Road Surface Runoff for the Oak Creek Watershed:
The Influence of Hillslope and Road Characteristics.

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AN ABSTRACT OF THE PROJECT

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Abstract Approved:

____________________________________________________________
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Understanding how forest roads interact with hillslope hydrology by intercepting and/or rerouting storm runoff will better enable land managers to reduce erosion related to forest roads. Watershed scale knowledge of how culvert runoff response varies across the landscape would provide valuable information to those individuals designing and maintaining forest road systems. In order to better understand the hydrologic interactions of the hillslope and the road, this study focused on all cross drain culverts in a 3rd order watershed of Oak Creek located in the McDonald/Dunn Research Forest 3 miles west of Corvallis Oregon. Stage recorders measured runoff response for winter months from October to March 2001 to 2002 and data for the January 25, 2002 storm event were analyzed in detail. Instantaneous peak discharge was measured at all culverts with either a crest gauge or a capacitance rod. Those culverts with a capacitance rod measured water height data every 10 minutes and provided a runoff response hydrograph. Fifty-eight of 74 gauged road segments were used in the analysis. Measurable instantaneous peak discharge was received from all 58 cross drain culverts and total runoff volumes were measured at 40 of the road segments. Frequency distributions of the runoff response for both instantaneous peak discharge and
total runoff volume follow a right skew distribution. This indicates that a majority of the culverts measured had lower amounts of runoff than the mean and that only a small fraction of the culverts had a large runoff response.

Geographic Information System (GIS) coverage for McDonald/Dunn Forest was used to calculate road and hillslope characteristics. The correlation of instantaneous peak discharge for the cross drain culverts to road and hillslope characteristics indicates significant relationship at the 99% confidence level ($p = 0.0030$). Road length ($p = 0.0029$) and elevation ($p = 0.0239$) are statistically significant at greater than a 90% confidence level. However, the multiple linear regression model only explains 34% of the variability of instantaneous peak discharge. This result indicates it will be difficult to predict variations in runoff. Total runoff volume correlated with road and hillslope characteristics provided a similar result. None of the independent watershed/road variables were found to be significant predictors.
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1. INTRODUCTION

1.1. PROBLEM STATEMENT

Forest roads are built and maintained to provide access to forests for management. This management can be primarily hauling logs from the forest to sawmills, but also includes recreation, fire management and other land management activities. Forest roads have long been the focus of environmental concerns, especially regarding accelerated erosion, both surface erosion and landslides. During the last two decades, considerable effort and resources have been put into building better forest roads. However, forest roads continue to be a cause for concern and recently have been implicated in changes in watershed hydrology, especially peak flows.

To understand how roads affect runoff, land managers need to understand how forest roads affect hillslope hydrology. Research indicated that interception of subsurface flow by roads is variable (Wemple, 1998; Gilbert, 2002). Studies that have investigated this problem have observed road ditch flow on isolated road segments. These individual road segments have rarely been selected for study randomly, thus it is not clear how the
variable ditch flow from these road segments is distributed in a watershed. This makes it difficult to hypothesize how roads might affect the hydrology of a given watershed. In this study, all of the road drainage structures in a 3rd order watershed, Oak Creek, have been instrumented to measure discharge. The purpose of this project is to determine how roads interact with hillslopes over a complete watershed.

1.2. STUDY OBJECTIVES

The overall goal of this project was to investigate the relationship between the characteristics of forest roads and forested hillslopes and the runoff from individual road segments. This was accomplished by measuring road runoff at all the cross drain culverts within a 3rd order watershed in the Oregon Coast Range. The following objectives were to be carried out:

- Measure runoff characteristics of all of the individual road segments that drain to the cross drain culverts within the Oak Creek watershed of the McDonald/Dunn Research Forest at Oregon State University.

- Correlate runoff characteristics from the road segments with the characteristics of the road segments and the hillslopes.
It was anticipated that the runoff characteristics, including instantaneous peak flows and storm runoff volumes, would be highly variable and vary greatly over the scale of the watershed. Further, it was expected that several of the hillslope and road characteristics would explain the variability in the runoff characteristics of the road segments. It was expected that peak flows and storm volumes would correlate with upslope contributing area and topographic index. However, road characteristics such as road grade, road length, or average cutslope height were not expected to explain runoff patterns.

2. LITERATURE REVIEW

Forest roads can and do affect many hydrologic processes throughout a watershed. The running ditch, cut at fill slopes and surface of roads generate surface runoff and sediment during storms. The running surface of the road is often highly compacted, and portions of the road prism have lower infiltration rates, leading to increased surface runoff. Forest roads can intercept subsurface flow from hillslopes and convert it to surface runoff on roads (Wemple, 1996; Megahan, 1972). Roads are hypothesized to increase the drainage density of a watershed by connecting road ditches directly to streams. Roads may also be directly connected to streams by gullies or ditches from the outfall of culverts to streams. Roads that are directly connected to streams are
conduits for chronic fine sediment delivery. Even when road segments are not directly connected to streams, there is increased probability for altered hillslope hydrology and landslides due to the concentration of water on fill slopes.

The exact consequence of forest roads on watershed hydrology is poorly understood. Forestland managers and researchers agree that ditch flow from individual road segments varies from culvert to culvert throughout a watershed however, the factors that drive this variance are unclear.

