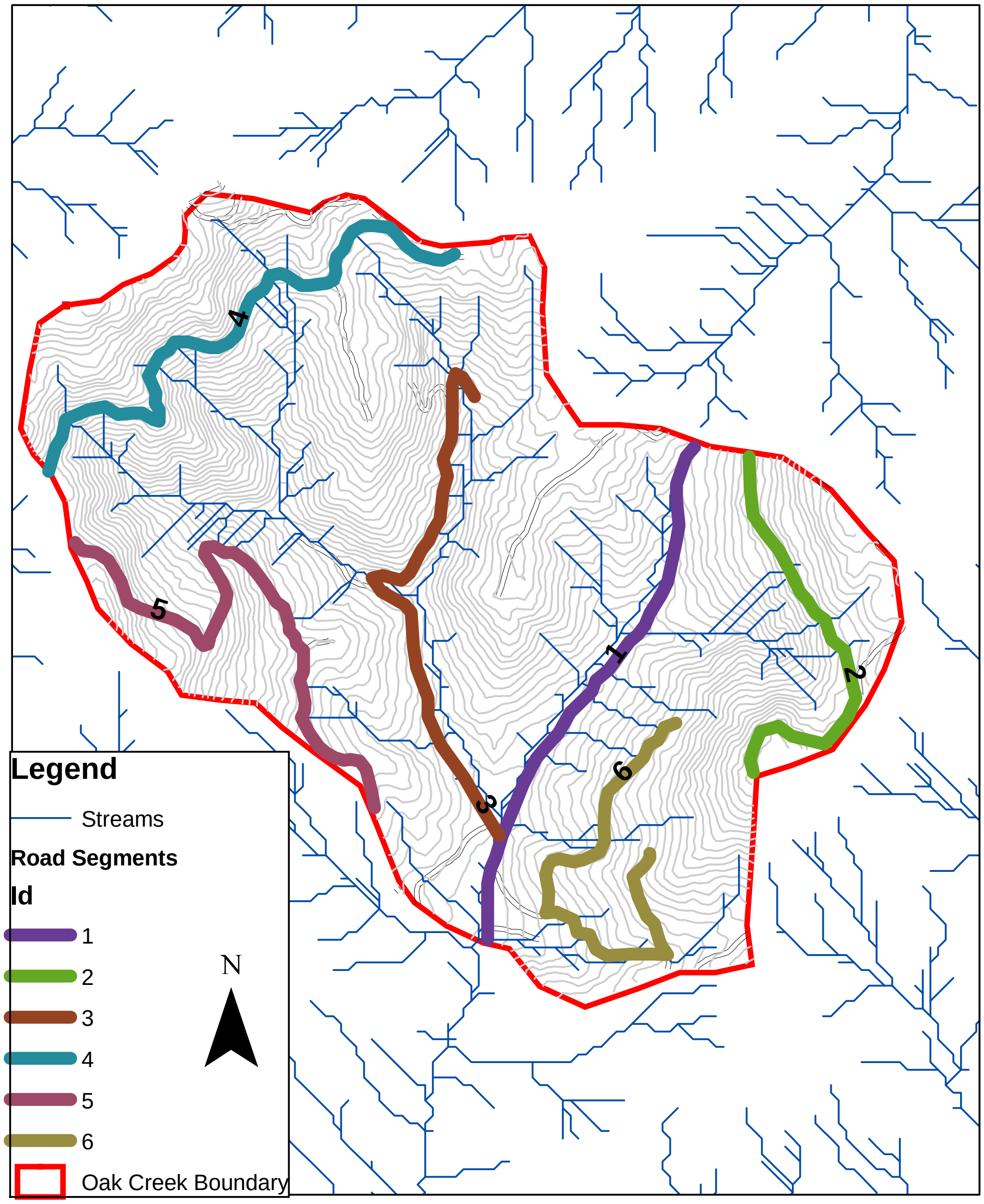
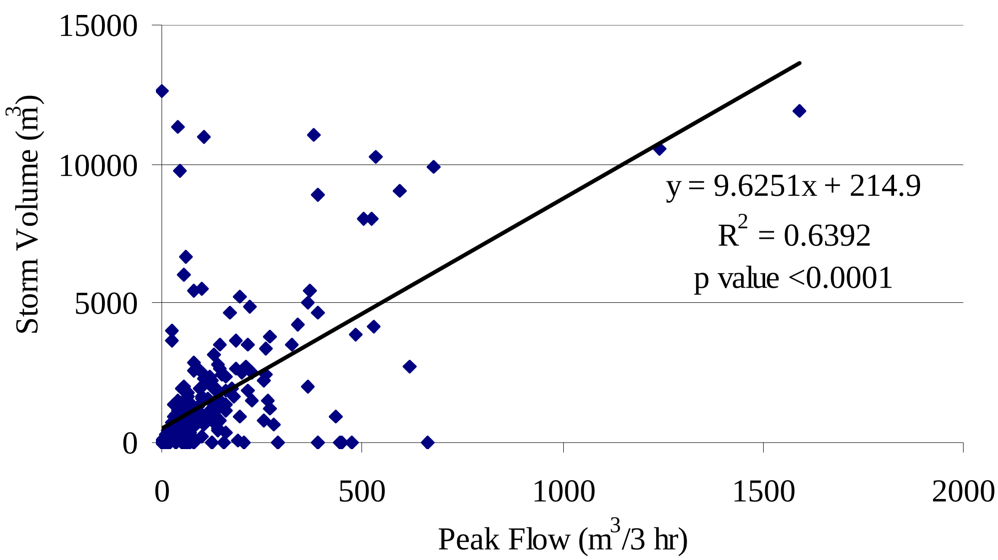


Figure 3. 2. Road Segments for Evaluation of Total Road Runoff Estimated by DHSVM.

For culverts with missing storm data, linear relationships were developed between adjacent culvert locations to estimate missing values. Relationships between peak flows and storm volumes were developed for intermittent and ephemeral classified culverts from all road discharge locations for the 2006 and 2007 water years (Figures 3.3 and 3.4). The peak flow to storm volume relationships were used to estimate storm volumes for crest gage sites. The average amount of ditchflow which occurred outside of storms was calculated to be 10%. The total of storm runoff volume for each culvert was increased by this average amount to provide an estimate of total runoff for each road discharge location.



<u>Figure 3. 3</u>. Observed Storm Peak to Volume Relationship for Ephemeral Road Sites, Oak Creek 2006-2007 Water Years.

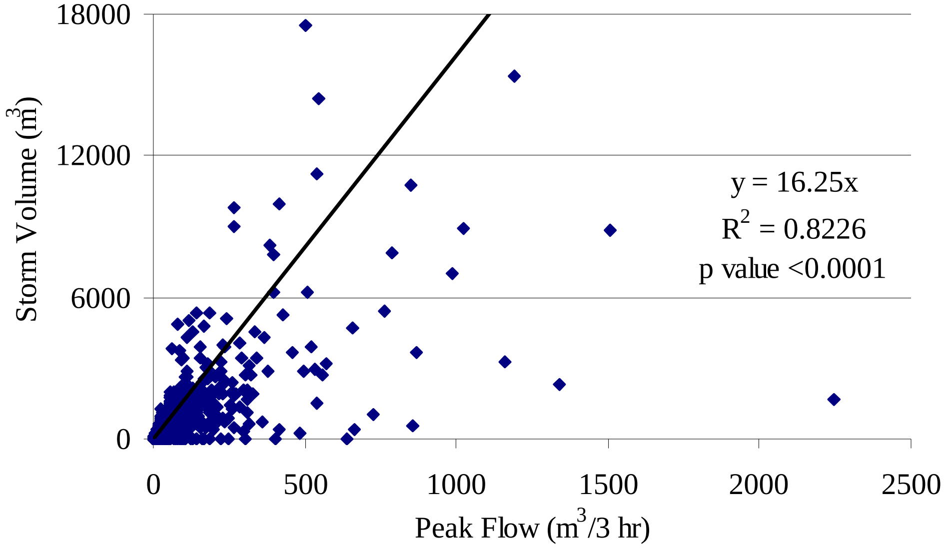


Figure 3. 4. Observed Storm Peak to Volume Relationship for Intermittent Road Sites, Oak Creek 2006-2007 Water Years.

Case Study: DHSVM Estimated Peak Flow and Run-Off Volume Change Due to Roads in Oak Creek

A case study on DHSVM's ability to predict peak flow and storm volume changes from forest roads was done for winter storms of the 2006 water year at Oak Creek. This analysis used road and stream flow data from Claire Creek and the outlet of Oak Creek. The analysis was done for the winter storms from November, 2005 through February, 2006; the most extreme and variable storms of the Oak Creek data set. Peak flow change was calculated from two stream crossings within Claire Creek (culverts 34 and 35) by dividing the ditchflow by the streamflow at the culvert (the streamflow is the total culvert flow minus the ditchflow). Culverts 34 and 35 were good road stream crossings for this case study because of their adjacency with one another and their similarities. They have similar upslope contributing areas, road segment drainage lengths, and cutslope dimensions, but different observed hydrologic responses; culvert 34 had higher discharge than at culvert 35.

RESULTS

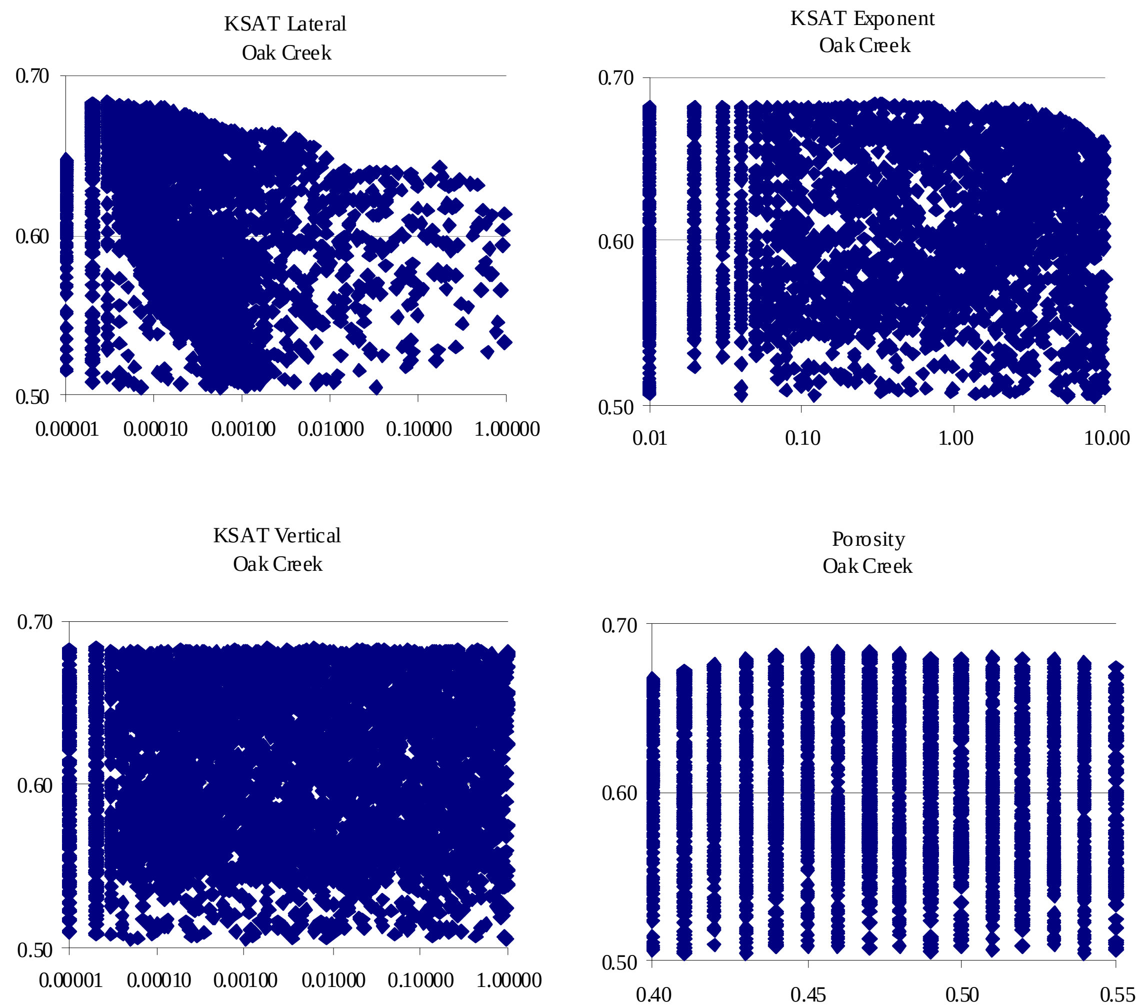
GLUE Assessment of DHSVM Parameters

For the parameter ranges evaluated with the GLUE procedure the proportion of behavioral model structures (simulations exceeding a specified NSE threshold) for DHSVM varied by location modeled (Table 3.2). For Oak Creek (630 ha) 44% of the 10,000 attempted model structures exceeded a 0.5 NSE threshold while 100% exceeded a 0.3 NSE. For Claire Creek (55 ha) 12% of attempted model structures exceeded a 0.5 NSE threshold while 45% exceeded a 0.3 NSE. Only six of the 11 road ditchflow sites had DHSVM simulations that exceeded the NSE criteria of 0.3. The six road ditchflow sites (<10 ha) had proportions of behavioral structures ranging from 0 to 12% exceeding a 0.5 NSE and 0 to 90% exceeding a 0.3 NSE. The remaining 5 road ditchflow locations did not have behavioral model structures demonstrating lack of fit for all DHSVM simulations.

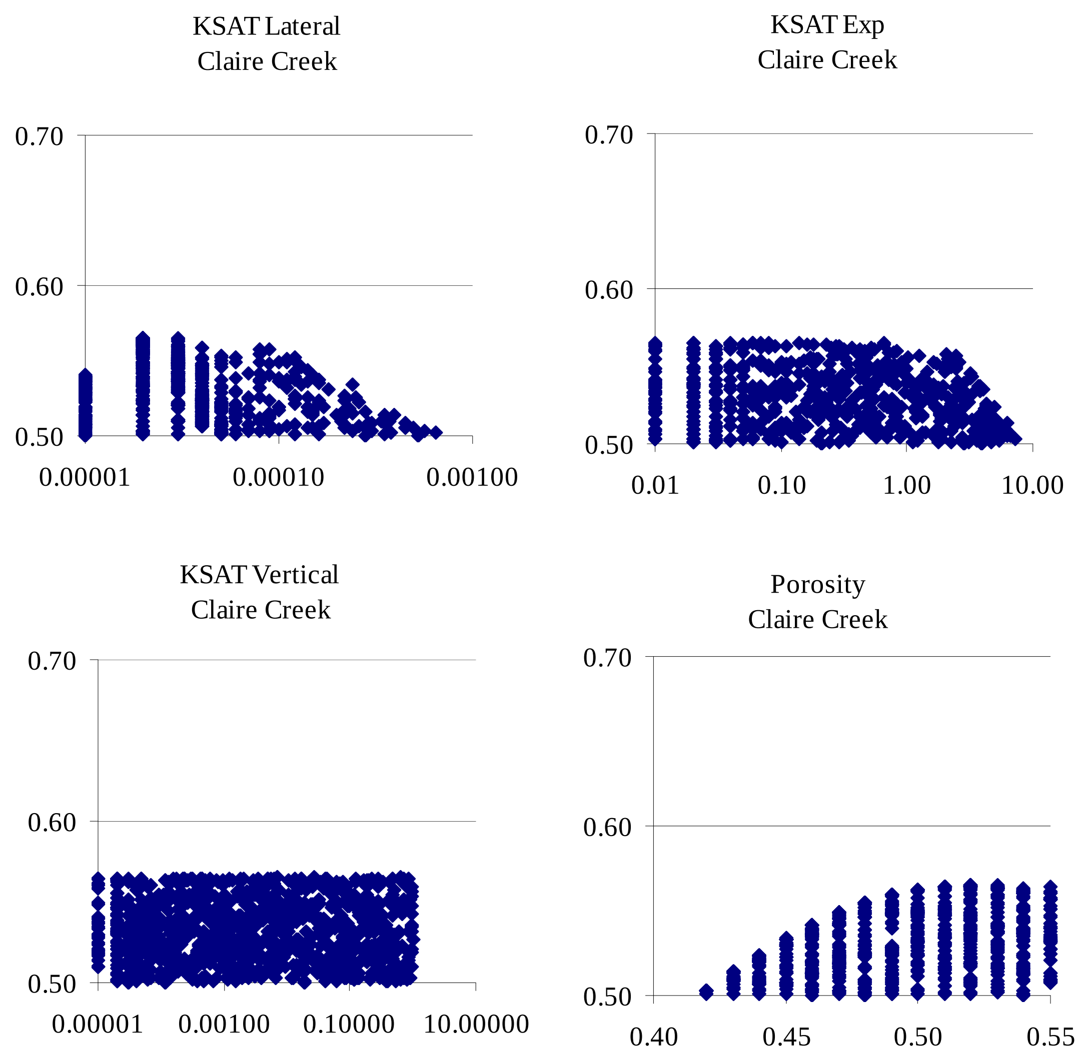
Table 3. 2. Percentage of DHSVM Simulations Producing Behavioral Model Structures.

Location	NSE > 0.5	NSE >0.3	Type
Oak Creek	44%	100%	Streamflow
Claire Creek	12%	45%	Streamflow
Culvert 27	1%	63%	Intermittent ditchflow
Culvert 30	2%	42%	Intermittent ditchflow
Culvert 54	12%	90%	Intermittent ditchflow
Culvert 79	0%	0%	Ephemeral ditchflow
Culvert 88	6%	19%	Intermittent ditchflow
Culvert 35	0%	0%	Intermittent ditchflow
Culvert 47	0%	0%	Intermittent ditchflow
Culvert 49	1%	54%	Intermittent ditchflow
Culvert 76	1%	9%	Intermittent ditchflow
Culvert 53	0%	0%	Intermittent ditchflow
Culvert 56	0%	0%	Ephemeral ditchflow

The dotty plots for the parameters of lateral hydraulic conductivity, exponent of decay of hydraulic conductivity by depth, vertical hydraulic conductivity, and porosity evaluated by the GLUE procedure for DHSVM are shown (Figures 3.5-3.12). The dotty plots did not indicate a well defined structure of the parameters across all sites modeled. Some trends of higher NSE values were observed for specific ranges of lateral hydraulic conductivity and porosity, and one site showed a trend for exponent of decay of hydraulic conductivity by depth; however the parameter ranges differed by site. For parameter values that were associated with behavioral model structures (higher NSE) there are many model structures that use the same parameter value but get poor fit (lower NSE). This indicates parameter values are highly influenced by their interaction with other parameter values.



<u>Figure 3. 5</u>. Oak Creek Dotty Plots for DHSVM Simulations with a NSE >0.5.



<u>Figure 3. 6</u>. Claire Creek Dotty Plots for DHSVM Simulations with a NSE >0.5.

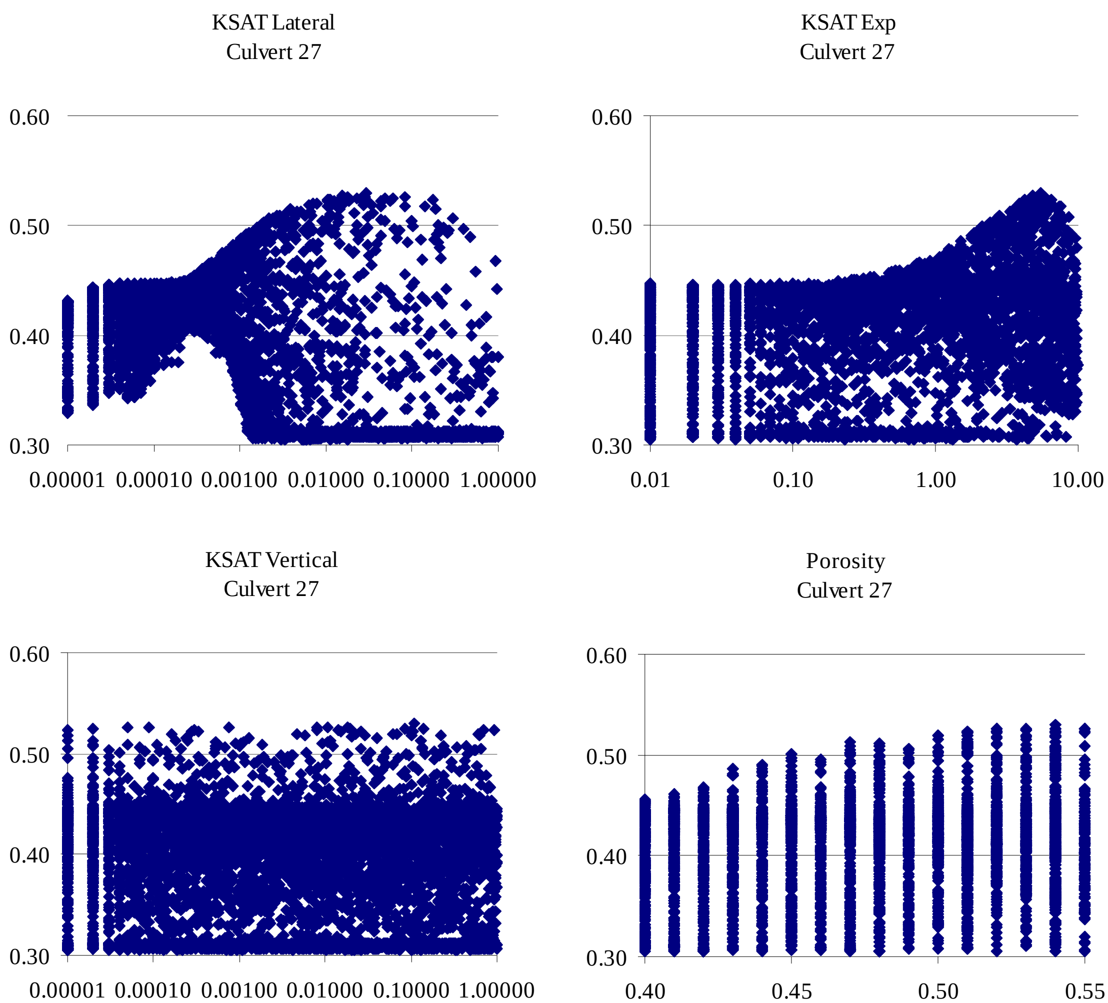
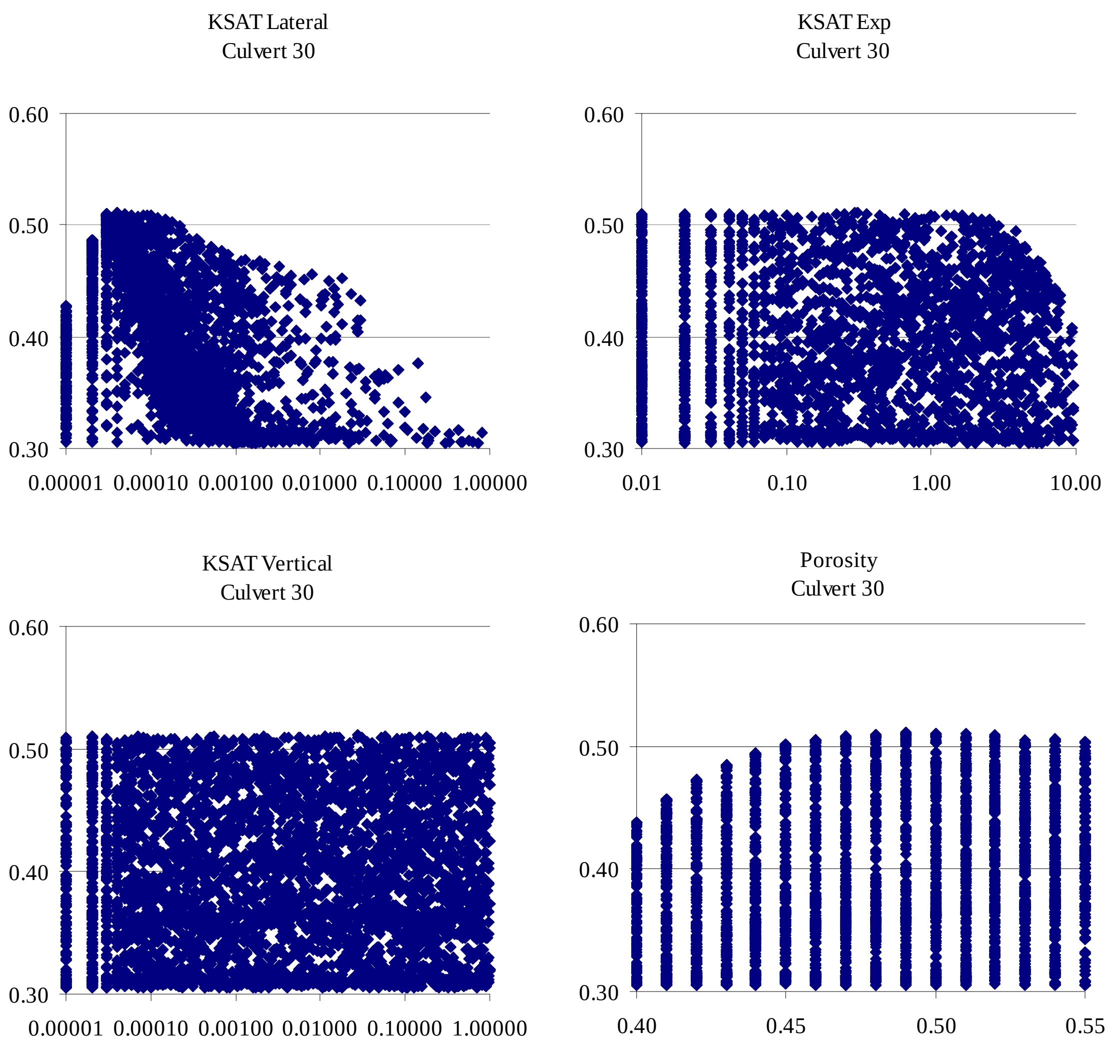
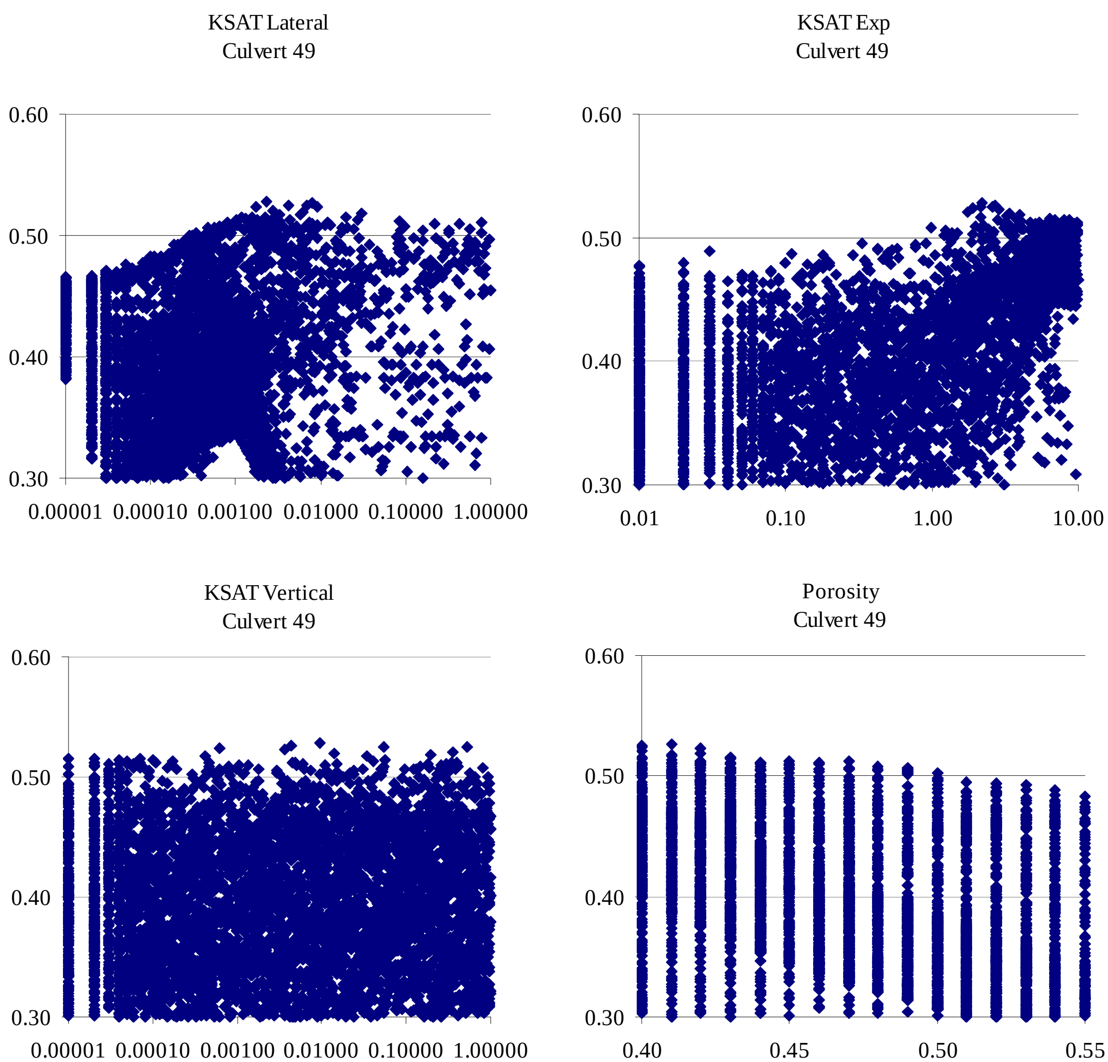


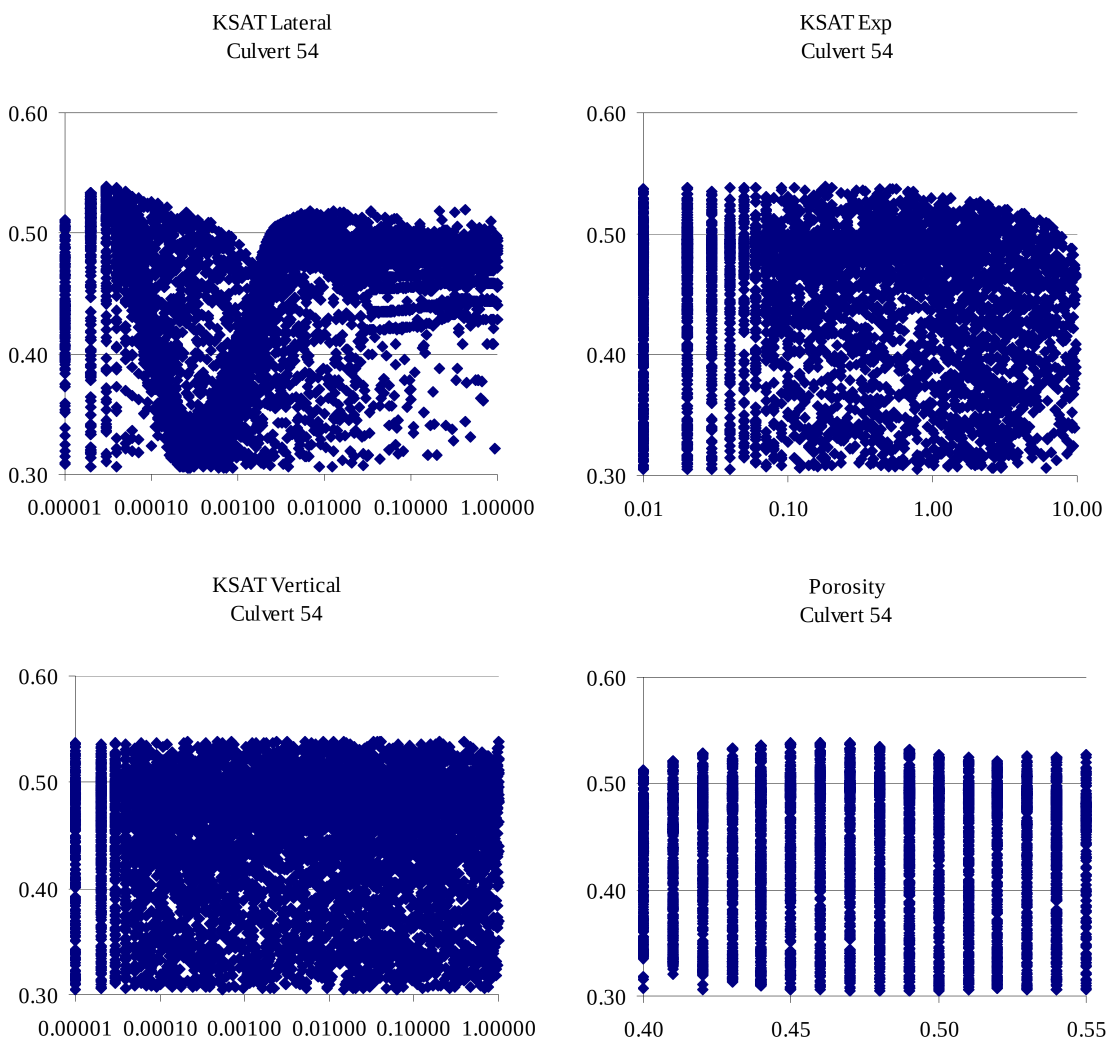
Figure 3. 7. Culvert 27 Dotty Plots for DHSVM Simulations with a NSE >0.3.



<u>Figure 3. 8</u>. Culvert 30 Dotty Plots for DHSVM Simulations with a NSE >0.3.



<u>Figure 3. 9</u>. Culvert 49 Dotty Plots for DHSVM Simulations with a NSE >0.3



<u>Figure 3. 10</u>. Culvert 54 Dotty Plots for DHSVM Simulations with a NSE >0.3.

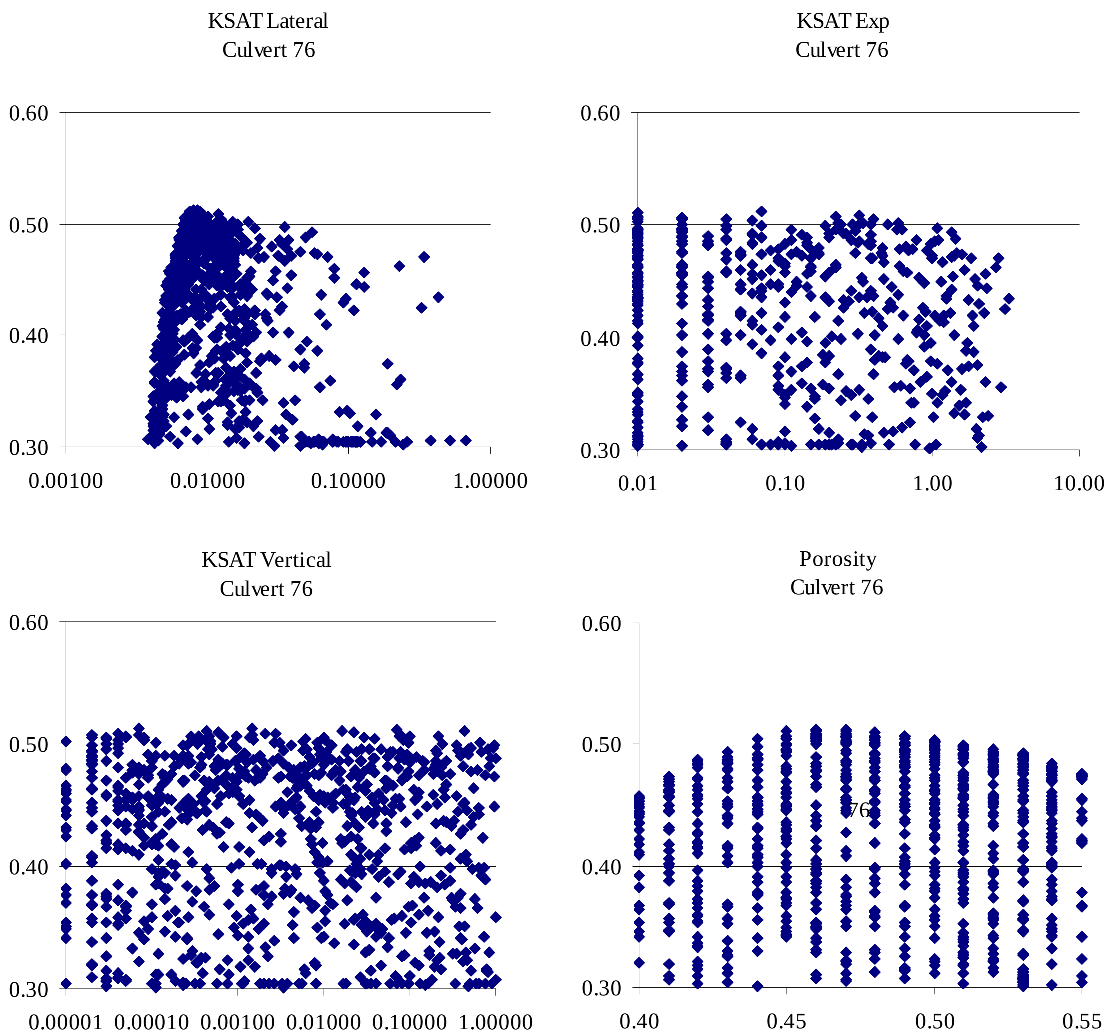


Figure 3. 11. Culvert 76 Dotty Plots for DHSVM Simulations with a NSE >0.

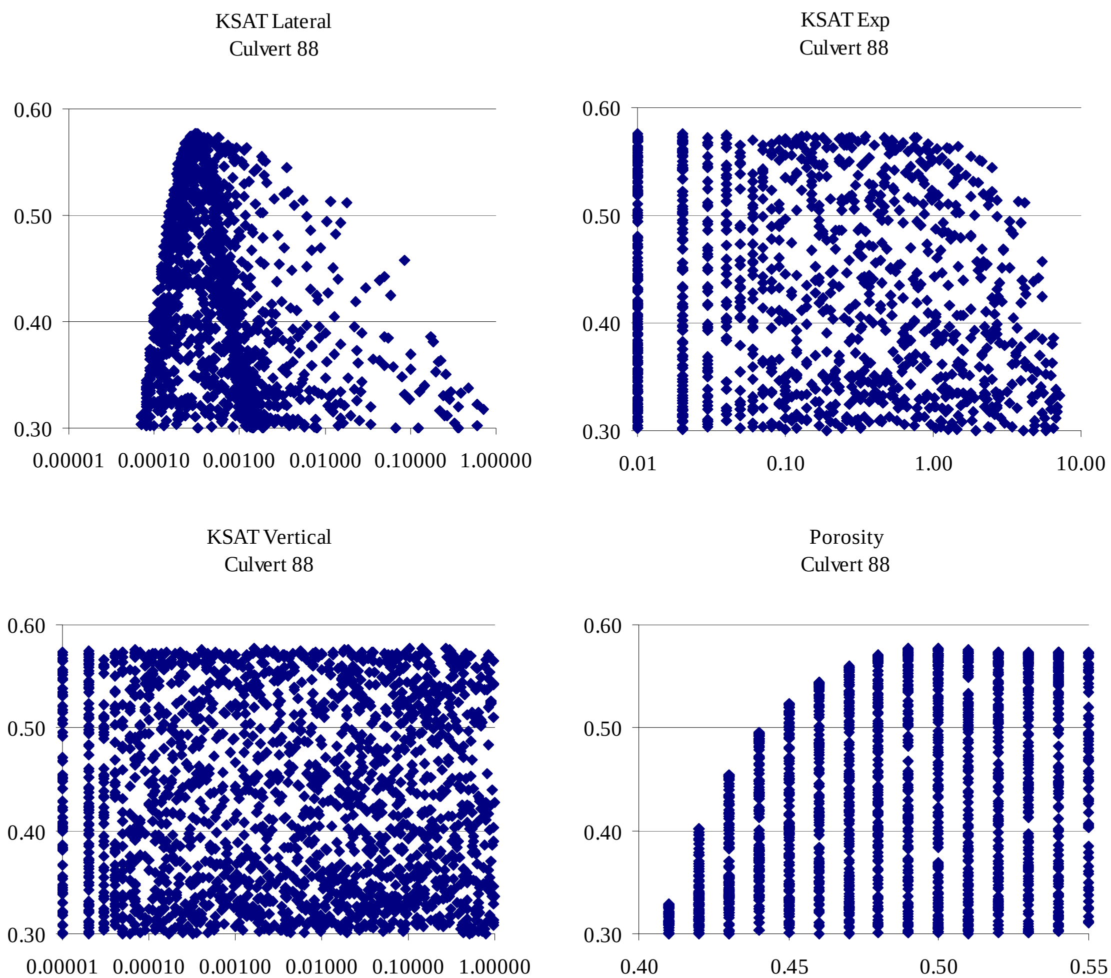


Figure 3.12. Culvert 88 Dotty Plots for DHSVM Simulations with a NSE >0.3

Sensitivity of Individual Parameters

Cumulative distribution functions (CDF) for lateral hydraulic conductivity, exponent of decay of hydraulic conductivity by depth, vertical hydraulic conductivity, and porosity were plotted by their resulting likelihood for each streamflow and ditchflow site simulated by DHSVM in Oak Creek (Figures 3.13- 3.20). This provides a measure of the sensitivity of each parameter within DHSVM. Dissimilarities in the CDF for varying likelihoods indicate the model was sensitive to that parameter, while similar CDF of the varying likelihoods indicated that the model was insensitive to that parameter.

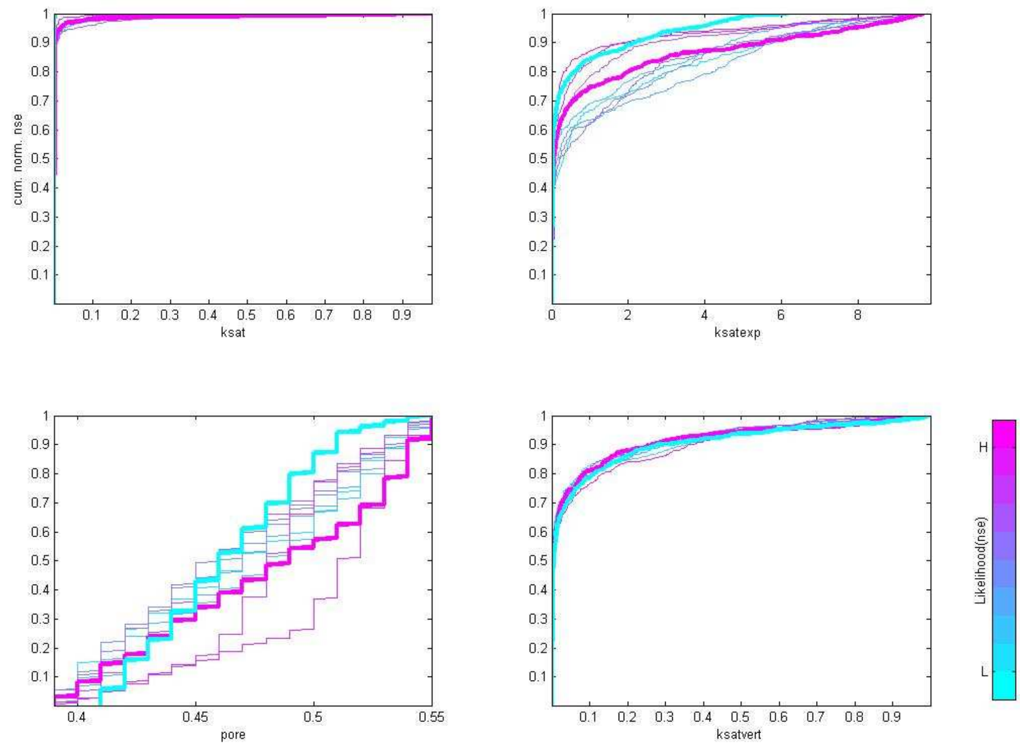
From the CDF plots, porosity and the exponent of decay of hydraulic conductivity by depth were interpreted to be sensitive parameters for all sites simulated by DHSVM in Oak Creek. The exponent of decay did not have as great a spread of the CDFs as porosity, but demonstrated changes in likelihood as values of the parameter changed. The vertical hydraulic conductivity parameter was insensitive for all sites. The sensitivity of lateral hydraulic conductivity varied by site simulated. The lateral hydraulic conductivity parameter was not a sensitive parameter for the streamflow sites and only exhibited sensitivity for three of the six sites with road ditchflow assessed with GLUE.

From the CDFs some indications of the range of parameter values that might be used for future simulations of the sites in Oak Creek were observed. One interpretation of the CDF was the location with the steepest slope on the high likelihood CDF curve. The length of the curve with the steepest slope indicates a range of the individual parameter values with the greatest sensitivity for DHSVM simulations. This can be further confirmed by comparing the parameter ranges identified with the corresponding dotty plot. It would be expected that high likelihood values would be present in the dotty plot for the range of parameter values identified from the CDF.

For the sites in Oak Creek the range of the parameter values with steep sections of the CDF varied by site. The lateral hydraulic conductivity, vertical hydraulic conductivity, and exponent of decay of hydraulic conductivity by depth had CDF curves with very steep slopes at the low end of the range of parameter values. The dotty plots generally confirm this interpretation for the hydraulic conductivity parameter; all but a couple of sites have the highest NSE at values of hydraulic conductivity less than 0.001 m/s.

However, the exponent of hydraulic conductivity by depth did not show higher NSE values for low values of parameters. In fact 2 of the sites had the highest NSE values for parameter values in the higher range of values analyzed. All model parameters have an influence through interaction with other parameters. This suggests that although the highest NSE values will not always be found using the low parameter values for exponent of decay of hydraulic conductivity the better overall models will be found.

