University of Washington
Department of Civil and Environmental Engineering

FOREST ROAD EFFECTS ON FLOOD FLOWS IN THE DESCHUTES RIVER BASIN, WASHINGTON

Jonathan LaMarche
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Water Resources Series
Technical Report No.158
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ABSTRACT

Forest harvesting in maritime mountainous watersheds is thought to affect flood flows by two primary mechanisms. The first mechanism is through reduction of canopy interception and ablation of snow prior to rain-on-snow storms, and subsequently, by enhanced melt due to increased turbulent energy transfer during warm storms. The second mechanism is through increased runoff brought about by increased effective stream drainage density resulting from forest road drainage systems.

To assess connectivity of the road drainage and stream network, the locations of 2171 forest road culverts were identified during summer, 1997 in the extensively logged 150 km^2 Deschutes River Basin, WA. Road characteristics, including cutslope height, culvert connectivities to the natural stream network, and hillslope position were identified for 140 culvert locations within 38 road segments. A logistic regression model based on topographic and vegetation attributes at these locations indicated that hillslope curvature and distance to the natural stream could be used to predict connectivity resulting from gullies below culverts extending to the stream channel. The model was applied to culverts classified in a previous study in Hard and Ware Creeks, two headwater sub-catchments in the Deschutes Basin, and was found to accurately predict channel connectivity below 81 percent of the ditch relief culverts. The algorithm was then used to predict connectivity for all ditch relief culverts within the Deschutes Basin. Approximately 24 percent of the culverts were connected to the stream network. In addition, 33 percent of all culverts were identified as stream crossing culverts in the field study and, therefore, were connected to the stream network. Runoff monitored in roadside ditches during winters 1996-97 and 1997-98 indicated higher flows occurred in ditches draining clearcut compared to forested areas. Valley bottom and mid-hillslope roads had a higher response than ridge top roads. Road segments with higher cutslopes did not have an increase runoff response.

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) was used to evaluate road effects on peak flows, using the field data and algorithm predictions of culvert

connectivity to the natural channel. The influence of topographic slope, road connectivity, vegetation, and road location on peak flows were investigated by comparing simulated discharge in nine sub-basins (2.2 to 21 km^2 in area), as well as the Deschutes basin outlet. Model results predicted increases in the mean annual flood due to forest roads alone in the sub-basins from 2 to 10 percent, and from 3 to 12 percent for the 10-year event. The corresponding changes at the Deschutes River outlet gauge were 4.6 and 5.2 percent, respectively. The largest predicted increases due to roads were roughly equivalent to the predicted effect of harvest (mature forest compared with current vegetation state) for the mean annual flood. Predicted road effects on peak flows were essentially independent of the vegetation state in all sub-basins. In general, predicted road effects increased with flood return period, while vegetation effects decreased.

Simulated ditch flows using DHSVM were higher below immature forests than mature forests, which concurred with field results. However, no synergism between forest harvest and roads was predicted by the model at the scale of the nine sub-basins. This apparent inconsistency between hillslope and catchment scale response was attributed to desynchronization of the hillslope responses at the sub-basin scale.

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Acknowledgments

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Thanks also go to the many people who provided support for this project. The Weyerhaeuser Company provided access to the research sites, all of which lay within their Vail Tree Farm. Ken Lentz and John Heffner of the Weyerhaeuser Co. provided access to and explanations of the hydrometeorological and land cover data used in this study. In addition, they provided background information about historic road construction protocols within the Deschutes River basin. The channel and stream routing algorithm used in the modeling study was developed by Bill Perkins and Mark Wigmosta of Pacific Northwest National Laboratory. Bart Nijssen and Pascal Storck, of the University of Washington Hydrology Group, made changes to the snow algorithm used in the modeling study, and provided other modeling support. Discussions with Ms. Beverly Wemple (Oregon State University) provided useful comparative information for the road-channel connectivity investigation. Special thanks go to Laura Bowling (University of Washington Hydrology Group) for her assistance with the field data collection and GIS work. Finally, thanks go to graduate students and staff members in the University of Washington Hydrology Group, including Tony Dubin, Keith Cherkauer, Greg O'Donnell, Paul DeVries, and Bernt Matheussen who assisted with various aspects of the modeling and field data collection.

Chapter 1: Introduction

The effect of land use changes on the ecology and hydrology of streams and rivers have long been debated. This is especially true in the Pacific Northwest, where the effects of logging are highly visible. For instance, since the 1930s, over 25% of national forest lands in Oregon have been harvested (Jones and Grant, 1996). Given the coincident decline of salmon runs and the occurrence of several large floods, such as those associated with the storm events of November 1990 and February 1996, the hydrologic effects of forest management practices have come under particular scrutiny.

There are two primary mechanisms by which logging is thought to affect hydrology. The first is through direct effects of vegetation removal. At the hillslope scale, vegetation removal decreases precipitation interception storage capacity, modifies accumulation and ablation of snow, and increases soil moisture through suppressed evapotranspiration (Anderson and Hobba, 1959; Anderson et al. 1976; Megahan 1983). These mechanisms are of particular interest during Rain-on-Snow (ROS) storm events, when rainfall is augmented by snowmelt from warm winds. Snow intercepted by the forest canopy has a higher surface to volume ratio than snow in a clear cut, which can result in frequent melting of the canopy snow. Therefore, prior to ROS events, a greater amount of snow accumulates on the ground in open plots compared to forested plots (Berris and Harr, 1987; Kattelmann, 1990). In addition, the forest canopy attenuates wind, thus limiting snowmelt under the canopy during a ROS event. The result is larger snowpacks with higher melt rates in clearcuts compared to forested plots during ROS events.

The second mechanism by which logging changes hydrology is through the effects of logging roads. Although less studied, Jones and Grant (1996), among others, have claimed that this could be a more important effect than vegetation removal. Unlike vegetation removal, which recovers over time, forest roads can have a more persistent and pervasive effect on hillslope hydrology. Forest roads affect hydrology through two mechanisms: 1) direct runoff from the compacted road surface, and 2) interception of subsurface flow by the road cutslope (Figure 1-1).

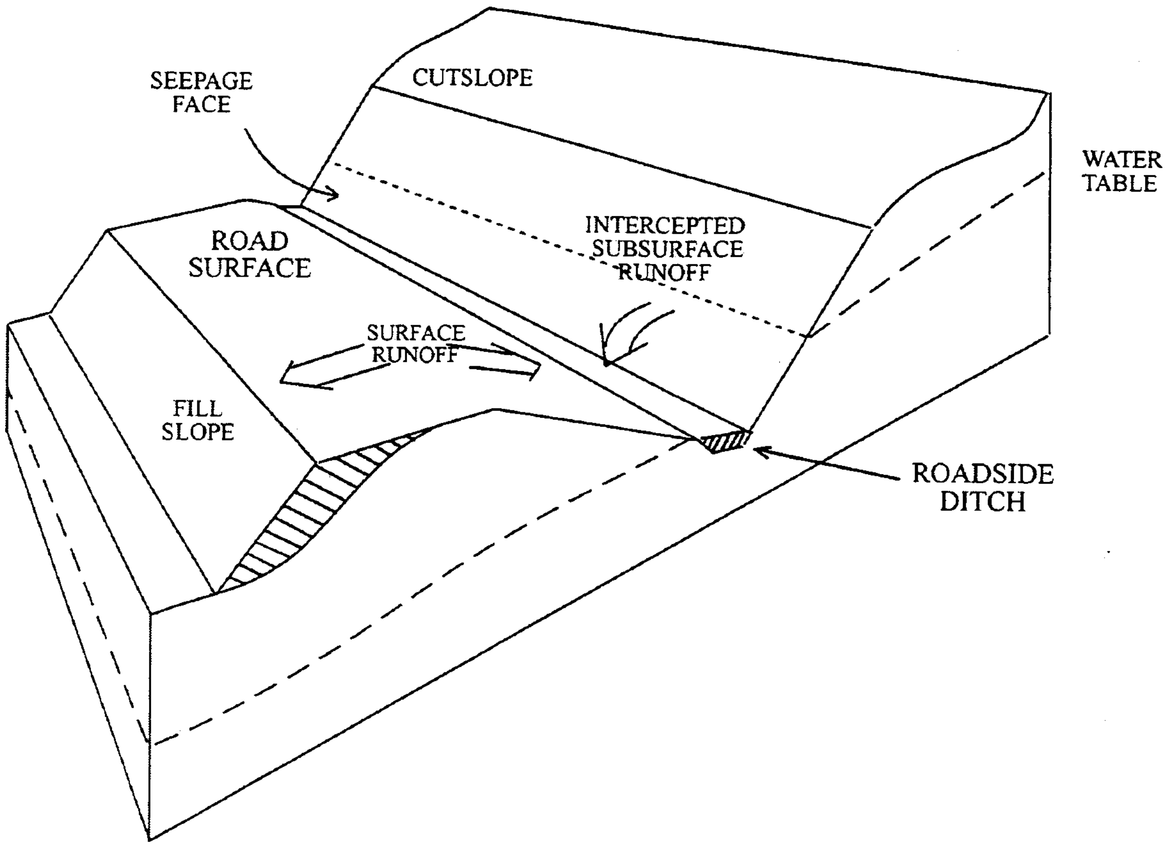


Figure 1-1: Runoff Mechanism of Forest Roads (Bowling and Lettenmaier, 1997)

Road surfaces have greatly reduced soil infiltration rates compared to the natural landscape (Luce and Cundy, 1994; Ziegler and Giambelluca, 1997). Therefore, they often produce overland flow (Figure 1-2) where precipitation would normally infiltrate in the undisturbed landscape and travel as subsurface flow. An additional and more influential effect on hydrology is due to interception of subsurface flow by the roads cutslope (Megahan, 1972; King and Tennyson, 1984). Road-generated flow from either

Figure 1-2: Road Surface Runoff in Northern California (Shepherd Miller Inc., February 1997)

mechanism may be routed by the roadside ditch to the stream network. This occurs at stream crossing culverts or through gullies formed below ditch relief culverts (non-stream crossing culverts) extending to a natural channel. Effectively, this modifies the mechanism of hillslope flow from one of slow subsurface to rapid surface flow. On the other hand, captured runoff may infiltrate below ditch relief culverts, in which case changes in hillslope runoff responses may be minimal.

There is statistical evidence of the combined effect of logging and roads on stream peak flows, especially smaller peaks occurring in the fall (e.g., Rothacher, 1973; Harr et al.

1975; Ziemer, 1981). However, studies that have addressed the relative magnitude of road and vegetative effects (Harr et al. 1975; King and Tennyson, 1984; Wright et al. 1990; Jones and Grant, 1996; Bowling and Lettenmaier, 1997) are less conclusive.

Evaluation of the relative contribution of roads and vegetation removal is difficult to determine via paired catchment studies because roads are usually constructed in conjunction with logging. This limits the amount of data available to examine road effects alone. At the watershed scale, it is extremely difficult to segregate forest harvest effects from road effects. Paired catchment studies at this scale would require logging an extensive area without the use of roads. Wemple (1994) noted that all paired catchment studies on road effects only, were less than four years in duration and conducted on basins less than five km^2. In addition, there is some concern about extrapolation of results from small to large watersheds. Streamflow from large watersheds is an integration of the hydrologic response of the contributing sub-basins. Theoretically, treatment effects concentrated in one area may be masked by the response from other areas, depending on spatial scales, antecedent snow conditions, spatial distribution of precipitation, soil and geology types, topographic characteristics, and lag times.

Hydrologic models that accurately represent the physical interactions of land, water and vegetation provide a non-destructive alternative to paired catchment experiments to evaluate the effects of roads, especially for large basins. Bowling and Lettenmaier (1997) modeled two small (2-3 km^2) headwater catchments in the Deschutes River Basin, WA. Their results suggested that roads have a comparable effect to logging on storm flows in these catchments. They also found the effects of roads and harvests were essentially additive—not synergistic, as suggested by Jones and Grant (1996).

This study extends the work of Bowling and Lettenmaier (1997) by examining the effects of forest roads on peak flows in an intermediate sized watershed (150 km^2) using a physically–based, spatially distributed hydrologic model. The watershed studied contains the sub-basins examined by Bowling and Lettenmaier (1997), which allows for a nested hydrologic analysis. In addition, this study investigates the mechanism by which forest roads interact with timber harvest to influence streamflow at both the sub-catchment and catchment scale (defined in this study as basins < 25 km^2 and > 100 km^2, respectively).

1.1: Hypothesis

The central hypothesis of this study is that the design and placement of roads, and their interaction with the natural drainage system, control the effect of forest roads and coincident timber harvest on streamflow peaks. Previous studies have shown that connectivity of the road drainage system to the natural channel network influences the timing and delivery of runoff generated by both the road surface and cutslope (Megahan, 1972; Harr, 1976). If the intercepted water is synchronized in time and place with peak responses from other areas in the catchment, increases in peak flows may occur (Megahan, 1972; King and Tennyson, 1984). Therefore, if the road connectivity to the natural drainage can be reduced, this potential influence should be diminished. Factors affecting road connectivity are related to volume of water discharged at the culvert and erosion resistance below the culvert, and are believed to be (Figure 1-3):

1) contributing uphill and road areas to individual culverts,

2) slope steepness (also related to cutslope height),

3) topographic convergence near culvert (convex/concave/straight),

4) vegetation state below culvert outlet,

5) vegetation state of contributing area,

6) soil thickness, and

7) proximity of culvert outlets to the natural drainage.

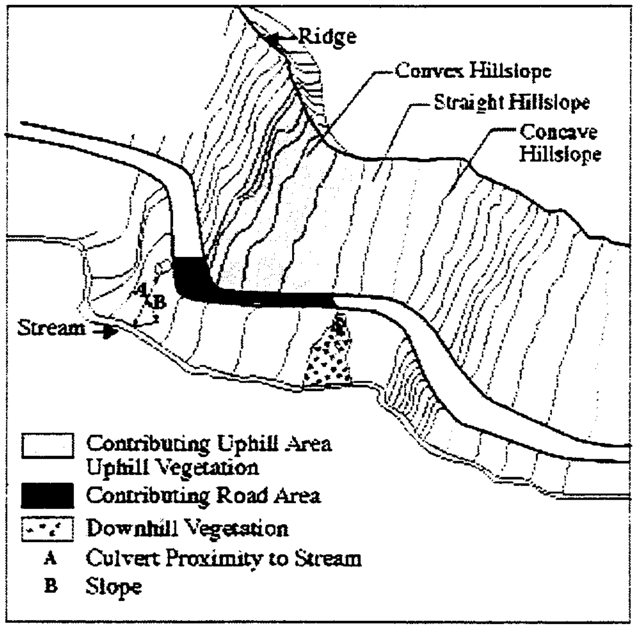


Figure 1-3: Conceptual Model of Factors Affecting Road Connectivity

The volume of surface flow generated by road surfaces and subsurface flow intercepted by the road cut slopes determine, in part, connectivity of the road drainage to the channel system, as described above. However, road–generated flow also determines the overall impact of roads and deforestation on the natural hydrology by shear volume of water. Factors affecting subsurface generated flow were noted above (contributing area, cutslope height, uphill vegetation, slope, and soil thickness). On the other hand, surface-generated runoff is a function of road surface area.

Under this hypothesis, it is clear that two basins with identical percentages of road and harvest areas could have very different hydrologic responses to storm events. For instance, a catchment with the majority of its road system constructed mid–hillslope should have a greater effect on peak flows than an equivalent system built along the catchment ridges. This effect is simply due to the contributing area draining to the road culverts. Likewise, a road system built near the stream channel may have an equivalent contributing area as one built mid-hillslope. However, changes in flow routing due to the valley road network are less since the subsurface intercepted flow is already near the stream network, and therefore, would soon become surface flow even in the absence of roads.

1.2: Objectives

The objectives of this study are as follows:

1) To examine topographic and vegetative characteristics affecting road–generated runoff through field investigations of a west slope Cascade Mountain catchment, lying primarily within the transient snow zone.

2) To develop a predictive relationship for connectivity of the road network to the natural drainage.

3) To identify the relative effects of vegetation removal and forest roads on peak flows, and identify topographic and vegetative characteristics affecting road generated runoff through a modeling investigation.

1.3: Approach

Paired watershed studies offer an ideal means for investigating the effects of forest harvest and roads on a catchments hydrologic response. However, these studies are only feasible at a few locations due to the following requirements:

1) close proximity of the catchments to ensure similar meteorological forcings for both,

2) long coincident discharge records,

3) similar topography, and

4) significantly differing land use histories.

An alternative to paired watershed studies is the use of "physically based" hydrologic models, which essentially can be used as a surrogate for paired catchment studies (Storck et al. 1995). If the model accurately represents the mechanisms by which land, soil, water, and meteorology interact, it can be used to detect changes in these variables on basin hydrology (e.g., streamflow). The Distributed Hydrologic Soil and Vegetation Model (DHSVM) developed by Wigmosta et al. (1994), and modified by Storck et al. (1995) and Perkins et al. (1996) for maritime climates and to account for road effects, is one such model. The philosophy behind the development of DHSVM has been to use field studies to evaluate the physical mechanisms represented in the model. For example, Storck et al. (1997) tested DHSVM's snowmelt and snow interception module using field data collected in forested and open areas in the Umpqua National Forest in Oregon. Bowling and Lettenmaier (1997) tested the model's road routing algorithm by sampling peak flows in road drainage ditches in two headwater creeks in western Washington. This study represents an extension of the work Bowling and Lettenmaier (1997) from relatively small sub-catchments (2-3 km^2) to the catchment scale (> 100 km^2).

The study uses DHSVM in conjunction with field measurements to explore the effects of roads on the hydrology of the Deschutes River Basin headwaters (150 km^2). Field measurements of roadside ditch flow in 1996 and 1997 for several road segments are compared to simulated runoff to further test the model's road routing algorithm. Simulations of streamflow for three sub-catchments, and the entire watershed, form the basis for evaluation of flows with and without roads. In addition, a predictive model is developed from field investigations and GIS analysis to predict the connectivity of the forest roads to the stream network.

The remainder of this thesis is organized as follows. Chapter 2 reviews the mechanisms by which vegetation removal and road construction can affect the hydrologic response of forested catchments and previous studies of these effects. Chapter 3 describes the study area. The field investigations and results are described in Chapter 4. The model description and calibration is described in Chapter 5. The model investigation and results are described in Chapter 6. Chapter 7 contains the study summary and conclusions.

Chapter 2: Background

To understand the potential effects of forest roads on streamflow, it is necessary first to understand the hydrology of undisturbed, forested catchments. This chapter briefly describes natural hydrologic processes and how they are modified by logging and forest roads. In addition, some previous studies pertinent to the Western Cascades of the Pacific Northwest region are reviewed.

2.1: Forested Hillslope Hydrologic Processes

Hydrologic processes in forested catchments of the western Cascades in the Pacific Northwest depend on precipitation, vegetation, and topography in a catchment. Peak flows in this region usually take place in winter, due to extended high volumes of precipitation occurring at modest rates. Infiltration rates are high, and most runoff is produced by subsurface flow. Snow processes play an important role in generating peak flows—specifically, Rain–On–Snow (ROS) events during intermediate intensity storms. The catchment area within the transient snow zone affects how responsive peak flows are to snow dynamics during ROS events. Vegetation exerts a strong effect, not only on the water balance in a catchment, but also on snow processes.

2.1.1: Forest Canopy and Precipitation

In the western Cascades, precipitation usually occurs over extended periods at low to moderate intensities—typically several millimeters per hour or less. The forest canopy will intercept between two to eight mm of precipitation when in the form of rain (Hewlett and Nutter, 1969; Dunne and Leopold, 1978). This amount represents a relatively small fraction of total precipitation during most storms. The intercepted precipitation eventually evaporates or falls to the forest floor, where it infiltrates. Additional precipitation is temporarily delayed by the canopy, then drips to the ground where it is available for runoff, storage, and evapotranspiration.

If precipitation is in the form of snow, the canopy plays a much larger role in the storage and release of water. In the western Cascades, the forest canopy may hold up to 30mm of snow water equivalent (SWE) (unpublished data, Pascal Storck). In a two-year study of a clear-cut and old growth plot in the H.J. Andrews Experimental Forest in Oregon, Berris and Harr (1987) noted that most snowfall was intercepted by old growth forest canopy. Once intercepted, the snow may fall from the canopies as wet clumps of snow where it augments the ground snowpack, or drips as melt water, most of which flows through the snowpack to the soil (Smith, 1974). Evaporation of intercepted snow is usually small compared to melt losses (Miller, 1966).

In the transient snow zone of the western Cascades, rapid snowmelt occurs via convective heat transfer to the snow pack from high winds and temperatures accompanying warm fronts. A popular misconception is that advection energy (rainfall) causes rapid snowmelt. However, energy inputs advected to the snow–pack from rainfall are diminutive compared to the turbulent heat transfer from warm winds. The forest canopy tends to reduce both radiation and turbulent heat transfer to the ground snowpack by attenuating solar radiation and wind speed, reducing melt. However, in the forest canopy, snow has a greater surface area to volume ratio and is exposed to higher winds than the ground snowpack. Thus, there is an enhanced energy transfer for snow in the canopy compared to snow on the forest floor. The result is an increased rate of snowmelt in the canopy, which limits snowpack accumulation under the trees (Berris and Harr, 1987). The majority of snowmelt preceded rain-on-snow (ROS) events in the forested canopy of Berris and Harr's (1987) study.

Most floods in western Washington and Oregon are produced by ROS events during the fall and winter. These storm events are characterized by warm rainfall accompanied by rapid snowmelt of the snowpack from high winds and warm air temperatures (Harr, 1981). The western Cascades are particularly susceptible to these events because the interior temperature of the snowpack remains at or near 0°C (Smith, 1974; McGurk, 1983). This warm or 'ripe' snowpack requires relatively little energy to initiate melt.

Because of this low thermal inertia and high water content, shallow snowpacks in the transient snow zone of the western Cascade range (350-1100m) can quickly yield meltwater during warm rainy periods (Berris and Harr, 1987). During ROS events, the forest canopy attenuates wind, reducing the ground snowpack that melts. Prior to ROS events, the canopy limits the amount of snowpack available for melt. Canopy snowmelt is constrained by the amount of snow the canopy can hold.

2.1.2: Forest Canopy and Evapotranspiration

Vegetation plays an important role in the water balance of a catchment through evaporation and transpiration (evapotranspiration). As noted above, the forest canopy intercepts a portion of precipitation, which evaporates or eventually falls to the forest floor. This canopy storage and subsequent evaporation is dependent on the leaf area of the trees, commonly described by the leaf area index (LAI)—the total leaf area per unit ground area. Vegetation also affects soil moisture by actively removing moisture from the soil root zone. Burges et al. (1989) estimated that evapotranspiration typically removes between 40-50 percent of annual precipitation from the Puget Sound lowland catchments. Thus, evapotranspiration affects water available for soil moisture storage, groundwater recharge, and ultimately, annual water yield in a basin. For example, during the summer growing season, evapotranspiration reduces soil moisture which tends to attenuate runoff from early fall storms by allowing more of the precipitation to be stored in the soil. However, during winter months when soils are saturated, evapotranspiration rates are low and the corresponding effects on streamflow are minimal.

2.1.3: Runoff Generation

There are three basic methods by which precipitation reaches a stream network: 1) channel interception; 2) overland flow; and 3) subsurface flow. Overland flow may be divided into two types: surface flow brought about by either rainfall intensities exceeding soil infiltration capacities (Horton Overland Flow [HOF]), or by precipitation falling on saturated soils (Saturated Overland Flow [SOF]). Likewise, there are two types of subsurface flow–groundwater flow and subsurface storm flow. Freeze (1974), defined subsurface storm flow (interflow) as water that infiltrates and moves laterally through the upper soil horizons as unsaturated flow or as shallow, perched saturated flow above the main groundwater table. Groundwater (base flow) is the other portion of subsurface flow derived from deep percolation of infiltrated water, which enters the saturated groundwater flow system and enters the stream below the seepage face (Figure 2-1).

Channel interception, defined as precipitation directly intercepted by the stream channel, accounts for only a small portion of total inflow to streams. Groundwater is primarily responsible for sustaining streams during low flow periods, but usually it is not a

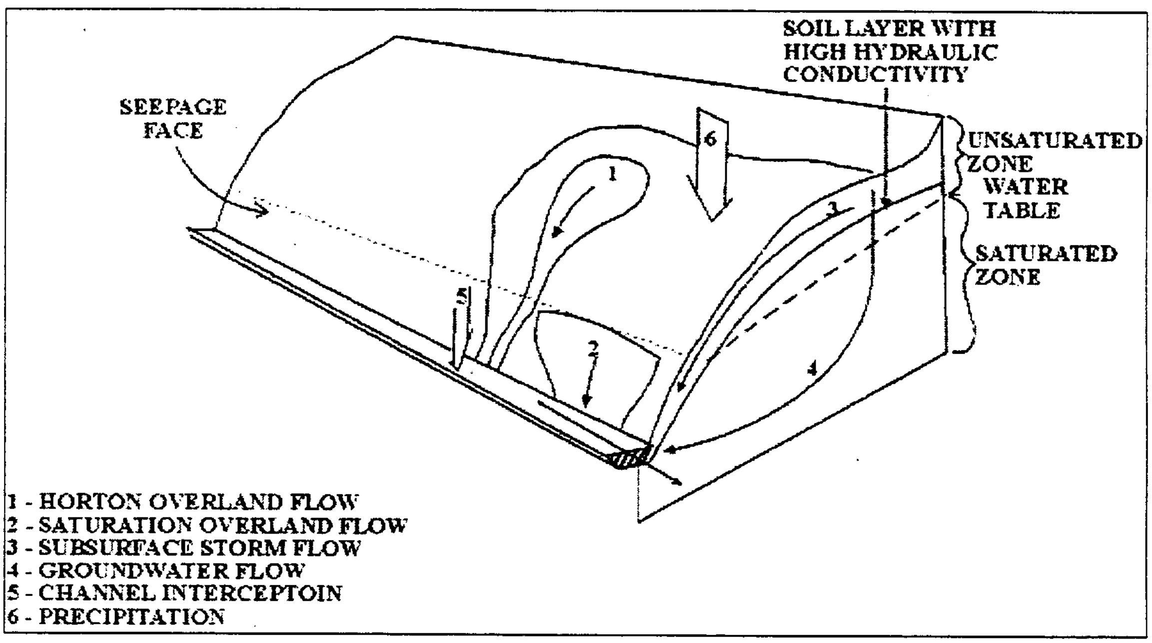


Figure 2-1: Hillslope Runoff Processes (Modified from Freeze, 1974)

significant contributor of runoff during storms. HOF rarely occurs in undisturbed forest soils in the Pacific Northwest because rainfall intensities seldom exceed infiltration capacities (Rothacher, 1965; Dunne, 1978; Harr 1976). SOF from variable source areas was found to be the main contributor to storm runoff in a field study in Vermont, by Dunne and Black (1970a). This mechanism is described as overland flow generated from rainfall on partial saturated source areas adjacent to the stream channel (Freeze, 1974). However, other studies indicate streamflow results primarily from subsurface storm flow through highly permeable subsurface layers or macropores—even if the soil profile is unsaturated (Hewlett, 1961b; Whipkey, 1965 and 1969; Harr, 1977; Montgomery et al. 1997; Wigmosta and Burges, 1997). This subsurface storm flow may either enter the channel directly or feed an expanding channel network that taps the subsurface flow. Harr (1977) found that 97 percent of storm flow resulted from subsurface flow in a 10 hectare (ha) watershed in Oregon's H.J. Andrews Experimental Forest. Likewise, Montgomery et al. (1997) reported that all runoff generated had originated from subsurface storm flow in a zero order catchment in the Oregon coast range.

2.1.4: Subsurface Flow

There are two mechanisms by which subsurface flow travels through soil. The first is through the soil matrix itself (Darcian) as saturated or unsaturated flow. The second occurs primarily from biological and structural openings (Figure 2-2) in the soil matrix (non-Darcian), even if the soil is unsaturated (Whipkey, 1969), termed pipeflow and macropore flow. Pipeflow and macropore flow can be viewed as interconnecting pipe networks with linkages to both groundwater and surface flow. The difference between pipes and macropores is somewhat ambiguous. Pipes are considered a larger diameter version of the capillary size macropores, often enlarged by erosion, and usually exhibit a greater degree of connectivity in the downslope direction (Anderson and Burt, 1990). These two mechanisms of flow, Darcian and non-Darcian, need not be independent and there is evidence that both contribute significantly to subsurface storm flow.

In Harr's 1977 study of a 10 ha watershed in the H.J. Andrews Experimental Forest in Oregon, unsaturated flow predominated during 14 moderate-size winter storms.

However, subsurface flow from seeps still accounted for 97 percent of storm flow. Piezometer data did show that saturated zones, with visible outlets at the toe of the study slope, gradually expanded upslope and laterally during rainfall. Flow conditions from these zones related to the drainage of soil pores filled with water during a storm. When

Figure 2-2: Macropores in Road Cutslope in Hard Creek, Deschutes River Basin, WA

these pores drained, there was a marked increase in the rates of discharge decrease. In addition, SOF near the stream was absent and the stream channel neither expanded nor contracted.

In a forested catchment in New Zealand, Pearce et al. (1986) found that a large portion of stormflow is 'old' water (soil water of long residence), as opposed to recent precipitation. This suggests that water held in soil matrix is displaced to the stream, and though macropore flow may be responsible for recharge of the water table and displacement of old water to the stream, it is not directly responsible for discharge.

In a study of storm runoff in forested plots of the Allegheny-Cumberland plateau of the eastern United States, Whipkey (1969) found that storm flow occurred primarily through pipe flow, even when the soil profile was unsaturated. Ziemer (1992) found that most stormflow was accounted for by pipeflow in three hollows in the Casper Creek watershed of northern California. Previously, in this same watershed, Ziemer and Albright (1987) measured pipeflow up to 8.5 liters per second in two swales of 1.4 and 0.9 hectares. They found the hydrologic response to be similar to that of adjacent surface channels and that pipe discharge did not initiate until the soil moisture had reached a certain level.

Soil drainage due to pipeflow and macropore flow is much faster than by soil matrix flow and can even exceed that of overland flow (Wilson and Smart, 1984; Jones, 1987). In a catchment in the Brecon Beacons, Wales, Wilson and Smart calculated an average pipe velocity of 0.9 m/s for a 212-meter pipe using dyes and travel times.

Subsurface storm flow occurs where slopes are moderate to high, surface soil is permeable, and a water-impeding layer is near the surface (King & Tennyson, 1984). This describes most headwater basins in the Pacific Northwest where shallow, highly permeable soils overlay impermeable volcanic or metamorphic rock on steep slopes.

2.2: Forest Management Effects on Streamflow

The effects of forest management on streamflow are determined by the methods of harvesting. In this section, harvesting by clear cutting areas with access by logging roads is examined. This has been the dominant logging practice in the western Cascades during the post World War II period. Vegetation removal affects both the water balance and snow dynamics in a catchment. In addition to removing vegetation, roads can alter the hillslope runoff mechanism from subsurface to surface flow. Vegetation removal above roads can increase soil moisture and therefore, the amount of subsurface flow intercepted by the road cut (Figure 1-3). However, the road network connectivity to the stream network will determine whether the intercepted subsurface flow will travel to the basin outlet as surface flow, or reinfiltrate into the soil and continue as subsurface flow. These mechanisms are described in detail below.

2.2.1: Vegetation Removal

Vegetation removal affects forest hydrology through two mechanisms: 1) decreased evapotranspiration; and 2) reduction or elimination of precipitation interception storage. Both mechanisms affect water delivery to the soil in amount and timing, which relates to water table depth, soil moisture, groundwater recharge and streamflow.

Removal of the forest canopy decreases evapotranspiration by reducing the root uptake of soil moisture and corresponding leaf area available for transpiration, and precipitation interception storage with subsequent evaporation. Thus, more precipitation reaches the soil and less is removed, resulting in an increase in soil moisture. In the H.J. Andrews Experimental Forest of the western Cascade Range of Oregon, Rothacher (1965) found water removed from the soil by evapotranspiration decreased approximately 80 percent in one recently clear-cut area. In addition, soils remained near field capacity for most of the summer. He hypothesized that slow drainage of these areas caused increased summer low flows and annual water yields. Other studies have shown similar effects of deforestation. Harr (1979) reviewed catchment studies at 11 western Oregon and Washington locations and reported increases in annual water yields and summer low flows in most catchments, following timber harvest. Keppler and Ziemer (1990) detected significant increases in annual flow and summer low flow volumes after clear cutting 67 percent of the 424 ha South Fork of the Caspar Creek watershed in northwestern California. However, the summer flow increases generally disappeared within 5 years, which they attributed to accelerated growth of the remaining vegetation, invading trees and brush.

These studies suggest that the increase in annual and summer streamflow should be related to the amount of area harvested. Hibbert (1967) reported increases in streamflow proportional to the amount of cover harvested. Similarly, in a review of paired catchment studies, Stednick (1996) found that in catchments that were less than 20 percent harvested, changes in annual water yield could not be determined by hydrometric or streamflow measurement methods. However, in a 162 ha watershed in the Idaho batholith, Megahan et al. (1995) found no significant changes in annual or monthly streamflow yield after 23 percent of the watershed was logged by helicopter. This suggests that another mechanism such as roads or the local topography of the area being harvest may also influence yields. For example, vegetation removed along water–stressed areas (ridge tops) would probably not affect streamflow as much as harvesting an area of convergent topography. Soil moisture along a ridge is likely to be low even without vegetation because the flow direction is away from the ridge. On the other hand, topographic hollows concentrate water, which would lead to higher water yields due to decreased transpiration if the vegetation were removed.

Higher soil moisture at the end of the growing season brought about by vegetation removal can increase peak flows of early autumn storms (Ziemer, 1981). However, during late fall and winter, the difference between soil moisture of harvested and forested areas may decrease as soils near saturation. Thus, vegetation removal effects on soil moisture, and hence peak flows, could be less pronounced during this period.

During ROS events, the difference in interception storage in harvested hillslopes plays a more important and complicated role. Berris and Harr (1987) described differences in snowpack accumulation and melt between clearcuts and old growth. In their study, snow water equivalent (SWE) in the clear cut was over twice that under the forested canopy. They attributed these results to enhanced energy transfer and accompanying snowmelt of canopy intercepted snow, and the resulting reduction in snow accumulation under the canopy. Prior to ROS events, up to 70 percent of accumulated snow contributed to meltwater in the forested plot. In clearcut plots, this mechanism of canopy interception and melt was absent; thus, greater amounts of snow accumulated on the ground. During ROS events, clearcut snowpacks are fully exposed to winds, while the canopy attenuates wind and reduces melt of ground snowpacks. However, any intercepted snow in the canopy will melt more rapidly due to higher surface areas and roughness. Still, the overall effect cited in various studies is an increase in snow accumulation and melt in clearings compared to forested areas, especially during ROS events. In a clearing near Soda Springs, California, Kattelmann (1990) found snow melted an average of 75 percent faster and had a peak accumulation 20 cm of SWE greater than in the forest. He also noted that in most cases, snow accumulated earlier in open areas than in the forest, which he attributed to greater residual heat storage in the forest soil.

2.2.2: Road Construction

Forest roads can influence the hydrologic response of a watershed in several ways. The most commonly cited effect is the conversion of subsurface flow to surface flow via interception of the water table by road cutslopes (Megahan, 1972; King and Tennyson, 1984; Bowling and Lettenmaier, 1997). A schematic of this mechanism was shown in Figure 1-1. This process may alter the natural synchronization of subsurface and surface water from the different units of the watershed (Megahan, 1972; King & Tennyson, 1984). If the routed water is synchronized with peak flows from other hillslopes, flood peaks can increase (Figure 2-3), although the reverse could also occur (Megahan, 1972).

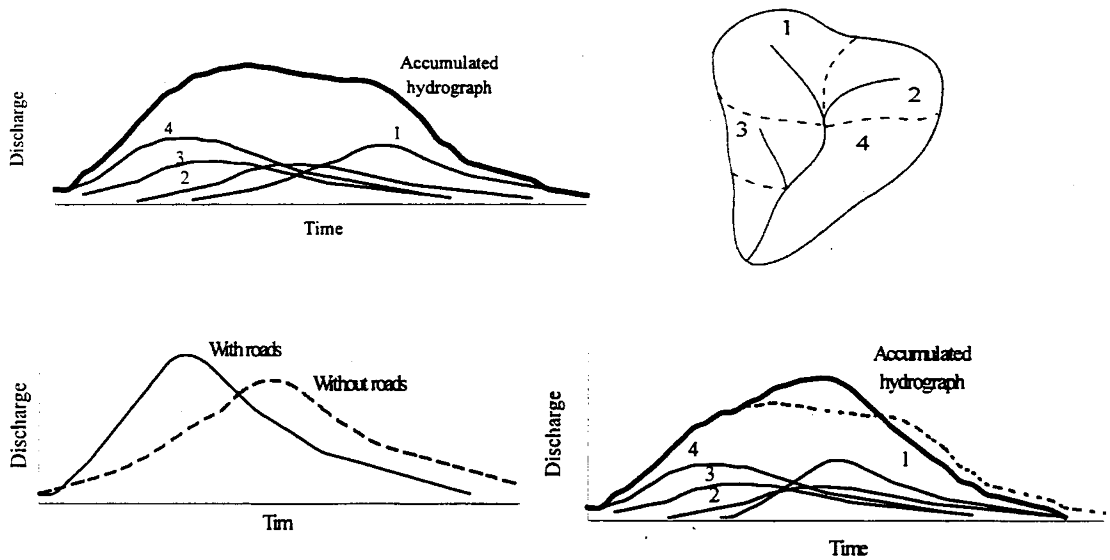


Figure 2-3: Schematic of Hillslope Flow Synchronization by Forest Roads and Corresponding Effect on Peak Flows (Bowling and Lettenmaier, 1997)

A secondary road effect is the generation of overland flow from the road surface. Forest roads are, in a sense, permanent clearings (Figure 2-4). From the standpoint of snow accumulation and ablation, they act as clearcuts. However, unlike clearcuts, little infiltration occurs on road surfaces, and snowmelt or direct rainfall often results in overland flow (Figure 1-2). Luce and Cundy (1994) found that road surfaces had infiltration rates of 0 to 4 mm per hour on forest roads in Idaho. Ziegler and Giambelluca (1997) reported surface hydraulic conductivity of forest roads in Thailand ranged from 0.2 to 5.3 mm per hour. In the Deschutes Basin in western Washington, Sullivan and Duncan (1981) observed 50 percent of precipitation contributed directly to runoff from a road segment.

Figure 2-4: Persistent Clearing Associated with Forest Road Spur, Deschutes River Basin, WA

Other studies have shown runoff rainfall ratios ranging from 0.55 to 0.80 for dry antecedent conditions, and 0.81 to 1.00 for wet antecedent conditions (Burroughs et al. 1984; Foltz and Burroughs, 1990).