2.1. **Accelerated erosion**

Research results, primarily using paired watershed studies, have repeatedly shown that forest roads are a source of accelerated erosion. Landslide inventories show erosion rates from mass movements are orders of magnitude greater for road rights-of-way than for similar, adjacent pristine terrain. Paired watershed study results show that landslides from roads can be the dominant source of accelerated erosion from harvested watersheds (Fredrikson, 1971; Beschta, 1978). Adequate design, placement, and maintenance of road drainage structures are needed to reduce erosion from roadside ditches and the road surface (Packer, 1967; Donahue and Howard, 1987; Piehl et al., 1988). Excessive distances between culverts and other ditch relief structures can cause ditch erosion (Piehl et al., 1988). Undersized
culverts can cause erosion at the culvert inlet, potentially causing road failure during large storms (Donahue and Howard, 1987; Piehl et al., 1988). Road related landslides are capable of producing erosion rates as great as three orders magnitude greater than surface erosion rates.

Mass movement or landslides related to roads are capable of producing erosion rates as great as three orders of magnitude greater than surface erosion rates (Fransen et al., 2001). Road location, road age, topography, soil type and geology influence the occurrence of road related landslides (Beschta et al., 1995; Fransen et al., 2001; Sessions et al., 1987; Swanson and Dyrness, 1975). Forest roads are also associated with chronic surface erosion from the road surface that results in the generation and transport of sediment to streams (Beschta, 1978; Bilby et al., 1989; Reid and Dunne, 1984; Megahan and Ketcheson, 1996). The distance between drainage structures, road gradient, soil type, surfacing, road use and the amount of exposed soil in the ditch and on the cut slope are all road characteristics implicated in the generation of erosion from road surfaces (Bilby et al., 1989; Luce and Black, 1999; Reid and Sunne, 1984).

2.2. Connectivity

Forest road ditches and gullies at culvert outlets can connect directly into adjacent stream channels (Megahan and Ketcheson, 1996; Wemple et al.,
Croke and Mockler (2001) reported that in Southeastern Australia 18% to 20% of the road network studied was connected to the stream channels via gullyng at the culvert outlet. This connectivity between forest road drainages and streams increases sediment delivery.

The interception of subsurface flow by roads is highly variable across the hillslope (Wemple 1998; Gilbert, 2002). Most of the culvert runoff measured in a 23-hectare watershed of the Deschutes River in Washington was from subsurface flow rather than surface runoff (Bowling and Lettenmaier, 2001). Fractures in the soil matrix and/or bedrock layer and preferential flow in macropores greatly impact routing of water through the soil to areas where it may be intercepted by a road cut slope. This impacts the timing of runoff that reaches the stream network as a result of rainfall events (Anderson et al., 1997; Jones and Grant, 1996).

2.3. **Road surface runoff**

- *Intercepted subsurface flow*

  Runoff from road segments in the Cascades of Western Oregon region showed that roads intercept a variable amount of subsurface flow and the timing of road runoff coincided with the timing of the flow in an ephemeral stream (Woods and Rowe, 1996). The interception of subsurface flow by a road cut slope occurs when the elevation of the ground water table reaches the
elevation of the road ditch (Woods and Rowe, 1996). Wemple (1998) studied twelve road segments in watershed 3 a 101-hectare watershed in the Lookout Creek drainage located within the H.J. Andrews Experimental Forest. An example of the variability of ditch flow at cross drain culverts from one storm is shown in Figure 1 (Wemple, 1998). Wemple (1998) concluded that the amount of subsurface flow intercepted by road cutslopes is a function of the ratio of the average soil depth to the average height of the road cutslope. This concept has been used in several models to estimate the effect forest roads might have on peak flows (Croke and Mockler, 2001; Luce and Black, 1999).

Figure 1. Variation of culvert response following one rainfall event, data collected by Beverly Wemple in the Cascade Range of Oregon, 1995.
Many culverts may run water as soon as rains begin and stay elevated throughout the entire rainy season. Other culverts respond to rainfall events with steep spikes of water height response and some stay dry throughout the year. Gilbert and Skaugset (2002) investigated surface runoff from 10 road segments in forested watersheds of the central Oregon Coast Range. The found road runoff was highly varied. Road segments could be divided into two categories; intermittent or ephemeral. Road segments exhibiting intermittent flow began runoff in the fall and ditches ran water throughout the winter. Road segments exhibiting ephemeral flow ran ditch flow only in direct response to rainfall and had very flashy hydrology with steep rising and falling limbs of the hydrographs. Gilbert and Skaugset hypothesized that the intermittent hydrology results from interception of subsurface flow while the ephemeral hydrology results from road surface runoff only.

The variability in the data suggests that our understanding of subsurface flow interception by forest roads is incomplete.

- **Infiltration Excess Runoff**

  The surfaces of forest roads are compacted, which results in surface areas with reduced infiltration capacities (Ziegler and Giambelluca, 1997). Rainfall cannot infiltrate into the road so it runs off and is routed to the road ditches. This runoff is routed along roadside ditches and to cross drain
culverts just like intercepted subsurface flow where all the subsequent erosion and flow impacts can occur (Fahey and Coker, 1989).

