AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Understanding the impact of low volume road networks on forested watersheds is important for future forest management and watershed restoration. This study characterized the hydrology of five segments of forest road in the Oregon Coast Range. Rainfall, infiltration, road surface runoff, and intercepted subsurface flow were measured at each road segment. Results indicate that these individual segments of forest road differ hydrologically, depending on how much subsurface flow they intercept from the hillslope.

The first objective of this study was to compare and contrast hydrologic behavior of ditch flow resulting from infiltration-excess overland flow on the road surface with ditch flow that was intercepted subsurface flow from the hillslope. Overland flow and intercepted subsurface flow were physically separated in the ditch by a divider and routed through two trapezoidal flumes at the bottom of each road study segment. Runoff derived from infiltration-excess overland flow on the road surface was ephemeral, responding to high intensity rainfall, and it ceased within minutes to hours after rainfall. This was the only type of flow observed in

road ditches at four of the five study sites. Subsurface flow intercepted from the hillslope was intermittent, occurring continuously during the rainy season with a more gradual, muted response to storms. This type of flow occurred, along with ephemeral ditch flow, at one of the five study sites. Ephemeral flow in the ditch of this site produced minimal runoff volume, no more than 4.5 m^3 (16 mm / m^2 of road), for storms up to 140 mm in depth. In contrast, intermittent ditch flow intercepted from the hillslope produced up to 801 m^3 (2800 mm / m^2 of road) for similar storms, 20 times more flow than all of the rainfall that had occurred on the road surface. Any ephemeral ditch flow derived from subsurface flow on the hillslope was not observed in this study, though it may exist.

The second objective of this thesis was to quantify the relationship between rainfall intensity, infiltration capacity and road surface runoff at the study road segments. A rainfall simulator was used to measure road infiltration capacities. Estimates of infiltration capacity from the rainfall simulation averaged 4 mm/hr and ranged from 0 to 11 mm/hr. Despite the low infiltration capacities, runoff volumes from the road surface were on average only 5 percent of natural rainfall, because rainfall intensity remained lower than infiltration capacity during most of the duration of storms. Infrequent pulses of high intensity rainfall overwhelmed the infiltration capacity of the road and produced surface runoff. Median lag time from peak rainfall intensity to peak discharge of road-derived ditch flow was 10 minutes on road segments with up to 250 m^2 of surface area. Two other estimates of the infiltration capacity of a given road were 1) the maximum rainfall intensity that did not produce runoff, and 2) the minimum rainfall intensity that did produce runoff. These intensities ranged from 0.5 to 11 mm/hr, similar to the infiltration capacity estimates from rainfall simulation.

Infiltration capacity and ephemeral road surface runoff were similar for all road segments in this study. Intermittent flow, intercepted from the hillslope, differed between roads and was two orders of magnitude greater than ephemeral runoff from the road surface. Intercepted subsurface flow has greater potential to

cause erosive damage than ephemeral runoff from the road surface, because of its large peak discharges and flow volumes.

HYDROLOGY OF FIVE FOREST ROADS IN THE OREGON COAST RANGE

By

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

Christine Erica Marbet, Author

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Hydrology of Five Forest Roads in the Oregon Coast Range

1. INTRODUCTION

The impact of forest roads on watershed hydrology and water quality in mountainous, forested terrain in western North America continues to be a focus of growing concern. Research on this topic in the past fifty years has addressed the impact of roads on peak flows, low flows, sediment budgets, and other watershed characteristics through paired watershed studies (Rothacher 1965, Harr et al. 1975, Beschta 1978, King and Tennyson 1984). In these studies, the effect of roads on watershed hydrology was hard to separate from the effects of logging, which often occurred simultaneously. However, the effect of roads on the sediment budget was much more clear. Chronic fine sediment from road surfaces and episodic mass failure of roads and adjacent hillslopes increased the amount of sediment in streams. Beschta (1978) described roads constructed during the late 1960's and early 1970's in the Alsea Watershed Study:

> "Though carefully located, constructed, and used, the roads nonetheless caused most of the sediment production from the watershed. The findings show that midslope roads in steep terrain can substantially increase sediment production. Continued improvements in road location, design, construction, and maintenance are needed if increases in sediment production are to be minimized."

New logging technology and improved road building practices have resulted in fewer, better built roads located in areas of the watershed that are less prone to failure (Wemple 1998, Sessions et al.1987, Robison et al. 1999). However, the legacy of forest road construction over the last century remains on the landscape. An extensive network of forest roads remains on National Forest land, even though logging has decreased to 1950's levels on public lands (Coghlan and Sowa 1998). At the same time, recreational use of National Forest roads is ten times higher than it was in the 1950's, and very little funding is available to

maintain the roads (Coghlan and Sowa 1998). Road densities ranged from 1.1 to 2.9 km/km^2 on private, state, and federal forest land that was surveyed in a landslide study in the Oregon Coast Range in 1999 (Robison et al. 1999). Wemple (1998) showed that forest roads remained a net source of sediment during a fifty-year return period flood on National Forest Land in the central Cascades of Oregon. Thus, despite the progress that has been made to improve roads in recent decades, a legacy of old road construction practices remains, and the comments of Beschta (1978) are still true.

Forest land managers have a suite of tools available to help minimize the delivery of sediment from the road surface into streams. These tools include shorter cross-drain spacing, sediment fences, settling ponds, armored culvert inlets and outlets, and vegetation. Also, recent efforts have focused on disconnecting the road network from the stream network. Similar strategies are used to handle groundwater intercepted by road cuts into the hillslope, even though this water source has greater erosive potential. Since Megahan (1972) and Burroughs et al. (1971) demonstrated that roads can intercept subsurface flow, other researchers have modeled the consequences for hillslopes (Dutton 2000, Tague and Band 2001, Wemple and Jones 2003 (In Press)) and for watersheds (La Marche and Lettenmaier 2001, Tague and Band 2001).

Currently, the design and maintenance of forest roads is blind to interception of subsurface flow, unless an obvious seep or gully is encountered. Accepted practices for road drainage may not prevent erosion from roads that intercept subsurface flow as well as they do for roads that do not intercept subsurface flow. To determine how important the interception of subsurface flow might be to the production of sediment from forest roads, a first step is to document the frequency of occurrence and magnitude of intercepted subsurface flow by roads in different topography and geology. This has been done in several ways in different mountainous regions (Burroughs et al. 1971, Megahan 1972, Fahey and Coker 1989, Reid and Dunne 1984, Vincent 1985, and Kahklen 1993, Ziegler and

Giambelluca 1997, Wemple 1998, McGee 2000, MacDonald et al. 2001, Gilbert 2002 and more). For this project, I have repeated the exercise in the Oregon Coast Range and physically separated the road surface runoff from the intercepted subsurface flow, in order to document its occurrence and attempt to predict the occurrence and magnitude of road runoff.

2. STUDY OBJECTIVES

This research project quantified the differences in the hydrology of road surface runoff and intercepted subsurface flow in road ditches. Road surface runoff is infiltration-excess overland flow (Horton 1945) from the road and ditch. Intercepted subsurface flow is ground water flow from the hillslope above the road. Gilbert (2002), in his master's project, monitored ditch flow and rainfall at six road segments in the central Oregon Coast Range in an area with sandstone geology and some igneous intrusions. He observed distinctly different hydrologic behaviors for these road segments. The hydrology of two of the six study road segments was characterized by intermittent ditch flow. The ditches of these roads segments supported a base flow throughout winter, and response to storms was muted and gradual. The hydrology of the remaining four road segments was characterized as ephemeral. For these road segments, the road ditch was dry most of the year and flowed only in direct response to rainfall. Intermittent and ephemeral ditches had very different hydrograph characteristics. Gilbert (2002) hypothesized that the different hydrologic behavior of the road ditches was caused by the source of water that flowed through them.

> "The data suggest that there are two potential sources of runoff to roadside ditches; 1) the road surface and 2) the upslope contributing area. The flow from road segments that have ephemeral flow is hypothesized to come from the road surface. The flow from road segments that have intermittent flow is hypothesized to come from subsurface flow from the upslope contributing area and is intercepted by the road. Runoff from both of these sources was undoubtedly present at all road segments, however differences in peak flows, flow volumes, and percent quickflow indicate that ditch flow was dominated by either one or the other source for any particular road segment."

I tested this hypothesis by dividing the ditch of a forest road into two ditches, one to carry intercepted subsurface flow from the hillslope and the other to

carry road surface runoff. I quantified the difference in hydrology between intercepted subsurface flow from the hillslope and road surface runoff. Since I knew the source of the water in each ditch, I could confirm the hydrograph characteristics of road surface runoff. Then I could use those characteristics to deduce the degree that intercepted subsurface flow made up ditch flow in Gilbert's road segments. Thus, the specific objectives of this thesis are:

1. To test the hypothesis put forward by Gilbert (2002) that the source of ephemeral ditch flow is the road and ditch surface, and the source of intermittent ditch flow is subsurface flow from the hillslope intercepted by the road.
2. To use rainfall, infiltration, and ditch flow data to describe the hydrology of surface runoff from forest roads.

3. LITERATURE REVIEW

3.1. ROAD CONSTRUCTION AND MANAGEMENT

Early guidelines for the spacing of ditch relief culverts for the Pacific Northwest were published forty years ago by Arnold (1957). These guidelines are still used in their original form or in some modified forms today (Baeder and Christner 1981). They use information on soil texture, road gradient, and rainfall intensity to prescribe ditch relief spacing for road surface runoff. Ditch relief spacing is the distance from one culvert (or a point of ditch drainage relief) to the next. A useful product of these guidelines is a table for the spacing of drainage relief, commonly called a table for culvert spacing, that engineers use to help layout roads. The objective of Arnold's (1957) spacing guidelines was to minimize ditch erosion from forest roads. A few years later, different objectives for cross drain spacing were presented in Packer and Christensen's (1964) "Guides for Controlling Sediment From Secondary Logging Roads." The objectives of the authors were to prevent the input of sediment to streams to maintain water quality for domestic and agricultural water uses. Packer and Christensen (1964) suggested that roads be located as far from streams as possible and that wood, vegetation, and large rocks be used to create roughness to minimize sediment movement from culvert outlets. They produced a table for culvert spacing for native surfaced roads in the Rocky Mountains that had shorter spacing between points of drainage relief than Arnold (1957).

Copstead et al. (1998) summarized road drainage guidelines that were published for several regions in North America. In this summary, the authors broadened the objectives for road drainage standards to include preventing roads from affecting stream channel development and the distribution of surface water and groundwater. Copstead et al. (1998) compared cross drain spacing tables from several publications and included additional factors that influence erosion, such as traffic volume, cross drain surfacing material, and drain geometry.

Piehl et al. (1988) carried out a survey of low-volume roads in western Oregon and found that culvert spacing was predominately longer than the standards recommended by Arnold (1957). This was especially true for state and private land. Erosion in the ditch was not common, but erosion at the culvert outlet increased with longer culvert spacing. In the entire survey of erosion at 515 ditch-relief culvert outlets, road-related landslides at two sites accounted for 72 percent of all erosion measured (Piehl et al. 1988). The presence or absence of intercepted subsurface flow at these sites was not mentioned.

Strategies to minimize surface erosion from roads include shorter cross-drain spacing, armored ditches, armored culvert inlets and outlets, geotextile sediment fences, geotextile liners within the road fill, check dams, grass seed, and mulches (Ministry of Forests, British Columbia 1997, Copstead et al.1998). Strategies to minimize erosion from interception of subsurface flow are less abundant. One strategy is to locate roads away from areas with high water tables or seeps. If roads are already constructed and cannot be relocated, shorter culvert spacing can be used. Under-drains and French drains can also be used where subsurface flow occurs to prevent damage to the road fill (Ministry of Forests, British Columbia 1997, Luce and Black 1999, Kramer 2001). For an under-drain, the road ditch is trenched below the water table, and a perforated drainpipe is installed. Graded aggregate is placed around the pipe to allow free drainage of water into it. Groundwater flows into the under-drain and is discharged through a standard cross-drain. A French drain is a simple version of the under-drain; graded aggregate is placed in a trench in the ditch and water is allowed to drain through a layer of large aggregate under the road subgrade. While useful for passing large volumes of water, under-drains and French drains are expensive and rarely used on low-volume logging roads. A final strategy to minimize the opportunity for a road to intercept subsurface flow is to build outsloped roads. Outsloped roads do not have drainage ditches and require less excavation of the hillslope, thus the potential

to intercept subsurface flow is less than a crowned road with a ditch (Kramer 2002).

During the late 1970's and early 1980's, forestland managers improved the planning, layout, construction, and maintenance of forest roads in western Oregon. Midslope road locations on steep hillslopes were avoided, and steep grades were used to access ridgetop locations (Sessions et al. 1987). Full bench, end-haul road designs replaced sidecast designs when steep hillslope locations couldn't be avoided. Sessions et al. (1987) reported a decrease in the occurrence and volume of road-related landslides associated with new construction practices, but no major storms had occurred since the new practices had been adopted. After a landslide-producing storm in 1996, several landslide inventories were carried out in Oregon. The density of road-related landslides in 1996 was similar to that of earlier inventories, however the average volume of the landslides had decreased significantly (Robison et al. 1999, Skaugset and Wemple 1999). In the central Cascades, road-related erosion was associated primarily with roads constructed before the 1960's and with midslope road locations, as opposed to valleys or ridgetops (Skaugset and Wemple 1999).

3.2. EFFECTS OF ROADS ON WATERSHEDS

The differences in the hydrology between forest roads and forest soils are well established. Infiltration-excess overland flow is rare in forested landscapes (Dunne and Black 1970), and this has been demonstrated for forested terrain in western Oregon (Harr 1977). Rainfall intensities rarely exceed the infiltration capacity of the forest floor. In contrast, infiltration capacities of the surfaces of gravel roads are less than 10 mm/hr (Table 3.1). Short-duration rainfall intensities (less than 15 minutes) would exceed that rate during most storms in the Oregon Coast Range. Overland flow occurs on road surfaces where such flow did not occur before the road was constructed. Subsurface flow can be intercepted by roads and routed to road ditches, where that process did not occur prior to road construction (Megahan 1972, Bowling and Lettenmaier 1997, Wemple 1998, Mcgee 2000). The ditch flow is discharged by culverts to discrete locations on forested hillslopes, or it is discharged directly into streams.