The identification of distinct ranges of parameter values for porosity were less conclusive. The shape and slope of CDF curves for porosity varied by site; most sites had little differences in slope for the porosity CDF curves. Culvert 27 showed a very steep increase in the CDF curve slope at values of porosity of between 0.40 and 0.43. Claire Creek and Culvert 49 showed greater model sensitivity at porosities of 0.50 to 0.55. While the remaining sites did not show particularly strong sensitivity for specific ranges of porosity. Dotty plots for the sites in Oak Creek showed ranges of porosity values with slight trends of increased NSE, but these ranges were also not consistent among sites.



<u>Figure 3. 13</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Oak Creek outlet.

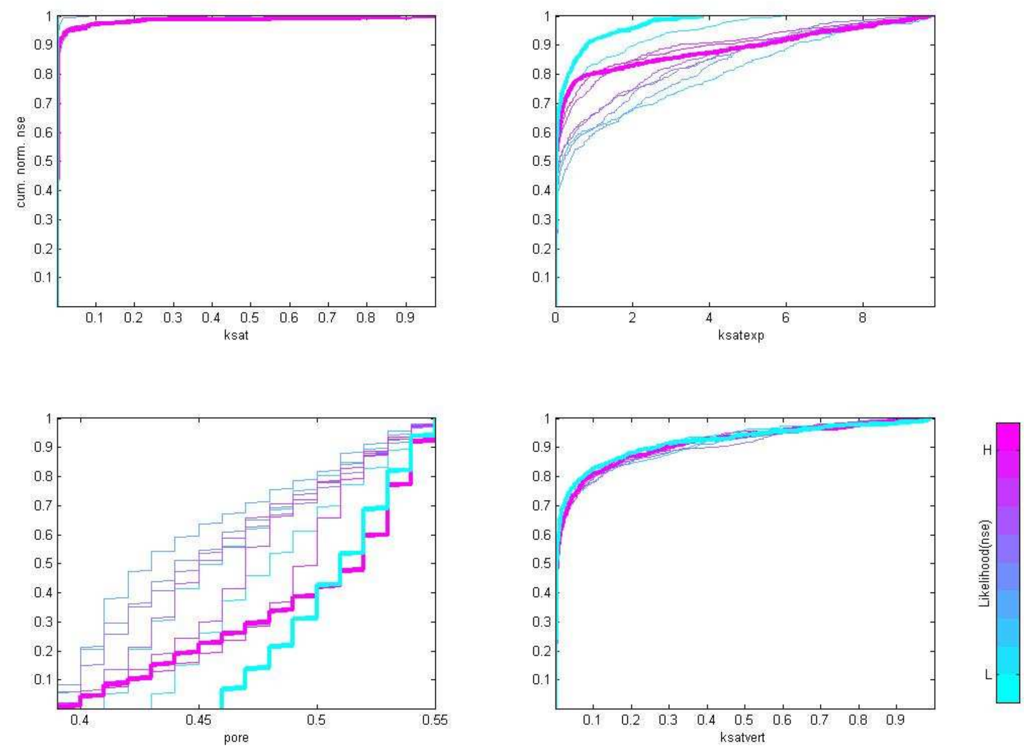
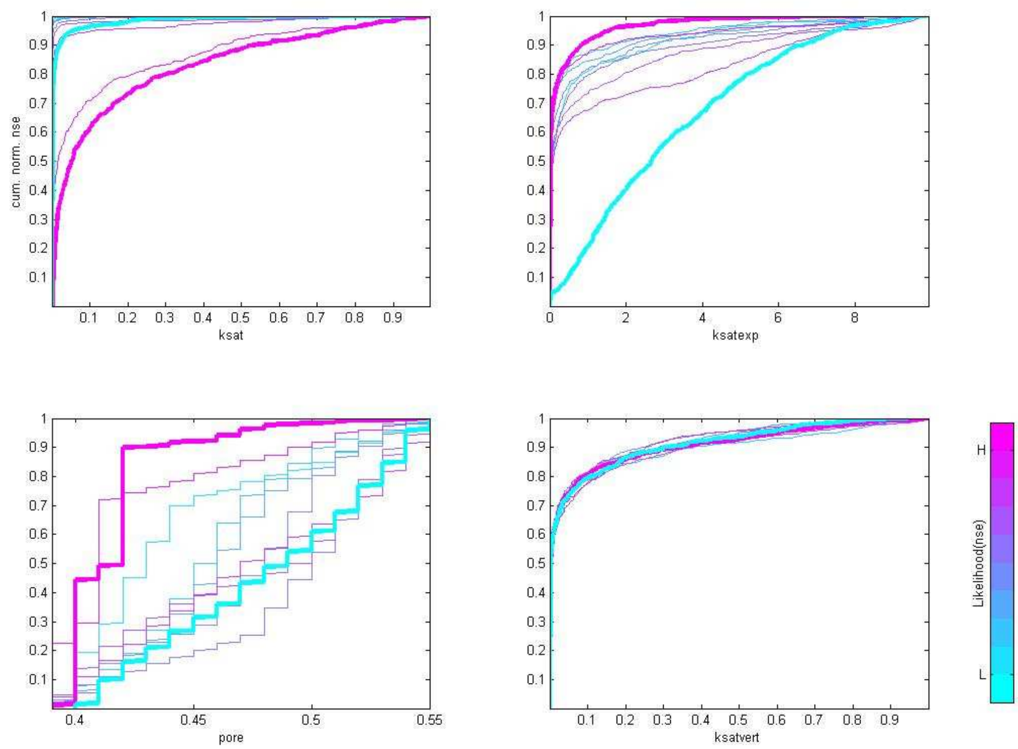
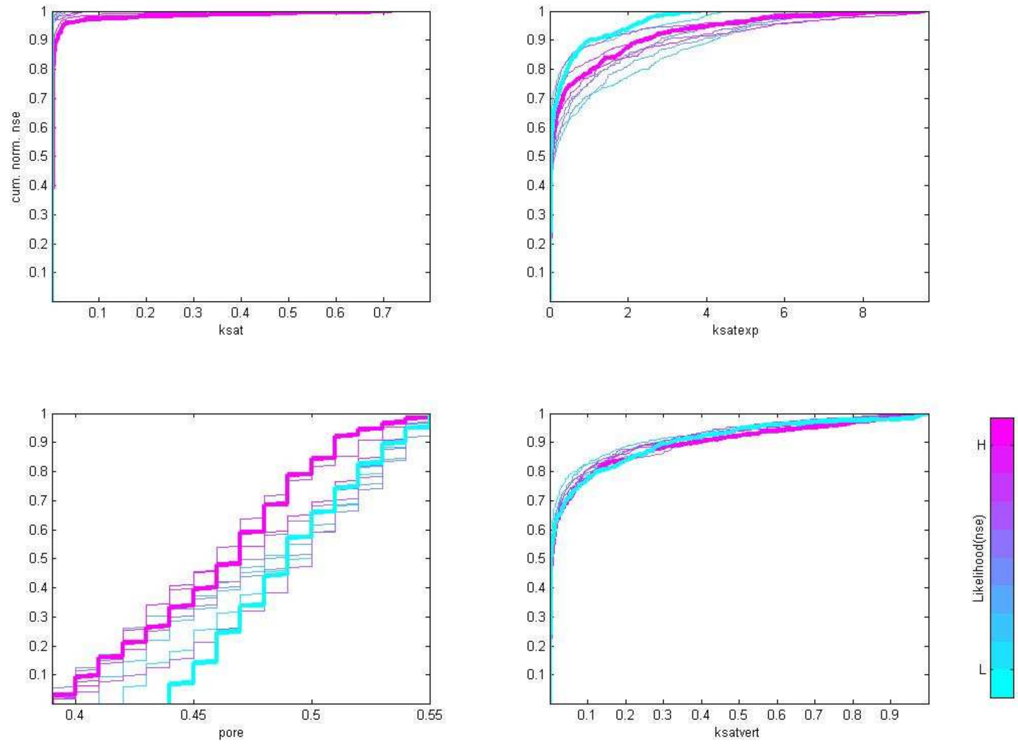


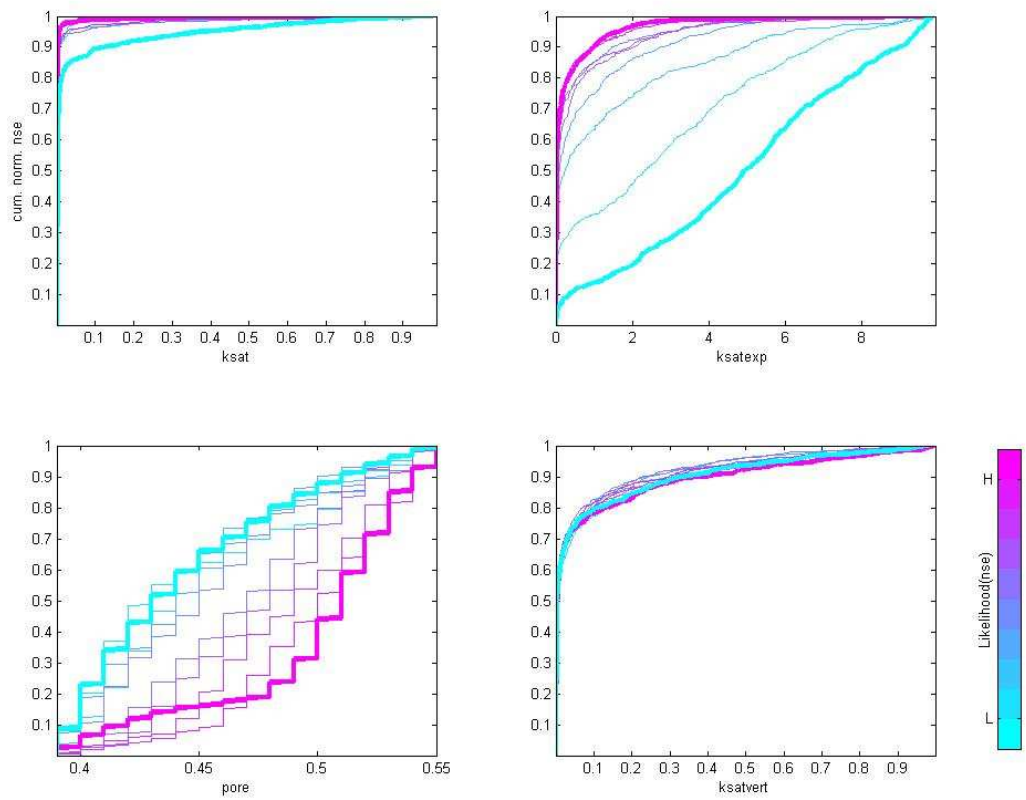
Figure 3. 14. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Claire Creek.



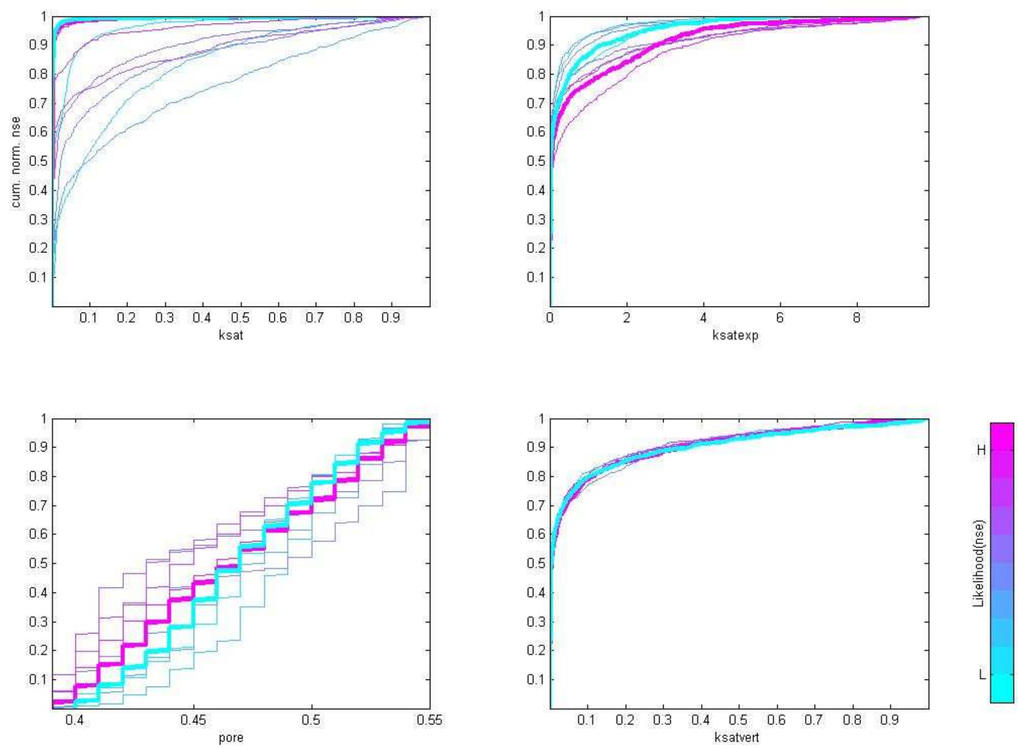
<u>Figure 3. 15</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 27.



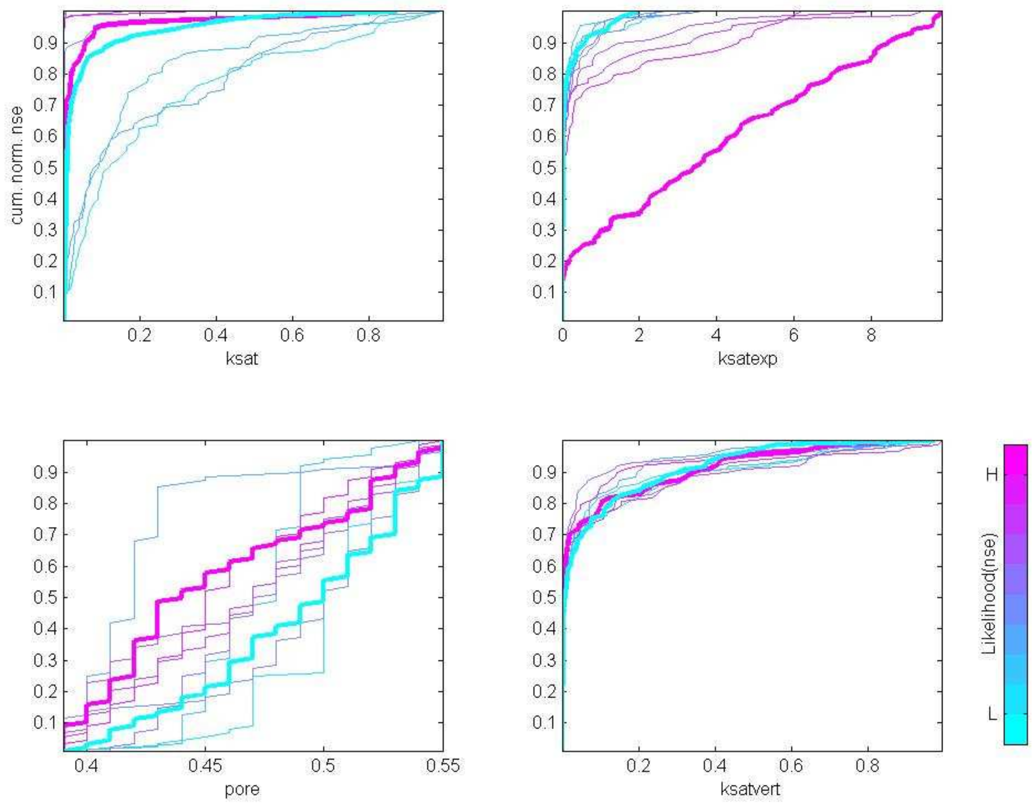
<u>Figure 3. 16</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 30.



<u>Figure 3. 17</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 49.



<u>Figure 3. 18</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 54.



<u>Figure 3.19</u>. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 76.

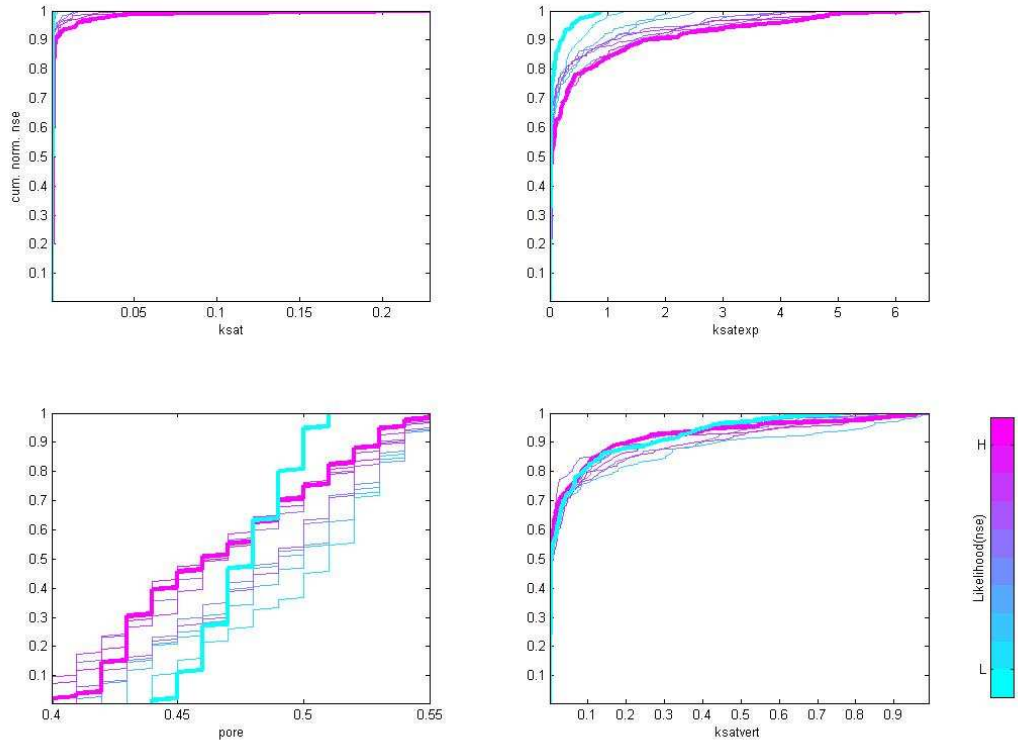
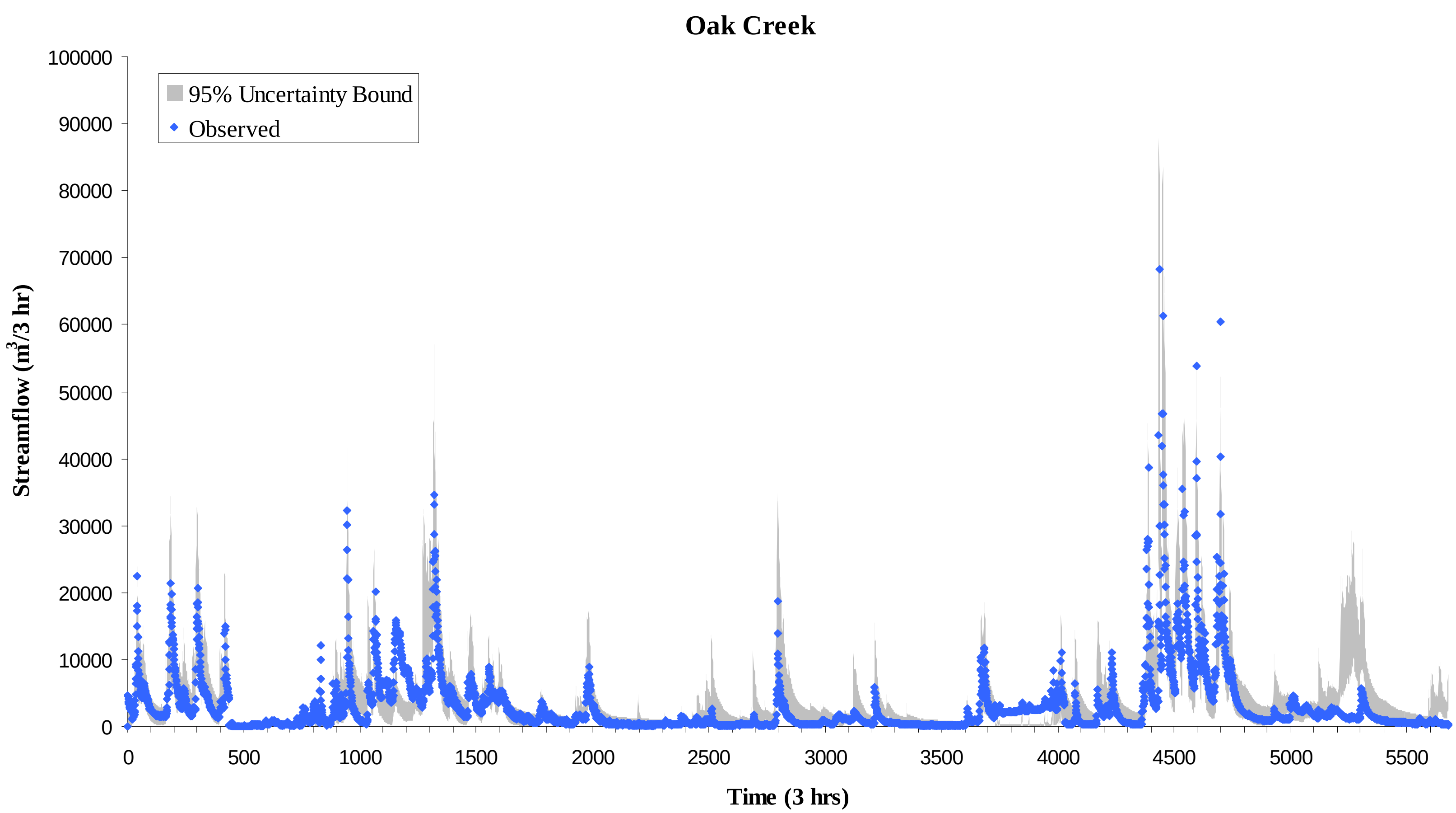


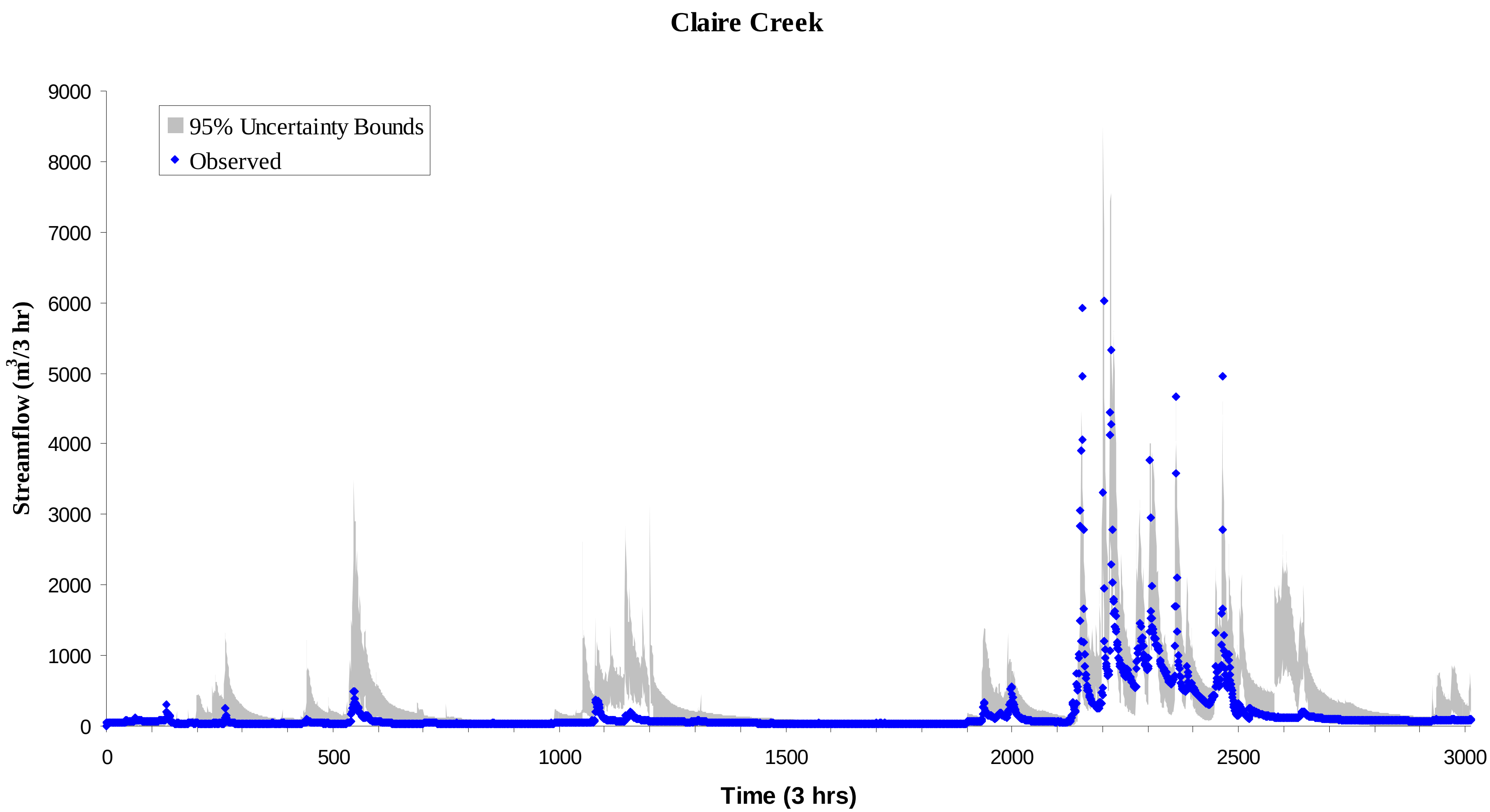
Figure 3. 20. Cumulative Density Function of 4 Individual Parameters by NSE for DHSVM Simulations at Culvert 88.

Uncertainty Bounds for DHSVM Simulations

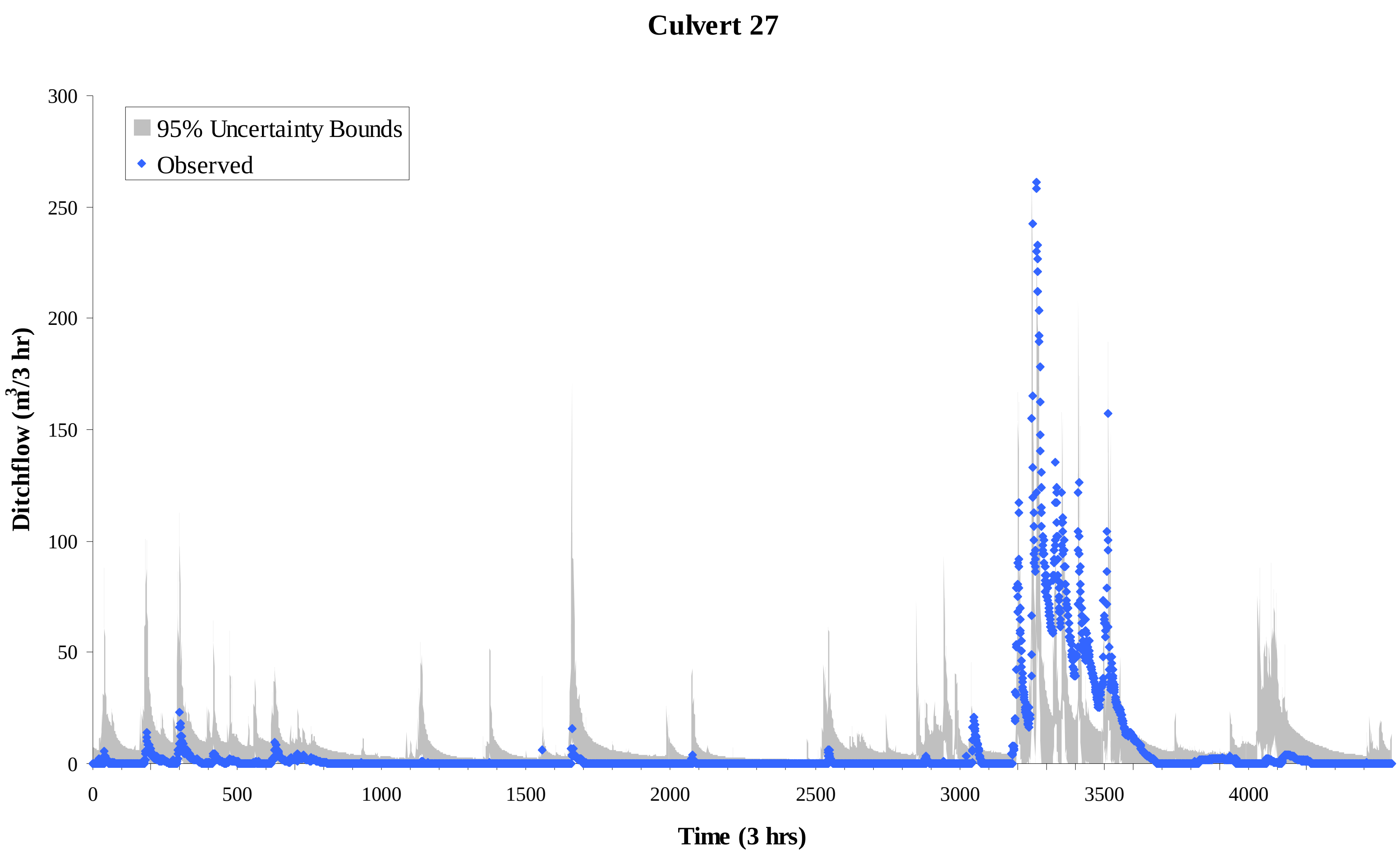
Uncertainty bounds for DHSVM simulations in Oak Creek were created for the GLUE assessment. The uncertainty bounds provide the 95% prediction interval of behavioral model structures. These uncertainty bounds represent the range of output for varying DHSVM model structures that meet an acceptable time series fit to observed data. The 95% uncertainty bounds for two streamflow and six road ditchflow sites in Oak Creek are shown (Figures 3.21 - 3.28). For the 5 road ditchflow sites that did not have behavioral model structures, one DHSVM simulation calibrated to Oak Creek streamflow and ditchflow was used to show the contrast in simulated and observed ditchflow (Figures 3.29 - 3.33).



<u>Figure 3. 21</u>. 95% Uncertainty Bounds for DHSVM Simulations of Oak Creek, 2003-2006. (data gaps and periods of no streamflow excluded)



<u>Figure 3. 22</u>. 95% Uncertainty Bounds for DHSVM Simulations of Claire Creek, 2003-2006. (data gaps and periods of no streamflow excluded)



<u>Figure 3.23</u>. 95% Uncertainty Bounds for DHSVM Simulations of Culvert 27, 2003-2006. (data gaps and periods of no ditchflow excluded)

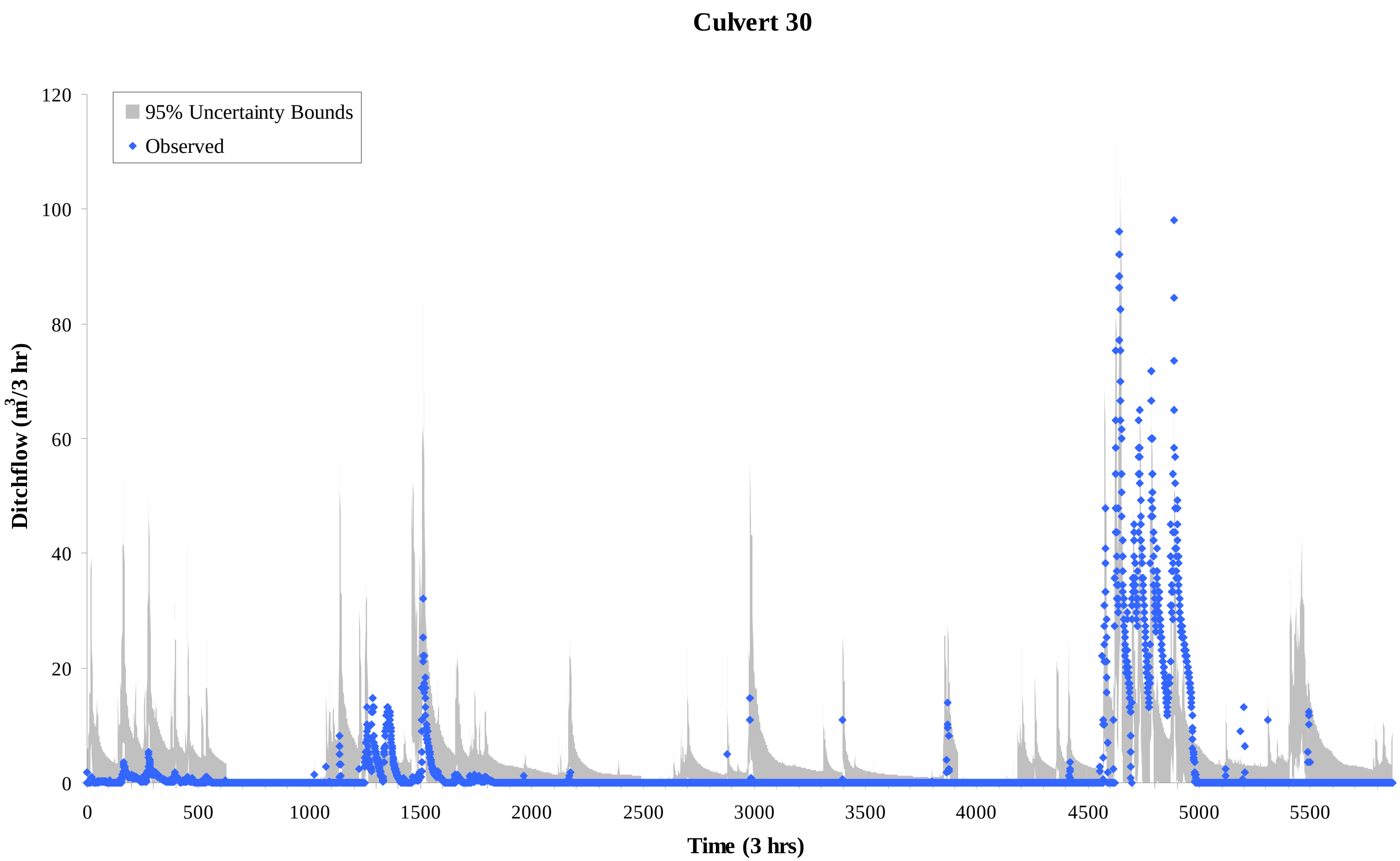


Figure 3. 24. 95% Uncertainty bounds for DHSVM Simulations of Culvert 30, 2003-2006. (data gaps and periods of no ditchflow excluded)

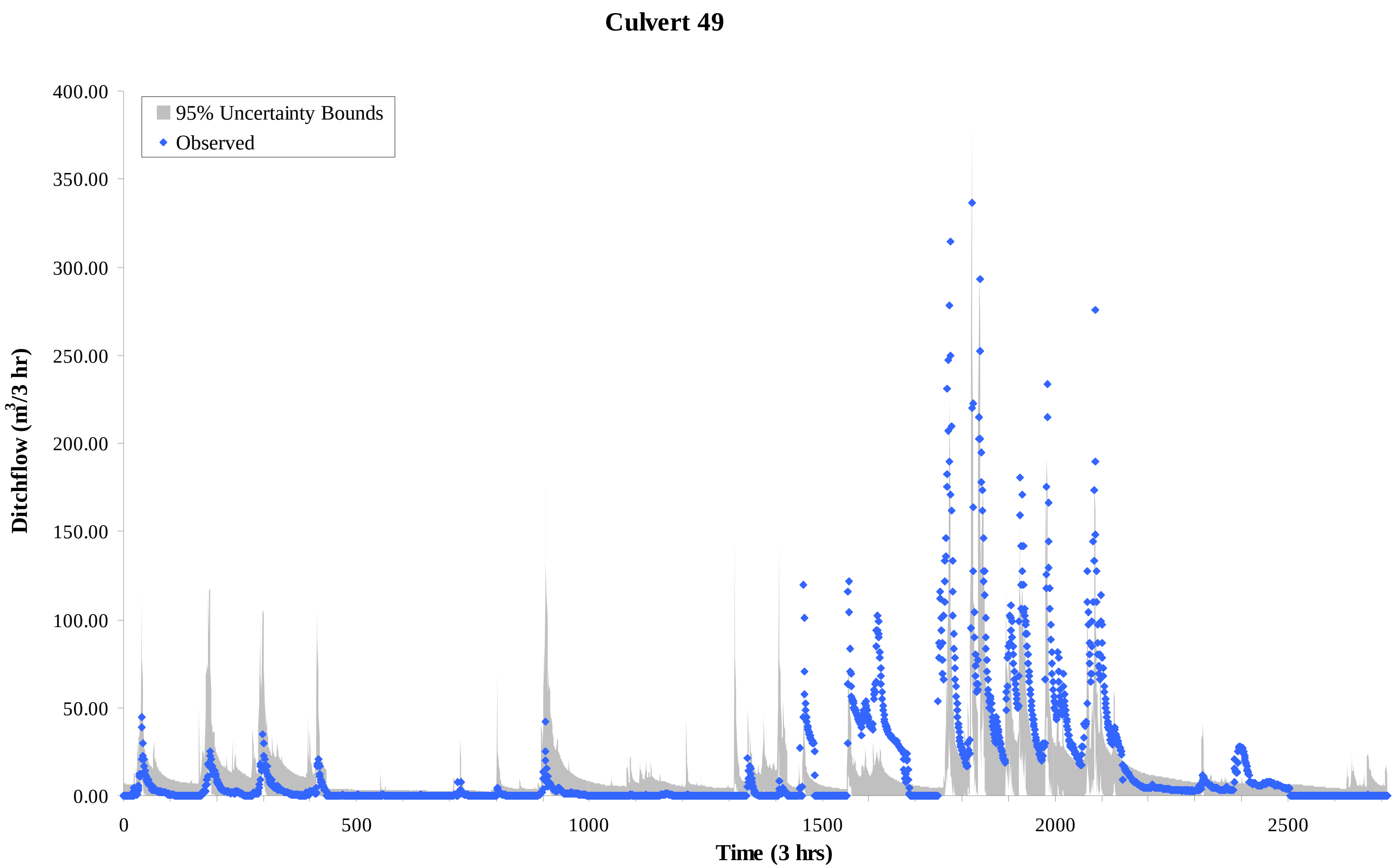
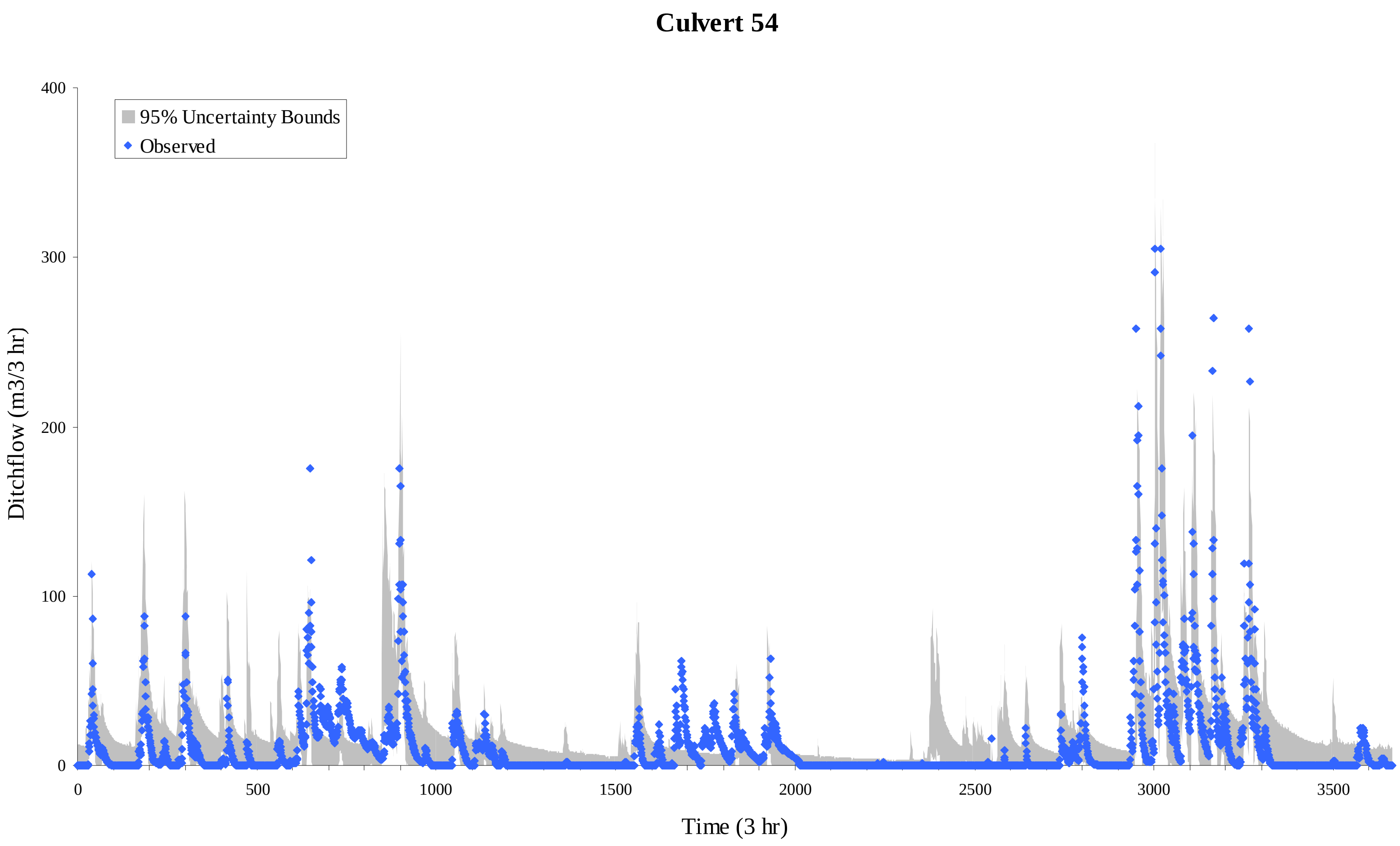
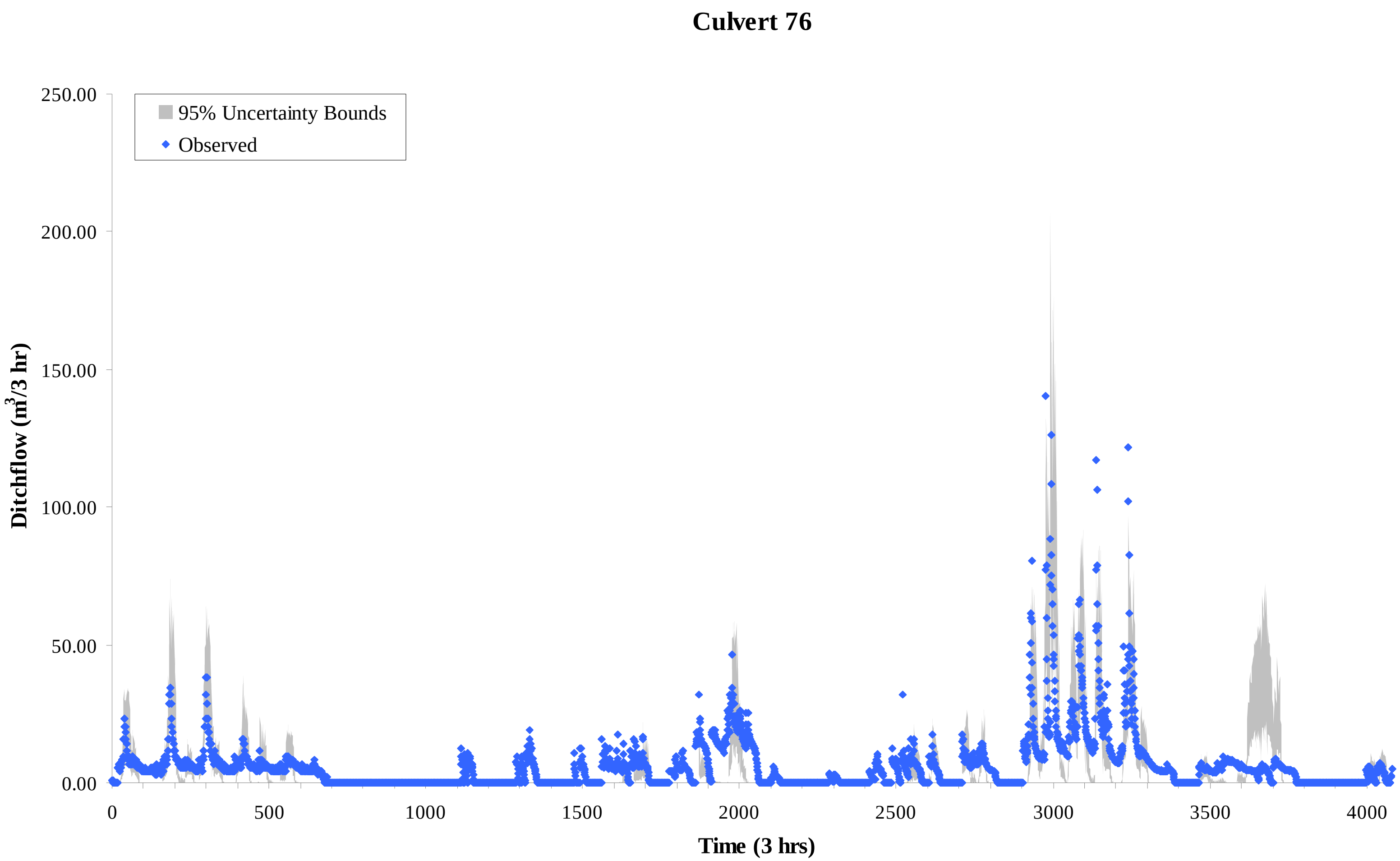