2.4. Forest roads and peak flows

The effect of forest roads on peak stream flows is inconclusive. Numerous paired watershed studies have produced varying results. Forest roads may increase, decrease or cause little or no change in peak stream flows (Beschta et. al., 1995; Jones and Grant, 1996). Jones and Grant (1996) evaluated discharge data for small watersheds in the Oregon Cascades following harvesting and road construction. They concluded that both direct runoff from precipitation and/or increased interception of subsurface flow can and does combine with rapidly routed runoff via ditches and gullies to impact the timing and magnitude of peak flows. Thomas and Megahan (1998) analyzed the same data and concluded that a 40% increase for the smallest peak flows in the roaded and harvested watershed did occur. However, these increases diminished for peak flows with return intervals greater than 2 years. They also found that watershed response recovered with the regrowth of the forest, suggesting that reduced evapotranspiration was the major factor in response. Peak flows were also found to increase in watersheds following road construction if roads in the watershed occupied 12% or more of the
watershed area (Harr et. al., 1975). Wright et al (1990) studied the impact of roads on peak flows and found no change in peak stream flows.

Some have concluded that peak flow increases attributable to roads are greatest for more common stream flow events (LaMarche and Lettenmaier, 2001). This hypothesis seems to be a particularly important to test if we are to analyze potential peak flows using physically based models (as attempted by Croke and Mockler, 2001; Luce and Black, 1999 and others).

2.5. **Subsurface hydrology**

The process hypothesized to cause most of the increased peak flow due to roads is the interception of subsurface flow. Subsurface flow is part of precipitation that infiltrates the soil and moves laterally through the soil to the stream as ephemeral, shallow, perched groundwater above the main groundwater level (Montgomery, 1994). Research conducted in the Idaho Batholith, an area dominated by spring snowmelt, showed that roads intercepted a significant amount of subsurface flow during spring snowmelt (Megahan and Clayton, 1983). A study that measured surface erosion from roads concluded that some road segments yielded more runoff than could be explained by rainfall on a completely impermeable road surface and cut slope, which implies that subsurface flow contributed to road runoff (Luce and Black, 2001; Megahan, 1972).
Subsurface flow that is intercepted by a forest road can also be classified by its age. Luce and Black (2001) used chloride tracers to assign an age to runoff, which categorized the origin of the runoff that indicated that the contribution of water measured at the cut-slope is often a mixture of displaced hillslope water and fresh precipitation. Direct interception of the groundwater table by roads was observed during a period of time following the February 7, 1996 storm. Further measurements collected 2 years later indicate that this brief interception of groundwater was unusual and that more often the interception of subsurface flow by the cut slope occurred while the groundwater table was well below the elevation of the road ditch. A grid of zero-tension lysimeters installed on the cut slope collecting seepage from the cut slope helped to determine the spatial distribution of seepage from the cut slope. The lysimeters most likely to collect seepage from the cut slope were about one meter from the top of the cut slope, near the boundary between the well-developed soils. Such a pattern could be the result of a transient perched water table at the soil boundary or from lateral unsaturated flow through the
rooting zone becoming saturated at the seepage face (Luce and Black, 2001; Megahan, 1972).

3. STUDY AREA

3.1. INTRODUCTION

The study area is the Oak Creek watershed within the McDonald/Dunn Research Forest, which is the Research Forest for the College of Forestry at Oregon State University. Oak Creek is located approximately 3 miles west of Corvallis Oregon in the foothills of the Oregon Coast Range. The watershed has an area of 824 hectares upstream of the School Forest boundary (Figure 2). Elevations within the watershed range from 140 to over 500 meters with slopes hillslope gradients ranging from 20 to over 60 percent. There are 4,877 meters of stream and 4,572 meters of road in the Oak Creek Watershed (Figure 3).
Figure 2. Location map of Oak Creek watershed in the McDonald/Dunn Forest, Oregon State University.
Figure 3. A map of the Oak Creek watershed, showing the road, stream systems and the location of all the road drainage structures.
3.2. **CLIMATE**

Oak Creek has a Mediterranean Climate with cool, wet winters and warm, dry winters. Mean Annual Precipitation is 55 inches, which occurs mostly as rain during the winter. Snow falls in the winter, but usually melts within a few days. During the summer, it is not unusual to go 90-120 days without rainfall.

3.3. **GEOLOGY**

The parent material for most of McDonald and Dunn Forest soils is from the Siletz River Volcanics, a basalt formation. This rock formation is the foundation for the ridges and underlies most of the valleys. The Siletz River Volcanics underlies the Jory, Price, Ritner, Witzel, Dixonville and Philomath soil series. The Flourney Formation, a rhythmically bedded marine sandstone with siltstone and mudstone interbeds (Tyee sandstone) is concentrated in the northwest corner of Dunn Forest and is the base for the Dupee, Hazelair, Panther and Steiwer soil series. The wide flat drainage bottoms are recent alluvium, which form the basis for McAlpin, Abiqua and Waldo soil series.
3.4. **SOILS**

Soils for the Oak Creek Watershed are divided into fifteen different series. The soil series range from coarse-grained soils to highly organic (Figure 4). The average soil texture is silty clay loam with an average soil depth of 50 inches. Soils for the area exhibit high values of moist bulk densities, 1.10-1.30 g/cm$^3$ and a low porosity. Such soil types are usually deep, well weathered and well drained (Oregon State University Soil Survey Manual, 1996).