The influence of forest roads on streamflow is determined, in part, by the amount of water generated as direct runoff from the road surface and intercepted by the road cutslope. Roads below clearcuts are expected to intercept more water than roads below mature vegetation, as suggested by field results from Bowling and Lettenmaier (1997). Cutslope height should also affect the amount of water intercepted. King and Tennyson (1984) reported an increase in the 25 percent exceedance flows in a headwater catchment in north central Idaho. The catchment's roads have high cutslopes (>6m) and a large uphill contributing area of 54.2 ha—67 percent of the catchment area. Cutslope height is dependent on road type (i.e., full bench or cut and fill), road width, and slope of the hillside. Road width determines road surface runoff, as will road surface type. If roads are outsloped, water is diverted off the outside edges of the road where it can infiltrate. Reid and Dunne (1984) found that 16 percent of road–generated runoff in the Clearwater Basin in western Washington was diverted to the outer roadside. Insloped roads concentrate runoff to the inboard ditch, while crowned roads divide the flow between the embankment and the ditch. Finally, as suggested by King and Tennyson (1984), uphill-contributing area affects the amount of water intercepted by the cutslope.

Routing of this surface or cutslope intercepted water is the other crucial factor that determines effects of forest roads on streamflow. Intercepted water may travel only a short distance in a roadside ditch before re-infiltrating into the soil, below a culvert outlet. Therefore, connectivity of the road drainage to the natural drainage also determines the potential road influence on stream flows. Wemple (1994) investigated road connectivity in the Lookout Creek and Blue River catchments in western Oregon and found approximately 57 percent of the road length was connected to the stream drainage. That is, surface flow paths exist from the culvert outflows to the stream network or to ditches, which drain directly to streams at stream crossing culverts. Likewise, in the Deschutes River Basin of southwest Washington, Bowling and Lettenmaier (1997) found that 57 percent and 45 percent of the culverts in Hard and Ware creeks, respectively, drained to the stream network.

One factor determining connectivity of the road network to the stream network is the volume of flow routed through the individual road segments and culverts. For instance, culverts with large outflows are more likely to form channels or gullies, which drain to the stream network. Another factor affecting connectivity is the proximity of the culvert outlet to the natural drainage. Culverts that drain close to stream segments are more likely to be hydraulically connected to the stream due to the concentration of flow and a relatively short distance for the flow to infiltrate. Vegetation and slope below culvert outlets affects soil stability, and therefore the likelihood that gullies will form and connect the culvert outflow to the natural drainage. Slope also affects the infiltration rate of culvert outflow. Shallow slopes are more likely to infiltrate than steep slopes. Likewise, topographic convergence determines whether flow from a culvert will be concentrated or diffused on the hillslope.

The position of the road on the hillslope will not only affect the volume of water intercepted, but also timing changes associated with routing subsurface flow as surface flow (Figure 2-5). Ridgetop roads have the greatest potential to change timing of flows because flow that would normally travel a relatively long distance as slow subsurface flow may now travel the same distance as quicker surface flow. However, the potential flow volume intercepted by ridgetop roads is small. For roads located in the valley bottom, the opposite is true. These road segments may have a large uphill contributing area, but the water may have already traveled most of the distance as subsurface flow, regardless of the presence of roads. Therefore, the timing impact is low. It stands to reason that roads located midslope should have the greatest effect on intercepted flow. The potential intercepted flow volume is high and timing changes are moderate.

If the majority of subsurface flow is associated with high velocity pipe flow, the timing change associated with converting subsurface flow to surface flow may be minimal. The opposite is true if the flow is Darcian. Logging may affect these subsurface flow paths by compacting soil. Chamberlin (1972), Cheng et al. (1975), and DeVries and Chow (1978) have all reported lag time increases after harvesting. They hypothesized this effect was due to soil compaction and corresponding collapse of pipes and macropores. Thus, water movement would occur through a slower route—the soil matrix. In a later study in the Casper Creek catchment in Northern California, Ziemer (1992) demonstrated that pre-logging peak pipeflow was 3.7 times greater than post-logging.

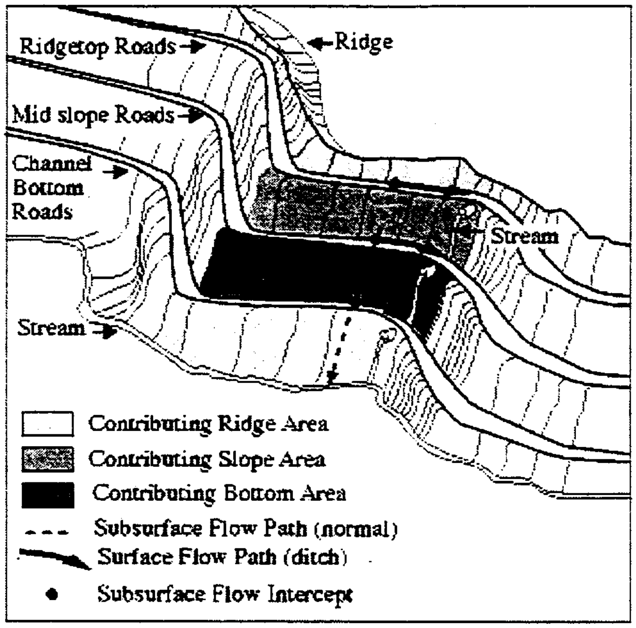


Figure 2-5: Schematic of Flow Routing Alteration from Forest Roads

2.3: Retrospective Studies

The above–described mechanisms have shown how forest management practices alter the means by which water enters the soil, as well as the routing and distribution of the water once in the soil. Although previous studies have generally shown increases in low flows and annual yields in response to logging, studies on the corresponding effects on peak flows have produced varying results.

In the Lookout Creek Basin in western Oregon, no increases in peak flow were found three years after eight percent of a 250-acre watershed was cleared and roads constructed (Rothacher, 1965). An additional 25 percent of the basin was harvested and no peak flow changes were found the following year. In addition, (Harr et al. 1982) found that the size and timing of peak flows were not altered significantly in a clear or shelterwood cut of a 13.0 ha and 15.4 ha catchment in the same basin.

In six small watersheds in the Alsea River Basin near Toledo, Oregon, roads constructed one year before logging were found to increase peak flows significantly when roads occupied at least 12 percent of the watershed (Harr et al. 1975). Roads had no detectable effect on storm hydrographs volumes and no changes in time to peak were observed. However, because roads were built only one year before harvest, there were few storms suitable for the analysis, so the results were somewhat inconclusive. Roads and partial clear–cutting produced significant increases in peak flows; the largest changes occurred in watersheds most extensively cut. Increases were largest in the fall, when the maximum difference in soil moisture between cut and uncut areas occurs.

In a paired catchment study of the 508–ha North and 424–ha South Fork of Casper Creek in the coast range of northern California, Ziemer (1981) detected a 300 percent increase in peak flows during the fall after harvest. However, no changes were found in large peak flows with five percent of the South Fork in roads, 10 percent in skid trails and 67 percent harvested. The increase in fall events was also attributed to large soil moisture differences between logged and forested catchments that decreased toward the winter months.

In the same catchment, Wright et al. (1990) found significant changes in runoff peaks and volumes for small storms after road building and logging. Larger storms (those occurring less than eight times a year) did not cause a change in peak flows. Road construction alone did not affect storm runoff. However, 6-km of the total 6.8-km road network was within 61 meters of the stream and sub-surface routing was probably affected only minimally throughout most of its path to the stream.

Harr and McCorison (1979) found that annual peak flows actually decreased by 32 percent after logging an old growth catchment in the H. J. Andrews Experimental Forest in Oregon. There was no change in peak flows resulting from rain events alone. Harr (1986) later reanalyzed the data and found that antecedent snow conditions seemed to relate to high variations in pre-logging peak flows. However, since post–logging data did not include ROS events with appreciable antecedent snow, the reanalysis was inconclusive with respect to the effect of logging on ROS floods. However, in the same study, Harr (1986) reanalyzed Rothacher's 1973 data from the H.J. Andrews Experimental Forest, partitioning the events between rain and ROS. The results suggested that snow accumulation and melt had changed sufficiently to affect size of peak flows from ROS events and point out the importance of separating storm events by type when investigating logging effects on peak flows.

In six forested watersheds in Idaho (28.3 to 147.7 ha) with snowmelt–dominated runoff, road construction significantly increased flows exceeded 25 percent of the year (Q25) in one watershed, yet decreased Q5 in another (King and Tennyson, 1984). The increase in the Q25 was associated with a road area with high cutslopes (>6m) and large uphill contributing areas. Overall, the hydrologic response to road building was highly variable, which was attributed to the synchronization or desynchronization of subsurface flow to stream flow described earlier. In addition, another study of two small watersheds in Idaho, Megahan (1972) reported intercepted flow from the cutslope was 7 times that of runoff generated from the road surface.

Bowling and Lettenmaier (1997) used a spatially distributed hydrology soil and vegetation model (DHSVM) to segregate the effects of roads and harvest on peak flows in two headwater catchments of the Deschutes River Basin in southwestern Washington. Roads were estimated to have increased the ten–year return period flood by 8 and 10 percent. A comparable effect was predicted to have occurred for timber harvest alone.

At a larger scale, Storck et al. (1995) used DHSVM to model harvest effects in the main stem Snoqualmie River Basin in western Washington. By comparing differences in the observed and simulated streamflow using a constant mature vegetation state, they were able to isolate vegetation removal effects on streamflow. No significant changes in the peak annual flow were found. However, a significant increase was found in smaller peaks (less than 650 m^3/s). In another study in the same basin, statistically significant increases in annual maximum peak flows were found in four catchments undergoing continuous harvesting in the Snoqualmie River Basin between 1961- 1993 (Rosencrantz et al. 1995). However, no significant trends were detected for two sub–catchments with contrasting harvest histories.

Lyons and Beschta (1983) found an increasing trend in the size of peak flows in a 668-km^2 watershed in western Oregon as harvesting and road construction increased. Duncan (1986) used a similar regression analysis to compare the effects of logging and road construction in the upper Deschutes Basin (232 km^2) with the unharvested Nashelle Basin (142 km^2), both in western Washington. No significant effects on peak flows were found. However, the elevation difference between the two catchments is as much as 400 meters, which would lead to variable antecedent snow conditions between the catchments.

Jones and Grant (1996) found that clear cutting increased peak discharge by as much as 50 percent in small basins and 100 percent in large basins in western Oregon over the past 50 years. Roads alone were found to advance initiation of peak flows and increase mean peak discharge by 20 percent in one watershed. However, the changes were not statistically significant in the four year period with roads only. In contrast, a small basin with roads and 25 percent of its area clear cut had a significant increase in peak discharge, comparable to a small basin with 100 percent clearcut without roads. This lends credence to the Jones and Grant (1996) hypothesis that roads and harvesting have a synergistic effect on streamflow due to increased water input to soils following harvest and consequent interception of higher subsurface flows by the road cutslope.

Megahan (1983) found evidence of such a synergism in the Pine Creek catchment in central Idaho. Following clear-cutting above the road, the volume of subsurface flow intercepted by a road cut increased by 2.5 times. In a later study, Megahan et al. (1995) found no significant changes in instantaneous peak flow after helicopter logging of 23 percent of the 162 ha Silver Creek drainage in Idaho. Because no roads were constructed in the Silver Creek study, comparison of the Pine and Silver Creek results lends credence to the theory of synergy between roads and clearcuts, as proposed by Jones and Grant (1996). However, the results may also reflect differences in topographic influences discussed in Section 2.2.1. Furthermore, the Bowling and Lettenmaier (1997) study found no evidence of synergy at the catchment (as opposed to hillslope) scale in their study of two Deschutes River headwater catchments.

Taken collectively, these studies do not show a clear indication of the effect of roads and the combination of roads and harvest on peak flows. Some of the differences among studies may be related to the statistical analysis and length of flow records. Typically, the significance level in these analysis, alpha (Type I error probability), is set to a low value—commonly $p < 0.05$. In terms of evaluating peak flows, this corresponds to the probability of concluding that changes in peak flows occurred where no change actually existed.

Less attention is given to the probability of Type II errors, which corresponds to concluding that changes in peak flows have not occurred when underlying changes are in fact present. The power of a statistical test (complement of the Type II error probability), depends on particulars of the experimental design, especially the number of observations (i.e., number of pre- and post-treatment flood peaks), as well as statistical characteristics of the data, such as its variance. It is much easier to control the significance level than the power of the test. Therefore, in interpreting differing tests, its is important to note than considerable variability in the power of the tests inevitably is present.

One example of a design consideration that affects power (ability to detect a change in peak flows) is the selection of a peak flow threshold. The peak flow threshold can be decreased, to increase the number of peak events and hence, the power of a study. However, smaller floods are influenced by different mechanisms relative to larger floods. For example, the fraction of snowmelt contributing to smaller floods is usually larger than that for larger floods. That is, the mechanisms causing enhanced runoff may differ between smaller and larger floods. For studies involving longer discharge records, vegetation may regenerate. Therefore, although the power of a test increases with period of record, the magnitude of the effect being studied may decrease (e.g., due to vegetation recovery).

Likewise, increases in peak flows may not be detectable from short discharge records, especially for small increases. For example, increases in the 10 year return flows of 8 to 10 percent simulated by Bowling and Lettenmaier (1997) following road construction may not be detectable over the temporal scale of the flow records. Since most statistical studies on the effects of roads alone have been on relatively short time periods, they are susceptible to this type of error.

2.4: Road Design and Construction

The relative length of forest roads constructed in a logged catchment is related to the harvesting method, which, therefore, impacts the potential for roads to alter the hydrologic response of catchment. Several logging techniques are used in the western United States, including harvesting by helicopter, skyline, ground cable, and tractors. Megahan (1981) summarized results from 16 studies of soil disturbances due to timber felling and skidding, and logging roads in the western states. The average total soil disturbance area was 4% for helicopter, 9.1% for skyline, 23.9% for ground cable, and 33.5% for tractor logging. Although helicopter logging causes the least soil disturbance, it is also the most expensive and is only used when both erosion risks and timber values are high (Megahan et al, 1995). The other methods represent improvements in available technology for yarding and hauling logs. In the 1950's and early 1960's, the primary harvesting method was by tractor and high-lead yarding (Carow and Silen, 1957). Road spacing to accommodate these systems optimally ranged from 1000 to 1600 feet (Silen 1955). By the late 1960's and early 1970's, skyline yarding systems became available which encouraged ridgetop road construction with higher grades and fewer intermediate roads and landings (Wemple, 1994).

Initially, road construction was driven primarily by economics and accessibility to harvestable timber (K. Lentz, personal communication, 1997, Weyerhaeuser Company). With the advent of state forest-practice standards, other factors began to influence the layout and construction of roads such as slope stability, topography, climate, and sediment delivery to streams (Sedlak 1985; Wemple, 1994).

Roads can be constructed into the hillslope as either full-bench or cut and fill construction. For full-bench designs, the roadbed is constructed entirely into the hillslope and the excavated material is deposited offsite. For slopes greater than 60 percent, this is usually the method of choice due to slope stability concerns (K. Lentz, personal communication, 1997, Weyerhaeuser Company). In a cut and fill design, a portion of the roadbed is cut into the hillslope and the excavated material is used to support the other part of the roadbed.

Three road surface templates are used in forest road design: 1) crowned, 2) in-sloped, and 3) out-sloped. Most road segments incorporate all three templates with in-slopes occurring at outside corners, out-slopes at inside corners and crowns in between. Technically out-slopes do not require a ditch. However, road segments linking crowned and in-sloped segments are usually ditched. In general, haul trucks and safety determine the amount and position of the surface templates within a road segment (K. Lentz personal communication, 1997, Weyerhaeuser Company). For grades over nine precent, outslope designs are not recommended due to safety considerations (Kramer, 1993).

Culverts are installed at stream crossings and at intermediate locations to relieve water from the ditch to the hillslope below the road (ditch relief culverts). Guidelines for placement of ditch-relief culverts are specified in the Road Preconstruction Handbook (USDA Forest Service, 1987). These guidelines consider road gradient, surface material, soil type, runoff characteristics and the effects of water discharge downslope of the culvert. However, local experience and engineering analysis generally govern the placement of ditch-relief culverts (Kramer, 1993), which can be highly variable. For example, Piehl et al (1988) found no consistent procedure had been used for the spacing of ditch relief culverts in the central Oregon Coast Range.

Chapter 3: Basin Description

The upper Deschutes River, which drains the western slope of the Cascade Range in southwestern Washington, was chosen as the site for this study. The Deschutes River originates near Cougar Mountain in the Snoqualmie National Forest and drains to the northwest, emptying into the southern end of Puget Sound (Figure 3–1). The drainage area is approximately 429 km^2, with roughly 80 percent as forestland. The Weyerhaeuser Company owns most of the land in the upper basin, which has been extensively logged, starting in 1950.

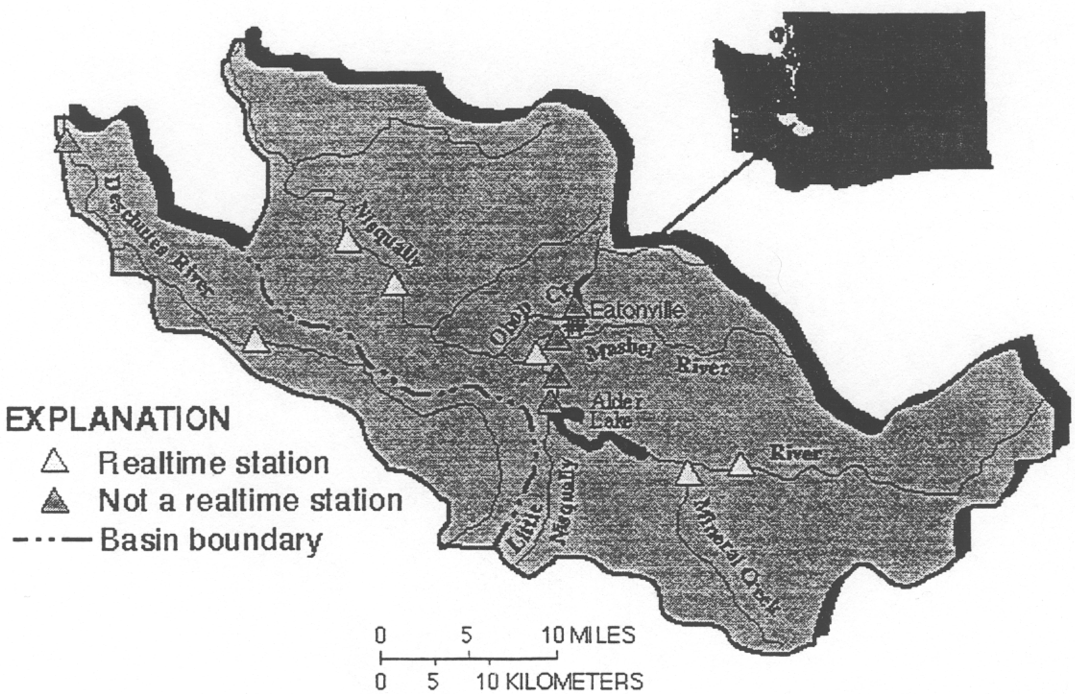


Figure 3–1: Deschutes River Location (USGS, 1997)

A gauging station owned and operated by the Weyerhaeuser Company is located on the main stem of the Deschutes near Weyerhaeuser's Road 1000 bridge in the upper basin (Figure 3-2). This marks the lower boundary of the study area, which includes 149 km^2 of land with elevations ranging from 147 to 1260 meters. Stage recorders also exist on Hard, Ware, and Thurston Creeks, as shown in Figure 3-2. Air temperature is recorded at these sites as well, along with precipitation at the Ware Creek gauge. In addition, a meteorological station was installed at the top of Cougar Mountain in 1995, which measures longwave and shortwave radiation, wind direction and speed, air temperature and relative humidity.

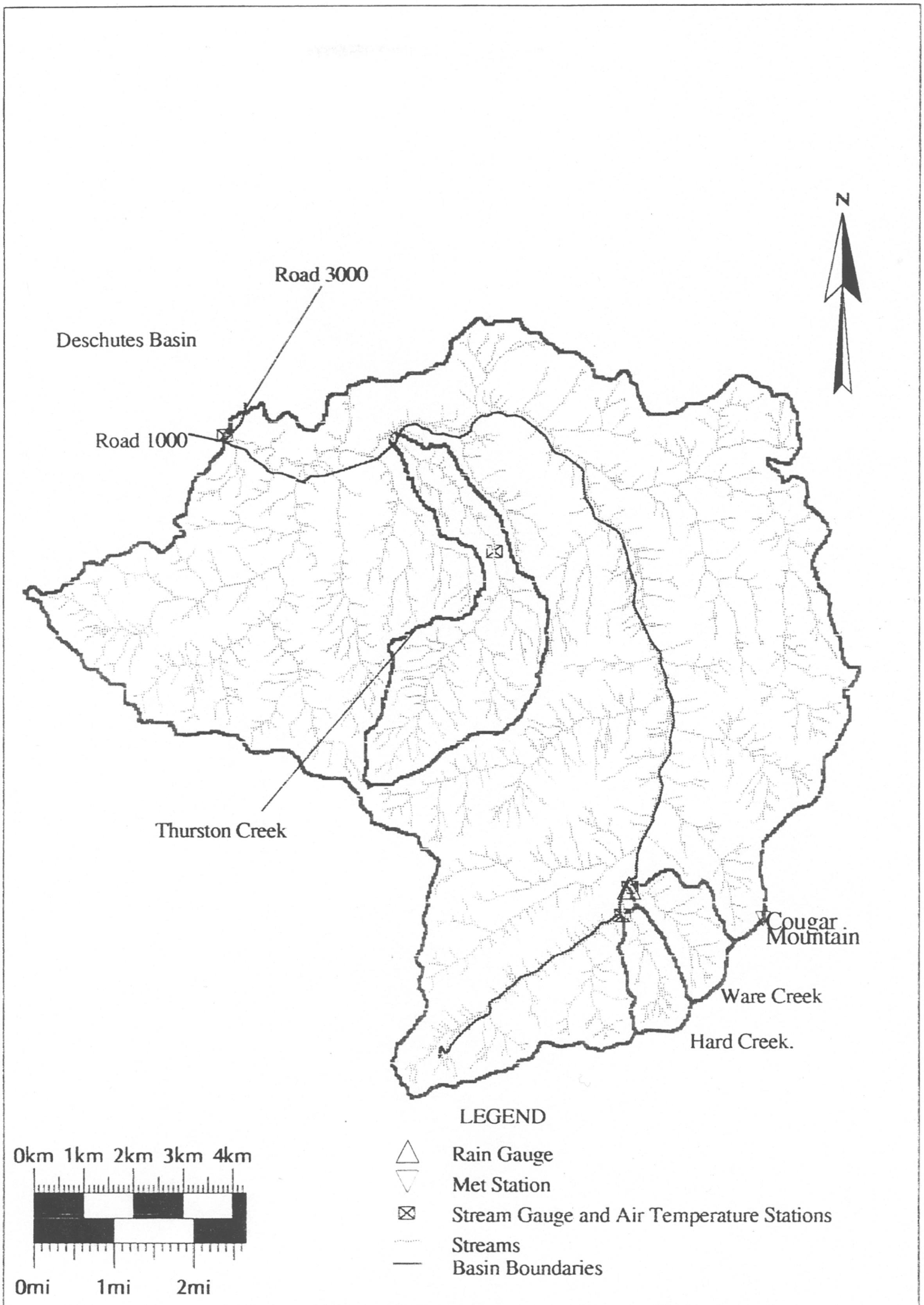


Figure 3-2: Meteorological and Stream Gauge Locations of Study Area

3.1: Climate

The climate of the Deschutes Basin is marine Mediterranean, with cool wet winters and warm dry summers. The majority of precipitation falls between November and March (Figure 3-3) and has ranged from 1500 mm to 3500 mm per year between 1975 and 1997 at the Ware Creek precipitation gauge (elevation 460m).

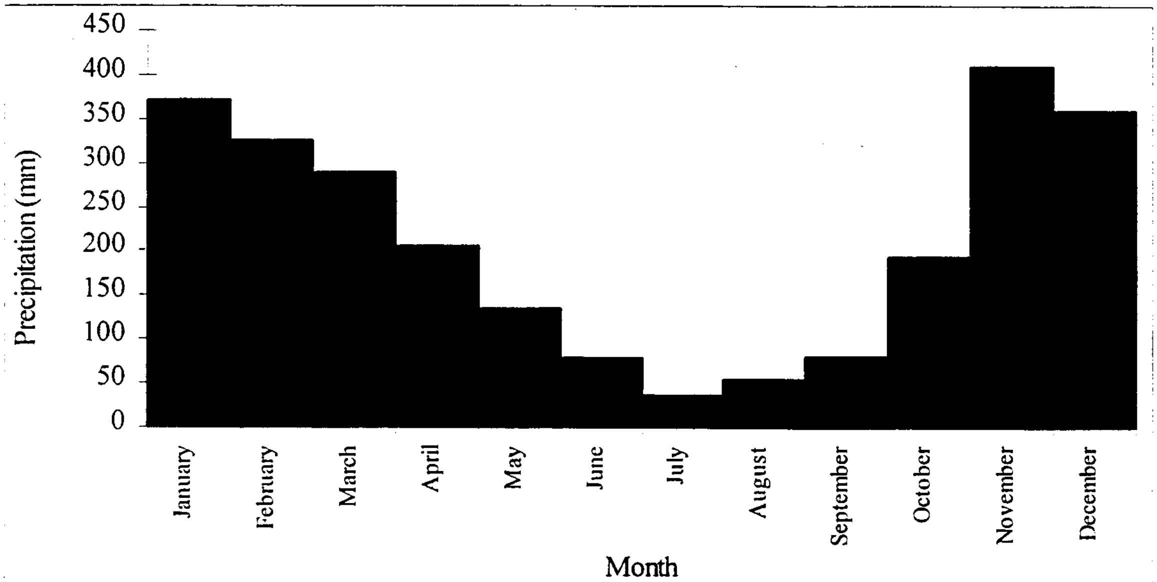


Figure 3-3: Average Monthly Precipitation, Ware Creek, WA 1974–1993
(Bowling and Lettenmaier, 1997)

Over 79 percent of the basin lies within the transient snow zone (taken as 350-1100 meters for the western Cascades of Oregon and Washington) and ephemeral snow packs occur several times throughout winter. The highest elevations in the basin lie above the transient snow zone and may develop deeper snow packs, which last throughout winter. At the intermediate elevations, snow pack depths may reach 0.5 meters.

Mean annual air temperature ranges from 9.75 °C at the Deschutes gauging location (elevation 174m) to 5.6 °C at Cougar Mountain (1260 m). Bowling and Lettenmaier (1997) found temperature lapse rates to average about -5.5 °C/km based on temperatures recorded at Ware Creek Gauge and Cougar Mountain. However, inversions can occur especially during fall and winter dry conditions.

Winds measured at Cougar Mountain are predominately from the southwest with some variability (Bowling and Lettenmaier, 1997). This is also thought to be the principal storm direction, except during summer months.

3.2: Sub-Catchments

Within the study area, there are fourteen named tributaries (Figure 3-4). Of these, Mitchell Creek and Little Deschutes Creek are the largest, representing 15.2 percent and 13.6 percent of the total study area. There are eight additional unnamed tributaries with an area of 1 km^2 or greater, which total approximately 15 km^2.

The headwater catchments consist of long straight v-shaped valleys and smooth steep slopes, commonly exceeding 70 percent (Figure 3-5). The lower basins have smooth ridges and gentler slopes (Duncan, 1986). Sub-basin topographic characteristics were derived from a 30-meter digital elevation model (DEM) and are summarized in Table 3-1. Area–elevation curves are shown in Figure 3-6. Derivation of the stream network from the 30-meter DEM is discussed in Chapter 4.

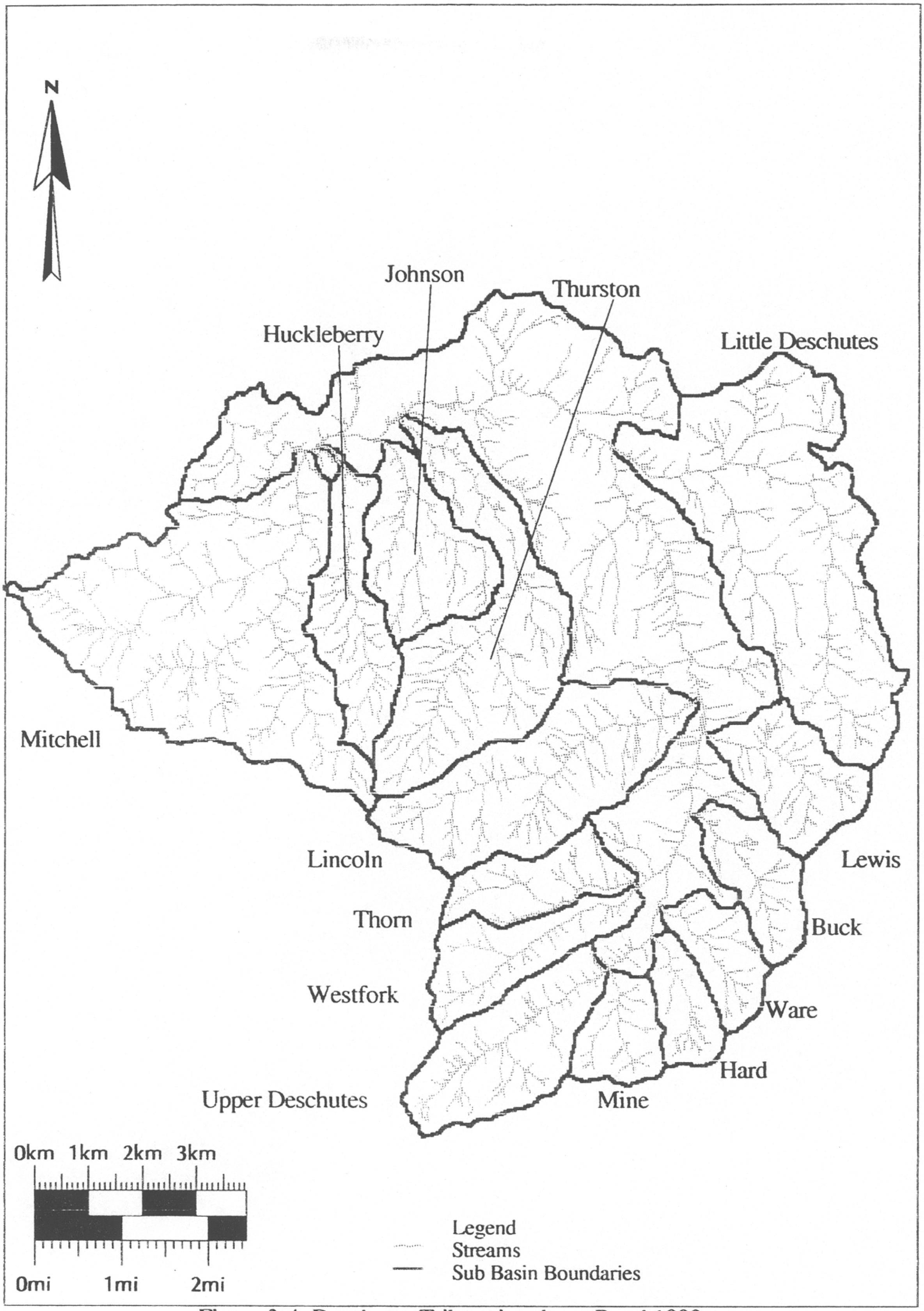


Figure 3-4: Deschutes Tributaries above Road 1000

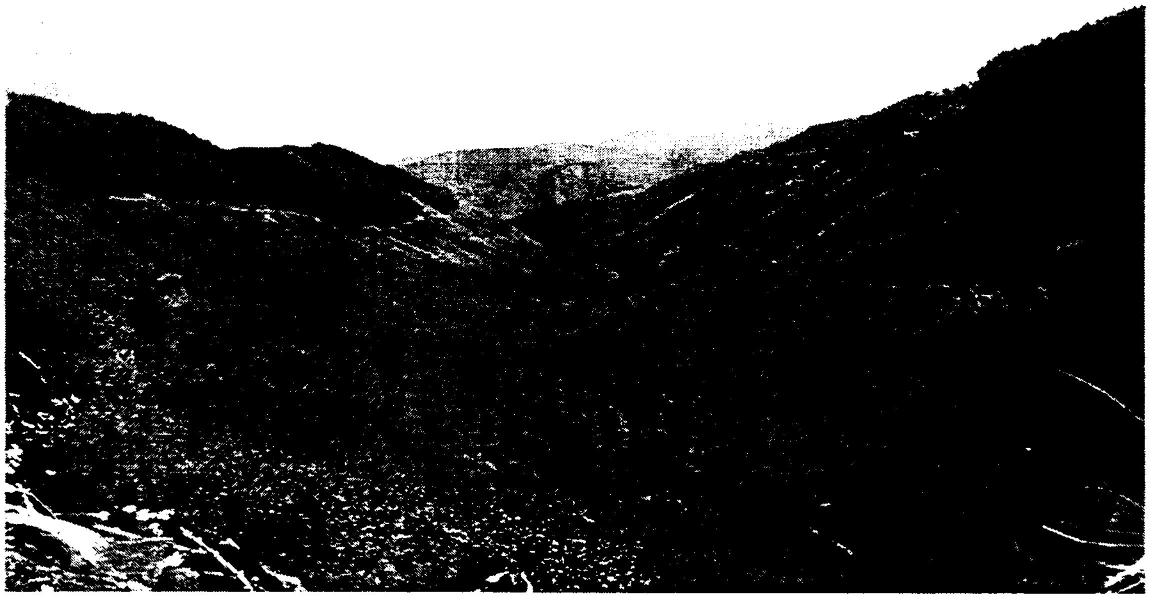
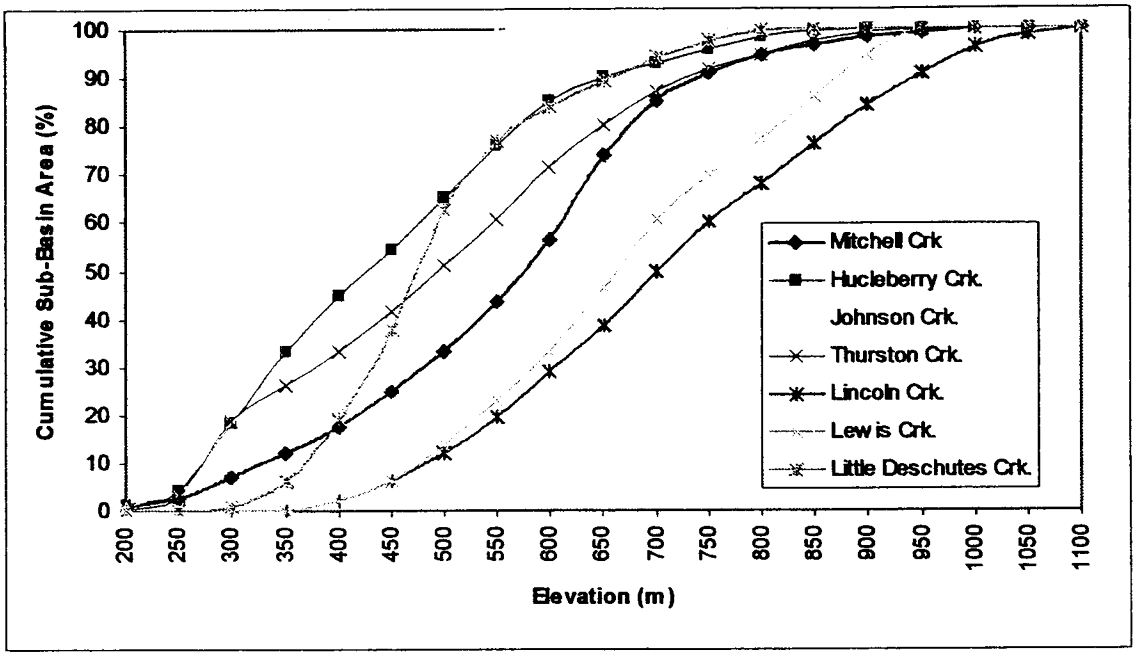


Figure 3-5: Upper Deschutes Creek, Typical Example of V-Shaped Valleys

Table 3-1: Sub-Catchment Topographic Summary

Sub-Basin	Area (km^2)	Average Slope (%)	Slope Range (%)	Average Elevation (m)	Elevation Range (m)	Drainage Density[a] (km/km^2)	Stream Order[a]
Mitchell	22.1	34.7	0-120	557	182-1097	3.8	5
Huckleberry	5.3	28.5	0-106	447	186-897	4.1	4
Johnson	5.8	21.1	0-94	342	195-599	3.7	4
Thurston	12.2	26.8	0-83	497	197-995	4.1	5
Lincoln	10.9	38.5	0-95	709	360-1114	4.1	4
Thorn	3.7	44.5	0-98	822	442-1153	3.8	4
West Fork	4.5	54.7	0-110	739	439-1158	3.3	4
Upper Deschutes	6.8	52.6	0-146	774	485-1111	3.8	4
Mine	2.7	57.4	0-98	812	488-1135	3.6	4
Hard	2.3	56.6	0-106	840	455-1183	3.7	4
Ware	2.8	51.0	0-96	810	434-1171	3.8	4
Buck	3.5	39.7	0-95	812	393-1260	3.5	4
Lewis	4.7	38.8	0-147	669	364-979	4.0	4
Little Deschutes	19.9	25.8	0-102	492	265-855	3.5	5
Deschutes River	144.8	32.9	0-147	546	169-1260	3.8	6

[a] Based on 2 ha source area as modified by field observations.



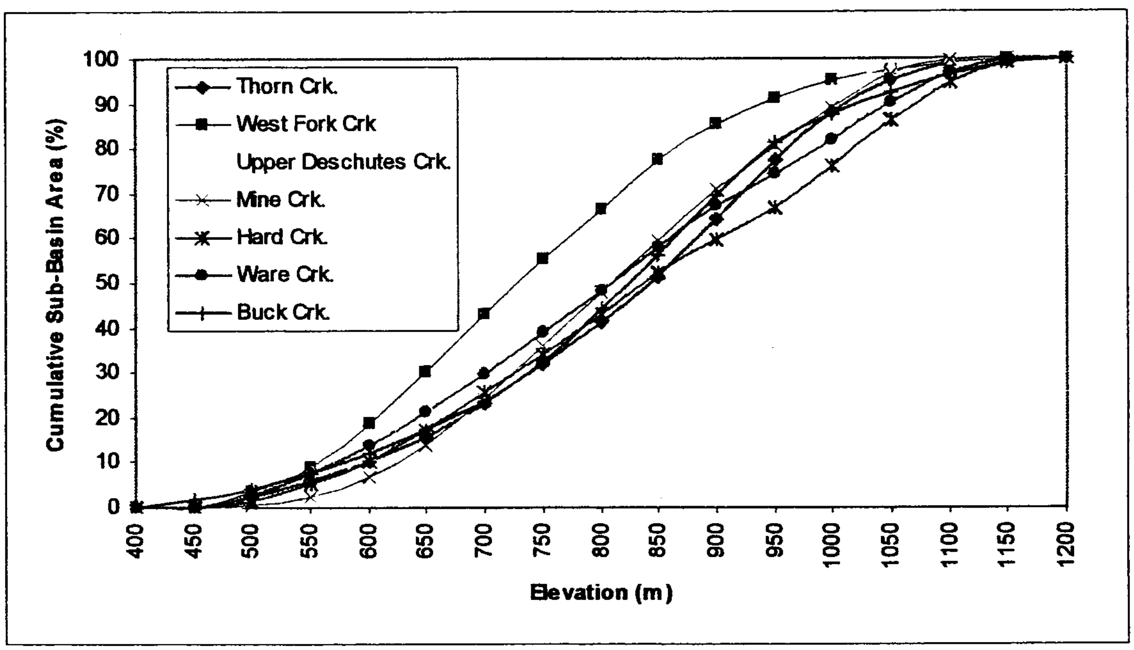


Figure 3–6: Cumulative Area Elevation Curves for Deschutes River Sub–catchments above Road 1000

3.3: Basin Geology

There are four major geological types within the upper Deschutes River Basin: Resistant Volcanic Rock, Weathered Volcanic and Sedimentary Rock, Highly Weather Fluvial Deposits, and Glacial and Alluvial Deposits (see Figure 3-7) (Sullivan et al. 1987). Valleys are partly filled with unconsolidated fluvial and glacial deposits, while steep slopes of the headwaters are dominated by resistant volcanic rock or weathered volcanic and sedimentary rocks (Sullivan et al. 1987). The river valley contains glacial deposits as far upstream as the mouth of Lewis Creek. Several tributaries including Huckleberry, Johnson, Thurston and Little Deschutes Creeks have significant portions of their lower basins filled by fluvial and glacial deposits (Sullivan et al. 1987). Resistant volcanic rock can be found in the headwater basins of Thorn, West Fork, Mine, Hard, Ware, Buck, and Upper Deschutes Creeks, with exposed rock present near ridges.