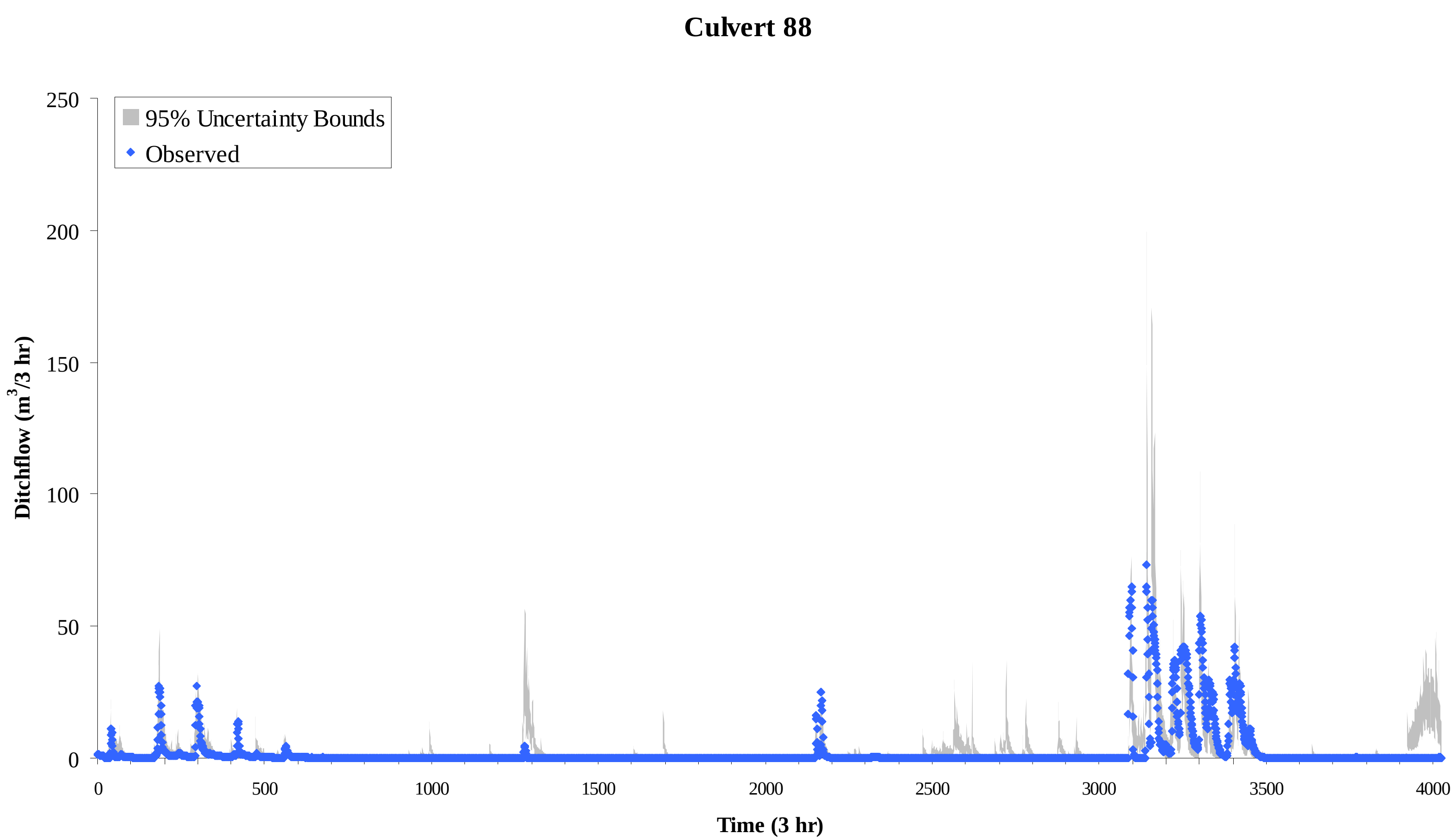
Figure 3. 25. 95% Uncertainty Bounds for DHSVM Simulations of Culvert 49, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3.26</u>. 95% Uncertainty Bounds for DHSVM Simulations of Culvert 54, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3.27</u>. 95% Uncertainty Bounds for DHSVM Simulations of Culvert 76, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3. 28</u>. 95% Uncertainty Bounds for DHSVM Simulations of Culvert 88, 2003-2006. (data gaps and periods of no ditchflow excluded)

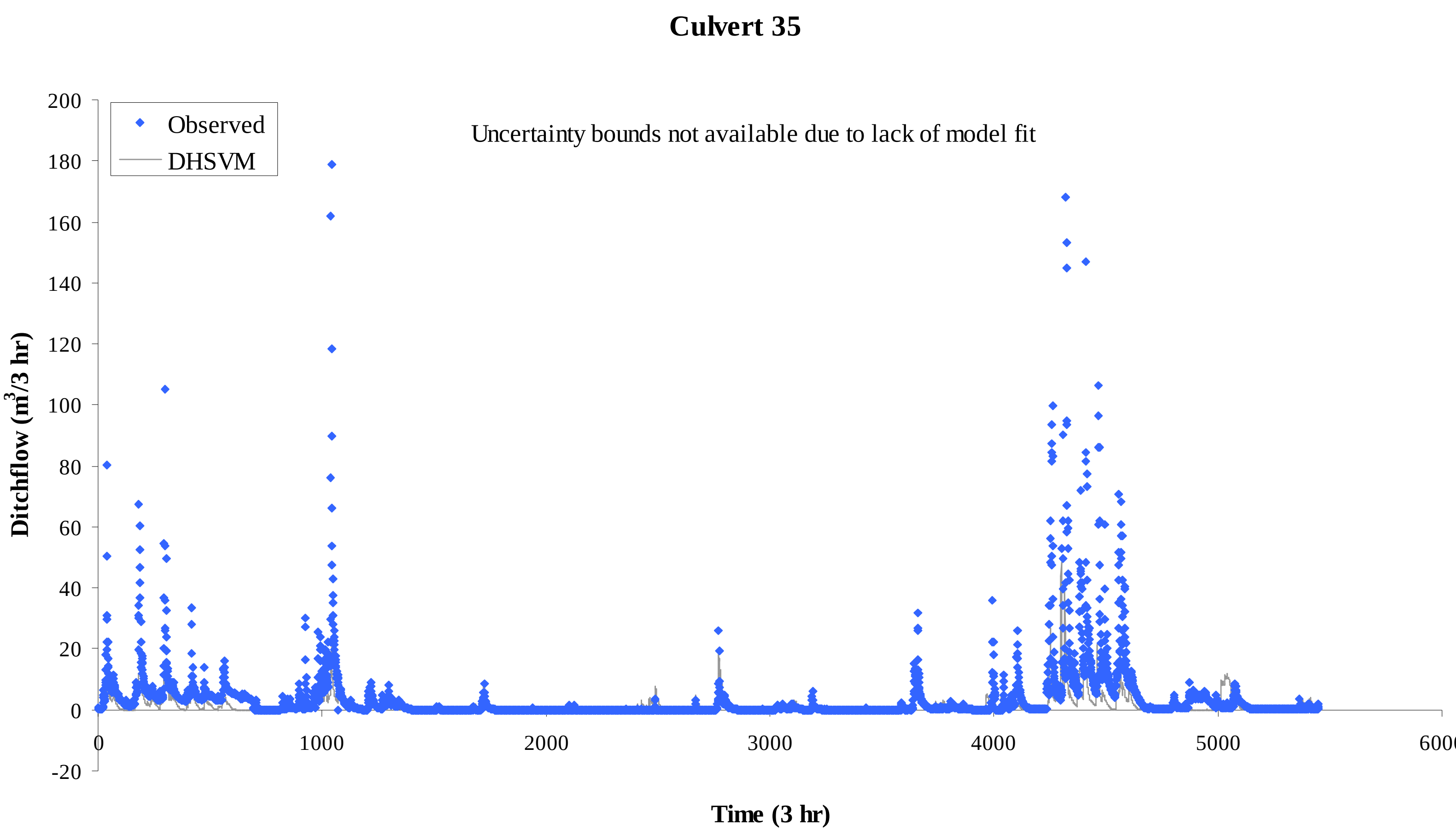
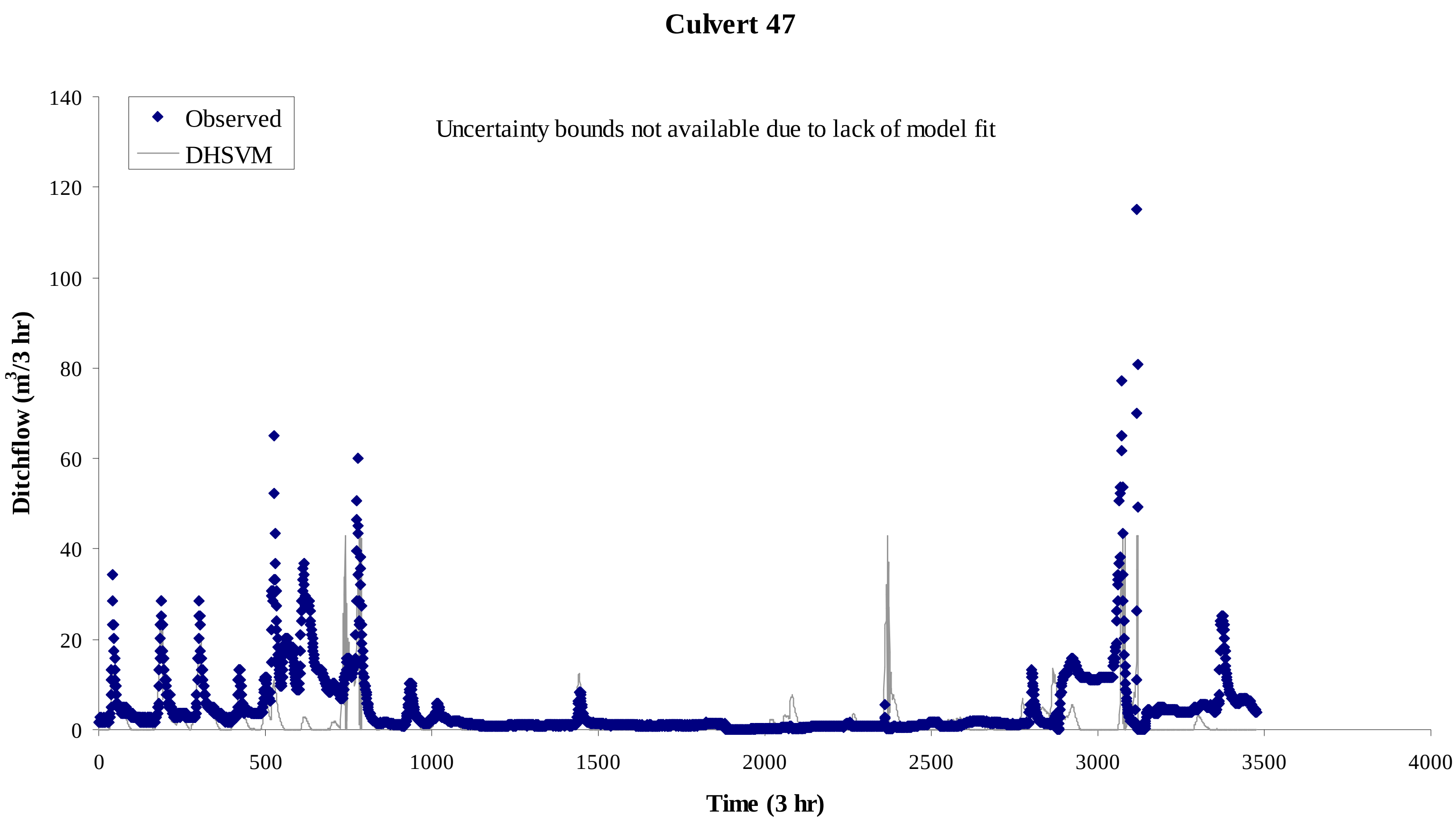
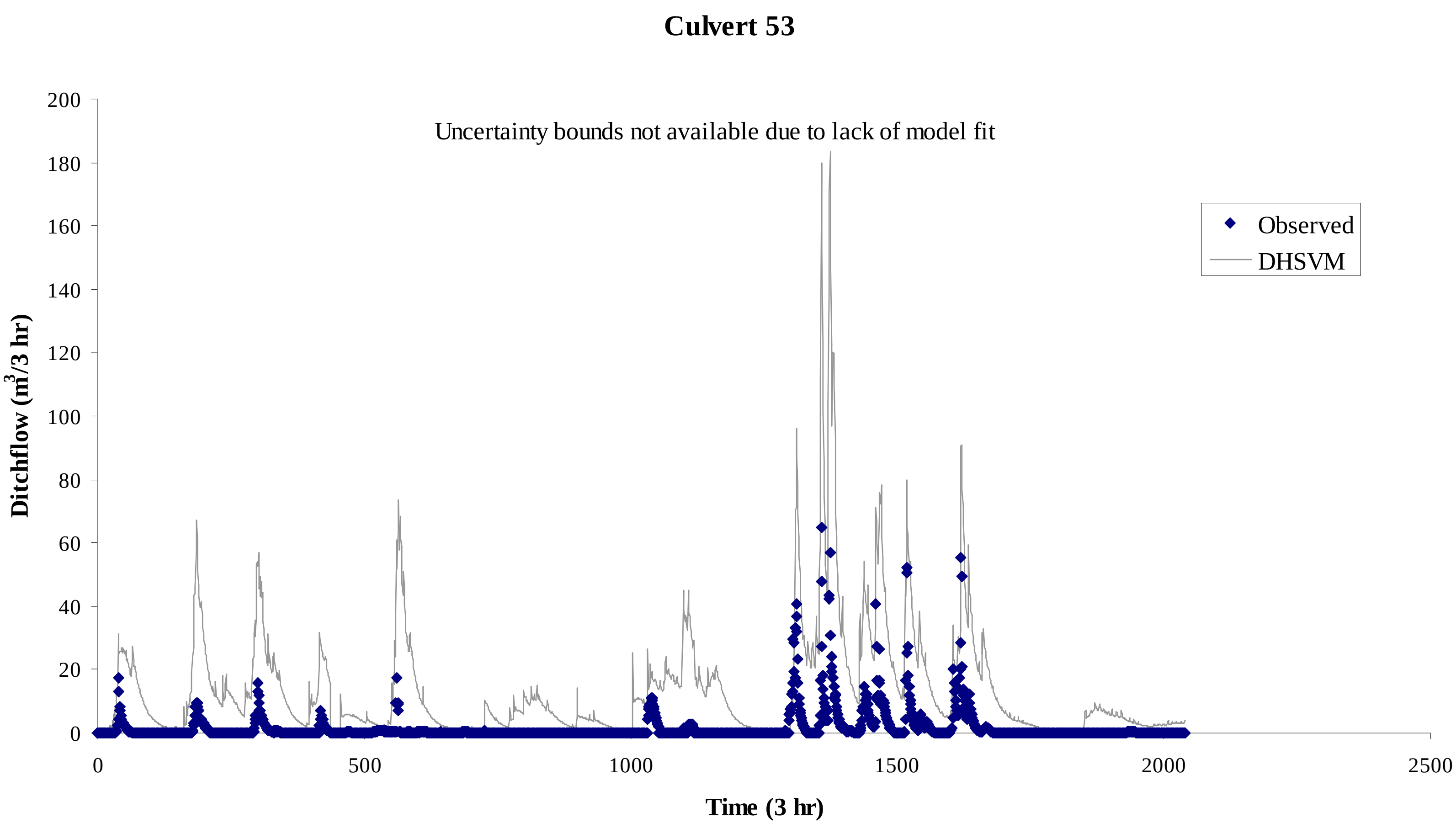


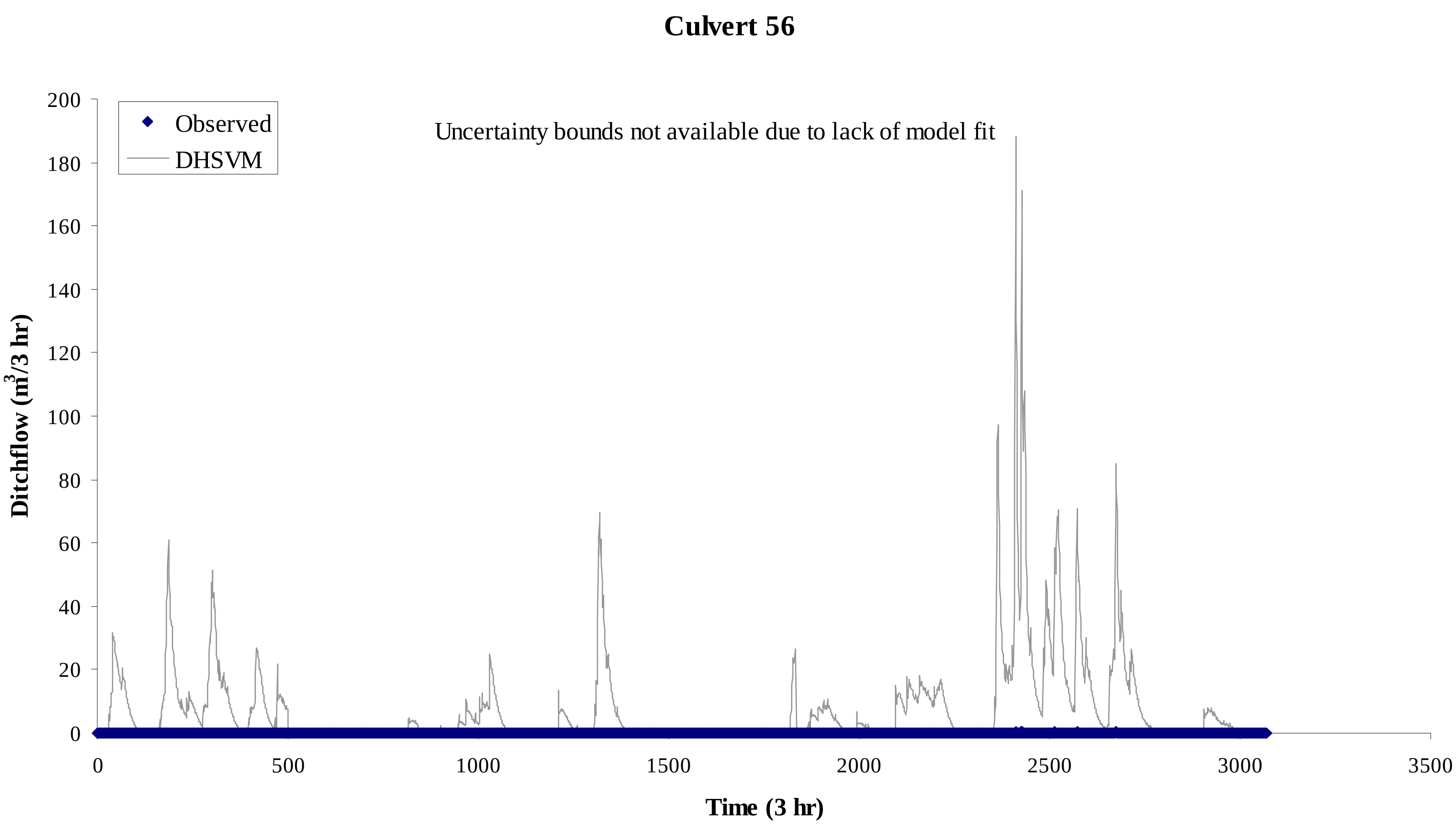
Figure 3. 29. Graph of DHSVM Simulation for Culvert 35, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3. 30</u>. Graph of DHSVM Simulation for Culvert 47, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3.31</u>. Graph of DHSVM Simulation for Culvert 53, 2003-2006. (data gaps and periods of no ditchflow excluded)



<u>Figure 3. 32</u>. Graph of DHSVM Simulation for Culvert 56, 2003-2006. (data gaps and periods of no ditchflow excluded)

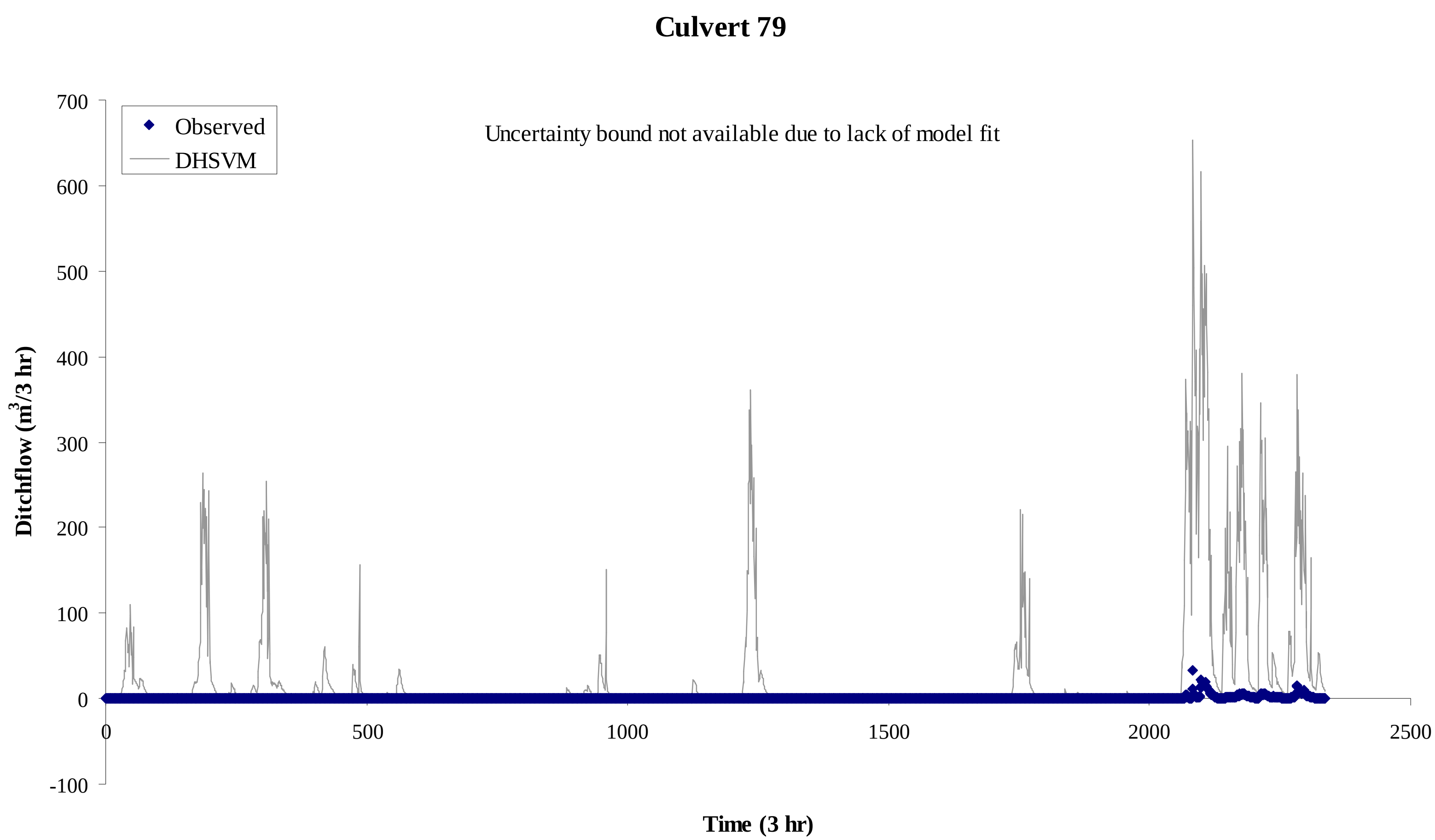


Figure 3.33. Graph of DHSVM Simulation for Culvert 79, 2003-2006. (data gaps and periods of no ditchflow excluded)

DHSVM simulations for the outlet of Oak Creek provided the least amount of uncertainty. Storm volumes and peak flows were generally within uncertainty bounds from the GLUE procedure (Figure 3.21) with only 10% of storm volumes observed outside of the uncertainty bounds and 12% of peak flows outside of uncertainty bounds (Table 3.3). The accuracy of DHSVM simulations decreased as the size of the area modeled decreased. Oak Creek was the largest catchment scale modeled with a 630 hectares area and DHSVM output provided the least amount of uncertainty based on percentage of storm volumes and peak flows outside of uncertainty bounds. DHSVM simulations for Claire Creek (55 hectares) showed greater uncertainty compared to Oak Creek with 22% of storm volumes and 22% of peak flows outside of uncertainty bounds. The six road ditchflow locations analyzed with GLUE (0.1-10 hectares) showed even greater uncertainty with between 28% and 52% of storm volumes and between 28% and 48% of peak flows outside of uncertainty bounds. There were five road ditchflow locations that did not meet criteria for model simulation fit demonstrating increased uncertainty depending on road ditchflow location.

Table 3. 3. Percentage Observed Storm Events Outside of DHSVM 95% Uncertainty Bounds.

	Percent of Storm Volume Outside Uncertainty Bounds	**Percent of Storm Peak Flows Outside Uncertainty Bounds**	**Percent of Storm Volumes >1 Year Event Outside Uncertainty Bounds**	**Percent of Storm Peak Flows >1 Year Event Outside Uncertainty Bounds**
Oak Creek	10%	12%	0%	25%
Claire Creek	25%	22%	0%	75%
Culvert 27	30%	30%	75%	0%
Culvert 30	33%	28%	50%	50%
Culvert 49	50%	48%	75%	100%
Culvert 54	14%	38%	0%	75%
Culvert 76	36%	46%	0%	75%
Culvert 88	30%	33%	0%	0%
Mean	***29%***	***32%***	***25%***	***50%***

During the time period modeled for Oak Creek, 2003-2006; there were four storms that had a greater than annual recurrence interval based on a partial series peak flow frequency analysis (Appendix C). The four storms were the largest four storms during the 2006 water year. These four storms are found at the right hand side of each of the time series graphs (Figures 3.21-3.28). Storm volume estimation for these events varied considerably (Table 3.3). The observed storm volumes for the largest spatial scales modeled, Oak Creek and Claire Creek, were within the uncertainty bounds for the four storms greater than a 1-year recurrence. While the greater than 1-year recurrence storms at road ditchflow sites varied from 0 to 3 of the storms within uncertainty bounds. Oak Creek had one of four 1-year recurrence peak flows outside of the uncertainty bounds; however Claire Creek had three of four 1-year recurrence peak flows outside of the uncertainty bounds. While the road ditchflow sites varied from 0 to four peak flows within uncertainty bounds. This demonstrated the large amount of variability of fit of DHSVM results within uncertainty bounds for the larger events. However, the trend observed is the largest scale simulations (Oak Creek) showed better fit than the smaller scale simulations (road ditches); like other DHSVM results found in this study.

The storm volumes for streamflow and road ditchflow locations with behavioural model structures and their subsequent uncertainty bounds are shown in Figures 3.34 – 3.41. The data is plotted from small to large storms (by volume of runoff) with the smallest storms on the right and largest on the left. The trend observed for most locations was smaller storm volumes were at the lower end of the uncertainty bounds, while larger storms were at the middle to upper ends of the uncertainty bounds, often outside of the uncertainty bounds. This suggests that DHSVM tends to over-predict the volume of small storms yet tends to under-predict the volume of large storms. This is particularly evident for the road ditchflow locations, while less evident for the streamflow locations.

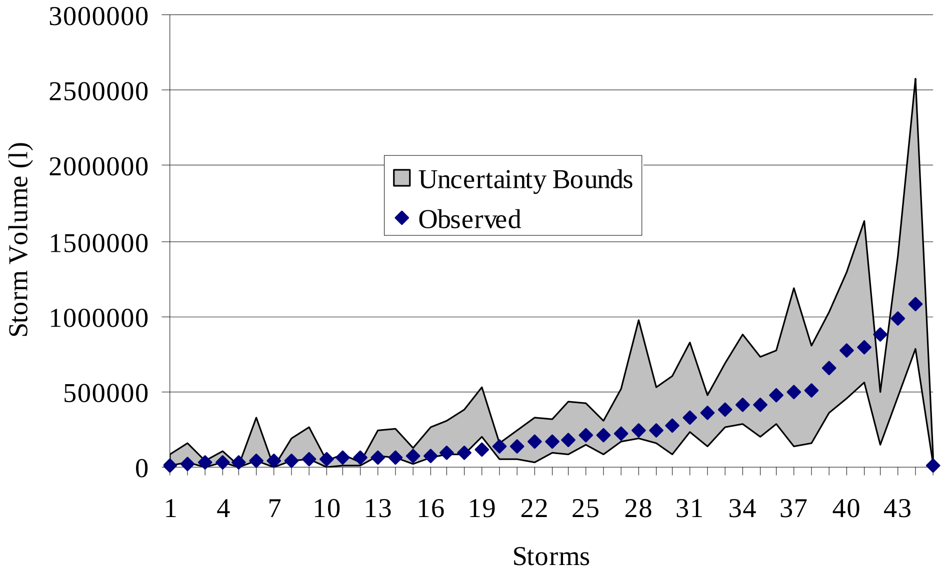


Figure 3. 34. Oak Creek Observed Storm Volumes and DHSVM Uncertainty Bounds.

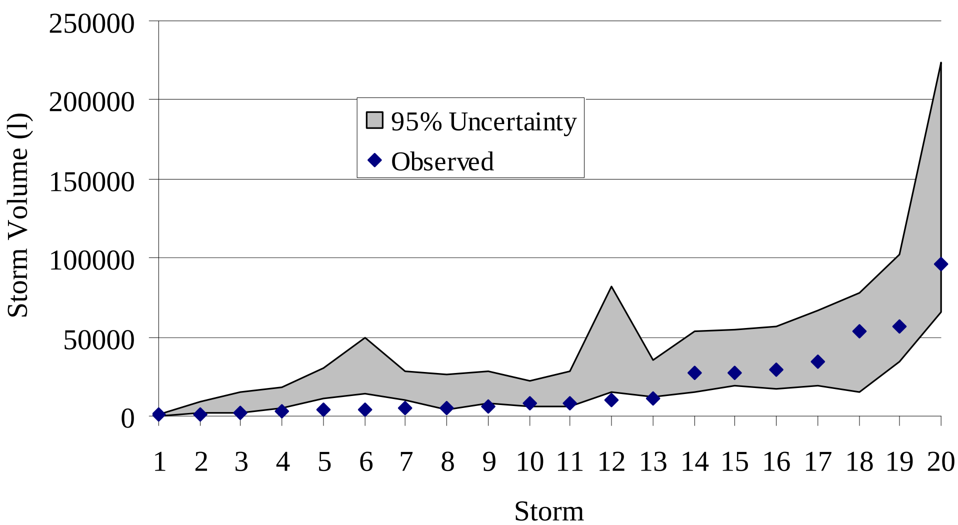
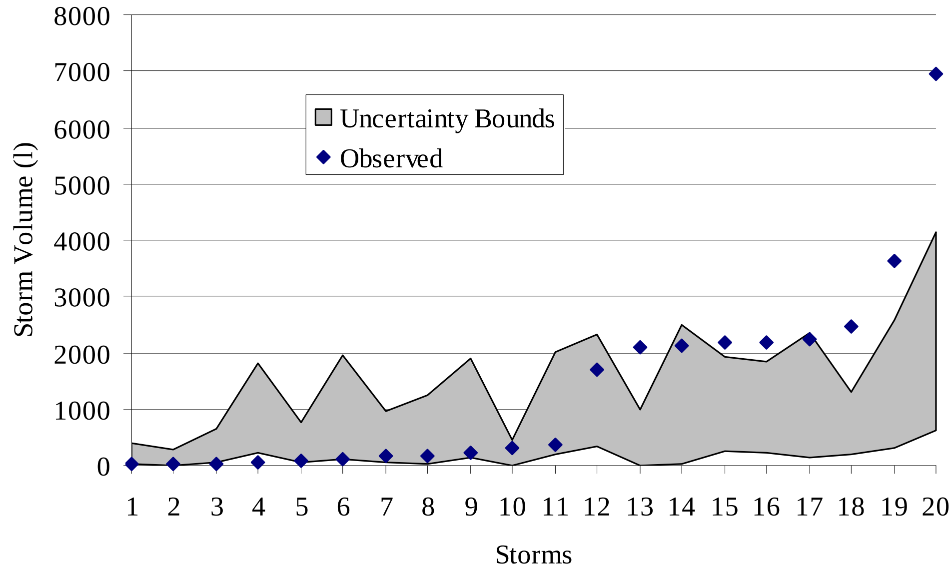
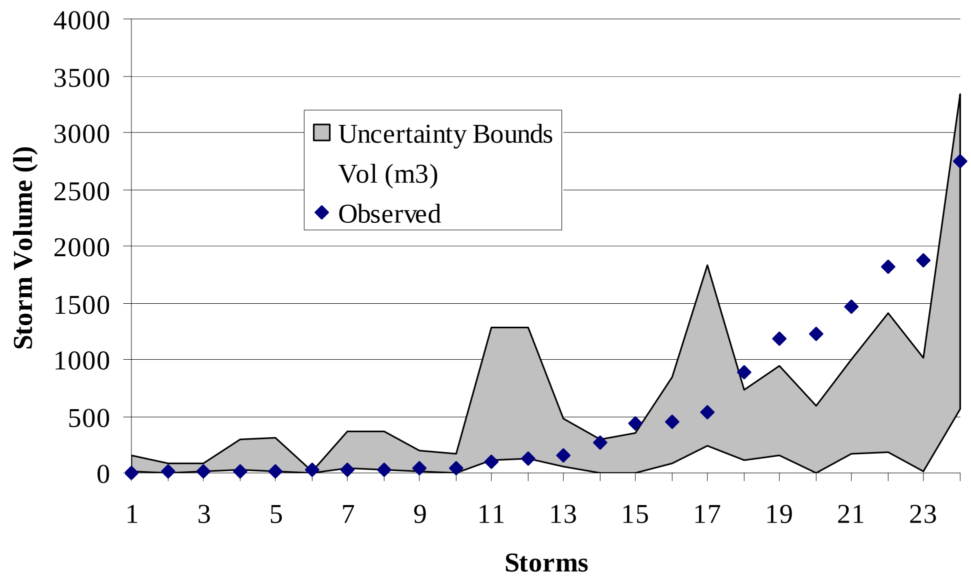


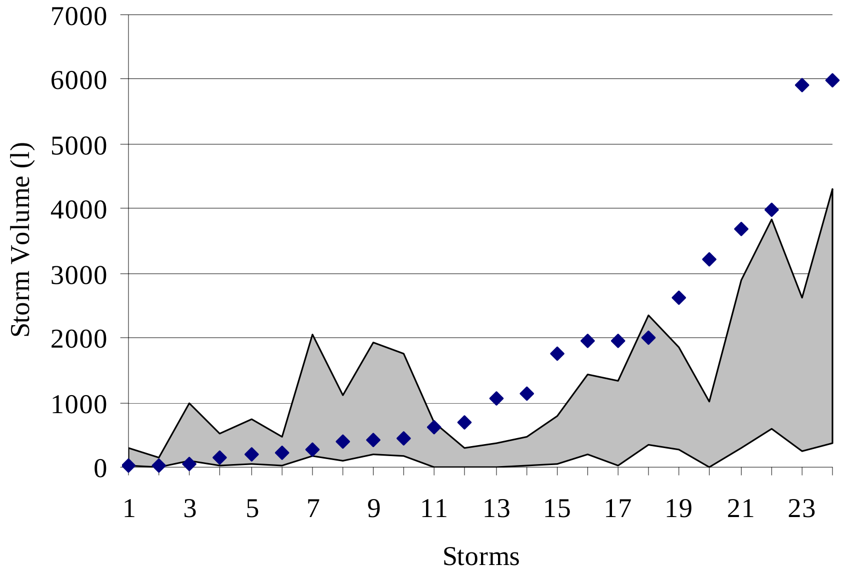
Figure 3. 35. Claire Creek Observed Storm Volumes and DHSVM Uncertainty Bounds.



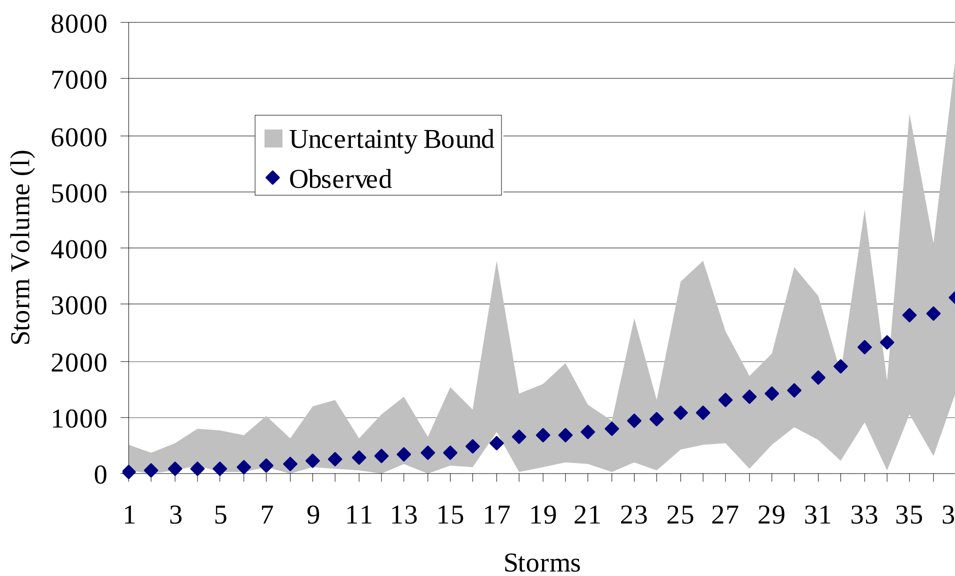
<u>Figure 3. 36</u>. Culvert 27 Observed Storm Volumes and DHSVM Uncertainty Bounds.



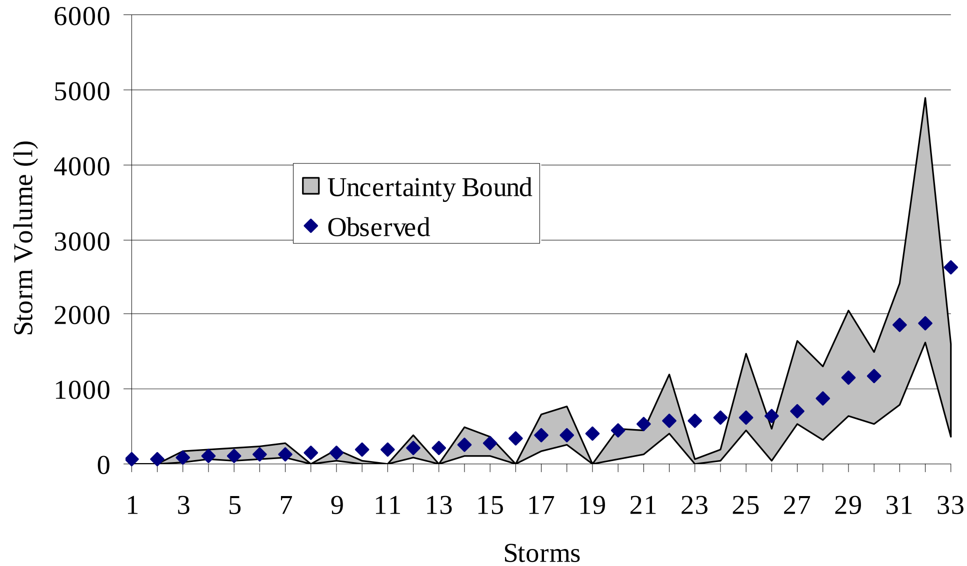
<u>Figure 3. 37</u>. Culvert 30 Observed Storm Volumes and DHSVM Uncertainty Bounds.



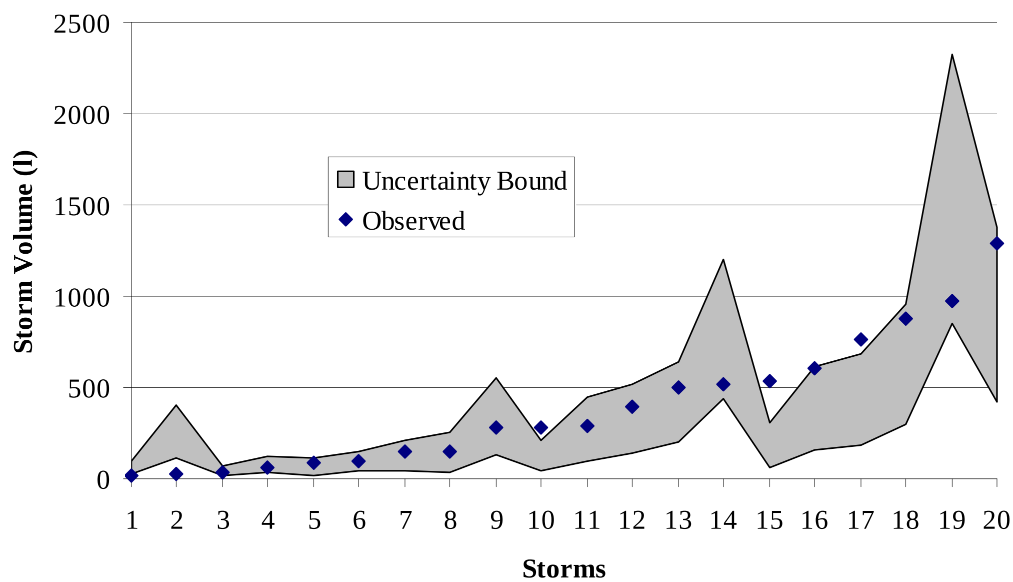
<u>Figure 3. 38</u>. Culvert 49 Observed Storm Volumes and DHSVM Uncertainty Bounds.



<u>Figure 3. 39</u>. Culvert 54 Observed Storm Volumes and DHSVM Uncertainty Bounds.



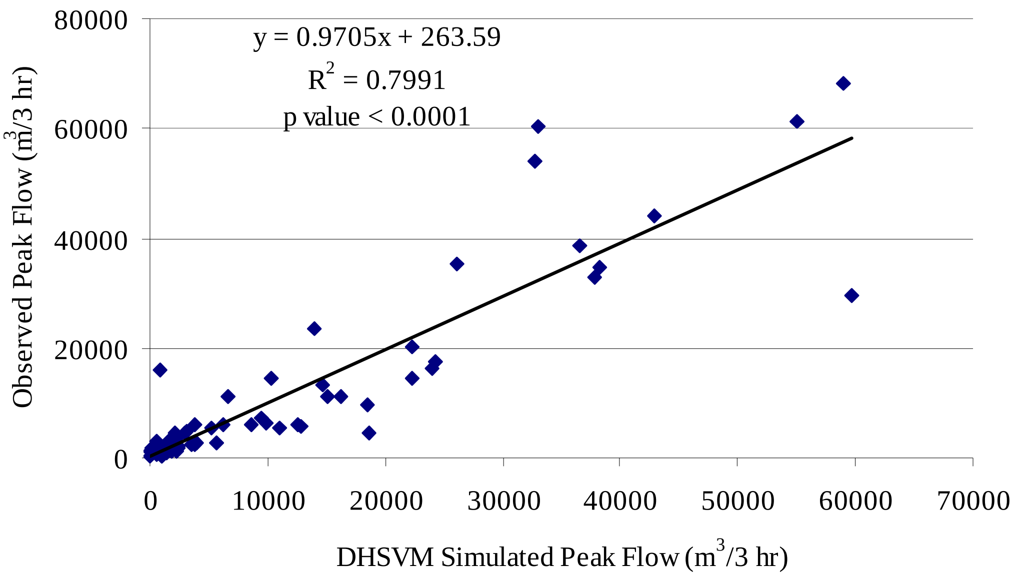
<u>Figure 3. 40</u>. Culvert 76 Observed Storm Volumes and DHSVM Uncertainty Bounds.



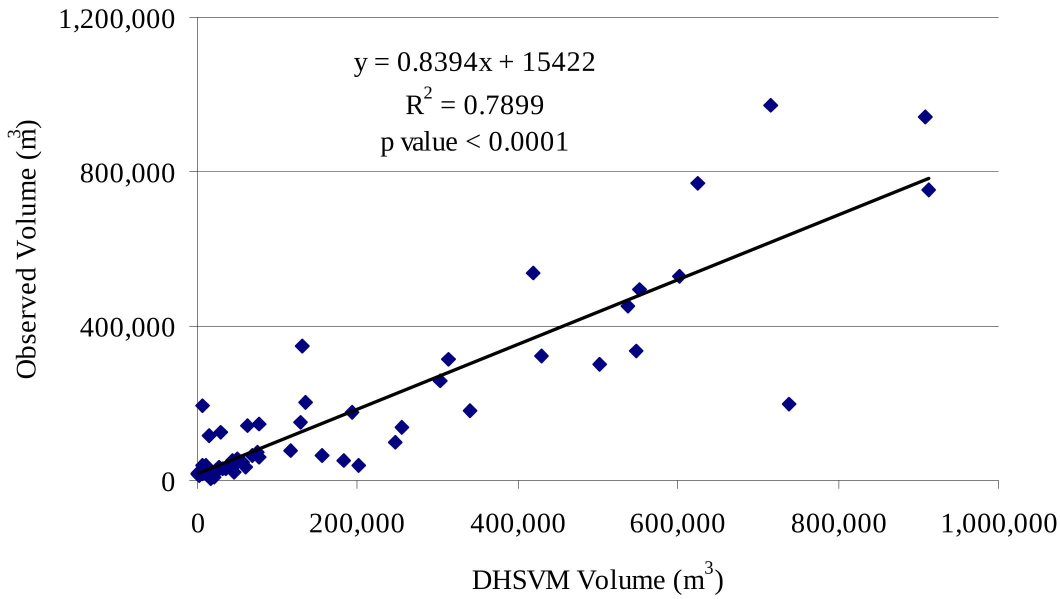
<u>Figure 3. 41</u>. Culvert 88 Observed Storm Volumes and DHSVM Uncertainty Bounds.