3.5. **VEGETATION**

The vegetation in the Oak Creek watershed is primarily Douglas-fir mixed with some grand fir, Oregon White Oak and big leaf maple. Red alder and Oregon ash are located along the steams. Understory species are predominately California hazel, ocean spray, trailing blackberry, common snowberry, vine maple and poison oak. The most common ferns are sword fern and bracken fern. The Research Forest staff developed the vegetation map for the Oak Creek watershed this map is represented in Figure 5.

3.6. **ROAD DRAINAGE STRUCTURES**

There is an existing road network in the Oak Creek Watershed. Most of the road network was constructed in the 1950’s and 1960’s. There are
4,572 meters of road in the 824 hectare watershed making a road density of 5.55 m/ha.

There are 98 drainage structures on the road system in Oak Creek (Figure 3). Of these, 24 culverts are installed at live stream crossings on topographic features that run surface water at least part of the year and show evidence of surface runoff scour and deposition. The remaining 74 drainage structures are drainage relief culverts or cross drain culverts. Of these 74, 46 are associated with a topographic swale and the remaining 28 are not associated with any topographic feature.
Figure 4. Soil series for the Oak Creek watershed.
Figure 5. Vegetation and land use map for the Oak Creek watershed.
4. METHODS

The primary dependent variable for this project is the road surface runoff from individual road segments as measured at the drainage relief culverts that bound the downslope end of the road segment. The discharge from road segments was calculated from water level measurements that were collected at the inlet of the cross-drain culverts. Water level was measured in two ways. One method was a crest gauge and the second was a capacitance rod. Either a crest gauge or a capacitance rod was installed at the inlet of every cross drain culvert in the Oak Creek Watershed.

The crest gauges are manual devices that are capable of recording only the maximum water height that occurred between visits to the crest gauge. It is comprised of a central rod within a casing that has slit open rings at the bottom. Fine ground cork was used to mark water level in the crest gauge. When water enters the crest gauge, the cork floats and then as the water recedes the cork adheres to the rod. By measuring the height of the cork in the crest gauge, the maximum water height can be determined. A diagram of a crest gauge is shown in Figure 6. The design and use of crest gauges is described in Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge (Rantz et. al., 1982 ).
During the winter of 2001-2002, crest gauges were installed at 29 cross drain culverts in the Oak Creek Watershed. One crest gauge was installed at a cross drain culvert located at a topographic swale and the other 28 were installed at cross drain culverts in locations without evidence of topographic swales (Table 1). Nominally, crest gauges should be visited after every storm.
to determine the maximum water height associated with each storm event. For Oak Creek during the winter of 2001-2002, the crest gauges were visited each time the capacitance rods were downloaded, which was approximately once every two weeks. Using this sampling frequency, and examining the capacitance rod data we could confirm that no maximum water level data was missed for any significant storm.

Capacitance rods were installed at the inlets of the remaining 45 cross drain culverts in the Oak Creek Watershed. Capacitance rods measure water level electronically. The capacitance rods that were used were 0.5meter TruTrack capacitance rods. They have a resolution of $\pm 1$ millimeter and have a data logger attached. The capacitance rods with data loggers allow for complete hydrographs to be measured instead of just maximum water level. The capacitance rods were initially set to log a value of water level every six minutes. In early December 2001, that sampling interval was changed to every 10 minutes. At a sampling interval of 10 minutes, the data loggers in the capacitance rods could collect data for approximately two weeks. Thus, water level data was collected from sensors in Oak Creek about every two weeks. An installed capacitance rod and crest gauge at the inlets of cross drain culverts are shown in figures 7 and 8.
Table 1. List of cross drain culverts and corresponding water height recorders including all gaged culverts.

<table>
<thead>
<tr>
<th>Gauged Culverts</th>
<th>Crest gauges</th>
<th>Capacitance rods</th>
<th>Total gauged culverts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross drains</td>
<td>28</td>
<td>0</td>
<td>28</td>
</tr>
<tr>
<td>Cross drains at swales</td>
<td>1</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>29</strong></td>
<td><strong>45</strong></td>
<td><strong>74</strong></td>
</tr>
</tbody>
</table>

Figure 7. Photo of installed capacitance rod at the inlet of a culvert cross drain in Oak Creek.
4.1. CALCULATING DISCHARGE

Discharge was calculated for every value of stage measured for all the culverts using an empirical stage height vs. discharge relationship. An attempt was made to use a peak flow nomograph (Normann et al., 1985) and Manning’s equation to estimate discharge, but neither approach was considered acceptable. A water height vs. discharge relationship was developed by measuring discharge traveling through pipes at a series of known water heights. Stage vs. discharge data was collected for five 18 inch diameter
culverts. Discharge was measured with a 0.5 foot, 60° trapezoidal flume.

Water heights at the culvert inlet and in the flume were measured using a 0.5 meter capacitance rod. The raw data for the five culverts is shown in Figure 9.