3.2.1. Paired Watershed Studies

The changes in watershed hydrology that can be caused by roads were first hypothesized as a result of paired watershed studies. Paired watershed studies involve multiple small watersheds. One watershed remains untouched as a control, while various combinations of road construction and forest harvest are applied to the others. It's difficult to separate the effects of road construction from forest harvest on water and sediment yield, because road construction and harvest occur too close in time to allow the effect of roads alone to be determined. However, changes in watershed hydrology are attributed to roads. Harr et al. (1975) hypothesized that when soil compaction from roads exceeded 12 percent of a watershed area, peak flows increased in the Alsea Watershed Study in the Oregon Coast Range (Harr et al. 1975). The volume of storm runoff in the Alsea Watershed Study did not increase by a detectable amount after road construction.

Table 3.1. Infiltration Capacities or Saturated Hydraulic Conductivities for forest roads.

Authors	i_c or K_s (mm/h)*	Location	Geology	Method
Reid and Dunne (1984)	0.5	Olympic Peninsula, Washington	sandstone, siltstone, graywackes	road plots of several hundred m^2, natural rainfall
Luce and Cundy (1994)	0.00005 - 8.82	Idaho and Montana	gneiss, sandstone, loess	road plots of $1m^2$ and $5m^2$, simulated rainfall
Vincent (1985)	< 1.0	Idaho	weathered, saprolitic granite	road plots of several hundred m^2, natural rainfall
Flerchinger and Watts (1987)	2.5 - 7.6	Nez Perce National Forest, Idaho	granite with gneiss surface grade	road plots less than 100 m^2, simulated rainfall
Flerchinger and Watts (1987) Literature Review	0.5 - 22.9	California, Idaho, New Mexico, Montana	multiple	multiple
Kahklen (1993)	< 1.0	Prince Of Wales Is., Alaska	glacial till over mudstone, siltstone, and greywackes	road plots of several hundred m^2, natural rainfall
Ziegler and Giambelluca (1997)	0.2 - 5.1	Thailand	granite, shale, sandstone, limestone	Disc permeameters
Luce (1997)	1.0 - 4.0	Salmon River, Idaho	granite, belt series	Road plots of $1m^2$, simulated rainfall

*i_c = infiltration capacity. K_s = saturated hydraulic condictivity

Jones and Grant (1996) reported that road construction and patch-cutting in the H.J. Andrews Experimental Forest (Oregon Cascades) increased peak flows as much as clearcutting alone. Upon reanalysis of Jones and Grant's data, Thomas and Megahan (1998) found that increases in peak flows were greater for the clearcut watershed than for the roaded and patch-cut watershed. Thomas and Megahan (1998) noted that peak flow increases attributed to logging in the clearcut watershed diminished with increasing storm size. That is, the larger the storm, the smaller the effect is of logging. For the roaded and patch-cut watershed, the effect of storm size on increase in peak flow was less evident. This difference in the effect of storm size on the increase in peak flow was attributed to the hypothesis that roads speed the flow of water from headwaters to outlet of watersheds the most during the largest peak flows (Thomas and Megahan 1998).

Wright et al. (1990) reported that road construction alone did not affect storm runoff in the South Fork of Caspar Creek (Northern California). However, 88 percent of the South Fork roads were within 61m of streams. The roads were located so low in the watershed that they had little potential to change hillslope processes and therefore change storm runoff. Forest harvest and road construction together did increase small storm peak discharges and storm volumes significantly in South Fork Caspar Creek, and hydrograph lag times decreased by 1.5 hours (Wright et al. 1990). Changes in peak flows were not detected for peak flows that occurred less than eight times per year. The increase in peak flows attributed to forest harvest was statistically significant for subannular peak flows but was not as significant for peak flows larger than the mean annual flood. For forest harvest, this effect can be explained by the potential for larger storms to overwhelm interception and evapotranspiration by vegetation. Thus, removal of vegetation should not have a significant impact on peak flows during large storms (Wright et al. 1990). Roads, on the other hand, have the potential to turn rainfall to surface runoff and to reroute subsurface flow to surface flow during storms of all sizes and possibly more so during large storms (Thomas and Megahan 1998). Another

explanation for the inability to detect changes in peak flows that are larger than the mean annual flood is that few of those storms have been observed. We simply don't have the statistical power to detect changes in peak flows for high return period storms, whether the changes are caused by logging or road building (Wright et al. 1990, Thomas and Megahan 1998, Bowling et al. 2000).

King and Tennyson (1984) investigated changes in streamflow in response to road construction in seven steep, forested watersheds (28-148 ha) in the Horse Creek Experimental Watershed, North Central Idaho. Less than 5 percent of the area of each watershed was converted to roads, and one watershed remained a control without any roads. In one watershed, where 67 percent of the watershed area was upslope of the road, a significant increase was observed in flows that were exceeded 25 percent of the time. Conversely, in another watershed where 25 percent of the area of the watershed was above the road, a significant decrease was observed in flows that were exceeded 5 percent of the time.

King and Tennyson (1984) hypothesized that the effect of roads on peak flows may be related to whether the contributions from road runoff are synchronized with the peak flows of the watershed. If peak discharges from roads occurred shortly before or at the same time as the peak discharge of the watershed, then contributions from road runoff would potentially increase the peak flow from the watershed. Wemple and Jones (2003 In Press) reported on this phenomenon in a study of culvert discharge from road segments in one of the H.J. Andrews experimental watersheds in the Oregon Cascades. Of the seventeen culverts where discharge was measured, five culverts produced peak discharge rates that totaled 5 to 10 percent of peak discharge at the watershed outlet, even though only 2.5 percent of the watershed's area was upslope from the road segments that drained to these culverts. Peak discharges from these culverts preceded or occurred simultaneously with the watershed outlet's peak.

The effects of forest roads on sediment yield, as demonstrated by paired watershed studies, are associated with road-related landslides. In contrast to

increased surface erosion from forest harvest, which increases after harvest and then gradually decreases with time, periodic mass wasting of road material during landslide-producing storms contributes the majority of road-produced sediment to sediment budgets of watersheds (Beschta 1978, Grant and Wolff 1991). Road-related debris flows during a 1964 storm in the H.J. Andrews Experimental Forest produced 88 percent of the total sediment yield during the twenty-nine year post-harvest record of Watershed 3 (Grant and Wolf 1991). Understanding the circumstances that lead to road-related landslides is essential to their prevention.

Improvements in road construction and logging practices have been demonstrated at Caspar Creek in northern California (Lewis 1998). During 1967, the North Fork Caspar was used as a control, and roads were constructed in the South Fork. Most of the roads were located within 61m of the creek, and they caused an initial 335 percent increase in annual suspended sediment yield. Subsequent tractor logging caused an additional 212 percent increase in annual suspended sediment yield. After several years of forest regeneration, South Fork was used as a control while North Fork was roaded and logged in 1985. Roads and cable yarding were kept away from streams, and no significant increases in suspended sediment or total annual yield of the North Fork were detected for the entire watershed. However, significant increases in storm suspended sediment load were observed at some of the sub-watersheds of North Fork, indicating that localized erosion of roads and logging areas in headwater streams did occur, even when their combined effect was not detectable at the outlet of the watershed.

3.2.2. Road Surface Runoff and Interception of Subsurface Flow

The surfaces of forest roads are compacted to provide strength and support under traffic from log trucks. The infiltration capacity of those surfaces is very low, often less than 10 mm/hr (Table 3.1). Runoff from road surfaces is infiltration-excess overland flow (Horton 1945), which is easily measured and modeled with precipitation data (Reid and Dunne 1984, Vincent 1985, Kahklen 2001). Overland flow from the road surface is the primary hydrologic process that was addressed in culvert spacing guidelines mentioned in Section 3.1.

Overland flow is rarely observed on forest soils in the Pacific Northwest, because the infiltration capacity of the soil is higher than maximum rainfall intensities (Rothacher 1965). The main pathway of storm runoff in forested soils is subsurface flow. Translatory flow is one mechanism suggested for subsurface flow (Hewlett and Hibbert 1967). Precipitation that falls on the hillslope infiltrates and displaces water stored in the soil matrix, which results in discharge of water at the stream channel. Movement of water through the soil of a steep hillslope is complex. Stormwater often flows laterally as a perched water table through steep hillslopes. This occurs when there is an abrupt transition from the highly permeable upper layers of the soil to mostly impermeable lower layers of the soil or bedrock (Whipkey and Kirkby 1978). Harr (1977) demonstrated that the saturated hydraulic conductivity of the soil decreased with depth to 1.5 meters on a steep hillslope in the Oregon Cascades. As a result, stormflow moved laterally downslope through the upper layers of the soil that had the greatest hydraulic conductivity. A large proportion of stormflow may move through soil macropores and fractures in weathered bedrock (Mosley 1979, Megahan and Clayton 1983, Ziemer and Albright 1987, McDonnell 1990, Montgomery et al. 1997, Keppler and Brown 1998).

The cutslope of a road creates an open face of soil and bedrock that can intercept subsurface flow. Megahan (1972) measured the intercepted runoff from a road cutslope and ditch in Northern Idaho. He found that 35 percent of hillslope

water was intercepted by the road, and 65 percent flowed under the road. He also determined that seven times more ditch flow came from the hillslope than from road surface runoff. McGee (2000) documented interception of soil water by cutslopes and lowering of the water table below two forest roads in Southeast Alaska, indicating that roads changed the path of stormflow from subsurface flow to surface runoff. Wemple (1998) found that potential runoff from the road surface was less than 10 percent of total storm runoff from nine monitored road ditches in the Oregon Cascades, indicating that large quantities of subsurface flow were intercepted.

3.2.3. Connection of Roads to Streams

In the absence of a road, subsurface flow passes through the soil of a forested watershed, concentrates in preferential flow pathways and topographic hollows, and emerges as surface flow in small streams. Once a road is built, some subsurface flow is routed to road ditches and discharged at point locations on the forest floor or into streams. Cross-drain culverts are often placed to drain ditch runoff into hollows, because they are natural drainage features. The contributing area of incipient channels is smaller in hollows that receive road drainage than in hollows that do not receive road drainage (Montgomery 1994). In other words, the addition of road drainage to an unchanneled hollow can cause subsequent channel formation and surface flow where there was none before. The contribution of water from road drainage in topographic hollows in steep terrain may increase the potential for landslides and debris flows (Montgomery 1994).

Concentrated water from culvert outlets also causes gullies to form. The conversion of subsurface flow to surface flow through road ditches and the connection of ditch flow to streams through gullies may speed the flow of water from headwaters to outlet of a watershed. In a study in the Oregon Cascades, Wemple et al. (1996) estimated that a length of road equivalent to 20 to 50 percent of the length of streams was directly connected to the stream system in the Blue

River and Lookout watersheds, depending on assumptions about road connections to streams and the lengths of the existing stream network. Bowling and Lettenmaier (1997) estimated that a length of road equivalent to 50 to 60 percent of the length of streams was directly connected to the stream system in two creeks in western Washington. Crocke and Mockler (2001) estimated that a length of road equivalent to 6 percent of the length of streams was directly connected to the stream system in a 57 km^2 watershed in southeastern Australia. Drainage density is defined as the number of channels in a watershed divided by the watershed area (Hewlett 1969). If the connected roads in the aforementioned studies acted as channels for surface runoff, then they effectively increased the drainage densities of their watersheds. This does not mean that roads increased the volume of water entering or leaving the watershed, but the flow path of water was rerouted from subsurface flow to surface channels. It is hypothesized that this would speed the flow of water from headwaters to outlet of a watershed, but little research has been done on the subject. Resulting changes in speed of drainage depend on the unique characteristics of individual watersheds.

The connection of roads to streams by runoff results in the delivery of road sediment to streams. Sediment from road surface runoff is generally finer than the stream sediments. Bilby (1985) and Bilby et al. (1989) reported that in western Washington, road sediment was finer than 0.004 mm and moved rapidly through first and second order streams. Duncan et al. (1987) experimentally introduced road sediment (less than 2mm in size) collected from ditches into two ephemeral streams in western Washington. Less than 45 percent of the added sediment ever reached the outlet of the study stream segments, which were approximately 100 m long. The sediment that did reach the outlets of the study segments was finer than 0.063 mm. The rest of the introduced sediment was trapped behind woody debris and vegetation in the channel, which demonstrates the potential for headwater streams to store sediment temporarily.

3.3. HYDROLOGIC MODELS AND ROAD SYSTEMS

The ability to model and predict runoff and erosion from forest roads is important for land managers who need to know their immediate impact on water quality and for researchers who are trying to understand their overall impact on watersheds.

3.3.1. Surface Runoff and Erosion

The unit hydrograph method (Viessman et al. 1989) was used to model infiltration-excess overland flow from roads in response to rainfall (Reid and Dunne 1984, Vincent 1985, Kahklen 1993, Kahklen 2001). Road segments were treated as individual catchments, and discharge and suspended sediment concentration were measured simultaneously. The average response of surface runoff to rainfall was used to develop a unit hydrograph, and a rating curve was developed to predict sediment concentration for any discharge. The unit hydrograph and sediment rating curve were used in combination with a long term rainfall record to predict water and sediment yield for individual storms and on an annual basis. Reid and Dunne (1984) used this method to determine that traffic significantly increases sediment yield from forest roads.

Researchers who used the unit hydrograph method assumed constant infiltration rates for road surfaces. Others modeled infiltration of road surfaces in greater detail. Luce and Cundy (1994) used a rainfall simulator to measure infiltration at 1 m^2 and 5 m^2 road plots. They used the Philip (1957) model of infiltration to predict runoff from road plots with different antecedent moisture conditions. Ziegler and Giambelluca (1997) used disc permeameters to measure infiltration of water into roads, roadside margins, agricultural land, and forest land in a watershed in Thailand. They also used the Philip model with a continuous rainfall record to simulate infiltration-excess overland flow from different types of land use in the watershed. The simulations suggested that roads and roadside

margins, due to their low infiltration capacities, contributed a greater proportion of runoff to the watershed hydrograph than other types of land use during small storms. Often, roads and roadside margins were the only surfaces that produced simulated runoff, because the rainfall intensities of storms are less than the infiltration capacities of agricultural and forest land in Thailand (Ziegler and Giambelluca 1997).

Physically based models can also be used to describe all the hydrologic processes that lead to infiltration-excess overland flow and erosion from small watersheds, and they can be applied to roads. Two examples are WEPP (Water Erosion Prediction Project) and KINEROS2 (A Kinametic Runoff and Erosion Model); both were developed by the U.S. Department of Agriculture. KINEROS2 is event based, so it does not address changes in vegetation, soil, and runoff between storms. KINEROS2 use a kinametic wave equation to simulate runoff and basic sediment transport equations to simulate erosion from raindrop splash and hydraulic forces (Smith et al. 1995). Ziegler at al. (2001) calibrated the model with rainfall simulation experiments on dirt road plots in Thailand with the goal of simulating erosion from an entire road system. They were able to use KINEROS2 to predict erosion from the plots, though they had to introduce a predictive relationship between erodibility and depth of loose sediment on the road surface.