Soils consist of stony loams, stony clay loams, and stony silt loams developed from volcanic ash combined with basalt, andesite, basaltic breccia and welded tuff with local inclusions of sedimentary rock (Sullivan et al. 1987). Soil depths range from shallow (less than 40 cm) to moderately deep (50 to 100 cm) (Duncan, 1986). Although soil stability is considered generally good (Duncan, 1986) there are many examples of slope failures within the basin (Figure 3-8).

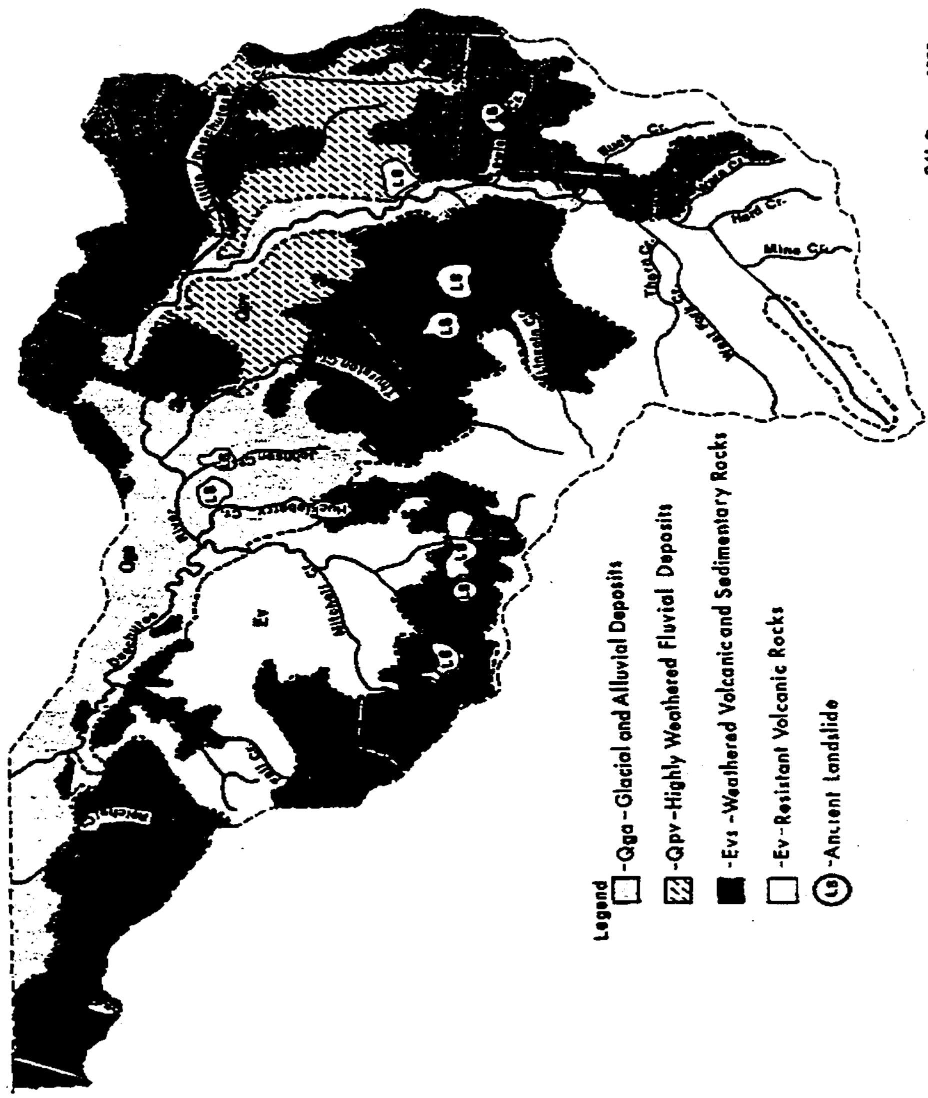


Figure 3-7: Geology Map of the Upper Deschutes River (Sullivan et al. 1987)

Figure 3-8: Example of Slope Failure Below Logging Road, Lincoln Creek

3.4: Road Construction and Timber Harvest

Logging and road construction has been ongoing in the Deschutes River Basin since 1950. As of 1987, over 50 percent of the basin had been harvested and regenerated (Sullivan et al. 1987). Vegetation consists of Douglas Fir (Pseudotsuga menziesii), Western Hemlock (Tsuga heterophylla) and Pacific Silver Fir (Abies amabilis), as well as deciduous trees such as Red Alder and Big Leaf Maple. Clearcuts have been regenerated mostly with Douglas Fir, but regrowth appears slow in some areas (Figure 3-9). By 1986, most of the existing 547-km road network had been constructed.

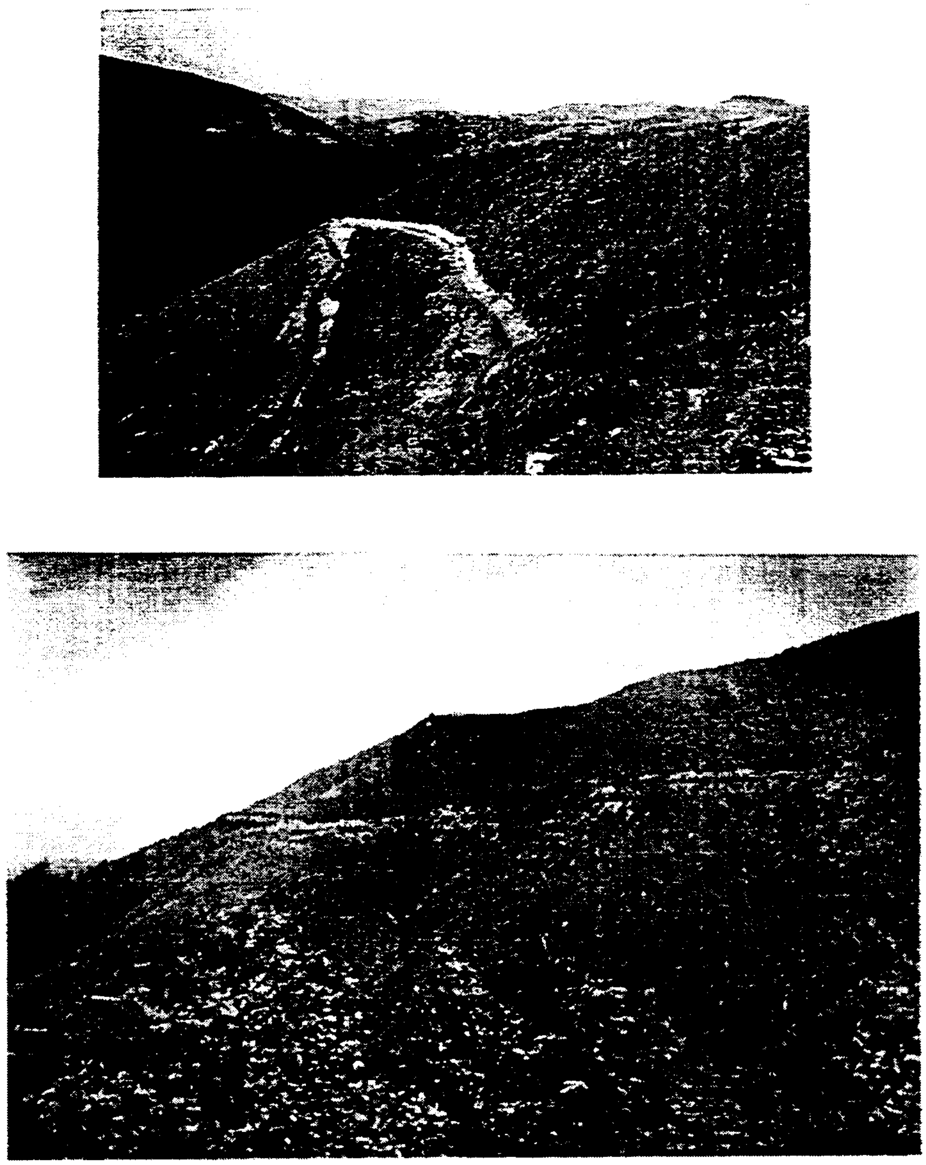


Figure 3-9: Vegetation Regeneration in Upper Deschutes (upper) and Hard Creeks (lower) Respectively

Current road lengths and harvested areas are summarized in Table 3-2. The information in Table 3-2 was tabulated from road and vegetation information supplied by Weyerhaeuser Company in the form of GIS coverage.

Table 3-2: Road and Harvest Summary

Sub-Basin	Road Length (km)	Road Density (km/km^2)	Area of Basin in Roads (%)[a]	Cumulative Area Harvested[b] (km^2)	% of Sub-Basin Harvested
Mitchell	70.5	3.2	4.9	8.9	45
Huckleberry	20.3	3.8	5.9	1.8	33
Johnson	24.1	4.2	6.4	0.9	15
Thurston	52.9	4.3	6.7	8.5	70
Lincoln	47.0	4.3	6.6	10.7	98
Thorn	14.1	3.8	5.9	2.9	79
West Fork	18.9	4.2	6.5	3.3	74
Upper Deschutes	23.6	3.5	5.3	5.6	82
Mine	9.6	3.6	5.5	1.9	71
Hard	11.4	5.0	7.6	0.8	36
Ware	10.7	3.8	5.9	2.5	90
Buck	16.1	4.6	7.1	3.5	99
Lewis	21.2	4.5	6.9	4.3	91
Little Deschutes	81.7	4.1	6.3	18.1	91
Deschutes River	***547***	***3.8***	***2.6***	***99.3***	***69***

[a] Based on 6.8 meter right of way. [b] Estimated from tree height

Road area was estimated using an average road width of 6.8 meters. Vegetation age did not correspond well to vegetation height and the oldest tree age given was only 20 years. Therefore, a vegetation height of 15 meters was set as a threshold to determine if an area had been harvested. Using this relatively low threshold height may result in classification of some second growth areas as non-harvested; especially in the lower basins, such as Mitchell Creek, where logging began in the 1950's.

During the early stages of harvesting, tractor skidding methods were used in conjunction with clear cutting on gentler terrain of the lower basin. However, the major form of timber harvest in the upper basin has been high lead cable systems and clear cutting (Duncan, 1986).

Road characteristics of the basin are described in Toth's (1991) inventory of forest road damage. In general, these roads can be classified by age. The oldest roads, built 53-72 years ago, followed old railroad grades and had large amounts of fill with cedar puncheon culverts at stream crossings. These roads are characterized by poor surface water drainage with few ditch relief culverts. Some of these roads have undergone partial or full reconstruction, while others have been abandoned. The next generation of roads, built 23-52 years ago, were constructed by Weyerhaeuser Company construction crews and generally had sparse culvert spacing and culverts that are undersized by current standards. These roads were built without the benefit of forest-practice standards or permits. Roads constructed from 13-22 years ago were built with the same construction techniques as the previous road age class. However, these roads had the additional requirement of meeting state forest-practice standards, including culverts designed for at least a 50-year storm event. Furthermore, since approximately 1985, ditch relief culvert placement was modified to avoid direct drainage to gullies when possible (K. Lentz, per communication, 1997, Weyerhaeuser Company). Toth (1991) found that much of the damage to and by roads resulting from the January 1990 storm event, (approximately 100-year, 24-hour event) was associated with roads built 23-52 years ago.

Chapter 4: Field Investigation

As described in Chapter 1, the potential effect of forest roads on stream flow should depend on two factors: 1) volume of water converted to overland flow either by infiltration excess runoff from the road surface or by subsurface flow intercepted by the road cutslope and, 2) delivery of the road generated runoff to the stream network through the road drainage network. A field research study was conducted to investigate both of these factors.

The first aspect of the field research focused on measuring sub-surface and surface flow generated by roads in Hard and Ware Creeks, headwater tributaries of the Deschutes River, Washington. This work was effectively a continuation of an investigation initiated by Bowling and Lettenmaier (1997). The research examined the effect of hillslope position, contributing area, cutslope height, uphill vegetation, soil type, and road surface area on road generated runoff, through a systematic measurement of peak discharges from road segments.

The second aspect of the field research focused on determining the connectivity of the road drainage to the natural stream drainage. A sub-sample of culverts within the Deschutes Basin above Road 1000 was examined for connectivity to the stream network. This field investigation, coupled with a GIS analysis, was used to evaluate the factors that affect connectivity of culvert outflows to stream drainage, and to subsequently develop a regression model to predicting connectivity of the remaining culverts in the basin.

4.1: Road-Generated Runoff in Hard and Ware Creeks

4.1.1: Methods

Bowling and Lettenmaier (1997) measured overland and sub-surface intercepted flow from thirteen road segments in the Hard and Ware Creek drainages using a combination of weirs and crest recording gauges at culvert entrances. This study used the same general methodology, equipment, and study sites, but included eight additional road segments with the original sites during the October 1996- September 1997 water year. The additional road segments were selected on the same basis as the original thirteen; hillslope position, upslope vegetation, soil type, cut slope height, and runoff mechanism. These attributes were identified during a preliminary field investigation in Hard and Ware Creeks by Bowling and Lettenmaier (1997). Table 4-1 summarizes characteristics of all 21 sites.

Crest stage recorders were installed to measure peak flows at the road segments' ditch relief culvert entrance. In addition, weirs were installed in roadside ditches draining to stream crossings culverts or at road fillslopes where surface flow exited over the fillslope. Figure 4-1 identifies location of weir and stage recorders within Hard and Ware Creeks, as wells as drainage area to these sites.

Bowling and Lettenmaier (1997) calculated contributing areas for the 13 original sites by delineating the uphill contributing area of the road segment draining to a culvert or weir. The delineation was performed in a GIS package (Arc/Info) using a 30-meter digital elevation model (DEM) and defining the local elevation maximums as micro ridges draining to the site. There is some uncertainty as to where the actual ridge may lie within the 30-meter pixel, which may lead to an error of up to 225 m^2 per boundary pixel or one-quarter of the pixel area (Bowling and Lettenmaier, 1997). Results are summarized in Table 4-2.

Table 4-1: Attributes of Monitored Road Segments (Modified from Bowling and Lettenmaier, 1997)

	Predominant Runoff Mechanism			Hillslope Position			Upslope Vegetation		Soil Characteristics			Cutslope Height		
	Road	Sub	Both	Base	Mid	Top	Imm.	Mature	Soil	Soil /Bed	Bed.	< 3M	3-6 M	> 6 M
H005*	X			X			X			X		X		
H007a	X			X			X				X			X
W030*	X			X			X				X	X		
W029*	X				X		X		X				X	
H010			X			X		X	X					X
H007b		X		X			X				X			X
W031*		X		X			X				X			X
H027*		X		X				X			X		X	
H042		X		X				X		X			X	
W017*		X			X		X		X			X		
W018		X			X		X		X			X		
H023		X			X		X		X					X
W038		X				X	X		X			X		
W040*		X				X	X		X				X	
W053		X				X	X			X			X	
W032			X	X			X				X			X
H018			X	X				X	X				X	
H028			X		X			X			X		X	
H046			X		X			X		X			X	
W014			X		X		X			X			X	
W036b*			X			X	X			X			X	

*Additional Study Sites

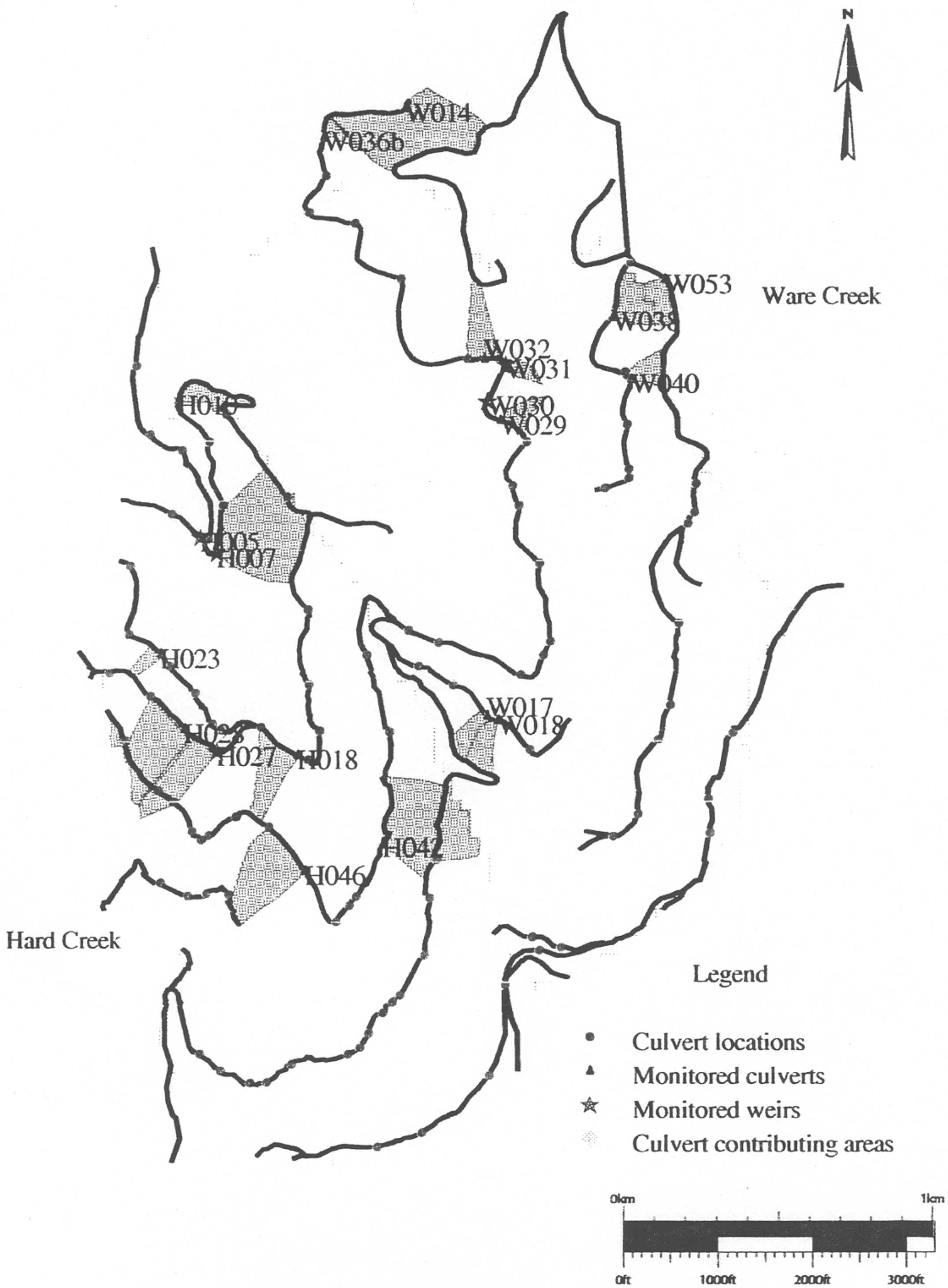


Figure 4-1: Culvert and Weir Locations with Contributing Areas
(Modified from Bowling and Lettenmaier, 1997)

Table 4-2: Culvert Contributing Areas and Road Lengths (Modified from Bowling and Lettenmaier, 1997)

Culvert ID	Contributing Area		Contributing Road Length (m)			
	Area(Ha)	Error(Ha)	Total	Insloped	Outsloped	Crown
H005	-	-	131	-	35.6	95.4
H007A	-	-	164	86	78.5	0.0
H007B	7.7	0.6	164	86	79	0
H010	1.2	0.2	344	166	50	129
H018	2.3	0.7	161	94	10	57
H023	0.5	0.2	63	16	0	47
H027	2.6	0.4	97	97	-	-
H028	3.9	0.5	203	77	60	66
H042	6.9	1.0	261	83	105	73
H046	4.2	0.7	189	98	0	91
W014	7.3	0.7	148	116	0	32
W017	0.9	0.3	347	-	-	-
W018	1.1	0.3	347	-	-	-
W029	0.8	0.4	92	24	15	53
W030	-	-	95	-	66	29
W031	0.5	0.3	153	76	35	43
W032	1.8	0.8	112	38	52	21
W036B	0.4	0.2	53	0	0	53
W038	1.5	0.4	150	0	79	71
W040	1.0	0.3	73	0	73	0
W053	1.1	0.4	192	0	0	192

Stage recorders consisted of four-inch diameter stilling wells with a flexible PVC inlet tube entering near the well bottom. Pools were dug or enlarged at the culverts entrance to accommodate the stilling well and inlet pipe to ensure the inlet pipe was below the culvert invert, and to reduce the velocity head of incoming water. These pools periodically filled with sediment, which was removed during site visits.

Six sharp-crested, V-notch box weirs were constructed and installed at road segments within the two basins. Stilling wells were attached to openings at the bottom of the weirs to record peak stages. As with the culvert inlet pools, sediment accumulation in several of the weirs was removed during site visits (Figure 4-2). Culvert and weir peak stages were recorded bi-weekly, when possible, from October 12, 1996 to May 17, 1997. Cork dust was added to each stilling well and was used to determine the peak stages between site visits. The cork dust usually formed a well-defined line inside the stilling well at the highest flow level since the previous visit. The distance between the top of the well and the line of cork dust nearest the top of the well was measured and subtracted from the distance from the top of the well to the culvert invert. This calculation gave the peak stage, which was assumed to have taken place during the largest precipitation event between site visits. After each field reading, new cork dust was added and washed to the bottom of the wells. If water was flowing in the culverts or weirs during a site visit, the stage and discharge were measured. Discharge was measured using a 5-gallon bucket to catch culvert outflow during timed intervals.

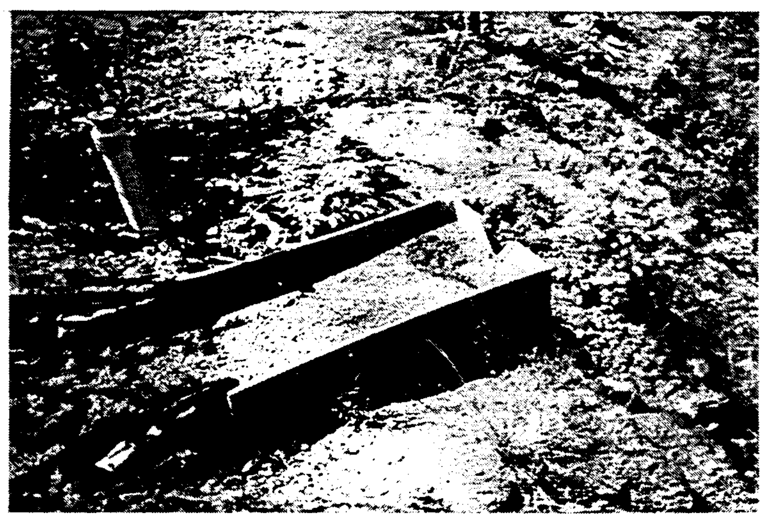


Figure 4-2: Sediment Accumulation in Weirs

The stage discharge relationship for a v-notch weir is given by:

$$Q = C_d \tan(\theta/2) g^{1/2} H^{5/2}$$

where H is the stage above the crest of the v-notch, g is the gravitational constant, θ is the notch angle, and C_d is the discharge coefficient. The discharge coefficient was back–calculated prior to the installation of four of the weirs by measuring steady state discharge values at different heads. These values were found to be 0.26 and 0.46 for the 90° and 60° v-notch weirs, respectively. Flow measurements were not performed on the two 60° v-notch weirs installed in the previous study. However, stage and flow measurements during this study indicate a C_d value of about 0.55 for those weirs. Sediment accumulation in a v-notch weir can cause error in the stage discharge relationship and thus, an error in the estimated discharge for a given stage reading. Sediment accumulation was usually less than 0.5 inches for the weirs, and would only minimally effect discharge calculations. However, weir 007a (Figure 4-2), repeatedly had five to six inches of sediment accumulated which would undoubtedly have a large impact on discharge estimates. Therefore, data from this site was not included in the analysis.

Relating stage to discharge in culverts is slightly more complicated. Culverts located in Hard and Ware Creeks are made of corrugated metal and in general have a free fall at the outlet and pool at the entrance. Thus, the culverts are under inlet control and discharge can be estimated from measured stage at the entrance. Normann et al. (1985) developed stage discharge relationships for culverts under these conditions based on experimental results for the Federal Highway Administration (FHA). However, these relationships were developed for the purpose of culvert design for high flows and stage-discharge relationships for low flows are not provided (Figure 4-3). Bowling and Lettenmaier (1997) combined extrapolated data from the Normann et al. study with field measurements to develop stage discharge curves for the low flow conditions, essentially by extrapolating the FHA stage discharge values from high to low flows. These low head/flow values were then combined with observed field data to fit a polynomial to the data. For this study, the same procedure was used and the polynomials from Bowling and Lettenmaier (1997) were updated to include data from this study, for each of the four culvert types (Figure 4-4).

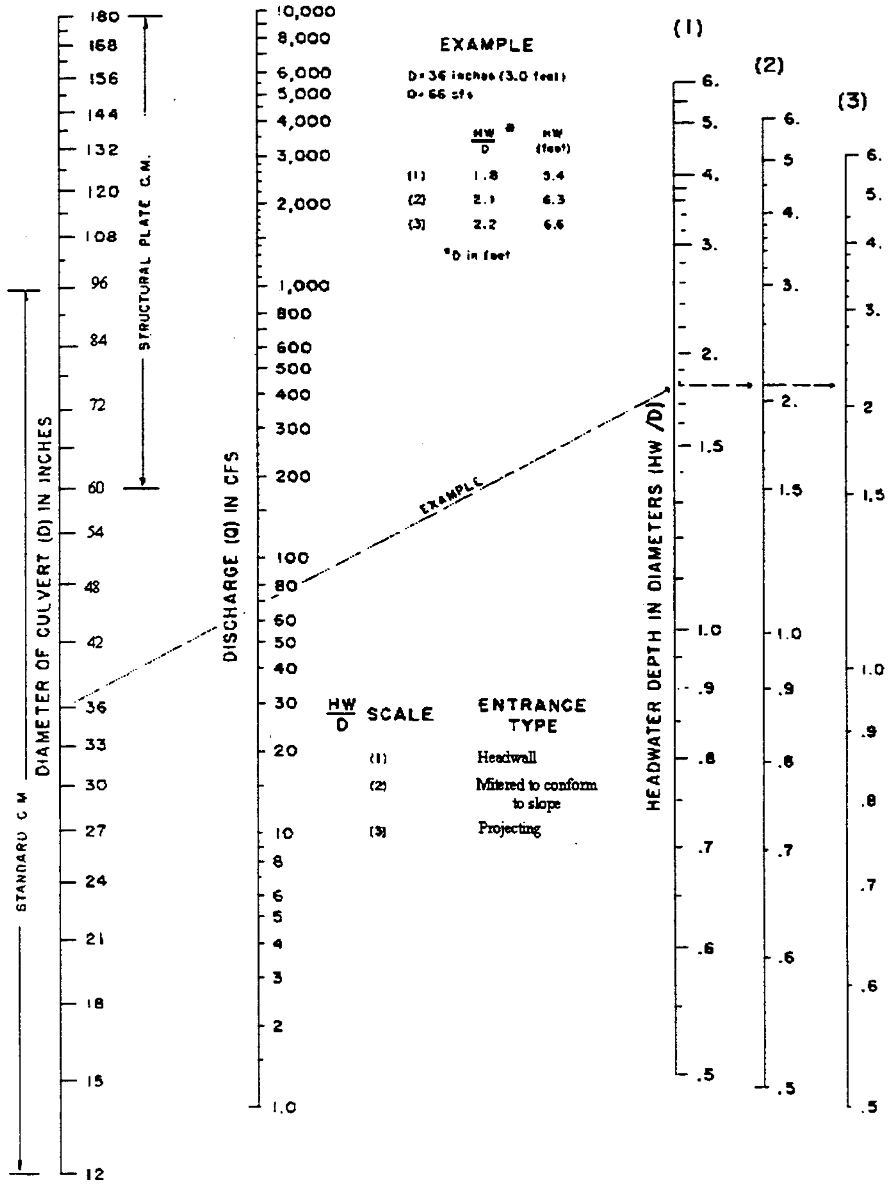


Figure 4-3: Stage Discharge Relationships for Corrugated Metal Culverts under Inlet Control (from Normann et al. 1985).

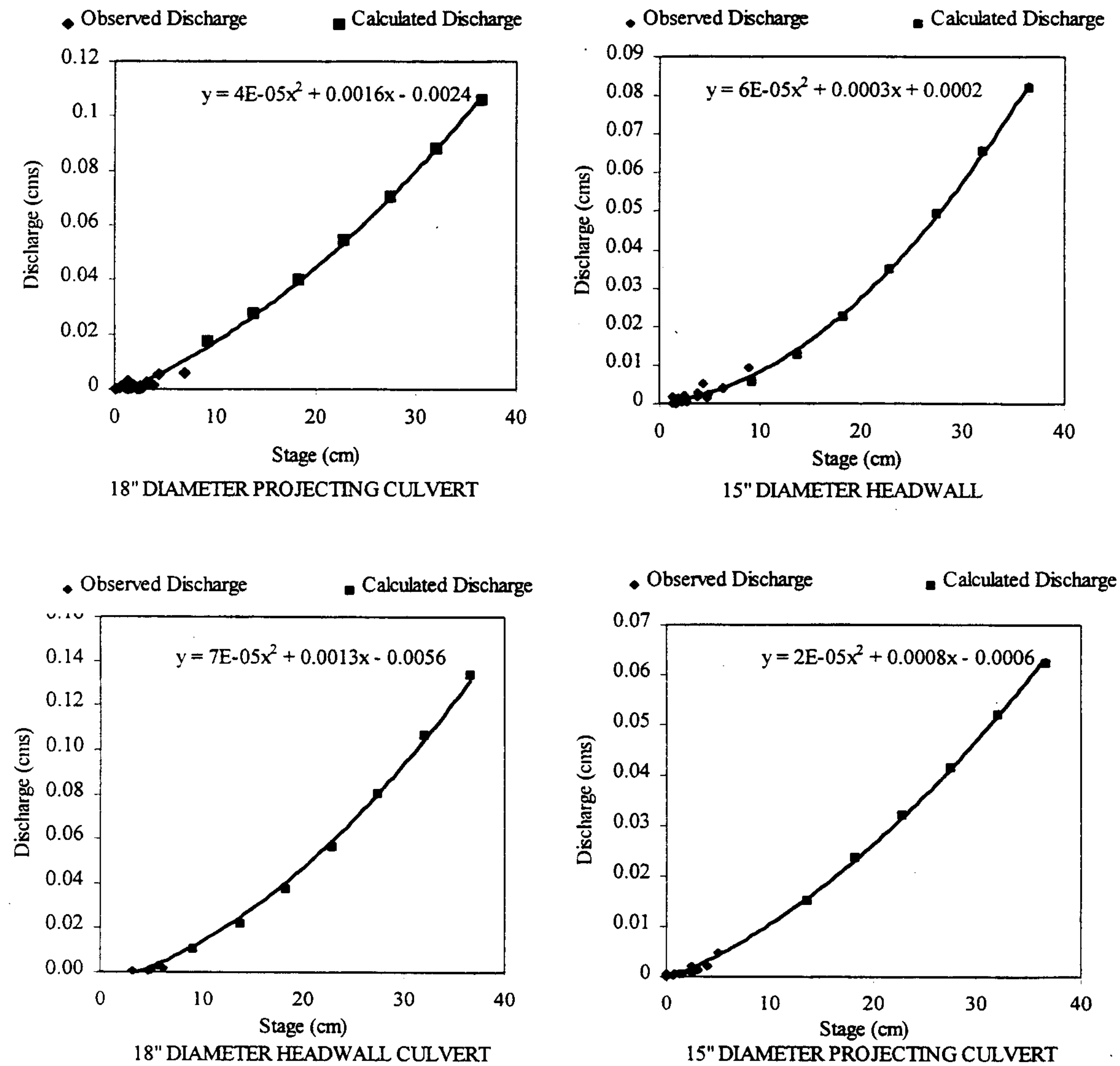


Figure 4-4: Derived Low Stage Discharge Curves For Corrugated Metal Culverts Under Inlet Control (modified from Bowling and Lettenmaier, 1997).

4.1.2: Results and Discussion

The results from the first part of the field investigation can best be interpreted according to the five categories used in selecting the segments: 1) runoff mechanism, 2) upslope vegetation, 3) soil type, 4) cut slope height, and 5) hillslope position. In general, road segments dominated by subsurface flow had the largest response during the study (Figure 4-5a). However, during fall events, surface runoff segments had an equivalent or slightly higher response than road segments dominated by subsurface or combination runoff, despite much smaller contributing areas. During the winter and early spring, the subsurface and combination response increased dramatically with respect to surface flow. This response is indicative of dry antecedent soil conditions in the fall and wet antecedent conditions in the winter and spring, which strongly affect the generation of subsurface runoff.

Normalizing flows by contributing area indicates the high runoff per unit area associated with the road surface runoff (Figure 4-5b). This simply reflects the low infiltration rates of the compacted road surface. However, two storm events produced high values of runoff per unit area at a subsurface flow dominated site, culvert W017. The first storm was a rain on snow event, which would increase the water input rate to the soil and result in a higher flow per unit area. The second storm was preceded by several smaller rain and snowmelt events, which would result in high soil moisture prior to the storm event and increase response during the storm event. Why this effect was more predominant at this location compared to other road segments may be indicative of the drainage area attributes. W017 is located mid-hillslope and drains a subsurface flow dominated road segment below a one hectare clear cut with loose unconsolidated soils. In addition, subsurface seepage through macropores was observed along the segments cutslope. All of these characteristics would tend to increase the response per unit area to an ROS event.

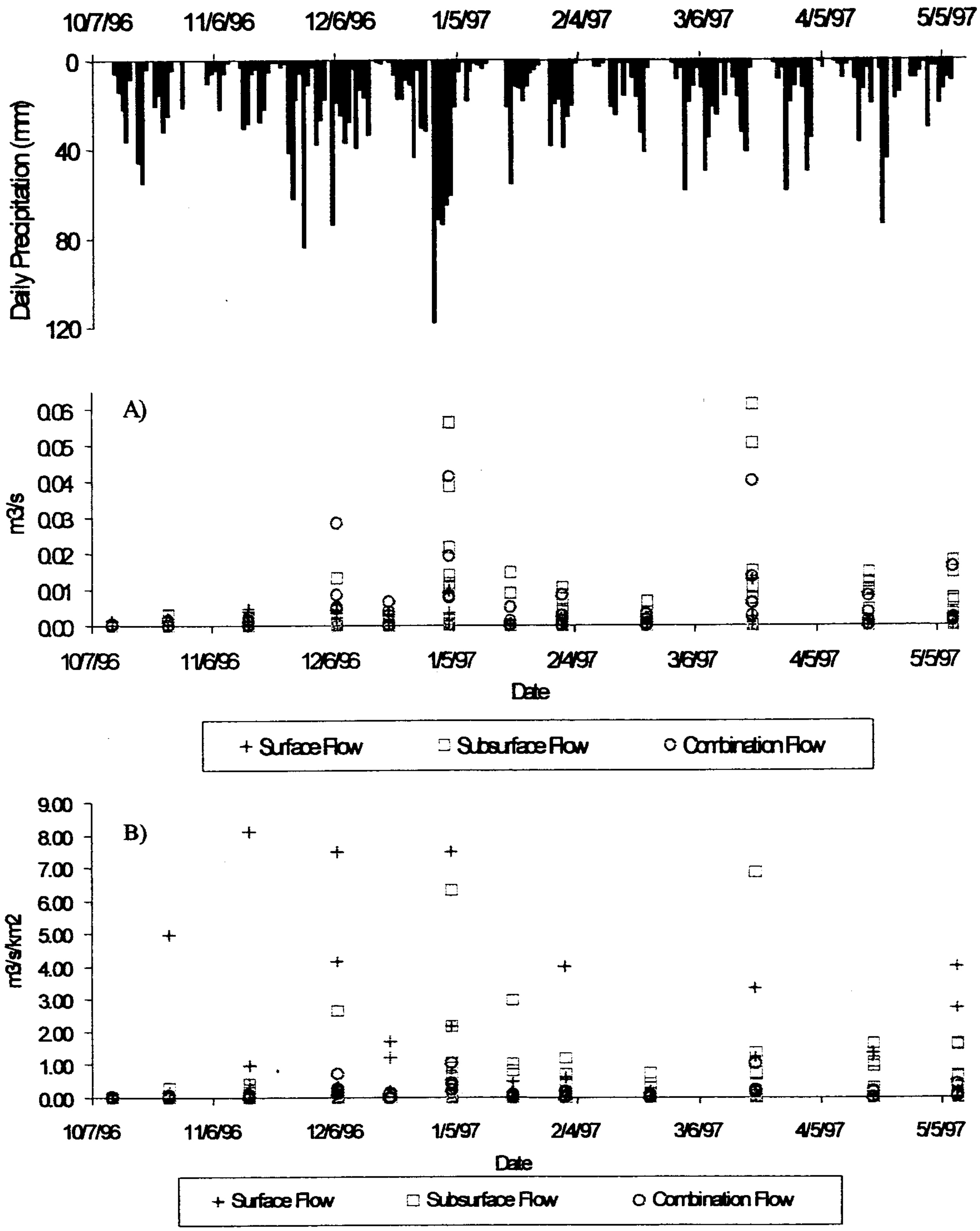


Figure 4–5: Road Segment Peak Flows Partitioned by Runoff Mechanism
A) Absolute Flow, B) Flow per Contributing Area

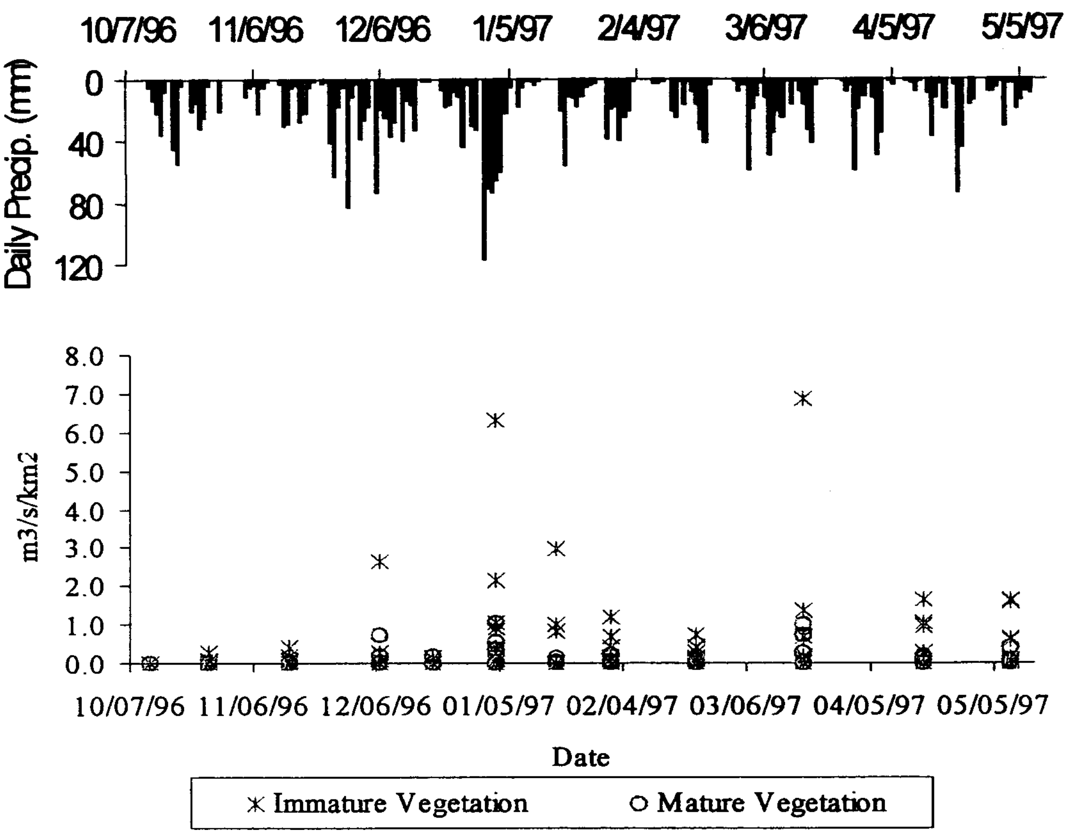


Figure 4–6: Subsurface Dominated Road Segment Peak Flows Partitioned Vegetation Type.