Linear regression was used to correlate water height with discharge. The rating equation is:

\[ Y = 0.0009x^{2.05} \]

\[ R^2 = 0.94; n = 46; \]

This rating equation was used to predict discharge for all values of water recorded including crest gauges and capacitance rods (Figure 10).
Figure 9. Water height vs. discharge relationship for 18 inch corrugated plastic pipes.

4.2. HILLSLOPE AND ROAD CHARACTERISTICS

Independent variables were determined that represented the hillslope and the road surface and were thought to have an influence on surface road runoff. Hillslope characteristics are those judged to affect subsurface flow and the interception of such flow by the road cutslope and inboard ditch (Wemple, 1998). These variables include upslope contributing area, hillslope gradient, topographic index, and a soil depth to hillslope gradient. Independent road characteristics tested included road segment length and road gradient. Elevation was used as a surrogate for local precipitation.
Road and hillslope characteristics were determined using a 5 meter digital elevation model (DEM) that was developed from 1 meter Laser Altimetry (LIDAR) data. For the LIDAR data used for Oak Creek, the average distance between LIDAR returns was 20 meters, thus a 5-meter grid was interpolated between LIDAR points. On the roads, the average distance between LIDAR returns was 6.7 meters.

Upslope contributing area for each road segment was generated using Topogrid in Arc-Info. Topogrid calculates the number of grid cells that drain to the location specified. Each cross-drain was selected and the software calculated the slope and direction of flow for each grid cell above the selected grid. The output is the number of cells that drain to the cross-drain location.

Road length between drainage structures was measured manually in Arc View. The culverts were georeferenced in Arc View with using a Trimble Global Positioning System (GPS).

The elevation at each cross-drain culvert was collected in the field using a Trimble hand-held (GPS) unit and then verified using the contours on the 5 meter DEM (Figure 10).

The difference in elevation from one culvert to the next along the length of the road divided by the road length between drainage structures is the road gradient. Profiles for calculating hillslope gradient were generated using Easy Profiler in Arc View. Profile lines were drawn manually across the road
section at each cross-drain culvert providing a cross-sectional view of the 
hillslope. Each value of elevation was represented where the profile line 
intersected the contour lines.

Topographic indices assigned to each culvert location or cell within the 
5-meter grid in Arc View were generated using the following equation:

\[
\ln\left(\frac{a}{\tan\beta}\right)
\]

\[a = \text{upslope contributing area}\]
\[\beta = \text{hillslope gradient}\]

The topographic index is a ratio of the upslope contributing area and the local 
slope gradient. The topographic index is a relative measure of the likelihood 
of subsurface flow at that point on the hillslope (Beven and Kirkby, 1979).

A ratio of soil depth to hillslope gradient was used to index the soil 
depth to road cutslope height ratio. The ratio of soil depth to cutslope height is 
perceived to be an important predictor of the potential for a road segment to 
intercept subsurface flow. Cutslope height could not be determined from the 5 
meter DEM generated with the LIDAR coverage available for the Oak Creek 
watershed. Thus, hillslope gradient was used as a surrogate for cutslope height 
in the index. Values of soil depth are available for the McDonald/Dunn
Research Forest through a soil survey carried out in 1982-83 (Oregon State University Soil Survey Manual, 1996). For each soil type in the soil survey, ranges of soil depths are listed. The value for average soil depth that was used was an average of the listed range in soil depths provided for each soil type in the soil survey. Estimates of hillslope gradient were determined from Arc View coverage generated from the LIDAR coverage and the procedure is described above.
Figure 10. A map of the Oak Creek watershed showing the road system and the location of all the road drainage structures and topography.
5. RESULTS

5.1. RAINFALL SUMMARY

Total annual precipitation for Corvallis, Oregon, located approximately 3 miles east of the study site was average for the winter of 2001-2002. The average monthly rainfall in Corvallis from 1961 through 1990 for the winter months of October to February was 111.6 cm. For 2001-2002 over the same winter months the average monthly rainfall measured 85.4 cm. The rainfall driven storm event that occurred on January 25, 2002 was selected for analysis. Several storms occurred prior to and following the January 25, 2002 rainfall event. One storm in November and one in December accumulated more rainfall over a similar time, yet less runoff was measured presumably due to antecedent moisture conditions. The largest peak flow at several cross drain culverts, including the gauged outlet of the Oak Creek watershed, occurred on February 7, 2002. Field observations, rainfall data and temperature data indicate that this February 7, 2002 storm was driven primarily by snow. Because the amount and water equivalent of the snow was not measured, this storm has not been analyzed in detail at this time.
5.2. ROAD AND HILLSLOPE CHARACTERISTICS