WEPP simulates all processes that influence runoff and erosion, including, rainfall, snow, snowmelt, evaporation, infiltration, plant growth, transpiration, plant residue and canopy effects, soil properties, roughness, infiltration-excess overland flow, and rill and interrill erosion (Flanagan et al. 1995). The USDA Forest Service has developed an application of WEPP to forest roads called X-DRAIN (Elliot et al. 1999). An X-DRAIN user can enter climate type, soil type, and vegetative cover information into the program, and the output will be an estimate of average annual sediment yield and a table of recommended cross-drain spacing (Elliot et al. 1999).

In summary, the above models have been successful at estimating and predicting erosion from infiltration-excess overland flow from roads. They predict erosion from roads that do not intercept subsurface flow, but they are inaccurate for roads that do intercept subsurface flow.

3.3.2. Subsurface Flow

Subsurface flow, which is very different from overland flow, is not modeled by WEPP and KINEROS. The processes that govern subsurface flow are less visible, more difficult to measure, and less predictable because of the heterogeneity of geology, soil, and roots that occur below ground. Yet interception of subsurface flow by roads is often greater in magnitude and has more potential for erosion than road surface runoff (Megahan 1972, Wemple 1998). Researchers have used physically-based hydrologic models to predict the interception of subsurface flow by roads. Though they vary in complexity, all use the same conceptual model of how road cutslopes intercept water from the hillslope (Dutton 2000, Tague and Band 2001, Wemple and Jones 2003 In Press) (Figure 3.1). The road will intercept and reroute, to the ditch, the proportion of the simulated transient water table that rises above the depth of the road cut. If the soil depth is less than the height of the road cut, then all of the transient water table will be intercepted by the road. If the water table does not rise above the road cut, then none of it will be intercepted by the road. Some researchers have used a topographic index of wetness in calculations of subsurface flow (Beven and Kirkby 1979, Tague and Band 2001). The topographic index indicates that the wetness of a location on the hillslope increases with contributing area above that location and decreases with slope and soil hydraulic conductivity. The transient water table model and the topographic index do not account for complex patterns of subsurface flow through macropores and bedrock fractures.

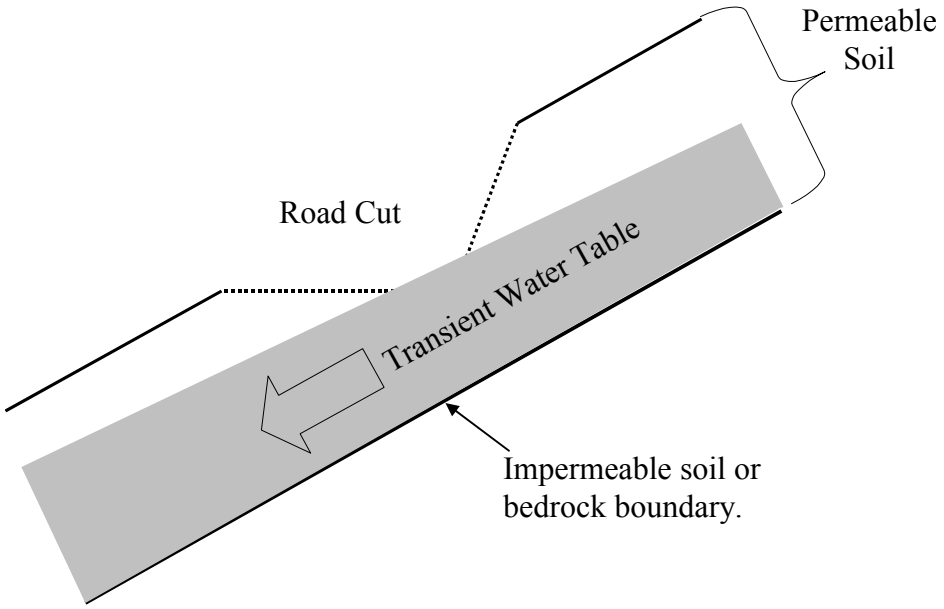

Figure 3.1 A conceptual model used by researchers to determine how forest roads intercept subsurface flow from the hillslope. The proportion of the transient water table that rises above the road cut is intercepted and routed down the road ditch.

Bowling and Lettenmaier (1997), La Marche and Lettenmaier (1998), and Bowling et al. (2000) used a physical model called DHSVM (Distributed Hydrologic Soil and Vegetation Model) (Wigmosta et al. 1994) that combines atmospheric, vegetative, soil, and topographic information to simulate streamflows. Tague and Band (2001) used RHESSys (Regional Hydro-Ecological Simulation System), another spatially distributed hydrologic model that incorporates the same water routing mechanism as DHSVM. Simulations by DHSVM and RHESSys predicted the same increases in mean annual flows that have occurred in paired watershed studies after logging and road building (Bowling and Lettenmaier 1997,

La Marche and Lettenmaier 1998, Bowling et al. 2000, Tague and Band 2001). Increases in peak flows attributed to roads were predicted by the models for smaller storms. The combined effects of logging and road building were predicted to be additive by both models. That is, there was no synergistic effect of the combination of logging and road building to increase peak flows (La Marche and Lettenmaier 1998, Tague and Band 2001).

As with any model that simulates complex physical processes, DHSVM and RHESSys simulate subsurface flow more simply and uniformly than real hillslope soils. However, they can be used for watersheds that have an impeding subsurface soil or bedrock layer, and they address road-affected physical processes not covered by infiltration-excess overland flow models.

4. METHODS

4.1. STUDY AREA

I selected five road segments for study in the central Oregon Coast Range (Figure 4.1), which is generally a steep, forested landscape. Summit elevations in the Oregon Coast Range average 450 to 750 m, and the highest summit, Mary's Peak, is 1250 m (Franklin and Dyrness 1973). Three of the road segments are located near the town of Burnt Woods, Oregon. They are identified as Bark Creek, Burnt Woods, and Eisele. The remaining two segments, Prairie Mountain and Bummer Creek, are located near Alsea, Oregon. Prairie Mountain is located on forestland managed by the United States Bureau of Land Management, and the other four segments are on forestland owned by Starker Forests Incorporated, a private, industrial forestland owner. All segments are gravel-surfaced roads used by recreational vehicles, management vehicles, and log trucks throughout the year.

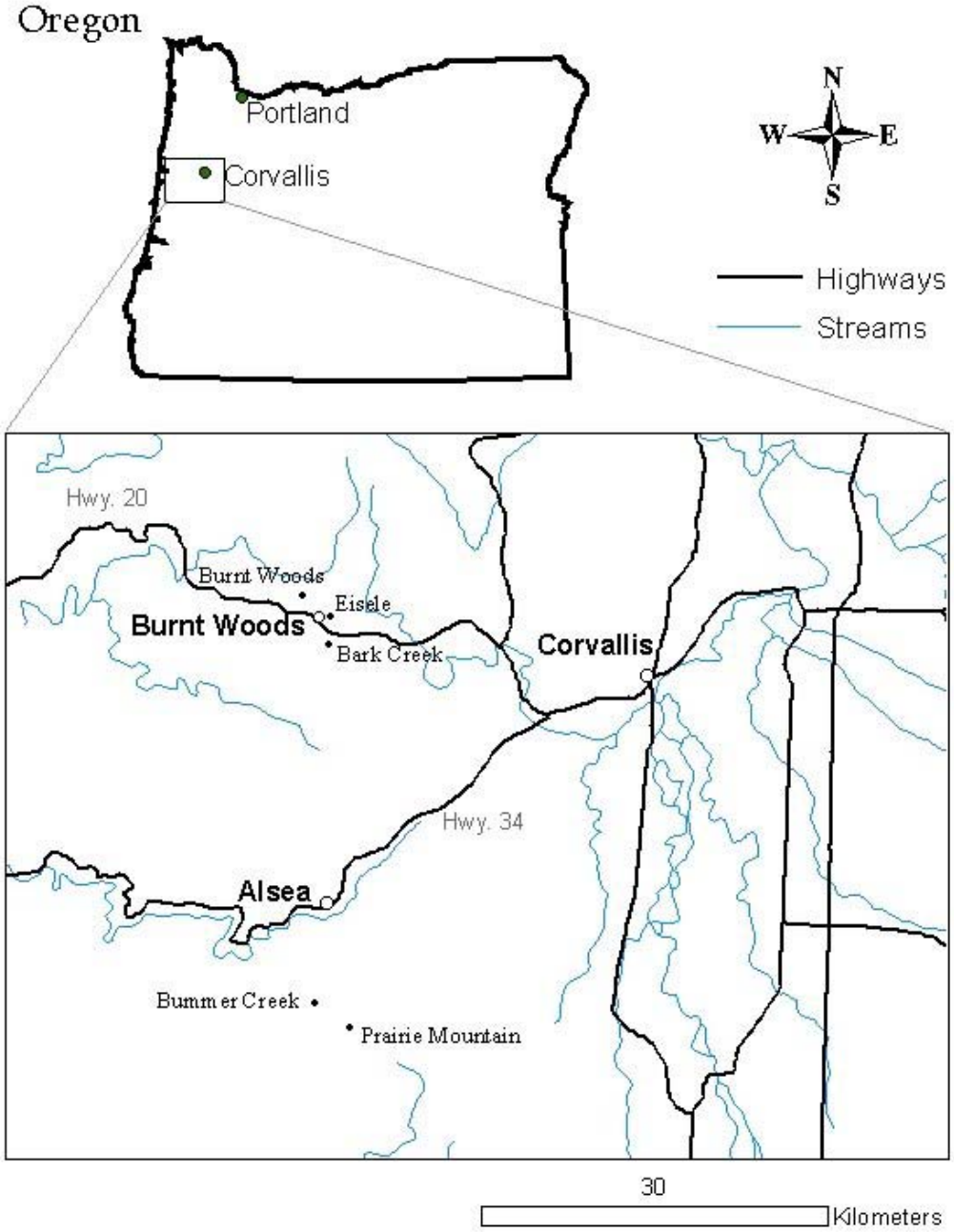

Figure 4.1. Location of study road segments in the Oregon Coast Range

4.1.1. Climate and Vegetation

The Oregon Coast Range has a marine climate with cool, wet winters and warm, dry summers. A thirteen-year record from a rain gauge in the study area indicates that the mean annual precipitation is 1722 mm. Rainfall intensity is very low; the maximum 2-year return interval 1-hour intensity from the same record is 16.5 mm/hr. Temperatures are mild; they rarely drop below 7 degrees C during the winter or rise above 35 degrees C during the summer at sea level. A transient snow zone exists at higher elevations, where a permanent snowpack is not formed, but snow may accumulate and melt several times during the winter. Research from the Oregon Cascades indicates that the transient snow zone is between 350 m and 1100 m (Berris and Harr 1986), but the range of elevation may be different in the Oregon Coast Range. A previous study in the Oregon Coast Range documented a transient snow zone at 650 m elevation (Gilbert 2002).

Overstory vegetation at the study sites is primarily Douglas-fir (*Psuedotsuga menziesii*) and Western Hemlock (*Tsuga heterophylla*), while the understory consists of salal (*Gaultheria shallon*), bracken fern (*Pteridium aquilinum*), sword fern (*Polystichum munitum*), and vine maple (*Acer circinatum*).

4.1.2. Bedrock Geology and Soils

The parent material of four of the study sites was rhythmically bedded marine sandstone, with interbedded silt and mudstone, of the Flournoy Formation (Early Eocene) (Orr et al. 1964). However the Prairie Mountain site was located on mixed sandstone and intrusive, igneous diorite or gabbro (Oligocene). Sandstone parent material weathers easily in the warm, moist climate of the Oregon Coast Range, resulting in deep, highly weathered soils. The Bark Creek, Burnt Woods, and Eisele study sites have soils of the Apt series, which are fine, isotic, mesic, Typic Haplohumults. Their most important characteristics are a very thick B-horizon, absence of gravel or cobble, and an underlying layer of weathered bedrock

(Kenezevich 1975). Despite the rapid soil-forming processes, the steep slopes of the Oregon Coast Range cause soils to creep and slide rapidly, and younger soils occur on steep slopes. Bummer Creek soils are Digger Series, loamy-skeletal, isotic, mesic, Dystric Eutrudepts, and Prairie Mountain soils were Bohannon Series, fine-loamy, isotic, mesic, Andic Dystrudepts (Corliss 1973).

Soils of the Oregon Coast Range have low base saturation, low bulk density, and high porosity. Infiltration capacities for forest soils in the area are rarely exceeded by rainfall rates (Corliss 1973). Overland flow over intact forest soil has not been observed in studies in the Oregon Coast Range (Harr et al. 1975).

4.2. SITE SELECTION

I chose five road study segments for observation and measurement of the hydrology of road runoff. A number of variables could have been used as selection criteria, including aspect, soil type, road surface material, time since construction, and hillslope shape (Luce and Black 1999). However, it was impossible to account for every variable with only five study sites. Rather, the selected road segments represented desirable characteristics for five process level case studies of road/hillslope interaction in the Oregon Coast Range.

Selection criteria for the study segments were:

- Expectation that the road would intercept subsurface flow
- Location midslope (neither valley nor ridge)
- Crowned road surface that was maintained
- Road gradient over 5 percent to ensure that water flowed out of the segment
- Sandstone parent material beneath the road
- Mature forest overstory on the hillslope above the road.

4.3. RAINFALL SIMULATION

We used a rainfall simulator (Modified Purdue) to measure the infiltration rate of the road surface at the five study sites, which provided insight into the hydrology of ditch flow in later analyses. The rainfall simulator was manufactured at the Rocky Mountain Research Station of the U.S.D.A. Forest Service, Moscow, Idaho. Its nozzle, located 3 m above the ground, dispensed water at a constant rate and swept across a fixed opening. We adjusted the rainfall rate of the simulator by changing the amount of time that the nozzle spent over the opening.

4.3.1. Experimental Setup

We installed three 1 m x 1 m plots randomly along the length of the road segment at each study site. The borders of the plots were made of aluminum, and we sealed them with bentonite (Figure 4.2). A vinyl apron was necessary to keep simulated rain that fell outside the plot from leaking through the loose gravel of the road surface and into the plot (Figure 4.2). However, the apron may have created raindrop splash that artificially enriched rainfall on the plot. This would have resulted in enriched runoff from the plot and caused us to underestimate the infiltration capacity of the road segments. The threaded outlet of the plot had a 30 cm pipe attached to it to capture runoff from the plot (Figure 4.2). The simulator itself was made of aluminum and was supported by three fiberglass legs at a height of 3 m. We surrounded the simulator and the plot with a windscreen, to minimize the variability of rainfall application caused by wind (Figure 4.3).