DHSVM Estimation of Peak Flows and Storm Volumes

The mean ratio between observed peak flows and DHSVM simulated peak flows for Oak Creek and Claire Creek for the 2006 and 2007 water years was 0.97 with a 95% confidence interval of 0.85 and 1.09 (p value <0.0001; adjusted $r^2 = 0.80$)(Figure 3.42). The mean ratio between the observed storm volumes and DHSVM simulated storm volumes for Oak Creek and Claire Creek was 0.84 with a 95% confidence interval of 0.73 and 0.95 (p value <0.0001; adjusted $r^2 = 0.79$)(Figure 3.43). DHSVM accurately predicted peak flows for Oak Creek and Claire Creek while slightly over-predicting storm volumes. The analysis demonstrates that statistically there was no difference between observed and simulated values of peak flow. There was weak evidence of difference between observed and simulated storm volume at 95% confidence for Oak Creek and Claire Creek.



<u>Figure 3. 42</u>. Relationship between Observed and DHSVM Simulated Peak Flows for Oak Creek and Claire Creek for the 2006 and 2007 Water Years.



<u>Figure 3. 43</u>. Relationship between Observed and DHSVM Simulated Storm Runoff Volumes for Oak Creek and Claire Creek for the 2006 and 2007 Water Years.

The ratio of observed peak flows and DHSVM simulated peak flows for ditchflow within Oak Creek for the 2006 and 2007 water years was 0.61 with a 95% confidence interval of 0.35 and 0.87 after accounting for the intermittent or ephemeral classification of the road ditch (p value =<0.0001; adjusted r^2 = 0.02). The resulting model did not explain much of the variability in the relationship as shown by the low adjusted r^2 of 0.02. There was evidence to suggest the regression model that included the intermittent or ephemeral classification provided a better model than without the classification (p value = 0.03). The resulting linear regressions of observed peak flows and DHSVM simulated peak flows for ephemeral and intermittent road ditches showed considerable difference, slopes of 0.22 and 0.78 respectively (Figures 3.44 and 3.45). The regression model between observed and DHSVM simulated peak flows considering road ditch classification was:

Observed road peak flow =

46.23 + 0.61 * (DHSVM road peak flow) + 55.95 * (road ditch classification)

Where: road ditch classification = 1 for intermittent

0 for ephemeral

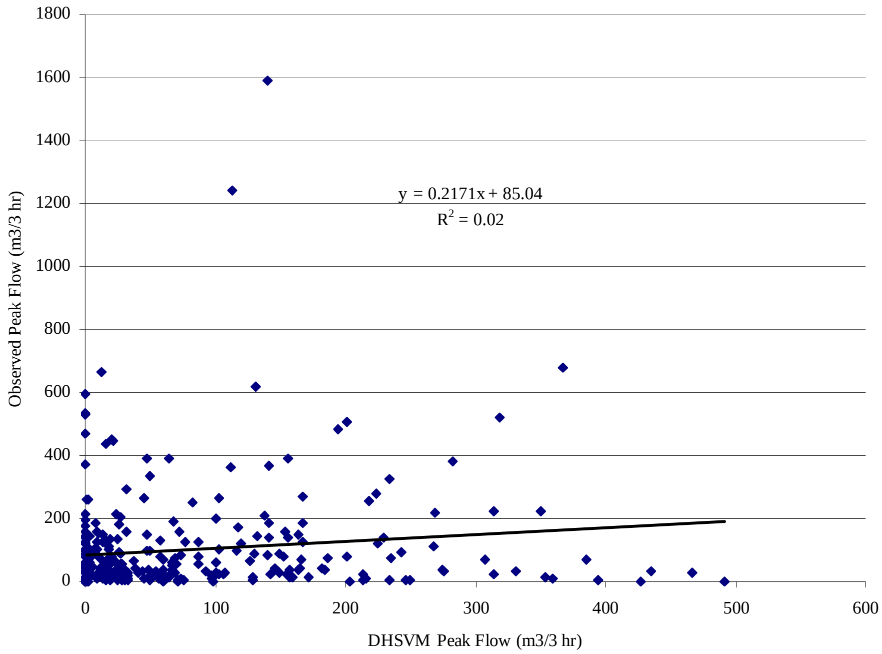
units of the intercept and peak flow are cubic meters per 3 hours

The ratio of observed storm volumes and DHSVM simulated storm volumes for road ditches within Oak Creek was 0.20 with a 95% confidence interval of 0.13and 0.27 (p value <0.04; adjusted $r^2 = 0.03$). For storm volumes there was not sufficient evidence that the regression model that included road ditch classification (intermittent or ephemeral) provided a better model than without (p value <0.0001). The resulting model explained little of the variability in the relationship as shown by the low adjusted r^2 of 0.03. The regression model between observed and DHSVM simulated road storm volumes was:

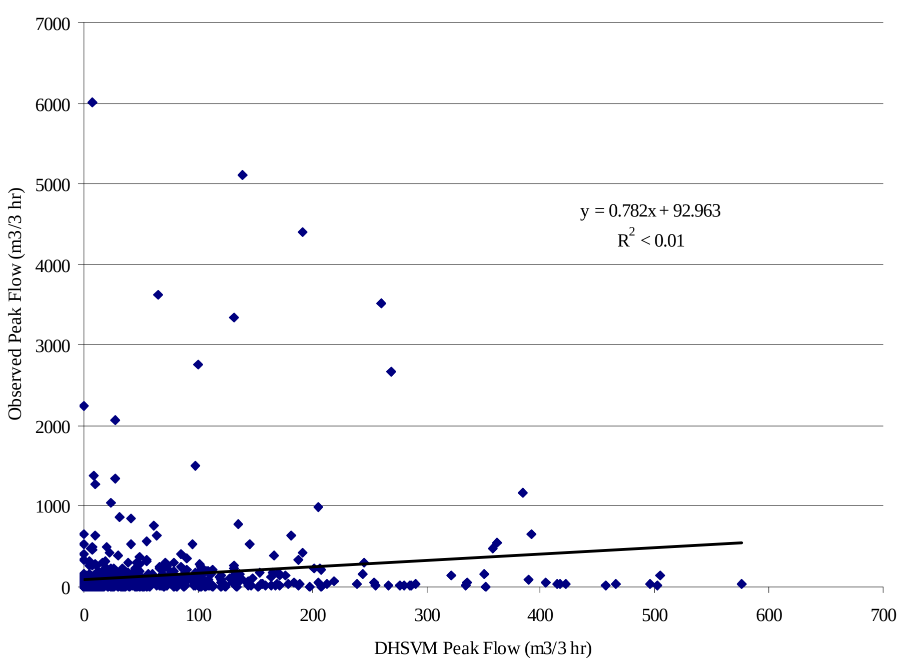
Observed road storm volume =

819.8 + 0.20 * (storm volume for DHSVM simulated road ditchflow)

Where: units of the intercept and storm volume are cubic meters



<u>Figure 3. 44.</u> Relationship between Observed and DHSVM Simulated Peak Flows for Ephemeral Road Ditchflow for the 2006 and 2007 Water Years.



<u>Figure 3. 45</u>. Relationship between Observed and DHSVM Simulated Peak Flows for Intermittent Road Ditchflow for the 2006 and 2007 Water Years.

For road ditch peak flows and road ditch storm volumes DHSVM substantially over predicted the hydrologic response. For road peak flows this response was partially explained by the ephemeral road ditches within Oak Creek. The ephemeral road ditches created circumstances where road ditches flowed less water than intermittent road ditches. DHSVM predicted road ditch flow at the ephemeral ditch location, even when no flow was observed. When storms for ephemeral road ditches were removed from the analysis, DHSVM, on average slightly over predicted peak flows as well (a ratio of observed to simulated peak flows of 0.78 compared to 0.22 with ephemeral ditches). For road storm runoff volumes the ephemeral ditch classification did not affect runoff in road ditches; after removing the ephemeral road ditch sites DHSVM still over-predicted storm volumes (a ratio of observed to simulated storm volumes of 0.28 for intermittent roads compared to 0.36 with ephemeral roads).

An attempt to improve the relationships between simulated and observed peak flows and storm runoff volumes by separating the data sets into large and small events, based on the 1 yr recurrence interval, was unsuccessful. For the road peak flow and storm runoff volume relationships there was no statistical correlation between observed and DHSVM simulated peak flows or storm runoff volumes for events greater than a 1-year recurrence interval, p values of 0.96 and 0.74 respectively. DHSVM simulated road peak flow and storm runoff volumes for less than a 1 year recurrence interval over-predicted the observed values for approximately the same amount for peak flows but much more for storm volumes; slopes for the ratios between observed and simulated peak flows and storm volumes for events less than 1-year were 0.31 and 0.21 respectively.

DHSVM Estimation of Total Road Runoff Volume

The total runoff volume observed for Oak Creek for the 2006 and 2007 water years was 13,623,000 cubic meters. DHSVM simulated 14,540,000 cubic meters for this same time period with an 95% uncertainty bound of 6,460,000 to 16,700,000 cubic meters (Table 3.4). The DHSVM total runoff estimate is approximately 7% more than observed. The uncertainty bounds of the simulated total volume of water intercepted by roads in Oak Creek (Table 3.4) encompass all but two of the road culvert locations with behavioural model structures. However, in most of the road locations the uncertainty bounds are extremely wide demonstrating considerable uncertainty in the estimates.

Table 3. 4. Uncertainty Bounds for Total Run-off for 2006 and 2007 Water Years

Site	Observed Total Runoff (m^3)	DHSVM Lower Uncertainty Bound (m^3)	DHSVM Upper Uncertainty Bound (m^3)	DHSVM Uncertainty Bound Width*
Oak Creek	13,623,000	6,460,000	16,700,000	1.6
Claire Creek	392,583	282,228	727,254	1.6
Culvert 27	28,012	3,825	59,331	14.5
Culvert 30	13,768	2,833	38,196	12.5
Culvert 49	38,784	3,224	31,055	8.6
Culvert 54	38,634	10,500	95,234	8.1
Culvert 76	18,171	7,005	16,739	1.4
Culvert 88	8,490	5,165	14,335	1.8

* - Uncertainty bound width calculated as difference between highest and lowest bound divided by lowest bound value

The total observed road runoff volume and DHSVM simulated road runoff volume for the 2006 and 2007 water years were 2,330,000 and 2,061,000 cubic meters, respectively. The total volume of runoff from roads in Oak Creek was 17% of the total runoff during the 2006 and 2007 water years; DHSVM simulated14% of the runoff from roads. When the road runoff for Oak Creek was separated into six road segments (see Figure 3.2), estimates of total road runoff from DHSVM varied from observed between 5 to 276% (Table 3.5). DHSVM estimated the road runoff portion of the mass water balance for the catchment well, however, did not capture the total runoff variability from road segments within Oak Creek.

For the 2006 and 2007 water years, estimates of total road runoff by DHSVM for the six road segments followed the conceptual view of road runoff (Table 3.5). DHSVM simulated the roads on the upper hillslopes intercepting a lower amount of water than the roads at middle hillslope positions; roads at the bottom of hillslopes intercepted the most water. Observed road runoff based on the six road segments did not follow this ordered response. Observed total road runoff was highest for the 2006 and 2007 water years on the bottom of the hillslope roads; however road four in an upper hillslope position also had high road runoff observed. The greatest percent difference between DHSVM simulated and observed total road runoff occurred for roads 3 and 4. In fact DHSVM over-estimated the road segment runoff volumes with the exception of roads 3 and 4. Roads 3 and 4 are on the same side of the catchment, perhaps suggesting a different hydrologic response for that aspect of the catchment.

<u>Table 3. 5</u>. Comparison of Observed and DHSVM Simulated Total Annual Road Runoff from Roads within Oak Creek, 2006 and 2007 Water Years (see Figure 3.2 for map of road locations).

		2006 Water Year			**2007 Water Year**			***2006 and 2007 Combined***		
Name	**Hillslope Position**	**Observed (m^3)**	**DHSVM (m^3)**	**Percent Difference**	**Observed (m^3)**	**DHSVM (m^3)**	**Percent Difference**	***Observed (m^3)***	***DHSVM (m^3)***	***Percent Difference***
Road 1	Bottom of Slope	168,910	467,172	64%	185,267	421,111	56%	354,177	888,283	60%
Road 2	Upper Slope	33,226	41,560	20%	49,487	37,128	-33%	82,713	78,688	-5%
Road 3	Bottom of Slope	673,523	178,935	-276%	312,872	151,811	-106%	986,395	330,746	-198%
Road 4	Upper Slope	150,333	114,383	-31%	317,074	124,300	-155%	467,407	238,683	-96%
Road 5	Mid-slope	20,700	169,017	88%	166,606	96,652	-72%	187,306	265,669	29%
Road 6	Mid-slope	87,323	130,869	33%	83,574	111,441	25%	170,897	242,311	29%
TOTAL		***1,134,015***	***1,101,936***		***1,114,879***	***942,442***		***2,248,895***	***2,044,378***	

Case Study: DHSVM Estimated Hydrologic Change of Peak Flow and Storm Runoff Volume from Roads within Oak Creek

The case study for DHSVM's prediction of peak flow and storm volume changes during the winter of 2006 water year for the two road stream crossings within Claire Creek showed mixed results (Table 3.6). At culvert 34, observed peak flow increases from the road were on average 77% greater. DHSVM model results suggested an average peak flow increase of 9% for the same location. At culvert 35, DHSVM results were similar to observed peak flow increases, with increases of 18% and 17%, respectively. Culvert 34 had greater runoff from the road than culvert 35, even though both sites have similar physical characteristics and upslope catchment area. The differences in peak flow increase may be explained by this difference in observed runoff. At culvert 34, DHSVM sends more of the water from the hillslopes into the stream channel, when field observations suggest more water is being transmitted in the hillslope and intercepted at the road cut; which creates an increased peak flow response from intercepted hillslope water.

Culverts 34 and 35 increased storm runoff volume at the road stream crossing an average of 75% and 74%, respectively. DHSVM under predicts the storm runoff volume increases for these two road crossings. Culverts 34 and 35 were simulated by DHSVM for the same time period to increase storm runoff volume at the road stream crossing an average of 8% and 17%, respectively. Culvert 34 storm volume responses may be explained by DHSVM sending more of the water from the hillslopes above culvert 34 into the stream channel, when observations suggest more water was being intercepted at the road cut. For the storms from November 2005 through February 2006 DHSVM predicted 50% more water volume during storms in the stream channel than observed, 3300 cubic meters compared to 2220 cubic meters, respectively. In the case of culvert 35, DHSVM under predicts the stream and road runoff volumes. In this situation sub-surface topography and flow paths must be different than the modeled soil depth input to DHSVM. At both road crossings sub-surface flow paths apparently were not adequately captured by the soil depth estimates or soil hydraulic properties used with DHSVM.

Table 3. 6. Observed and DHSVM Simulated Peak Flow and Storm Runoff Volume Increases due to Roads for 2 Road Stream crossings, Claire Creek, and Oak Creek.

Location	Observed Peak Flow Increase	Modeled Peak Flow Increase	Observed Runoff Volume Increase	Modeled Runoff Volume Increase
Road Point 34	77%	9%	75%	8%
Road Point 35	18%	17%	74%	17%
Claire Creek	-	3%	-	1%
Oak Creek	-	3%	-	2%

DHSVM predicted an average increase in peak flow from roads for Claire Creek and Oak Creek of 3%. DHSVM predicted an average increase in storm runoff volume from roads for Claire Creek and Oak Creek of 1% and 2%, respectively. The argument might be taken that because DHSVM under predicted peak flow and storm runoff increases for culverts 34 and 35 in Claire Creek, the models cumulative predictions for both Claire Creek and Oak Creek may be under-predicted as well. However, the statistical analysis of road ditch flow for Oak Creek demonstrates that DHSVM was over-predicting peak flows and storm volumes, which suggests that the catchment scale results may be over-predicted. These increases in peak flows and storm volumes were very small but difficult to interpret given the substantial differences in model results that were observed.

DISCUSSION

Spatial Scale and Uncertainty for DHSVM

The spatial scale simulated by DHSVM showed considerable influence on the uncertainty of model results. As the catchment scale increased the model uncertainty decreased. For this study the largest scale streamflow simulated was the outlet of Oak Creek (630 hectares); Oak Creek produced the highest proportion of behavioral model structures from the GLUE procedure. Oak Creek simulations also provided the greatest proportion of modeled storm runoff volumes and peak flows within uncertainty bounds. Claire Creek produced the second highest amount of behavioral model structures and the second largest proportion of peak flows and third largest proportion of storm volumes within uncertainty bounds. The smallest catchment scales, the road ditchflow locations, had low proportions of behavioral model structures and low proportions of storm volumes and peak flows within uncertainty bounds. Several of the road ditchflow locations studied were so inaccurately modeled that behavioral model structures could not be identified for those locations.

The percentage of behavioral model structures decreased by size of the spatial scale modeled (Table 3.2). This demonstrates that a greater variety of model structures can produce reasonable outcomes as the scale of the modeled catchment area increased. Because the outlet of a catchment was shown to accept a larger amount of model structures, it is likely that model structures that are behavioral at smaller scales will produce behavioral responses at a larger scale. This suggests that model structures chosen for DHSVM may be better determined with internal catchment data, at smaller scales, than the outlet of the catchment to be researched. Using internal catchment information for model calibration is counter to what most modelers actually do; models are calibrated from analysis of the catchment outlet, with some validation of this to internal catchment data. Most streamflow observations available to evaluate models are at larger catchment scales.

The results here suggest more emphasis should be placed on collecting and adjusting models from small scale observations. Certainly this is the point of using distributive hydrologic models; to have greater control of the model calculations for small scale processes. The results from this uncertainty analysis suggest that if small scale observations are not used in improving model response; a distributive hydrologic modeling approach would be pointless. The modeler should save themselves the effort and use a simpler non-distributive modeling approach.

Parameter Values of DHSVM and Uncertainty

The parameter values that were associated with behavioral model structures (higher NSE) had many model structures that use the same parameter value but get poor fit (lower NSE). This indicates the parameter values manipulated in the GLUE assessment are highly influenced by their interaction with each other. The dotty plots indicate that no optimum model structure could accurately estimate the run-off for all road and streamflow sites across Oak Creek. Different parameter value ranges and interaction of parameters on each other suggest that equifinality, the relative ability or likelihood of many model structures to estimate the observed data, would be an appropriate approach for DHSVM evaluations.

The model parameters of porosity and the exponent of lateral hydraulic conductivity were the most sensitive for producing behavioral model structures for DHSVM. The model parameter of lateral hydraulic conductivity was not sensitive for the streamflow locations of Claire Creek and Oak Creek and only slightly sensitive for the ditchflow locations. However, lateral hydraulic conductivity did exhibit a noticeable trend in the dotty plots for specific ranges of values. The lack of sensitivity of lateral hydraulic conductivity was surprising as this parameter is considered influential for calculations of sub-surface hydrologic response. Technical support for DHSVM on a University of Washington web site suggests the use of this parameter, among others, to assist in calibration of the model (Land Surface Hydrology Research Group, 2008). However this result showed that setting the lateral hydraulic conductivity at a value reasonable for the various soil types is important but doing a lot of adjustment to this parameter to improve model fit was not successful. Adjusting the exponent of decay for the lateral hydraulic conductivity to improve model fit was found to be more successful.

The porosity parameter directly influences the volume of water calculated for each grid cell of DHSVM. Increases in porosity produces more water storage at each grid cell in DHSVM calculations. The same relationship would be true with increases in soil depth. As shown in Chapter 2, soil depth influenced DHSVM output. A parameter relating to the distribution of pore sizes may also be influential on volume available for water storage and transport in DHSVM, however this parameter was not analyzed in this study.

The range of porosity values that produced model structures with high likelihoods varied among road ditchflow locations. Because porosity could be viewed as a surrogate for soil depth in model calculations, the varying ranges of porosity may be attributed to inaccuracies in soil depth upslope from road culvert locations. Within the Monte Carlo simulations for the GLUE analysis the porosity value is held constant across the catchment for each simulation yet results varied spatially. Soil depth was influential to improve DHSVM results and varied spatially yet could not be accurately predicted deterministically. Perhaps manipulation of porosity may be the key to improve DHSVM results for smaller scale locations. In the previous chapter the mean soil depth was adequate for the larger catchment area streamflow modeling, while smaller scale road ditchflow responded better to soil depths developed from a physically based approach that captured variability in soil depth that may be emulated by altering porosity. The GLUE analysis provides uncertainty for DHSVM results for specific spatial locations. If enough simulations were conducted and the observations were balanced across the spatial extent of a catchment the resulting trends observed could then adjust parameter values across space as required. Certainly this type of approach for porosity would have been beneficial for Oak Creek simulations. This approach implies confidence that the hydrologic model will give reasonable simulations at smaller scales. Given the results of this study this assumption may need to be further examined for DHSVM.

Use of the GLUE Assessment with DHSVM

The GLUE assessment provided useful information toward the equifinality of DHSVM results. In this case uncertainty bounds were created based on several influential parameter sets that demonstrated the wide range of acceptable results that can be achieved for road hydrologic modeling by DHSVM. The influence of interaction of parameter values was shown and some *a priori* parameter ranges can be interpreted for future DHSVM applications. Likewise, knowledge of the sensitivity of parameters such as porosity (a surrogate for soil depth), the exponential decay of hydraulic conductivity, and to a lesser extent lateral hydraulic conductivity can assist future DHSVM uses. The fact that so many repetitions of DHSVM were used is in itself an argument for using the GLUE assessment. As pointed out by Oreskes and Belitz (2001), more research has gone into the development of predictive models than attempting to understand the accuracy of those models. However, isolating whether specific processes such as how preferential flow paths exert an influence on the road hydrologic response was not specifically captured with the GLUE assessment. Certainly GLUE did provide information to make suppositions in this regard; but it was not a technically pure answer rather deductive reasoning by the hydrologist doing the modeling. Investigations or hypothesis tests with model structure manipulations enabling the hydrologist to exert thoughtful reasoning is perhaps an argument to maintain some use of manual calibrations in hydrologic modeling. Depending on the application and objective of the outcome both seem to have a place; for now at least.

Why Were DHSVM Simulated Road Responses Inaccurate in Oak Creek?

Sub-surface water routing within hillslopes of Oak Creek are highly variable as shown by ephemeral or intermittent road ditch responses. Almost all of the road ditches in Oak Creek have road cuts which can intercept hillslope water (there are only a few lengths of ridge top roads with no road cuts). For most road ditches in Oak Creek, when large storms occurred in the catchment water flow was observed in road ditches. It was in the smaller precipitation events that water often did not flow in ephemeral road ditches, yet DHSVM would predict water flow. The varied response of road runoff suggests that there are either preferential flow paths or variable thresholds to sub-surface flow within Oak Creek. This was not accounted for by DHSVM's calculations based on sub-surface flow due to a hillslope water table dispersed throughout the soil matrix.

Despite a reasonable effort for field measurement of soil depth and attempts at a variety of different spatial extrapolation efforts (see previous chapter) an accurate spatial representation of the soil depths in Oak Creek was not achieved. Variable weathering and fracturing of the basalt geology in Oak Creek has created topography at the bedrock surface that is highly erratic and does not reflect the shape of the surface topography. The soil depths were poorly predicted by the physical characteristics used in the soil depth model (Westrick, 1999) provided with DHSVM. The variable response of sub-surface water and complex soil development within the Oak Creek catchment appears to be the reason hydrologic modeling of a road network by DHSVM was so inaccurate. Because DHSVM is a fully distributed model it may be possible to find parameter sets that provide a better fit to individual road cuts and hillslopes. However, this increases the complexity of the modeling exercise perhaps beyond the scope of most decision based analysis.

A similar over prediction of road hydrologic response by DHSVM was observed in an application in the Deschutes River, Washington (La Marche and Lettenmaier, 2001). It was hypothesized this could be indicative of ditch infiltration which, although observed in the field, is not modeled in DHSVM. They also noted that road surface runoff, is only crudely represented in DHSVM. The majority of hydrologic effects for roads modeled by DHSVM are from the interception of hillslope water at the cutslope. Some of the roads in Oak Creek did not consistently have interception of hillslope water, creating an over-prediction of road runoff.

The total volume of water runoff from roads in Oak Creek estimated by DHSVM for the 2006 and 2007 water years was accurate (see Table 3.5). Yet individual storm events for individual road locations were poorly predicted by DHSVM in Oak Creek. No statistical relationship was observed for DHSVM simulated and observed storm volume and peak flows for events > 1 year recurrence interval. However, the scatter plots of the data (Figures 3.48 and 3.49) show many large events under estimated by DHSVM. Likewise, many of the smaller events estimated by DHSVM simulations were greatly over-estimated. These factors may have balanced each other creating similar total runoff volumes but different individual storm responses between DHSVM and observed road runoff.

Additional Sources of Uncertainty

Errors from model input and observed data likely have contributed to some of the uncertainty associated with DHSVM simulations. Precipitation gages were well representative of the varying elevations. The climate data used by DHSVM was collected within the catchment. However, at times the weather station or precipitation gages were not operating and climate information from outside of the catchment was extrapolated for use in Oak Creek. These discrepancies in climate inputs could have created a different DHSVM response as compared to what was observed in the catchment.

For this study a 30 meter DEM was used for the basis for the DHSVM calculations. Most notably the soil depth inputs to DHSVM were not well matched to a 30 meter scale and might have provided a better representation of the sub-surface topography at a smaller scale.

The comparison of DHSVM to observed data introduces uncertainty in the interpretation of DHSVM results. The measurement of continuous road ditchflow in Oak Creek was done with capacitance rods often using a culvert as the control structure for flow measurement. The calculation of flow within a culvert used a rating curve developed from observations of varying stage (Toman, 2004); within this relationship error exists. Approximately half of the culverts in Oak Creek used crest gages for measurement of peak discharge. Often there were multiple storms between crest gage observations. The assumption was made that the crest gage observation represented the largest storm, as observed at the outlet of Oak Creek, within the time period between observations. However, many times throughout the road runoff record the largest event at the outlet does not necessarily translate to the largest event at individual road sites. Therefore it seems likely that some of the crest gage data comparisons to DHSVM created some inaccuracies. The assessment of total road runoff volume required extrapolation of data holes from adjacent sites or determination of storm runoff volumes from relationships with the sites peak flows. Although these extrapolations were done with good relationships they represent uncertainty in the observed estimates.

A GLUE approach was used to identify equifinality of model structures to simulate an observed phenomenon. Although this is a reasonable way to quantify uncertainty in model estimates a fundamental source of uncertainty is still not addressed. All of the physical relationships used within models like DHSVM were developed through empirical study with mathematical relationships that describe the processes. In all of the mathematical relationships “fit” to the various physical phenomenon modeled there was error and variability associated with that “fit”. This error, to my knowledge, is never expressed in model output. I argue that for each model result there is confidence bands associated with the result. If these confidence bands were propagated through the Monte Carlo simulations of GLUE, I suggest that the uncertainty bounds that were produced would be wider than what is currently produced by a GLUE assessment. Because confidence or error bands around model results are not a part of most of the calculations in hydrologic models, I suggest that GLUE results should be interpreted as a minimum of uncertainty of a model.

The uncertainty from model input data and observed data for comparison of the model influence the interpretations of DHSVM results. For example, the total runoff from Oak Creek as simulated by DHSVM was 7% larger than observed. Given the uncertainties discussed, I am not inclined to interpret this as anything but a small difference in prediction. However, when the linear regression relationship suggests that DHSVM is over-predicting observed peak flow or storm runoff values by as much as 5 times it is probably safe to suggest that this is a big difference.

DHSVM as a Change Detection Tool

Considerable uncertainty was identified through the various applications of DHSVM in Oak Creek. Uncertainty bounds for behavioural model structures had wide ranges of values for the road runoff simulations, while several roads had no behavioural model structures at all. The overall mass balance of water discharge intercepted by roads in Oak Creek was estimated reasonably well by DHSVM for the two water years examined. Yet, individual road discharge and even large road segments had inaccurate results from DHSVM. These results suggest that using DHSVM as a change detection tool in a catchment such as Oak Creek with highly variable hillslope water flow and road interception must be approached carefully. Indeed the approach of using one model structure may be misleading (i.e. the case study in this chapter; Bowling and Lettenmaier, 2001; La Marche and Lettenmaier, 2001).

The fact that many of the road runoff locations analyzed in Oak Creek within the GLUE assessment produced behavioral model structures suggests that individual road locations could be assessed for hydrologic change within an equifinality approach. Behavioural model structures identified for the individual road runoff locations in the GLUE analysis could be simulated in DHSVM with the road removed. The difference in simulated road runoff with and without the roads for all the behavioural model structures would provide a range of road hydrologic changes that could be interpreted from DHSVM. Likewise, this same approach could be done at the larger catchment scale, where behavioural model structures identified at streamflow locations could be modeled with the roads removed in DHSVM providing a range of hydrologic change from the roads. The assumption that must be accepted is that the behavioural model structure identified with roads in the catchment would still be behavioural when the roads are removed.

Several of the individual road runoff locations in the GLUE assessment for Oak Creek had no behavioural model structures produced by DHSVM. For these sites DHSVM could not be used as a change detection tool. Therefore the modeler will be limited in change detection assessment for individual sites by the locations in the catchment that behavioural model structures can be produced. The question becomes what does this mean to the assessment of catchment scale change detection for roads? If not all road runoff locations provide behavioural model structures in a catchment can a catchment scale assessment of change detection of roads be trusted? I suggest the answer depends on how well DHSVM does overall in the catchment; however the modeler must provide in the change detection interpretation of the short comings and uncertainties of their modeling effort so that any conclusions can be interpreted accordingly.

In the case of Oak Creek the population of road peak flows and storm runoff volumes were substantially over-predicted by DHSVM. However, the model did very well at simulating the streamflow at the outlet of Oak Creek and fairly well at Claire Creek. Total road runoff for the Oak Creek catchment was simulated accurately by DHSVM, while the individual road segments had poor total runoff estimates by DHSVM. In this case, I would find it reasonable to approach a change detection assessment for road effects by DHSVM at the Oak Creek catchment scale, but not for smaller tributaries in the catchment such as Claire Creek. In the case study of Oak Creek, a 3% change in peak flows and storm runoff volumes for Oak Creek were identified with one model structure manually calibrated to the catchment. However, if an equifinality approach was taken a range of answers would be produced. Given errors in observations, model inputs, and DHSVM simulations in this case I would not be confident that hydrologic change from the roads was predicted with certainty at the catchment scale in Oak Creek.

CONCLUSIONS

The uncertainty assessment of forest road modeling by DHSVM provided insights into the use of DHSVM and distributive models in general. Considerable uncertainty in DHSVM estimates of road hydrologic response were observed in the Oak Creek catchment. The variable response of sub-surface water, complex soil development, and complex soil/water interactions within Oak Creek appears to be the reasons DHSVM results were so uncertain. As the spatial scale and temporal scale was increased the uncertainty in DHSVM results decreased. Streamflow observations at the outlet of Oak Creek showed the least uncertainty and provided the most diverse range of behavioural model structures in the GLUE assessment. Because the outlet of a catchment was shown to accept a larger variety of model structures, it is more likely that model behavioural structures at smaller scales will produce behavioural model structures at larger scales. This suggests that model structures chosen for DHSVM or distributive hydrologic models would be better determined with internal catchment data, at smaller scales, than the outlet of the catchment to be researched.

The research of many diverse model structures with DHSVM made the GLUE assessment useful for interpretation of DHSVM results. The GLUE assessment also showed that certain roads within the catchment did not produce behavioural model structures. This is important when considering the use of DHSVM as a change detection tool. It suggests that change detection will be limited to sites or scales of the catchment that behavioural model structures can be identified. Additional effort is needed for determination of behavioural model structures where not previously found. The GLUE analysis provided uncertainty for DHSVM results for specific spatial locations. If additional simulations were conducted and the observations were balanced across the spatial extent of a catchment the resulting trends observed could then adjust parameter values across space as required.

The overall mass balance of water discharge from Oak Creek intercepted by roads was estimated well by DHSVM. Yet, DHSVM simulated discharge from individual road segments or aggregate road segments were not accurately modeled. With the amount of uncertainty in small scale simulated responses the approach of using one calibrated model structure that is commonly used with distributive models does not provide an accurate representation of the actual hydrologic response.

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CHAPTER 4: CATCHMENT SCALE ASSESSMENT OF FOREST ROAD SEDIMENT YIELD

INTRODUCTION

A large amount of the sediment caused from timber harvest activities is attributed to roads and road building (i.e. Reid, 1981; Ketcheson and Megahan, 1996, California Department of Forestry, 2002; Surfleet, 2004; Gucinski et al., 2001). The increase in sediment production from timber harvest activities, which includes forest roads, can degrade water quality and aquatic habitat (e.g. Gucinski et al., 2001; Spence et al., 1996; Haskell, 2000). Concerns regarding the impacts of sediment due to timber harvest have resulted in regulations that require landowners to repair sediment sources, use improved harvesting practices, and monitor reductions in sediment production. The implementation of policies such as Total Maximum Daily Loads (TMDL), the Endangered Species Act, and State Water Quality Regulations requires that landowners accurately monitor reductions in sediment production and the subsequent improvement of aquatic habitat over time.

A common difficulty when monitoring sediment is separating natural sources of sediment from the sediment produced from land management, for example forest roads. This is a complex problem given the high variability in sediment production in space and time caused by the many influences on sediment production, transport, and storage. The problem becomes more complex when an attempt is made to isolate the different sources of sediment production at a watershed scale. In addition to the challenge of isolating the production of sediment from roads at a watershed scale is the need to accurately and cost effectively measure sediment production from roads. The common techniques to estimate road sediment production have used “catching” techniques, road erosion models, suspended sediment sampling, and turbidity observations. The catching techniques involve either catching eroded soil particles in troughs, or settling suspended sediments in settling basins (i.e. Reid, 1981; Kelly, 1967; Luce and Black, 1999; Amann, 2004). Though widely used, catching techniques lack real-time hydrology information and no accurate measurement of the timing of the sediment delivery. For soil erosion catching troughs, there is a lack of measurement of suspended particles and high labor costs to maintain the catching devices.

Analytical models of road erosion provide catchment scale estimates of sediment production, but rely on algorithms developed from previous surface erosion studies (i.e. SEDMODL2, Forest Service WEPP, or the Washington Road Surface Erosion Model). Estimates of road sediment production can be generated from road surface erosion models provided the assumptions used to develop the model are understood. Lack of regional calibrations and applicability of model algorithms can make model results inaccurate. The results can be improved if field observations of road erosion and runoff are included with a modeling effort as shown in the Road Sediment Model (RSM) (Petersen et al, 2004). However, field observations must be taken with an appropriate sampling design to allow inference to catchment scale results.

The two most common models of sediment production from roads that are used in the Pacific Northwest are SEDMODL2 and the Washington Road Surface Erosion Model (WARSEM). These models were originally developed to analyze surface erosion from forest roads for the Washington State Watershed Analysis and are widely used across the region for a variety of objectives. For example, SEDMODL2 was used as an evaluation tool in a model to reduce culvert spacing to reduce sediment (Damian, 2001), incorporated in haul routing evaluations (Krogstad and Schiess, 2000), or road design and alignment evaluations (Akay and Sessions, 2005). WARSEM and SEDMODL2 are used in regulatory planning and decision making in California for Total Maximum Daily Loads (La Plante, 2005) and monitoring of aquatic habitat conservation in Washington (Raines et al., 2005).

Explicit in the uses of WARSEM and SEDMODL2 are the accuracy of the model results. The assumption is that the models give a reasonable interpretation of the magnitude and spatial extent of road sediment production. However, in Oak Creek Amman (2004) demonstrated that SEDMODL2 did not accurately estimate the magnitude of sediment production for road sites. The problem lies in the use of averages for rainfall, traffic and road attributes over a relatively course spatial and temporal scale. Without site specific information of the hydrologic response of roads it cannot be expected that these models will provide accurate results for the variety of hydrologic responses and erosion that roads exhibit. However, the models could provide a platform for the spatial extrapolation of sampled road hydrology and sediment observations.

The measurement of suspended sediment can provide the most accurate assessment of sediment production because direct observations are taken. However, sediment samples are costly to analyze and the number of samples needed to characterize a storm flow event are large. Because of this turbidity is measured and used as a surrogate for suspended sediment observations. Turbidity correlates with suspended sediment concentrations; however the relationship between the turbidity and suspended sediment is localized and should be determined on a site specific basis (Lewis, 1996). Turbidity cannot replace suspended sediment samples, but is an asset as an auxiliary sampling method to supplement suspended sediment observations. Turbidity observations can be taken continuously minimizing the number of sediment samples to be taken. Because turbidity is collected continuously it allows observations of sediment “spikes” not accounted for by periodic storm flow suspended sediment samples (Lewis and Eads, 2001).

A method of turbidity and suspended sediment observations to assist with sediment load estimation is provided by Lewis and Eads (2001). Their method uses continuous turbidity observations with suspended sediment randomly sampled within turbidity threshold ranges. This turbidity threshold sampling (TTS) reduces the amount of suspended sediment samples needed to estimate the sediment load. When combined with storm run-off observations TTS can provide accurate road sediment rates at road discharge points. Road discharge and TTS observations would need to be taken with a statistically appropriate sampling scheme to allow inference to catchment scale results.

Although the use of TTS reduces the cost of sediment sampling compared to taking continuous sediment samples, TTS can be labor intensive to implement and the instruments used in TTS are expensive. Challenges also occur associated with low run-off levels from roads that make the turbidity observations difficult with the turbidity sensors on the market at this time.

A relationship between road runoff volume and sediment load was observed in Oak Creek (Amman, 2004). If this relationship can be identified across an entire catchment then measurements of road runoff could be used in conjunctions with sampling road sediment delivery locations. The relationship between the sediment load and road runoff sampled in the catchment could be used to extrapolate sediment load to the remaining road sediment delivery locations by using road runoff observations. This potentially could provide a more accurate spatial extrapolation of estimated sediment load than the use of road erosion models. Similarly, if a hydrologic model, like DHSVM, which can estimate road runoff is used in combination with a road runoff and sediment load relationship it may provide a better estimate of road sediment contribution then current road erosion models.

Another inexpensive approach to estimate road sediment delivery is the use of synoptic sampling. This approach requires water and sediment samples collected at all road discharge locations at approximately the same time during a runoff event. This approach provides information on the relative magnitude of sediment delivery from road locations. This would not necessarily be an approach to quantifying sediment load rather a tool to identify which road locations are producing the greatest magnitude of sediment delivery for prioritization of maintenance or infrastructure improvement needs.

This chapter presents an analysis of road discharge, turbidity, and suspended sediment sampling from forest roads in Oak Creek in the Coast Range of Oregon and the South Fork of the Albion River in the Coast Range of California. The road hydrologic and sediment observations were used in conjunction with road erosion models, road runoff observations in Oak Creek, and a distributive hydrologic model for spatial extrapolation of individual road observations.

The objectives of this chapter are:

- To examine the use of road runoff data to estimate fine sediment production from forest roads.
- To determine the utility of road runoff and sediment production for use with existing road sediment models and a distributive hydrologic model for spatial extrapolation of sampled roads to a catchment scale.
- To determine sampling methods for accurate estimation of road sediment production using road runoff observations.

METHODS

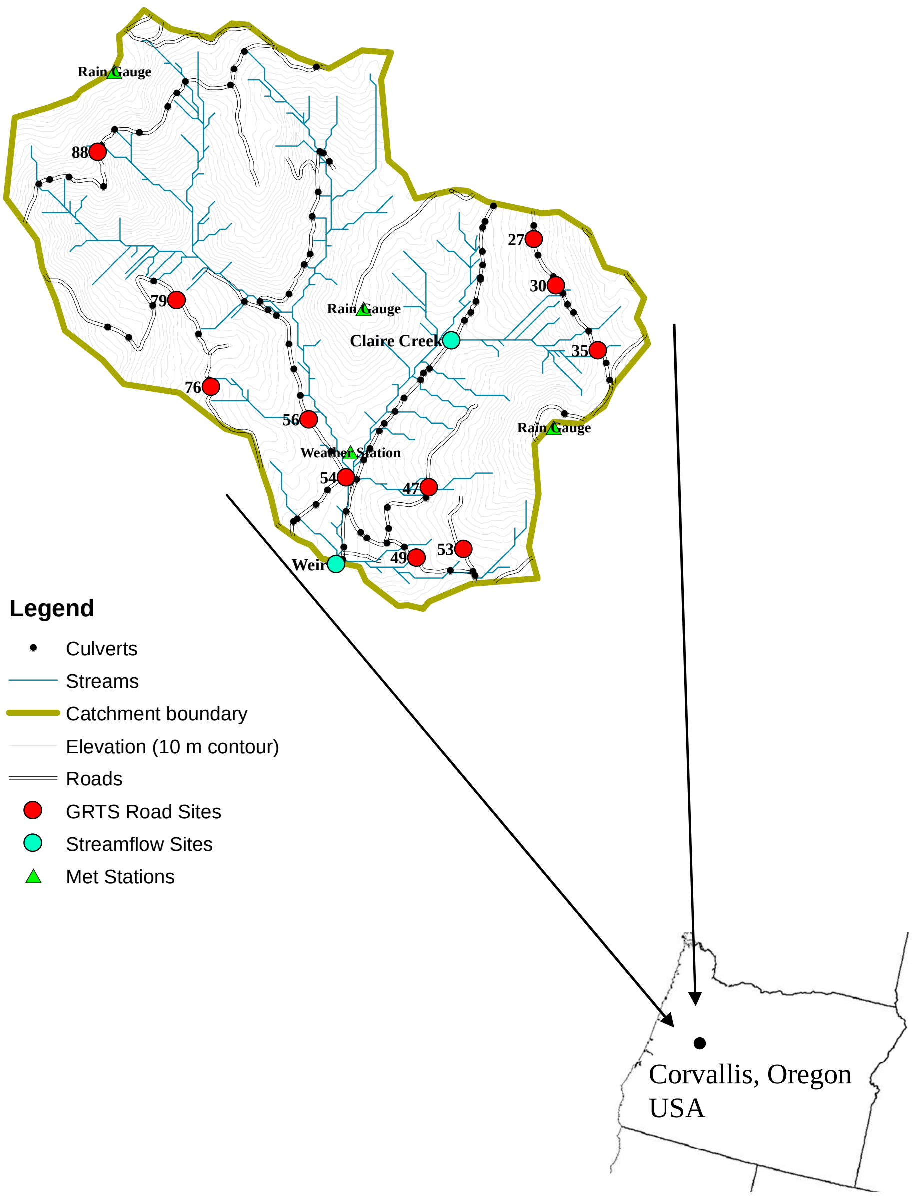
Road Hydrology, Turbidity, and Suspended Sediment Measurements for Oak Creek, Oregon

Study Area: Oak Creek, Oregon

This study was conducted in the upper Oak Creek catchment. The upper portion of Oak Creek is part of the McDonald/Dunn Forest, owned and managed by the College of Forestry, Oregon State University. The study catchment area was 630 hectares; measured to the Oak Creek stream gaging weir (Figure 4.1). Elevations within the research catchment ranged from 140 to over 600 meters and hillslope gradients ranged from 20 to over 80 percent. The average annual precipitation for the Oak Creek catchment for 2003 thru 2007 water years was 970 mm per year, with a range of 830 to 1110 mm. Precipitation comes predominately as rain, the low lying foothills of the Coast Range have an annual average snowfall of approximately 110 mm per year (Oregon Climate Service, 2005). The bedrock underlying the watershed was the Siletz

River Volcanics, a basalt formation (Knezevich 1975). Soils in the watershed were classified as silty clay loam; some areas of silty loam were present (Knezevich 1975). The forest type was predominately Douglas-fir (*Psuedotsuga menziesii*), with minor components of other conifer, hardwood species, and grass meadows.

There was an estimated drainage density of 24 m/ha as based on the stream channels created with the “createstreamnetwork.aml” that accompanies DHSVM (see Chapter 3). The road density was 5.55 m/ha (Toman, 2004). The roads were, on average, five meters wide, had unpaved crowned surfaces, and roadside ditches. There were 114 drainage structures (culverts) within the study catchment for 2006 and 2007 water years, the time period of this study. Of these structures, 23 were stream crossing culverts and the remaining 91 were drainage relief culverts. A stream crossing culvert was defined as a culvert that ran surface water at least part of the year and was directly connected to the stream channel as evidenced by a defined channel for at least 10 meters upslope of the culvert invert and a defined channel below the culvert outlet that converged with another stream channel (Toman, 2004).



<u>Figure 4. 1</u>. Upper Oak Creek Study Catchment and Study Sites, Corvallis, Oregon.

The 114 drainage structures were instrumented to collect stage measurements for calculation of storm run-off. The majority of these instruments have been in place since 2001 and continuously maintained by the Department of Forest Engineering, Oregon State University. The 23 stream crossings have capacitance rods installed at the invert of the culverts to continuously measure stage. Trapezoidal flumes were installed in the adjoining ditches just up-road from the stream crossing culverts; capacitance rods measured stage at the flumes. The 91 cross-drain culverts, culverts that drained water from the road surface or road cut-bank from a ditch then drained the water under the road, had stage measured either with capacitance rods or crest gages. Capacitance rods are installed at the inlet of 45 of the cross drain culverts; the remaining 29 cross drain culverts have crest gages installed to measure the peak stage. Crest gages were randomly distributed among the cross drain culverts. The gaging station at the outlet of the Oak Creek had continuous stage and turbidity observations, collected since 2001 and 2003 respectively.

Road Turbidity and Sediment Runoff Sample Design for Oak Creek

The equipment used to measure suspended sediment and turbidity in Oak Creek could only be used at the outlet of culverts, so only ditch relief culverts were sampled. Stream crossing culverts had water and sediment passing through the culvert that did not necessarily come from a road, which eliminated them from selection. The road segments within Oak Creek were further classified as either intermittent or ephemeral. Culverts that drained road segments classified as intermittent (~48% of the culverts) flow seasonally. Culverts that drained road segments classified as ephemeral (~52% of the culverts) flow only in direct response to rainfall. In Oak Creek, the intermittent culverts produced the greatest amounts of road run-off and subsequently the majority of sediment. Sediment and turbidity measurements were concentrated on intermittent road segments with a weighting of 80% on intermittent culverts and 20% on ephemeral culverts.