Characteristics of the roads and the adjoining hillslopes were determined for 76 road segments. The summary statistics for these segments are listed in Table 2. The upslope contributing area ranged from 0.003 to 3.15 hectares with an average area of 0.21 hectares. Hillslope gradient ranged from 0 to 61 percent with an average of 28 percent. Road lengths ranged from 0 to 375 m with an average road length of 113 meters. The gradients of the road ranged from 0 to 18 percent with an average road grade of 6 percent. The road segments were located at elevations that ranged from 148 meters at the outlet of Oak Creek at the Research Forest boundary to 501 meters with an average elevation of 275 meters. Values of topographic index ranged from 0 to 14.4 with an average value of 8.4. Finally, the soil depth/hillslope gradient ratio, which indexed a potential soil depth/cutslope height ranged from 0 to 1331 with an average value of 219.
Table 2. A table of the road and hillslope characteristics compiled for the Oak Creek watershed.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Sdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upslope Contributing Area (ha)</td>
<td>0.003</td>
<td>3.155</td>
<td>0.212</td>
<td>0.512</td>
</tr>
<tr>
<td>Hillslope Gradient (%)</td>
<td>0.00</td>
<td>0.61</td>
<td>0.28</td>
<td>0.17</td>
</tr>
<tr>
<td>Road Length (m)</td>
<td>0.0</td>
<td>375.0</td>
<td>113.0</td>
<td>87.0</td>
</tr>
<tr>
<td>Road Grade (%)</td>
<td>0.00</td>
<td>0.18</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>148</td>
<td>501</td>
<td>275</td>
<td>101</td>
</tr>
<tr>
<td>Topographic Index</td>
<td>0.00</td>
<td>14.42</td>
<td>8.36</td>
<td>3.88</td>
</tr>
<tr>
<td>Ratio of Soil Depth to Hillslope Gradient</td>
<td>0.00</td>
<td>1330.77</td>
<td>219.24</td>
<td>270.47</td>
</tr>
</tbody>
</table>

5.3. PEAK DISCHARGE

Forest road design standards and the environmental impact associated with forest roads are driven by large peak flows. Because of this fact, it is the maximum storms that are of interest with regard to the influence of road and hillslope characteristics. The maximum peak flow at Oak Creek for the 2002 water year was on February 7, 2002. However, that peak flow was a snowmelt driven peak flow and high quality data was not uniformly available throughout the watershed. Thus, the second highest peak flow was analyzed for interactions with hillslope and road characteristics. This was a rainfall-dominated storm and the peak flow occurred on January 25, 2002. The storm began at 5:00 pm on January 24, 2002 and lasted until 12:00 midnight on
January 25, 2002.  2.8 inches of rainfall fell in the Oak Creek watershed during this event.

For all of the road segments that a peak flow was recorded, with the exception of two segments, the peak flow measured occurred on January 25, 2002.  Two cross drain culverts registered peak flows on days other than January 25, 2002.  One occurred on January 27 and the other on January 28.

Of the 74 cross drain culverts studied, one gauge malfunctioned, 9 had no discharge for the instantaneous peak on January 25 and 6 were removed from the database because of culvert size.  They were 12 inch culverts and the water level versus discharge rating curve was developed for 18 inch culverts only.  Thus, the smaller culverts had to be removed.  Of the 9 culverts where no runoff was recorded, five were capacitance rods and four were crest gauges.  Four of the nine culverts were on ridgetop roads and the remaining five culverts have only road surface runoff with no hillslope contribution.

Of the 58 cross drain culverts used in the analysis that did have maximum water levels recorded, 40 were capacitance rods and 18 were crest gauges. A frequency distribution of the maximum instantaneous discharges is shown in Figure 11. The distribution has an extreme right skew and values that range from 0.25 l/sec to 87.5 l/sec. The mean is 10.3 l/sec and the mode is 5.6 l/sec.
A frequency distribution of maximum instantaneous peak discharge response for all 58 culverts, separated by gauge type is shown in Figure 12. Capacitance rods measured water height at 40 culvert cross drains and crest gauges at the remaining 18 culverts.
Of the 58 cross drain culverts with a flow response 31 were classified as swales and 27 as non-swales. For the purpose of this study a swale is any cross drain that intercepts both ditch and hillslope flow and a culvert at a non-swale is believed to only intercept ditch flow. A frequency distribution of maximum instantaneous discharge for all 58 cross drain culverts used for analysis separated into swales and non-swales is shown in Figure 13.
Figure 13. Instantaneous peak discharge of all 58 cross drain culverts categorized by swale and non-swale flow interception.

To demonstrate the variability of the runoff response across the watershed seven culverts of the 40 that were outfitted with capacitance rods, were selected and graphed in Figure 14. A hydrograph of the response to the January 25, 2002 storm at the outlet of Oak Creek is also provided in Figure 14.
Figure 14. Graph of hydrograph response for 7 culvert cross drain runoff responses, selected to demonstrate the variable response measured across the Oak Creek watershed on January 25, 2002.

5.4. Runoff volumes

Capacitance rods were installed on 47 road segments in order to capture information about complete storm hydrographs. Of the 47 capacitance rods, 40 recorded data and were used in the analysis of the January 25, 2002
storm. Five capacitance rods recorded no runoff response, one capacitance rod malfunctioned, and one capacitance rod was positioned at the inlet of a 12” culvert and was eliminated from analysis.

Of the five culverts that had no water level data, four were classified as swales. One of the five was a ridgetop cross drain culvert that appeared to carry road surface runoff and intercepted hillslope flow.