We used a small gas-powered pump to supply water from a 120 gallon (455 liter) tank to the simulator (Figure 4.3). Pressure gauges on the intake hose and at the simulator nozzle allowed us to set the water pressure at the same level for every simulation that we performed. Clean tank water, the windscreen, and the pressure gauges allowed us to maintain uniform rainfall spatially and temporally on the plots. We used a small generator to power the control box for the simulator.

We performed the simulations in July, August, and September 2001. Little rainfall occurs at that time of year in Oregon, so we carried out all of our simulations on dry roads. Each plot received two simulations. The first simulation was the dry run, because the road had been exposed to hot summer sun and no rain for several days. The second simulation was the wet run, because the plot was wet from the first simulation.

We began each run by placing a calibration box over the plot and turning on the simulator. The aluminum calibration box had the same dimensions as the plot (1 m x 1 m), but it was impervious. Therefore the discharge rate from the box was equal to the rainfall rate of the simulator. We placed a mesh screen on the floor of the box to minimize loss from splash. We turned the simulator on and waited ten minutes to fill storage capacity in the screen. When discharge from the box was steady, we took six to ten 30-second discharge measurements and averaged those measurements to estimate precipitation rate of the simulator.

After calibration of the rainfall rate, we simulated rainfall onto the plot itself. We noted the time at which ponding began on the plot surface and also the time of first runoff through the outlet pipe. As soon as runoff was produced, we took a 30-second volume measurement every minute. After 30 to 35 minutes of rainfall for the dry run, we again placed the calibration box over the plot. Twenty to thirty minutes passed with no rainfall on the plot as we calibrated the simulator for the wet run. Then we removed the calibration box and simulated rainfall on the plot for another 30 to 35 minutes; this was the wet run.

Figure 4.2. A rainfall simulation plot.

Figure 4.3. Rainfall simulator with windscreen cover.

4.3.2. Estimating Infiltration Capacity

I used two methods to estimate the infiltration capacity of the road surfaces at my study sites. The first was to measure the steady-state infiltration rate at the end of the second simulation (wet run) on each plot. Runoff and therefore infiltration had reached a steady state at the end of the second simulation. There was neither an increasing nor decreasing trend in consecutive runoff measurements. The infiltration rate is the rainfall rate minus the runoff rate. I calculated this steady state infiltration rate as the infiltration capacity by averaging measurements of infiltration rate for the last ten minutes of the wet run.

The second method for estimating infiltration capacity was to use empirical equations to model infiltration rates of road surfaces at the study sites. I used linear regression with the simulation data to parameterize the Philip (1957) and the Green and Ampt (1911) models of infiltration. The Philip model was used by Luce and Cundy (1994) and Green and Ampt was used by Flerchinger and Watts (1987) to model infiltration on gravel surfaced roads. The Green and Ampt (1911) infiltration equation, as presented by Hillel (1998) takes the form:

$$\boldsymbol{i = i_c + b/I} \qquad \textbf{(4.1)}$$

Where $\boldsymbol{i}$ is the infiltration rate (mm/hr), $\boldsymbol{I}$ is cumulative infiltration (mm), $\boldsymbol{i_c}$ is steady state infiltration rate (mm/hr), reached as cumulative infiltration approaches infinity, and $\boldsymbol{b}$ is an empirical coefficient (Figure 4.4). The assumptions for the Green and Ampt infiltration model are a sandy soil, surface ponding, a sharp wetting front, and uniform moisture content behind the wetting front. When no infiltration has occurred ($\boldsymbol{I} = 0$), infiltration rate is infinite.

The Philip (1957) infiltration equation, as presented by Hillel (1998) takes the form:

$$\boldsymbol{i = i_c + S/2t^{1/2}} \qquad \textbf{(4.2)}$$

Where $\boldsymbol{i}$ is the infiltration rate (mm/hr) at time $\boldsymbol{t}$ (hr), $\boldsymbol{i_c}$ is the steady state infiltration rate (mm/hr), and $\boldsymbol{S}$ is sorptivity, a measure of the initial absorptive properties of the soil (Figure 4.4). Surface ponding is an assumption of the Philip model.

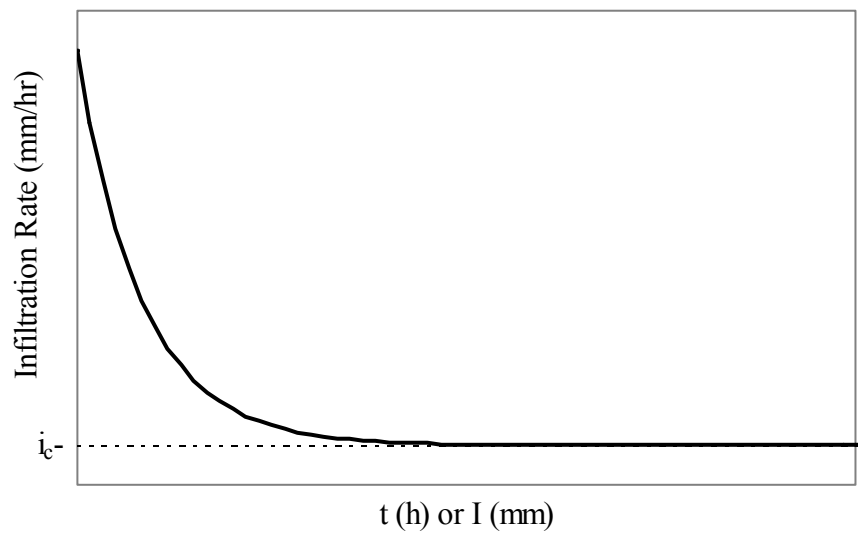

Figure 4.4. Infiltration curve for Philip (1957) or Green and Ampt respectively. The y-axis is infiltration rate. Infiltration rate starts out at infinity and then decreases until it reaches $\boldsymbol{i_c}$, the infiltration capacity of the soil.

4.4. MEASUREMENT OF NATURAL RAINFALL

4.4.1. Experimental Setup

My objective was to measure the rainfall that fell on each road segment. I installed tipping bucket rain gauges (NovaLynx Corp., Grass Valley, CA.) with Hobo event data loggers (Onset Computer Corp., Bourne, MA.) in an open area no more than 900 m from each road study segment to measure precipitation. Each rain gauge had an 8-inch (20.3 cm) orifice with buckets that held 0.01 inches (0.254 mm) of rain. Prior to the field season, I calibrated the rain gauges to within 5 percent measurement error. Temperature monitors (Hobo, Onset Computer Corp., Bourne, MA.) installed at each road segment recorded temperature. A drop in temperature to below 0 degrees C indicated the precipitation had changed from rain to snow. I downloaded rainfall and temperature data every two weeks from October 2001 to May 2002.

4.4.2. Precipitation Analysis

I summarized the rainfall record from each rain gauge several ways. It is reasonable to assume that ditch flow from the largest storms causes the most damaging erosion on forest roads, so I selected the ten largest storms for this analysis. A storm was a period of time when more than 2.5 mm of rain fell, and no more than two hours passed between tips of the rain gauge bucket. This corresponds to a minimum rainfall rate of 0.1 mm/hr and delineates the periods of precipitation that increased intercepted subsurface flow from the hillslope. Rainfall occurred more continuously at the Prairie Mountain study site due to its higher elevation, and consequently a single storm event at Prairie Mountain was often divided into multiple storms at the lower elevation sites. Runoff from the road surface has been shown to be driven by pulses of high intensity rainfall that occur several times during a storm (Gilbert 2002, Reid and Dunne 1984). I defined a

pulse of high intensity rainfall as a period of time when more than 1 mm of rain fell and no more than twelve minutes passed between tips of the rain gauge bucket. This corresponds to a minimum rainfall rate of 1 mm/hr.

The information I extracted for each storm was: begin time, end time, depth (mm), duration (hr), average intensity (mm/hr), and storm centroid. I calculated the average storm intensity by dividing storm depth by storm duration. I gathered the same data and calculated the same variables for the pulses of high intensity rainfall.

I identified periods of snowfall using field notes, the temperature record, and the precipitation record (Figure 4.5). Periods of no precipitation had large diurnal temperature fluctuations, and periods of active rainfall had temperatures above 0 degrees C that only fluctuated slightly. Periods of snowfall had temperatures below 0 degrees C and no record of precipitation at the rain gauge. A period of snowmelt could be observed in the rainfall record when the temperature rose above 0 degrees C immediately following a period of snowfall (Figure 4.5). I eliminated any storms from the analysis that showed evidence of snowfall, snowmelt, or rain-on-snow in the precipitation/temperature record.

I converted the event-based rainfall data into 5-minute intensities (mm / 5 minutes) for the analysis described in Chapter 7. Some information may have been lost in this process, because rainfall intensity is not uniform across 5-minute intervals (Habib et al. 2001). I observed that the buckets in rain gauges with eight-inch orifices tipped no more than three times per minute during the highest intensity rainfall. Three tips per minute equals a rainfall intensity of 46 mm/hr, which is much higher than a normal rainfall rate for the Oregon Coast Range. A more normal rainfall rate of 3 mm/hr would have caused the buckets to tip only once in five minutes. If the buckets tipped less than once every five minutes, the rainfall attributed to one tip would be distributed among several time intervals. The rainfall intensity that causes less than one tip in five minutes may not always be uniform. However, the benefit of 5-minute data was that the 5-minute timescale was short enough to capture rapid changes in ditch flow on the road surface runoff.

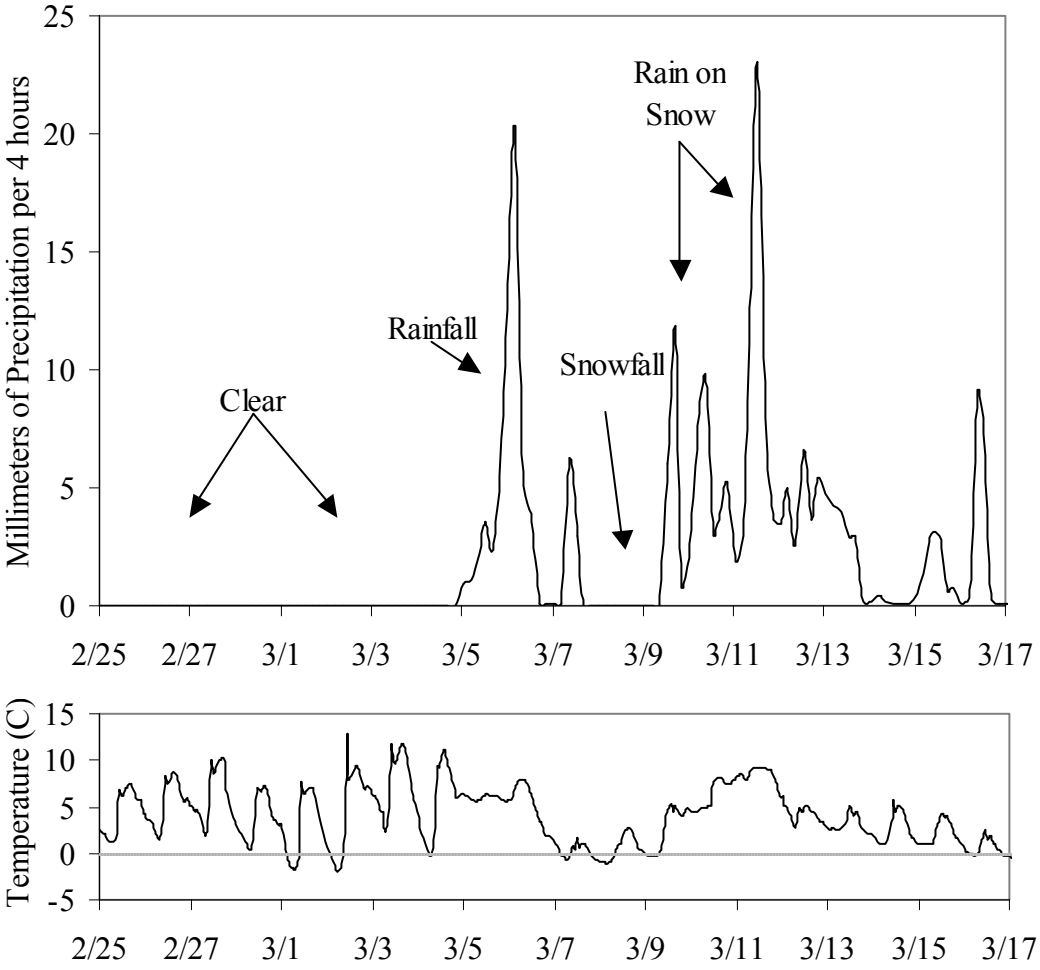

Figure 4.5. An illustration of precipitation and temperature patterns for Bummer temperature graph indicates zero degrees Celsius.

4.5. MEASUREMENT OF DITCH FLOW

4.5.1. Experimental Setup

My objective was to measure the quantity of runoff that flowed from each road segment in response to rainfall. I used trapezoidal flumes to measure runoff. I installed a divider and two flumes in each ditch in order to measure intercepted water from the hillslope separately from road surface runoff. Figure 4.6 illustrates the layout of the study sites and establishes the terminology that will be used in the rest of the thesis. The ditch space that is between the divider and the cutslope will be called the hillslope side of the ditch, which carries subsurface flow intercepted from the hillslope. The flume at the base of the hillslope side will be called the hillside flume. The ditch space between the divider and the road will be called the road side of the ditch, which carries overland flow or surface runoff from the road. The flume at its base will be called the roadside flume. Because the roads were crowned, surface runoff was generated only by the inboard side of the road (Figure 4.6).

Several people helped with installation of equipment at each road segment, which will be explained below. We isolated the contributing area of the road surface by digging water bars at the top and bottom of each segment. We then separated the ditch longitudinally into two ditches. We did this by installing a vinyl divider into the ditch (Figure 4.7 and Figure 4.8). The divider was buried 30 cm deep into the ditch and stood 20 cm high above the ditch floor. We compacted the soil around the divider and allowed it to settle for one year. This divider acted as a barrier that separated road surface runoff from subsurface flow that was intercepted by the road cutslope. It was assumed to be water-tight, and it did appear to be so in most of the later results. However, there is no way of confirming the assumption. Occasions when the divider did not appear to be water-tight are documented.