To further investigate these characteristics, road segments dominated by subsurface flow were partitioned by uphill vegetation type. Figure 4–6 indicates that for the road segments studied, segments below clearcuts had a larger response than those below mature vegetation, which agrees with results from Bowling and Lettenmaier (1997). Culvert H028 was the only mature forest location to have significant response to storm events during this study. In addition to subsurface flow, approximately 143 meters of steep road surface drain to this culvert. Significant snow accumulation was observed on the road surface prior to December 29th, 1997 storm and the March 20th, 1997 reading, which may have contributed to the peak flows for these events.

Although there is a general trend of higher response associated with road segments draining clearcut areas, several of these road segments did not have significant responses. To investigate other attributes affecting road segment response, subsurface–dominated segments draining clear cut areas were further separated by soil type. Figure 4-7a indicates that higher flows were associated with areas dominated by soils, as opposed to bedrock. Again, these results coincide with findings of Bowling and Lettenmaier (1997). Fractures in bedrock were observed in many areas, which lead to high infiltration rates. Soils, on the other hand, are generally loose and porous with visible macropores, which would lead to a rapid response to precipitation.

The last subset, subsurface–dominated road segments below clearcuts draining predominately loose soils, were partitioned by cut slope height to investigate its effect. Figure 4-7b shows no clear trend with discharge per unit area associated with cut slope height. This may indicate that differences in the type of subsurface flow, (i.e., Darcian or non-Darcian flow), are more important than cutslope height in the amount of flow response from road segments cutslope.

The effects of hillslope position on runoff for subsurface draining road segments are shown in Figure 4-8a. In all cases, the base and mid hillslope position road segments had a higher response than the top segments. This result is expected since most base and mid hillslope segments have larger contributing areas than ridge top roads, as evidenced by normalizing flows by contributing area (Figure 4-8b).

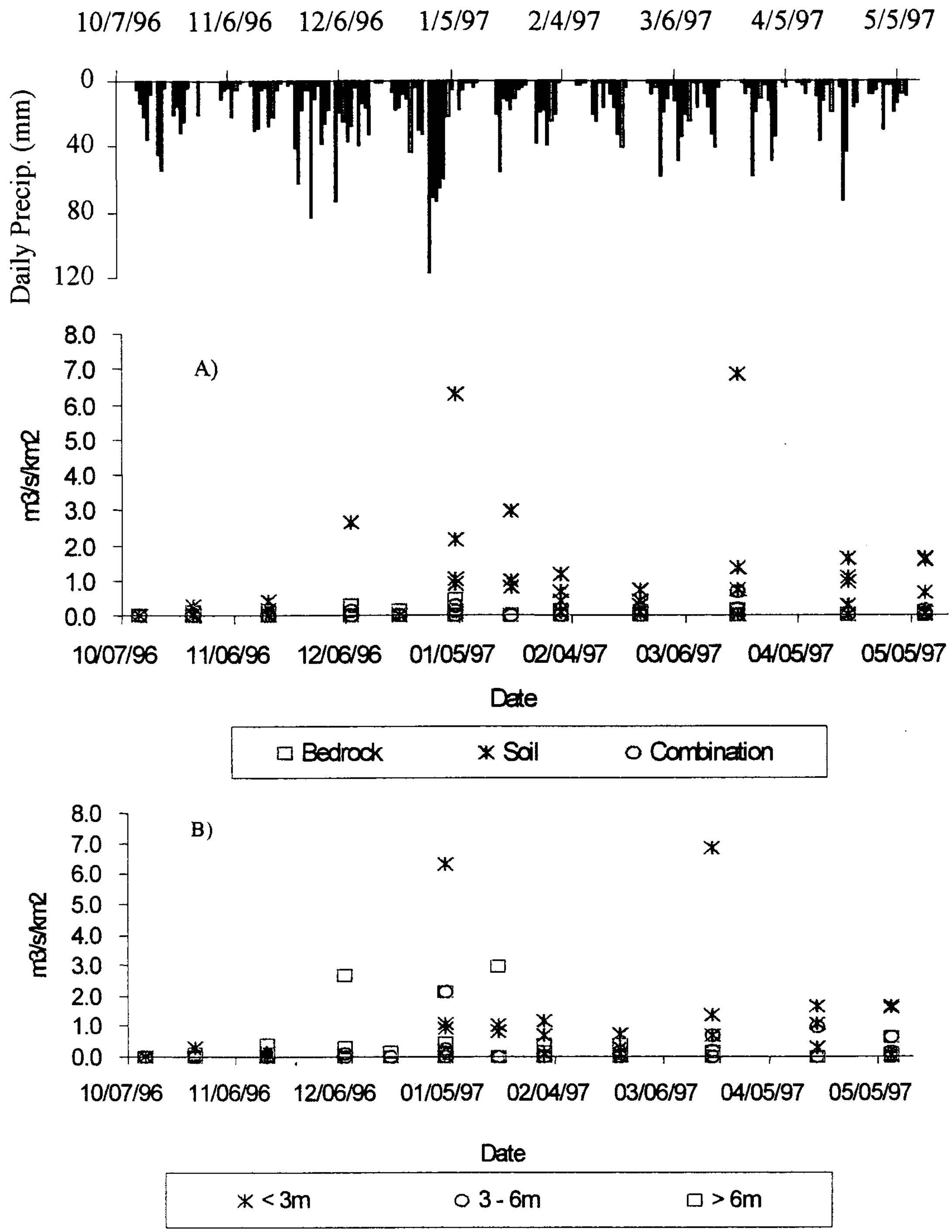


Figure 4–7: Road Segment Subsurface Flow Response by A) Soil Type and B) Cutslope Height.

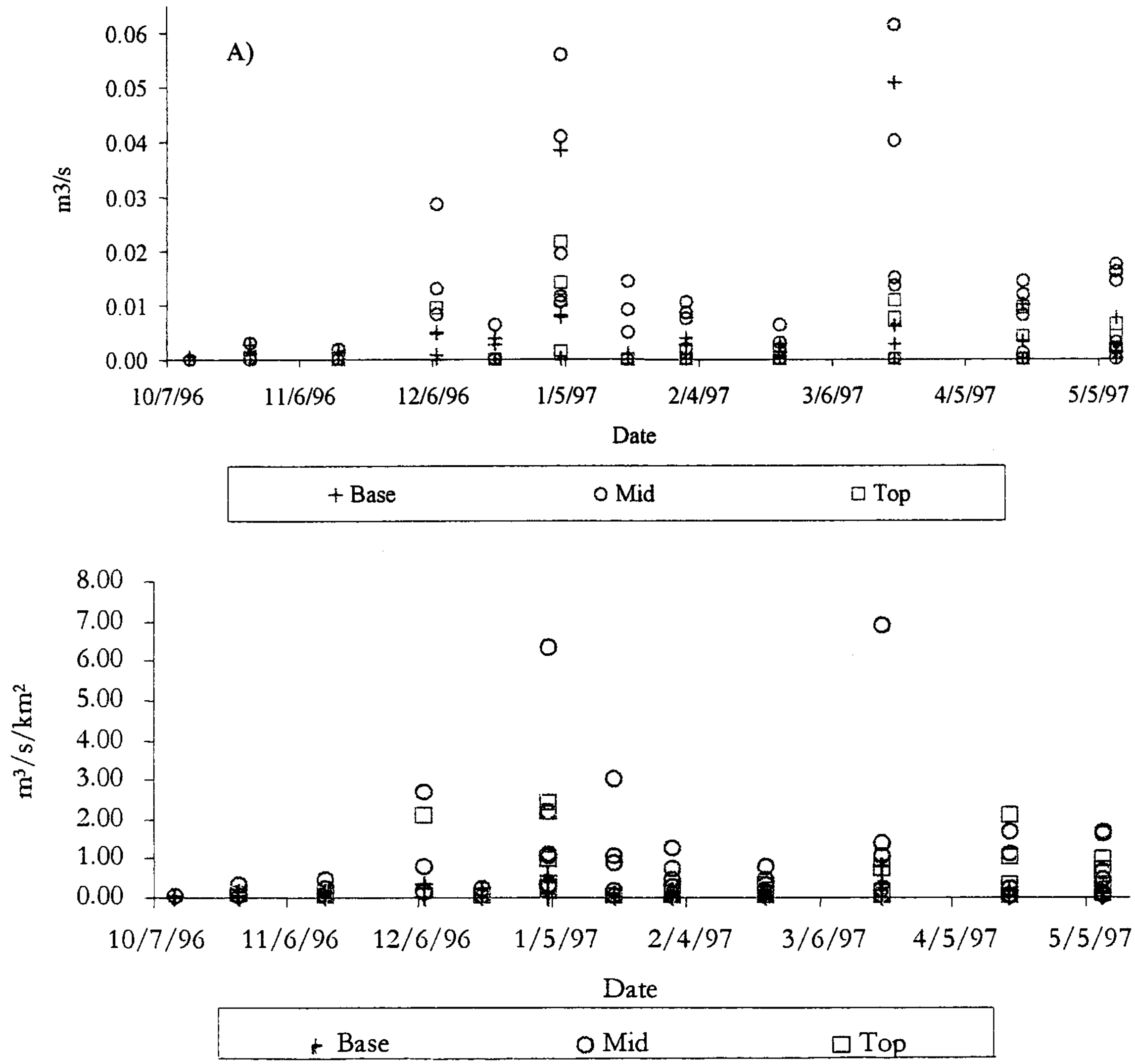


Figure 4–8: Peak Flow Response by Hillslope Position. A) Absolute Flows, B) Flow per Unit Area

4.2: Road Drainage Connectivity

The connectivity of the road drainage to the stream network determines the efficiency by which road cutslope and surface intercepted runoff are routed to the stream via culverts. There are two types of culvert installations: 1) stream-crossing culverts installed at the junctions of streams and roads, and 2) ditch relief culverts which route runoff from the drainage ditch to the outboard hillslope. At culvert locations, road intercepted runoff can either enter the stream or reinfiltrate into the soil. Figure 4-9 shows possible flow paths for cut-slope intercepted flow. Road runoff may: a) reinfiltrate into the soil directly below a ditch relief culvert, b) enter a stream directly at a stream–crossing culvert, c) reinfiltrate below a gully that does not extend to the stream channel, and d) enter a stream indirectly through the formation of a gully below a ditch relief culvert, which does extend to the stream or saturated zone near the stream.

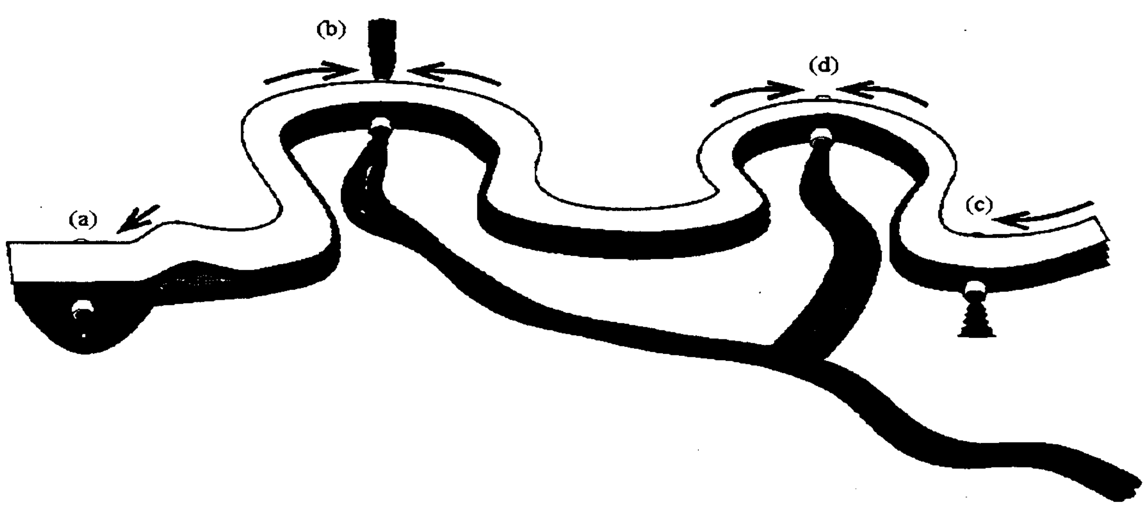


Figure 4-9: Road Drainage Connectivity to Stream Network (Wemple 1994).

In case a) or c) the road drainage is said to be "not connected" to the stream network. In case b) or d), the road network is said to be directly connected, or indirectly connected to the stream network, respectively.

4.2.1: Methods

To determine the connectivity of the road drainage to the natural stream drainage 530 of the 548 km road network in the Deschutes Basin above Road 1000 were examined by foot, mountain bike, and four–wheel drive to identify culvert locations. The remaining 18 km of roads were not accessible due to active logging in the area. At every culvert the following were recorded:

1) culvert location determined by a handheld Global Positioning System (GPS) (accurate within 2-7 meters),

2) visual estimate of uphill and downhill vegetation height taken as <2m, 2-6m, or >6m,

3) cutslope height visually estimated as either <2m, 2-6m, or >6m,

4) whether the culvert was a stream crossing as evidenced by the presence of a channel above and below the culvert,

5) soil characteristics determined as bedrock, soil, or combination of the two,

6) distance to the nearest road junction, and

7) sub–basin location of road.

In addition, if a well-defined channel was present below the culvert, but not above it, the culvert was flagged as draining to a probable gully for future reference. Locations of the 2171 surveyed culverts were exported from the GPS and subsequently imported into a

GIS package (Arc/Info) as a point coverage with attributes corresponding to the above information (Figure 4-10).

A 30–meter DEM was used in conjunction with algorithms in Arc/Info to generate planar hillslope curvatures, slopes and the stream network for the basin. For the stream network, a two-hectare source area was used to determine stream channel initiation. This method of deriving the channel network from a constant source area matched the location of observed stream channel heads and channels better than the slope-dependent critical area method, described by Montgomery and Foufoula-Georgiou (1993). In addition, the derived stream network served only as a foundation, which was adjusted based on field observations, along with stream maps provided by Weyerhaeuser, Company.

Using Arc/Info, the local hillslope curvature, slope, and downslope distance to a stream channel were found at each culvert location. In addition, the contributing road and land areas to each culvert were generated by assuming the road drainage followed the local transverse topology as the road (i.e., cutslopes are constant).

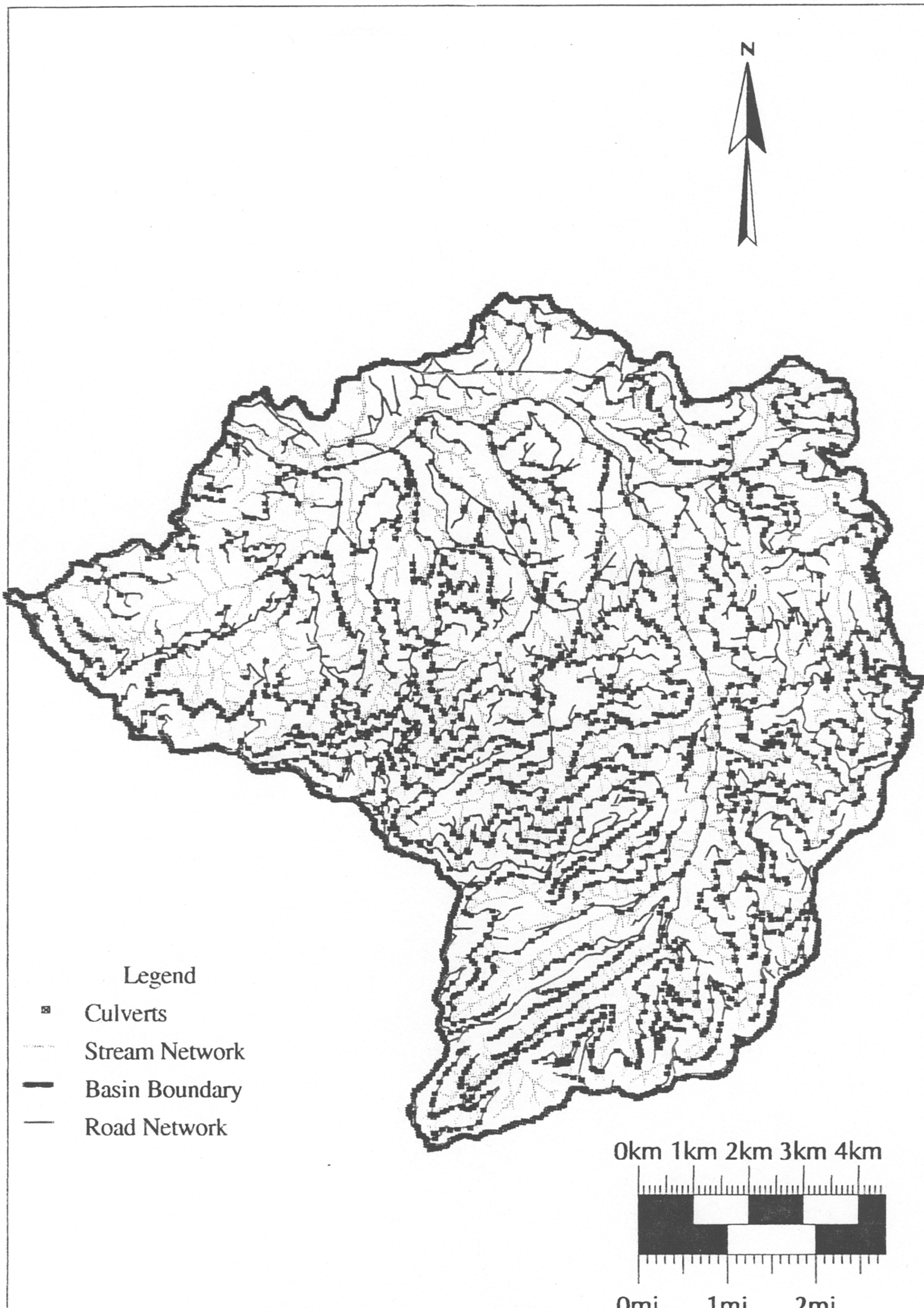


Figure 4-10: Culvert Locations, Deschutes Basin

In summary, the following information was compiled at each culvert location:

1. Hillslope curvature (i.e., convex/straight/concave in the plane of the road)
2. Slope
3. Contributing Uphill Area
4. Contributing Road Area
5. Upslope and Downslope Vegetation Height
6. Downslope Distance to a Natural Channel
7. Cutslope Height
8. Soil Thickness
9. Geology Type
10. Soil Characteristics (Bedrock/Soil/Mix)
11. Elevation

To predict the occurrence of gullies below ditch relief culverts, 22-km of the 548-km road network were sampled to evaluate ditch relief culvert connectivity. The sampled road segments were chosen based on hillslope position, underlying geology type and vegetation age, resulting in 38 road segments of varying lengths (Figure 4-11).

Figure 4-11: Road Network and Sampled Transects, Deschutes Basin

Culverts draining these road segments were classified during the summer of 1997, using the categories of Bowling and Lettenmaier (1997), which they originally adapted from Wemple (1994). These classifications are:

- Directly Connected

  1. Stream Crossing: ditch drains to a stream crossing culvert, identified by the presence of a channel above and below the culvert.

  2. Gully: ditch drains to a gully via a ditch relief culvert, identified by the presence of surface flow paths extending from the culvert outlet to a natural channel. There is no evidence of a channel above the culvert.

- Not Connected

  1. Ditch drains to a ditch relief culvert where water infiltrates into the soil as identified by the absence of surface flow paths extending to the natural channel network.

For each culvert sampled, the hillslope from the culvert outlet to the nearest downhill channel network was examined for signs of surface flow. Only if signs of overland flow (i.e., erosion) existed to a well-defined channel, was the culvert classified as connected via a gully. If evidence of overland flow existed for any distance, but did not extend completely to the natural channel, the culvert was classified as not connected. An exception to the classification was made if the surface flow extended to a flood plain, but not to the channel, in which case the drainage was then classified as connected. This exception was typically applicable only to road segments located in valleys of the lower basin.

From the culvert sampling, a multiple logistic regression was performed on the occurrence of gullying, based on the 11 characteristics taken at each culvert location. This regression was then applied to culverts surveyed and classified by Bowling and Lettenmaier (1997) for comparison. Finally, the regression was applied to the remaining culverts in the basin to predict connectivity.

4.2.2: Results and Discussion

From the sampled road segments, 140 culverts were classified for connectivity. The results are presented in Table 4-3.

Table 4-3: Culver Connectivity Results from Surveyed Road Segments

Culvert Classification	Number of Culverts	Percent of Total Culverts
Stream Crossing Culverts	39	28
Ditch Relief Culverts	101	
Connected (Gully)	39	28
Not Connected	62	44

The results are similar to findings from a survey of roads by Wemple (1994) in the Lookout Creek and Blue River catchments in Oregon. In Wemple's study, culverts were classified as being 35% stream crossings, 23% gullies, and 42% infiltrating culverts.

Based on the 11 characteristics previously described, a multiple logistic regression of the surveyed culverts was performed to predict the occurrence of connected culverts through gullies using a backward stepwise approach with a 0.05 significance level. Suprisingly, neither slope, road, nor uphill area draining to a culvert were statistically significant in determining the occurrence of gullying, in contrast to the study by Wemple. Field results of ditch flow volumes segregated by cutslope height (a surrogate for slope) reported in Section 4.1.2, support these findings. As previously suggested, this may indicate that the presence of macropore or pipeflow is more important than hillslope steepness to determine the amount of subsurface flow intercepted by a road segment and, hence, the formation of gullies below the culverts in this hydro-geologic-soil context. The non-significance of culvert drainage area may be due to the absence of road slope in the analysis. Field observations showed that runoff frequently infiltrates in ditches with low gradients. Therefore, a culvert with a large contributing area from a roads cutslope may receive little runoff due to infiltration of slow moving water in the road side ditch. Another factor influencing the significance of drainage area may be the methods used in Arc/Info to determine drainage area to the culverts. Road drainage was assumed to follow the local hillslope topography at a constant cut depth. In reality, there are frequent occurrences where a road cuts across local ridges instead of rising over them, or vice versa. In such a situation, the modeled drainage area maybe misrepresented.

Only hillslope curvature and downslope distance to the natural stream channel were found to be statistically significant ($p < .05$) in the analysis. Hillslope curvature represents the convergence or divergence of flow, both above and below a culvert. If a culvert drains to a topographic hollow (i.e., converging hillslope), flow from the culvert concentrates in the hollow, increasing the likelihood of overland flow. The opposite is true if the culvert drains to a diverging hillslope. Flow should disperse, decreasing the likelihood of overland flow. Distance to the stream represents the opportunity that flow from the culvert can reinfiltrate into the soil. The shorter the distance to the stream the more likely overland flow will reach the stream before infiltrating.

The form of the model is:

$$P(\text{Gully}) = 1/(1 + \text{EXP}(-.00337 - 2.3941 * \text{CURV} - .0071 * \text{DIST}))$$

Where DIST is the downhill distance in meters from the culvert outlet to the nearest stream and CURV is the hillslope curvature in the plane of the road. A gully was predicted to occur if $P(\text{Gully}) \geq 0.5$.

As an independent test of the statistical model's ability to accurately predict gullying, it was applied to the culverts surveyed by Bowling and Lettenmaier (1997) in Hard and

Ware Creeks. The results are shown in Table 4-4. The model accurately predicted occurrence or non–occurrence of gullying below ditch relief culverts in 59 of 73 cases (81%) surveyed in the Bowling and Lettenmaier (1997) study. The model tends to be conservative in predicting the occurrence of connectivity by gullying. That is, the model predicts the non-occurrence of gullies more accurately than it predicts the occurrence of gullies.

Table 4-4: Statistical Model Results for Predicting Gullying of Surveyed Culverts

			Predicted		Percent Correct
			Not Connected	Connected	
Observed Culvert Classification	Deschutes River Sample	Not Connected	53	9	85
		Connected	13	26	67
				Overall	78
	Hard/Ware and Ware Creek	Not Connected	46	7	87
		Connected	7	13	68
				Overall	81

The final step in the analysis was the classification of the remaining culverts in the basin. Of the 2171 culverts surveyed, 724 were classified as stream–crossing culverts from the original field survey. Of the 1447 remaining ditch relief culverts, 174 were classified from the two culvert connectivity surveys. Connectivity for the remaining 1273 ditch relief culverts was determined via the statistical model. Table 4-5 summarizes classification results for the remaining locations.

Table 4-5: Statistical Model Results for Culvert Connectivity

Sub-Basin	Total Culverts	Stream Crossing Culverts		Connected Ditch Relief Culverts		Non Connected Ditch Relief Culverts	
		Total	Percent of Total	Total	Percent of Total	Total	Percent of Total
Mitchell	277	75	27.1	55	19.9	147	53.1
Huckleberry	71	32	45.1	13	18.3	26	36.6
Johnson	97	28	28.9	18	18.6	51	52.6
Thurston	223	84	37.7	30	13.5	109	48.9
Lincoln	221	83	37.6	36	16.3	102	46.2
Thorn	61	17	27.9	8	13.1	36	59.0
West Fork	54	18	33.3	9	16.7	27	50.0
Upper Desch	153	48	31.4	34	22.2	71	46.4
Mine	54	14	25.9	7	13.0	33	61.1
Hard	69	18	26.1	13	18.8	38	55.1
Ware	42	18	42.9	6	14.3	18	42.9
Buck	59	19	32.2	9	15.3	31	52.5
Lewis	89	42	47.2	12	13.5	35	39.3
Little Desch	282	65	23.0	42	14.9	175	62.1
Other	419	163	38.9	59	14.1	197	47.0

The corresponding inferred changes to drainage density due to formation of gullies are summarized for each sub-basin in Table 4-6. Gullies formed in topographic hollows may be thought of as an uphill migration or extension of the channel heads. The length of ditch draining to each culvert was beyond the scope of the field study and is not included in the analysis. However, the modeling study presented in Chapter 5 implicitly takes into account ditches draining to connected culverts.

Table 4-6: Contribution of Gullies to Natural Drainage

Sub-Basin	Stream Length (km)	Gully Length (km)	Increase in Stream Length from Gullies (%)	Original Drainage Density (km/km^2)	Modified Drainage Density (km/km^2)
Mitchell	82.2	5.0	6.1	3.7	3.9
Huckleberry	21.9	1.3	6.0	4.1	4.4
Johnson	21.3	0.9	4.1	3.7	3.8
Thurston	50.0	2.0	4.1	4.1	4.3
Lincoln	45.1	2.5	5.5	4.1	4.4
Thorn	14.2	0.6	4.4	3.8	4.0
West Fork	15.0	0.9	6.0	3.3	3.5
Upper Desch	26.1	2.7	10.2	3.8	4.2
Mine	9.7	0.6	6.0	3.6	3.8
Hard	8.3	0.9	10.8	3.6	4.0
Ware	10.5	0.6	5.6	3.8	4.0
Buck	12.4	0.6	5.2	3.5	3.7
Lewis	18.9	0.8	4.5	4.0	4.2
Little Desch	70.0	2.6	3.7	3.5	3.6
Other	133.4	3.9	2.9	3.5	3.7
Deschutes	539	26	4.8	3.7	3.9

Chapter 5: Model Implementation

In this chapter, the application of the Distributed Hydrology-Soil-Vegetation Model (DHSVM, Wigmosta et al. 1994) to the Deschutes River Basin is described. A brief model overview, including data preparation as well as a description of the model calibration process are also included.

5.1: The Distributed Hydrology-Soil-Vegetation Model

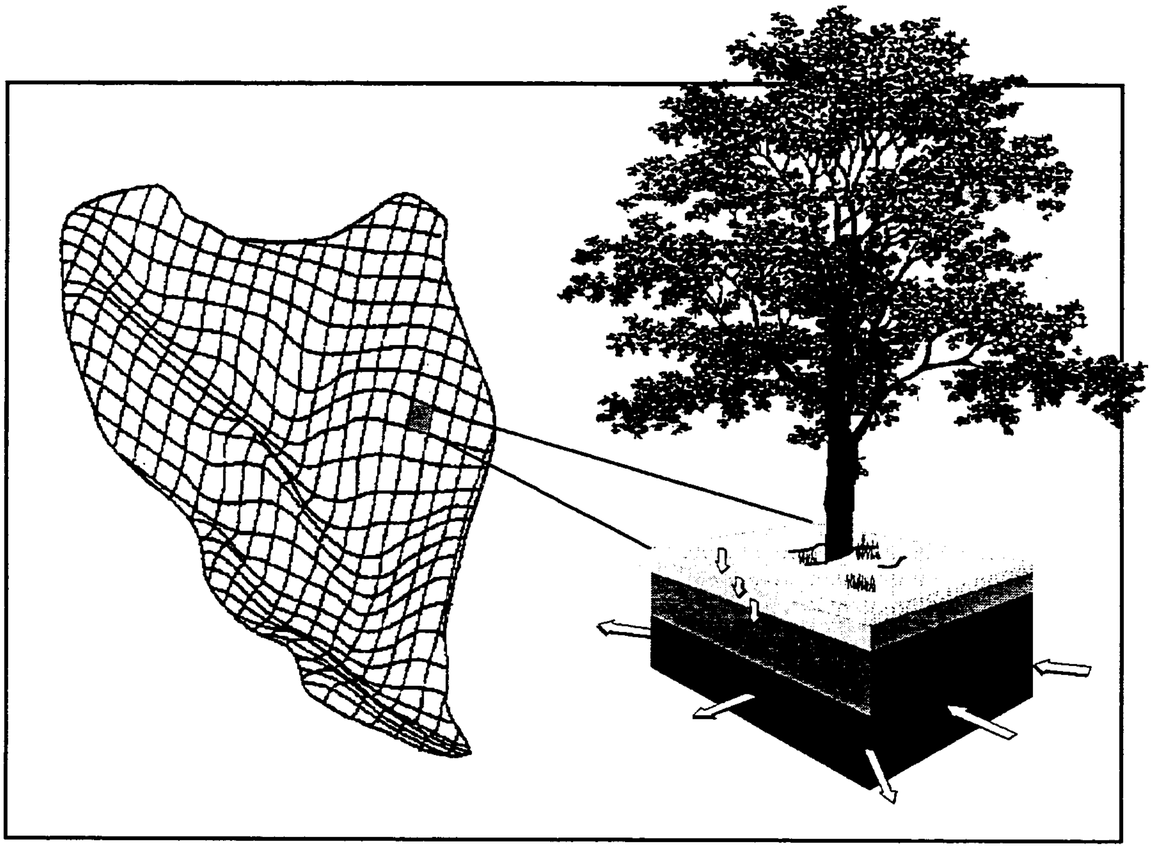
The Distributed Hydrology-Soil-Vegetation Model is a physically based, spatially distributed hydrology model that explicitly simulates the interaction of topography, soils, vegetation, meteorology, snow physics, and road networks on runoff production. The model was developed by Wigmosta et al. (1994) and later adapted for use on maritime mountainous basins by Storck et al (1995). An additional enhancement was made by Wigmosta and Perkins (1997) to include the effects of roads on runoff production in forested catchments. The road algorithm was applied to two small sub–catchments of the Deschutes River by Bowling and Lettenmaier (1997).

DHSVM is described in its original form by Wigmosta et al. (1994) and in subsequent investigations by Storck et al. (1995), Bowling and Lettenmaier (1997), and Storck et al. (1997). The model simulates interactions between soils, vegetation, meteorology, topography, and water movement by representing a catchment as discrete pixels or grid cells. Energy and mass flux can occur between each pixel and its surrounding cells, the stream/road network, and/or the atmosphere using prescribed algorithms. The model subroutines include a two-layer energy-balance algorithm to represent snow accumulation and ablation, a two-layer canopy algorithm to represent evapotranspiration, a multi-layer one-dimensional unsaturated soil flow algorithm, and a two-dimensional saturated subsurface flow algorithm.

Each pixel within the basin is assigned attributes that define the soil, vegetation and terrain characteristics of that pixel (Figure 5-1). Vegetation characteristics are represented by an understory and overstory, if present. Water intercepted by vegetation is evaporated at the potential rate, while transpiration is calculated using a Penman-Monteith approach. Both vegetation layers have rooting zones with depths that coincide with defined soil layer depths. Moisture is removed from soil layers via transpiration based on the fraction of roots specified in each layer. Soil evaporation on bare ground is predicted using the method of Entekhabi and Eagleson (1989).

Each soil type may have multiple soil layers with associated attributes such as depth, hydraulic conductivity, porosity, field capacity, and wilting point. Water travels through the soil column as either unsaturated flow according to Darcy's law to recharge the ground water table, or as saturated flow to one of its four adjacent neighbors based on elevation differences. Saturated overland flow and return flow occur when a pixel's water table intersects with ground surface.

Snow accumulation and melt are simulated using a two-layer algorithm based generally on Anderson (1968). Precipitation below a prescribed temperature threshold is assumed to fall as snow. If the pixel contains an overstory, snow is intercepted based on LAI and thereby reduced by wind and temperature conditions. Canopy snowmelt is calculated using a single layer energy balance with energy inputs from rain, net radiation, sensible and latent heat. Intercepted snow may also be removed through sublimation and mass release. Mass release is assured to occur when enough melt–water is generated for snow to slide off the canopy following the parameterization of Bunnell et al. (1985) and Calder (1990). Snow released from the canopy is added to the ground snow pack. A two-layer, energy-balance approach is used to simulate accumulation and melt of snow under the canopy or in clearings. Energy inputs are similar to that of the canopy, with the addition of throughfall or drip from the canopy. Where present, the overstory attenuates both incoming radiation and wind speed, thereby reducing snowmelt.



S9411055.2

Figure 5-1: Model Representation of Catchment Soil, Vegetation, and Topographic Characteristics as Discrete Pixels (Adapted from Wigmosta, 1994).

Runoff is routed to the basin outlet through stream channels and road ditches as open channel flow. Flow routing through the road and stream network is calculated from Arc/Info scripts prior to model simulations. These scripts register the road and stream networks to the digital terrain and calculates slopes, channel, and cutslope incisions based on prescribed stream and road parameters (e.g., width, depth, aspect) relative to the pixel topographic attributes (e.g., aspect, elevation). Subsurface and saturated overland flow from individual pixels can be intercepted by the road cutslope and stream bank based on the pixel's water table elevation relative to the channel or road cutslope bottom (refer to Figure 1-1). The portion of the subsurface flow above the bottom of the channel cut contributes to channel/ditch flow, while the rest of the flow passes beneath the channel. The model then routes flow through the channels and ditches using a Muskingum-Cunge scheme. At non-stream crossing culverts, flow in the roadside ditch is dumped onto pixels below the culvert. Here, the water may infiltrate or, if the pixel is saturated, travel as saturated overland flow. At all subsequent pixels, the water may reinfiltrate dependent on the pixel's water table depth. At stream crossing culverts, road– generated runoff is added to the flow in the stream channel. Ditch flow is also added to streams though gullies, connecting culvert outlets to the stream channel. Gullies are mapped into the stream network prior to the model run.

5.2: Model Inputs

Model inputs can be broadly classified as temporal and spatial. Spatial data are represented as pixel elements, which define the soil, vegetation, and terrain attributes of the catchment. The basin boundary is defined by a mask of pixels classified as either inside or outside the basin. For this study, Arc/Info GIS software was used to process the spatial data into 30-meter resolution pixels, which were later exported as raster files. For the upper Deschutes Basin, this translates to approximately 167,000 pixels. Other spatial data include the stream and road network. Both networks were processed in Arc/Info as line coverages and registered to the pixels containing the vegetative, soil, and elevation data. The temporal data consisted of precipitation, temperature, humidity, incoming long and short wave radiation, and wind speed at points (meteorological stations) within the basin at variable time steps from 1985 to 1997. The chosen model time step reflects a trade off between computer processing time and response time of the catchment. The time interval should be short enough to capture the catchment's hydrologic response for a storm event, but long enough to reduce computational requirements. A three-hour time step was chosen for this study. Spatial resolution also affects computing time. The 30-

meter resolution grids represent the most accurate resolution of the available spatial raw data that still enabled reasonable simulation run times. This resolution was also provides the most accurate representation of flow routing in the road and stream channels.

5.2.1: Spatial Data

A one-arc second ($\cong$ 30 m) USGS Digital Elevation Model (DEM) for Washington State was obtained to provide the necessary topographic information required for the model. The DEM was imported into Arc/Info as a grid and cropped to an area slightly larger than the basin. The grid was then processed to remove anomalous depressions and the basin was delineated using watershed analysis scripts provided in Arc/Info. The final masked DEM is shown in Figure 5-2.