Of the 40 cross drain culverts with capacitance rods that did record a runoff response to the January 25, 2002 storm, total runoff volumes were calculated. A frequency distribution of the total runoff volumes is shown in Figure 15. This distribution has a right skew and total volume values that range from 19.4 m$^3$ to 8000 m$^3$. The mean is 1,490 m$^3$ and the Standard Deviation is 1,540 m$^3$. Three common ranges of runoff volume response exist for the 40 road segments that measured flow. Four of the road segments measured volumes of 100-200 m$^3$, four measured 800-900 m$^3$ and four measured total runoff volumes of 1000 to 1100 m$^3$. 


Figure 15. Frequency distribution of total runoff volume for the 40 cross drain culverts with capacitance rods installed.

5.5. Runoff Volume versus peak instantaneous discharge

In Figure 16 instantaneous peak discharge is graphed versus total runoff volume and as expected the relationship is linear with an $R^2$ value of 0.76. This indicates that the road segments measuring high peak discharge also measured high total runoff volumes in response to the January 25, 2002 rainfall event. This may also indicate that the generation of a runoff volume from a peak discharge measurement is possible. However, also visible in
Figure 16 is the increase in the range of error on the graph when moving from left to right across the axis toward a larger runoff response.

Figure 16. A graph of instantaneous peak discharge versus total runoff volume for the January 25, 2002 storm in the Oak Creek watershed for the 40 cross drain culverts with capacitance rods installed.

\[
y = 0.0076x + 1.2021
\]

\[
R^2 = 0.76
\]

5.6. STATISTICAL EVALUATION

5.7. Results of Correlation of Instantaneous Peak Discharge Response

Multiple linear regression was used to evaluate the correlation between the dependent variables, maximum instantaneous peak discharge and total
runoff volume, and the dependent variables, the road and hillslope characteristics. For regression using maximum instantaneous peak discharge, the final equation was statistically significant \((p = 0.0030)\) with an \(r^2\) value of 34\%. There were 58 peak flows in the analysis and the standard error of the estimate was 11.7 l/sec. The Durbin-Watson value indicates that there is not any serious autocorrelation in the residuals.

There are two variables that were statistically significant at greater than a 90\% confidence level; road length \((p = 0.0029)\), and elevation \((p = 0.0641)\). While these variables are significant predictors, the amount of variability they explain is very low as evidenced by the \(r^2\) of the least squares relationships for each of the variables. The graphs for the least squares relationships are shown in Figure 17. The relationships indicate that a meaningful regression model is not likely.
Figure 17. Scatterplots and values of least squares for instantaneous peak discharge versus all road and hillslope independent variables.

Discharge vs. Topographic Index
- Equation: $y = 0.0206x + 8.1765$
- $R^2 = 0.0052$

Discharge vs. Contributing Area
- Equation: $y = -2E-05x + 10.658$
- $R^2 = 0.0048$

Discharge vs. Road Grade
- Equation: $y = -33.349x + 12.544$
- $R^2 = 0.0246$

Discharge vs. Road Length
- Equation: $y = 0.0174x + 3.8896$
- $R^2 = 0.1324$

Discharge vs. Hillslope Gradient
- Equation: $y = -2.4076x + 10.93$
- $R^2 = 0.0063$

Discharge vs. Elevation
- Equation: $y = -0.0137x + 22.6$
- $R^2 = 0.1154$

Discharge vs. Soil Depth to Hillslope Ratio
- Equation: $y = 0.0124x + 7.4342$
- $R^2 = 0.063$
5.8. **Results of Correlation of Runoff Volume Discharge Response**

For the analysis using total storm volume as the dependent variable, the scatterplots and least squares relationships for all the independent variables is shown in Figure 18. Once again, as evidenced by the scatterplots, no meaningful regression equation is expected. The multiple linear regression equation was not statistically significant and none of the independent variables showed a significant relationship with the dependent variable.
Figure 18. Scatterplots and values of least squares for total runoff volume vs. all road and hillslope independent variables.
6. DISCUSSION

The data collected throughout this study clearly indicates a variety of flow response at culvert cross drains across an entire small watershed. Culverts ranged in instantaneous peak flows spatially from one culvert to the next and 20 percent of the road segments did not measure any runoff and remained dry throughout the January 25, 2002 storm event. Road segments that did not measure any runoff are distributed throughout the watershed. A number of the road segments located on ridgetop roads, several along midslope roads and several in the valley bottom measured no runoff response.

Maximum instantaneous discharge response across the watershed clearly indicates a right skew distribution. This implies that the majority of the road segment runoff response is small (mode = 6 l/sec). However, this distribution pattern also indicates that it is a minority of the road segments that run a majority of the water. The three road segments running the largest runoff response are all located along valley bottom road segments and are classified as swales.

Runoff response collected for road segments by both the crest gauges and capacitance rods also follow a right skew distribution indicating that it is really the minority of the road segments that measure the highest relative runoff response. The other interesting point to mention is the method of field
placement for both crest gauges and capacitance rods. During summer installation capacitance rod location was selected based on likelihood of runoff response. The road segments were selected based on preliminary water height data gathered the previous (2000-2001) winter and whether or not the cross drain appeared to intercept a swale. The crest gauges were placed on the road segments on the ridgetop roads and in areas where little or no flow was expected. Also, once the winter rains began and data was being collected in the field the water height response at each road segment was observed. If high response was being measured at a road segment instrumented with a crest gauge the gauge was removed and replaced with a capacitance rod whenever possible. The interesting result is that the frequency distribution for both the crest gauges and the capacitance rods are very similar and follow the same right skew distribution pattern.