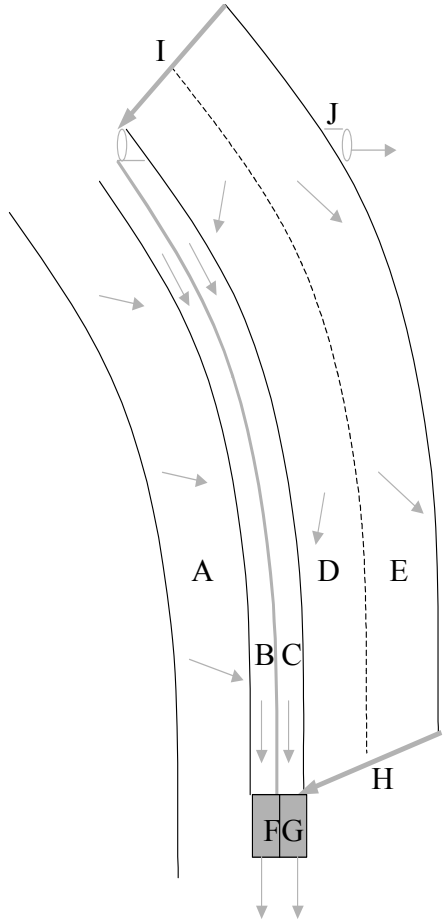

Figure 4.6. A plan view of study road segments with associated terminology.

A. Cutslope
B. Hillslope side of the ditch, carries intercepted subsurface flow.
C. Road side of the ditch, carries overland flow, surface runoff from the road.
D. Inboard side of the road, drains to road side of ditch.
E. Outboard side of the road, drains away from road.
F. Hillside flume
G. Roadside flume
H. Lower water bar, drains to roadside flume.
I. Upper water bar, drains water from above the segment into a culvert.
J. Culvert, drains water from upper water bar underneath the road.

Figure 4.7. Installation of a divider into the ditch at Burnt Woods, Oregon.

Figure 4.8**.** Placement of flumes in the ditch at Burnt Woods, Oregon.

At the bottom of each segment, we installed two trapezoidal flumes (Composite Structures Inc., Aromas, California), one for either side of the divider (Figure 4.8). The upstream ends of the flumes were fitted with a ¾ inch (1.9 cm) plywood board, which was buried 15 cm below the soil surface to prevent subsurface leakage below the flumes. The downstream ends of the flumes were fixed to fenceposts to ensure that they were stable and level. The flumes were equipped with polyvinyl chloride stilling wells. Float/weight pulley systems with Starlog data loggers (Unidata (America), Lake Oswego, Oregon) measured and recorded water level in the wells at one-minute intervals. Resolution of these systems was 0.2 mm. The flume stage-discharge relationship was provided by the manufacturer:

$$\textbf{Discharge} = 1.55*(\textbf{Stage})^{2.58} \qquad (4.3)$$

Stage units were in feet, and discharge units were in cubic feet per second. I converted the metric data from the stilling well into feet in order to use the stage-discharge equation.

4.5.2. Hydrograph Analysis

I characterized hydrographs from both the hillslope side and road side of the ditch divider, in order to compare intercepted subsurface flow to road surface runoff. The characteristics of the hydrograph illustrate how ditch flow from different sources respond to rainfall. I expected to find a hydrograph that resulted from road surface runoff as a sharp rise from no discharge to maximum discharge and then a steep fall back down to no ditch flow. I expected to find a hydrograph that resulted from intercepted subsurface flow as an increase in ditch flow that occurred during the recession of a previous hydrograph or during a period of slowly receding base flow. I used two methods to determine the end of storm flow for hydrographs resulting from subsurface flow. First, I used the Hewlett and Hibbert (1967) base flow separation method to separate quickflow from baseflow. The hydrograph separation line was an objective means of delineating quickflow. The total volume of water that ran off from the hillside component of ditch flow, including base flow, was also important. Total runoff volume is defined as the amount of flow that would pass through a culvert between the initial rise in the hydrograph to three days after the end of rainfall. I matched hydrographs manually (by date and time) to the storms or pulses of rainfall that resulted in ditch flow.

I determined begin time, end time, duration (hr), time of peak, peak stage (mm), peak discharge (l/sec), total runoff volume (liters), and concentration time (hr) for each hydrograph. Concentration time was the elapsed time from the initial rise in the hydrograph to the peak discharge. This definition of concentration time is for subsurface flow (Beven 1982), but I also used it for overland flow from the road surface in order to compare with subsurface flow. An alternative definition of concentration time for overland flow in urban watersheds is the time it takes for runoff to flow from the headwaters to the watershed outlet (Dunne and Leopold 1978). I did not use this definition.

I calculated runoff ratios for storms and pulses of rainfall.

Runoff Ratio = Total Volume of Runoff / Total Volume of Rainfall (4.4)

The runoff ratio is the proportion of water that fell on the road surface that actually occurred as runoff in the ditch.

It was also possible do a simple water balance for rainfall on the road surface, assuming that interception was negligible in the canopy gap over the road.

Rainfall – Runoff = Infiltration (4.5)

Using equations 4.6 and 4.7, I calculated average rainfall and infiltration rates for the road by dividing rainfall depth and depth of infiltrated rainfall by the duration of the storm.

Total Storm Rainfall / Storm Duration = Average Rainfall Rate (4.6)

Total Infiltration / Storm Duration = Average Infiltration Rate (4.7)

Finally, I estimated the infiltration capacity of the road surface to be the maximum five-minute rainfall intensity that did not produce runoff and also as the minimum five-minute rainfall intensity that did produce runoff (Reid and Dunne 1984, Vincent 1985, and Kahklen 1993). I compared these estimates of infiltration capacity with those determined using the rainfall simulator.

5. RAINFALL SIMULATION

5.1. RESULTS

The first step in determining the hydrology of forest roads is to measure the infiltration capacity of the road surface and understand how this property affects infiltration-excess overland flow. I used a rainfall simulator to estimate infiltration capacity of the road surface at every study site. A typical rainfall simulation is shown below (Figure 5.1). During the first simulation (dry run) it took an average of five minutes for water to pond on the plot and cause surface runoff. The first runoff was clear of sediment during some dry runs, which indicated that the cover on the downslope end of the plot had leaked. The leakage showed up in the data as an early plateau of low-volume runoff during the dry run (Figure 5.1). Once detected, this initial runoff was subtracted from subsequent runoff values. Simulated rainfall ponded almost immediately during the second simulation (wet run), and the final runoff rate at the end of this run was almost always greater than the final runoff rate during the dry run.

I estimated the infiltration capacity of each road plot by averaging infiltration rates from the last ten measurements of the second run (Figure 5.1). I used the mean infiltration capacity of all three plots on the road as an estimate of mean infiltration capacity for the road segment. Infiltration capacities of individual plots ranged from 1.7 mm/hr to 9.0 mm/hr (Figure 5.2). The mean infiltration capacity for individual road segments ranged from 2.4 to 5.4 mm/hr (Table 5.1). An overall mean infiltration capacity for the forest roads in this study was 4.0 mm/hr with a 95 percent confidence interval of 2.9 to 5.1 mm/hr.

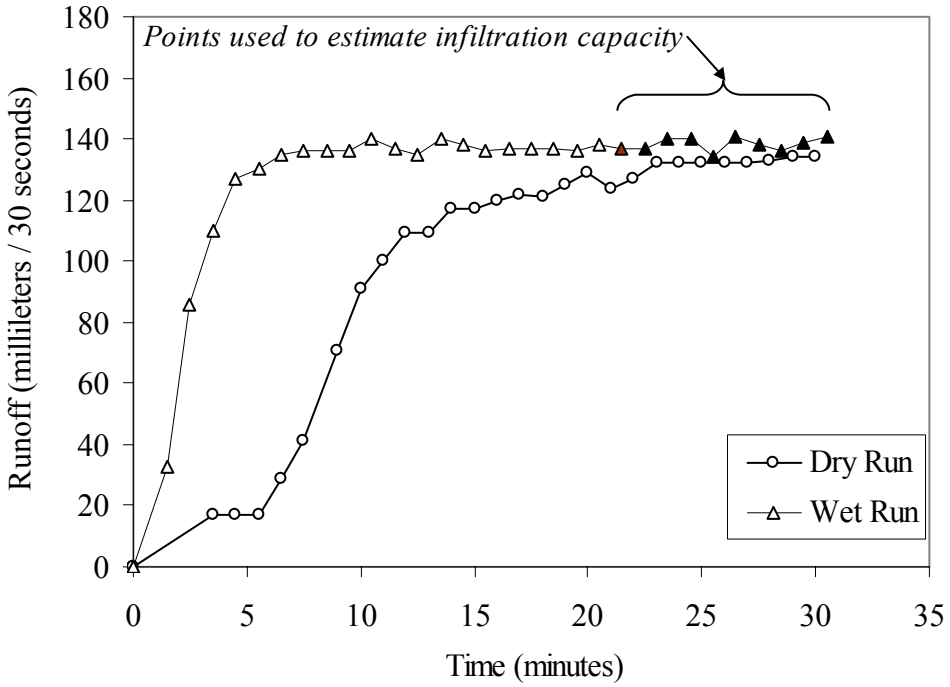

Figure 5.1. Runoff from a plot on the Bummer Creek road segment

Table 5.1. Means and 95 percent confidence intervals of infiltration capacity (mm/hr), as estimated from three plots at each of the of the five study sites. The overall mean is an average of infiltration

Site	Mean	Upper 95% CI	Lower 95% CI
Bark Creek	3.2	6.1	0.4
Bummer Creek	5.4	6.5	4.4
Burnt Woods	4.8	10.7	0.0
Eisele	2.4	4.0	0.8
Prairie Mtn.	3.8	4.3	3.2
Overall Mean	**4.0**	**5.1**	**2.9**

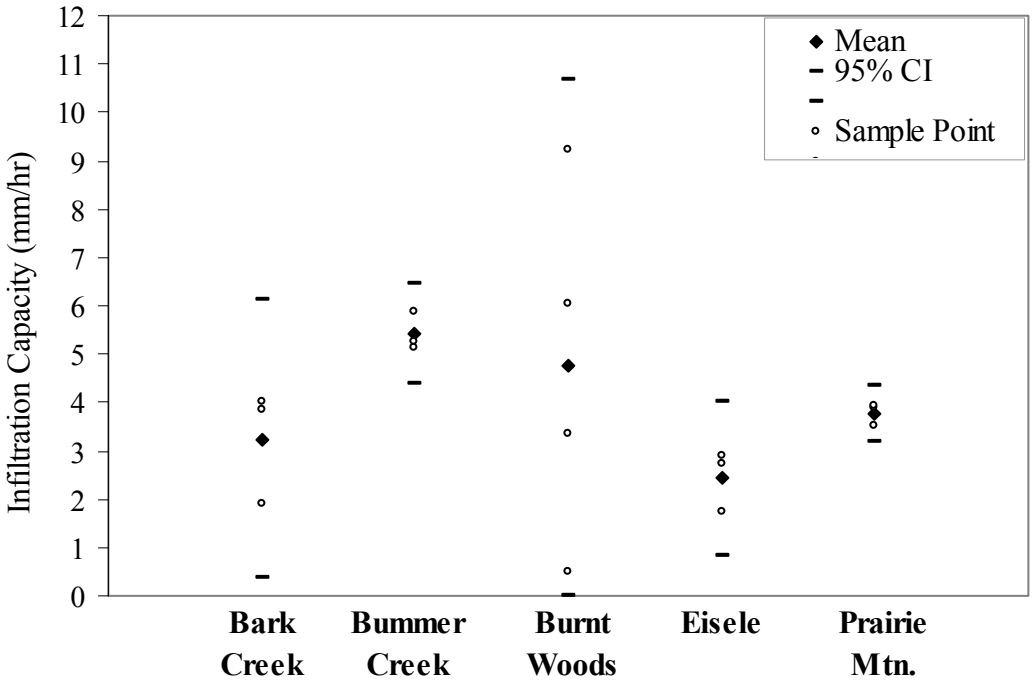

Figure 5.2. Infiltration capacities for the five study sites based on rainfall individual plots. The diamond is the average of all plot estimates, and the dashes are the 95 percent confidence intervals.

I assumed that the plot reached a steady-state infiltration rate by the end of the wet run, so I used the data from the wet run to parameterize the Green and Ampt and the Philip equations for infiltration. The data from the wet runs always had a steeper decrease in infiltration rate than could be reproduced by the inverse function in Green and Ampt (Figure 5.3).

The Philip model fit the data better than Green and Ampt, however it was still inadequate (Figure 5.4). The estimate of infiltration capacity generated by the model was not reached within the range of the data, even though steady state infiltration was reached during the simulation. Both models occasionally produced

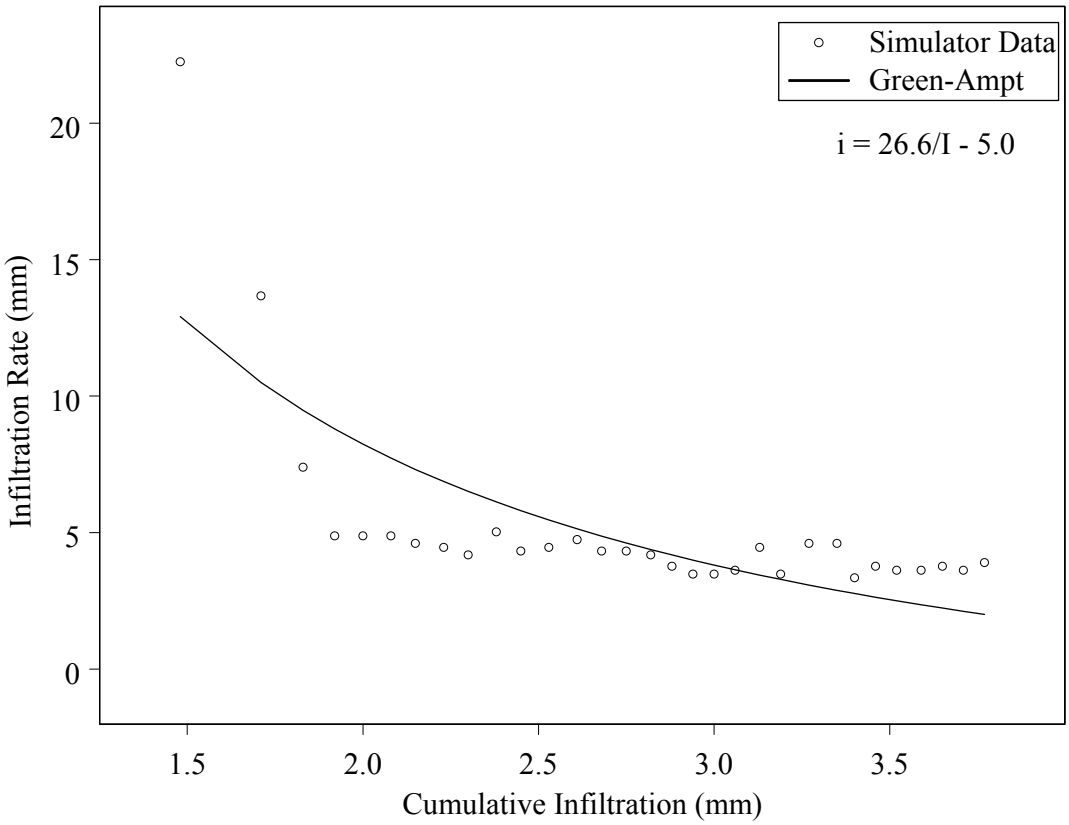

Figure 5.3. An attempt to fit the Green and Ampt equation to infiltration data from the second run of a plot at the Bark Creek road segment. **I** in the equation is cumulative infiltration in millimeters, and **i** is infiltration rate in mm/hr.

negative estimates of infiltration capacity. They did not adequately estimate the steady-state infiltration rate that had been reached at the end of the wet run. The Green and Ampt and the Philip model were based on infiltration into sandy soil that was not artificially compacted. The roads in this study were compacted, so the infiltration of the road was reached more quickly than on natural soil. This may be the reason why runoff data from these simulations did not fit the infiltration models.