There were 91ditch relief culverts in the sample frame. The culverts that were selected for turbidity and suspended sediment measurements were selected based on a Generalized Random Tessellation Stratified design (GRTS) (Stevens and Olsen, 2004). The sample arranged the culverts in the sample frame into a randomly selected list such that selection of sites was balanced spatially across the watershed. The goal was then to collect measurements from as many of the culverts as possible for the 2006 and 2007 water years. To ensure more measurements on intermittent culverts, for intermittent culverts were selected for each ephemeral culvert. Initially the plan was to move the road sediment and turbidity monitoring stations to a different culvert after individual storms. However, difficulty in set-up and movement of equipment led to multiple storms being monitored at every culvert. There were 3-5 monitoring stations set up throughout the watershed at any one time. These monitoring stations were relocated after 1-2 months at a culvert.

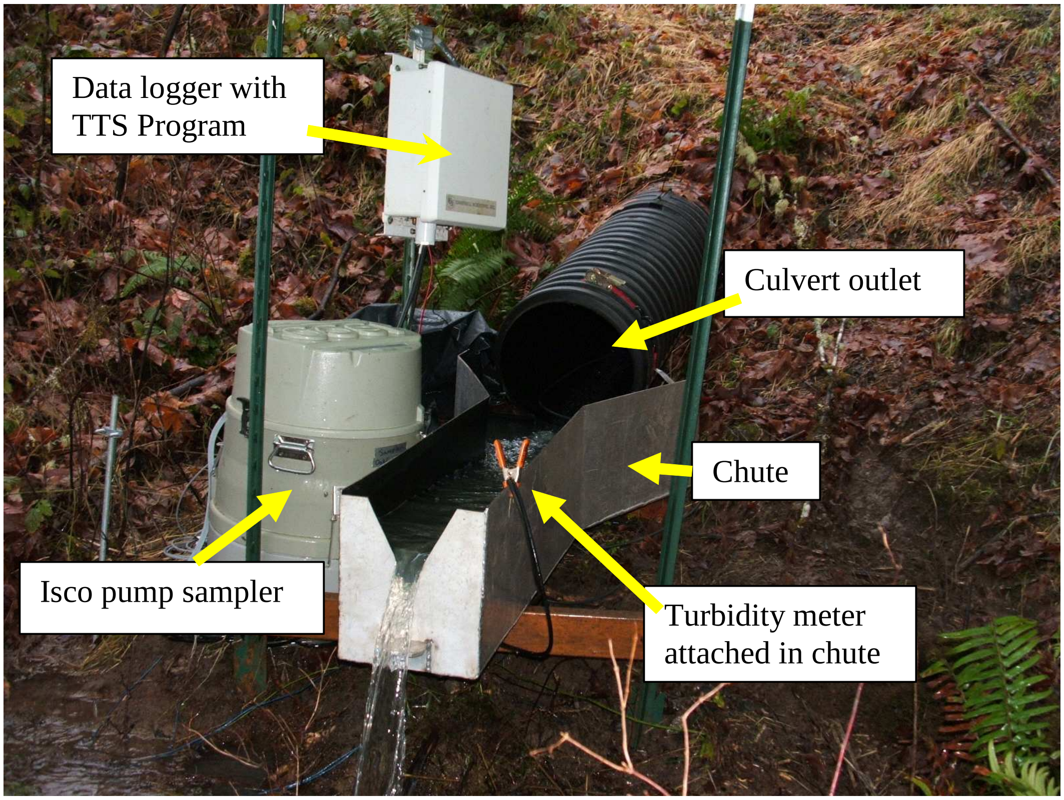
At total of 18 culverts had measurements of turbidity and suspended sediment during the two winters, 15 intermittent and 3 ephemeral. Culverts that could not have equipment set-up at the outlet were skipped and the next culvert in order was selected. Reasons that equipment could not be installed included: inlet/outlet of culvert was buried, insufficient length of pipe to attach extension or chute, inability to excavate outlet for chute/extension attachment, or culvert drained into a water body.

Turbidity Threshold Sample Measurements in Oak Creek

The turbidity and suspended sediment measurements from roads in Oak Creek used a Turbidity Threshold Sampling (TTS) approach (Lewis 1996). The TTS measurements were conducted by Matthew Meadows for use in his Master of Science Thesis research (Meadows, 2007). The TTS approach used an integrated set of measurements of stage, turbidity, and sampled suspended sediment. Turbidity and stage were measured continuously while suspended sediment samples were taken based on changes in incremental turbidity and discharge thresholds (Lewis and Eads, 2000).

The equipment used for the TTS sampling was a chute attached to the outlet of the culvert to briefly pond and mix water for turbidity measurements and water samples (see Figure 4.2). The chute was installed on a 5^0 angle (9% grade) at all sites to minimize differences between locations caused by non-uniform particle settling. The stage of water entering the culvert was measured with a pressure transducer at the culvert inlet. Discharge through the culvert was calculated from stage with a rating curve (Toman 2004). Measurements of turbidity and stage were taken at ten minute intervals and recorded in a data logger. Water samples were taken using an ISCO 3700 automated water sampler within the chute at the culvert outlet. A program supplied by the Redwood Sciences Lab (United States Forest Service Pacific Southwest Research Station, Arcata, CA) controlled suspended sediment sampling based on the turbidity levels being measured.

The water and suspended sediment samples from the ISCO samplers were put on ice then transported to Oregon State University (OSU). The samples were put in a refrigerator at 40 degrees Fahrenheit until the samples were analyzed. In the OSU lab, each water sample was filtered through 1.5 μm glass fiber filter paper then oven dried to provide the oven dry weight of suspended solids, including organic material. The suspended sediment concentration of the sample was determined by dividing the oven dry weight of the filtered solids by the volume of the water sample. Turbidity was measured in the lab by vigorously mixing the sample then reading the turbidity with a Hach Turbidimeter.



<u>Figure 4. 2.</u> TTS Equipment at Outlet of Culvert in Oak Creek for Measurement of Turbidity and Suspended Sediment from Roads.

Ongoing hydrologic measurement from roads at Oak Creek was being done at the same time as the TTS measurements. Each culvert measured for sediment and turbidity maintained either a capacitance rod or a crest gage even when the TTS equipment was installed on a culvert. More importantly these road run-off measurements were maintained before and after the TTS equipment was used on a culvert providing road run-off information for the entire water year. The culvert number, time of monitoring, and number of storm events captured is documented (Table 4.1).

Table 4. 1. Summary of Sediment, Water, and Turbidity Measurements for Culverts in Oak Creek, 2006 and 2007 Water Years.

Culvert ID	Type	Period of Measurement	Water Year	Number of Storms Measured
7	Intermittent	12/14/05 – 1/5/06	2006	3
43	Intermittent	12/19/05 – 1/2/06	2006	3
68	Ephemeral	12/19/05 – 1/4/06	2006	3
80	Intermittent	12/20/05 – 1/4/06	2006	3
66	Intermittent	1/6/06 – 1/24/06	2006	6
81	Ephemeral	1/6/06 – 1/24/06	2006	0*
91	Intermittent	1/6/06 – 1/24/06	2006	4
10	Intermittent	11/20/06 – 12/6/06	2007	5
15	Intermittent	12/8/06 – 1/13/07	2007	5
25	Intermittent	2/7/07 – 3/16/06	2007	4
26	Intermittent	11/3/06 – 1/10/07	2007	7
27	Intermittent	11/6/06 – 12/20/06	2007	7
28	Intermittent	12/20/06 – 3/6/07	2007	11
33	Intermittent	10/16/06 – 11/20/06	2007	7
40	Intermittent	11/2/06 – 1/24/07	2007	10
47	Intermittent	1/26/07 – 3/16/06	2007	5
73	Intermittent	1/19/07 – 3/16/07	2007	8
116	Ephemeral	10/18/06 – 12/6/06	2007	0*

0* - No flow at culvert

Calculation of Sediment Load for Culverts with TTS Measurements in Oak Creek

The run-off, turbidity, and suspended sediment measurements from roads were used to calculate the total suspended sediment load for each storm. Following the approach discussed in Lewis (1996) relationships between turbidity and suspended sediment were developed by storm or groups of storms that had four or more sediment samples. Sediment concentrations (mg/l) were estimated for each turbidity measurement from the turbidity to suspended sediment relationship developed for storms. The total sediment mass (mg) for each ten minute time period that stage was measured was calculated by multiplying the suspended sediment concentration (mg/l) by the volume of water discharged for that time period (liters/10 minutes). The total sediment load for the storm was the sum of the sediment mass per 10 minute time period for the storm. This total mass is represented in tons for comparison with SEDMODL2 and WARSEM output.

Sediment rating curves (a linear relationship between discharge and suspended sediment concentration) were developed for each road culvert from all of the sediment samples taken at a culvert. The sediment rating curve estimated sediment load for the portion of the water year before and after the TTS equipment was used at the culvert. From sediment rating curves sediment load was calculated by summing for each time interval the product of discharge (l/s) by the sediment estimated from the sediment rating curve (mg/l) times the amount of time between measurements (600 seconds). The estimates from the sediment rating curve were then adjusted based on the sediment load results of the TTS approach. The rating curve estimate was divided by the TTS estimate for the time period TTS results were available; the rating curve estimates for the remaining portion of the year were adjusted by this quotient. Total sediment load for the water year was only calculated with this combined TTS and rating curve approach for culverts with continuous run-off measurements for the water year. These were culverts 7, 26, 27, 43, 47, 73, 80, and 116. The remaining culverts had crest gages that could not be used with a rating curve.

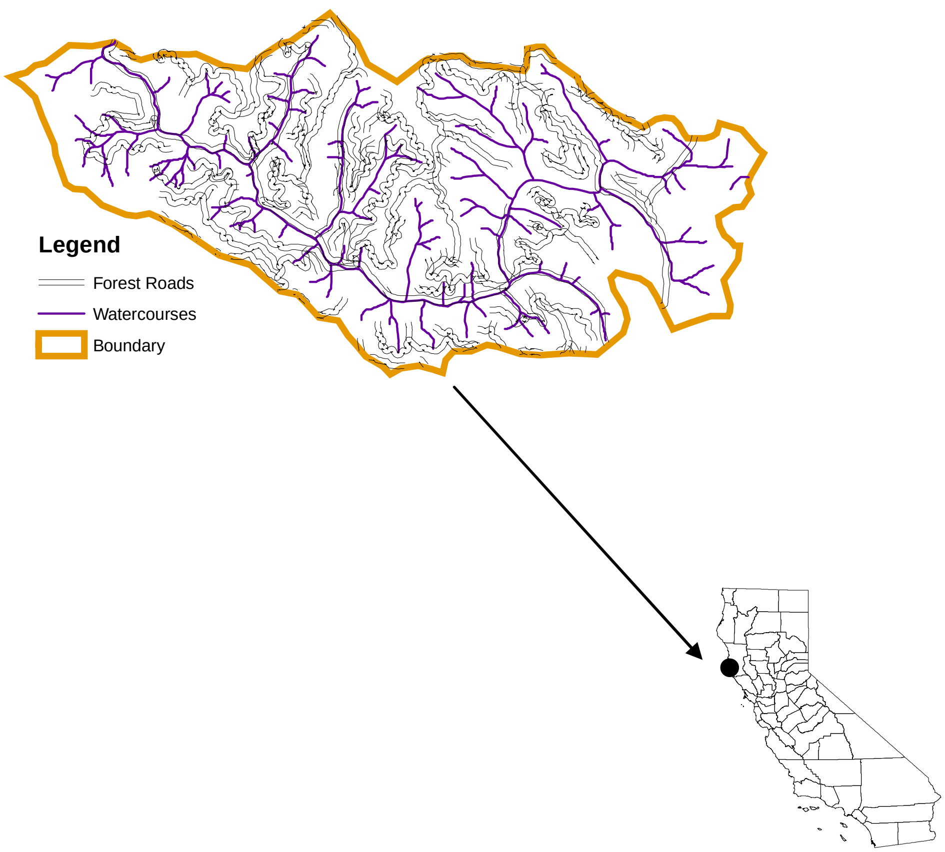
The road culverts with crest gages had measurements observed once per month when equipment maintenance and capacitance rod data download occurred. Only the highest discharge for the month was available for the crest gage culverts. To estimate the missing storms, relationships were developed for storm volume between culverts with continuous flow and crest gages. The first choice was to develop a relationship between sites for storm volumes with the run-off data collected from the TTS equipment. If this was not possible then the relationship was developed from capacitance rod information from a culvert in close proximity to the crest gage site being estimated.

The storms with TTS sediment load estimates were used to develop peak flow to sediment load and storm volume to sediment load linear regression equations. These relationships were used to estimate sediment load for missing storms at culverts with crest gage measurements. The storm sediment loads were summed for the water year providing an estimate of total fine sediment for the culvert for the water year.

Road Hydrology, Turbidity, and Suspended Sediment Measurements for the South Fork of the Albion River, California

Study Area – The South Fork of the Albion River, California

The South Fork of the Albion River is a 5,830 acre tributary of the Albion River. The Albion River is a coastal watershed located in western Mendocino County, California, approximately 16 miles south of Fort Bragg, with the river outlet adjacent to the town of Albion (Figure 4.3). Rainfall is seasonal in this region, with most of the rain (approximately 1200-1400 mm/year) occurring between October and May. The Albion River is characterized by the Coastal Belt of the Franciscan Complex, except for the eastern headwaters of the Upper Albion River Planning Watershed which is underlain by Mesozoic volcanics. Rocks of the Coastal Belt are highly sheared and comprised of structurally deformed massive, hard greywacke sandstone and shale interbedded with small amounts of limestone and pebble conglomerate. Soils in the Coastal belt hard rocks are of the Inceptisol soil order.



<u>Figure 4. 3</u>. South Fork of the Albion River, California

Mendocino Redwood Company owns 81% of the land in the South Fork of the Albion River; managing the land primarily for timber production. At the time of this study there were 64 miles of forest roads within the South Fork of the Albion River of which 24.9 miles had rocked surfaces, 38.4 miles had native surfaces, and 0.7 miles were undetermined. The road density was 7.0 miles per square mile. Within the road network there were 266 culverts and crossings that consisted of 10 bridges, 93 watercourse crossing culverts, and 173 ditch relief culverts.

Sample Design for Road Runoff and Suspended Sediment Measurement for the South Fork of the Albion River

The road hydrologic and sediment measurements were sampled randomly from six road classes. The six road classes were developed to capture the range in road hydrologic and erosion conditions in the catchment. A description of each road class and number of locations selected for measurement is shown in Table 4.2. The sampling frame for each road class was locations of road sediment delivery to a watercourse. This was assumed to be road watercourse crossings and ditch relief culverts for roads directly adjacent to a watercourse. A sample of 4-8 culverts was initially selected from each road class. Complexities in field conditions varied the amount of sites sampled per road class. The 10 bridges were excluded from the sample frame due to the difficulty in making hydrologic and erosion observations on the road approaches to the bridges.

Table 4. 2. Road Class Descriptions and Number Road Hydrologic and Erosion Sample Sites.

Road Class	Road Class Description	Total Number of Sites in the Sample Frame	Total Number of Sites Sampled
1	Mainline road (Keene Summit road) with log hauling during 2006 or winter 2006/2007.	51	3
2	Mainline road (Keene Summit road) without log hauling during 2006 or winter 2006/2007.	7	2
3	Seasonal or temporary roads on upper hillslopes with log hauling during 2006 or winter 2006/2007.	3	3
4	Seasonal or temporary roads on upper hillslopes without log hauling during 2006 or winter 2006/2007.	44	4
5	Seasonal or temporary roads on lower hillslopes with log hauling during 2006 or winter 2006/2007.	4	3
6	Seasonal or temporary roads on lower hillslopes without log hauling during 2006 or winter 2006/2007.	52	8

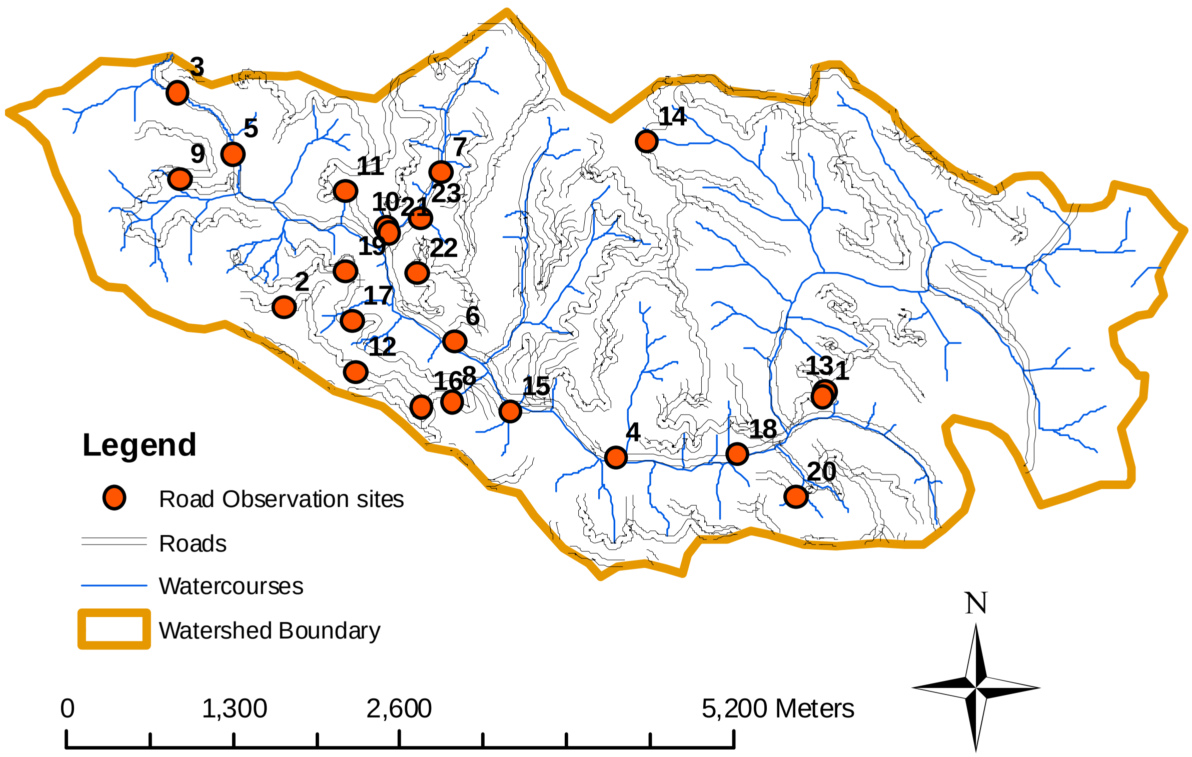
The road sites selected for road hydrologic and sediment measurements were observed for the winter of 2006 through 2007. Of the 23 sites selected 12 were deployed in November, 2006 and removed in May, 2007. The remaining 11 sites had 9 added to the study in January, 2007 then removed in May, 2007 and two sites were added in February, 2007 and removed in May, 2007. The 11 sites were added in early 2007 when it was realized that having additional sites for measurements would benefit the study.

Road hydrologic measurements were collected in a circular flume as described in Samani and Herrera (1996). This type of flume is a low cost water measuring device made with PVC pipe, all parts of the flume can be purchased at a plumbing or hardware store and built by hand. A stilling well was added to the flumes to allow use of electronic stage recording instruments (capacitance rods or pressure transducers) or crest gages (Figure 4.4). Prior to installing flumes in the field the published rating curve (Samani and Herrera, 1996) was tested by running water at varying flow levels through the flumes; a graduated cylinder and stop watch measured the flow. These observations agreed with the published rating curve; however I was not able to simulate the very highest flows capable of measurement in the flume. A 10-20% deviation was found from the published rating curve at the lowest stage observations (<25 mm). Because of this discrepancy for the rating curve at the lower stages several timed water volume samples for varying water stages were taken from the flumes while in the field. A linear relationship was determined from these observations and used as the rating curve for stages less than 25 mm.

There were 23 flumes placed on roads; 17 small flumes (6 inch inlet) and six large flumes (12 inch inlet). The 12 inch flumes were put in locations where it was suspected a large amount of road water flow would occur. The small and large flumes were put either in the road ditch or at the road edge. If the road surface and cutslope drained to a ditch then the flume was installed in the ditch. If the road surface drained to the outside edge of the road then the flume was placed at the location on the road edge where water was discharged (typically at the outlet of a water bar or dip in the road). A few of the locations were initially placed in the road ditch then moved to the road edge when it was determined it was a better measure of the hydrologic and erosion characteristics of the road segment.

<u>Figure 4. 4</u>. Hand Made Circular PVC Flume Fitted with a Stilling Well for Road Hydrologic Measurement; This View is Looking into the Flume Inlet.

Of the 23 road sites, 12 had electronic data loggers for water stage measurement and 11 were fitted with crest gages for measurement of peak water stage. The 12 electronic data loggers were capacitance rods, 10 manufactured by Odyssey and 2 manufactured by Omnilog. The initial locations for the data loggers were the first 12 sites selected from the sample design. The data loggers were moved to other sites throughout the winter when it was learned a site was not flowing water or a record of continuous flow was wanted at another location. The locations of road hydrology and sediment measurements are shown (Figure 4.5). The details of data logger and crest gage use are shown (Table 4.3).



<u>Figure 4. 5</u>. Road Hydrologic and Erosion Observation Sites in the South Fork of the Albion River, California.

<u>Table 4. 3</u>. Description and Timing of Data Loggers and Crest Gages for Road Observation Sites, South Fork of the Albion River Water Year 2007.

Site #	Road Class	Flume Size	Flume Placement Location	Data Logger Installed	Data Logger Removed	Crest Gage Installed	Crest Gage Removed	Comments
1	6	small	Ditch	11/7/2006	5/1/2007			
2	4	small	Road Edge	11/7/2006	2/8/2007	2/8/2007	5/1/2007	
3	2	large	Ditch	11/7/2006	5/1/2007			
4	1	large	Ditch	11/7/2006	1/5/2007			
5	2	large	Ditch	11/7/2006	5/1/2007			
6	1	large	Ditch	11/7/2006	5/1/2007			
7	6	large	Ditch	11/7/2006	5/1/2007			
8	3	large	Ditch	11/7/2006	2/7/2007	-	-	
8a	3	small	Road Edge	2/8/2007	5/1/2007			#8 moved to edge
9	5	small	Ditch	11/7/2006	2/8/2007	2/8/2007	5/1/2007	
9a	5	small	Road Edge			2/8/2007	5/1/2007	#9 moved to edge
10	6	small	Ditch	11/7/2006	5/1/2007			
11	3	small	Ditch	11/7/2006	2/8/2007			
11a	3	small	Road Edge	2/8/2007	5/1/2007			#11 moved to edge
12	4	small	Edge	11/7/2006	5/1/2007			
13	6	small	Ditch			1/3/2007	5/1/2007	
14	4	small	Road Edge			2/7/2007	5/1/2007	
15	5	small	Ditch			1/4/2007	5/1/2007	
16	4	small	Road Edge			1/4/2007	5/1/2007	
17	6	small	Ditch			1/4/2007	5/1/2007	
18	1	small	Ditch	1/5/2007	5/1/2007			
19	6	small	Ditch			1/4/2007	5/1/2007	
20	6	small	Ditch			1/3/2007	5/1/2007	
21	6	small	Ditch			1/3/2007	5/1/2007	
22	3	small	Road Edge	2/8/2007	5/1/2007	1/3/2007	2/8/2007	
23	5	small	Road Edge	2/9/2007	5/1/2007	1/3/2007	2/9/2007	

Road Sediment and Turbidity Measurements

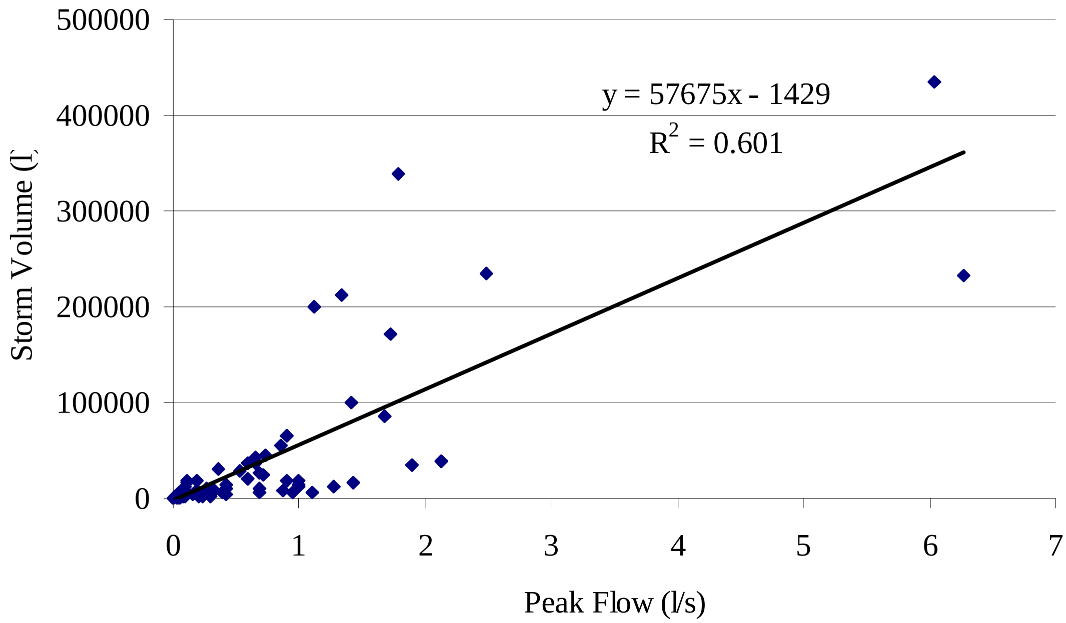
Sediment and turbidity observations were obtained from water samples “grabbed” by hand at flumes. The grab samples consisted of filling a 500 milliliter bottle at the flume outlet. The stage, date, and time of the sample were recorded. The roads had water samples taken during four storm events in January and February, 2007. The samples were collected by traveling around the road network during a rain storm. No systematic pattern or design was used to collect water samples; generally all sites were visited prior to taking another sample at a site. The sediment and turbidity samples were repeated until the storm ended or the person doing the sampling needed to sleep or rest. For the four storms sampled, 180 water samples were collected.

Immediately after collection the water samples were put on ice then transported to Oregon State University (OSU). The samples were put in a refrigerator at 40 degrees Fahrenheit until the samples were analyzed. In the OSU lab each water sample was filtered through 1.5 μm glass fiber filter paper then oven dried to provide the oven dry weight of suspended solids, including organic material. The suspended sediment concentration of the sample was determined by dividing the oven dry weight of the filtered solids by the volume of the water sample. Turbidity was measured in the lab by vigorously mixing the sample then reading the turbidity with a Hach Turbidimeter. Of the 180 samples: 170 samples had both sediment and turbidity measured, 10 samples were not transported to the lab and had only turbidity observations.

Data Analysis of Hydrologic Measurements

The stage measurements collected with the capacitance rods were used to estimate the run-off for the road site. Generally the Odyssey data loggers provided accurate information on flume stage throughout the observation time period. Each time a road site was visited the stage in the flume and time of observation was recorded. These observations were used to check the stage levels recorded by the data loggers. In some cases inaccuracies in the flume's recorded stage occurred due to sediment or debris in the flume or stilling well. The observations from site visits allowed for corrections to the stage records. Once the stage records were confirmed or adjusted the flow was calculated from the published rating curve for the flumes (Samani and Herrera, 1996) and the observed relationship of stage to discharge for stages less than 25 mm.

For each of the road sites with continuous hydrologic measurements, storms were isolated and the storm runoff volume and peak discharge determined. Linear regression was used to determine the relationship between peak discharge and storm volumes (no estimated or simulated data used). This linear regression showed a statistically significant relationship for the storm peak flow and storm volume (adj. $r^2 = 0.60$; p value <0.0001) (Figure 4.6). Three storms were removed from this analysis because they were outliers; the storms represented abnormal hydrologic response due to a spring in the road cut. When these three storms are left in the data set, the linear relationship is still statistically significant, but the adjusted r^2 lowers to 0.28.



<u>Figure 4. 6</u>. Relationship between Storm Peak Flow and Volume for Road Run-off; South Fork Albion River Watershed.

The roads and time periods that had continuous stage measurements were used for extrapolation to sites with crest gages or sites with time periods without measurements. Several techniques were used to extrapolate hydrologic information from one site or time period to another. These were relationships between sites storm peak flow, sites storm volumes, development of unit hydrographs from precipitation information, and the relationship between the mean of storm sediment samples and sediment load. The following (Table 4.4) summarizes each sites data set and number of storms estimated using the extrapolation techniques.

Table 4. 4. Number of Storms Observed by Site or Extrapolated for Missing Hydrologic Data for the South Fork of Albion River; 2007 Water Year.

Site	Number of Storms					
	Continuous or Crest Gage Observed	Peak Flow Relationship	Storm Volume Relationship	Unit Hydrograph	Suspended Sediment Samples to Load	Total
1	7	4		1	2	14
2	5			10		15
3	7		7			14
4	14					14
6	14					14
7	14					14
8	3			11		14
9	4			11		15
10	6	5			3	14
11	14					14
12	12	3				15
13	14					14
14	3			12		15
15	14					14
16		4		10	1	15
17		11			3	14
18	8		6			14
19	14					14
20	14					14
21	4	11				15
22	9			5		14
23	6			7	1	14

Road site 5 was removed from the analysis because a watercourse drained into the road ditch. The water from the watercourse was much greater than road run-off and made the observations from the site not representative of the effect from the road.

Calculation of Sediment Load for Sampled Road Segments in the South Fork of the Albion River

The hydrologic data and sediment samples from roads were used to calculate the total suspended sediment load for each storm. Sediment rating curves (a linear relationship between discharge and sediment) were developed for each road site for the winter or for individual storms or groups of storms that had four or more sediment samples. The sediment rating curve with the best fit to the data was used to predict the total sediment load. If sediment rating curves could be developed for individual storms, these were used for those respective storms. For all other storms the sediment rating curve for the entire winter was used. In many cases, because of low number of sediment samples, only a sediment rating curve for the winter was developed for a site. Total sediment load for each storm event was calculated by summing the product of the volume of each discharge measurement by the sediment amount predicted from the sediment rating curve times the amount of time between measurements.

The calculated storm sediment loads were used to develop peak flow to sediment load and storm volume to sediment load relationships. These relationships were attempted from data for all sites, for individual sites, by road classes, and by road surface (rocked vs. native). The relationships for individual sites and by road class provided the best linear relationships. There was not good correlation for peak flow or storm volume and sediment load when data from all sites was combined or when only separated by road surface type (Appendix D).

Sediment load was estimated for sampled roads from the relationships between peak flows, storm volumes, or the mean of sediment samples and sediment load for storms from missing time periods at road sites. The peak flow to sediment load relationship was used for road sites with crest gages. The relationship for the road class or from a road with similar characteristics was used to estimate sediment load for storm runoff at the road. The load estimate for each storm was summed for each road measured to provide the total fine sediment for the road for the 2007 water year.

Calculation of Variance and Confidence Intervals for Sediment Loads of Observed Road Locations in Oak Creek and the South Fork of the Albion River

Suspended sediment measurements and their associated runoff are variable. Because of this variability, relationships developed from sediment measurements will have a large amount of uncertainty associated with them. In addition, the extrapolation of sediment load, storm volume, or peak flow estimates to sites with missing information introduces more uncertainty and error. To quantify the uncertainty, 95% confidence intervals were derived from the variance of the various measurement and estimation techniques. The 95% confidence intervals were presented for the total sediment loads to demonstrate uncertainty in results.

The variance of the total sediment load was the sum of the variances for each storm sediment load. The resulting standard error of the total sediment load was the square root of annual sediment load variance. The variance of storm sediment load for storms when a sediment rating curve was used calculated the variance for each discharge observation (see equation below) then summed the individual discharge variances to obtain the variance for the entire storm.

Storm sediment load variance (1) = $\sum_{i=1}^{n} [(1/n + \frac{(x_i - \bar{x})^2}{(n-1)\sigma_x^2})^{1/2} * \sigma_y]^2$

Where: n = number of flow observations in storm

x_i = ith observation of flow

$\bar{x}$ = mean of flow observations of storm

σ_y = standard deviation for suspended sediment estimates

σ_x^2 = variance of flow estimates of storm

A different method to calculate variance was used for storm sediment load estimates where two relationships were used for the estimate. For example, if a site had storm volumes or peak flows predicted from another site then a relationship was used based on storm volume or peak flow to estimate sediment load the variance must consider both relationships. The following equation was used for calculating variance developed from two relationships:

Storm sediment load variance (2) =

$$Var(y) + Var(y)*Var(b_0) + (b_0)^2 *Var(y) + (\hat{y})^2*Var(b_0) + Cov(b_0\ b_1)$$

Where: $Var(y)$ = variance of observed independent variables used for estimate of missing hydrologic variables.

b_0 = slope term for linear regression equation estimating storm sediment load.

B_1 = intercept from linear regression equation estimating storm sediment load.

$Var(b_0)$ = variance of slope term for the dependent variable in linear regression equation estimating storm sediment load.

$Cov(b_0\ b_1)$ = result of multiplication of covariance of slope and intercept term of linear regression equation estimating storm sediment load.

$\hat{y}$ = the independent variable (storm volume or peak flow).

Road Erosion Model Use

SEDMODL2 and WARSEM

To attempt the spatial extrapolation of the suspended sediment loads sampled from roads to the larger catchment scale two road erosion models were used. The models were SEDMODL2, a Geographic Information System (GIS) based road erosion delivery model (NCASI, 2002), and the Washington Road Surface Erosion Model (WARSEM), a database road erosion delivery model. Both models use the same calculations for estimating road surface erosion, the difference between the models is data input to the models. For SEDMODL2 the road characteristics and sediment delivery potential are determined from evaluation of the road based on a digital elevation model (DEM). Parameter values such as slope, proximity to watercourses, road cutslope heights, and contributing road tread length are determined from a road layer and DEM in a ArcInfo program. WARSEM does its calculations based strictly on user defined values of the road network, typically from field observations. The parameters used for the two models are only briefly described. A more thorough description of SEDMODL2 can be found in a technical document provided from a web page maintained by the National Council of Air and Stream Improvement (NCASI, 2002). A thorough description of WARSEM can be found in a technical document (Dube et al, 2004) and downloaded from a web page maintained by the Washington Department of Natural Resources (WA DNR, 2007).

In SEDMODL2 and WARSEM total sediment delivered (in tons per year) from each road segment is calculated by the road tread plus the cutslope delivered sediment times a road age factor.

The Tread Delivered Sediment = Geologic Erosion Factor x Tread Surfacing Factor x Traffic Factor x Segment Length x Road Width x Road Slope Factor x Rainfall Factor x Delivery Factor

Cutslope Delivered Sediment = Geologic Erosion Factor x Cutslope Cover Factor x Segment Length x Cutslope Height x Rainfall Factor x Delivery Factor

The road age factor increases the sediment delivery estimate if a road was built in the last two years. The road segments in the GIS layers for Oak Creek and the South Fork of the Albion River used for this analysis were over two years old so no road age factor adjustment was used.

Estimation of Road Sediment from SEDMODL2 and WARSEM in Oak Creek

The road slope factor, cutslope height, and delivery factor were calculated in SEDMODL2 for Oak Creek using a DEM and stream layer. The digital elevation model (DEM) was created from 6 meter laser altimetry topography data using light detection and ranging technology (LIDAR) collected by the College of Forestry, Oregon State University. A 10 meter DEM for Oak Creek was projected from this LIDAR data and used in SEDMODL2. The stream layer was the same stream layer used in the hydrologic modeling of forest roads in Oak Creek (see Chapter 2 and 3). This stream layer was created by the “createstreamnetwork” Arcinfo script provided with the Distributive Hydrology Soil Vegetation Model (DHSVM, 2007). All roads were treated as secondary roads and were modeled with a light traffic factor. The road tread material, length, tread prism (outsloped, insloped, crowned), width, and cutslope cover were determined by a 100% field inventory of the roads. Road gradient, contributing length, and percent contribution of sediments were calculated from the DEM within SEDMODL2. The geologic erosion factor used was 1, which represents the underlying basalt geology of the catchment. The rainfall factor used was 4, based on a mean annual rainfall of 1020 mm.

WARSEM estimates of sediment delivery were calculated for all road segments in the Oak Creek catchment. The values of geologic erosion factor (1), precipitation factor (2), tread surfacing factor, and traffic factor were the same as used in the SEDMODL2 modeling. Field observed values of cutslope area (height x contributing length), cutslope vegetation cover, road contributing area (length x contributing width), and road gradient were used for the model calculations.

Estimation of Road Sediment Using SEDMODL2 and WARSEM in the South Fork of the Albion River

The road slope factor, cutslope height, and delivery factor were calculated by SEDMODL2 using a DEM and watercourse GIS layer. A DEM was provided by the Mendocino Redwood Company developed from United States Geological Survey data. The 30 meter DEM was “touched up” into a 10 meter DEM following instructions in Appendix B of the SEDMODL2 Technical Document (NCASI, 2002). The watercourse locations used were from a GIS shapefile provided by the Mendocino Redwood Company.

All roads were modeled as secondary roads, with the exception of the Keene Summit road (the main haul road in the watershed) which was a primary road. All secondary roads were modeled with a moderate traffic factor (value of 2), the primary road with high traffic factor (value of 10). The road tread, length, tread prism (outsloped, insloped, crowned), and width were supplied by Mendocino Redwood Company from field observations. The geologic erosion factor used was 1, to represent the coastal Franciscan belt geology. The rainfall factor used was 5.6, based on a mean annual rainfall of 1400 mm. Cutslope vegetation cover percentage was measured for the 22 road sites; for all other roads a uniform value of 55% cover was used.

Field measurements of road gradient, delivery factor, or contributing road length were not available for all road segments of the South Fork of the Albion River. Therefore a direct estimate of sediment delivery from the entire watershed with WARSEM was not done. An indirect estimate of sediment production was calculated to represent what a WARSEM estimate for the watershed might be. This indirect estimate used the ratio of the WARSEM and SEDMODL2 sediment estimates for the 22 road segments times the total sediment estimated by SEDMODL2. Although this is not an entirely accurate representation, it allows discussion and comparison of the two techniques.

Calculation of Parameters for Use in WARSEM and SEDMODL2 for Oak Creek and the South Fork of the Albion River based on Field Measurements of Road Sediment

The sediment load estimates based on road runoff, turbidity, and suspended sediment measurements from roads were used to calculate a combined geologic erosion factor, precipitation factor, and traffic factor within WARSEM and SEDMODL2. The geologic erosion factor represents the erosion rate based on the geology of the watershed; direct measurement of erosion from roads replaces this factor. The precipitation factor represents the hydrology affecting road erosion, the direct observations of road runoff replaces this factor. The traffic factor represents the amount of hauling and vehicle use on the road tread. The roads measured within Oak Creek and the South Fork of the Albion River were chosen by statistical sampling designs that selected roads spatially across the catchment. The roads in Oak Creek have similar design and use so a spatially balanced sample should capture the associated variance in road response. The roads within the South Fork of the Albion River Roads were sampled based on a stratification of position and use (log hauling in the previous year or not). Roads were selected that had both recent hauling and were inactive thus capturing the range of traffic effects on road erosion. This allowed the replacement of the traffic factor from the WARSEM and SEDMODL2 calculations with the road hydrology and sediment observations.

Within SEDMODL2 and WARSEM, the geologic erosion factor, precipitation factor, and traffic factor are multiplied, which allowed the three factors to be represented by one variable. For each of the road sites measured for runoff and suspended sediment a variable that represented the combined geologic erosion, precipitation, and traffic factors was adjusted within SEDMODL2 and WARSEM until results from the models equaled the annual sediment load estimate for the sampled road. A mean of all of the variables that represent the geologic erosion factor, precipitation factor, and traffic factor from each road was calculated for both Oak Creek and the South Fork of the Albion River. This mean value of the geologic erosion, precipitation, and traffic factor was used in SEDMODL2 and WARSEM to calculate the fine sediment contribution for the Oak Creek watershed for the 2006 and 2007 water years and the South Fork of the Albion River watershed for the 2007 water year.

The sediment measured from Oak Creek and the South Fork of the Albion River was the fine or suspended sediment in the road runoff. Both WARSEM and SEDMODL2 model total sediment, fine and coarse sediment, from road surface erosion. Some information on the percentage of coarse and fine sediment of the total sediment from road runoff was available in Oak Creek from Amann (2004). He found that settable sediment (coarse) varied in percentage of the total sediment load from 10-90%. In Mendocino County, on the Jackson State Demonstration Forest a few miles north of the South Fork of the Albion River, the percentage of coarse sediment in road runoff was observed to range from 12 to 67% (Barrett and Tomberlin, 2007). To provide an estimate of total sediment production from road surface erosion the fine sediment load estimates were adjusted by these percentages for the respective watersheds.

Calculation of Sample Size

To estimate the number of road sites in Oak Creek and the South Fork of the Albion River that should be monitored to reduce errors in catchment scale sediment load estimates the following equation was used:

$$\text{Number of road sites} = (Z_{\alpha/2})^2 * S^2/e^2$$

Where: $(Z_{\alpha/2})^2$ = Z statistic squared for a standard normal distribution with a two tailed probability of $\alpha/2$.

S^2 = Variance of sediment load estimates from 2007 water year.

e^2 = the acceptable error of the answer squared.

Catchment Scale Estimates of Road Sediment using Measured Road Runoff and Simulated Runoff in Oak Creek

A relationship between the peak flow or storm runoff volume and sediment load for storms was developed from culverts with TTS observations in Oak Creek. Oak Creek had road runoff measurements collected at every culvert in the catchment. The relationship between the peak flow or storm runoff volume and sediment load was used to calculate storm sediment loads for the remaining road runoff locations. The relationship between the peak flow or storm runoff volume and sediment load was also used to estimate sediment loads from roads for storms calculated by the Distributive

Hydrology Soil Vegetation Model (DHSVM). The description of how storms were identified, calculated, missing events extrapolated, and the process of simulation by DHSVM can be found in the method section of Chapter 3. The sediment load for storms for culverts calculated from runoff estimates were totaled and divided by two years to yield the total annual road sediment contribution (tons/year) for Oak Creek for the 2006 and 2007 water years. The sediment load for storms for culverts in Oak Creek for the 2006 and 2007 water years was also estimated using DHSVM simulated road runoff using the same relationship and procedure. The annual sediment load estimates were for fine sediment contributions, these estimates were adjusted by the percentage of coarse sediment discussed previously.

Grab Water Samples for Estimation of Road Sediment Load

Estimating Storm Sediment Load from Grab Water Samples

The culverts in Oak Creek with TTS measurements were used to determine if grab samples for suspended sediment concentration (SSC) could be related to storm sediment load. The SSC samples from the TTS measurements were used to represent grab samples. The TTS measurements were collected systematically and developed to reduce errors in storm sediment load estimates. A grab sample would be collected at random times when a person is available to collect samples during a storm. To attempt to replicate this random collection timing four, three, and two randomly selected TTS samples per storm were selected. Linear regression was used to determine if there was a relationship between the mean of the randomly selected suspended sediment concentrations and storm sediment load. Additional variables of storm peak flow and storm runoff volume were also tested to determine if these improved the relationship between suspended sediment concentration and storm sediment load.

Using a Synoptic Sampling Approach for Determining Sediment Production from Forest Roads

Synpotic or grab samples were collected during two large winter storms, one during the 2006 water year and the other during the 2007 water year. The collection of the synoptic samples was carried out by 5-6 people collecting grab samples at every road runoff point (culverts) in Oak Creek at approximately the same time during the storms. By using 5-6 people, it was possible to collect grab samples from all road runoff locations within one hour. The samples were then measured for turbidity and suspended sediment concentration of each sample. The discharge for the roads in Oak Creek with continuous runoff measurement (culverts with capacitance rods) at the time of the sample was determined. The storm sediment load and annual sediment load were calculated for each site (as described in previous sections). Linear regression was used to determine if there was a relationship between the discharge at the sample time, storm volume, storm sediment load, annual sediment load and the suspended sediment concentration or turbidity of the sample.

RESULTS

Annual Sediment Estimates for Monitored Road Sites of Oak Creek and the South Fork of the Albion River

For the 17 road sites observed in the 2006 and 2007 water years in Oak Creek the total suspended sediment load was 0.40 tons/yr with a 95% confidence interval of 0.36 and 0.44 tons/yr (Table 4.5). SEDMODL2 and WARSEM without adjustments from field observations of sediment and hydrology estimated an average annual sediment load of 1.66 and 1.52 tons/year respectively for the 17 road sites (Table 4.5).

Table 4. 5. Observed and Modeled Sediment Load for 17 Road Segments in Oak Creek 2006 and 2007 Water Years.

Road Culvert #	WARSEM (tons/yr)	SEDMODL2 (tons/yr)	Observed (tons/ water year)	95% Confidence Interval for Observed
7	0.02	0.05	0.084	(0.083, 0.85)
10	0.08	0.15	0.012	(0.01, 0.013)
15	0.08	0.07	0.025	(0.00001, 0.05)
25	0.07	0.07	0.014	(0.01, 0.02)
26	0.05	0.05	0.026	(0.0262, 0.0264)
27	0.06	0.06	0.113	(0.111, 0.114)
28	0.19	0.04	0.002	(0.001, 0.004)
33	0.04	0.15	0.011	(0.00001, 0.04)
40	0.23	0.02	0.007	(0.002, 0.012)
43	0.23	0.05	0.001	(0.0008, 0.001)
47	0.06	0.32	0.059	(0.058, 0.059)
66	0.05	0.20	0.005	(0.004, 0.006)
68	0.06	0.07	0.007	(0.00001, 0.02)
73	0.17	0.06	0.023	(0.022, 0.023)
80	0.19	0.01	0.003	(0.0025, 0.0028)
91	0.07	0.14	0.010	(0.002, 0.02)
116	0.02	0.02	0	0
TOTAL	***1.66***	***1.52***	***0.40***	***(0.36, 0.44)***

For the 22 road sites observed in the South Fork of the Albion River watershed the total fine sediment load was 0.41 tons with a 95% confidence interval of 0.0014 and 1.63 tons for the 2007 water year (Table 4.6). SEDMODL2 and WARSEM without adjustments from field observations of sediment and hydrology estimated an average sediment load of 3.3 and 4.2 tons/year respectively for the 22 road sites (Table 4.6).