What might be even more interesting is the graph of the swale vs. non-swale frequency distribution. Thirty-one of the 58 cross drains analyzed were classified as swales and 27 as non-swales, one might expect a frequency distribution of the runoff response for each to look very different and they are actually very similar. Their distributions once again follow the right skew distribution pattern and are very closely aligned. This would strongly support a conclusion that a definitive channel or swale has very little if anything to do with the location and/or predictability of road segment runoff response.
Total runoff volumes measured at all culverts gauged with a capacitance rod yet again follow a right skew distribution pattern. The three road segment with the largest total runoff response are all located on valley bottom road systems. However, they are not located in the same area of the watershed and are not found along the same valley bottom road. They are distributed in three separate locations. Three common ranges of runoff volume response exist for the 40 road segments that measured flow. Four of the road segments measured volumes of 100-200 m³, four measured 800-900 m³ and four measured total runoff volumes of 1000 to 1100 m³.

This variation in runoff response across the watershed was believed to be predictable by physical characteristics of the watershed at the culvert cross drain locations. Road and hillslope characteristics were measured using GIS software based on LIDAR data for the watershed. The lack of correlation of runoff response to physical characteristics of the hillslope and road surface may be due to the manner in which the physical features were measured. For purposes of this study watershed characteristics were calculated and collected via Geographic Information Systems (GIS). The data layers available for the Oak Creek watershed are some of the most accurate available yet no ground verification of this data was performed within the scope of this study. Expected correlation between values of upslope contributing area and topographic index to total runoff volume were not visible within the results of
this study. At culvert cross drain locations where hillslope contributing areas were observed and high flows were apparent during field visits a correlation was expected between flow response and hillslope features. While at other cross drain locations with no apparent hillslope component, with observed ditch flow and surface road drainage correlation to road length and road gradient were expected and again no correlation was apparent from analysis of the data. Wemple in the Western Oregon Cascades measured soil depth, cutslope height, road features and hillslope features in the field and determined a distinct correlation between runoff response of twelve culverts measured and a ratio of soil depth and cutslope height. This study did not see a similar result. This could be due to differences in geology, varying soil characteristics and/or study methodologies.

Land managers are increasingly faced with decisions regarding data of this kind and understanding the capabilities and limitations of computer generated data is essential. This analysis was performed with the intent of compiling road and hillslope characteristics for the watershed using the best available GIS data. The coverage generated for the Oak Creek watershed was developed specifically to generate a one-meter LIDAR coverage for the area and while ground assessment of the data was not performed it is believed to be a good representation of the landscape. This may or may not be the best
procedure for generating the most accurate road and/or hillslope data, but it is data that is widely used and readily available.

The analysis of runoff response included one average winter storm over an average winter of rainfall for the region. Further analysis including runoff response to more storm events would provide additional information necessary to better categorize cross drain runoff response for the Oak Creek watershed. Another component of the rainfall analysis is the inability at this time to precisely measure rainfall amounts at each cross drain location. This meant that any analysis of rainfall response needed to be lumped across the watershed and that any difference in measurable rainfall amounts from one culvert to the next could not be accounted for.

With continued research geared toward a land manager’s ability to predict surface and subsurface flow interception by forest roads, resources may be allocated more accurately to areas of the watershed with the most need.

7. CONCLUSIONS

Summary of flow response to the January 25, 2002 rainfall event at all culvert cross drains in the Oak Creek watershed indicate a wide range of
variability. As expected, some cross drain culverts ran little or no water the entire rainy season, while other cross drain culverts had a large runoff response to rainfall. This variation is clearly represented by differences in interception of runoff at different road segments spread across the watershed. Both the instantaneous peak discharge and the runoff volumes measured at the cross drain culverts demonstrate the variance in response to one storm event.

Instantaneous peak discharge captured at all 74 cross drain culverts in the watershed ranged from nine road segments with no flow to 87.5 L/second. This variation in culvert response provides adequate support that the instantaneous peak discharge response does vary. Variation in both instantaneous peak discharge and runoff volume captured for road segments in the watershed indicate that it is only a small portion of the cross drain culverts that measure high amounts of runoff. The data for both peak discharge and runoff volumes imply that most of the cross drain culverts in the watershed measure small runoff amounts.

Predicting where on the landscape this runoff response occurs is proving to be more difficult. The varied runoff response across the watershed was not characterized by physical upslope contributing area, road gradient, soil depth/hillslope gradient, hillslope gradient or topographic index. Road length and elevation appear to be the only landscape characteristics related to the location of peak discharge response and even this relationship is unclear.
Topography and upslope contributing area does not indicate where runoff interception will occur. Whether or not a cross drain is intercepting ditch flow only or ditch flow and some additional hillslope flow component does not appear to be a good tool for predicting runoff response. The data categorized by culvert type (swale vs. non-swale) does not provide an indication of storm runoff response.
8. LITERATURE CITED


Wemple, B.C., Investigations of runoff and sediment production from forest roads in western Oregon, Ph.D. dissertation, Department of Forest Science, Oregon State University, Corvallis, Oregon, 1998.