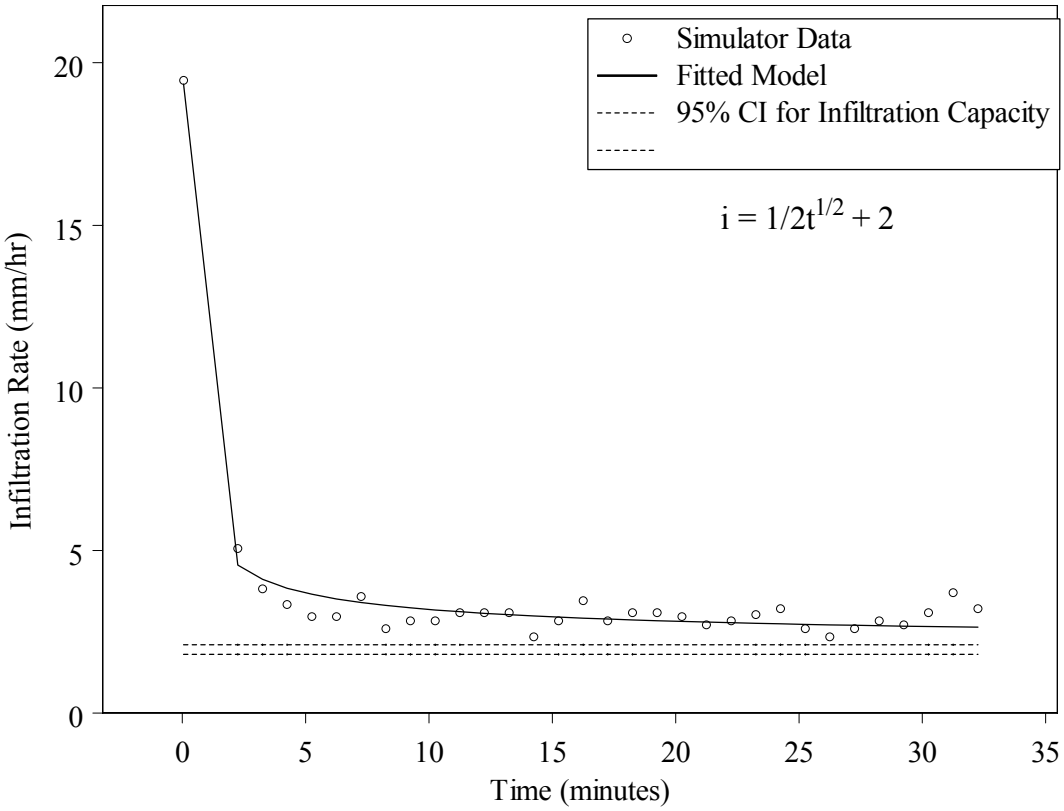

Figure 5.4. An attempt to fit the Philip equation to simulator data from the second simulation on a plot at the Eisele road segment. In the Philip equation, **i** is the infiltration rate (mm/hr), and **t** is time (hr). 95 percent CI is a confidence interval for the infiltration capacity.

5.2. DISCUSSION

5.2.1. Limitations of the Rainfall Simulator

The differences between simulated rainfall and natural rainfall have implications for this study. The kinetic energy of the simulated rainfall has been estimated at 50 percent of natural rainfall (Foltz et al. 1995), but this detail is more important when one is using simulated rainfall to estimate erosion. The rainfall produced by simulators is variable in space and time, as described by Lascelles et al. (2000).

> "Small-scale and short-period variations in natural rainfall are averaged out when rainfall is extrapolated over larger areas and longer times. Thus, for experiments that are concerned with some aggregate or mean effect of a given rainfall application over the whole area and for the entire duration of the experiment, small scale variation will be unimportant. "

This experiment was concerned only with the mean effect of the rainfall simulation, which produced a steady-state runoff rate from the plot. The most important difference between simulated and natural rainfall is that the minimum rainfall rate produced by the simulator was 20 mm/hr. That rate is much higher than the average rainfall intensities observed at the study sites during this study. The infiltration capacity of the roads should be reached faster with rainfall simulations than with natural rainfall.

5.2.2. Road Surface Characteristics

Estimated infiltration capacities for each study site conformed to expectations based on road surface characteristics. The Eisele and Prairie Mountain study sites had the most frequent traffic and the lowest infiltration capacities. Both sites had wide, compacted wheel ruts that encompassed most of the sample plot area, which may be the reason why their infiltration capacities were

lower. The Bark Creek site had less traffic, and the road surface had not been maintained in several years. Most of the plot area on each of the Bark Creek plots consisted of the running surface of the road, where ruts had formed. The remainder of the plot consisted of the shoulder or crown of the road, which was covered with grass. The average infiltration capacity of the Bark Creek segment was higher than the road segments at either Eisele or Prairie Mountain. The road segments at Bummer Creek and Burnt Woods received very little traffic, and both of these roads were freshly rocked and graded a year before the study started. Wheel ruts were not as compacted at Bummer Creek and Burnt Woods as they were at other road segments. The crown and shoulder of the Bummer Creek and Burnt Woods segments consisted of large, loose gravel that was hard to seal around the plot borders, and though the sample plots were eventually sealed, estimates of infiltration capacity were higher and more variable than at the other sites.

5.2.3. Comparison With Other Studies

Flerchinger and Watts (1987), Luce and Cundy (1994), and Luce (1997) used rainfall simulators to determine infiltration capacities for logging roads in Idaho and Montana (See Table 3.1, Section 3.2.2). Their estimates of the infiltration capacities of road surfaces ranged from almost zero to 8.8 mm/hr. The results from this study are similar. Infiltration capacities ranged from 2.9 to 5.1 mm/hr. These are initial estimates of the infiltration capacity for logging roads in the Oregon Coast Range, although geographic location of the study site may not be important. Roads are compacted and used in a similar manner, regardless of geographic location, and thus it should not be surprising that infiltration capacities are similar. For example, Ziegler and Giambelluca (1997) estimated that infiltration capacities for low volume roads in Thailand are 0.2 to 5.1 mm/hr, within the range of infiltration capacities for roads in the western United States.

6. MEASUREMENT OF RAINFALL AND DITCHFLOW

6.1. ROAD CHARACTERISTICS

Dimensions of the road prism varied between sites (Table 6.1). The Prairie Mountain road segment was insloped, and all other road segments were crowned. The segments ranged in gradient from 5 to 15 percent and in cutslope height from 2 to 11 m. All sites had similar basalt surface material for the road tread. The Bummer Creek and Burnt Woods sites were graded and resurfaced with fresh rock to make them usable in the study. All of the ditches contained grass and other herbaceous plants.

Prairie Mountain was different from the other study sites in a few ways. The other sites ranged in elevation from 245 to 280 m, while Prairie Mountain was located at 646 m (Table 6.1). Also, as mentioned in the study area description, Prairie Mountain differed slightly in geology and soil characteristics from the other sites. Intercepted subsurface flow, though expected at all study sites, only occurred at Prairie Mountain. None of the other sites intercepted subsurface flow, as their hillside flumes recorded only traces of water during the largest storms.

Table 6.1. Characteristics of the study road segments.

Road Segment	Elevation (m)	Road Gradient (%)	Road Length (m)	Road Surface Area (m^2)	Upslope Drainage Area (ha)	Average Cutslope Height (m)	Soil Depth (m)
Bark Creek	245	15	81	152	0.22	7	1.1 to 2
Bummer Creek	255	12	108	257	0.35	11	0.5 to 0.9
Burnt Woods	270	5	64	128	0.32	3	1.2 to >3
Eisele	280	12	72	129	0.36	2	>3
Prairie Mtn.	646	10	56	286	0.95	2	>3

6.2. WEATHER DURING THE 2002 WATER YEAR

Total rainfall ranged from 1600 to 2000 mm between October 2001 and May 2002 at the five study sites. In order to place the rainfall that occurred at my study sites during the 2002 water year into a historic hydrologic context, I compared my data with data from a nearby rain gauge that had a thirteen-year record. This rain gauge is located in the Lobster Creek drainage at an elevation of 366 m, approximately 15 km from the Prairie Mountain and Bummer Creek sites. No long-term record was available for the three sites near Burnt Woods, which are approximately 35 km from Lobster Creek. I performed a frequency analysis of the annual maximum rainfall intensities (1/2, 1, 2, 6, 12, and 24 hour) for the Lobster Creek rain gauge using the Log Pearson cumulative frequency distribution. Based on that analysis, I built an intensity duration frequency curve for Lobster Creek and then plotted maximum rainfall intensities for all study sites in 2002 on the same curve (Figure 6.1).

Maximum ½-hour to 24-hour rainfall intensities at the three study sites near Burnt Woods had approximately a 2-year return interval (Figure 6.1). Maximum ½-hour to 24-hour rainfall intensities at the Bummer Creek study site were approximately a 5-year return interval. The maximum ½-hour to 2-hour intensities at the Prairie Mountain study site were less than a 5-year return interval, and 6-hour to 24-hour maximum intensities had a return interval of between 5 and 10 years. The Prairie Mountain site is 280 m higher in elevation than the Lobster Creek rain gauge, which may explain why the Prairie Mountain rain gauge had the highest return interval rainfall intensities. The return interval of the rainfall intensities at Prairie Mountain would probably be lower if they were compared to a record for a rain gauge at a similar elevation. The main conclusion from this intensity frequency duration analysis is that the study sites did not experience rainfall intensities of greater than a 5-year return interval. Rather, the rainfall rates that they experienced during 2002 were typical for Oregon winters.

According to the definition of a storm presented in Section 4.4, storm analysis included ten storms for all roads except Prairie Mountain, which included six storms (Table 6.2). The rain at Prairie Mountain was more continuous due to the higher elevation, and snow was more common. Total storm rainfall amounts for storms ranged from 26 mm to 140 mm, and duration ranged from 12 to 65 hours (Table 6.2). The flumes and water level recorders generally functioned well at all sites except the Eisele site. All but three of the storms at Eisele had to be eliminated from analysis due to sediment-laden water and a sticky float/weight pulley system in the roadside stilling well (Table 6.2). Hyetographs and hydrographs for every storm at Prairie Mountain are available in the Appendix.

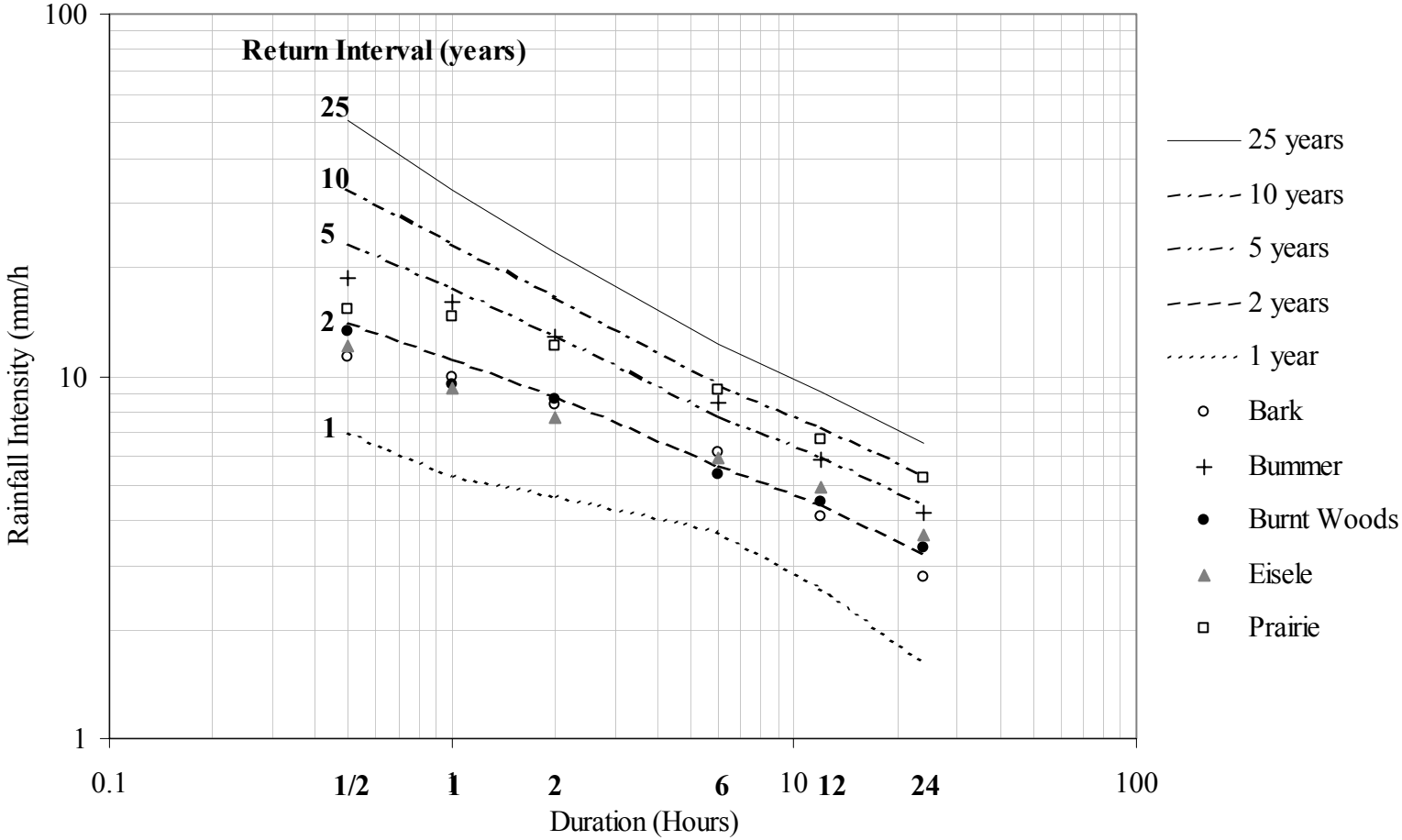

Figure 6.1. An intensity frequency duration curve for a thirteen-year precipitation record at a rain gauge located in Lobster