Soil characteristics were obtained from the National Resource Conservation Service's (NRCS) State Soil Geographic (STATSGO) database. The data consisted of a 1-km^2-resolution polygon Arc/Info coverage. Each defined STATSGO coverage unit contained several different soil textures and associated soil layer depths. Properties of the entire units were calculated based on a weighted average from the constituent soil types. STATSGO properties associated with soil types include percentage of organic, sand, silt, clay, and gravel, permeability, available water capacity, and soil layer depth. Soil parameter derivations follow Bowling and Lettenmaier (1997) and are listed in Table 5-1. The areal extent of the soil types is shown in Figure 5-3.

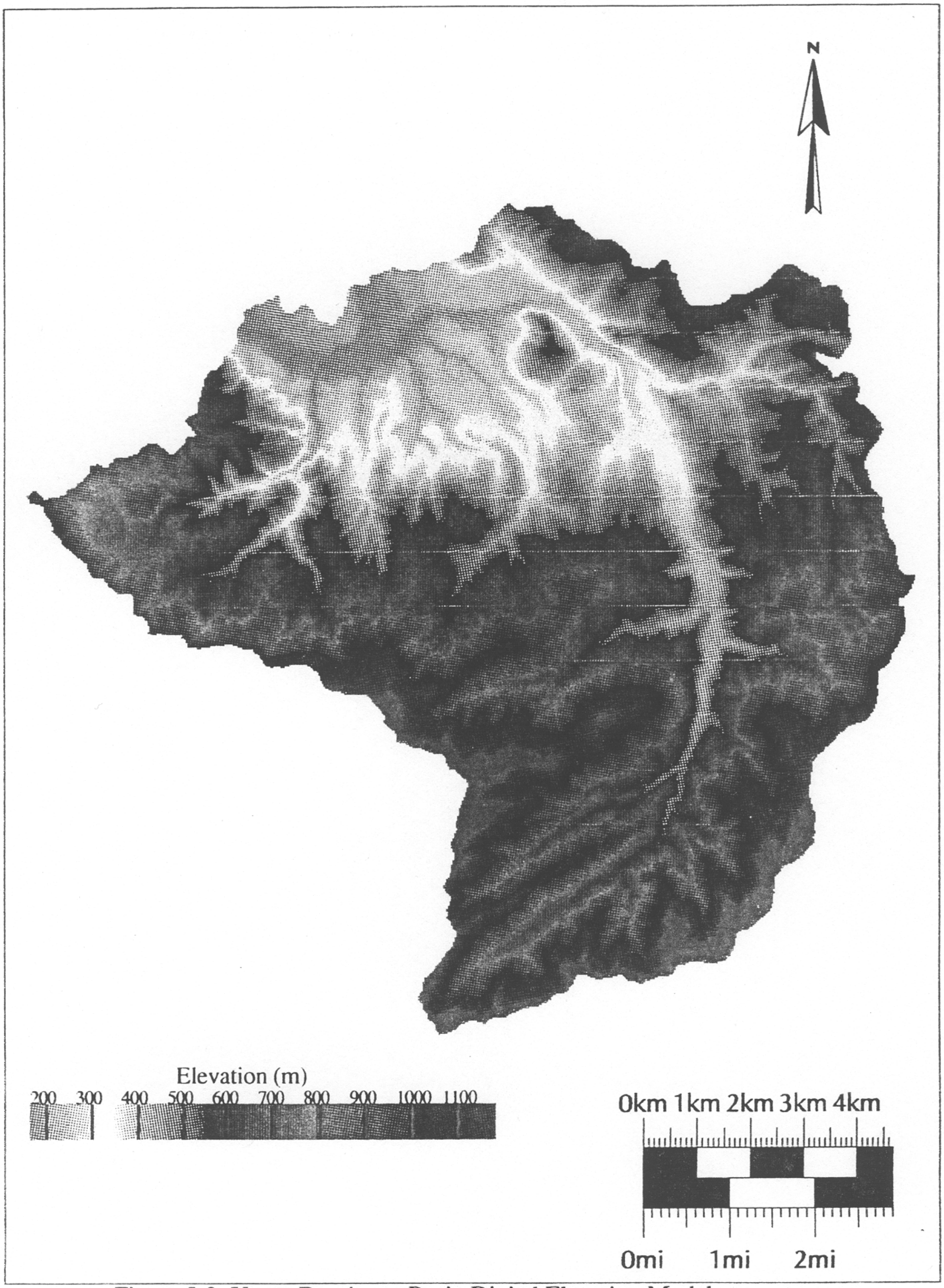


Figure 5-2: Upper Deschutes Basin Digital Elevation Model

Table 5-1: Soil Parameters

Soil Type	lower depth	upper depth	% organic	% clay	% sand	% silt	% gravel	USDA Text	porosity (%)	Bulk Density (kg/m^3)	Vert Sat Hyd Cond (m/s)	Pore-Size Index	Air Bubbling Pressure	Field Capacity	Wilting Point
Soil Class 1															
Layer 1	0.0	0.1	4.9	2.9	33.2	26.1	30.8	Gravely Sandy Loam	0.50	1.3	2.0E-05	0.38	0.13	0.21	0.08
Layer 2	0.1	0.7	1.1	4.8	22.4	19.6	45.0	Very Gravely Silt Loam	0.45	1.5	2.6E-05	0.35	0.12	0.33	0.12
Layer 3	0.6	1.5	6.5	4.1	18.1	10.2	61.0	Very Gravely Coarse Sand Loam	0.40	1.6	9.9E-05	0.35	0.10	0.21	0.15
Soil Class 2															
Layer 1	0.0	0.3	7.4	20.8	43.3	17.6	10.9	Gravely Silt Loam	0.53	1.2	9.3E-06	0.31	0.17	0.33	0.13
Layer 2	0.3	0.7	2.0	13.2	37.1	24.3	19.0	Gravely Silty Clay Loam	0.49	1.4	9.3E-06	0.28	0.29	0.37	0.15
Layer 3	0.7	1.2	0.8	13.2	22.2	30.2	27.0	Very GravelyClay	0.44	1.6	9.3E-06	0.27	0.24	0.32	0.15
Soil Class 3															
Layer 1	0.0	0.2	7.1	27.4	40.4	5.3	16.7	Gravely Silt Loam	0.48	1.4	1.3E-05	0.32	0.11	0.27	0.08
Layer 2	0.2	0.6	2.3	22.2	37.5	8.0	24.0	Very Gravely Silt Loam	0.53	1.2	8.5E-06	0.32	0.12	0.33	0.10
Layer 3	0.5	1.0	0.0	14.1	31.6	6.8	35.0	Very Gravely Silt Loam	0.53	1.2	2.8E-05	0.32	0.11	0.27	0.11
Soil Class 4															
Layer 1	0.0	0.3	7.4	20.2	69.6	6.2	3.0	Silt Loam	0.56	1.1	1.1E-05	0.35	0.28	0.32	0.05
Layer 2	0.3	0.6	0.2	14.7	71.0	9.5	4.0	Silt	0.53	1.2	2.1E-05	0.34	0.32	0.32	0.07
Layer 3	0.6	1.2	0.0	16.7	72.2	7.7	2.0	Silt	0.56	1.1	3.1E-05	0.35	0.31	0.27	0.18
Soil Class 5															
Layer 1	0.0	0.2	9.6	16.0	49.3	0.0	25.0	Gravely Silt Loam	0.55	1.2	7.6E-06	0.36	0.20	0.32	0.07
Layer 2	0.2	0.5	3.4	13.4	47.4	0.0	25.0	Very Gravely Silt Loam	0.55	1.2	7.6E-06	0.34	0.20	0.32	0.07
Layer 3	0.5	0.9	1.5	11.1	33.4	0.0	41.0	Cobbly Silt Loam	0.58	1.1	7.6E-06	0.35	0.20	0.39	0.08

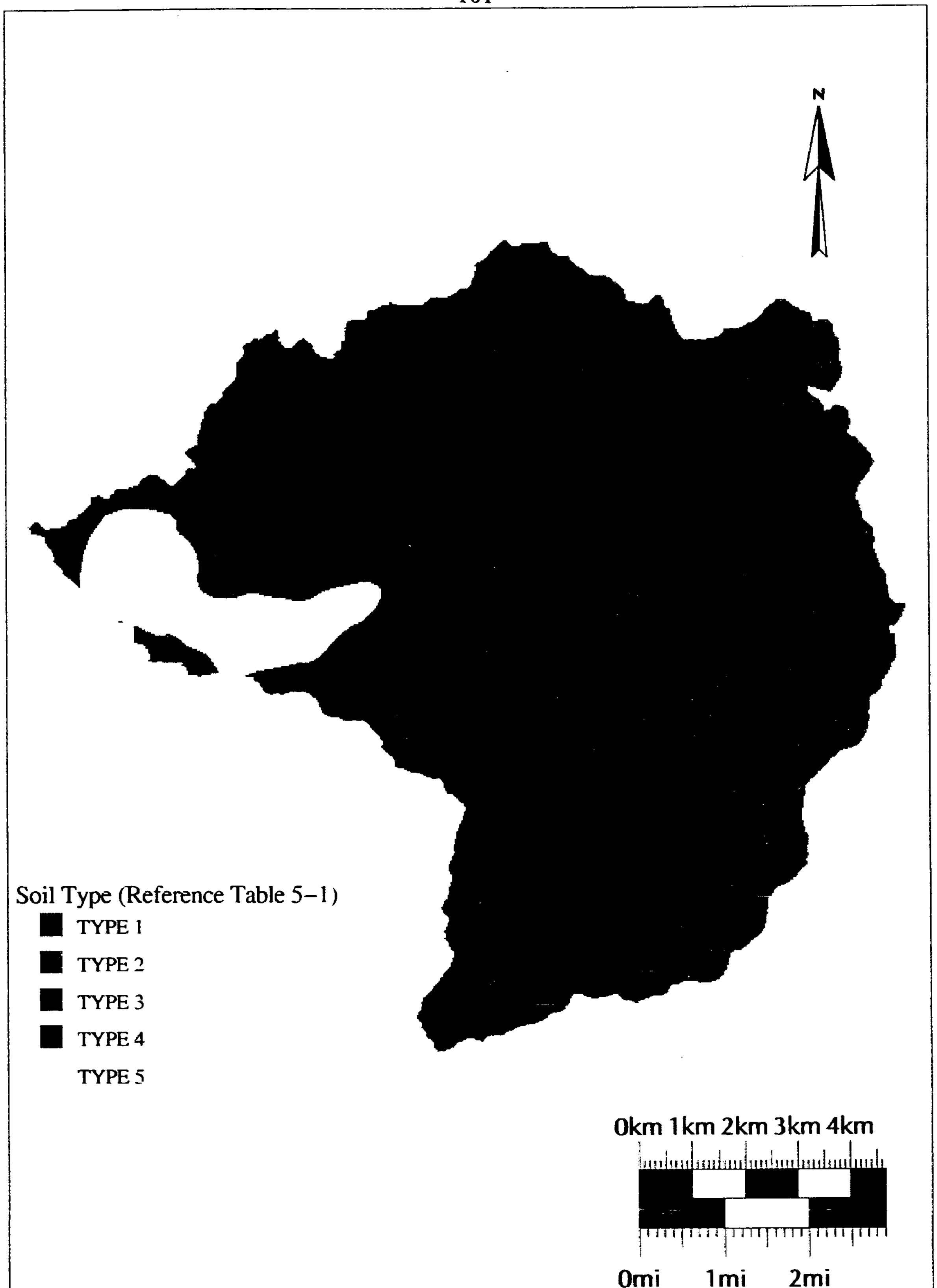


Figure 5-3: Upper Deschutes Basin Soil Types

Vegetation data consist of overstory and understory characteristics for each pixel. Arial extent of forest stand boundaries along with attributes of LAI, tree height and fractional coverage values for 1996, were provided by Weyerhaeuser Company as Arc/Info polygon coverage. The LAI values were calculated by scaling maximum LAI at specified tree heights to the 1996 tree height. Vegetation types were grouped together based on stands with similar attributes resulting in 17 final classes (Figure 5-4). General class attributes were calculated based on the weighted average of the constituent vegetation types and are listed in Table 5-2.

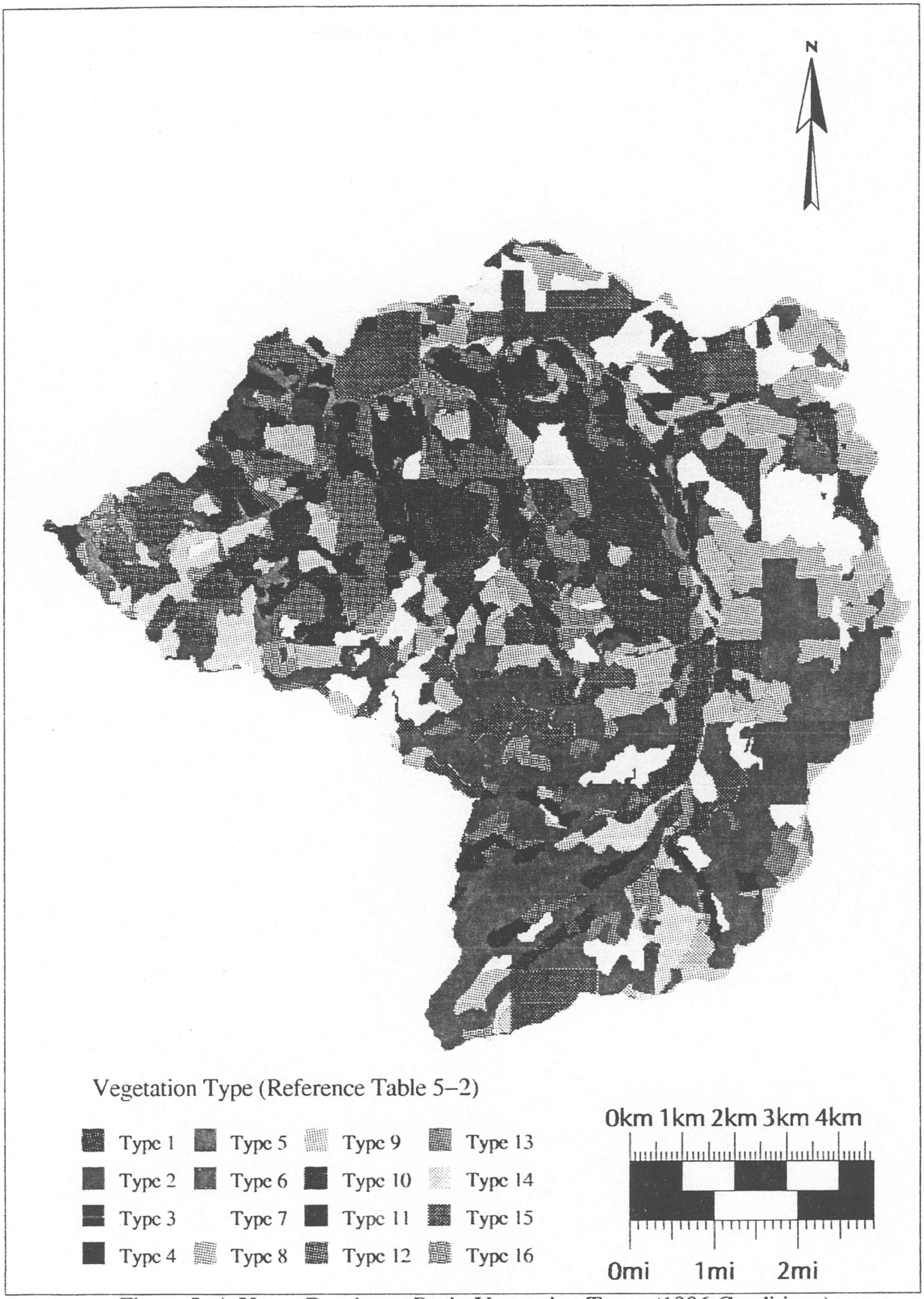


Figure 5–4: Upper Deschutes Basin Vegetation Types (1996 Conditions)

Table 5-2: Vegetation Parameters

Overstory

Parameter	Vegetation Class (Classes 1-3 have no overstory)													
	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Fractional Coverage	0.90	0.90	0.08	0.27	0.43	0.60	0.82	0.90	0.90	0.68	0.90	0.22	0.80	0.90
Height (m)	9.0	21.7	2.3	5.7	8.9	12.6	17.2	23	29	9.4	23.8	3.2	12.2	28.6
Summer LAI	7.20	7.20	2.2	3.8	5.1	6.5	8.4	9.0	9.0	9.0	16.0	4.21	11.5	12.7
Winter LAI	1.50	1.50	2.2	3.8	5.1	6.5	8.4	9.0	9.0	9.0	16.0	4.21	11.5	12.7
Overstory Root Fraction in Soil layer 1	0.30	.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.24
Overstory Root Fraction in Soil layer 2	0.50	.36	0.50	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.43
Overstory Root Fraction in Soil layer 3	0.20	.33	0.20	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.34
Understory Root Fraction in Soil Layer 1	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.48
Understory Root Fraction in Soil Layer 2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.35
Understory Root Fraction in Soil Layer 3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.17

Constants

Parameter	Understory	Overstory
Height (m)	0.3	-
Summer LAI/Winter LAI	2.175	-
Radiation Attenuation Coefficient	-	0.1
Vapor Pressure Threshold for Stomatal Closure (Pa)	4000	4000
Maximum Resistance (Pa)	5000	1000
Minimum Resistance (Pa)	250	333.3
Fractional Trunk Space	-	0.50
Surface Albedo	0.20	0.18
Aerodynamic attenuation coefficient	-	1.0
Transpiration Limiting Moisture Threshold	0.13	0.33

5.2.2: Temporal Data

Temporal data consist of time series of meteorological conditions at specified station(s) within the basin. The meteorological records include air temperature, relative humidity, wind speed, vapor pressure, precipitation, and solar radiation at a prescribed reference height above the canopy.

Although temperature was observed at several locations within the basin, precipitation was only recorded at the Ware Creek gauge (see Figure 3-2). Therefore, meteorological data were assembled only at this site. Bowling and Lettenmaier (1997) constructed data records at this location from the fall of 1985 to the spring of 1996 at two-hour time steps. For this study, the time-step was increased to 3-hours, as a compromise to reduce computational time associated with simulating a much larger area (150 km^2 versus 5 km^2 in Bowling and Lettenmaier, [1997]). In addition, the records were updated to include the 1996-97 water year. In general, the approach used to construct the meteorological records closely followed Bowling and Lettenmaier (1997), and most of the material in this section is taken from that source.

Precipitation at the Ware Creek gauge was provided by Weyerhaeuser Company between 1985 and 1997. Data were collected at variable time intervals ranging from 12 minutes to 2 hours. All data were aggregated to 3-hour intervals. Data that bridged intervals was partitioned evenly between the intervals. Data were missing for February 12-13, 1991 and the gauge malfunctioned between November 1988 and October 1989, as well in March 1997. Data during these periods were replaced using a normal-ratio method from four regional stations, as described by Bowling and Lettenmaier (1997):

$$P_{wc} = \frac{1}{4}\left(\frac{N_{wc}}{N_A} \cdot P_A + \frac{N_{wc}}{N_B} \cdot P_B + \frac{N_{wc}}{N_C} \cdot P_C + \frac{N_{wc}}{N_D} \cdot P_D\right)$$

Where P_{wc} represents the precipitation at Ware Creek. N_x and P_x represent the normal annual precipitation and the time-step precipitation at the four regional locations, respectively. The regional precipitation stations (Olympia Airport, Cinebar, Rainer CR, and Longmire) were all located in southwestern Washington.

Air temperature was averaged over the 3-hour periods from hourly and half-hourly data recorded at the Ware Creek gauge between 1989 and 1997. Prior data was filled in by scaling temperatures from the Olympia Airport by the ratio of monthly mean temperatures between Ware Creek and Olympia stations calculated between 1989-1996 (Bowling and Lettenmaier, 1997). An average lapse rate of –5.5 C/km was calculated between the Cougar Mountain meteorological station (see Figure 3-2) and the Ware Creek gauge from the available data (January 1995 to June 1996). Although inversions occur in the basin (Bowling and Lettenmaier, 1997), they do not generally occur during precipitation events and ROS events when temperature is critically important.

Humidity was calculated using daily minimum temperature as a substitute for dew point temperature according to the equation (Maidment, 1992):

$$RH = {}^{e}\!/_{e_s} = {}^{\exp\left(\frac{17.27T_{\min}}{237.3 + T_{\min}}\right)}\!\Big/_{e_s}$$

Where T_{min} is the minimum daily temperature (°C) and e and e_s is the vapor pressure (Pa) and saturated vapor pressure (Pa), respectively.

Longwave radiation was estimated from air temperature following Bras (1990) as:

$$I_l = U_c E_a \sigma T_a^4$$

Where T_a represents the local air temperature (K) at the given time step, U_c is the day cloudiness factor, σ is the Stefan-Boltzmann constant (5.67 x 10^8 W/m^2K^4) and E_a is the atmospheric emissivity. The cloudiness factor is determined by the fraction of sky covered by clouds (N) from Bras (1990):

$$U_C=1+0.17N^2$$

Although cloud cover was not available, it may be estimated from daily T_t and clear sky transmittance T_{cs} (Gates 1980, Bras 1990):

$$N=\sqrt{\frac{1.0}{0.65}\left(1-\frac{T_t}{T_{CS}}\right)}$$

where T_{cs} is the clear sky transmissivity typically taken as 0.72. T_t is the daily transmittance which can be estimated from Bristow and Cambell (1984):

$$T_t = A\left[1-\exp\left(-B\Delta T^C\right)\right]$$

where ΔT is the daily range of air temperature, and A, B, and C, are empirical coefficients described by Bristow and Campbell (1984). In the Seattle/Tacoma area, A and C were found to be 0.72 and 2.4 respectively, while B was calculated from monthly mean delta T as:

$$B = 0.036\exp\left(-0.154\overline{\Delta T}\right).$$

Finally, atmospheric emissivity needed to calculate longwave radiation is given as:

$$E_a = 0.7 + 0.0000595 \cdot e \cdot \exp(1500/T_a)$$

where e is vapor pressure in millibars.

Incoming short wave radiation is affected by shading and reflections from the surrounding terrain. DHSVM accounts for these effects with short wave radiation maps, which give unique values of diffuse and direct beam radiation at each pixel. The radiation maps were created prior to the model runs for each of the12 months using SOLARFLUX algorithms (Rich et al. 1995) in Arc/Info. SOLARFLUX calculates incoming direct and diffuse radiation based on the pixels latitude, longitude, slope, aspect, elevation, Julian day, and time of day for each pixel.

Wind speed was estimated using data from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project, as described by Bowling and Lettenmaier (1997). The archived reanalysis data represent optimal combinations of atmospheric model predictions and observations for U and V wind components at specified levels in the atmosphere. The reanalysis values, which were given at 17 pressure levels at a 2.5 degree latitude-longitude resolution and a 6-hour time step, were linearly interpolated using 700, 850 and 925 mbar elevations to Cougar Mountain using the four nearest reanalysis fields. The longitudinal vectors were interpolated first, followed by the latitudinal vectors, and finally the vertical components. Wind within the Deschutes Basin was assumed to follow that at Cougar Mountain. That is, the wind was assumed spatially consistent throughout the basin.

5.2.3: Network Data

Network data consists of the stream and road drainages that are used for simulating interception and redirection of subsurface flow and surface runoff by road cuts and stream channels (Wigmosta and Perkins, 1996; Bowling and Lettenmaier, 1997). The stream network was defined using Arc/Info "watershed analysis" scripts. These Arc Macro Language (AML) scripts use the elevation grid (DEM) to define flow direction and uphill contributing area for each pixel in the basin. Stream channel heads were defined at pixels with at least a two-hectare source area, as in Bowling and Lettenmaier (1997). These channel heads were then modified from field observations obtained from the culvert survey described in Chapter 4. Gullies were added to the derived stream channel coverage as arcs connecting culvert outlets to the nearest downhill stream channel along the flow direction. The location of gullies were estimated from the regression model described in Chapter 4. Culverts were located using a GPS system described earlier. The road network was supplied as an arc coverage by the Weyerhaeuser Company.

AML scripts written by Wigmosta and Perkins (1997) were used to further process the stream network in Arc/Info using the DEM. These scripts divided the networks into a series of connected reaches segregated by stream junctions; each associated with one or more grid cells. An AML script sampled pixel elevations along each reach, which was then used to calculate local slopes, flow directions, and rank the reaches for proper flow routing. Each stream reach was assigned a class based on its Strahler stream order. These orders relate to physical parameters of the channel width, depth, and roughness (Table 5-3). Roughness parameters were estimated by visual comparison of channel characteristics to examples in Barnes (1967). Width and depth estimates were based on field observations at representative stream order locations.

Table 5-3: Channel Parameters

Strahler Order	Bankfull Channel Width (m)	Channel Depth (m)	Manning's Roughness
1	0.5	0.25	.075
2	1.0	0.35	.070
3	2.5	0.5	.065
4	3.5	1.00	.060
5	5.5	2.50	.055
6	8.0	3.00	.050
Gullies	0.25	0.10	.150

The same set of AML scripts were used to process the road network. However, road segments were not only delimited by junctions, but also by culvert locations and divides located within the road network. Road slopes and flow directions were obtained as previously described—by sampling the elevation grid along the roads every one and one half pixels. Sinks and divides within the network were identified by local road slope sign changes. This process not only produced divides, but also many sinks between culverts. Figure 5–5 is a typical example of sinks located at non–culvert locations (see arrows). The field observations (Chapter 4) indicated that sinks in the road drainage rarely occur, except at culvert locations.

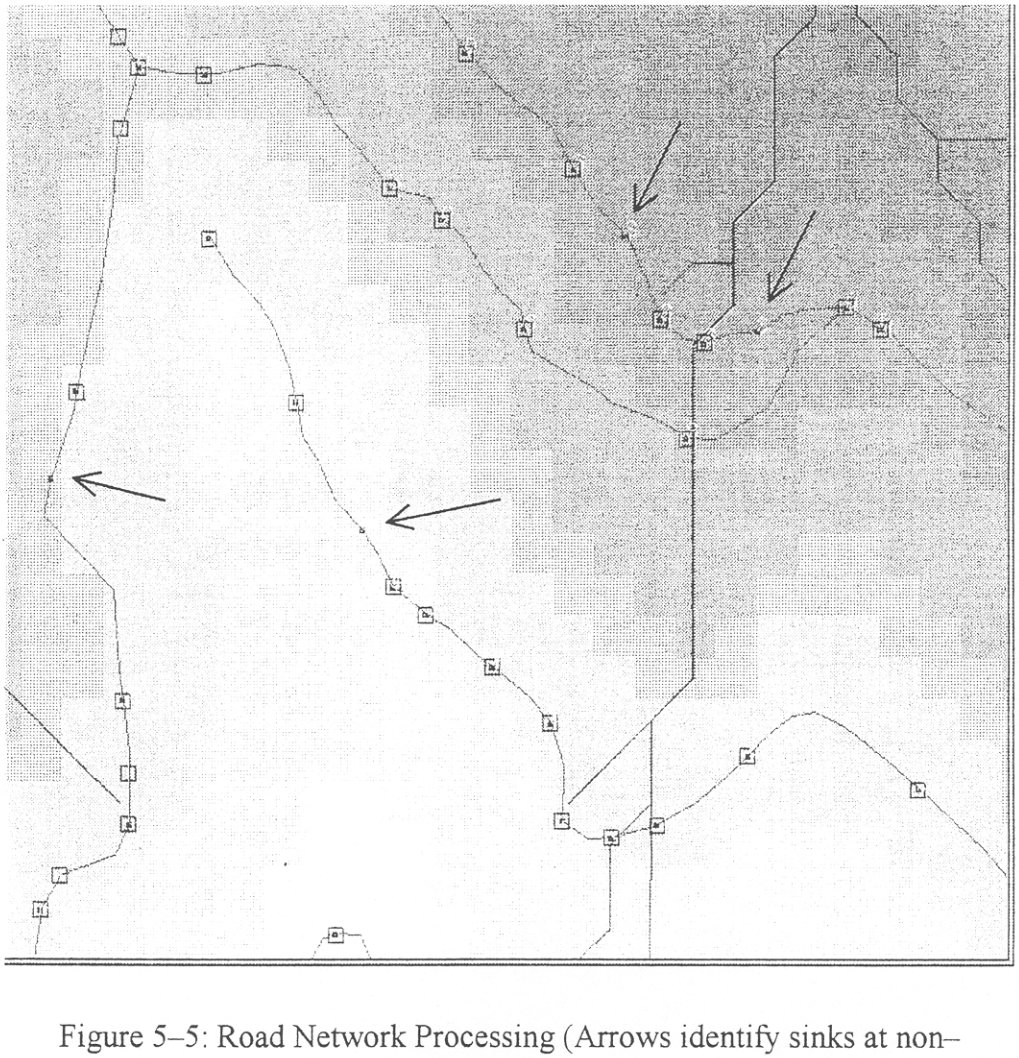


Figure 5–5: Road Network Processing (Arrows identify sinks at non–culvert locations)

Therefore, all sinks not occurring at culvert locations were deleted and the segment lengths and local slopes updated. Figure 5-5 shows the original processed roads with blue squares representing sinks and divides labeled as S and D, respectively. The green boxes represent the updated road segments as delineated by culvert locations and divides with intermediate sinks removed. The occurrence of non-culvert sinks is an artifact of the method used to process the road slopes—that is, the assumption that the road surface is at the same elevation as the corresponding pixel. Effectively, the roads are draped over the DEM following local ridges and valleys. In reality, roads often cut across ridges to maintain a uniform road gradient. Deleting these intermediate sinks produced several road segments delineated by two successive divides with an undetermined flow direction (Figure 5-5). For these sections, sinks were added back into the segments based on the local minimum elevation, so that no road segment had an undefined drainage location. This process was performed at approximately 200 of the 3652 road segments. The majority of these segments were located along ridge tops where little sub-surface flow would be intercepted by the road cutslope. Therefore, these adjustments are not expected to have much effect on the model–predicted flows.

The processed segments were assigned road surface width, ditch roughness, ditch depth, and ditch width parameters based on three classes segregated by hillslope position. These attributes were estimated based on field observations. Roads within 150 meters of a third or greater order stream channel were assigned as Class 1, while roads within 150 meters of the ridgetops were assigned as Class 3. All other roads were assigned as Class 2. Road width was used to calculate cutslope height and width using Arc/Info scripts based on the segments aspect, slope, and width of the road surface relative to the pixel slope and aspect, as described by Wigmosta and Perkins (1997). The final parameters are list in Table 5-4.

Table 5-4: Ditch Parameters				
Road Class	Ditch Width (m)	Ditch Depth (m)	Road Width (m)	Cutbank Rise/Run (m/m)
1	1.0	0.20	8.5	0.79
2	1.0	0.32	6.0	1.4
3	1.0	0.45	6.0	0.79

5.2.4: Basin Parameters

Some parameters were not varied spatially or temporarily due to limited data or model limitations. Several of these parameters were adjusted during model calibration, discussed in later sections. The initial values were set to estimates based on Storck et al. (1995) and Bowling and Lettenmaier (1997). These parameters are listed in Table 5-5.

Table 5-5: Constant Value Basin Parameters	
Parameter	Value
Ground Roughness (m)	0.01
Snow Roughness (m)	0.03
Rain Threshold (minimum temperature for rain [^{o} C])	-0.5
Snow Threshold (maximum temperature for snow [^{o} C])	0.5
Snow Water Capacity (Fraction)	0.03
Reference Height (m)	90.0
Rain LAI Multiplier (for rain interception)	0.0005
Snow LAI Multiplier (for snow interception)	0.00085
Minimum Snow Threshold which must be melted (m)	0.005
Temperature Lapse Rate (^{o} C/m)	-0.0055
Precipitation Lapse Rate (m/m)	0.000358
Grid Resolution (m)	30
Lateral Hydraulic Conductivity (m/s)	0.002
Exponential Decrease in Lateral Hydraulic Conductivity	2.0

5.3: Model Calibration

Although DHSVM is a physically based model, some calibration is required since uncertainty inevitably exists in estimates of the input parameters. However, recognizing the physical basis of the model, only those parameters that are most uncertain were varied (i.e., are not as well related to physical catchment characteristics). The varied parameters were the snow–rain threshold temperature, lateral hydraulic conductivity, exponential decrease in hydraulic conductivity with depth, cutslope height, wilting point, and leaf area index. The period between October 31, 1994 and June 29, 1997 was chosen for calibration. This period includes several large peak flows and contains the period for which culvert discharge estimates were made. Prior to the calibration period, a basin–wide simulation was made between October 31, 1992 and October 31, 1994. This was done to remove biases associated with the initial conditions (model state) of soil moisture, snow conditions, and intercepted precipitation conditions needed to start the model. The initial conditions for this "spinup" phase were set to 0.0 meters of SWE, 0.0 meters of canopy water storage, and soil moisture equal to roughly half of field capacity. These settings represents typical hydrologic conditions for catchments of the western Cascades in early fall. At the end of model spinup simulation, a new model state condition was output on October 31, 1994, representing the initial conditions for the calibration period. Discharge records obtained from Weyerhaeuser Company at Ware, Hard, and Deschutes sites shown in Figure 3-2, were used in conjunction with field estimates of culvert discharge and snow levels for model calibration. Model calibration followed the procedure described by Bowling and Lettenmaier (1997) modified to the following order:

- water balance check in the basin (simulated versus observed annual flows),
- general calibration of observed and predicted snowlines in Hard and Ware Creeks,

- check of predicted and observed ditch flows, and
- calibration of observed and predicted hydrographs at Ware, Hard, and Deschutes gauges.

5.3.1: Catchment Water Balance

A water balance analysis was performed for the Deschutes Basin using base parameters from the calibration period of October 31, 1994 to October 31, 1996. The initial parameter set simulated an annual evapotranspiration (ET) rate of roughly one–meter per year, which is high by a approximately a factor of two for catchments in the western Cascades. The initial simulation also overpredicted annual flows by about 30 percent, compared to observed flows. Long term soil moisture changes were small, as indicated by comparison of simulated ET plus predicted outflow less average catchment precipitation. Therefore, it was concluded that changes in soil moisture storage did not account for the mass balance error between predicted and observed flows. Furthermore, because simulated evapotranspiration rates appear to be high and simulated outflows were overpredicted, the modeled precipitation distribution in the basin appeared to be upwardly biased. The precipitation was based on a single gauge within the basin and a simple elevation lapse–rate. Therefore, it was considered likely that the modeled precipitation distribution was probably responsible for the overpredicted streamflow.

In an attempt to better represent the precipitation spatial distribution, annual average precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) was obtained for Washington State. The PRISM data, in the form of a gridded annual precipitation map, were developed by Daly et al (1994) from point data and topography to account for orographic effects on precipitation. PRISM accounts for variations in the relationship between precipitation and elevation on a hillslope based on its location and orientation relative to other topographic features. The Washington State data were clipped to the basin area (Figure 5-6). The annual PRISM precipitation values were divided by the Ware Creek annual precipitation to obtain an area scaling factor which was used to scale the 3-hourly Ware Creek gauge precipitation over the entire basin.

Initial hydrograph results using PRISM compared to the constant lapsed precipitation method for a winter storm in 1995 were greatly improved (Figure 5-7). The PRISM-based precipitation map reduced average annual precipitation over the basin from 3.3 meters to 2.3 meters per year. A recalculation of the basin water balance indicated that overall flows were now underpredicted by about 10 percent. Since evapotranspiration rates were still overpredicted, the LAI values for all vegetation classes were reduced by 20 percent. As indicated by Bowling and Lettenmaier (1997), this variation is consistent with the uncertainty associated with scaling LAI values based on tree height. However, scaling down LAI values only decreased the yearly evapotranspiration to 0.9 meters per year, which is still high for this area. A further reduction in LAI values seemed extreme when compared to values from similar modeling studies of Storck et al. (1995) and Bowling and Lettenmaier (1997). Therefore, a further reduction in evapotranspiration was obtained by increasing the soil wilting point to 0.16 for all soil layers. This produced annual average ET rates of 0.6 meters and annual simulated basin flows of 1.64 meters, which are within 3 percent of annual observed flows.