Table 4. 6. Observed and Modeled Sediment Load for 22 Roads in the South Fork of the Albion River for the 2007 Water Year.

Road Site	WARSEM (tons/yr)	SEDMODL2 (tons/yr)	Observed (tons/2007 water year)	95% Confidence Interval for Observed
1	0.18	0.04	0.002	(0.000005, 0.028)
2	0.07	0.05	0.006	(0.000008, 0.044)
4	0.01	0.51	0	(0,0)
5	0.04	0.21	0.0006	(0.00002, 0.0021)
6	0.35	0.32	0.0026	(0.00015, 0.0012)
7	0.11	0.16	0.00049	(0.000002, 0.0001)
8	0.94	0.12	0.07	(0.000005, 0.35)
9	0.87	0.82	0.0098	(0.001, 0.0005)
10	0.10	0.02	0.006	(0.00004, 0.0093)
11	0.01	0.05	0	(0, 0)
12	0.32	0.04	0.26	(0.000004, 0.7)
13	0.17	0.02	0	(0, 0)
14	0.04	0.12	0.0019	(0.000003, 0.04)
15	0.29	0.04	0	(0, 0)
16	0.03	0.05	0.002	(0.000004, 0.031)
17	0.05	0.03	0.0007	(0.000003, 0.02)
18	0.21	0.23	0.02	(0.00005, 0.19)
19	0.01	0.04	0	(0, 0)
20	0.14	0.15	0	(0,0)
21	0.10	0.12	0.0019	(0.000009, 0.003)
22	0.08	0.08	0.007	(0.000008, 0.07)
23	0.06	0.09	0.017	(0.00007, 0.2)
TOTAL	***4.19***	***3.33***	***0.41***	***(0.0014, 1.63)***

Field Measured Adjustment to Geologic Erosion, Precipitation, and Traffic Factors for SEDMODL2 and WARSEM

For the 17 road segments with sediment load estimates in Oak Creek the average product of the geologic erosion, precipitation, and traffic factors was 2.7; the suggested values for the models using the technical documentation would be 8 (Table 4.7). The variable representing the product of the geologic erosion/precipitation/traffic factor Oak Creek by road culvert measured is shown in Table 4.7.

<u>Table 4. 7</u>. The Variable Representing the Product of Geologic Erosion, Precipitation, and Traffic Factors for SEDMODL2 and WARSEM.

Road Culvert #	SEDMODL2/WARSEM Geo/Precipitation/Traffic Suggested Factor	Geo/Precipitation/Traffic Factor Calculated from Observed Sediment Load
7	8	17.5
10	8	0.9
15	8	2.1
25	8	1.1
26	8	3
27	8	10.5
28	8	0.1
33	8	2
40	8	0.3
43	8	0.1
47	8	5
66	8	0.6
68	8	0.5
73	8	1
80	8	0.1
91	8	0.3
116	8	0
Mean	***8***	***2.7***

For the 22 road segments with sediment load estimates in the South Fork of the Albion River the average product of the geologic erosion, precipitation, and traffic factors was 1.16. The suggested values for the models using the technical documentation varied between 11.2 and 56 (Table 4.8). The calculated geologic erosion/precipitation/traffic factor for the South Fork of the Albion River for each road segment is shown in Table 4.8.

Table 4. 8. The Variable Representing the Product of Geologic Erosion, Precipitation, and Traffic Factors for SEDMODL2 and WARSEM and from Observed Sediment Load Estimates in the South Fork of the Albion River.

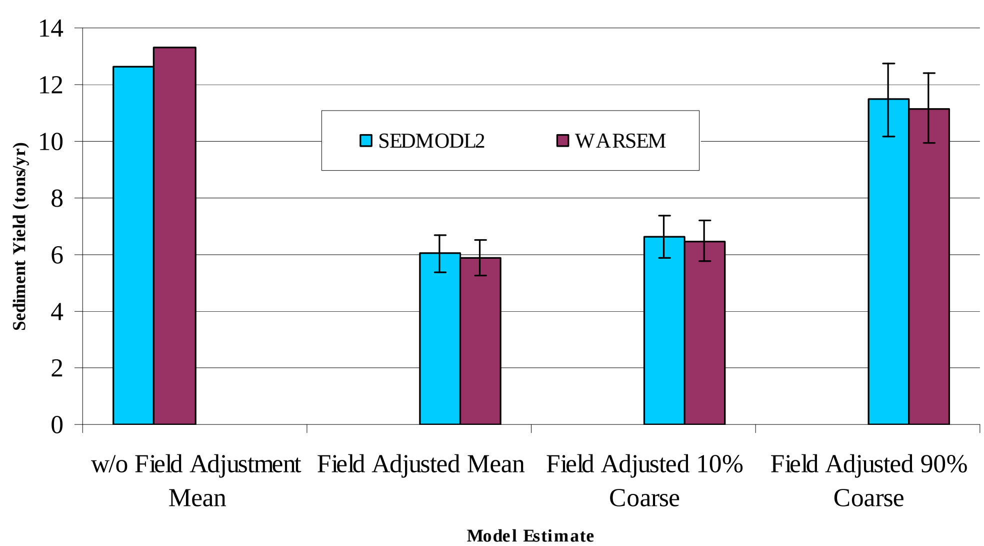
Site	SEDMODL2/WARSEM Geo/Precipitation/Traffic Factor	Geo/Precipitation/Traffic Factor from Observed Sediment Load
1	11.2	0.08
2	11.2	0.89
4	11.2	0*
5	11.2	0.08
6	56	0.2
7	11.2	0.03
8	56	3.5
9	11.2	0.14
10	11.2	0.57
11	11.2	0*
12	11.2	8.85
13	11.2	0*
14	11.2	0.52
15	11.2	0*
16	11.2	0.28
17	11.2	0.09
18	56	4.4
19	11.2	0*
20	11.2	0*
21	11.2	0.21
22	11.2	0.07
23	11.2	1.92
Mean	***15.87***	***1.16***

*- 0 represents no runoff or sediment delivery was observed from the road.

Road Sediment Estimated for Oak Creek and the South Fork of the Albion River using SEDMODL2 and WARSEM Adjusted by Measurements of Road Runoff and Sediment

Using the mean product of geologic erosion, precipitation, and traffic factors calculated from the observed road sediment observations SEDMODL2 estimated fine sediment delivery for roads of the Oak Creek watershed for the 2006 and 2007 water year at 6.0 tons/year with a 95% confidence interval of 5.4 and 6.7 tons/year (Figure 4.7). Using the product of geologic erosion, precipitation, and traffic factors suggested by the technical documentation (without field measurements) SEDMODL2 estimated average annual road sediment delivery for roads of the Oak Creek watershed at 12.7 tons/year. Using the mean product of geologic erosion, precipitation, and traffic factors calculated from the observed road sediment observations WARSEM estimated fine sediment delivery for roads of the Oak Creek watershed for the 2006 and 2007 water year at 5.9 tons/year with a 95% confidence interval of 5.3 and 6.5 tons/year (Figure 4.7). Using the product of geologic erosion, precipitation, and traffic factors suggested by the technical documentation (without field measurements) WARSEM estimated average annual road sediment delivery for roads of the Oak Creek watershed at 13.3 tons/year.

The annual sediment estimates from the field measurement adjusted WARSEM and SEDMODL2 estimates were increased by the range of 10 to 90 percent, representing the range of coarse sediment previously observed in Oak Creek (Amann, 2004). The resulting annual road sediment for the SEDMODL2 estimate with 10% and 90% coarse sediment was 6.6 tons/year and 11.5 tons/year respectively. The resulting annual road sediment estimate by field adjusted WARSEM with 10% and 90% coarse sediment was 6.5 tons/year and 11.2 tons/year respectively (Figure 4.7).



<u>Figure 4. 7</u>. WARSEM and SEDMODL2 Estimates of Road Sediment Load for the 2006 and 2007 Water Years in Oak Creek

Using the mean product of geologic erosion, precipitation, and traffic factors calculated from the observed road sediment observations SEDMODL2 estimated fine sediment delivery for roads of the South Fork Albion River watershed for the 2007 water year at 8.6 tons with a 95% confidence interval of 0.03 and 34.6 tons (Figure 4.8). Using the product of geologic erosion, precipitation, and traffic factors suggested by the technical documentation (without field measurements) SEDMODL2 estimated average annual road sediment delivery for roads of the South Fork Albion River watershed at 103.2 tons/year. The extrapolation of WARSEM sediment load estimates to the South Fork Albion River watershed estimated an average annual sediment yield of 129.7 tons/year (Figure 4.8).

The sediment estimates from the field measurement adjusted SEDMODL2 were increased by the range of 12 to 67 percent, the range of coarse sediment observed in the area (Barrett and Tomberlin, 2007). The resulting annual road sediment estimate by SEDMODL2 with 12% and 67% coarse sediment added was 9.6 and 14.3 tons/year respectively (Figure 4.8).

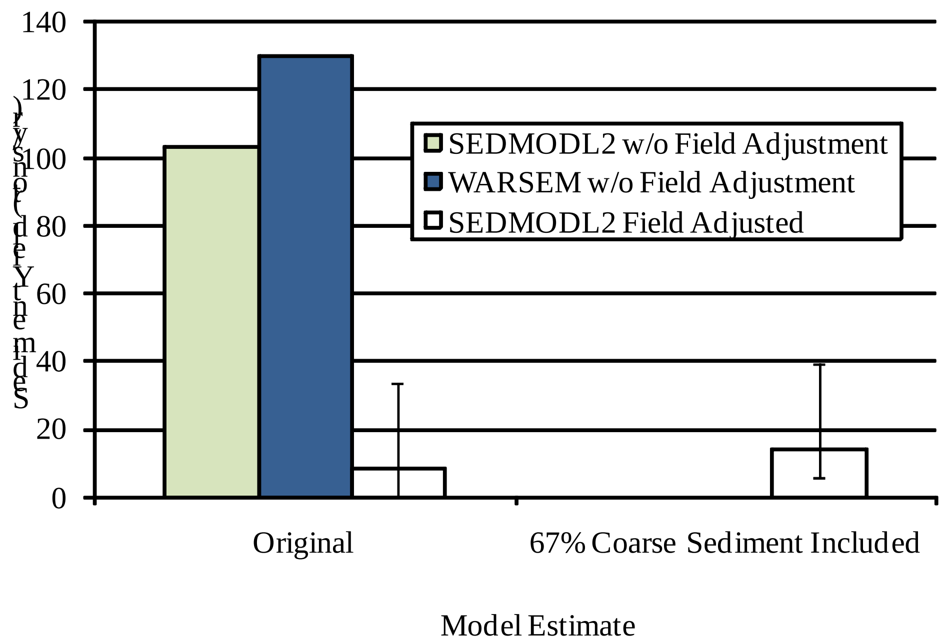


Figure 4. 8. Road Sediment Load from WARSEM and SEDMODL2 for the South Fork of the Albion River for the 2007 Water Year.

Catchment Scale Estimates of Road Sediment Using Road Runoff Measurements and Simulated Runoff in Oak Creek

The ratio of storm sediment load (tons) and storm runoff volume (liters) for road ditches measured with TTS within Oak Creek for the 2006-2007 water years was found to be $5.177754*10^{-9}$ with a 95% confidence interval of $2.328 * 10^{-9}$ and $8.027 * 10^{-9}$ (p value <0.001; adjusted $r^2 = 0.23$)(Figure 4.9). The resulting model explained little of the variability in the relationship as shown by the low adjusted r^2 of 0.23. The regression model between observed and DHSVM simulated road storm volumes was:

Storm sediment load (tons) =

$$-0.0004443 + 5.177754*10^{-9} * (\text{road ditchflow storm volume in liters})$$

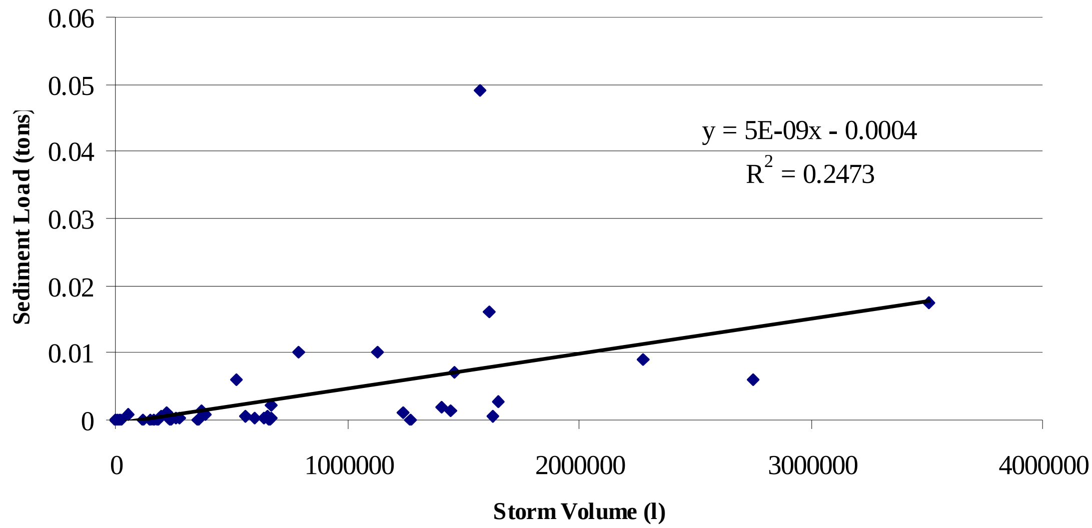


Figure 4. 9. Relationship between Storm Volume and Suspended Sediment Load for the Culverts with TTS Observations in Oak Creek; 2006 and 2007 Water Years.

The ratio of storm sediment load (tons) and storm peak flow (liters/second) for road ditches measured with TTS within Oak Creek for the 2006-2007 water years was found to be 0.000603 with a 95% confidence interval of 0.00029 and .00092 (p value <0.001; adjusted $r^2 = 0.25$)(Figure 4.10). The resulting model explained little of the variability in the relationship as shown by the low adjusted r^2 of 0.25. The regression model between observed and DHSVM simulated road storm volumes was:

Storm sediment load (tons) =

-0.00017 + 0.000603 * (road ditchflow storm peak flow in liters/second)

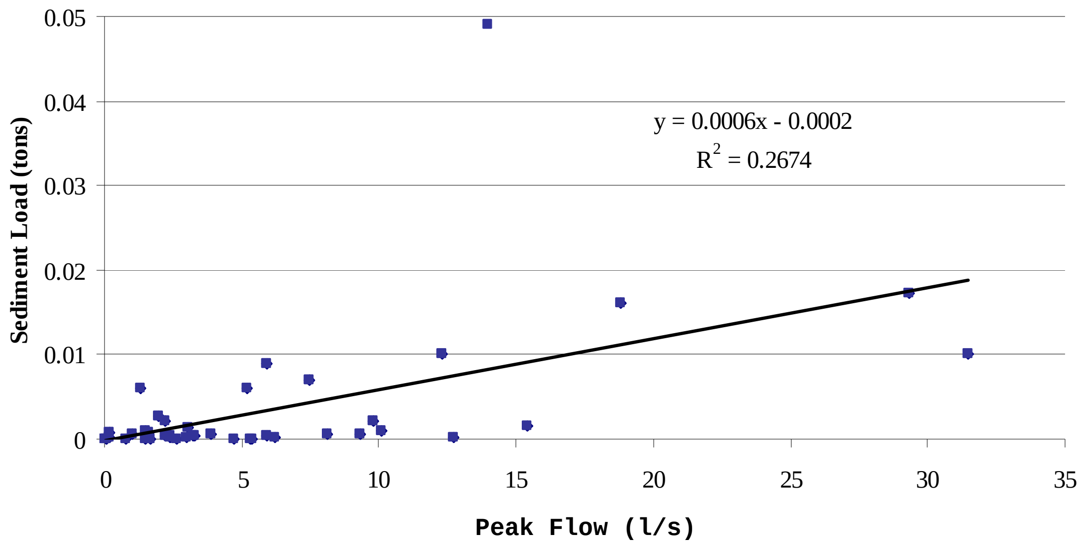
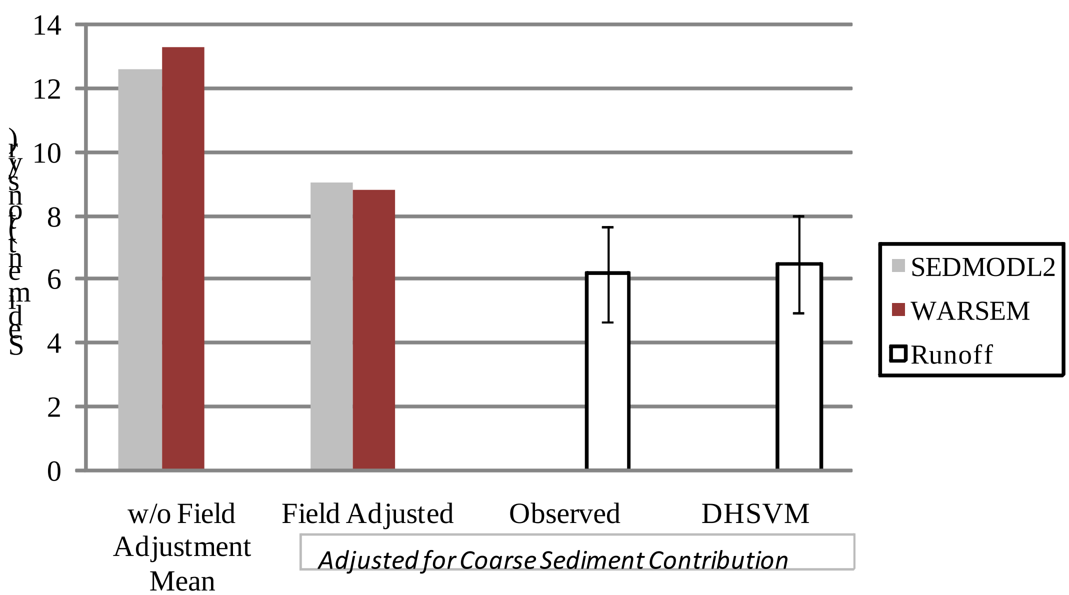


Figure 4. 10. Relationship between Storm Peak Flow and Suspended Sediment Load for Culverts with TTS Observations in Oak Creek; 2006 and 2007 Water Years.

The storm event peak flow and runoff volume relationships with storm sediment load in Oak Creek had high variability. This is common with sediment/runoff relationships. However, one culvert (culvert 27) used in this relationship had chronic soil failures at the inlet of the culvert. As a result culvert 27 had much higher storm sediment loads then the other culverts with TTS observations. If culvert 27 is removed from the analysis for the storm volume and peak flow to sediment load the relationships are statistically significant and the adjusted r^2 increases to 0.5 and 0.52, respectively. I chose not to remove culvert 27 from the runoff/sediment relationships used to predict sediment load from Oak Creek roads. Culvert 27 is an outlier, however it would be expected that problem erosion spots, like culvert 27, will occur in watersheds. It is my view that a relationship which considers these isolated occurrences would provide a more realistic estimate of the total sediment load for roads in the watershed; at the very least a more conservative estimate of sediment load (higher estimate).

The catchment scale estimate of sediment production from roads in Oak Creek using the road runoff observations and the relationship of observed storm volume and storm suspended sediment load was 4.1 tons/year with a 95% confidence interval of 2.0 and 6.3 tons/year. The catchment scale estimate of sediment production from roads in Oak Creek calculated by the relationship of DHSVM simulated storm volume and storm suspended sediment load was 4.3 tons/year with a 95% confidence interval of 1.8 and 6.9 tons/year. After the suspended sediment load estimates were increased by the range of 10 to 90 percent, representing the percentage of coarse sediment previously observed in Oak Creek (Amann, 2004) the sediment load estimated from observed road runoff ranged from 4.5 to 7.8 tons/year. The coarse and suspended sediment load estimated from DSHVM simulated road runoff ranged from 4.7 to 8.2 tons/year (Figure 4.11).



<u>Figure 4.11</u>. Comparison of Total Annual Road Sediment Load for Oak Creek with SEDMODL2, WARSEM, Observed Road Runoff, and DHSVM Simulated Road Runoff for 2005 and 2006 Water Years.

Sample Size Estimate for Catchment Scale Road Sediment Measurement from Road Runoff

From the field measurement efforts in Oak Creek and the South Fork of the Albion River an estimate of numbers of road sites to be monitored for runoff and sediment measurements based on confidence level and error is presented (Table 4.9 and 4.10).

Table 4. 9. Number of Road Sites to be Sampled Based on Error and Confidence Level from the Oak Creek Measurements.

	Number of Road Sites by Confidence Level (α)		
Error (β)	90% confidence	95% confidence	99% confidence
1%	13	18	21
5%	1	1	1

Table 4. 10. Number of Road Sites to be Sampled Based on Error and Confidence Level from the South Fork of the Albion River Measurements.

	Number of Road Sites by Confidence Level (α)		
Error (β)	90% confidence	95% confidence	99% confidence
1%	10620	15000	20600
5%	425	600	825
10%	110	150	210
20%	26	37	52

Grab Water Samples for Estimation of Road Sediment Load

Estimating Storm Sediment Load from Grab Water Samples

The ratio of storm sediment load (tons) and the mean of four randomly selected suspended sediment samples (mg/liters) for individual storms was found to be 0.0001 with a 95% confidence interval of 0.00005 and 0.00015 (p value = 0.01; adjusted r^2 = 0.54)(Figure 4.12). The regression model between storm sediment load and the mean of suspended sediment samples in individual storms was:

Storm sediment load (tons) = -0.0015 + 0.0001 * (mean of storm sediment samples)

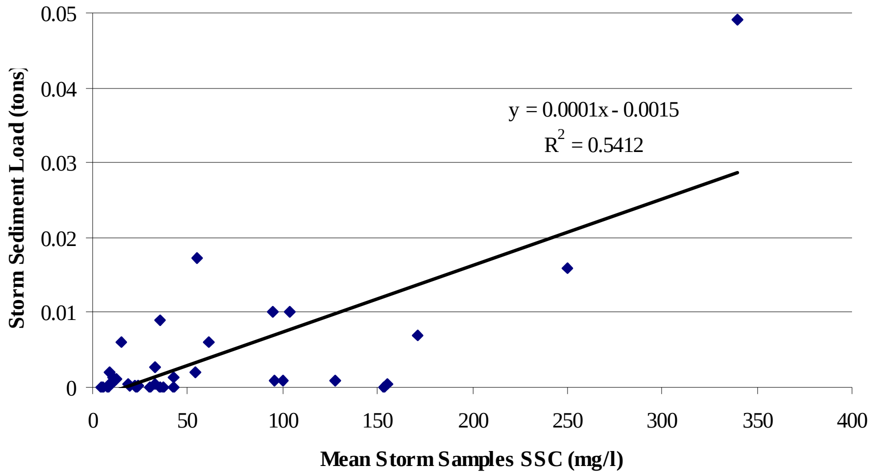


Figure 4. 12. Relationship between the Mean of Suspended Sediment Samples and Suspended Sediment Load for Storms in Oak Creek, 2006 and 2007 Water Years.

The ratio of storm sediment load (tons) and the mean of 4 randomly selected suspended sediment samples (mg/liters) for individual storms was found to be 0.0001 with a 95% confidence interval of 0.00005 and 0.00015 (p value = 0.01; adjusted r^2 = 0.19)(Figure 4.13). The resulting model explained little of the variability in the relationship as shown by the low adjusted r^2 of 0.19. There was no statistically significant relationship between the mean of 3 or 2 randomly selected suspended samples in a storm and the storm sediment load at the 95% confidence level; p values were 0.07 and 0.84 respectively. The regression model between storm sediment load and the mean of 4 randomly selected suspended sediment samples in individual storms was:

Storm sediment load (tons) =

-0.0003 + 0.0001 * (mean of 4 random suspended sediment samples per storm)

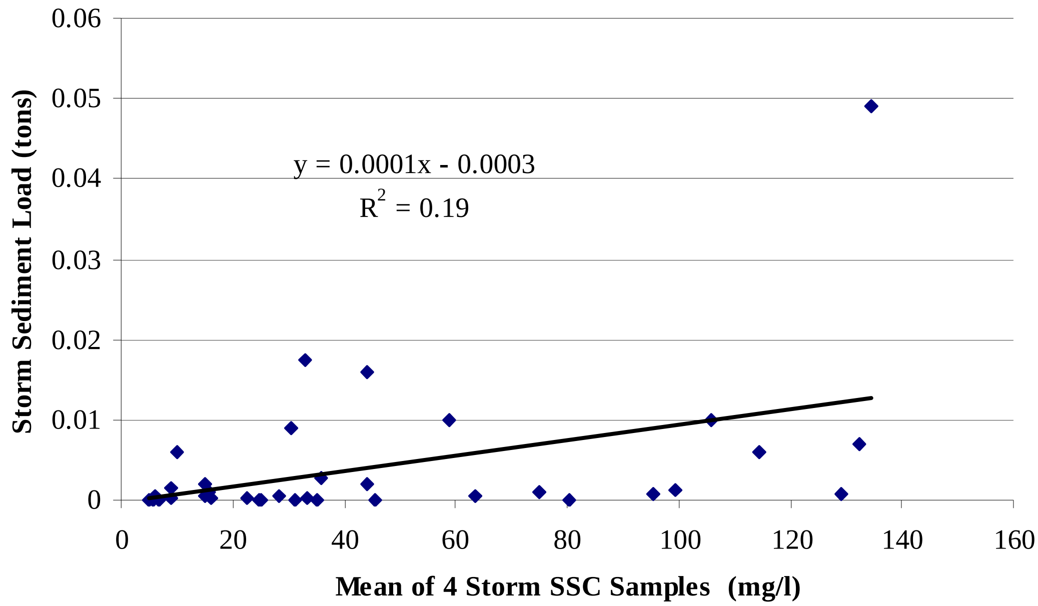


Figure 4. 13. Relationship between the Mean of 4 Randomly Selected Suspended Sediment Samples and Suspended Sediment Load for Storms in Oak Creek, 2006 and 2007 Water Years.

Multiple linear regression showed that if the peak flow value was included in the model more of the variability was explained around the storm sediment load estimate. A statistically significant relationship use found for the estimate of the natural log of the storm sediment load by a combination of the mean of 4 randomly suspended sediment samples and the storm peak flow (p value <0.02, adjusted $r^2 = 0.47$). The regression model between the natural log of storm sediment load and the mean of 4 randomly suspended sediment samples and peak flows for individual storms was:

Ln Storm sediment load (tons) =

-9.2239 + 0.0198 * (mean of 4 suspended sediment samples) + 0.1581 * (peak flow)

A statistically significant relationship use found for the estimate of the natural log of the storm sediment load by a combination of the mean of three randomly selected suspended sediment samples and the storm peak flow (p value <0.03, adjusted r^2 = 0.44). The regression model between the natural log of storm sediment load and the mean of suspended sediment samples and peak flows for individual storms was:

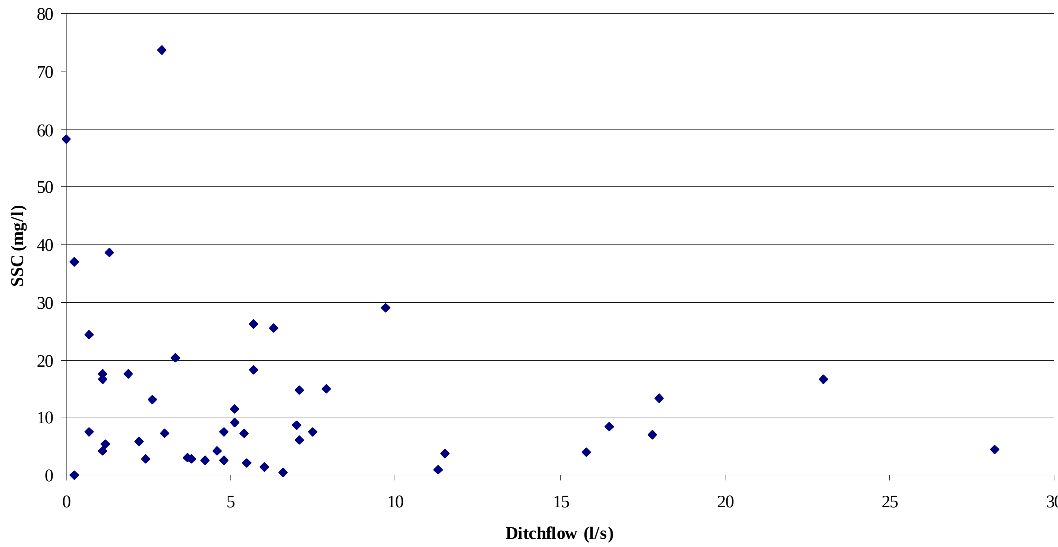
Ln Storm sediment load (tons) =

-9.0946 + 0.0178 * (mean of 4 suspended sediment samples) + 0.1531 * (peak flow)

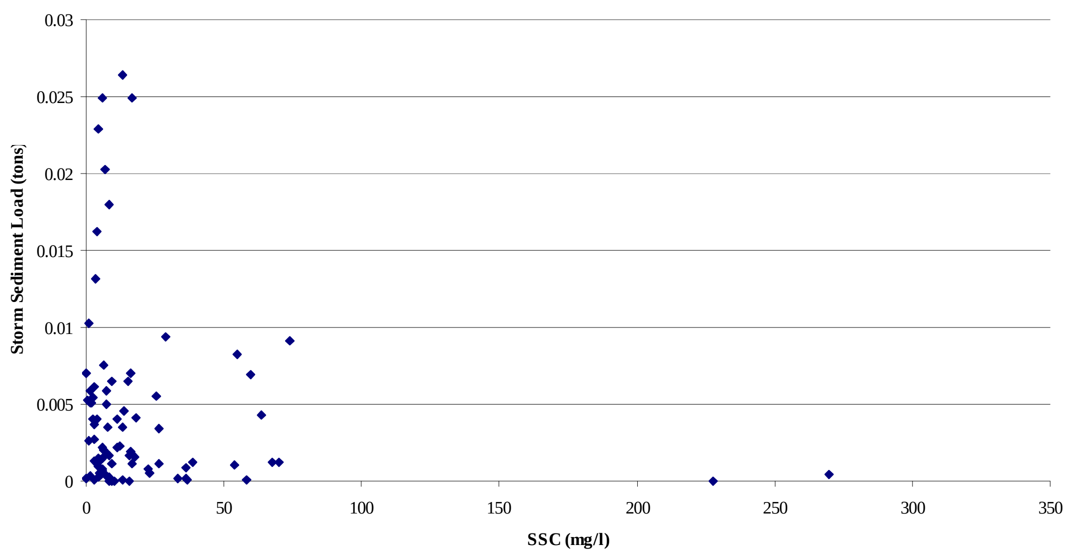
There was not a statistically significant relationship between the storm sediment load and the mean of two randomly selected suspended sediment samples along with the peak flow. There was not sufficient evidence that regression models to estimate storm sediment load with randomly selected suspended samples and storm volumes (instead of peak flows) provided a better model than without (p value <0.001).

Synoptic Sampling Approach for Determining Road Sediment

The suspended sediment concentrations and turbidity from 2 synoptic samples collected at road culverts in Oak Creek did not show a relationship with discharge at time of the sample, storm sediment load, or annual sediment load. The scatter plots for the attempted relationships for the suspended sediment concentrations from the synoptic samples for water years 2006 and 2007 are provided (Figures 4.14 – 4.19).



<u>Figure 4. 14</u>. Road Ditchflow and Suspended Sediment Concentration at time of Sample for Synoptic Sample of Road Discharge Locations in Oak Creek, Dec. 22, 2005 (2006 WY)



<u>Figure 4. 15</u>. Suspended Sediment Concentration and Storm Sediment Load for Synoptic Sample of Road Discharge Locations in Oak Creek, Dec. 22, 2005 (2006 WY)

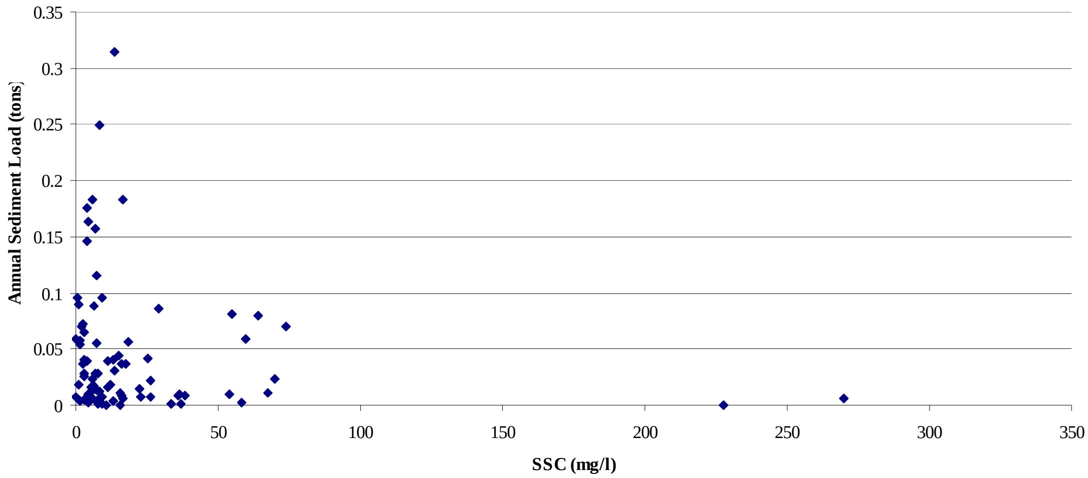


Figure 4. 16. Suspended Sediment Concentration from Synoptic Sample Dec. 22, 2005 and Annual Sediment Load for Road Discharge Locations in Oak Creek

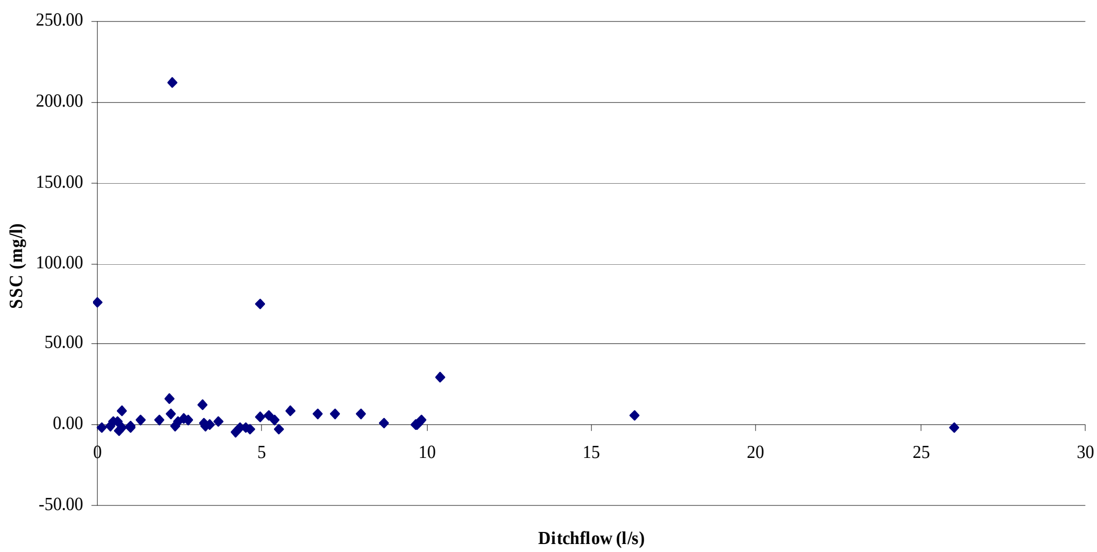
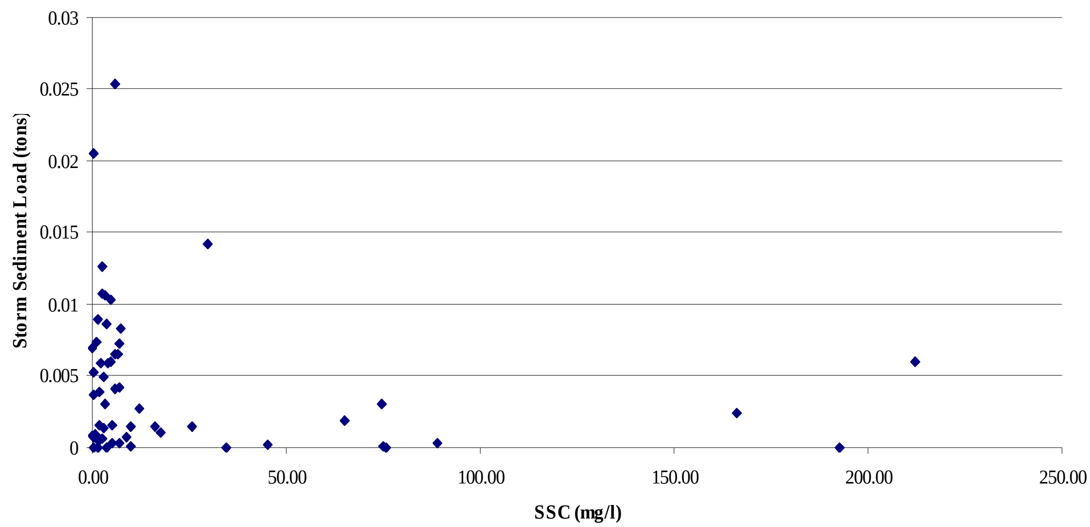
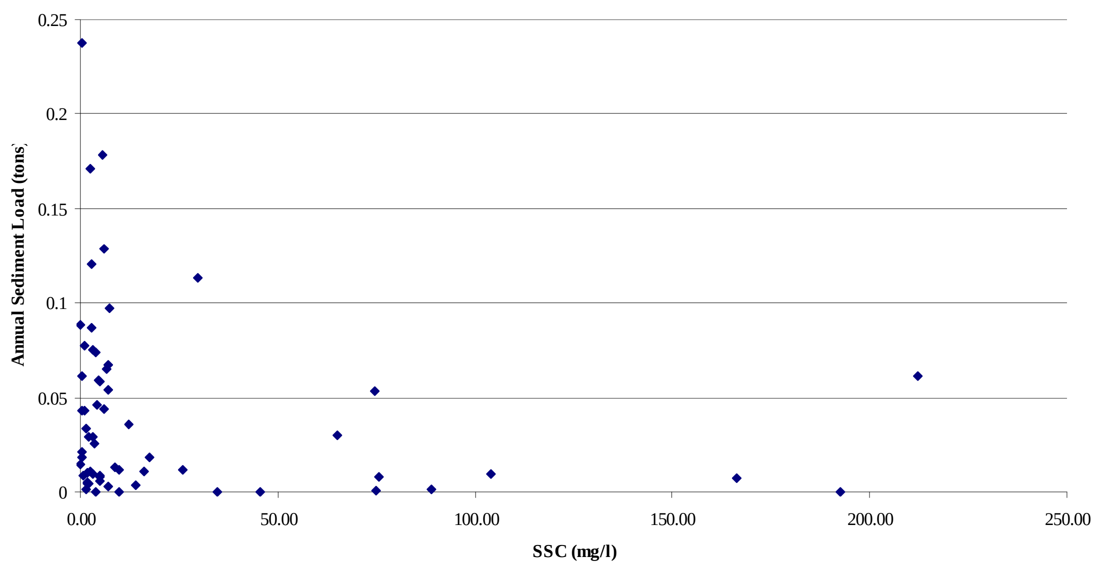


Figure 4. 17. Road Ditchflow and Suspended Sediment Concentration at Time of Sample for Synoptic Sample of Road Discharge Locations in Oak Creek, Feb. 16, 2007 (2007 WY)



<u>Figure 4. 18</u> Suspended Sediment Concentration and Storm Sediment Load for Synoptic Sample of Road Discharge Locations in Oak Creek, Feb. 16, 2007 (2007 WY)



<u>Figure 4. 19</u>. Suspended Sediment Concentration from Synoptic Sample Feb. 16, 2007 and Annual Sediment Load for Road Discharge Locations in Oak Creek.

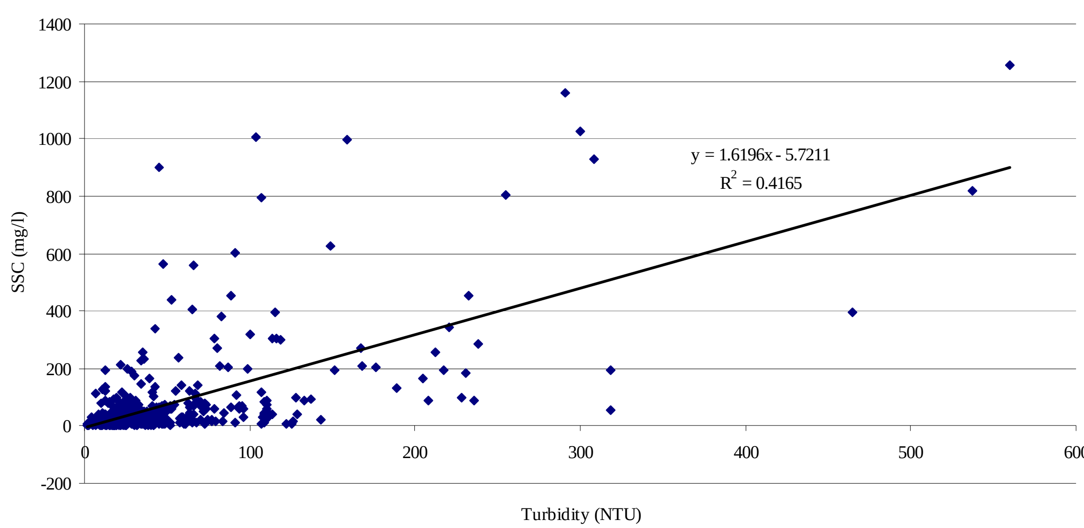
Suspended Sediment and Turbidity from Road Sediment Samples

To lower the cost of measuring sediment from road runoff the relationship between the suspended sediment samples and their measured turbidity was examined. Depending on the strength of the relationship between suspended sediment concentration and turbidity, turbidity could be measured as a surrogate in road sediment measurement. The measurement of turbidity of water samples removes the expense of filtering the sediment from the water.

The ratio of suspended sediment concentration (mg/l) and the turbidity for all water samples collected from road ditches in Oak Creek for the 2006 and 2007 water years was found to be 1.62 with a 95% confidence interval of 1.46 and 1.78 (p value <0.0001; adjusted $r^2 = 0.41$)(Figure 20). The regression model was:

Suspended sediment concentration (mg/l) =

-5.7211 + 1.62 * (turbidity of suspended sediment sample)

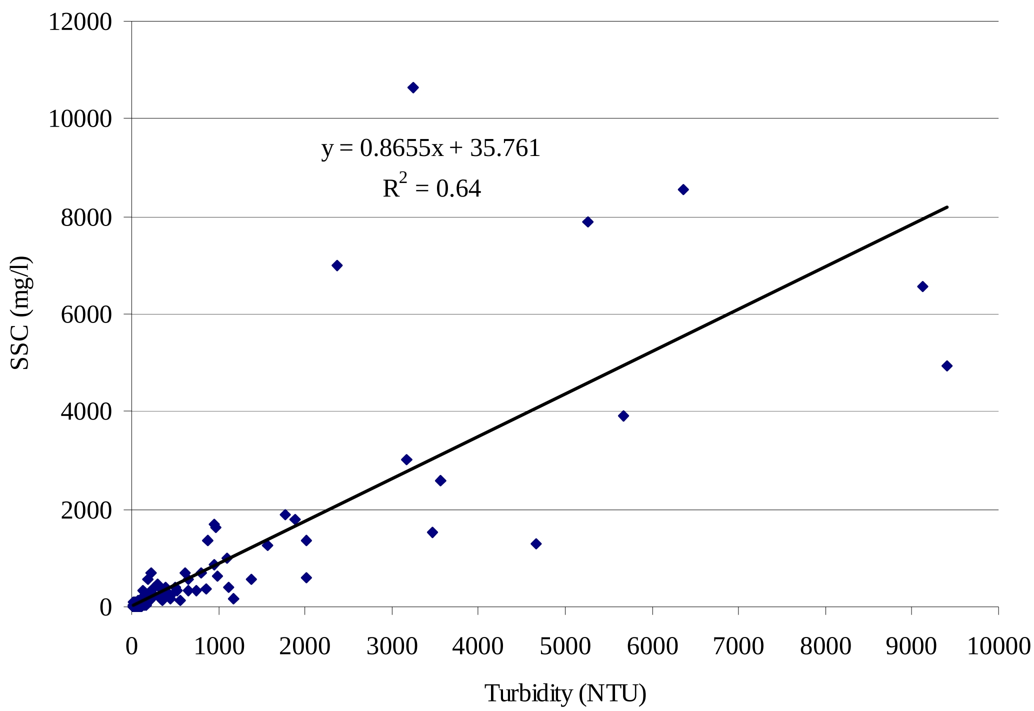


<u>Figure 4. 20</u>. Relationship of Turbidity and Suspended Sediment Concentration for Road Suspended Samples for TTS Observed Culverts of Oak Creek, 2006 and 2007 Water Years.

The ratio of suspended sediment concentration (mg/l) and the turbidity for all sediment samples collected from roads in the South Fork of the Albion River for the 2007 water year was found to be 0.87 with a 95% confidence interval of 0.76 and 0.97 (p value <0.0001; adjusted $r^2 = 0.64$)(Figure 4.21). The regression model was:

Suspended sediment concentration (mg/l) =

35.671 + 0.87 * (turbidity of suspended sediment sample)



<u>Figure 4. 21</u>. Relationship of Turbidity and Suspended Sediment Concentration for all Road Suspended Sediment Samples for the South Fork of the Albion River, 2007 Water Year.