Table 6.2. A table of storms used for hydrograph analysis in 2002 water year. Units are millimeters for Depth and

		Bark Creek		Bummer Creek		Burnt Woods		Eisele		Prairie Mtn.	
Storm	Date	Depth	Duration	Depth	Duration	Depth	Duration	Depth	Duration	Depth	Duration
1	Nov. 21 - 22	89	29	118	29	89	29	97	29	140	30
2	Nov. 28 - 29	81	32	107	41	67	31	Instrument Error		Rain-on-Snow	
3	Nov. 30 - Dec. 2	74	42	124	47	90	44	Instrument Error		Rain-on-Snow	
4	Dec. 4 - 5	38	18	47	17	38	17	Instrument Error		112	51
5	Dec. 5 - 6	34	26	26	28	27	24	Instrument Error			
6	Dec. 12 - 14	61	29	96	46	70	47	Instrument Error		100	41
7	Jan. 5 - 8	103	57	130	61	98	60	92	59	156*	
8	March 5 - 6	44	26	61	33	42	27	42	26	84	38
9	March 9 - 10	26	25	34	27	Instrument Error		Instrument Error		144	65
10	March 11	34	16	46	16	39	12	Instrument Error			

* Estimated with a regression on Prairie Mountain Storm Depth Vs. Bummer Creek Storm Depth

Prairie Storm Depth = 2.66 + 1.18 * Bummer Storm Depth, 29 Degrees of Freedom, Standard Error = 8.193, $R^2 = 0.96$

95% Confidence Interval = 156 $\pm$ 22 mm for Storm 7.

6.3. COMPARISON OF SURFACE RUNOFF AND INTERCEPTED SUBSURFACE FLOW

Differences in the hydrology of the hillside and roadside components of ditch flow are readily apparent by observing hydrographs of these components during a storm at the Prairie Mountain study site (Appendix, Figure 6.2). The differences visible in Figure 6.2 will be quantified in the following sections. The onset of winter rains caused the discharge in the hillside flume to gradually increase, thus Figure 6.2 shows positive discharge in the flume before the beginning of the storm. A storm began on November 21st that caused the discharge to increase gradually and peak a day later at 4.3 liters/second. The total amount of precipitation for the storm was 140 mm. The concentration time, or the time from the initial rise in discharge to peak discharge, for the hillside flume was 37 hours, and 384 m^3 of quickflow passed through the hillside flume. The volume of water that passed through the hillside flume from the beginning of the storm until three days after the end of rainfall was 801 m^3. That volume was discharged into an intermittent stream that passed underneath the road in a culvert downslope of the flumes. In contrast, the discharge initiated, ceased, and reoccurred several times in the roadside flume during the storm (Figure 6.2). Maximum peak discharge for all the roadside hydrographs was only 0.3 liters/second. The concentration time ranged from 6 minutes to 2.1 hours. Only 4.5 m^3 of total runoff passed through the roadside flume during the storm.

At the Bark Creek site, surface runoff from the road generated all of the ditch flow during Storm #1 (Figure 6.3). Total storm precipitation was 89 mm at this site. Only a trace of runoff from the hillslope side of the ditch occurred in the hillside flume. Maximum peak discharge in the roadside flume was 0.05 liters/second, and concentration time ranged from 12 minutes to 8.7 hours. Total storm runoff was 0.9 m^3.

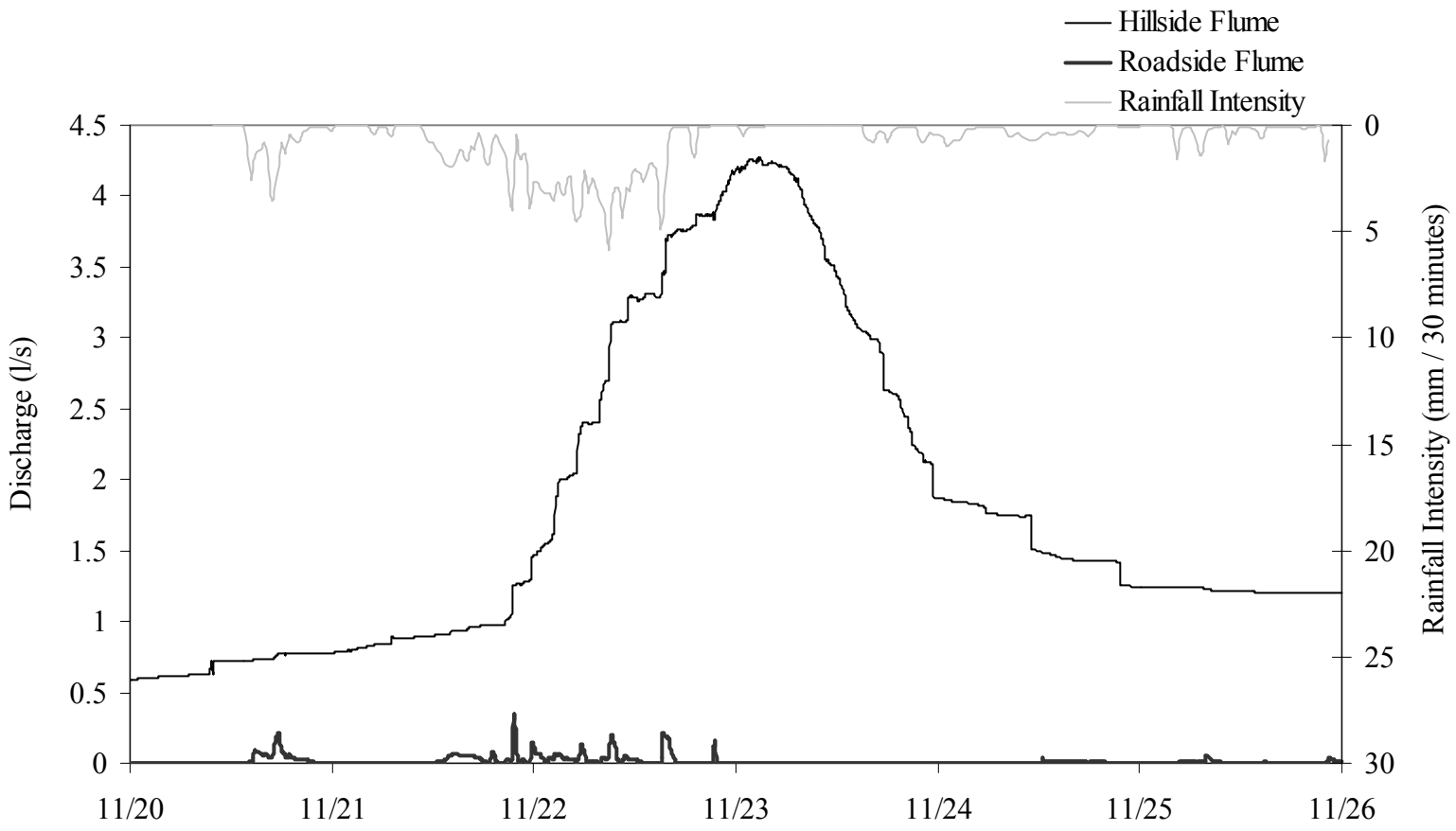

Figure 6.2. Rainfall and the hillside and roadside components of ditch flow at the Prairie Mountain site during Storm #1, November 2001. Road surface area is 286 m^2.

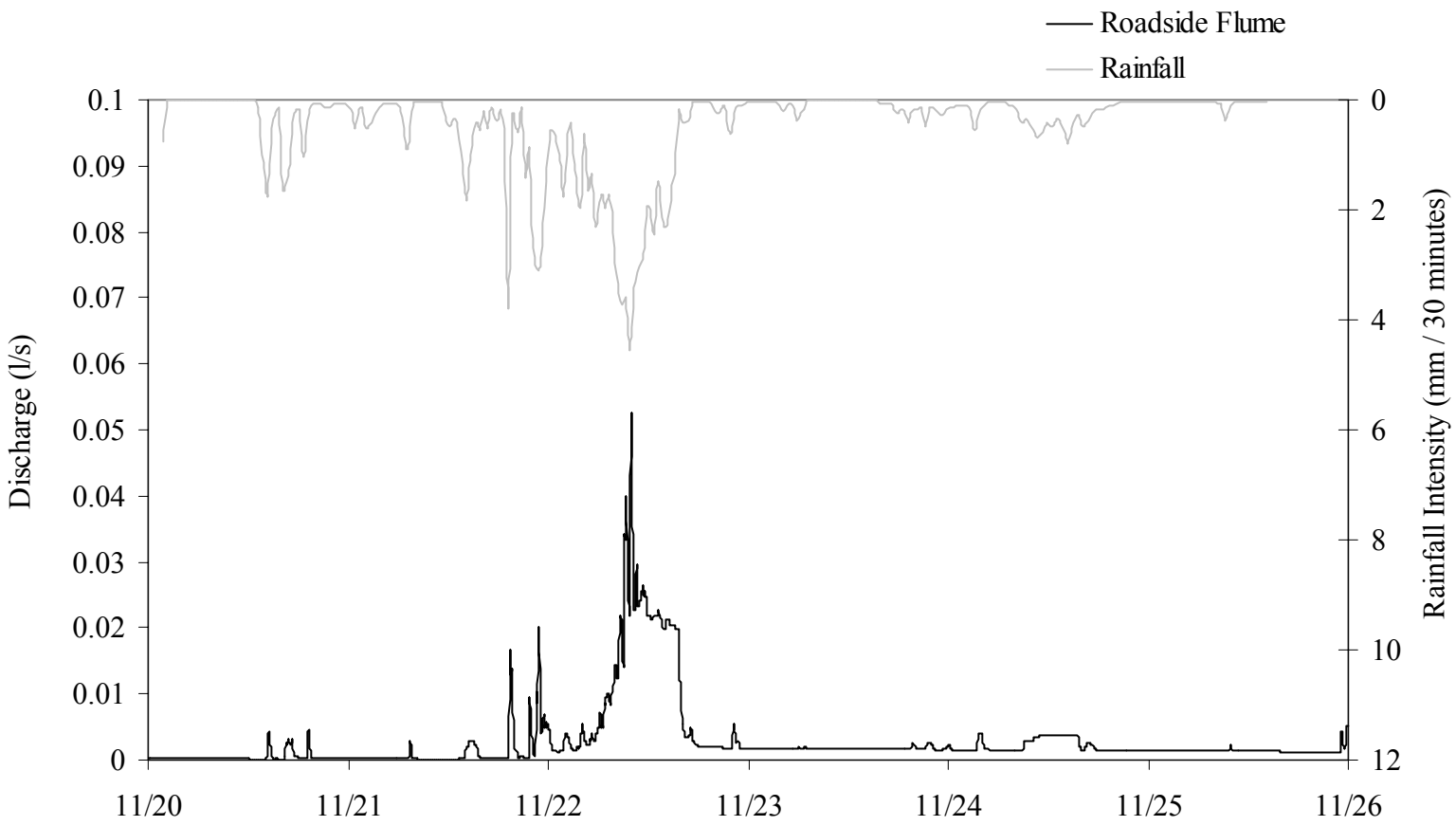

Figure 6.3. Rainfall and the roadside component of ditch flow at the Bark Creek site during Storm #1, November

In between the periods of runoff in Figure 6.3, the discharge did actually cease at Bummer Creek. The trace of discharge visible between storms was not ditch flow but equipment malfunction. The float in the stilling well got stuck as it descended, or there was dirt in the flume.

6.3.1. Instantaneous Peak Flows

Peak discharges in the hillside flume at Prairie Mountain were one to two orders of magnitude greater than peak discharges in the roadside flumes at all sites. For the six storms measured at Prairie Mountain, peak discharge in the hillside flume ranged from 1.1 to 4.3 liters/second. Multiple peak discharges occurred in roadside flumes during ten storms at all sites. Maximum peak discharges ranged from 0.05 to 0.34 liters/second (Table 6.3).

Table 6.3. Instantaneous peak flows from roadside flume hydrographs

Site	Number of Hydrographs	Average Peak Discharge (l/s)	Maximum Peak Discharge (l/s)
Bark Creek	40	0.01	0.05
Bummer Creek	21	0.07	0.27
Burnt Woods	21	0.02	0.09
Eisele	16	0.04	0.12
Prairie Mountain	25	0.11	0.34

6.3.2. Storm Volumes

Runoff from the hillside flume at the Prairie Mountain study site was like a groundwater-fed stream and was easily separated into quickflow and baseflow. Quickflow was calculated using a baseflow separation line of 0.0055 l/s/ha/hr (Hewlett and Hibbert 1967). Total volume was the absolute volume of ditch flow that occurred from the initial rise in the hydrograph to three days after the end of

rainfall. Quickflow volume ranged from 74 to 538 m^3, and total volume ranged from 292 to 802 m^3 (Table 6.4). Total volume was roughly twice the quickflow volume. No runoff from the hillslope occurred in the hillside flumes of the other four study sites. The roadside component of ditch flow had no baseflow. Thus, total storm volume for these sites was the cumulative discharge from all of the separate hydrographs that occurred during the storm. For a combination of five sites and ten storms, the grand mean for total storm volume was 0.7 m^3 and ranged from 0.02 to 4.5 m^3 (Table 6.5).