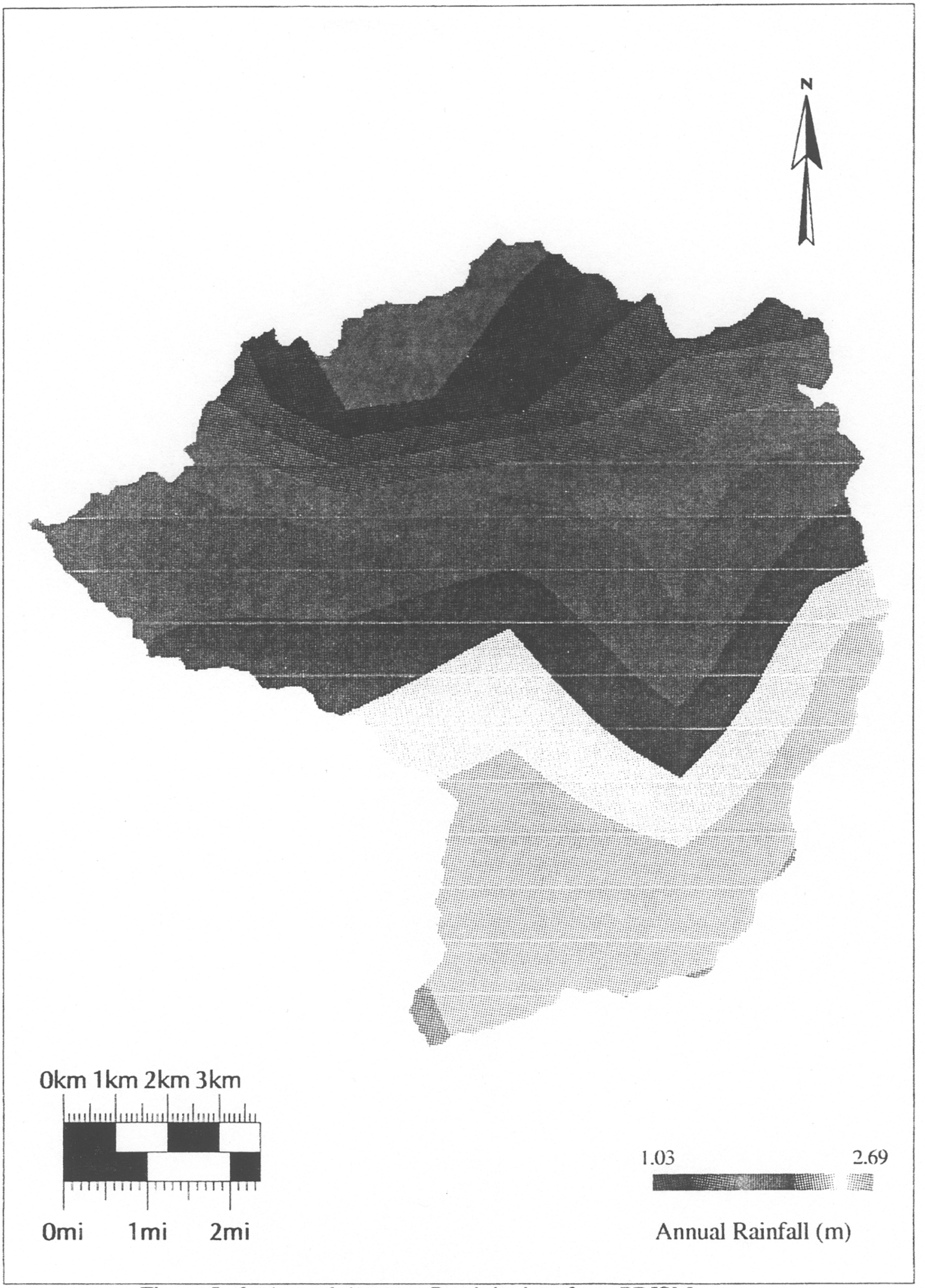


Figure 5–6: Annual Average Precipitation, from PRISM

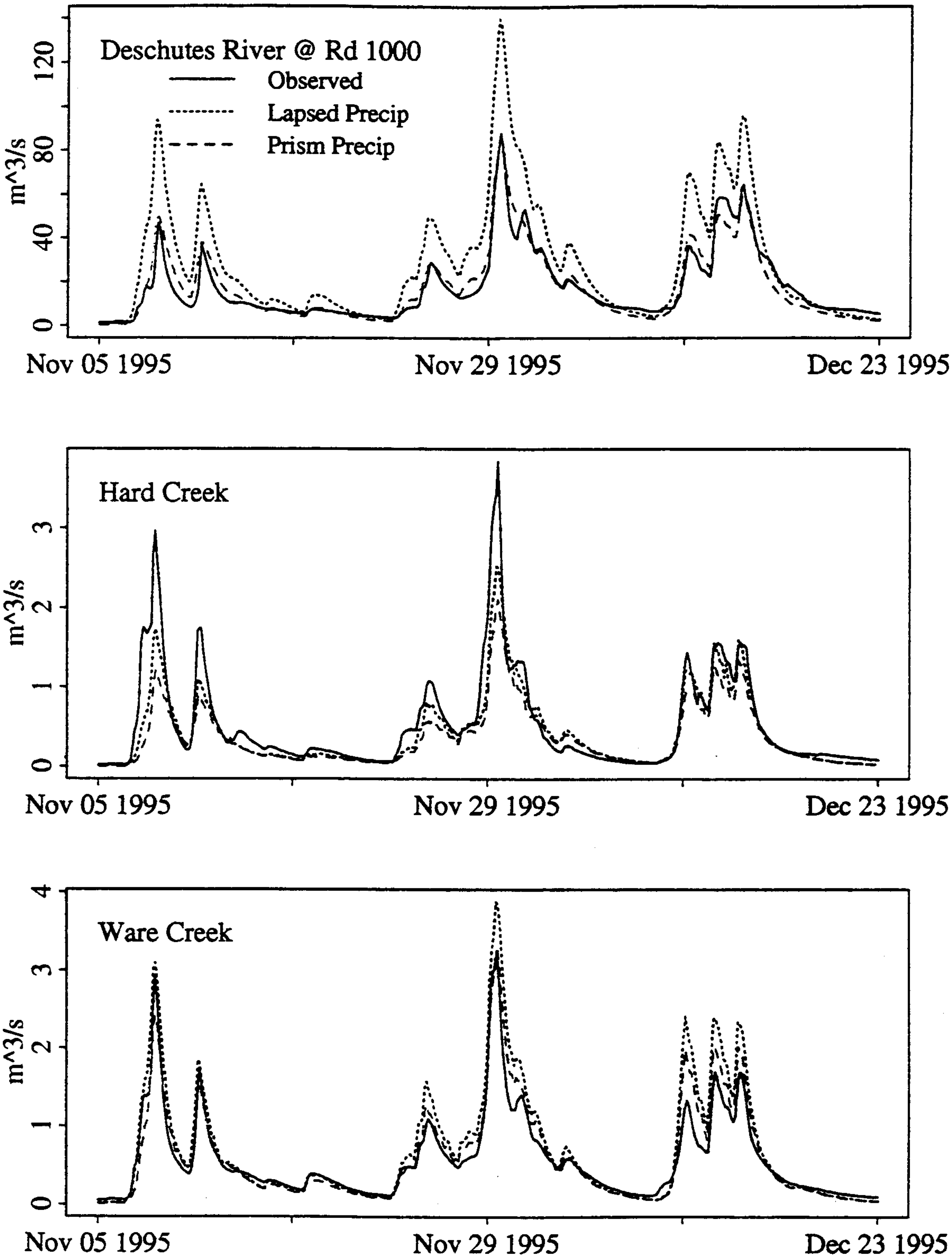


Figure 5-7: Simulated Hydrographs Using Lapsed Precipitation and PRISM Precipitation

5.3.2: Snow Calibration

The next step in model calibration consisted of comparing observed snowlines to predicted SWE in Hard and Ware Creeks. Snow line elevations were visually estimated in Hard and Ware Creeks during six field visits between the fall of 1996 to the spring of 1997. The estimation consisted of noting the culvert location(s) where snow was first encountered, then extrapolating the snow line to the remaining areas of Hard and Ware basins based on the culvert(s) elevation. In addition, snow level estimates from Bowling and Lettenmaier (1997) were included in the analysis for January 1, March 27, and April 27, of 1996. Collectively, these snowlines were compared to the simulated spatial distribution of ground SWE.

Simulated snow accumulation and ablation depends on net radiation, wind speed, canopy cover, snow roughness, temperature lapse rate, precipitation lapse rate, and rain and snow temperature thresholds. Of these parameters, the predicted snow lines appeared to be most sensitive to rain and snow temperature thresholds, which also have a moderate level of uncertainty. The rain threshold temperature is the temperature above which all precipitation falls as rain. The snow threshold temperature is the temperature below which all precipitation falls as snow. In between these temperatures, precipitation is a mixture of rain and snow which is estimated by linearly interpolating between the rain and snow threshold temperatures. These values were set to initial estimates from Bowling and Lettenmaier (1997) of –1.5 C and 0.5 C for the rain and snow thresholds, respectively.

Using these thresholds, the model underpredicted estimated snowlines (predicted snowlines were above estimated snowlines from field observations). The rain threshold was iteratively increased to a final value –0.25 C. A comparison of observed snow levels and simulated SWE is shown in Figure 5-8. Observed snowlines are represented as a solid line. The simulated snowlines compared favorably to the observed snowlines in the late fall and winter. Spring snow levels tend to be underpredicted, but this may be a result of using a constant elevation to extrapolate the observed snow level to the sub-basins. This "observed" snow level would not capture the dynamics of varying snow levels from topographic shading and differences in vegetation. Another cause of underprediction of spring snow levels might be from overpredicting radiation dominated spring snowmelt. However, in general, this comparison shows the DHSVM simulates snow accumulation and ablation reasonably well.

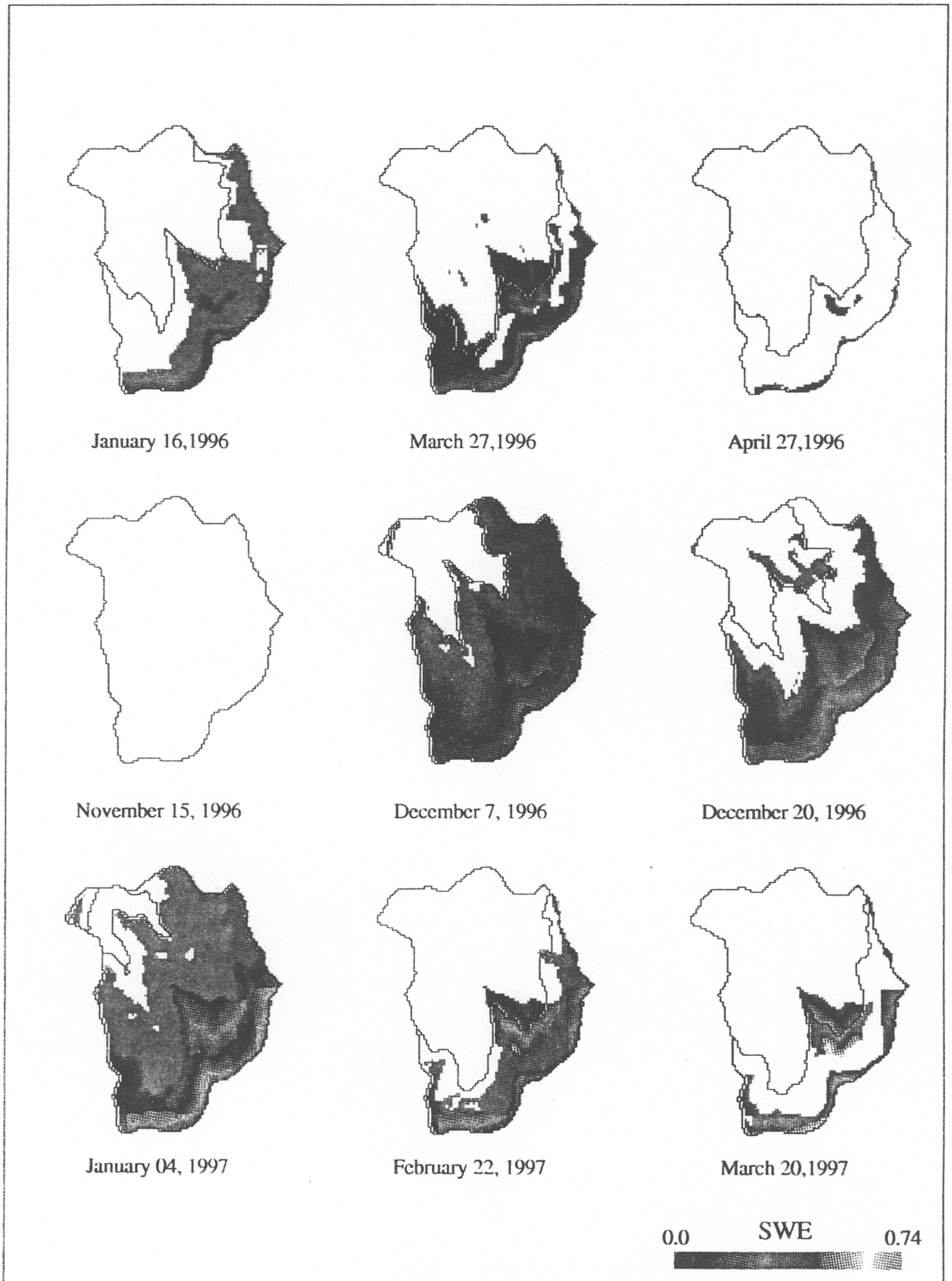


Figure 5–8: Observed Snowline Versus Predicted SWE

5.3.3: Predicted and Estimated Ditch Flows

The next step in the model calibration was to compare simulated ditch flows to estimated peak culvert flows between October 15, 1996 and April 21, 1997. Culvert discharge estimates were taken (described in Chapter 4) from the fall of 1996 to the spring of 1997.

The simulated ditch flows depend on the amount of subsurface flow intercepted by the road cutslope, which is determined by soil depth and cutslope height. Initial road cutslope heights calculated from Arc/Info scripts developed by Wigmosta and Perkins (1997) exceeded soil depths in many locations. Although field observations show that cutslopes indeed often exceed soil depths, the transmissivity of water at the cutslope face calculated by DHSVM is based on the height of the water table relative to the cutslope bottom. Therefore, transmissivity will be overestimated at locations were the cutslope depth exceeds soil depth. Cutslope heights also may exceed soil depths due to lack of soil depth variation from topographic influences associated with the STATSGO soil database.

To remedy the inaccurate transmissivity calculations, the maximum cutslope height was set to the maximum soil depth. Initial results showed that simulated ditch flows were overpredicted. Therefore, overall cutslope heights were iteratively reduced. Figures 5-9, 5-10, and 5-11 represent the calibrated simulated versus estimated culvert discharge. For the largest two storms, the model overpredicts road response. This could be indicative of ditch infiltration, which although observed in the field, is not modeled in DHSVM. Ditch infiltration should occur when a ditch traverses an area where the water table depth is below the bottom of the ditch. In the field study described in Chapter 4, ditch infiltration was observed at sites W031 and H028; two sites having oversimulated flows compared to other locations. Other discrepancies may be due to differences in subsurface flow paths, as determined by the 30-meter DEM. The model underpredicts the smaller events, which may be indicative of road surface runoff, also not represented in the model. Figure 5-12 demonstrates that the simulated and estimated culvert discharge for the largest four events during the field study are comparable.

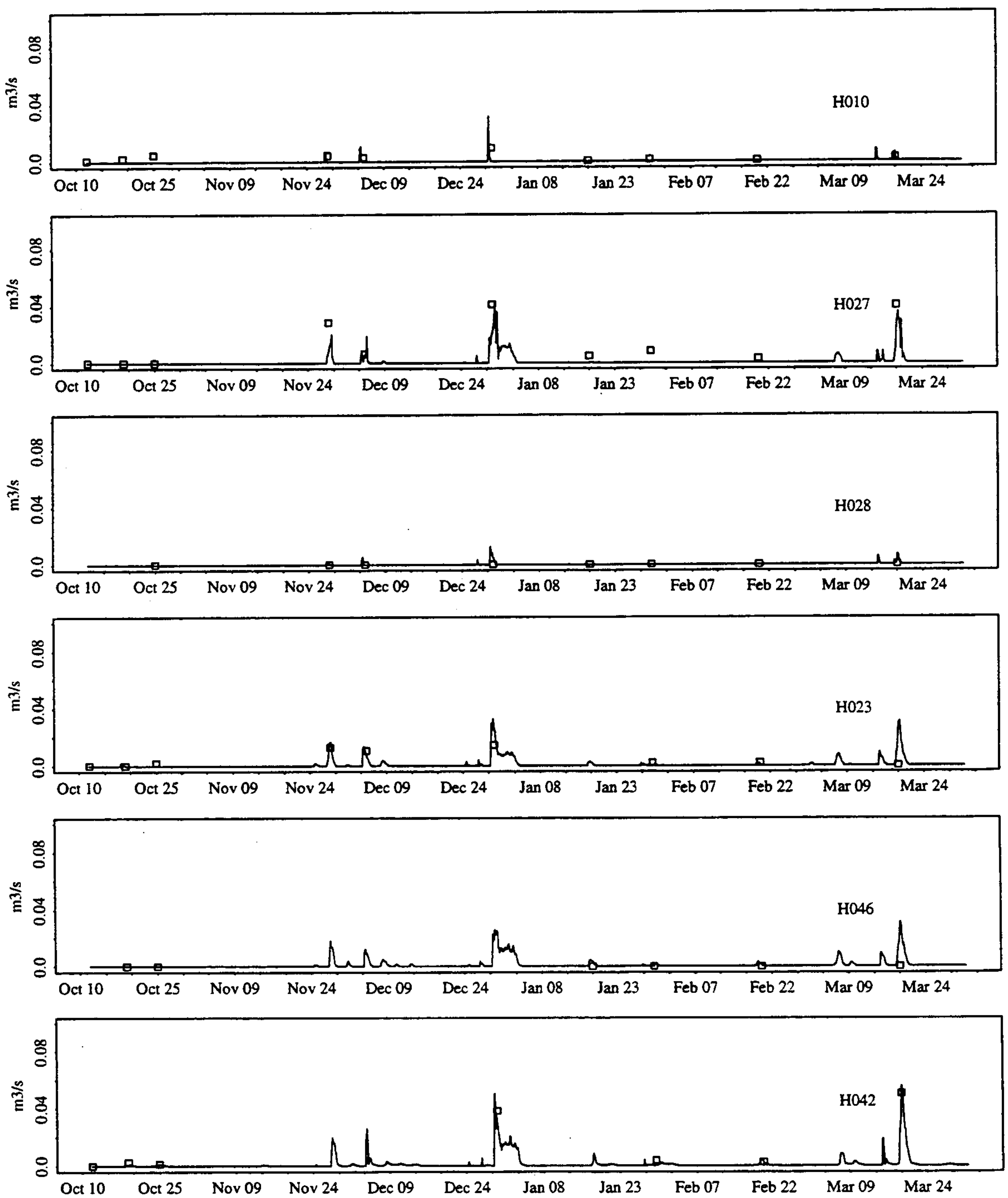


Figure 5-9: Simulated and Estimated Culvert Discharge
October 6th, 1996 - April 4th, 1997
lines-simulated discharge, squares-estimated peak culvert discharge

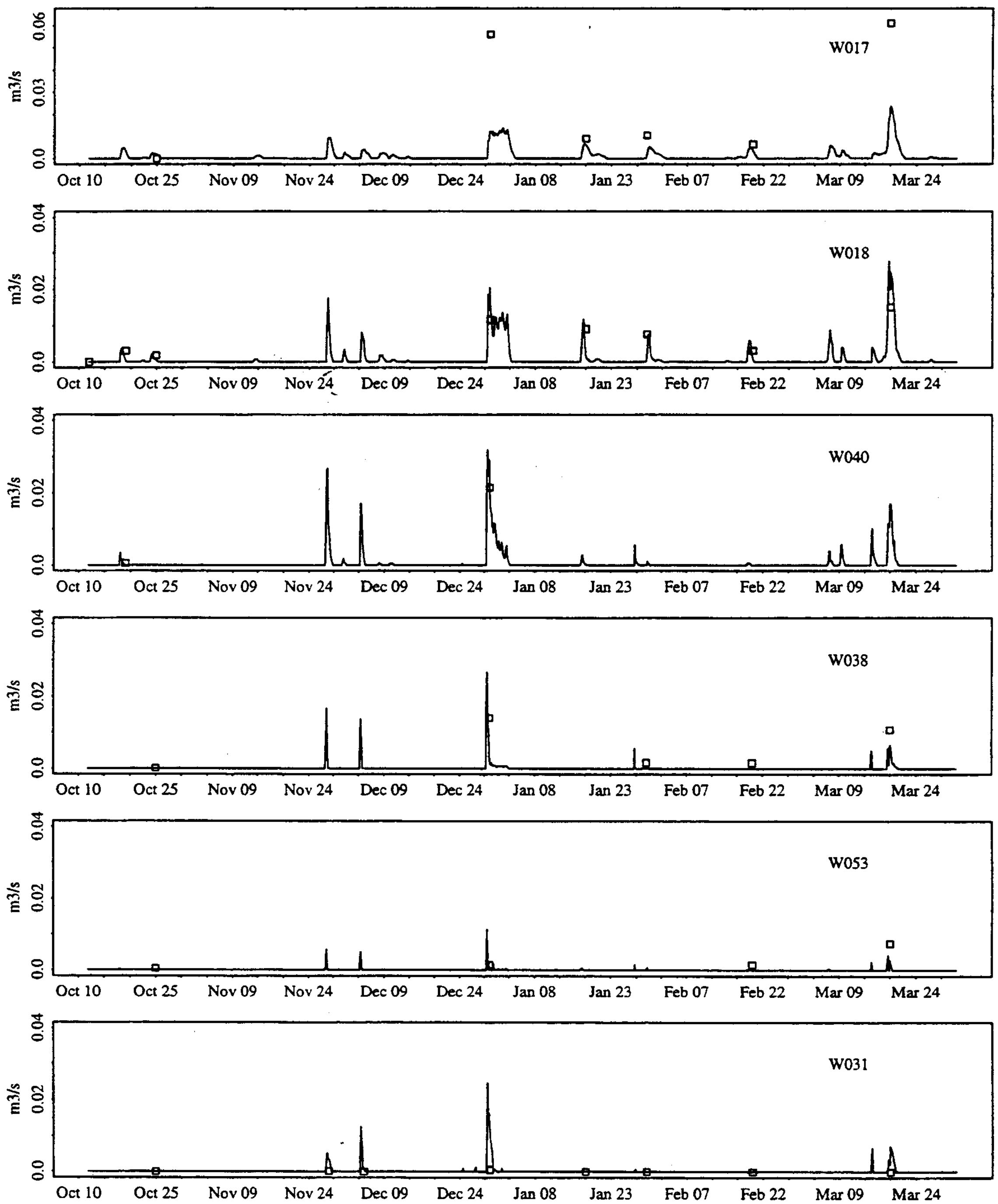


Figure 5-10: Simulated and Estimated Culvert Discharge
October 6th, 1996 - April 4th, 1997
lines-simulated discharge, squares-estimated peak culvert discharge

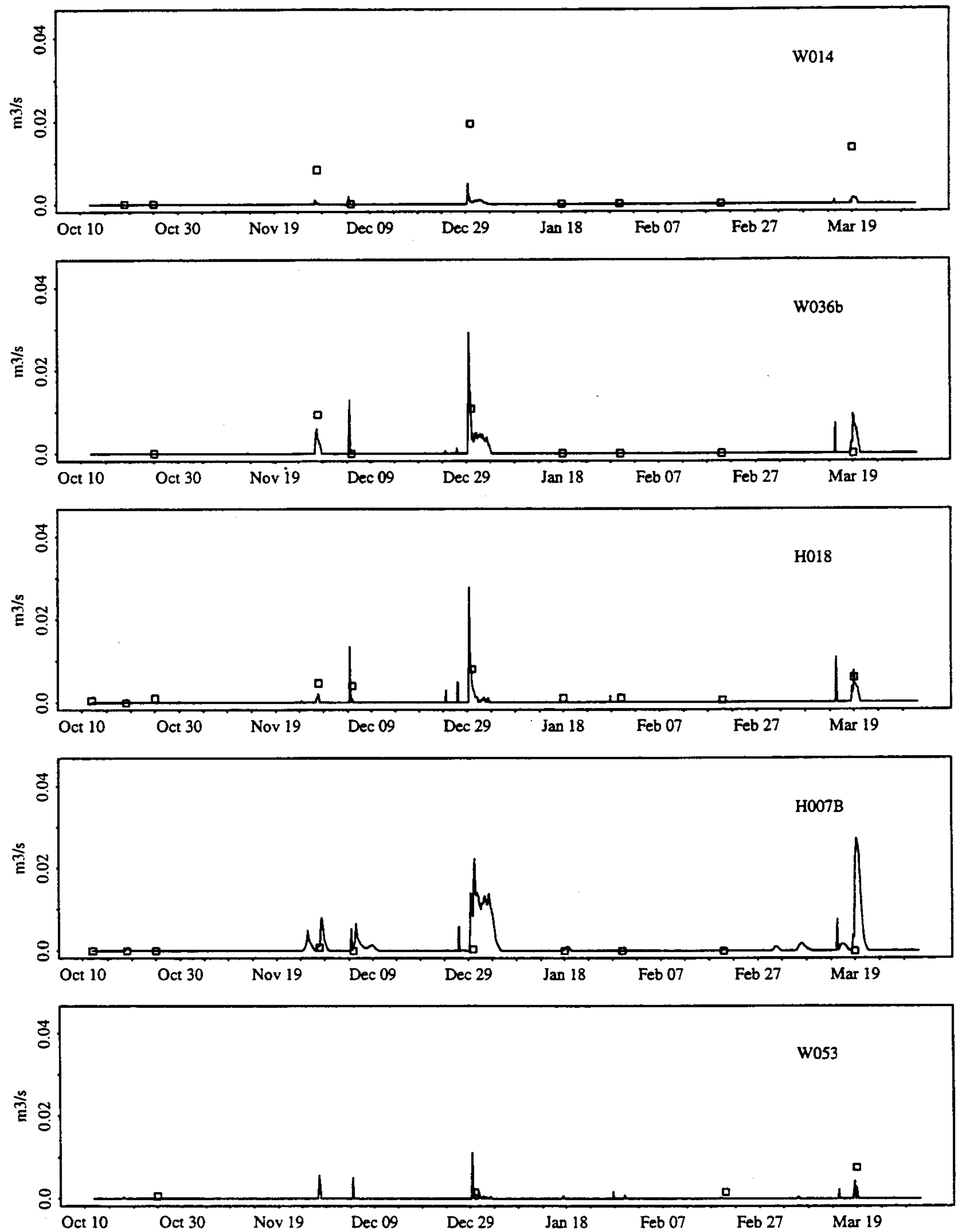


Figure 5-11: Simulated and Estimated Culvert Discharge
October 6th, 1996 - April 4th, 1997
lines-simulated discharge, squares-estimated peak culvert discharge

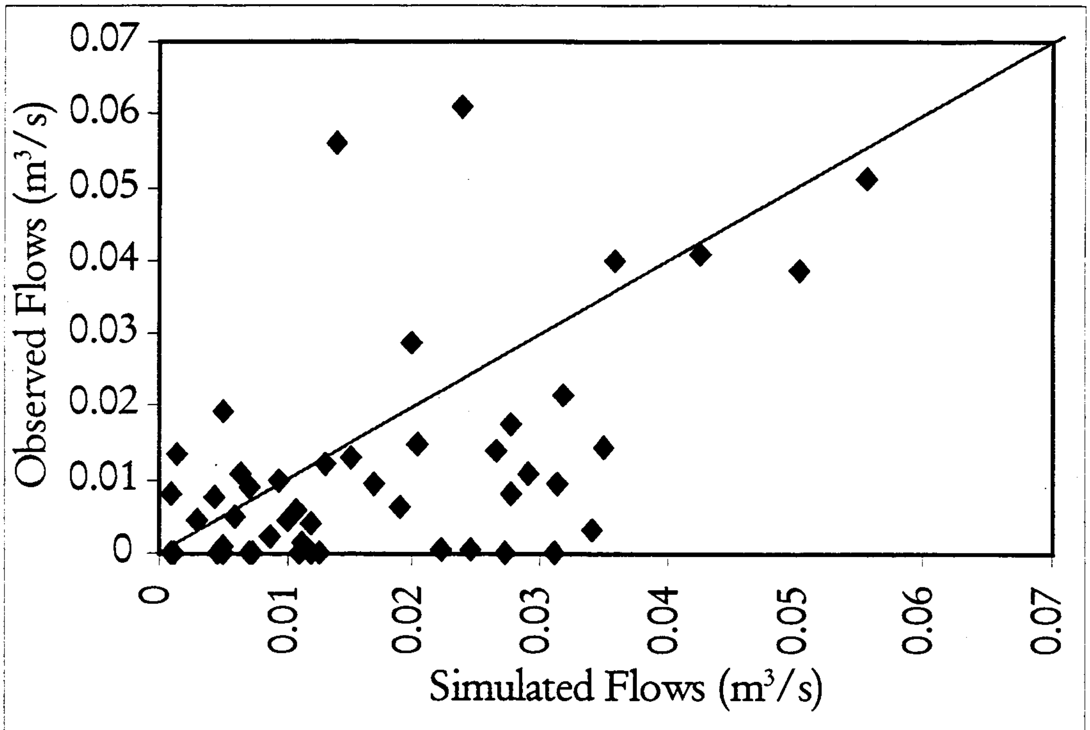


Figure 5-12: Simulated and Estimated Culvert Discharge for Largest Four Storms between October 6th, 1996 – April 4th, 1997

5.3.4: Calibration of Predicted to Observed Hydrographs

The last step in model calibration was comparison of simulated and observed flows in the Deschutes, Hard, and Ware Creeks between October 31st 1995 and June 31st 1997. Although of secondary concern, hydrograph comparisons were also made during the first three phases of model calibration. The previously described changes in precipitation and evapotranspiration greatly improved the simulated hydrographs. During the final calibration phase, only lateral hydraulic conductivity and the exponential decrease in hydraulic conductivity were adjusted. The initial parameter set yielded hydrographs that overpredicted peaks and underpredicted base flows. This was especially true of late winter storms.

To reduce peak flows and increase base flows, the exponential decrease in hydraulic conductivity was increased and the lateral hydraulic conductivity decreased. This generally improved base and peak flows, especially for late winter and early spring events associated with wet antecedent soil conditions (Figure 5-13). However, for events associated with dry antecedent conditions (fall and early winter) the model underpredicted streamflow (Figure 5-14). This was especially true for Hard Creek, which has been less harvested than Ware Creek and the Deschutes as a whole. This may reflect overly dry soil conditions in Hard Creek, from over prediction of evapotranspiration by mature vegetation. However, as Bowling and Lettenmaier (1997) noted, it could also represent differences in microclimatology between Ware and Hard Creeks not represented by the spatial distribution of precipitation. A mass balance analysis of Hard and Ware Creeks tends to support this theory and concurs with results from Bowling and Lettenmaier (1997). Hard Creek observed annual flows are higher than Ware Creek, even though the Hard Creek drainage area is smaller and vegetation is more mature. If the average annual precipitation were equal in Hard and Ware Creeks, as related by the PRISM data set (due to its spatial resolution), Hard Creek flows should be less than those of Ware Creek. However, in general, the model predicts most events during the calibration period reasonably well, with the noted exception being the large ROS event beginning December 29th, 1996 (Figure 5-15). For this event, the model under predicts peak flows at all three gauges, which may indicate an anomaly for this particular storm between precipitation at the Ware Creek gauge and actual basin precipitation. For the February 1996 ROS event, the model predicts peak flows fairly accurately.

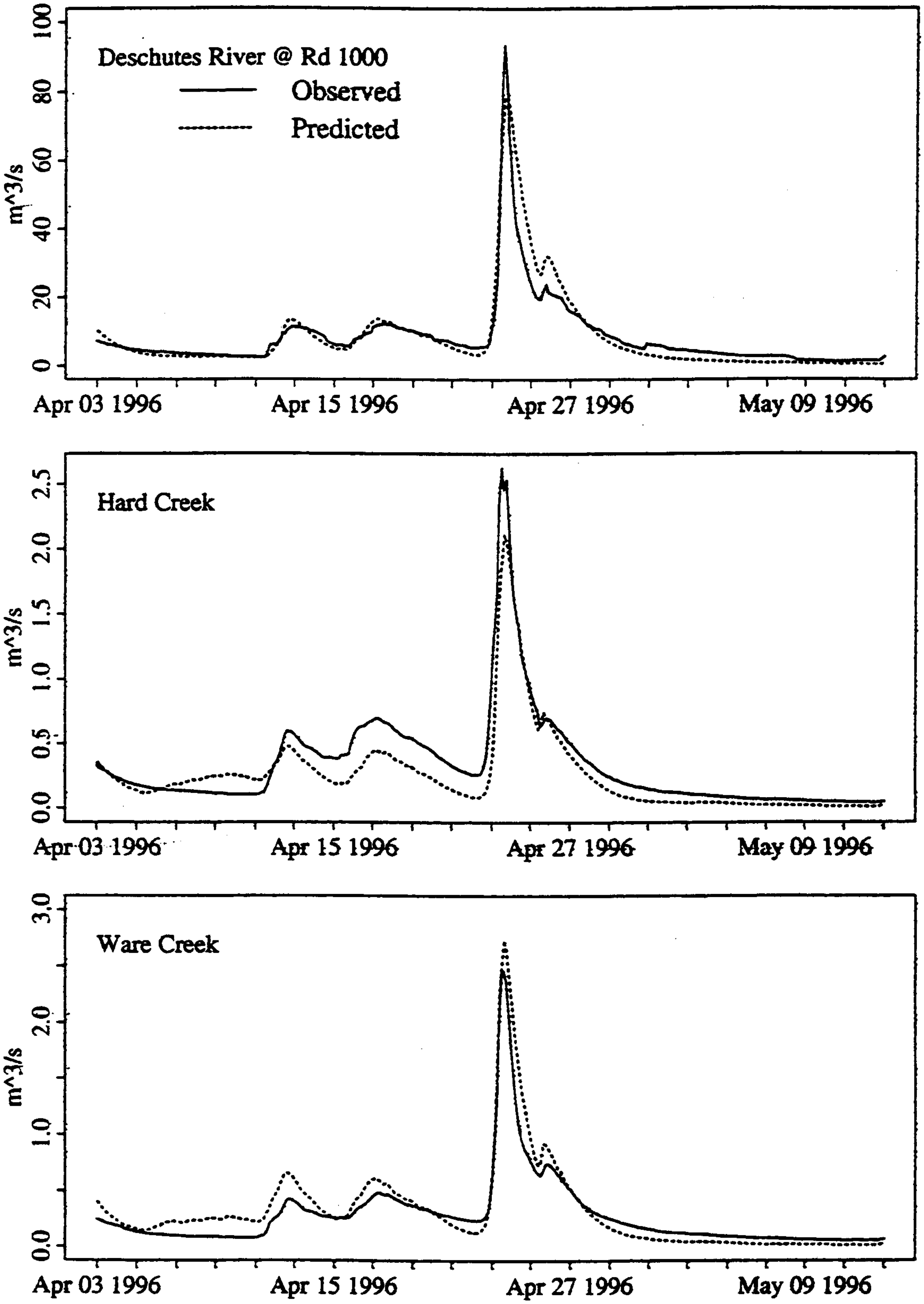


Figure 5-13: Observed and Simulated Discharge for Wet Antecedent Conditions

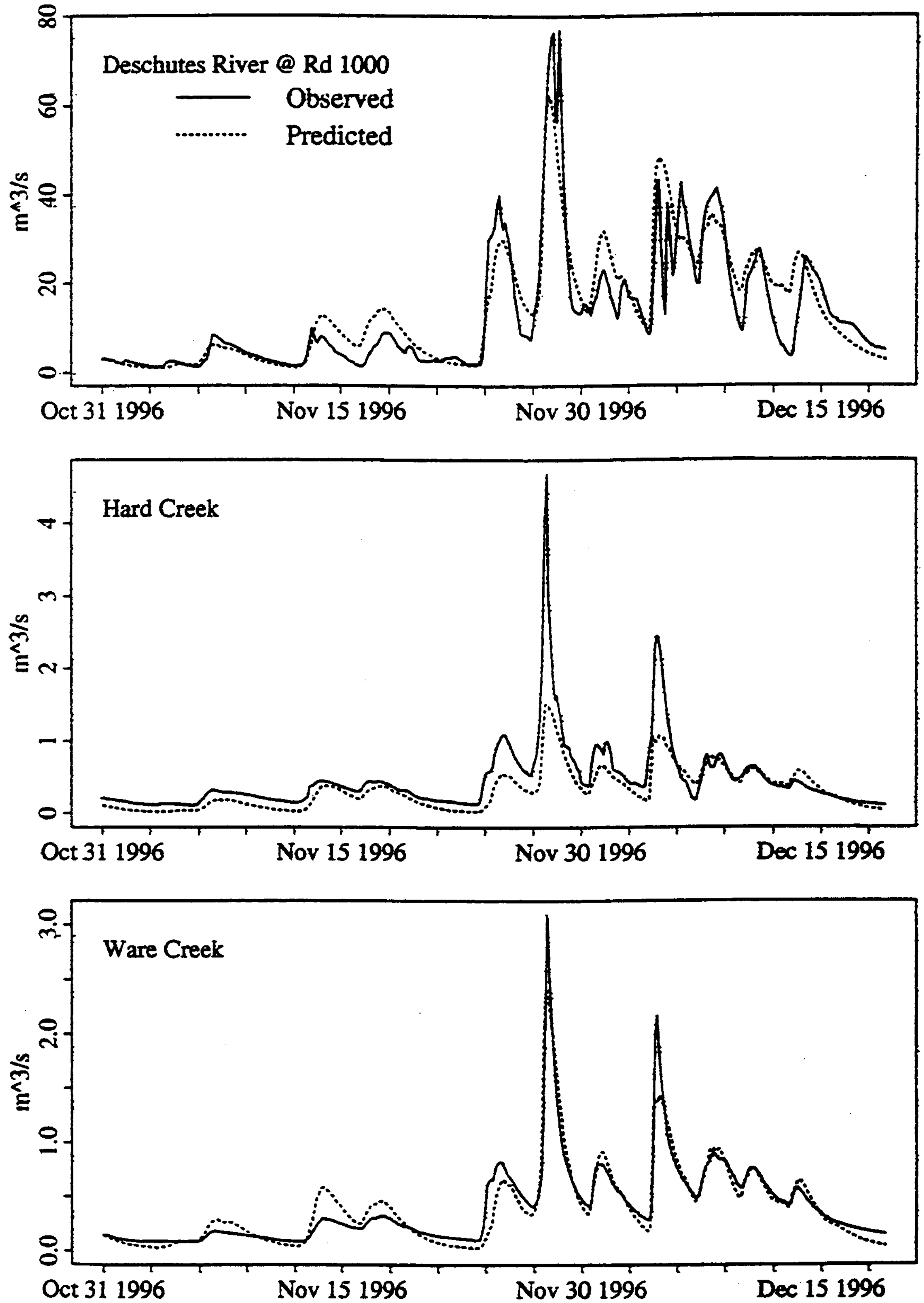


Figure 5-14: Observed and Simulated Discharge for Dry Antecedent Conditions

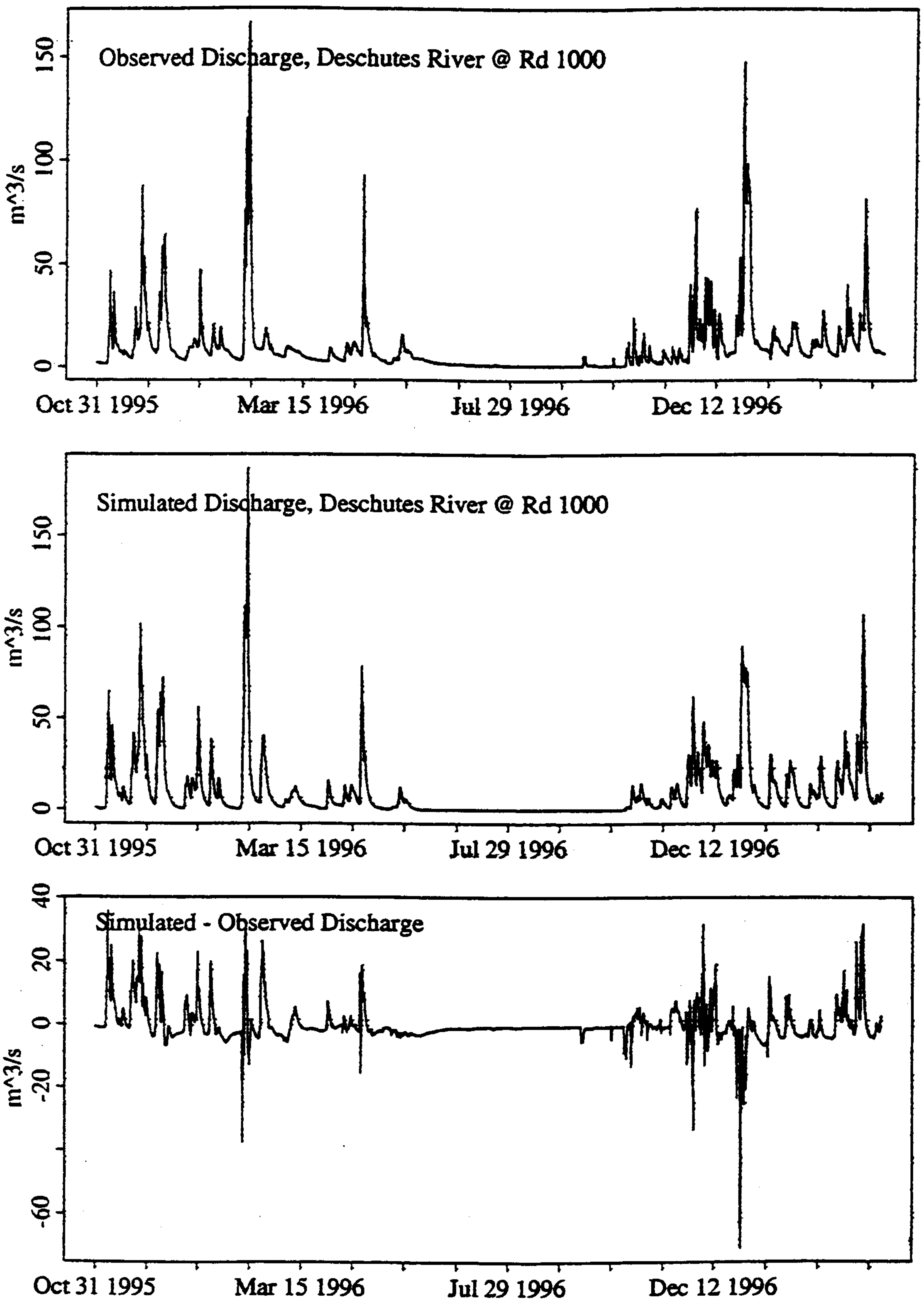


Figure 5-15: Observed and Simulated Discharge for Calibration Period, October 1995 – June 1997

Chapter 6: Simulated Effects of Forest Roads and Harvest on Peak Flows

To evaluate the effects of forest roads and harvest on peak stream flows in the Deschutes River Basin, field data described in Chapter 4 were used in the spatially distributed hydrologic model DHSVM to predict changes in peak flows under different road and harvest scenarios. For consistency, simulations were performed for four combinations of road and vegetation states used by Bowling and Lettenmaier (1997) in nine of the Deschutes sub–catchments, as well as the entire Deschutes catchment above Road 1000. The combinations, tabulated in Table 6-1, form the basis for the analyses described in the remainder of this chapter. The initial simulations (Section 6.1) were performed to investigate whether a synergism exists between roads and vegetation, as hypothesized by Jones and Grant (1996). Subsequently, simulated peak flow changes in the nine sub–catchments were compared to evaluate how differences in topography, soils, vegetation, and stream and road drainage networks affect peak flow changes. Finally, the combined effects of harvest and forest roads on storm hydrographs for selected sub-catchments were examined. All simulations were based on the period of continuous climatic records excluding the calibration period, specifically October 1985 through October 1994.