Many of the individual road sites showed strong linear relationships between suspended sediment and turbidity in Oak Creek (Figures 4.22 – 4.23 as examples) and the South Fork of the Albion River (Figures 4.24 – 4.25 as examples). These relationships are from samples taken within multiple storm events where sediment and turbidity samples were collected.

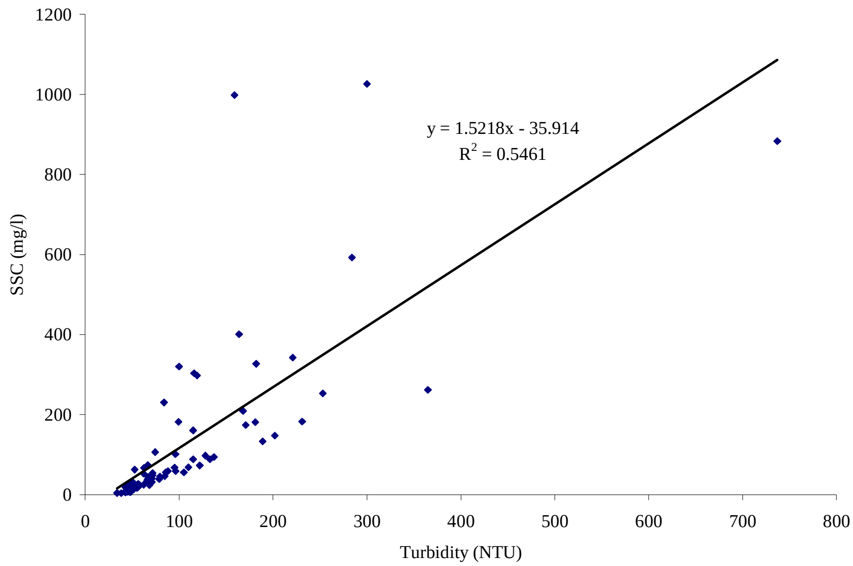
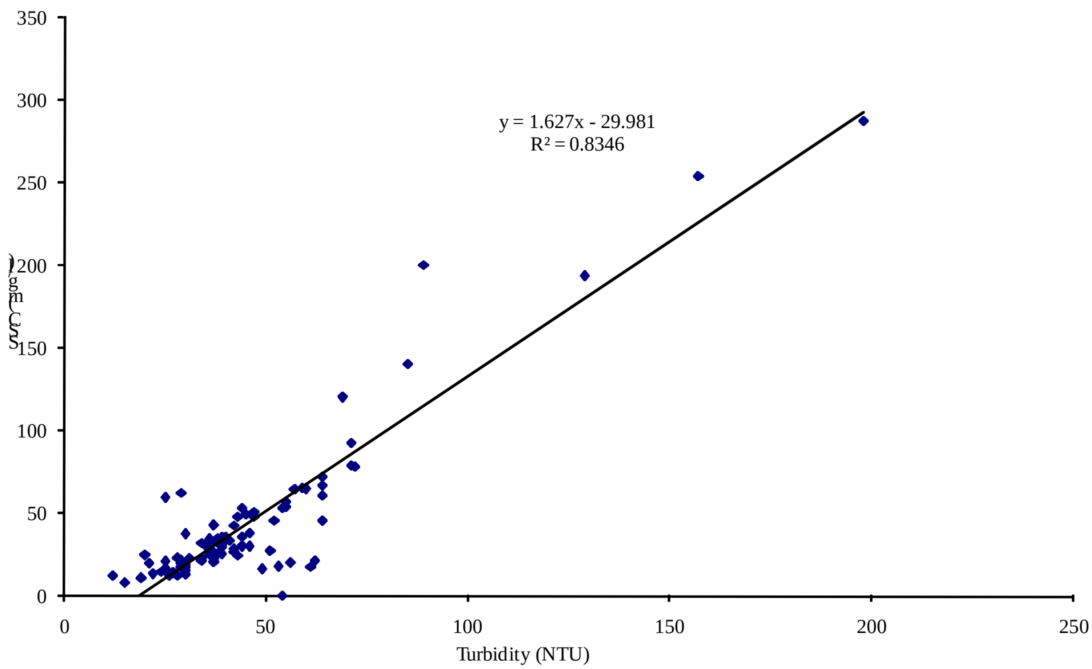
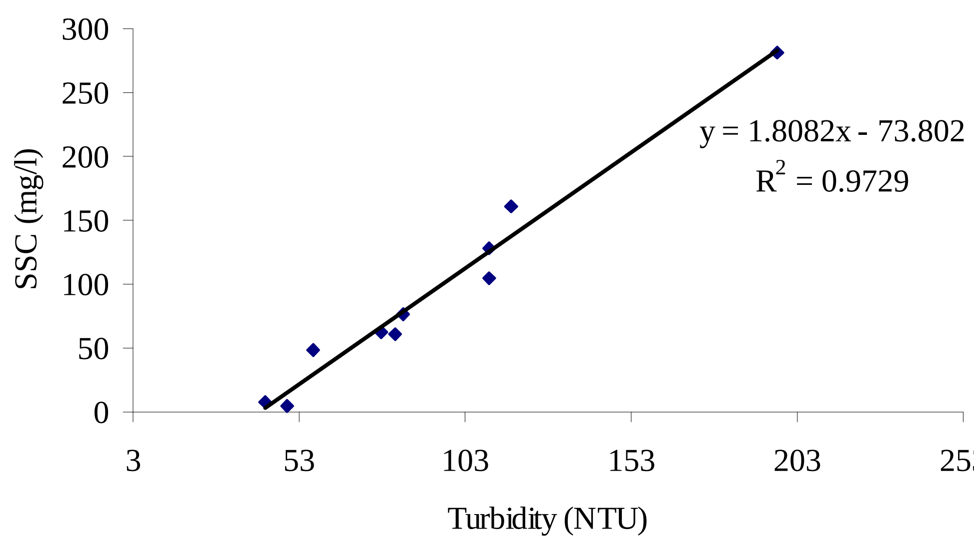


Figure 4. 22. Example of Linear Relationship between Turbidity and Suspended Sediment for Road Culvert 7; Oak Creek 2006 Water Year.



<u>Figure 4. 23.</u>. Example of Linear Relationship between Turbidity and Suspended Sediment for Road Culvert 10; Oak Creek 2007 Water Year.



<u>Figure 4. 24</u>. Example of Linear Relationship between Turbidity and Suspended Sediment for Road Site 17; South Fork of the Albion River 2007 Water Year.

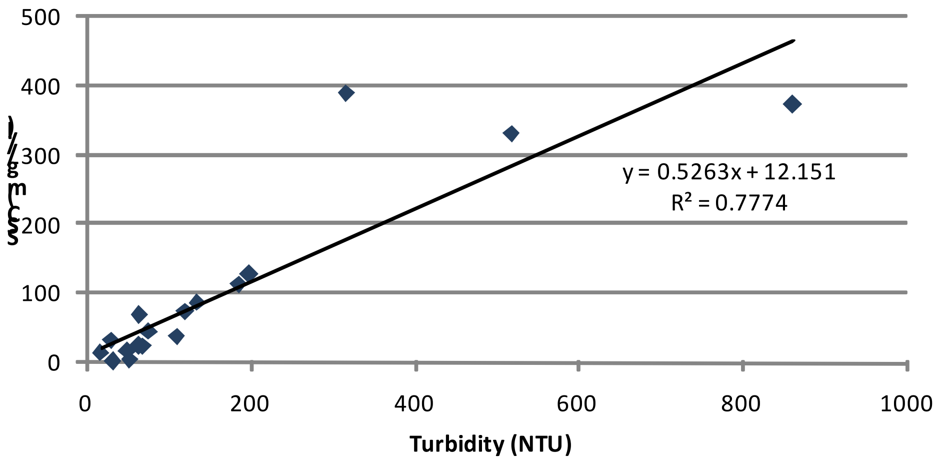


Figure 4.25. Example of Linear Relationship between Turbidity and Suspended Sediment for Road Site 6; South Fork of the Albion River 2007 Water Year.

DISCUSSION

Annual Sediment Yield Estimates for Roads with SEDMODL2 and WARSEM

The sediment yield estimated by SEDMODL2 and WARSEM without adjustment from field measurements ranged from 200% and 220% higher respectively than the measured sediment load increased for coarse sediment yield for the 17 roads measured in Oak Creek. The average sediment yield for the entire Oak Creek catchment for the 2006 and 2007 water years was 10-193% higher when modeled by SEDMODL2 and WARSEM without adjustment from field measurements. At the South Fork of the Albion the sediment yield estimated by SEDMODL2 and WARSEM without adjustment from field measurements ranged from 480% and 610% higher respectively than the measured sediment load increased for coarse sediment yield for the 22 roads measured. The average sediment yield for the entire catchment for the 2007 water year was 398-1060% higher when modeled by SEDMODL2 and WARSEM without adjustment from field measurements.

WARSEM and SEDMODL2 provide estimates interpreted as "long term" averages of erosion from roads. Average erosion for several years spanning both wet and dry years is assumed in the WARSEM and SEDMODL2 estimates. The field measured sediment yield was only for the two water years for Oak Creek and the one water year for the South Fork of the Albion River. The 2007 water year was a water year with below average annual precipitation in the South Fork of the Albion River; the 2007 water year had a little over 32 inches of precipitation, the average estimated for the watershed was 50 inches. The 2006 and 2007 water years had average annual precipitation levels at Oak Creek, but several large storms (four storms with greater than a 1-year recurrence interval) during the 2006 water year. It might be argued that the low precipitation year for the South Fork of the Albion River was part of the reason that WARSEM and SEDMODL2, without adjustments for field measurements, over-estimated the sediment yield. However, the difference in sediment yields estimated is so large that a low precipitation year is probably not the only source of discrepancy. It seems more likely that the inputs to the models were the main source of error.

The magnitude of road erosion estimated for roads with road runoff and estimated with WARSEM and SEDMODL2 without adjustments for field measurements (see Tables 4.5 and 4.6) were not the same. The estimates of sediment load using WARSEM and SEDMODL2 did not capture the spatial distribution of the sediment measured in Oak Creek or the South Fork of the Albion River. This suggests that even with an improved estimate of the factors used in the model, as generated by road runoff and sediment samples, the magnitude of erosion at individual sites cannot be relied upon when WARSEM or SEDMODL2 is used.

The primary factor for influencing hydrologic effects in WARSEM and SEDMODL2 was the road tread and cutslope surface area. If all other factors are the same in the models then the surface area of the road is the only variable that adjusts the calculated erosion in the models. For example, five road sites with similar WARSEM and SEDMODL2 factors were selected from the road in Oak Creek; the only difference between the roads is the area contributing erosion to watercourses. These five sites show a linear relationship with the road area being modeled and the sediment yield, with higher sediment yield estimated with greater road area (Figure 4.26). However, the sediment yield measured for the roads does not correlate with the road area.

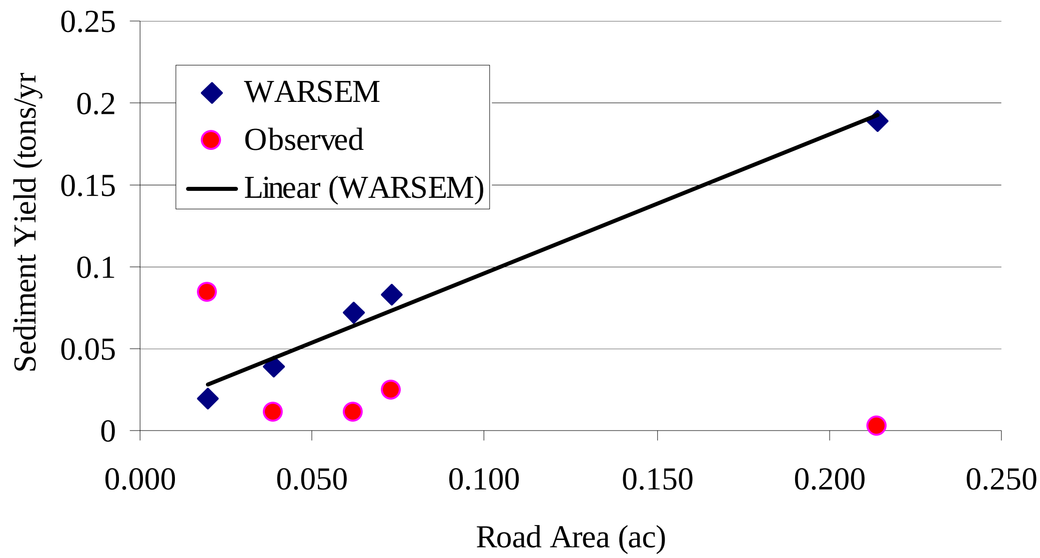
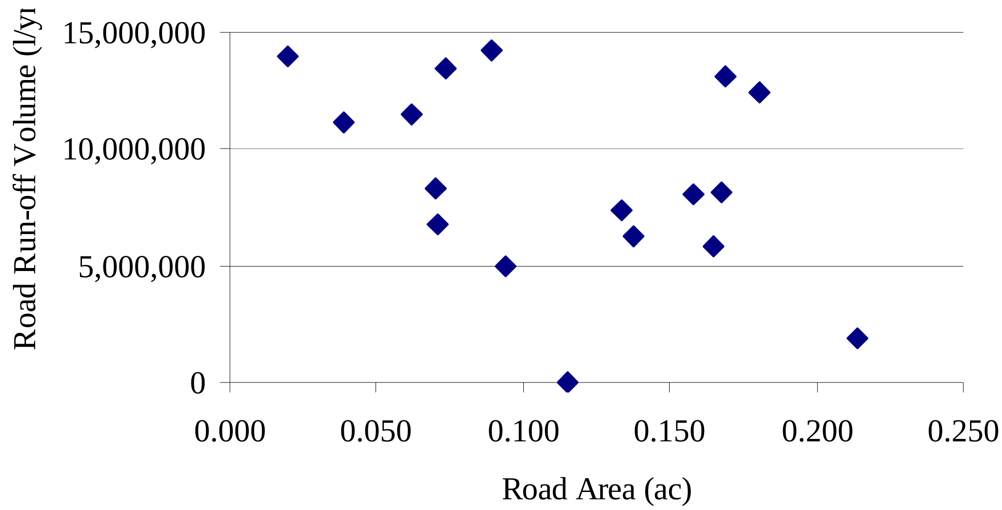


Figure 4.26. Relationship between Road Area and Sediment Yield as Observed in Oak Creek and Estimated by WARSEM for 5 Roads with Similar WARSEM Factors.

We observed a correlation between the storm volume and storm sediment yield. It follows that the annual runoff from a road correlates with the annual sediment production. Therefore, if road area is a reasonable predictor of road sediment yield then the road area should also correlate with road runoff volume. For the 17 road sites measured with TTS in Oak Creek there did not appear to be a linear relationship for road runoff volume and road area (Figure 4.27).



<u>Figure 4.27</u>. Road Area and Road Runoff Volume for 17 Roads in Oak Creek; 2006 and 2007 Water Years.

SEDMODL2 and WARSEM, without adjustments from field measurements, over predicted the sediment yield and did not capture the magnitude of sediment yield from individual sites. In this study, these same models were used to spatially extrapolate the results from the road runoff and sediment sample observations. Using the field observed road erosion and hydrologic information within the models should provide a more accurate estimate of the sediment yield. However, given the poor correlation of sediment yield and road area, which the models use as one the factors to make the sediment estimates, we are left with some uncertainty as to how accurate the catchment scale estimates really are. Certainly our catchment scale estimates are better than without the field observations; but we are not achieving the magnitude of sediment delivery from individual road sites nor the truly correct answer at the catchment scale.

Road Hydrologic Response and Sediment Yield

The linear relationship found between storm peak flow or runoff volume and suspended sediment load demonstrates the use of road runoff observations for estimating sediment production from roads. As seen in Oak Creek (see Chapter 3) road runoff is highly variable with some roads exhibiting infiltration excess overland flow from the road surface other roads intercept significant amounts of hillslope water, while other roads have very high infiltration capacity with little to no runoff. In Oak Creek, physical features of roads and hillslopes above roads only have a weak relationship with road runoff (Ellingson, 2002) that does not allow prediction of where the variability of hydrologic response occurs. This suggests that modeling of road surface erosion based on physical features of a road will not be accurate. This leaves land managers in a quandary as most road inventories or surveys rely on measurement of the physical attributes of roads. If a method to accurately predict the hydrologic response of roads can be identified for a watershed then it would provide an important tool for assessment of road sediment yield. Given the uncertainties associated with SEDMODL2 and WARSEM this would provide a more accurate estimate of annual sediment yield from roads. It would also provide an indication of magnitude of sediment delivery from individual road locations.

It is not feasible to measure road runoff at every road runoff location in a catchment like was done in Oak Creek. Given the high variance of storm responses from roads in Oak Creek the number of storms needed to be sampled from roads across the catchment calculates to be higher than if all storms and roads are measured in Oak Creek. So some other alternative approach is needed to quantify the hydrologic response of roads in a catchment for sediment yield. In this study DHSVM was used to estimate the road hydrologic response. Sediment yield was estimated using the storm volume to sediment load relationship for the road runoff simulations from DHSVM. The coarse and suspended sediment load estimated from DSHVM simulated road runoff ranged from 4.7 to 8.2 tons/year. This was closer to the sediment yield estimate produced from the actual road runoff observations than the estimates produced from SEDMODL2 and WARSEM adjusted by road runoff and sediment sampling.

The work I did with DHSVM (Chapter 3) showed DHSVM over predicted the hydrologic response of road peak flows and volumes in Oak Creek. However, at the catchment scale the total volume of water that ran off of roads simulated by DHSVM was very close to the observed volume. In Oak Creek, DHSVM performed poorly at simulating site specific effects from roads, but at the catchment scale DHSVM simulated the hydrologic response from roads well. This suggests that there may be utility in using a hydrologic model that estimates road response in conjunction with a road runoff and sediment sampling scheme to more accurately quantify the road sediment yield at a catchment scale. However, the catchment size must be of a scale that the hydrologic model will accurately quantify the true volume of road runoff. Yet, this approach will not provide quantification of the magnitude of sediment production for individual road sites or entire roads.

Reducing Uncertainty for Estimated Road Sediment Yield

Using a TTS approach for measuring road sediment and turbidity combined with continuous measurement of road runoff provided estimates of sediment yield with low variance. In the South Fork of the Albion River measurement of road runoff was distributed throughout the winter at varying locations with road sediment and turbidity observations done by hand at varying times throughout a few storm events. This approach provided a sediment yield estimate with high variance. To achieve comparable precision in results at a 95% confidence interval within a 1% error it would require 18 roads sampled using the Oak Creek TTS approach while 15,000 roads using the South Fork of the Albion River approach. This demonstrates that continuous observations of road runoff throughout a winter and sampling techniques that provide accurate measurement of sediment and turbidity will provide considerable reduction in uncertainty of estimated sediment yields.

The sediment load estimated by SEDMODL2 adjusted by field measurements for the South Fork of the Albion River resulted in a wide 95 % confidence interval, 0.03 to 34.6 tons/year; a range of around 400% of the estimate of 8.55 tons/year. For most sediment budget calculations that accept an order of magnitude margin of error, a 400% range would be considered good. However, to discern long term changes in sediment delivery trends from forest roads, a 400% range in the confidence interval is probably too high. The suggested number of roads, as calculated from the South Fork of the Albion River results, to be measured to achieve a 95% confidence interval within a 10% error was 150. This was much larger than the 22 roads measured in this study. In Oak Creek we showed that roads do not need to be measured in the same year, rather could be spread over several consecutive years to represent the road sediment contributions for that time frame. Monitoring a greater number of road sediment delivery locations would reduce uncertainty in catchment scale estimates.

In the South Fork of the Albion River the flumes and 12 capacitance rods which measured road runoff were moved throughout the winter to measure a greater number of roads. In Oak Creek, the TTS system was moved throughout the winter but road runoff measurement equipment remained in place. By moving the road runoff equipment in the South Fork of the Albion River it was necessary to extrapolate hydrologic responses from one road to another based on linear relationships between sites; this introduces error increasing the variance in the resulting estimates. The number of grab samples for determination of sediment rating curves influences the variance of sediment load estimates as well. Using a greater number of grab samples to develop sediment rating curves and the resulting sediment load relationships will also reduce the uncertainty in the sediment yield estimate.

Sampling for Road Sediment Estimates

Sample Design

The road runoff and sediment measurements in the South Fork of the Albion River were stratified and sampled from six road classes to capture spatial variability due to road use and hydrologic response. The data from each road class resulted in relationships of storm volume or peak flow for use on roads in each class. This was important because linear relationships between storm volume or peak flow and sediment load were not observed at the catchment scale in the South Fork of the Albion River. The use of a stratified sample increased the variance of the sediment load estimate due to greater uncertainty introduced within and between sample strata. The South Fork of the Albion River roads showed importance of sampling from the variety of road types, topographic positions influencing road hydrologic response, and varying soil and geologic types in a catchment. It is also important to consider the relative influence of particular roads within a watershed. For example in the South Fork of the Albion River the Keene Summit road (the main haul road out of the watershed) represents an increased sediment delivery hazard due to its close proximity with a fish bearing watercourse and higher level of use. Increasing measurements on roads with greater sediment delivery hazards will strengthen interpretations of the road sediment impacts within watersheds.

To capture the spatial variability in road sediment delivery it is recommended that a spatially balanced sample of roads be used (Stevens and Olsen, 2004). For Oak Creek a spatially balanced sample was used successfully to select road locations for TTS measurement. The benefit to a spatially balanced sample is it distributes sample selection across the spatial extent of the area being characterized. Because it does not rely on a stratified sample the variance of the estimate is more likely to be smaller producing greater precision in sediment load estimates across a catchment. If needed data analysis on different classes of road can still be broken out from the sample. It will be important that a sufficiently large sample of roads is used in conjunction with a spatially balanced sample to ensure the variability in road designs, soils, geology, and rainfall are captured. Individual roads or collections of roads may need to consider increased weighting in sample selection within a spatially balanced sample. Increased weighting in the sample enables users to specify greater road observations on roads with greater interest or sediment delivery risks, such as the Keene Summit road in the South Fork of the Albion River watershed.

Sample Size for Road Sediment Estimates at the Watershed Scale

Due to the high variability of road sediment delivery, it is suggested that a high number of road sites be sampled. The estimates of sample size based on confidence level and error show a high number of samples need to be collected to minimize error and confidence level. For example, to achieve an estimate with 95% confidence and within a 10% error 150 sediment delivering road sites need to be monitored. In the South Fork of the Albion River there were 161 road segments that were determined to deliver sediment to a watercourse. This creates a sample frequency of almost 100% of the population of road segments. If road segments are sampled over multiple years, this sampling frequency can be achieved. If the number of samples selected has a sampling frequency greater than 100% of the potential road sites this implies that many of the road segments will be monitored more than once over different years.

The number of road segments to be monitored will be a decision based on the cost, objective, and desired precision of the final estimate. If the objective of the road monitoring is to discern a 50% reduction in road sediment, then a sample size based on errors of 10-20% may be acceptable. If the objective is for between year differences, than a smaller error or 5-10% may be necessary.

Storm Sediment Load Estimation

Linear relationships between storm sediment load and storm volume or peak flow and the low variance associated with sediment estimates based on TTS suggest that emphasis on sediment sampling within individual storms was important to sediment load estimation. In the South Fork of the Albion River, study sediment samples were collected at all of selected road sites within storms. This resulted in low numbers of samples per storm per site due to the distance between sites. In Oak Creek sediment samples were taken within a TTS approach with several storms measured for a road site then the TTS equipment was moved to another site. The Oak Creek sediment estimates had low variance. This demonstrates that focusing the sediment samples for a few road sites for individual storms then rotating the road sites sampled for sediment each storm or group of storm events provided effective results. However, at Oak Creek several storms were measured at a site before moving the equipment. Given the variability in the Oak Creek results it is unlikely the results would have been as precise if only one storm was measured per site.

The rotation of road sites for sediment sampling requires that hydrologic observations be collected at all selected road sites throughout the winter. The most accurate storm sediment load estimates will be those generated from actual hydrologic observations of road run-off for the storm being estimated. The hydrologic observations are necessary to allow the extrapolation of sediment and discharge relationships to other storms. Continuous observation of discharge at road sites was found to be preferable, but crest gages that provide the peak flow can be useful for a sub-set of road sites.

Turbidity as a Surrogate for Suspended Sediment

Lewis (1996) and Lewis and Eads (2001) show that continuous observations of turbidity combined with sampling of suspended sediment provided better estimates of sediment load than the use of streamflow. Turbidity might be a superior measurement but continuous turbidity measurement is expensive to collect and difficult to achieve in the low water depths that often result from road runoff.

TTS was used for sediment load estimates in Oak Creek but not in the South Fork of the Albion River study. We did learn that individual sites generally showed good linear relationships between turbidity and suspended sediment concentration (see Figures 4.22 - 4.25). There was a statistically significant relationship between turbidity and suspended sediment concentration for all roads sampled in Oak Creek (Figure 4.20) and the South Fork of the Albion River (Figure 4.21). When using grab samples a few turbidity observations for suspended sediment observations can save time and cost, provided enough suspended sediment observations are collected to create adequate relationships with discharge and sediment. The measurement of turbidity for individual water samples can be performed either in the field or office with portable turbidimeters such as made by Hach. These portable turbidimeters are relatively inexpensive and can be used for many years.

For turbidity to predict suspended sediment it is best to develop relationships for the same location within the same storm (Lewis, 1996), next best would be from the same location within the same winter (i.e. Figures 4.22 – 4.25), and finally use of a relationship by road class or type for the entire watershed for the same winter (i.e. Figures 4.20 and 4.21). If a sampling approach that follows recommendations from this study is used, turbidity and suspended sediment relationships can be calculated for individual sites for a few storms, particularly if using a rotating sediment sample design for selected road sites. However the relationships for individual sites or the entire watershed for the entire winter do provide reasonable estimates for suspended sediment concentrations.

Total Sediment Contribution from Roads

The sampling approaches used in this study only quantified fine sediment from road surface erosion. The samples in a mixed water column would not capture much of the coarse sand or gravel transported from surface erosion. Estimates of total sediment yield had to be produced based on previously observed proportions of coarse sediment in the total surface erosion load. Although not used in this study, there are techniques to capture the coarser sediments from road surface erosion. Catch basins put in the road ditch or at the outlet of road drainage locations can be used to collect coarse sediments. The use of geotextile fabric, straw waddles, or silt fences can also trap coarse sediment particles resulting from surface erosion. Coarse sediment collected by these techniques needs to be measured frequently and catch basins cleaned; in some cases the sediment needs to be dried and weighed following each storm event. The collection techniques need to be properly installed and no one collection device can be used in all situations. The collection devices also must be well maintained, particularly during large storm events to ensure reliable measurements.

Although not measured in this study, it is reasonable to assume that coarse sediment transported from roads correlates with fine sediment transported; the processes of transport and erosion are governed by the same physical processes. Thus by measuring fine sediment delivery at many locations, the magnitude of sediment delivery may be assumed to be captured. This makes the assumption that the fine sediment measurements are a reliable index of all surface erosion from roads, if not an accurate quantification of it. However, the covariance of fine and coarse sediments from roads needs further study to confirm this assumption.

Finally, mass wasting, gully erosion, or wash-outs of watercourse crossing fills are not explicitly quantified from the methods used in this study. Separate efforts of mass wasting mapping and quantification of large scale erosion processes such as generated from road inventories are still needed to understand the total sediment load from roads.

Supplemental Sampling for Improving Catchment Scale Estimates of Road Sediment

In Oak Creek, taking 3-4 suspended samples within a storm combined with a peak flow observation provides a statistically significant relationship with storm sediment load. This suggests that a number of road sites within a catchment could use crest gages to measure the peak discharge with 3-4 grab samples taken to provide the data for estimating the storm sediment load. This approach still requires visits to the site after each storm event to observe the peak stage on the crest gage and re-set the crest gage for the next storm. Given that continuous ditchflow measurements throughout a winter were important, this approach only provides minimal savings in ditchflow instrument costs or reduction of uncertainty of results.

Synoptic samples of sediment were tested in Oak Creek to see if this approach could yield supplemental information to assist with road sediment monitoring and sediment yield. A synoptic sample using one measurement per site did not provide information to observe the magnitude of sediment delivery from individual road discharge locations. The variability in suspended sediment concentrations throughout a storm was too large for this approach to be successful. However, if the sediment load for all road locations for an entire storm can be determined this information does provide a representation of the magnitude of sediment delivery for individual road segments. Total sediment load from each storm that synoptic samples were analyzed by linear regression with the dependent variable being annual sediment load from the roads (Figures 4.28 and 4.29). In both water years it was found that there was a statistically significant relationship between storm sediment load and the total annual sediment load for a road; this was observed for the 2006 and 2007 water years, p values <0.0001 for both relationships.

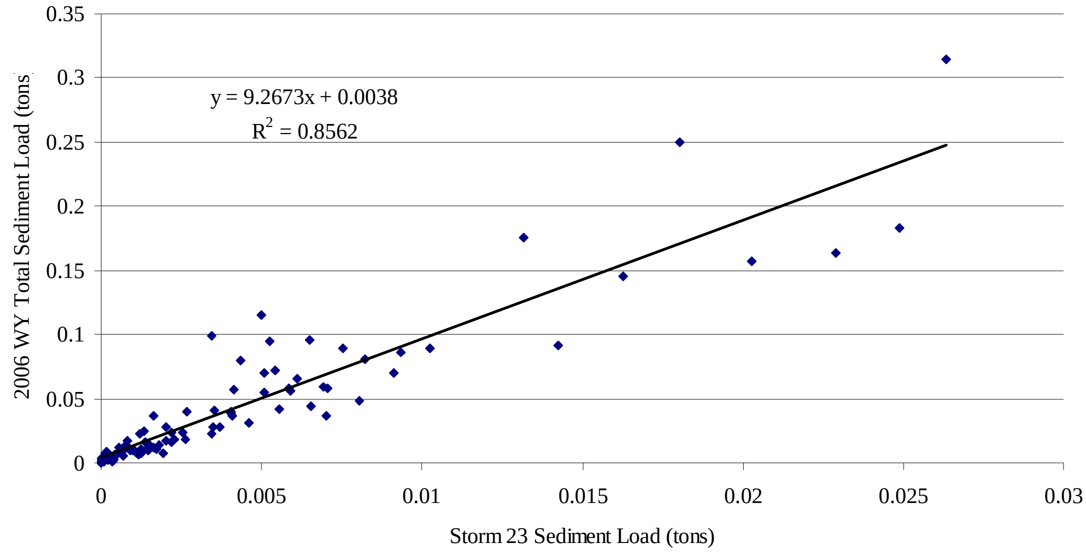


Figure 4. 28. Relationship between Storm Sediment Load and Total Annual Sediment Load for 1 Storm in the 2006 Water Year.

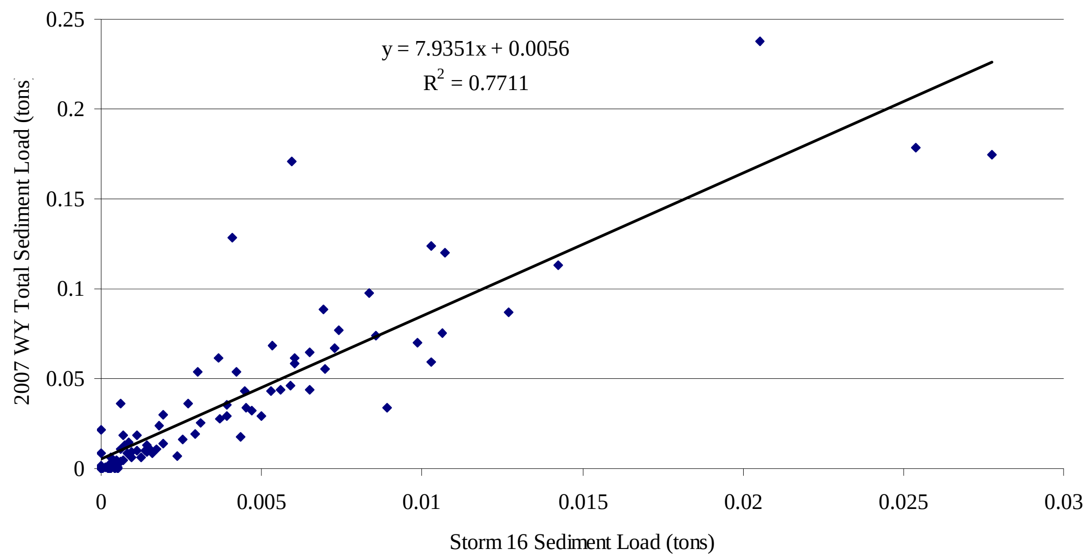


Figure 4. 29. Relationship between Storm Sediment Load and Total Annual Sediment Load for 1 Storm in the 2007 Water Year.

Once the relationship between road runoff and sediment load is available for a catchment, storm sediment load from a road can be estimated with as few as four suspended sediment concentration samples, however the uncertainty in this estimate was high. If peak flow of storm or additional samples of the suspended sediment concentrations was added then the amount of variability explained by the relationship was improved. It was also shown that 3 or more suspended sediment samples used along with the peak flow for a storm gave a reasonable estimate of the road sediment production for the storm.

A synoptic approach that has the objective of quantifying the sediment load for a single storm using some mix of grab samples and hydrologic information would provide information to describe the magnitude of sediment delivery from roads in a catchment. In this case of Oak Creek 50% of the annual sediment delivery came from 13 road segments out of a total of 94 road segments. From a management perspective that may be a more important result than accurate quantification of catchment scale sediment delivery.

CONCLUSIONS

This study demonstrated that measurements of road runoff and suspended sediment combined with the road erosion models of WARSEM or SEDMODL2 can provide improved catchment scale estimates of road sediment delivery. Estimates of the sediment from roads using SEDMODL2 or WARSEM that were adjusted from field measurements were substantially lower than using SEDMODL2 or WARSEM without adjustments from field measurements. Using field adjustments of SEDMODL2 and WARSEM did not improve estimates of sediment production for individual road segments because of the lack of correlation between road runoff and road area.

The peak flow and the volume of road runoff during storms were correlated with the storm sediment load in Oak Creek. Using this relationship the production of sediment from the road at the catchment scale was accurately estimated when road runoff was collected for all of the roads. The relationships observed in Oak Creek between sediment load and storm volume or peak flow were also observed in the South Fork Albion River. However, the relationships between sediment load and storm volume or peak flow were developed by road type in the South Fork Albion River due to variability in road use and hydrologic response.

In Oak Creek, the sediment yield estimated using road runoff was lower than sediment yield estimated using WARSEM and SEDMODL2 adjusted with field measurements. When the sediment yield from roads was estimated for Oak Creek using simulated road runoff generated by the DHSVM, the result was similar to the sediment yield estimated from road runoff. The estimated sediment yield from roads calculated using continuous measurements of runoff and sediment with capacitance rods, flumes, and TTS sediment sampling had the lowest variance. When fewer sediment samples were taken or when the sediment loads or hydrologic responses from roads were extrapolated from other roads, the variance of the sediment estimates increased. A synoptic sampling approach which quantifies storm sediment load for every road provides a measure of the magnitude of sediment delivery from individual roads.

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UNCERTAINTY IN FOREST ROAD HYDROLOGIC MODELING AND CATCHMENT SCALE ASSESSMENT OF FOREST ROAD SEDIMENT YIELD

CHAPTER 5: GENERAL CONCLUSIONS

The assessment of the impacts of roads on the hydrology and sediment yield of forested catchments has a high amount of uncertainty. The variability of the hydrologic response of hillslopes and sediment transport and yield makes quantification of these processes difficult. This study showed that the use of DHSVM, a distributed hydrologic model, to assess hydrologic responses to roads at a catchment scale must be approached carefully. Also, that the estimation of sediment yield from roads is better when data from road runoff are used in the analysis.

The uncertainty with hydrologic responses simulated with DHSVM was affected by many factors. This study showed that soil depth estimated from field measurements improved the results from DHSVM. The influence of different methods to estimate soil depth on the hydrologic response predicted by DHSVM varied with spatial scale and the hydrologic process modeled. When simple physically based approaches were used to estimate soil depth the correlation with field measurements of soil depth ranged from low correlation to no correlation. However, even with this lack of predictive capacity, a soil depth model that was fit to the field measurements of soil depth improved the ability of DHSVM to model ditchflow and runoff from the rising limb and peak flow of storm hydrographs for individual roads and small scale streamflow (5 hectares in area). However, mean field observed soil depth was as good as or better than using the soil depth model fit to field observations for the larger scale streamflow location (55 hectares in area).

Estimates of the response of the hydrology of the roads using DHSVM in Oak Creek exhibited considerable uncertainty. Complex soil development coupled with a variable rainfall/runoff response for sub-surface flow appeared to be the reason that DHSVM performed poorly. DHSVM estimated the total runoff from Oak Creek and the total volume of water intercepted by roads well. But, estimates of discharge at individual road segments and aggregate road segments were inaccurate. As spatial scale and temporal scale increased, the uncertainty in the results from DHSVM decreased. Estimates of the streamflow at the outlet of Oak Creek using DHSVM were the least uncertain and had the most diverse range of model structures as determined from the GLUE assessment. This demonstrated that the conceptual model used to simulate hydrologic response of forest roads in DHSVM had reasonable results at the catchment scale but not at the scale of individual roads in Oak Creek. The uncertainty assessment provides future users of DHSVM a quantification of the uncertainty, demonstrated that sensitive parameters of the model are porosity and the exponent of the decay of hydraulic conductivity, and that calibration of the model with internal catchment data was best.

The peak flow and the volume of road runoff during storms were correlated with the storm sediment load in Oak Creek. Using this relationship the production of sediment from the road at the catchment scale was accurately estimated when road runoff was collected for roads. The relationships between storm volume or peak flow and storm sediment load were also observed in the South Fork of the Albion River. However, the relationships between sediment load and storm volume or peak flow were developed by road type in the South Fork Albion River due to variability in road use and hydrologic response.

Estimates of the sediment from roads using SEDMODL2 or WARSEM that were adjusted from field measurements were substantially lower than using SEDMODL2 or

WARSEM without adjustments from field measurements. Using field adjustments of SEDMODL2 and WARSEM did not improve estimates of sediment production for individual road segments because of the lack of correlation between road runoff and road area. In Oak Creek, the sediment yield estimated using road runoff was lower than sediment yield estimated using WARSEM and SEDMODL2 adjusted with field measurements. When the sediment yield from the roads was estimated for Oak Creek using simulated road runoff generated by DHSVM, the result at the catchment scale was similar to the sediment yield estimated from road runoff. The estimated sediment yield from roads calculated using continuous measurements of runoff and sediment with capacitance rods, flumes, and TTS sediment sampling had the lowest variance. When fewer sediment samples were taken or when the sediment loads or hydrologic responses from roads were extrapolated from other roads, the variance of the sediment estimates increased.

FUTURE WORK

DHSVM did not accurately simulate the hydrologic response of individual roads or road culverts in Oak Creek. This appears to be in response to preferential flow paths that affect the routing of sub-surface flow in the soils of Oak Creek. The macro-pores or fractured regions of the underlying bedrock become more efficient at routing water once soils are saturated. Development and research of this change in sub-surface hydrologic response based on the threshold of soil water content is necessary. It may enable models to better estimate the hydrologic responses of small scale features such as forest roads. Research that provides the ability to model more accurately the hydrologic response of individual roads or culverts can improve road management decisions across a catchment.

The research that investigated the effect of measured soil depth on the accuracy of model estimates in this dissertation demonstrated the need for better approaches to estimate soil depth in mountain catchments. Soil depth is a highly influential variable when modeling the hydrologic response of the shallow soils common in mountainous terrain. Future research should focus on whether a balance of field measurement combined with digital terrain models can better estimate soil depth in mountain catchments. Research on the appropriate scale for measurement of soil depth as it aides hydrologic models would be beneficial as well.

The production of road sediment that is estimated using continuous measurements of turbidity and road runoff provided accurate estimates of sediment yield and low levels of error associated with those estimates. Currently the instruments and procedures to measure turbidity in low runoff environments, such as road ditches, are challenged by the limitations and cost of the turbidity measuring instruments. Research and development into low cost, small turbidity measurement sensors could revolutionize the way sediment is measured in land management settings.

Future work needs to focus on the implications of sampling road runoff to determine changes in sediment production over time. Further work should attempt to isolate the road uses and road types that affect the runoff and sediment yield relationship. This would be useful for development of road monitoring for varying geographies and climate. Future work should look at low cost measurements to estimate the coarse sediments from roads in conjunction with road runoff measurement. Further, an investigation of the relationships between road runoff and larger scale road erosion, such as mass wasting, road crossing failure, or gullies, would be very beneficial.

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APPENDICES

APPENDIX A: DETAILS ON DATA INPUTS FOR DHSVM OAK CREEK MODELING 2003-2007

Stream and Road Inputs

The stream network for Oak Creek was generated by the "createstreamnetwork" Arcinfo script provided with DHSVM. The "createstreamnetwork" script builds the lines and assigns the attributes of the stream network for DHSVM use. The stream channel lines created are based on a flow accumulation model where the user specified the minimum area for channel creation; 2 hectares was used for Oak Creek. The script assigned the channel dimensions (width and depth) for the stream network based on area. Table A.1 shows the channel classes, area, and dimensions used for creating the Oak Creek stream network. Once created the stream network was edited by deleting a few of the stream segments created that were not in the catchment. Several of the stream segments began too far upslope in the catchment and these segments were shortened to reflect actual conditions.

Table A. 1. Stream Channel Classes and Dimensions Used to Create the Oak Creek Stream Network for Input to DHSVM.

Stream Class	Stream Gradient (m/m)	Area (ha)	Channel Width (m)	Channel Depth (m)	Manning's Roughness (n)
1	>0.025	<10	1.5	1.0	0.035
2	>0.025	10 - 25	2.0	1.5	0.035
3	>0.025	25 - 100	3.0	5.0	0.035
4	>0.025	100 - 1000	5.0	7.5	0.035
5	<0.025	<25	2.0	1.5	0.035
6	<0.025	25 - 100	5.0	4.0	0.035
7	<0.025	100 - 1000	7.5	7.0	0.03

The road network GIS layer for Oak Creek was mapped using a 1 meter global positioning system (GPS). Each road drainage feature or watercourse crossing (culverts and bridges) was mapped as point features along the road arcs using the GPS. Because the road and culvert spatial information was measured using a 1 meter resolution it was considered more accurate spatial data for the catchment than stream segments. Stream segments that did not align with road culvert crossings were moved to match the culvert location. Usually this was not a problem because the road crossing structure and the stream segment were in the same 30 meter pixel of the DEM. However, when road crossings and stream segments were not in the same pixel, the DEM had to be edited as well. This occurred on only a few locations. The DEM was edited by altering the elevation slightly in the pixels that surrounded the stream crossing culvert. The editing was to ensure that the stream segment was traveling in the lowest elevation in its route on the hillslope (within a depression, canyon, or swale) to ensure best performance of the sub-surface water routing within DHSVM. If these pixel elevations were not altered it would have created artificial ponding and storage of water in locations not encountered in the catchment. Within a GIS the road drainage features and road arcs were snapped together to ensure that the drainage features were exactly on the road arc. The road arcs were than separated into segments based on road drainage features and intersections, with each drainage feature creating a sink in the road segment for simulation of water run-off from the road within DHSVM.

Road dimensions of cutslope depth, road width, ditch width, road type (crowned, outsloped, insloped), and road ditch depth were from field observations collected in September, 2006. Road dimensions were collected at 30 meter intervals (to correspond with the DEM) for all roads within Oak Creek. The road segments were assigned as arcs (segments of lines) between culverts or road intersections. DHSVM used 1 road cutslope depth, road width, ditch width, road type, and ditch depth per road segment. For each road segment, the dimensions of the road were measured in the field and averaged to represent the dimensions for that road segment. There was a linear relationship between the width of the road and the width of the road ditch, and the width of the road ditch and the depth of the ditch. This allowed the representation of road segment cutslope depth, road width, ditch width, and ditch depth per road segment by road class. Road segments were assigned to the following road classes for calculations in DHSVM. The road infiltration rate assigned to all road segments was 4 mm/hr, an average road surface infiltration rate found on five Oregon Coast Range roads (Marbet, 2003). The Manning's roughness coefficient was assumed to by 0.025 for all road ditches in Oak Creek.

The dimensions for each road segment by road class were entered into the Oak Creek Road GIS coverage. The average road cutslope depth was used to represent the cutslope depth for each road segment in DHSVM. The GIS road coverage was processed for use in DHSVM by the "createroadnetwork" Arcinfo script provided with DHSVM. This script prepares the road network and road map files used by DHSVM for analysis of roads. My notes for processing the road network and road drainage locations for use in DHSVM are found in Appendix B.

Oak Creek Meteorological Data

The DHSVM modeling spanned the time period from February, 2003 (the beginning of meteorological observations in the catchment) through the winter of 2006. The meteorological inputs for DHSVM were primarily from the weather station within Oak Creek. The Oak Creek weather station was located along the main channel of Oak Creek at the confluence of the East and West forks of Oak Creek (see Figure 3.1). The weather station began operation in February, 2003 collecting air temperature, relative humidity, photosynthetically active range (PAR) solar radiation, and precipitation. Short wave radiation collection was added in December, 2005 and long wave solar radiation collection added in May, 2006. Within Oak Creek there were four tipping bucket rain gages, one at the weather station location and three others throughout the catchment (see Figure 3.1 for locations). The four tipping bucket rain gages have been in use since October, 2002.

DHSVM requires air temperature, relative humidity, wind speed, short wave solar radiation, long wave radiation, and precipitation as input for each time step of the model. This information was available at the weather station location but not at all the tipping bucket rain gage locations. To take advantage of the additional rain gage locations the climate information collected at the weather station was attached to each tipping bucket rain gage record. This provided four meteorological input files; however, only precipitation was unique within each file.

The weather station and tipping bucket rain gages within Oak Creek had periods of missing data for the time period that was modeled (Table A.2). Meteorological data from the United States Bureau of Reclamation Agrimet climate station in Corvallis, Oregon was used to fill missing time periods from the Oak Creek meteorological data. The Corvallis Agrimet station is approximately 8 miles northeast of Oak Creek and had hourly climate information for the time period that was modeled. The Corvallis Agrimet station collected all required meteorological information used in DHSVM except long wave radiation.

Table A. 2. Periods of Missing Climate Data for Oak Creek Weather Station February, 2003 thru June, 2006.

Water year	From Time	From Date	To Time	To Date	Comment*
2003	1200	5/7/2003	930	5/27/2003	20 days
2003	1040	7/2/2003	1240	9/21/2003	81 days
2004	1250	11/17/2003	1600	12/14/2003	27 days
2004	1710	1/20/2004	1730	4/25/2004	97 days
2004	1840	5/31/2004	1700	6/1/2004	1 day
2004	1810	7/7/2004	1410	7/27/2004	20 days
2005	1140	12/5/2004	1430	12/26/2004	21 days
2005	430	3/18/2005	1600	3/22/2005	4 days
2006	1110	1/22/2006	1310	1/22/2006	2 hours
2006	1630	4/2/2006	1420	4/14/2006	12 days

* - Total of 271 days missing data

Linear relationships for hourly precipitation between each of the tipping bucket rain gages in Oak Creek and the Corvallis Agrimet precipitation were developed (Table A.3). The linear relationships were developed for time periods in the 2003-2006 water years when precipitation occurred at both gages (no zero values used). The best relationship, based on the r^2 value, for each rain gage and time period was used to estimate the missing precipitation. Precipitation gages within Oak Creek were used first to estimate missing data; the Corvallis Agrimet precipitation was used only when there was no precipitation data available from the Oak Creek gages.

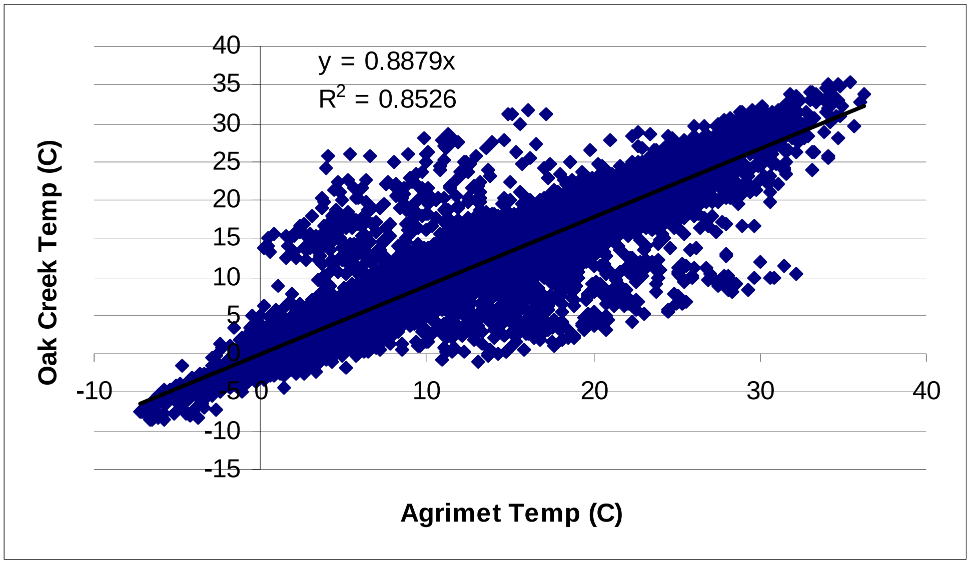
Table A. 3. Linear Relationships for Hourly Precipitation of Oak Creek Tipping Bucket Precipitation Gages (Water Years 2003-2006).

Dependent Variable (Y)	Independent Variable (X)	Linear Relationship	R^2	P Value
Meadows Precipitation/Hr.	Starker Precipitation/Hr.	Y=0.7094X	0.79	<0.001
Meadows Precipitation/Hr.	Dimple Precipitation/Hr.	Y=0.8536X	0.77	<0.001
Meadows Precipitation/Hr.	McCullough Precipitation/Hr.	Y=0.6631X	0.57	<0.001
Meadows Precipitation/Hr.	Agrimet Precipitation/Hr.	Y=0.7868X	0.30	<0.001
Starker Precipitation/Hr.	Meadows Precipitation/Hr.	Y=1.0575X	0.79	<0.001
Starker Precipitation/Hr.	Dimple Precipitation/Hr.	Y=1.0303X	0.77	<0.001
Starker Precipitation/Hr.	McCullough Precipitation/Hr.	Y=0.8397X	0.72	<0.001
Starker Precipitation/Hr.	Agrimet Precipitation/Hr.	Y=0.8992X	0.40	<0.001
Dimple Precipitation/Hr.	Starker Precipitation/Hr.	Y=0.799X	0.77	<0.001
Dimple Precipitation/Hr.	Meadows Precipitation/Hr.	Y=0.9596X	0.77	<0.001
Dimple Precipitation/Hr.	McCullough Precipitation/Hr.	Y=0.7358X	0.69	<0.001
Dimple Precipitation/Hr.	Agrimet Precipitation/Hr.	Y=0.832X	0.34	<0.001
McCullough Precipitation/Hr.	Starker Precipitation/Hr.	Y=0.9362X	0.72	<0.001
McCullough Precipitation/Hr.	Meadows Precipitation/Hr.	Y=1.0118X	0.57	<0.001
McCullough Precipitation/Hr.	Dimple Precipitation/Hr.	Y=1.0395X	0.69	<0.001
McCullough Precipitation/Hr.	Agrimet Precipitation/Hr.	Y=X	0.28	<0.001

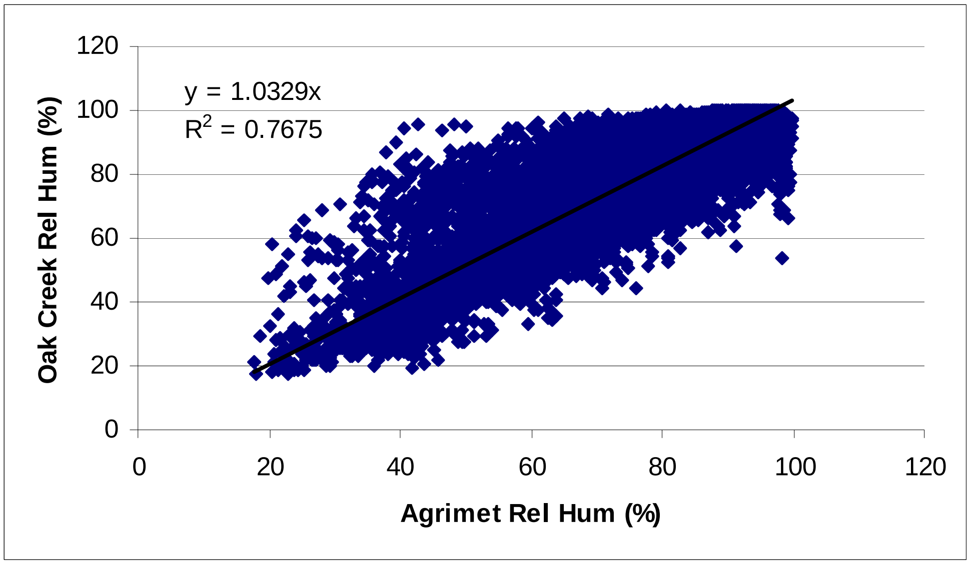
Linear relationships between the Oak Creek weather station and Corvallis Agrimet station were developed for time periods with missing air temperature and relative humidity measurements (Figures A.1 and A.2). Wind speed did not show any relationship between the Agrimet and Oak Creek observations. The Corvallis Agrimet wind speed observations were used for filling missing data from the Oak Creek weather station without any correction.

Short wave solar radiation was collected in Oak Creek for a short period of time (since Dec. 2005). PAR solar radiation was collected within Oak Creek since the weather station inception (Feb. 2003). A relationship between Oak Creek PAR and short wave solar radiation was used to estimate reflected shortwave solar radiation inputs for time periods without shortwave solar radiation measurements (Figure A.3). When PAR observations were missing from Oak Creek the Corvallis Agrimet shortwave solar radiation observations were used.

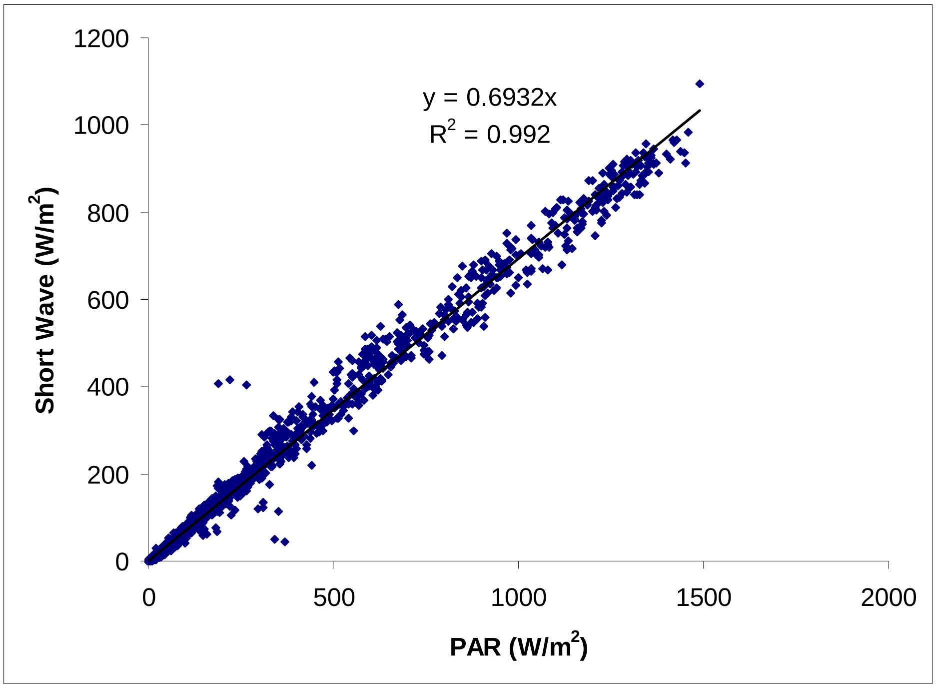
Long wave solar radiation had been collected for one week at the time of this analysis. Long wave solar radiation was estimated for this one week using the Stefan /Botlzman's equation following the procedure described in Burman and Pochap (1994). The results from the Stefan /Botlzman's equation were compared to observed long wave radiation by linear regression. A linear regression relationship was also developed between observed air temperature and observed long wave radiation from Oak Creek. The observed air temperature and long wave radiation observations had similar r^2 value as the Stefan/Boltzmann's equation versus observed long wave solar radiation, 0.76 versus 0.75 respectively. The prediction of long wave solar radiation by the air temperature was used for DHSVM inputs (Figure A.4) because air temperature was a consistent value measured in Oak Creek that provided a more reliable estimate than some of the inputs to the Stefan/Boltzmann's equation.



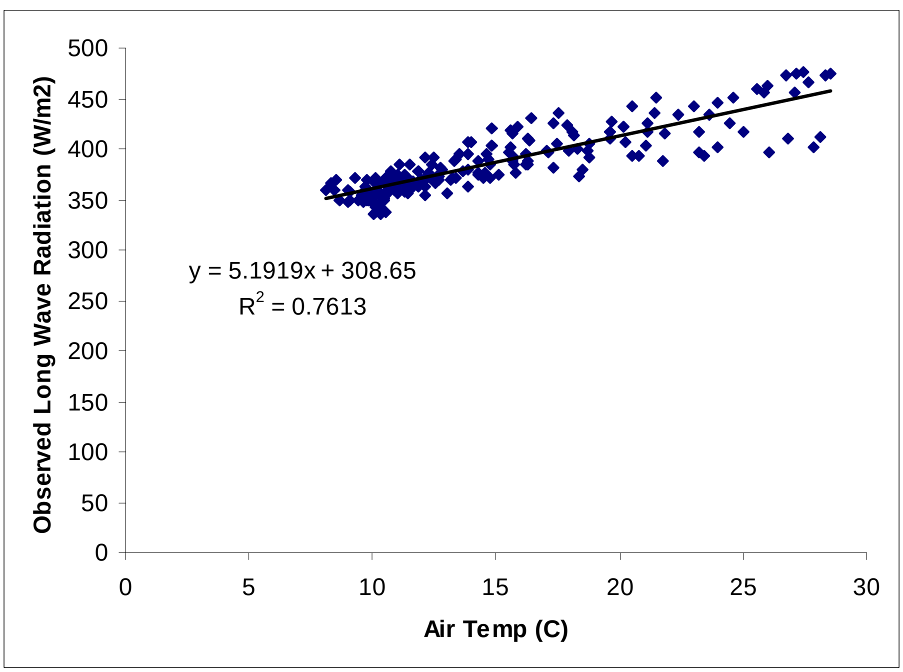
<u>Figure A. 1</u>. Linear Relationship between Oak Creek and Corvallis Agrimet Air Temperature Water Years 2003-2006.



<u>Figure A. 2</u>. Linear Relationship between Oak Creek and Corvallis Agrimet Relative Humidity Water Years 2003-2006.



<u>Figure A. 3</u>. Relationship between Photosynthetically Active Range (PAR) Solar Radiation and Total Short Wave Solar Radiation Oak Creek (Dec. 05-May 06).



<u>Figure A. 4</u>. Relationship between Observed Air Temperature and Downward Long Wave Radiation at Oak Creek, May 2006.

APPENDIX B: STEPS FOR CREATING ROAD LAYERS FOR USE IN DHSVM

Creating Road Layers for use in DHSVM

These notes do not contain all of the key strokes to complete each task, but each command in ArcMap, ARCINFO, or ArcCatalog is noted.

1. In ArcCatalog
    a. Copy needed files to your own local workspace.
    b. You will need:
        i. stream network coverage
        ii. dem
        iii. soil depth raster
        iv. mask raster
    c. Make a shapefile of the stream network coverage, if it will be edited.

2. In arc map:
    a. Clip the road layer to the basin mask.
        i. Add the basin mask raster and the roads shapefile to a project.
        ii. Make a polygon of the basin mask using spatial analyst.
        iii. Clip the road coverage so that only the roads within the mask polygon remain.
    b. Clip the road crossing structure[1] layer (culverts, bridges, etc) to the basin mask.
        i. Add the basin polygon and the road crossing shapefile to a project.
        ii. Clip the road crossing coverage so that only the roads within the mask remain.
    c. Edit the road and road crossing structures (culverts, bridges, etc.) so that the road crossings are lined up with the roads. When moving road arcs to a road crossing structure, or vise versa, be sure that the "snapping" feature is turned (in ArcMap 9.0 this is within the editing toolbar) for the road crossing structures to ensure the road arc is attached to the road crossing structure.
    d. Populate the 'Class' field in the road layer.
        i. If not available add a field in the attribute table titled 'Class'.
        ii. Populate each road arc with an appropriate class (from 1-9) based on width of road, width of road ditch, width of road arc, and road cutslope height. See the road class definitions in the create.road.network.aml for guidance. If necessary edit the road

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[1] If there is not a road crossing structure coverage then only edit DEM and stream network in step 2 as necessary.

class definitions within the create.road.network.aml to personalize your road classes.

e. Edit DEM, road crossing structure locations, and/or stream arcs so that streams go through stream crossing structures, excess stream arcs are deleted (delete arcs created by the create.stream.network.aml that are not stream channels in the watershed), and move incorrectly placed stream arcs. Typically editing a combination of two of these map layers is necessary; edit those layers with the least accurate spatial information. Do not edit layers with accurate spatial information.
    i. Edit DEM in isolated situations where stream arcs do not travel through DEM pixels with a culvert or where stream locations are obviously wrong. This process I did by “brute force” by having a text file open of the DEM grid and viewing the DEM within ArcMap (however this can be done within Arcinfo as well). When a group of pixels were edited I would perform a search of the text file for those values and make my changes. Only edit DEM in situations where other data, stream arcs, field observations, or culvert location are considered more accurate then DEM. Once the DEM text file editing is completed it must be converted to the new DEM layer.
    ii. Edit stream arcs as necessary. This is done within a shapefile created from the stream network layer. Move or delete stream arcs to give a more accurate representation of the stream network. Move stream arcs to ensure that stream arcs travel through road crossing structures (bridges, culverts, etc.). Be very careful to consider DEM elevations, DHSVM routes water downhill and moving a stream arc to an improper elevation can cause an inaccurate hydrologic response. When moving stream arcs to a road crossing structure be sure that the “snapping” feature is turned (in ArcMap 9.0 this is within the editing toolbar) for the road crossing structures layer to ensure the arc is attached to the road crossing structure.
    iii. Edit road crossing structure locations if these locations are considered less accurate spatially then stream arcs or DEM data. Move road crossing structures to ensure that stream arcs travel through road crossing structures (bridges, culverts, etc.). Be very careful to consider DEM elevations, DHSVM routes water downhill and moving a stream crossing to a stream arc with an improper elevation can cause an inaccurate hydrologic response. When moving a road crossing structure be sure that the “snapping” feature is turned (in ArcMap 9.0 this is within the editing toolbar) for the stream arcs to ensure the road crossing structure is exactly attached to the stream arc.
    iv. If the stream network was edited use Xtools or some similar tool to calculate the new arc lengths.

v. Convert the edited stream network shapefile to a coverage (this should be done in ArcInfo see step 3).
vi. Convert the road network to a coverage (this should be done in Arcinfo see step 3).

3. Arcinfo
    a. To convert the stream and road shapefiles to coverages use shapearc.
    b. Then use “clean” command to establish topology and clean errors.
    c. Then use "matchnode" to match the node ends of the arcs to culvert points.
    d. Run the create.stream.network.aml with the edited DEM and stream network coverages from step 2 to create input files for DHSVM.

4. ArcCatalog
    a. Covert the basin polygon shapefile into a line coverage “basinedge”.

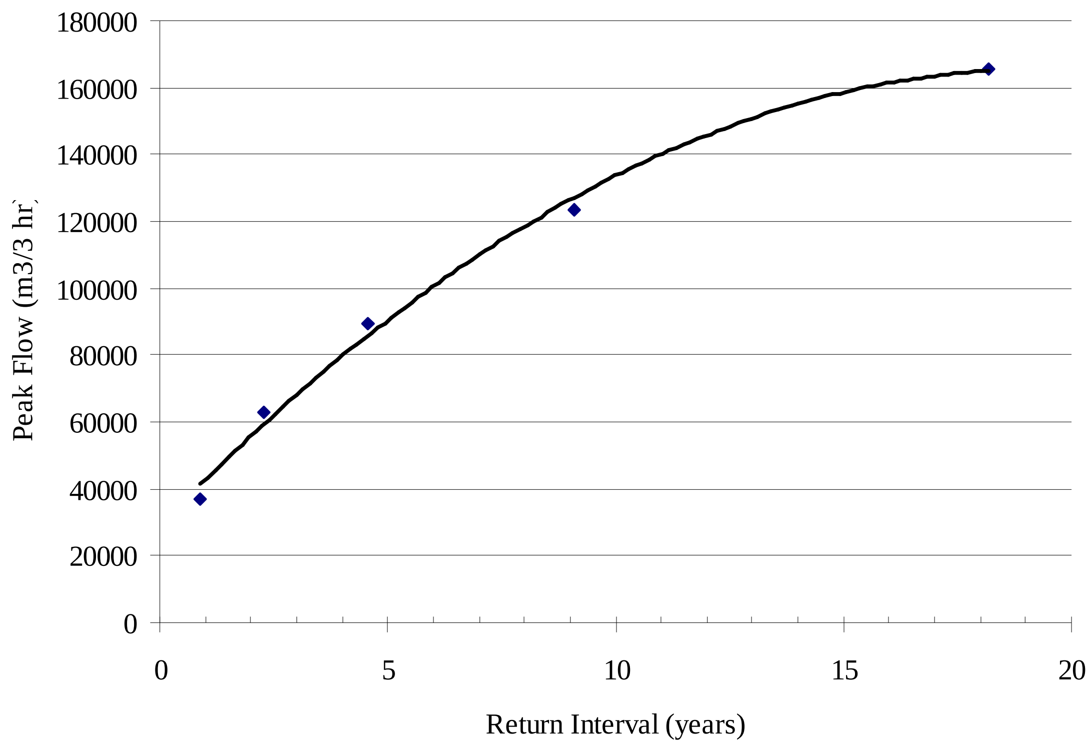
5. In ArcINFO
    a. Change workspace to directory where you copied files to in step 2.
    b. If you have a culvert coverage skip this step, if you do not then you can generate a stream crossing culvert coverage by running the script arcintersect, do the same for the basin edges.
        i. &run arcintersect roads streams culverts
        ii. &run arcintersect roads basinedge edges
    c. Run the script roadbreak to create sinks at culvert locations
        i. &run roadbreak dem streams roads culverts
        ii. &run roadbreak dem streams roads edges (if necessary)
    d. Run script createroadnetwork (NOTE: be sure that fixroad program is compiled and the path for executing the fixroad program in the createroadnetwork script is correct; the fixroad program is essential for a properly built road network).
        i. &r createroadnetwork dem soildepth roads
            1. soildepth is the raster previously made when creating the stream network.

APPENDIX C: PARTIAL SERIES FREQUENCY ANALYSIS FOR OAK CREEK

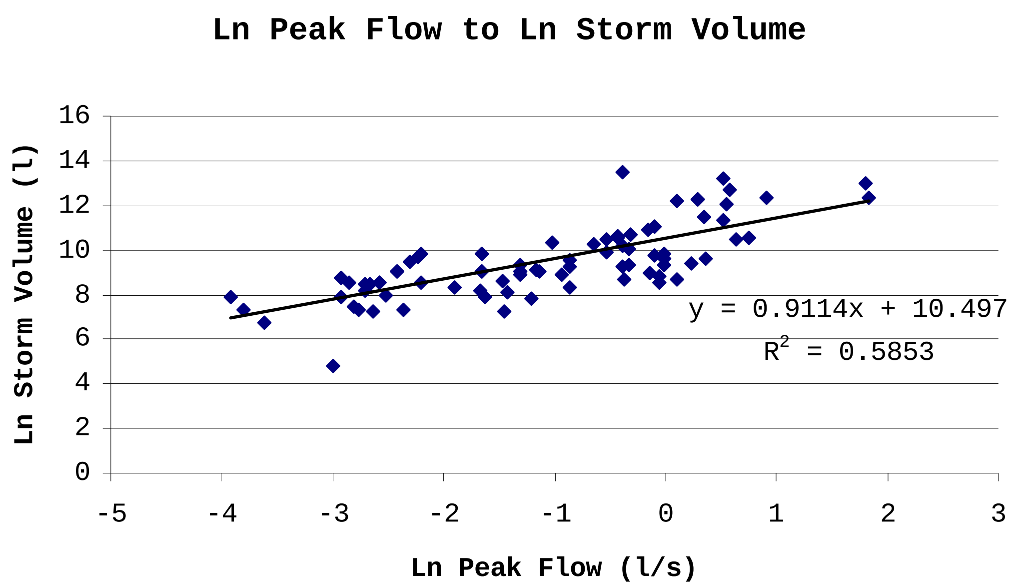
A partial series frequency analysis was done on the peak flows for Oak Creek at the gaging station.

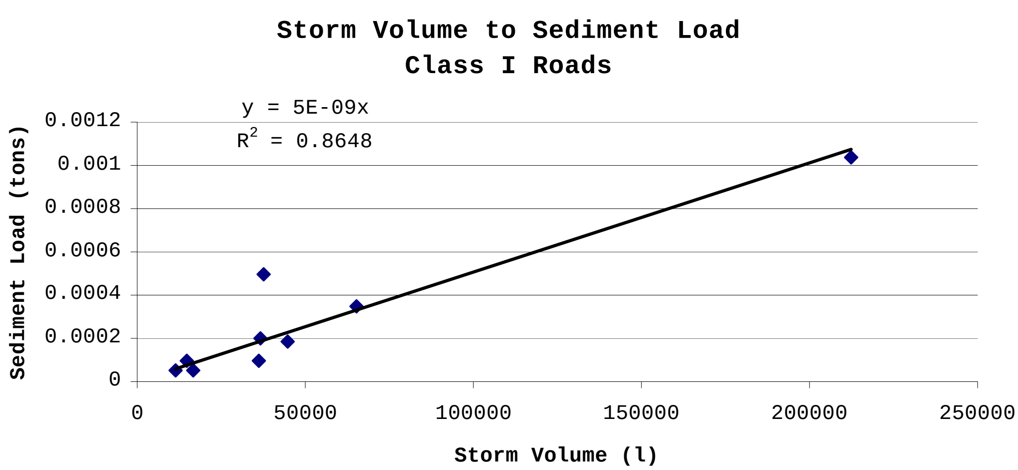
The frequency analysis fit the Log Pearson Type III distribution to the partial series peak flows.

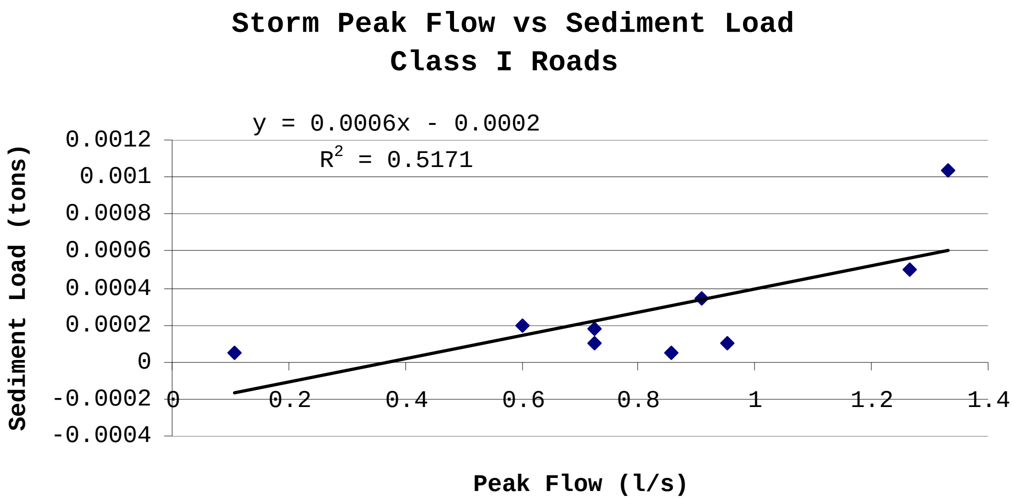
Return Interval(yr)	Peak Flow (m3/3hr)	Peak Flow (l/s)
0.9	36776.33	3405.215
2.3	63010.72	5834.326
4.5	89567.32	8293.27
9.1	123347.1	11421.03
18.2	165652.9	15338.23

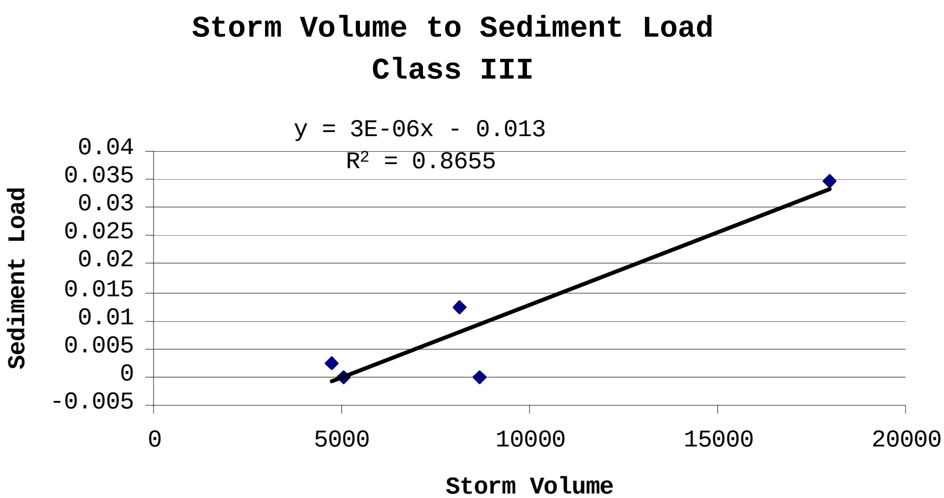


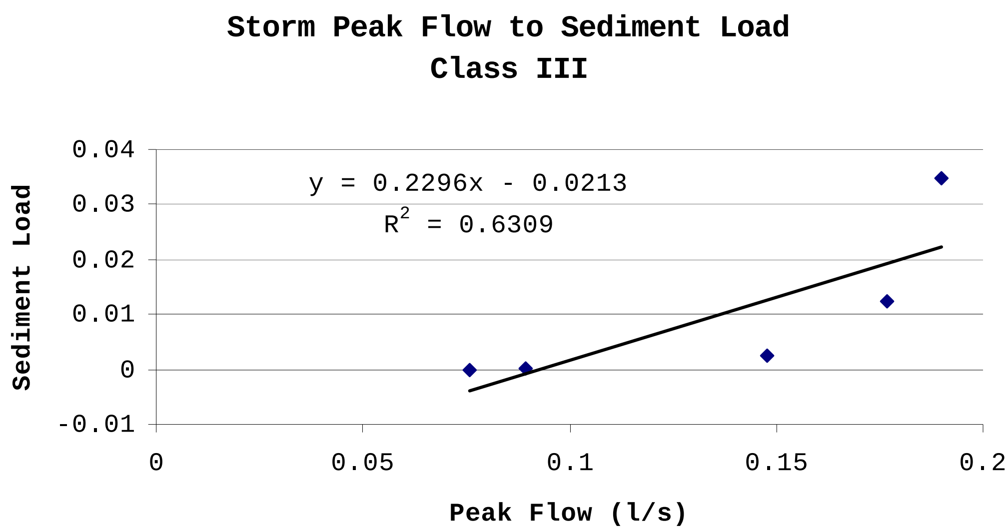
APPENDIX D: PLOTS OF ROAD RUNOFF AND SEDIMENT YIELD FOR VARIOUS TYPES OF ROADS IN THE SOUTH FORK OF THE ALBION RIVER

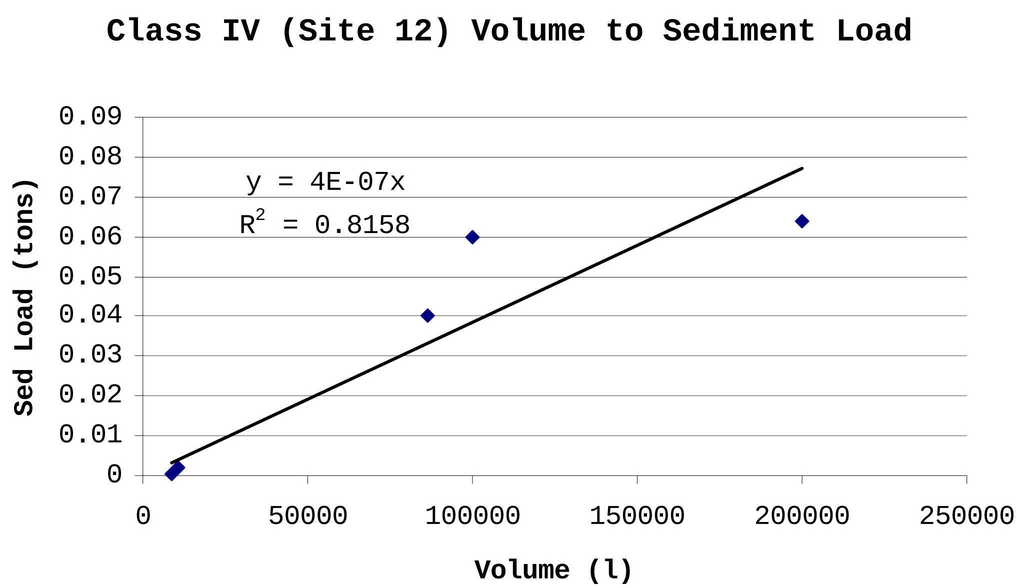

Ln Peak Flow to Ln Storm Volume
y = 0.9114x + 10.497
R2 = 0.5853
Ln Storm Volume (l)
Ln Peak Flow (l/s)
16
14
12
10
8
6
4
2
0
-5
-4
-3
-2
-1
0
1
2
3


Storm Volume to Sediment Load
Class I Roads
y = 5E-09x
R2 = 0.8648
Sediment Load (tons)
Storm Volume (l)
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0
50000
100000
150000
200000
250000

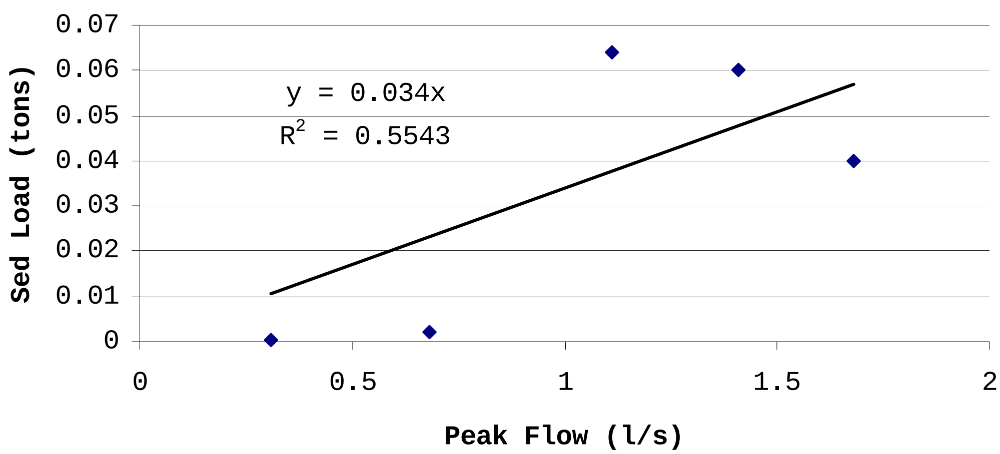

Storm Peak Flow vs Sediment Load
Class I Roads
y = 0.0006x - 0.0002
R2 = 0.5171
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Sediment Load (tons)
Peak Flow (l/s)


Storm Volume to Sediment Load
Class III
y = 3E-06x - 0.013
R2 = 0.8655
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
5000
10000
15000
20000
Sediment Load
Storm Volume

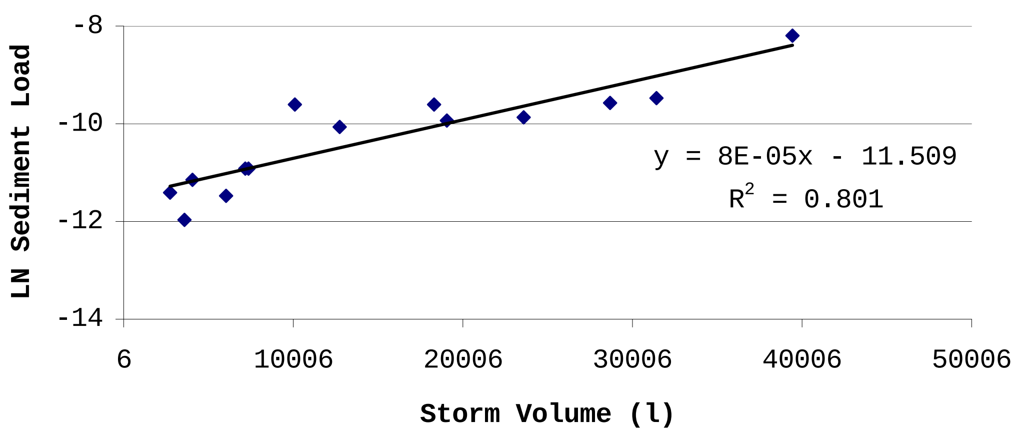

Storm Peak Flow to Sediment Load
Class III
y = 0.2296x - 0.0213
R2 = 0.6309
Sediment Load
0.04
0.03
0.02
0.01
0
-0.01
0
0.05
0.1
0.15
0.2
Peak Flow (l/s)

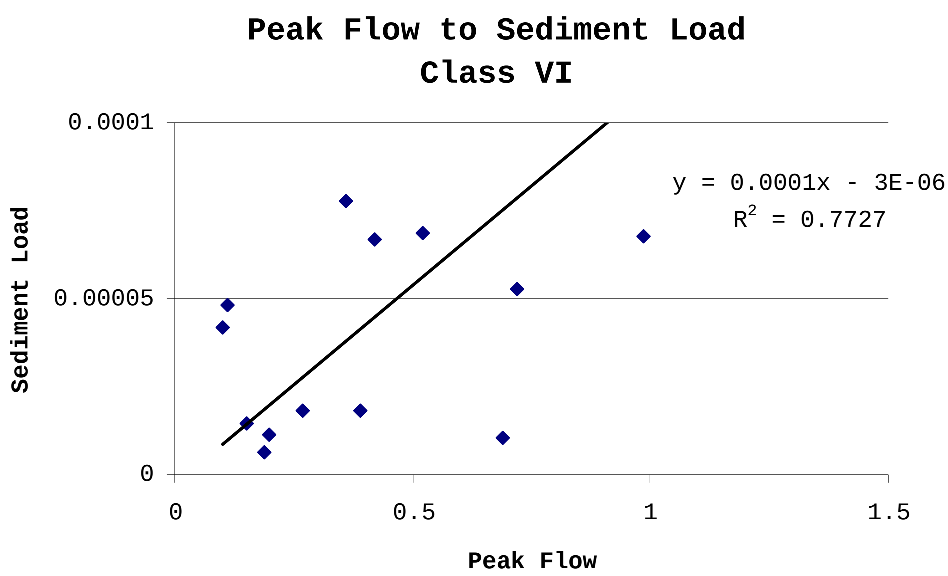

Class IV (Site 12) Volume to Sediment Load
y = 4E-07x
R2 = 0.8158
Sed Load (tons)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
50000
100000
150000
200000
250000
Volume (l)

Class IV (Site 12) Peak Flow to Sediment Load

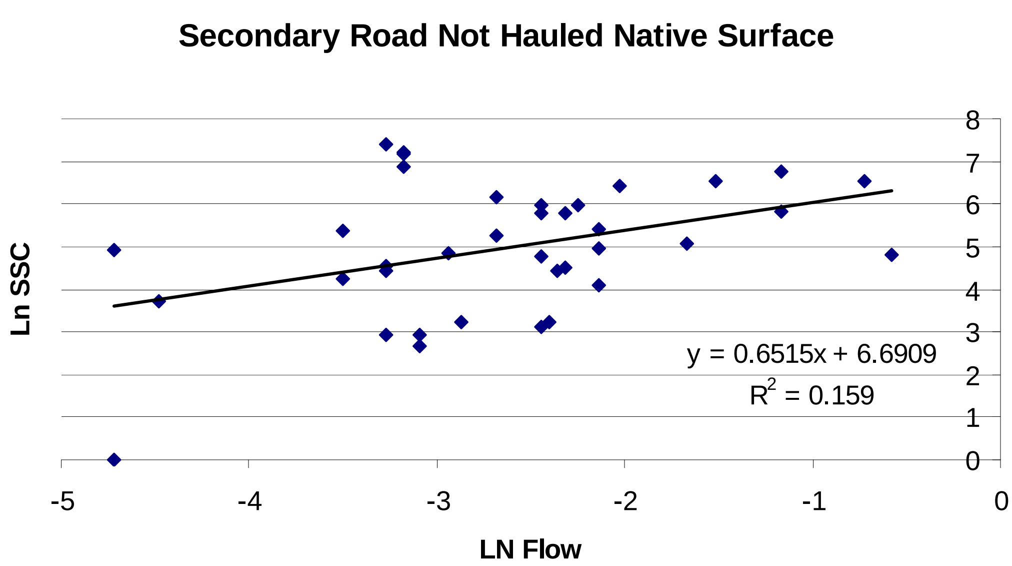


Storm Volume to Sediment Load Class VI





The next 2 graphs show that rock and native surface was not sufficient for hydrology and sediment relationships, particularly the rocked roads.



APPENDIX E: CONSIDERATIONS FOR A PROTOCOL FOR SAMPLING ROAD SEDIMENT PRODUCTION

The following points are suggested for monitoring fine sediment from roads when using SEDMODL2 to extrapolate the results to the catchment scale. These points were put together from the results and discussions of this study and were meant to assist Mendocino Redwood Company meet Habitat Conservation Plan requirements of monitoring reduction in road sediment. These points do not consider use of continuous turbidity observations.

Initial Sample:

- Roads to be sampled (the sample frame) are roads determined to deliver sediment to watercourses, typically watercourse crossings but can also be road drainage locations which drain to watercourses.
- Number of roads to be sampled should be based on acceptable error and confidence interval needed. This determination will be based on logistics, cost, and objective of results.
- The numbers of roads to be monitored can and should be spread over several consecutive years. The more years of consecutive observation the more likely to capture wet and dry year variations. I suggest 3-5 years be considered for monitoring.
- A spatially balanced sample design (Stevens and Olsen, 2004) would provide an excellent sample design for roads to be monitored. Within the spatially balanced sample selection process more weight should be put on main haul roads or specific roads of interest. This increased weight will ensure a better representation of these roads in the sediment load estimates.

Road Site Set-up:

- Road water run-off needs to be measured at the location where the water and sediment leave the road. This can be either in the road ditch approaching a culvert, the outlet of a water bar or rolling dip, or low spot on the outside edge of a road. If it is uncertain which location has the water and sediment delivery then put instruments in the location that is believed to have the water run-off then observe the site during storms moving the instruments to a different spot on the road if necessary.

- If a road site selected for monitoring has a watercourse draining into the road prism this site must be removed from the sample. This would make the hydrologic observations unrepresentative of the road. The next road site from the spatially balanced sample will replace it.
- For each road segment monitored measure the contributing road tread area, road cutslope area, road cutslope vegetation cover, road slope, and road surface type. This information will be used in the subsequent WARSEM or SEDMODL2 application.
- Water discharge must be measured in a controlled structure. A flume is the most versatile but discharge can be measured at culvert inlets or with weirs. An inexpensive flume that can be made from PVC pipe from a hardware or plumbing store was used in this study (Samani and Herrera, 1996).
- It is recommended that continuous water stage recording instruments (such as capacitance rods or pressure transducers) be used at all road sites to be monitored for the entire winter of measurement.
- If continuous water stage recording instruments cannot be used at all locations, then crest gages can be used but must be measured and re-set following each storm event.
- There will be a few roads that will not have any water discharge, in these cases continuous recording instruments are not needed and can be moved to another road site. If no water discharge is observed a continuous recording instrument can be removed but a crest gage still needs to be maintained at the site in case water does flow.

Sediment Samples:

- Collect water samples for suspended sediment or turbidity observations for a portion of the roads to be monitored in each storm event. This allows more sediment samples per road site per storm compared to trying to measure every road during every storm. Every road to be sampled in a water year should have at least 1 storm of sediment observations; however having more storms measured per road is beneficial.
- Collect as many water samples for suspended sediment or turbidity observations as possible during a storm event.
- When water samples are taken record water stage, time, location, and current weather. Put samples on ice and keep dark until lab analysis can be done.
- Turbidity can be used to predict the suspended sediment from the relationship between the two variables. This study did not explore when turbidity can replace sediment analysis, this will need to be determined in the future by trial and error.
- For each road site develop sediment rating curves for each storm or collection of storms measured and then use to estimate sediment load by storm from discharge measurements.
- Develop linear relationships based on road site, type, class, or watershed for storm volume to storm sediment load and storm peak flow to storm sediment load.
- Use storm volume or peak flow to sediment load relationship to estimate sediment load for storms without a sediment rating curve, calculate each storms sediment load variance.
- Calculate total sediment load for each road site monitored by summing sediment loads from each storm. Calculate confidence intervals by summing the variance for each storm then derive the standard error for the entire year by taking the square root of this total variance.

WARSEM or SEDMODL2 Spatial Extrapolation of Sediment to Watershed Scale:

- Using the field measured annual sediment load solve by iteration the geologic erosion/precipitation/traffic factor from the equation for predicting sediment load from WARSEM for each road monitored. Use the measured parameters of road slope, surface, area, etc. measured at each site.
- Calculate the mean geologic erosion/precipitation/traffic factor for all the roads monitored.
- Use the mean geologic erosion/precipitation/traffic factor within WARSEM for the entire watershed. WARSEM is preferable to use because it uses field observed road specifications, however if appropriate field observations are not available then SEDMODL2 can be used.

Potential to Monitor Roads for a Large Regional Land Base

A similar approach to the road monitoring protocol points for watershed scale estimates could be used to quantify road sediment across a large regional land base. Across a regional area there will be much greater variations in precipitation, soils, geologic influences, road maintenance, and road design. This increased variability will result in a larger sample size than needed to quantify road sediment for a single watershed. The logistics of sampling storm events will also be more difficult due to greater distances between roads to be sampled. The approach of getting sediment samples for portions of roads for each storm event will assist in accomplishing this.

When considering monitoring watersheds to quantify road sediment delivery it is likely that several watersheds will need to be monitored to represent conditions for roads in a large regional land base. Monitoring 2 or more watersheds could very easily produce a similar or perhaps greater sampling effort than might be needed if the entire region was monitored. However, this question cannot be answered until the variation in road sediment delivery for the region is known. Although a reasonable sample design can be inferred for watershed scale monitoring from this study, it cannot reliably make inference to a large region. A pilot study of road hydrology and sediment delivery involving other areas with differing soils, geology, and precipitation would be needed. Hydrology and sediment data from about 4-5 road sites clustered within 4 or 5 different geographic locations of the lands would provide enough information to determine the variability of road sediment delivery across the lands. From this determination of variability appropriate sample sizes based on error and confidence of results can be estimated.