Table 6-1: Deschutes River Study Design and Comparisons

Simulation		Comparison	
Number	Road and Vegetation	Number	Effect Studied
1	Current Veg. w/ Roads	A) Simulations 1 and 2	Percent change in peak flows due to roads with current vegetation state
2	Current Veg. w/o Roads	B) Simulations 3 and 4	Percent change in peak flows due to roads with mature vegetation state
3	Mature Veg. w/o Roads	C) Simulations 2 and 3	Percent change in peak flows due to harvest without roads constructed
4	Mature Veg. w/ Roads	D) Simulations 1 and 4	Percent change in peak flows due to harvest with roads constructed
-	-	E) Simulations 1 and 3	Percent change in peak flows due to harvest and roads from pristine condition

[a] Current Vegetation States Refers to 1996 Vegetative Conditions

6.1: Forest Roads and Harvest Effects on Peak Flows

Changes in peak flows associated with forest roads and harvest were determined by extracting peak events from the 3-hour simulated flows at the 10 locations noted in Table 6-2. These peaks were used to construct the mean annual-floods (MAF) and peak-over-threshold (POT) series. The annual flood series was determined by taking the annual simulated maximum peak flow for each year. The POT series were generated by taking all independent events over a specified threshold—set to capture two to three independent peaks per year over the nine-year simulation. A two-week interval between events was set as a minimum time threshold to assure independence of the peaks. This interval was chosen because the majority of storms, and thus peak discharge events, last less than two-weeks. If two events occurred within two weeks of each other, the lower magnitude event was removed from the analysis. For each simulation, peak thresholds were established in the POT analysis in order to sample the same number of events over the 9-year simulation in each sub–catchment. The threshold ranges for each basin are listed in Table 6-2. A threshold range was used for each basin in order to generate the same number of events for each road/harvest scenario.

Table 6-2: Basin Thresholds for POT Analysis

Basin	Threshold Range (m^3/s)	Number Independent Events
Deschutes @ Rd 1000	39-52.0	21
Mitchell	5.1-6.1	21
Little Deschutes	5.6-7.3	21
Thurston	3.6-4.6	21
Lincoln	4.1-4.9	22
Lewis	1.7-2.1	22
Ware	1.4-1.8	22
Hard	1.2-1.3	22
Upper Deschutes	3.3-3.9	22
Mine	1.5-1.6	22

Average peak flow changes associated with the road and harvest scenarios for both the MAF and POT series are summarized in Table 6-3.

Table 6-3: Increase in Peak Discharge Associated with Roads and Harvest

Comparison	Deschutes	Mitchell	Little Desch.	Thurston	Lincoln	Lewis	Ware	Hard	Upper Desch	Mine
Average Change in Mean Annual Flood (%)										
A) Δ due to roads w/ current veg. state	5.0	2.4	2.8	5.5	8.7	5.7	10.0	8.1	8.0	2.6
B) Δ due to roads w/ mature veg. state	5.0	2.4	2.5	5.2	8.9	5.2	10.2	8.3	6.2	2.9
C) Δdue to harvest w/o roads constructed	13.6	11.7	18.0	11.5	11.5	11.4	10.8	4.2	6.0	5.0
D) Δ due to harvest w/ roads constructed	13.6	11.7	18.3	11.8	11.3	11.9	10.5	4.1	7.8	4.6
E) Δ due to harvest and roads from pristine forest	19.2	14.3	21.3	17.6	21.2	17.7	21.8	12.6	14.5	7.7
Average Change in Peaks Over Threshold (%)										
A) Δ due to roads w/ current veg. state	5.3	1.8	2.0	4.2	7.4	4.0	9.0	6.5	7.7	1.9
B) Δ due to roads w/ mature veg. state	4.0	1.8	2.0	3.8	7.4	3.5	10.0	7.3	8.0	2.1
C) Δ due to harvest w/o roads constructed	14.9	10.2	19.2	10.6	13.1	13.0	12.3	5.5	9.5	5.7
D) Δ due to harvest w/ roads constructed	16.3	10.2	19.2	11.1	13.0	13.5	11.4	4.6	9.2	5.5
E) Δ due to harvest and roads from pristine forest	20.9	12.2	21.6	15.3	21.4	17.5	22.5	12.3	18.0	7.7

The simulated average increase in mean annual flood due to roads under current vegetation conditions was 5.0 percent for the Deschutes Basin. The corresponding increase in MAF for Ware and Hard Creeks was 10.0 percent and 8.1 percent, respectively. These values are lower than the 11.2 and 11.1 percent increases simulated by Bowling and Lettenmaier (1997) in the Ware and Hard Creeks, respectively. The difference in results between the two studies is probably related to the method used in determining flow routing from the roads. In the Bowling and Lettenmaier (1997) study, flow routing generated from the road network algorithm of Wigmosta and Perkins (1997) (described in Chapter 5) was verified and corrected by hand from field observations. A similar process was not feasible for this study given the much larger size of the Deschutes Basin. Instead the two-step process in described in Chapter 5 was used to determine flow routing. Therefore, flow routing through the road drainage probably differs somewhat between the two studies.

Another difference in the two studies was the topographic variations in soil depth imposed in the Bowling and Lettenmaier study. In the Bowling and Lettenmaier study, original soil depths provided in the STATSGO data set were modified based on hillslope location. Soils depths near ridge tops were reduced, while depths near valleys were increased. Again, a similar process was not feasible for the entire Deschutes Basin due to the interaction of soil depths and vegetation classes as described in DHSVM. Soil depth in DHSVM is linked to rooting zone depth, which is prescribed for each vegetation class. Therefore, each vegetation type may yield several vegetation classes, differing only in the rooting zone depths associated with the specified soil depths. Extending the method of Bowling and Lettenmaier (1997) to the entire Deschutes Basin would have resulted in up to five times the number of vegetation classes (85) used and would have complicated model implementation considerably. Therefore, soil depth information was taken directly from the STATSGO data, without attempting to impose a topographically based gradient in soil depth.

Results from DHSVM (Table 6-3) indicate the predicted combined road and harvest effects on stream peak flows, although varied, are essentially additive for all catchments studied. These results support previous findings in Hard and Ware Creek from Bowling and Lettenmaier (1997). That is, the model predicts that road effects are additive to harvest effects not synergistic, as proposed by Jones and Grant (1996). This effect will be discussed further in Section 6.2.3. Roads increased the average MAF from 2.4 to 10.2 percent, while the average POT increased from 1.8 to 10.0 percent. The increase due to harvest ranged from 4.2 to 18.0 percent for the MAF and from 5.5 to 19.2 percent for the average POT.

The increases in the mean of the POT series were generally equivalent to the increases in the MAF series for all catchments modeled for all combinations of road and vegetation states. However, for vegetation effect comparisons C and D (changes due to vegetation without and with roads, respectively), the average POT increase was slightly larger than the MAF flow in most catchments. In contrast, for road comparisons A and B (changes due to roads with current and mature vegetation, respectively), the MAF increase was generally higher than that for the POT series. These findings suggest that as peak floods increase, the effect of roads increase, while the effect of forest harvest decrease.

To further investigate the relative effects of forest harvest and roads, an exponential distribution (EV1) was fitted to the POT series for the Deschutes Basin and sub-catchments for all four simulations using the method of maximum likelihood. The process followed methods described in Beverton and Paton (1975) and resulted in 40 fitted distributions for the Deschutes and modeled tributaries. Figure 6-1 shows an example of a fitted distribution for the Deschutes POT series with roads and mature forest. From this analysis, the 2.3-year and 10-year return floods were calculated for all catchments modeled. Table 6-4 summarizes the results.

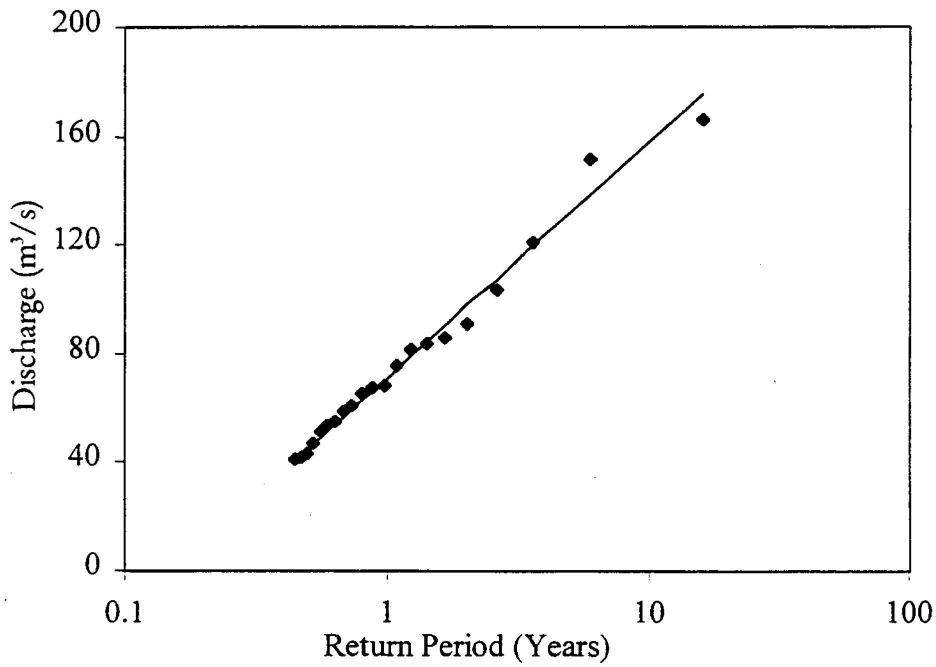


Figure 6-1: Fitted EVI Distribution for Simulated Deschutes Peak Discharge Exceeding $40m^3/s$ with Roads and Mature Vegetation

The 2.3-year flood should be approximately equal to the MAF. Comparing results in Tables 6-3 and 6-4 show that the estimated 2.3-year return flood from the fitted distribution is in fact approximately equal to the empirical MAF estimate. Floods of this magnitude (approximately bankfull capacity in the lower gradient reaches of the Deschutes) were studied because of their importance in relation to erosion and salmon habitat.

The results shown in Table 6-4 indicate that although the percentage increase in peak flows is similar between the 2.3-year and 10-year return period events, there are some systematic differences. As suggested in the comparison of empirical MAF and mean of POT series, road effects on peak flows generally increase for larger floods, while harvest effects decrease for larger floods. Figure 6-2 shows that for a mature forest the simulated

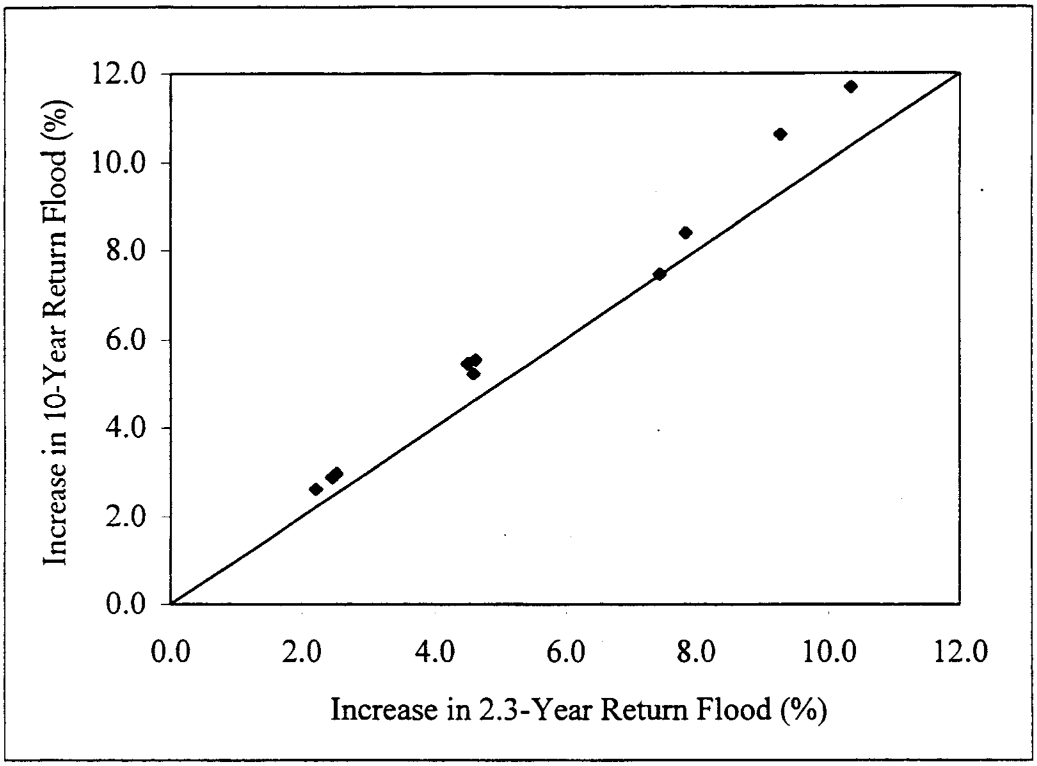


Figure 6-2: Peak Flow Response to Roads w/ Mature Forest for Different Flood Size

road effects on peak flows increase for larger events (simulated increases above 1:1 line). Figure 6-3 indicates the opposite trend for harvest effects. Increases in the 10-year event are all smaller than increases in 2.3-year event, when roads are absent.

The combined results from the MAF and POT analysis summarized in Tables 6-3 and 6-4 also suggest that the simulated effects of roads on peaks flows are roughly equivalent to those of forest harvest for Upper Deschutes, Hard, Ware and Lincoln Creeks. Simulated road effects on peak flows are much lower than those of harvest for Mine, Mitchell, and Little Deschutes Creeks. A moderate road effect compared to harvest effect was modeled for the Deschutes River and Thurston and Lewis Creeks. Collectively, these simulated results indicate that forest roads affect peak flows to varying degrees. The differing forest road effects on peak flows within the Deschutes' sub-catchments are discussed in the next section.

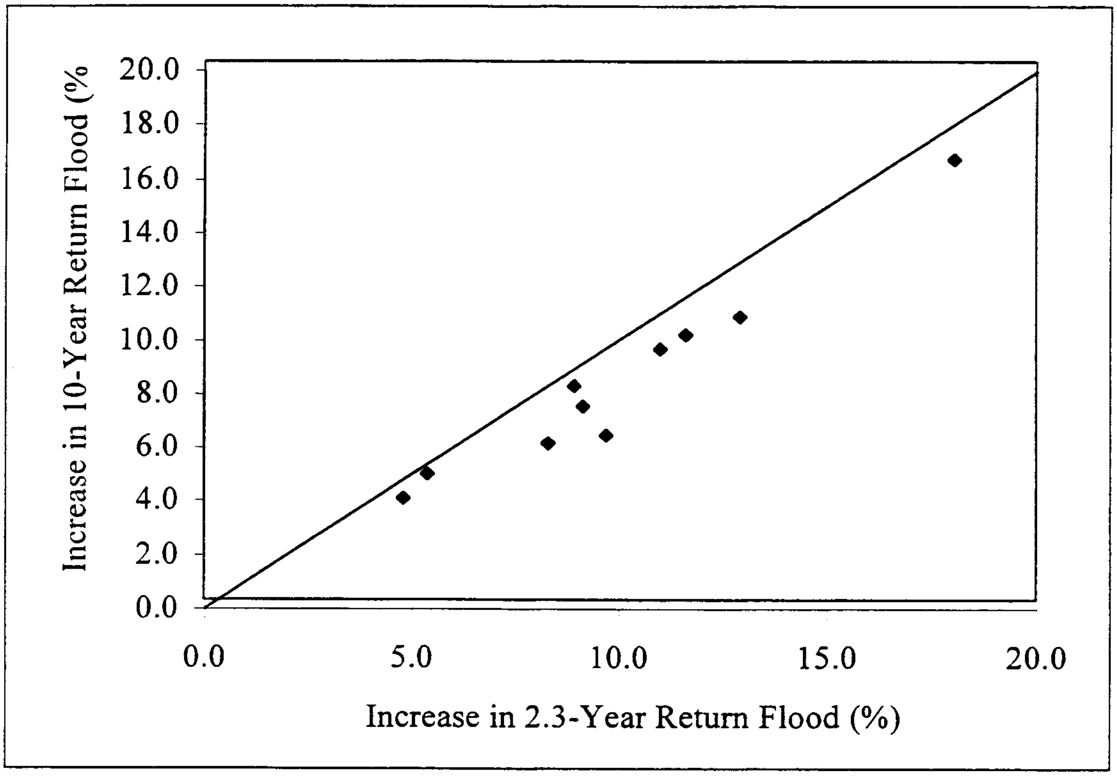


Figure 6-3: Peak Flow Response to Forest Harvest without Roads for Different Flood Size

Table 6-4: Increase in Discharge for POT Series Associated with Roads and Harvest

Comparison	Deschutes	Mitchell	Little Desch.	Thurston	Lincoln	Lewis	Ware	Hard	Upper Desch	Mine
Change in 2.3 Year Return Event (%)										
A) Δ due to roads w/ current veg. state	4.6	2.3	2.5	4.6	8.7	5.1	9.5	7.7	9.0	2.2
B) Δ due to roads w/ mature veg. state	4.6	2.2	2.4	4.6	7.4	4.5	11.1	7.8	9.3	2.5
C) Δ due to harvest w/o roads constructed	12.9	8.3	18.0	9.1	11.6	9.7	11.0	4.8	8.9	5.4
D) Δ due to harvest w/ roads constructed	11.4	7.7	15.3	8.4	11.5	9.3	8.6	4.4	8.0	4.8
E) Δ due to harvest and roads from pristine forest	18.1	10.7	21.0	14.1	21.3	15.3	21.5	12.9	18.7	7.7
Change in 10 Year Return Event (%)										
A) Δ due to roads w/ current veg. state	3.8	2.8	3.1	5.0	10.1	6.2	10.0	9.0	10.4	2.5
B) Δ due to roads w/ mature veg. state	5.2	2.6	2.9	5.5	7.5	5.5	12.2	8.4	10.6	3.0
C) Δ due to harvest w/o roads constructed	10.9	6.2	16.8	7.5	10.2	6.5	9.6	4.1	8.3	5.0
D) Δ due to harvest w/ roads constructed	8.6	5.9	14.5	6.5	11.4	6.8	6.9	4.5	7.5	4.4
E) Δ due to harvest and roads from pristine forest	15.1	9.1	20.3	12.9	21.3	13.1	20.6	13.5	19.6	7.7

6.2: Comparison of Road Effects on Peak Flows Between Sub-Catchments

As shown in Section 6.1, simulated road effects on peak flows varied considerably between sub-catchments from as little as a 2.4 percent change in the MAF for Mitchell Creek to as much as 10.2 percent in Ware Creek. In this section, factors influencing the effects of peak flow changes are investigated, following the hypothesis presented in Chapter 1. The possible effects of road location, road connectivity, vegetation conditions, soil type, and topography on simulated peak flow changes are evaluated. Table 6-5 summarizes relevant characteristics of the nine sub-catchments and the simulated changes in the 2.3–year return period flood ($2.3T_r$) as estimated in Section 6.1.

Table 6-5: Sub-Basin Attributes and Associated Increases in Peak Flows

	Mitch.	Little Des.	Thurs.	Linc.	Lewis	Ware	Hard	Upper Des.	Mine
Major Soil Types	5,3,2	2	2,3	3,2	3,2	4,3	4,3	4,3	4,3
Avg. Elev. (m)	557	450	497	709	670	810	840	774	812
Slope (%)	34.7	26	26.8	38.5	38.8	51	56.6	52.6	57.4
Increase Drainage Density from Gullies	6.1	3.7	4.1	5.5	4.5	5.7	10.8	10.2	6
% Culverts Connected	52	38	51.1	54	61	57	45	54	39
Road Density (km/km^2)	3.2	4.1	4.3	4.3	4.5	3.8	5	3.5	3.6
% Area in Roads	4.9	6.3	6.7	6.6	6.9	5.9	7.6	5.3	5.5
% Harvested	45	91	70	98	91	90	36	82	71
% Clearcut [a]	22	32	26	57	74	57	35	68	44
% Roads Located Midslope	41.6	48.6	45.7	63.8	59.2	47.2	31.5	57.5	51.8
% Increase in 2.3yr Flood due to Roads w/Mature Veg.	2.4	2.4	4.6	7.4	4.5	11.1	7.8	9.3	2.5
% Increase in 2.3yr Flood due to Roads w/Current Veg.	2.4	2.5	4.6	8.7	5.1	9.5	7.7	9.0	2.2

[a] Based on cumulative area with vegetation height below 2 meters.

6.2.1: Culvert Connectivity Influences

As hypothesized in Chapter 1, the effects of roads on peak flows should be related to the connectivity of the road and the stream channel. That is, the degree to which the road generated runoff is delivered to the stream channel should determine, in part, the road effect on peak flows. Two parameters related to road network connectivity are; 1) percentage of culverts connected and, 2) increases in drainage density due to the formation of gullies (DD_g) (defined in Chapter 4). The increases in the $2.3T_r$ associated with roads for mature forest for these two factors are shown in Figures 6-4 and 6-5. The results are partitioned by the sub-catchment soil type to isolate the effects of soil parameters on the independent variable. Figure 6-4 suggests that as the percentage of connected culverts increases in a basin, so does the response of the $2.3T_r$ to roads, although there is considerable scatter, which is probably related to other factors affecting catchment response. Figure 6-5 suggests that there may also be a relationship between DD_g and increases in $2.3T_r$.

To further investigate these relationships, increases in simulated $2.3T_r$ from the POT analysis were compared for three paired sub-catchments with and without roads for a mature vegetation state. These comparisons were made to isolate differences in the road drainage, specifically culvert connectivity and increase in DD_g, from differences in soils, road area, road density, vegetation, and topography.

The first comparison was conducted for Upper Deschutes and Mine Creek sub-catchments. These sub-catchments have similar topography, road density, and percent area in roads, and soil types as shown in Table 6-4, but differ in culvert connectivity (54 percent and 39 percent for Upper Deschutes and Mine Creeks, respectively). The simulated increase in $2.3T_r$ for Upper Deschutes Creek was 9.3 percent, compared to a 2.5 percent increase for Mine Creek. These findings support the hypothesis that road connectivity is related to road effects on peak flows. The percentage of connected culverts in a catchment reflects the general road connectivity. Upper Deschutes Creek

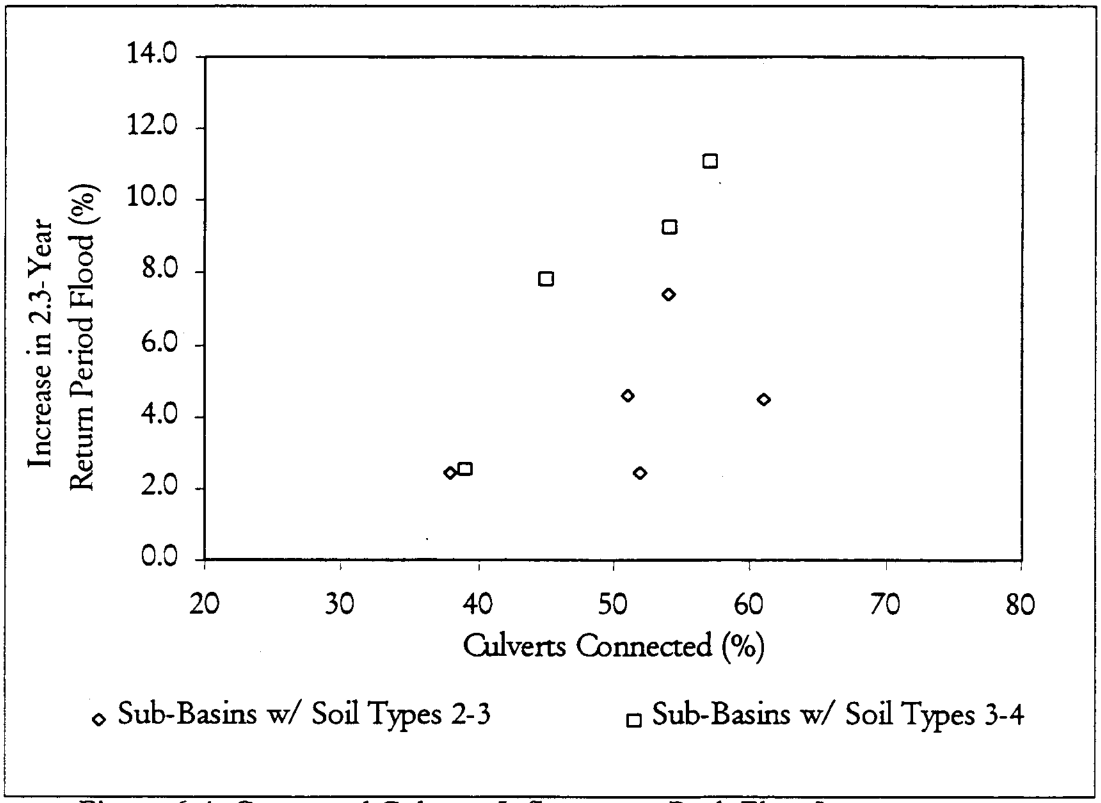


Figure 6-4: Connected Culverts Influence on Peak Flow Increases Associated with Roads

also had a larger increase in DD_g due to gullies than did Mine Creek (10.2 % compared to 4.1 % for Mine Creek), which may also reflect the relative degree of road connectivity between the catchments.

A comparison of the increase in $2.3T_r$ related to roads for Upper Deschutes and Hard Creeks also indicates the relationship between culvert connectivity and road effects on peak flows. These two catchments have comparable slopes, elevations, and soil types, and similar increases in DD_g (10.2 and 10.8 percent, respectively), but differ in levels of culvert connectivity—54 and 45 percent, respectively. The culvert connectivity difference is reflected in the simulated increase in $2.3T_r$—9.3 and 7.8 percent, respectively, for Hard and Upper Deschutes Creeks.

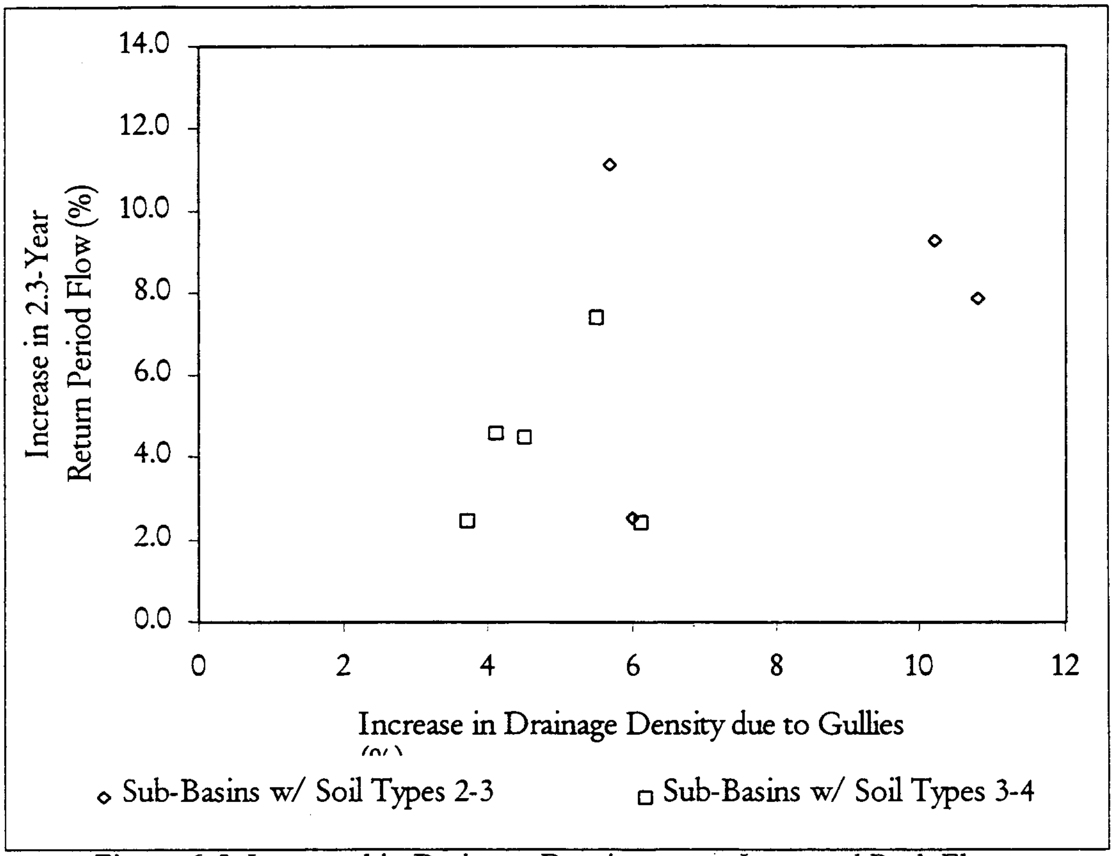


Figure 6-5: Increased in Drainage Density versus Increased Peak Flows Associated with Roads

However, the effect, as evidenced in increased $2.3T_r$, is somewhat less than that of the Upper Deschutes – Mine Creek pair. This implies that the effective connectivity of the roads may be similar in Hard and Upper Deschutes Creeks even though the percentage of culverts connected differs. That is, the percentage of connected culverts may not exclude a comparable degree of road lengths connected to the stream network in the two catchments. Because Hard Creek has a higher road density than Upper Deschutes Creek, a lower percentage of connected culverts would be required to produce comparable total lengths connecting to a stream channel.

Comparison of the Upper Deschutes, Mine, and Hard Creeks results suggest that the product of the road density and percentage of connected culverts (RDCC), as opposed to the percentage of connected culverts may be a reasonable predictor of road effect. However, for Mine, Upper Deschutes, and Hard Creeks the RDCC estimates were 1.4, 1.9, and 2.3, respectively, which does not support RDCC as a general predictor of road effects on peak flows, as Hard Creek had less of an increase in $2.3T_r$ than Upper Deschutes Creek. However, it is difficult to draw conclusions from such a small sample size. The results for all sub-catchments are shown in Figure 6-6. There may be some general trend for sub-catchments with major soil types 3-4, which is less obvious for sub-catchments with major soil types 2-3.

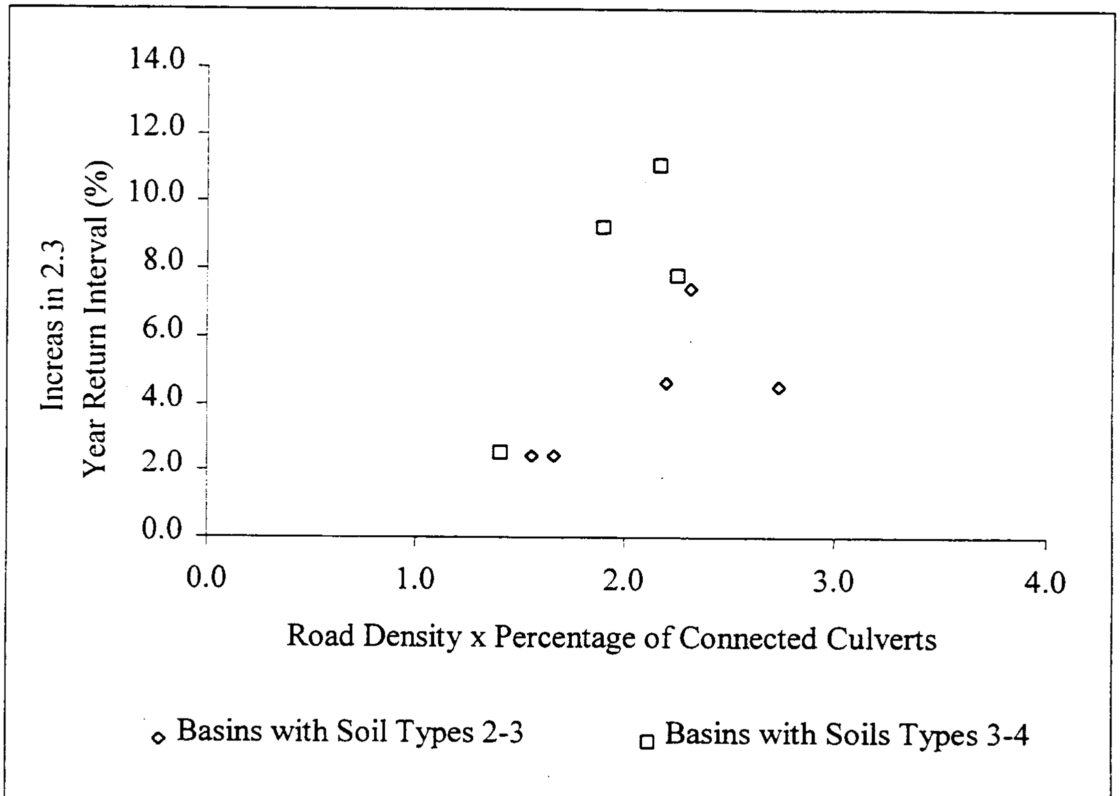


Figure 6-6: Average Road Connectivity Influence on Peak Flows Increases Associated with Roads

To further explore the possibility of using the above parameters as indicators on peak flow effects resulting from roads, an additional comparison between two of the lower catchments was made. Little Deschutes and Thurston Creeks have relatively low average slopes (26%), low average elevations (450-497 m), and similar road density and percent of basin area in roads. The increase in $2.3T_r$ for Thurston Creek (4.6 %) was almost twice that of Little Deschutes Creek (2.4%). The value of RDCC was 2.2 and 1.6 for Thurston Creek and the Little Deschutes, respectively. The increase in DD_g due to gullies was 4.1 and 3.7 percent.

These simulated results suggest that road effects on peak flows are related to the extent to which the road network extends the natural stream drainage. In addition, road density and percentage of basin area in roads in of themselves are not well related to increases in peak flows due to roads (see Figure 6-7). For example Upper Deschutes and Hard Creeks have different road areas and densities, yet the road effect on peak flows were similar.

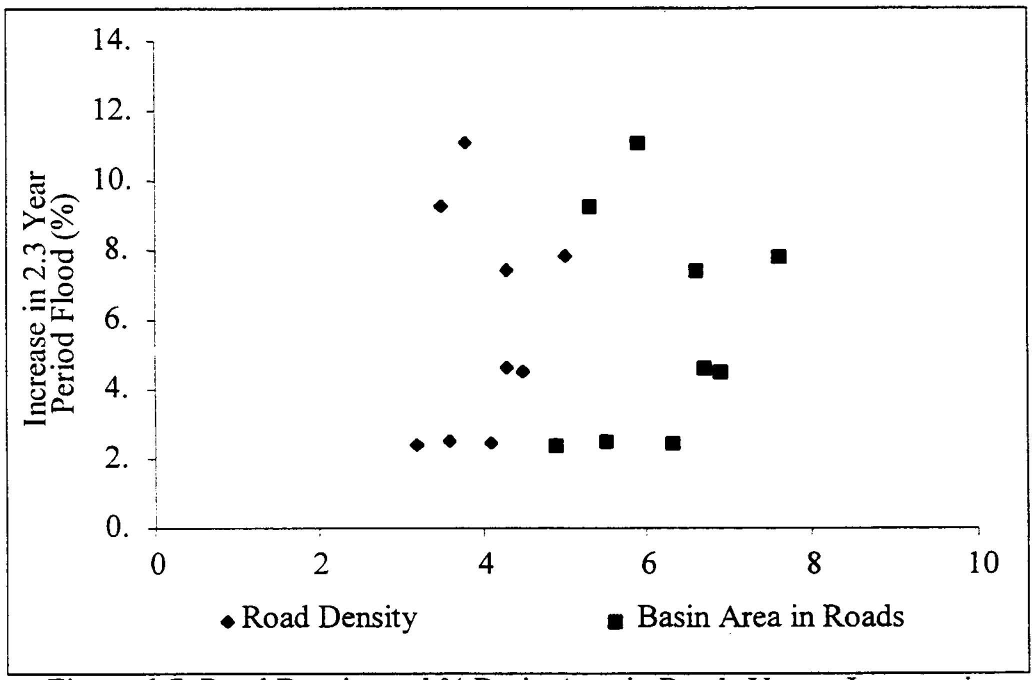


Figure 6-7: Road Density and % Basin Area in Roads Versus Increase in Peak Flows

6.2.2: Influence of Road Location on Road-Related Peak Flow Increases

As hypothesized in Chapter 1, roads located midslope should have a greater potential for contributing to peak flows than ridge top or valley bottom roads. To investigate this effect, the percentage of roads located midslope was calculated for all sub-catchments. The percentage of roads located midslope was determined by subtracting the total length of valley and ridge roads from the total road length in a given basin. Valley road lengths were calculated as all road segments within a 150 m buffer width on each side of a third order or higher streams. Likewise, ridge segments were calculated based on a 150 m buffer on each side of any ridge defining at least a one square km catchment. Two pairs of sub-catchments were compared to isolate road location effects on peak flows.

As summarized in Table 6-5, Mitchell and Lincoln Creeks have similar topographic characteristics, as well as culvert connectivity. The road density in Mitchell Creek is lower than Lincoln Creek. However, Mitchell Creek has a larger increase in DD_g than Lincoln Creek. These two catchments have a large difference in the percentage of roads located midslope (64 percent for Lincoln Creek and 41.6 percent for Mitchell Creek). Results from the POT analysis indicate that Lincoln Creek has a much larger increase in $2.3T_r$ flows due to road effects than Mitchell Creek. These results are consistent with the hypothesized importance of road hillslope position effects on peak flows.

A comparison of Lewis and Lincoln Creeks also supports the hypothesis of the effect of road hillslope position. Again, most of the topographic, road density, and culvert connectivity parameters are similar between the two sub-catchments. However, Lincoln Creek has a higher response in the $2.3T_r$ due to roads. The percentage difference between the $2.3T_r$ flows is not as great as the previous example. However, the difference in percent of roads located midslope is also not as great—59 percent for Lewis Creek versus 64 percent for Lincoln Creek.

Although both of these comparisons suggest a road hillslope position effect on peak flows, a much more comprehensive study would be required to evaluate the effect conclusively. Peak flow changes for all sub-catchments as a function of fraction of midsloped roads partitioned by major soil type are shown in Figure 6-8. Although the results do not indicate a strong trend relating road location to increase in $2.3T_r$, there is some apparent effect for sub-catchments with soil types 2-3.

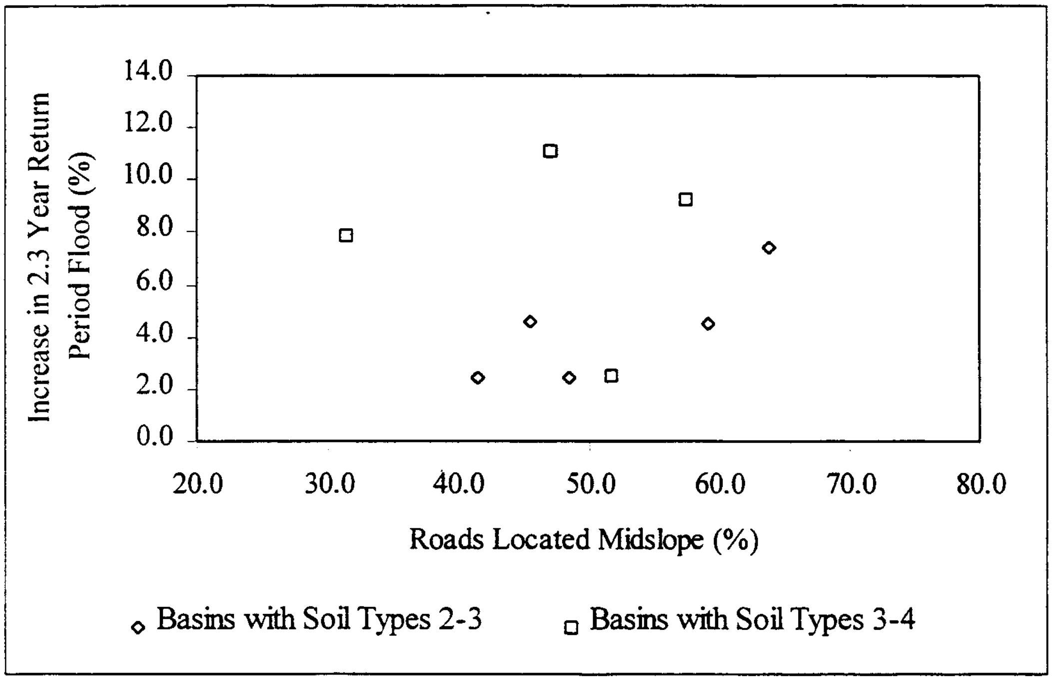


Figure 6-8: Road Hillslope Location Influence on Peak Flow Increases Associated with Roads

6.2.3: Vegetation Effects on Road Related Peak Flow Increases

As hypothesized in Chapter 1, vegetation conditions should increase the effects of roads on peak flows by increasing the volume of sub-surface flow intercepted by the cutslopes. However, as noted in Section 6.1, simulated peak flows do not support this hypothesis at the sub-catchment/catchment level. As shown in Figure 6-9, the increase in both the 2.3 T_r and 10 T_r associated with roads are comparable for the current and mature vegetation states. This finding contrasts with field results described in Chapter 4. However, the field results in Chapter 4 were at the local-hillslope scale and may not reflect the aggregate effect over a catchment. Figure 6-10 shows that the model-simulated results at the hillslope scale are consistent with the field study results—higher flows below immature vegetation than below mature vegetation. The reason this effect is not present at the sub-catchment scale is most likely due to desynchronization of peak flows from the collective hillslopes as demonstrated in Figure 2-3. Roads and clear cut locations over an entire catchment are essentially random, hence cancellation of peak flows at the catchment level may occur from desynchronization of flows. The model results may also indicate that the location of clearcuts is more important than the total amount of clearcuts in determining road effects on peak flows. That is, clearcuts located above areas with low road connectivity should not affect peak flows to the same extent as clearcuts above roads with high road connectivity.

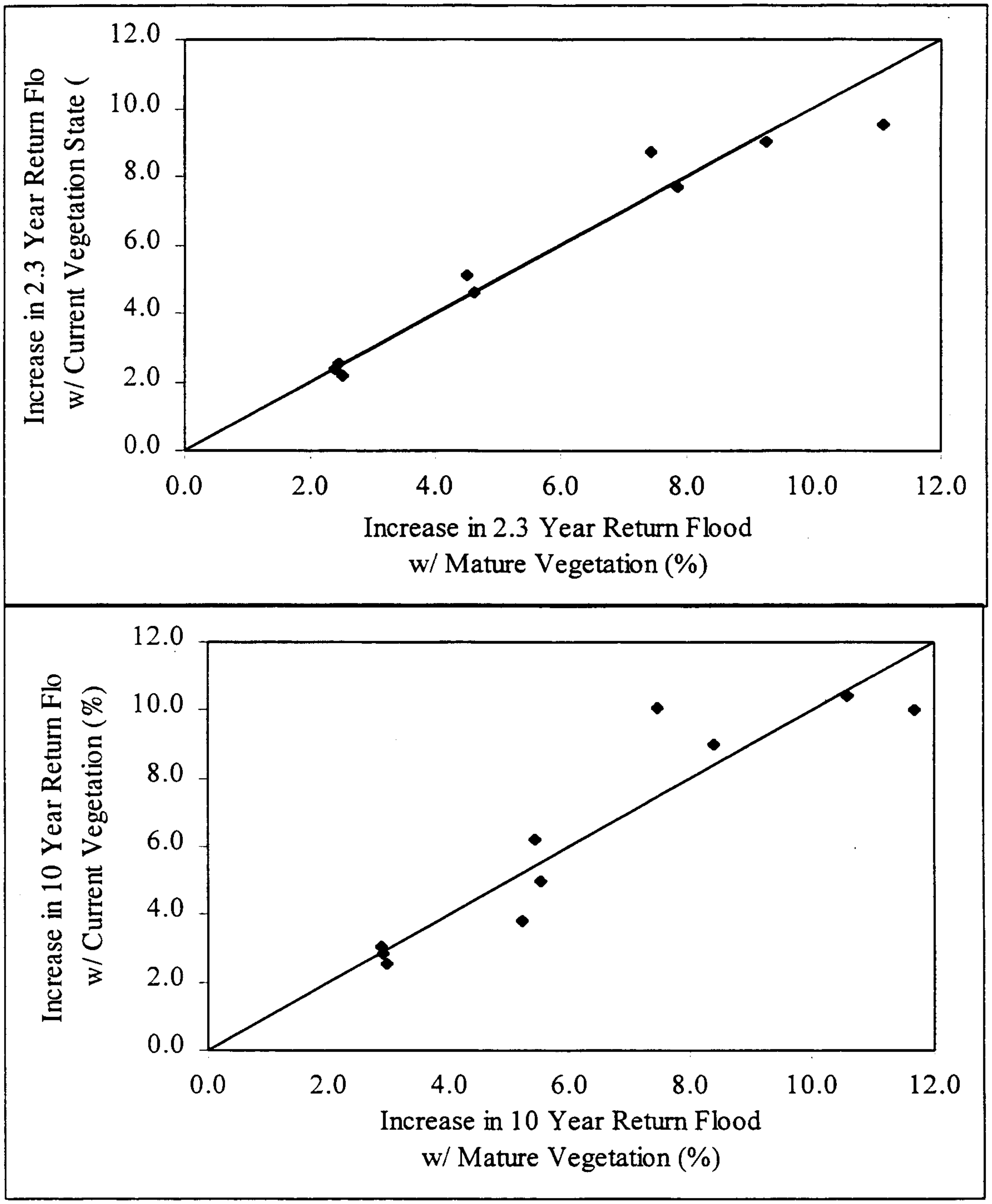


Figure 6-9: Effect of Vegetation State on Peak Flows Increases Associated with Roads

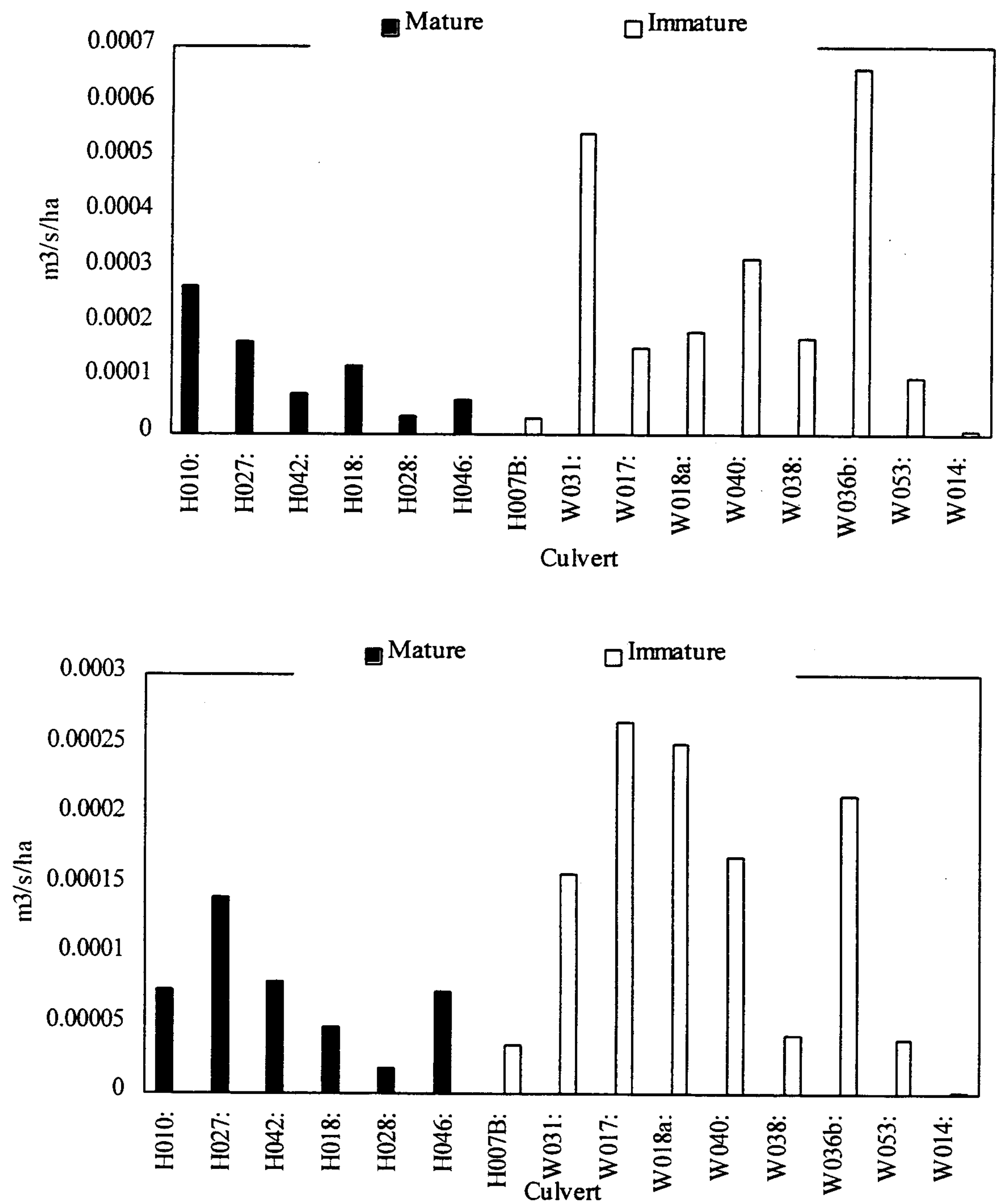


Figure 6-10: Simulated Culvert Flows for December 1996 (top) and March 1997 (bottom) Storms

6.2.4: Slope Influences on Road–Related Peak Flow Increases

Paired sub-basin comparisons to isolate road effects on peak flows associated with different slopes were not possible due to varying levels of culvert connectivity, increases DD_g, soil type, road area, road density, elevation, and road location. Therefore, only a general assessment can be made of slope effects. Figure 6-11 indicates that the simulated increase in $2.3T_r$ generally seems to be related to increases in slope. However, when soil type is isolated, the trend disappears for catchments with major soil types 3-4. Slope was hypothesized to influence the effect of roads on peak flows due to its interaction with sub-surface flow velocity and the road cutslope height. However, the road cutslope height was modified (as described in Chapter 5) to account for problems associated with soil depth and transmissivity calculations in DHSVM. The cutslope height was further modified to calibrate simulated ditch flows to field estimates. Therefore, the relationship between slope and road cutslope height is not direct, and a high correlation between slope and road effects on peak flows is not expected.

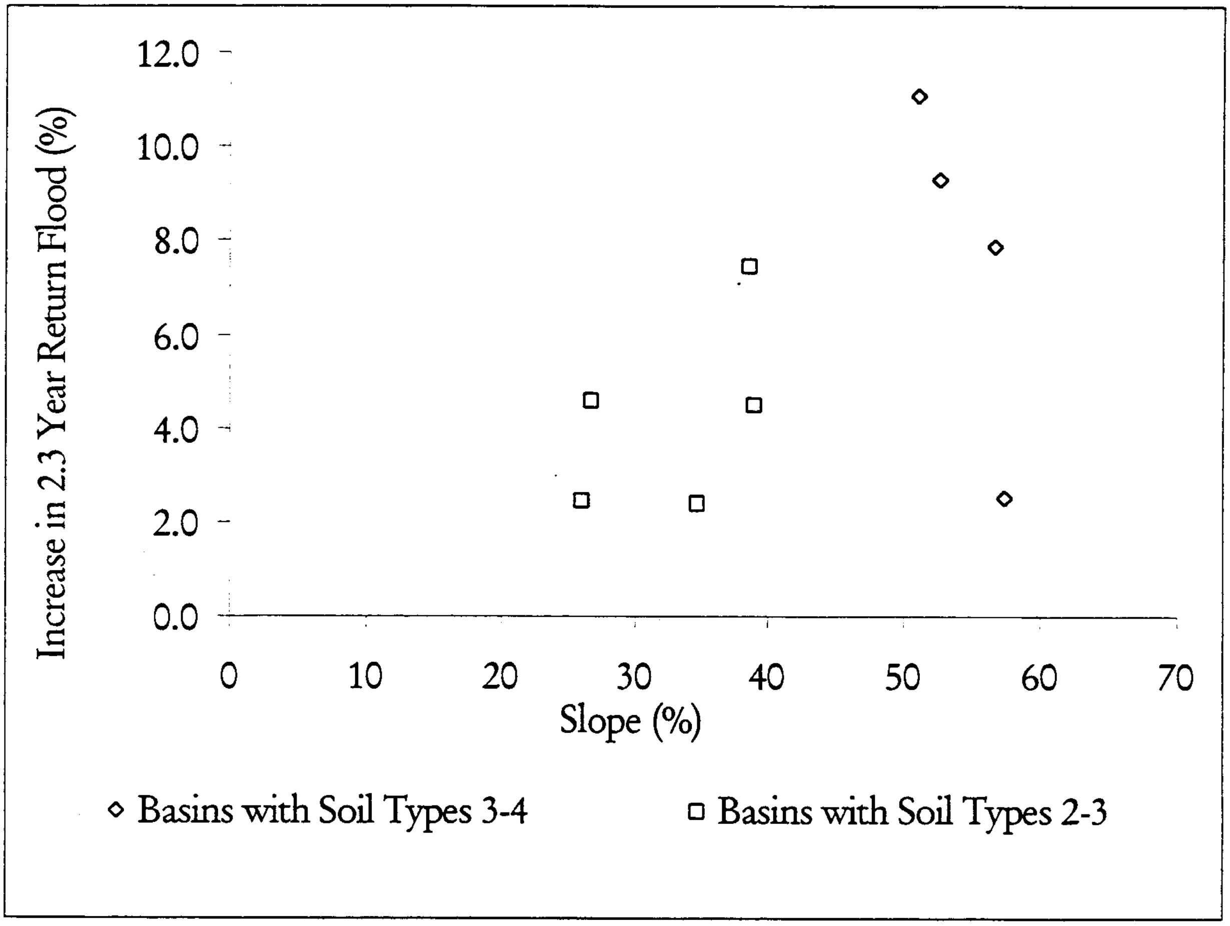


Figure 6-11: Effects of Slope on Peak Flows Increases Associated with Roads

6.3: Road Effects on Flood Hydrographs

The evaluation of road and harvest effects on peak flows have to this point focused on the magnitude of peak flows. In this section, general changes in the shape of the storm hydrograph associated with forest roads and harvest are investigated.

For the majority of storms, no changes in time to peak were observed from the simulated discharge in any of the catchments. This may be related to the length of the model time–step relative to the basin response time. Peak timing changes less than three hours would not be simulated by the model. Rise and recession times were typically advanced slightly as shown in Figures 6-12 through 6-14. The changes were somewhat more pronounced in catchments exhibiting a higher degree of road connectivity, specifically Lincoln, Hard, Ware, and Upper Deschutes Creeks. This effect is expected since it represents the degree to which sub-surface flow paths are altered. Nonetheless, changes in hydrograph shape were modest compared with observed changes in hydrograph shape associated with more extreme land use change, such as urbanization.

The predicted effect of forest harvest is to increase the magnitude of peak flows (Figure 6-15), an effect that has been observed in many previous field and modeling studies (reviewed in Section 2.3). Simulated rise and recession times did not change, nor did time to peak to within the 3-hour model time step. The magnitude of the increases in peak flows was related to the amount of forest harvest in a catchment.

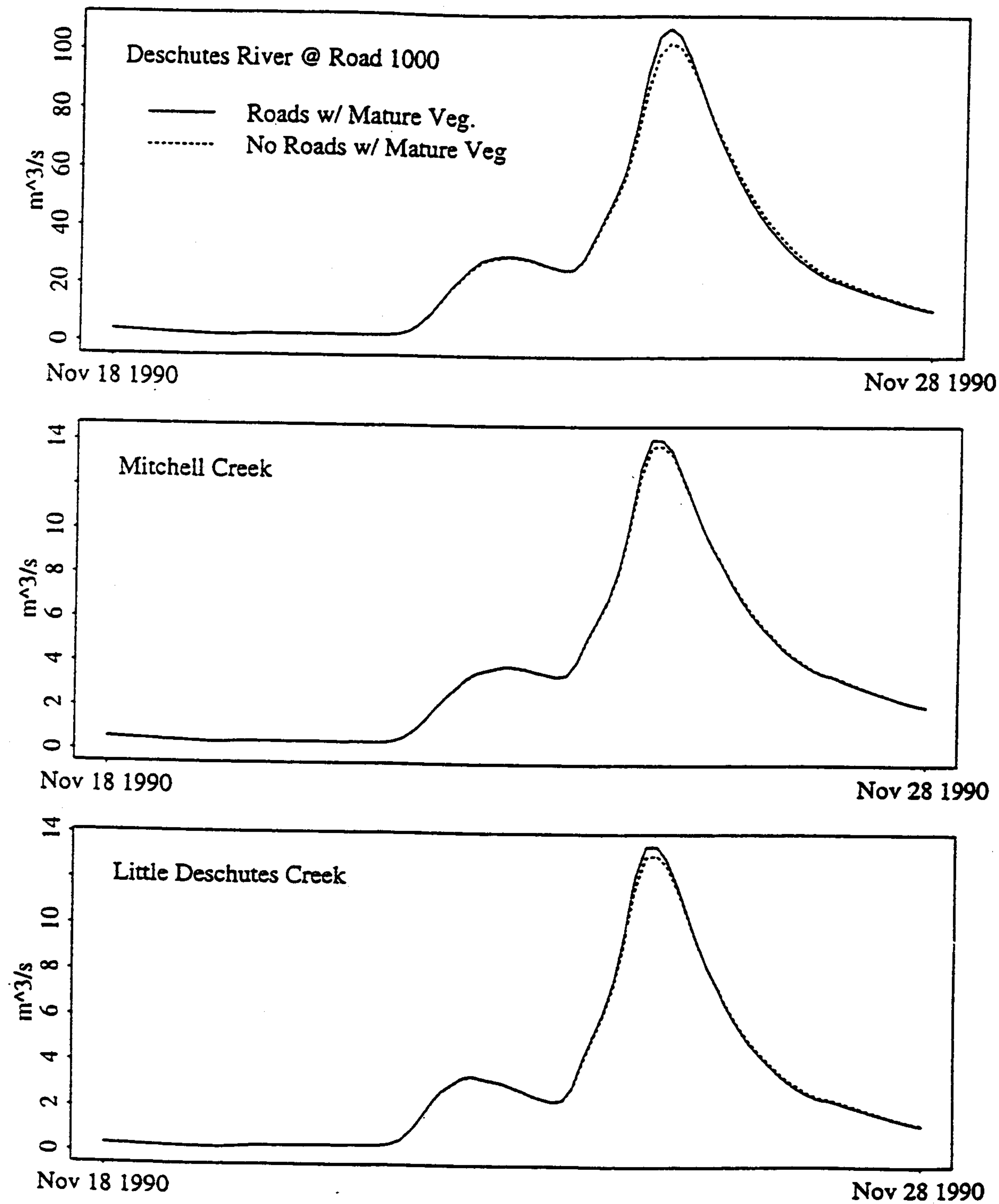


Figure 6-12: Simulated Road Effects on Storm Hydrographs for Deschutes River, Mitchell and Little Deschutes Creeks

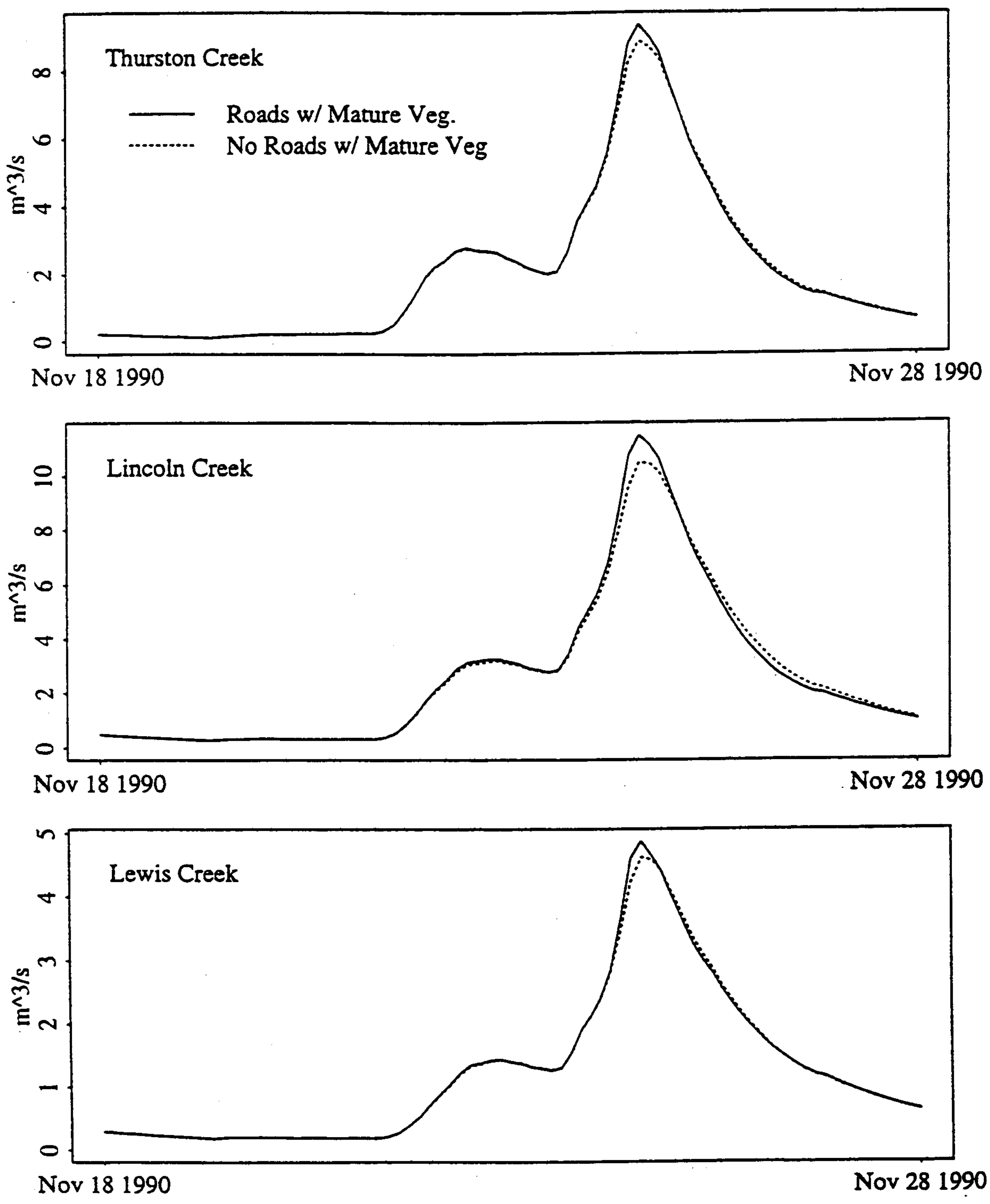


Figure 6-13: Simulated Road Effects on Storm Hydrographs for Thurston, Lincoln, and Lewis Creeks

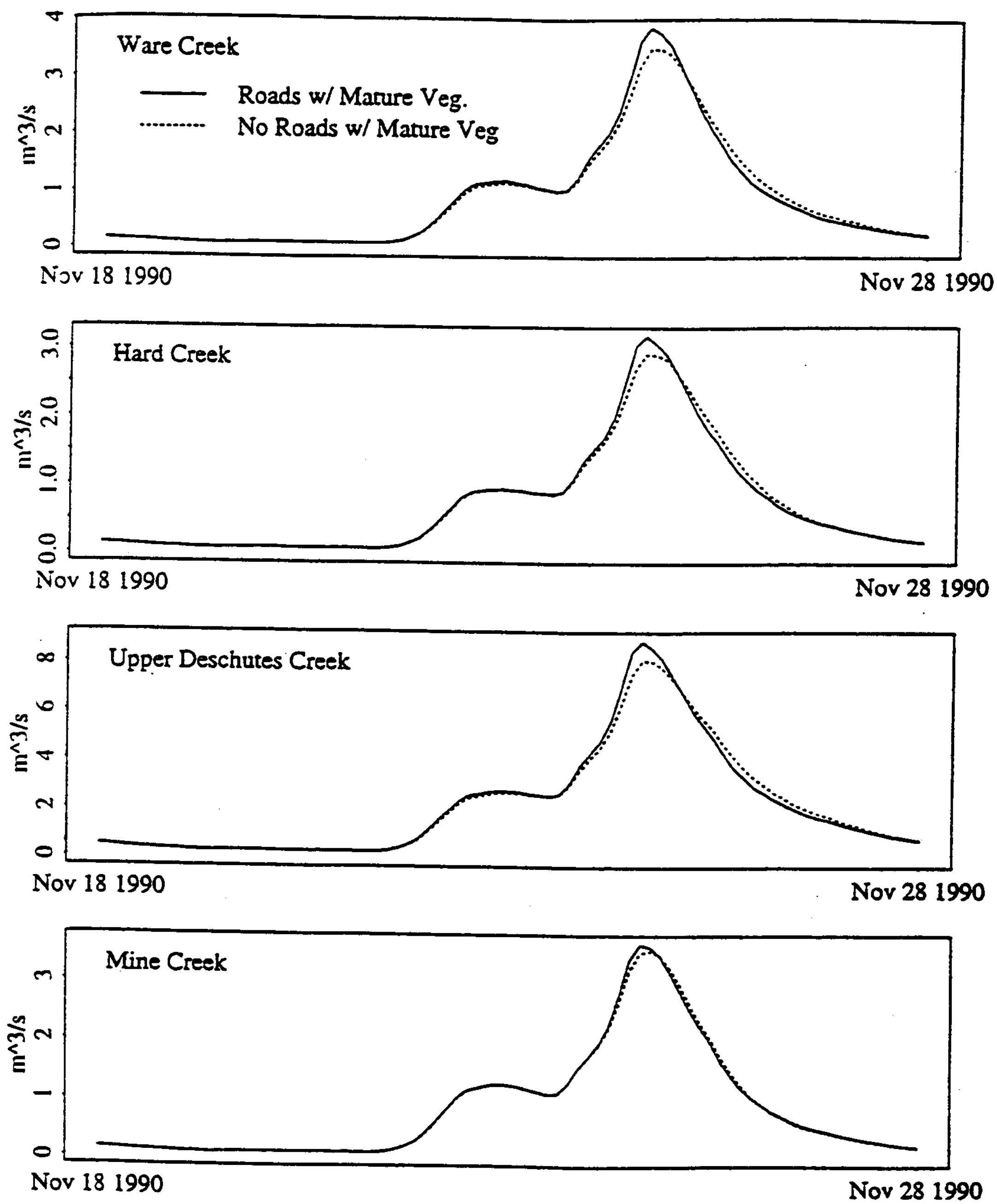


Figure 6-14: Simulated Road Effects on Storm Hydrographs for
Ware, Upper Deschutes, and Mine Creeks

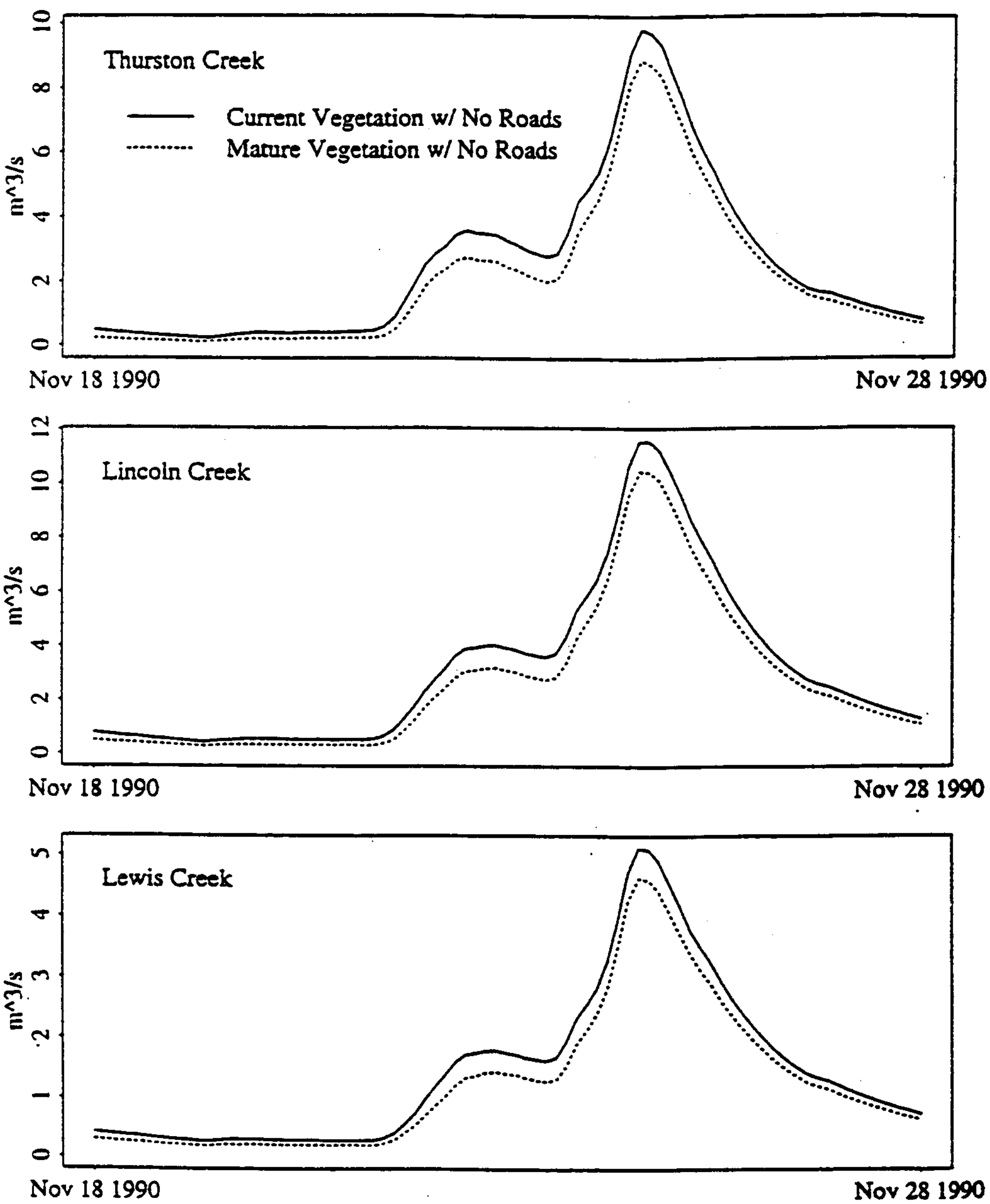


Figure 6-15: Simulated Harvest Effects on Storm Hydrographs for Thurston, Lincoln, and Lewis Creeks

Chapter 7: Summary and Conclusions

The objectives of this study were to: 1) examine topographic and vegetative characteristics affecting road generated runoff, 2) develop a predictive relationship between connectivity of the road networks to the natural drainage, and 3) identify relative effects of vegetation removal on peak flows. A central hypothesis of this research was that the design and placement of roads, and their interaction with the natural drainage system control the effect of forest roads and coincident timber harvest on streamflow peaks.

The first and second objectives were addressed through a field study that investigated factors influencing road-generated runoff in Hard and Ware Creeks, two headwater basins of the Deschutes River. Ditch runoff monitored in selected road segments indicated higher runoff in ditches draining clear cut areas than those draining forested areas. These results suggest that an interaction might exist between forest cover and road effects on hillslope runoff. Furthermore, valley bottom and mid hillslope position roads were found to have a higher ditch flow than ridge top roads. These results suggest that road hillslope location affects the potential for forest roads to enhance peak flows. Alternatively, road cutslope height did not appear to affect ditch runoff. These results extend a previous study in the same basin by Bowling and Lettenmaier (1997) by increasing the number of monitored sites from 13 to 20, but the results of the two studies are qualitatively similar.

Connectivity of the road drainage system to the natural channel was evaluated at 140 culvert locations selected by hillslope position and uphill vegetative conditions throughout the Deschutes Basin. Field estimates of topographic and vegetative conditions were collected at a total of 2171 culverts in the Deschutes Basin, including the 140 for which stream channel connectivity was evaluated. A logistic regression model was developed from this field information and GIS-derived topographic parameters at these 140 sites to predict the occurrence of ditch relief connectivity through gullies extending to the stream network. The model indicated that hillslope curvature and distance to the natural stream were the most important predictors of culvert connectivity. The model was tested on 73 ditch relief culverts classified in Hard and Ware Creeks by Bowling and Lettenmaier (1997) and correctly classified connectivity in 81 percent of all ditch relief culverts. Subsequent application of the logistic regression model to all 1447 ditch relief culverts in the Deschutes Basin indicated that roughly 24 percent of ditch relief culverts in the basin are connected to the stream network through the formation of gullies extending from the culvert outfall to the stream network. An additional 33 percent of the 2171 culverts sampled were classified as stream crossing culverts during the field survey. For the remaining 1100 culverts, no connection to the natural channel was identified. The results of the culvert connectivity study were used in the subsequent modeling study to evaluate road effects on peak flows.

The third study objective was addressed by application of the Distributed Hydrologic Soil and Vegetation Model (DHSVM) to the Deschutes River Basin above Road 1000. DHSVM explicitly models the hydrologic interactions of soils, vegetation, and meteorology. Flows were also predicted for nine major tributaries. The model was calibrated using field data and discharge records from the Deschutes River and Hard and Ware Creeks between October 1994 and July 1997. Calibration consisted of: 1) matching observed and simulated annual flows in the Deschutes basin, 2) general matching of predicted and observed snow lines in Hard and Ware Creeks, 3) general matching of observed and simulated ditch flows from monitored road segments in Hard and Ware Creeks, and 4) calibration of observed and predicted hydrographs in the Deschutes River, and Hard and Ware Creeks.

Much of the model implementation effort was associated with assuring drainage consistency of the road network. Another factor important in the calibration was the use of the PRISM precipitation data to represent the spatial distribution of precipitation within the basin.

Peak flows were simulated with and without roads for current and mature vegetative conditions in the upper Deschutes Basin as well as nine sub-basins with drainage areas ranging from 2.3 to 21 km^2. Results from these simulations suggest that:

- Road effects increase with flood magnitude. Roads alone increased the mean annual flood from 2.2 to 9.5 percent in the sub-basins modeled, with a 4.6 percent increase in the Deschutes Basin. However, the increase due to roads for the 10-year event ranged from 2.9 to 12.2 percent, with a 5.2 percent increase in the Deschutes Basin.

- Vegetation effects decrease with flood size. The simulated increase in the 10-year flood due to harvest ranged from 4.1 to 16.8 percent for the sub-basins modeled. However, the simulated increase in the 2.3-year return flood ranged from 4.8 to 18.0 percent.

- The largest increases in peak flows due to roads were roughly equivalent to those from harvest effects and were related to sub-catchments with high levels of road connectivity as determined by the logistic regression model.

- The effects of roads were roughly independent of the vegetation state in all sub-basins modeled. No synergistic effect was found in any of the basins modeled. However, as in the field study, a synergistic effect was found at the hillslope scale. The reason that this synergism is not seen at the catchment scale is thought to be related to desychronization of the peak flows from the hillslopes. The overall combined effect of roads and harvest was found to be roughly additive of the component effects.

- The combined effect of roads and harvest in the Deschutes Basin was simulated to increase the 10-year return flood by roughly 15 percent. For the modeled sub-basins the range was from 7.7 to 21.3 percent.

The modeling results suggest that road connectivity to the stream channel was the most important parameter in determining road effects on peak flows. That is, the extent to which the road modifies the effective channel network density relates to the magnitude of road effects on peak flows. These results indicate the effects of forest roads may be mitigated by the proper placement of drainage structures (culverts) to reduce road connectivity to the channel network. The regression model indicates that culverts placed to drain to concave hillslopes are more likely to connect the road drainage to the stream network. Likewise, culverts placed near streams are also more likely to form gullies below the culvert outfall.

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