In conclusion, storm volumes from the hillside component of ditch flow at Prairie Mountain were as much as three orders of magnitude greater than storm volumes from the roadside components of ditch flow at all study sites. The smallest volumes that passed through roadside flumes represented only a trace of ephemeral runoff, while the smallest volumes that passed through the Prairie Mountain hillside flume represented a small, intermittent stream.

Table 6.4. Storm volumes from the hillside flume at Prairie Mountain.

Storm	Quickflow (m^3)	Total Volume (m^3)
1	394	802
4, 5	74	703
6	252	522
7	538	935
8	142	292
9, 10	332	777

Table 6.5. Total storm volumes for roadside flumes at the five study sites. Number of sites indicates the number of sites for which data were available and reliable.

Storm	Number of Sites	Avg. Volume (m^3)	Max. Volume (m^3)
1	5	1.9	4.5
2	3*	0.8	1.2
3	3*	0.4	0.7
4	4+	0.4	1.3
5	3*	0.4	1.0
6	3*	0.5	0.9
7	4-	0.7	1.6
8	5	1.0	3.7
9	2#	0.1	0.1
10	3*	0.2	0.3

* Prairie and Eisele missing. + Eisele is missing. - Prairie is missing
# Prairie, Eisele, and Burnt Woods are missing.

6.3.3. Concentration Times

Concentration times for the hydrographs of six storms from the hillslope component of ditch flow at Prairie Mountain ranged from 17.1 hours to 57.6 hours. The median concentration time for the roadside component of ditch flow at all study sites was 0.8 hours (48 minutes) and ranged from 3 minutes to 8.7 hours. Most hydrographs from the roadside component of ditchflow had only one peak and a concentration time of an hour or less (Figure 6.4). During the part of a storm with the highest rainfall intensity, ditch flow would continue for several hours and would have multiple peak discharges (Figure 6.3). Concentration times were more than an hour for ditch flow occurring during the high intensity parts of a storm (Figure 6.4). The longer concentration times for the hillslope component of ditchflow at the Prairie Mountain site are indicative of the flow pathway of the runoff. The passage of water through the ditch and hillside flume was linked to passage of stormflow through the hillslope. The greater volume of water stored in the hillslope and the slower path of water through soil and/or bedrock would lead to longer concentration times than road surface runoff. For the roadside flume, runoff produced was only from the current rainfall on the road surface. There was little or no storage of water on the road surface. Any runoff would have been closely tied to changes in rainfall intensities (Section 7.2), thus producing shorter concentration times. These results indicate that concentration time of road surface runoff, as defined in Section 4.5.2, is a property of rainfall intensity more so than it is a property of flow velocity in the road watershed.

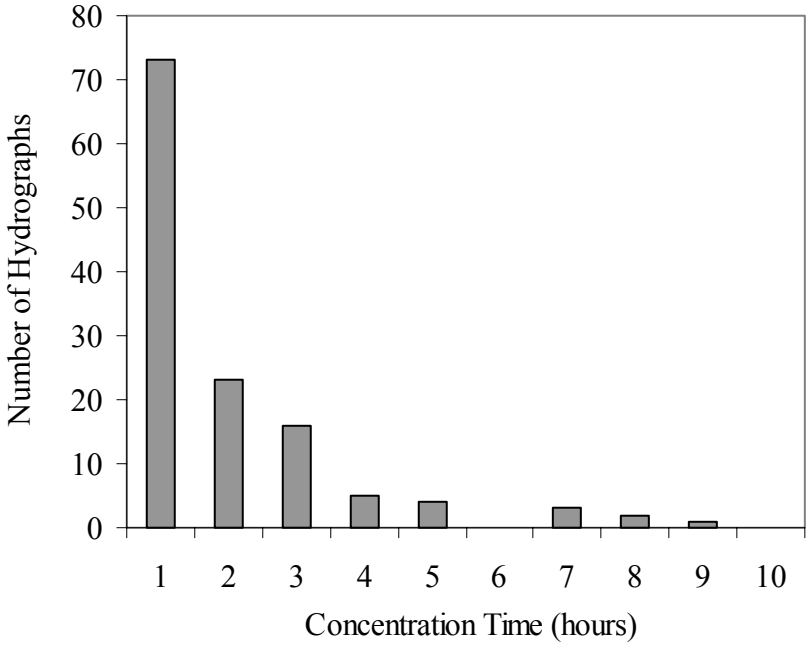

Figure 6.4. A frequency distribution of concentration times of the

Sample size is 127 hydrographs.

6.3.4. Runoff Ratios

The runoff ratio is the proportion of rainfall that fell on the road contributing area that occurred as runoff in the roadside flume (Section 4.5.2). The contributing area was the inboard side of the road and half of the ditch (Section 4.5.1). At the Prairie Mountain study site, the inboard and outboard sides of the road were captured. I used contributing area of the road to normalize total runoff volume from the hillslope and illustrate the magnitude of intercepted subsurface flow compared to road surface runoff at all sites. A runoff ratio greater than 1 indicated that more runoff flowed through the ditch than could have come from rainfall on the road surface. The average runoff ratio for the roadside component of ditch flow for all study sites was 0.05. Runoff ratio for quickflow volumes and total storm volumes of the hillside component of ditch flow at Prairie Mountain

were respectively 9 and 21 (Table 6.6). Only a small proportion of rainfall occurred as ditch flow on the roadside at every site. In contrast, the volume of intercepted subsurface flow that became ditch flow and passed through the hillside flume was, on average, twenty-one times more than the ditch flow that could have come from the road surface alone. The term runoff ratio is therefore not relevant to intercepted subsurface flow, but it can still be used as an indicator of the source of ditch flow.

Table 6.6. Runoff ratios for all study sites. The number of storms indicates how many storms were available for calculating an average runoff ratio. Total storm volumes, rather than quickflow volumes, were used to calculate runoff ratios for

Flume	Site	Number of Storms	Average Runoff Ratio
Hillside	Prairie Mountain	6	21
Roadside	Prairie Mountain	3	0.10
Roadside	Bark Creek	10	0.04
Roadside	Bummer Creek	10	0.02
Roadside	Burnt Woods	9	0.05
Roadside	Eisele	3	0.17

6.4. DISCUSSION

6.4.1. Error in Ditch flow Measurements

The trapezoidal flumes used in this study were designed to be self-cleaning. That is, the water that moved through the flumes was supposed to push dirt and debris through them, leaving them clean. This was generally true for the flumes that I used in the field, except at very low discharges. As storm flow moved through the flume, it carried dirt with it, but as discharge decreased, eventually the dirt settled out in the bottom of the flume. When stormflow began again, the water picked the dirt up out of the flume and moved it through. So error due to sediment and debris in the flume was occurring mostly in the very beginning and end of each hydrograph, when discharge was very small. Error was always positive; dirt in the flume caused the water level recorder to read a stage that was higher than the true water depth in a clean flume.

Error of the water level recorder in the stilling well, as determined by the manufacturer, was only 0.2 mm. Through field observations, I determined that stage error in the flumes was generally 1 mm. There were two exceptions to these generalizations. Water that flowed through the Eisele and Prairie Mountain roadside flumes was laden with organic matter and fine sediment. It produced error of 4-6 mm, an unacceptable amount. Therefore much of the data for these two flumes was eliminated from further analysis. Finally, error in the Prairie Mountain hillside flume was closer to 0.2 mm, because abundant clean water from a seep flowed though it constantly.

Using stage error and the flume rating curve (Equation 4.3), I plotted discharge error as a percentage of the true discharge value (Figure 6.5). Discharge error decreases exponentially as stage increases, but dirt drastically increases the error in discharge measurements. When the flume is clean and only has 0.2 mm uncertainty, error is less than 10 percent of discharge at a stage of 5.4 mm. If the stage were overestimated by 1 mm, error would not be less than 10 percent of

discharge until stage reached 27 mm. In the flumes that measured road surface runoff, stage was less than 27 mm the majority of the time, so error was closer to 20 percent or 30 percent. Estimates of peak discharge, flow volume, and runoff ratio would then have the same error.

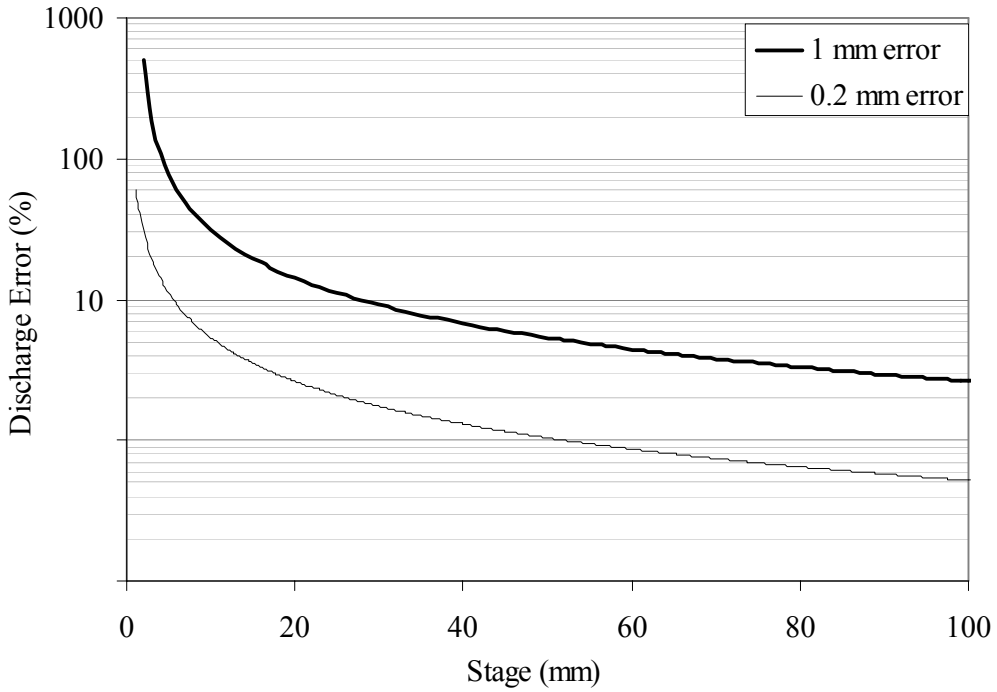

Figure 6.5. Discharge error (as a percent of true discharge in the flume) at a given stage. The light solid line represents a 0.2 mm overestimate.

The Prairie Mountain site had two different issues with error. First, a stepping pattern was observed in hydrographs from the hillside flume (Appendix). As the water level increased or decreased in the flume, the pulley in the stilling well would temporarily stick and then break free. There was no way to correct the stepping pattern that would increase quality of the data, so the water level data were left as is. There was also some leakage from the hillslope side of the ditch into the road side of the ditch at Prairie Mountain. The leakage was a steady baseflow, clearly different from the surface runoff that entered the road side of the ditch during storms. In later analyses, I subtracted the baseflow from the road side discharge and added it to the hillslope side discharge.

6.4.2. Runoff Ratios

MacDonald et al. (2001) estimated runoff ratios of 0.04 to 0.12 for 5 by 10 m plots on dirt roads in the U.S. Virgin Islands. They attributed the low values to infrequent use of the roads, which led to less compaction and thus a higher infiltration capacity, and to bedrock fractures beneath the road, which led to more infiltration and less surface runoff. The road surfaces in this study had similar runoff ratios. Infiltration capacity was spatially variable over the surface of the road. Surface runoff often occurred in the compacted wheel ruts of the roads, while the loose gravel and vegetation on the shoulder of the road and in the ditch provided roughness that caused rainfall to infiltrate. Another reason for the low runoff ratios is that, even though the infiltration capacity of the road is low, most of the time the rainfall intensity is lower than the infiltration capacity of the road (Figure 6.1, also see Section 7.1). Therefore, most of the rainfall infiltrates directly into the road, except during the infrequent pulses of high intensity rainfall that exceed the infiltration capacity of the road. Finally, the divider in the center of the ditch was the newest feature and may have affected infiltration. Though the dirt around the divider had compacted and settled for a year, it may still have had a

greater infiltration capacity than the rest of the ditch and therefore increased infiltration of rainfall.

The contributing area of the hillslope above the Prairie Mountain road segment was 0.95 hectares. I used this value with rainfall depth and quickflow volume to calculate a runoff ratio for intercepted subsurface flow from the hillslope. Runoff ratios from hillslope runoff ranged from 0.07 to 0.36. Hillslope runoff ratios for quickflow from other studies have been more variable. McGee (2000) estimated hillslope runoff ratios of 0.12 to 1.56 for two road segments in southeast Alaska. Wemple (1998) estimated hillslope runoff ratios of almost 0 to 1.2 for eight road segments in the Oregon Cascades. There are several reasons why the hillslope runoff ratios would be so variable. In this study, the hillslope side of the ditch was not a water-tight outlet for the hillslope above, but rather it represented a random, partial interception of subsurface flow pathways. This same statement could be made for McGee (2000) and Wemple (1998). However, at times both McGee (2000) and Wemple (1998) estimated runoff ratios greater than 1, which begs a point. The hillslope contributing area, as indicated by surface topography, may not be a perfect indicator of the contributing area to the road. Subsurface bedrock topography and fractures in bedrock may direct water in or out of the contributing area of the road (as indicated by surface topography). This may produce more runoff than was available from rainfall input alone. The magnitude of that contribution depends on the depth and intensity of rainfall (Montgomery et al. 1997, Freer et al. 2002).

6.4.3. Comparison With Gilbert (2002) Data

One of the objectives of this study was to test the hypothesis presented by Gilbert (2002) that the source of ephemeral ditch flow is primarily the road and ditch surface, and the source of intermittent ditch flow is subsurface flow from the hillslope that was intercepted by the road (Section 2). Gilbert observed the hydrology of six study road sites in the central Oregon Coast Range. Four sites had ephemeral flow in the ditch, and Gilbert hypothesized that the source of ephemeral ditch flow was the road surface. Two sites had intermittent flow in the ditch, and Gilbert hypothesized that the source of intermittent ditch flow was intercepted subsurface flow from the hillslope. One of Gilbert's sites that had intermittent ditch flow, the Prairie Mountain site, was used again in this study.

Gilbert calculated quickflow volumes for the sites that had intermittent flow, and he calculated total runoff volume for the sites that had ephemeral flow. I compared Gilbert's results to the results from this study, where the ditch was physically divided and the source of ditch flow was known. Area-normalized runoff or runoff depth is defined as runoff volume divided by the road surface area. Gilbert hypothesized that intermittent ditch flow was governed by intercepted subsurface flow from the hillslope at two of his study sites. Those sites had similar area-normalized runoff depths to the hillslope-derived runoff of this study's Prairie Mountain site. At the study sites where Gilbert hypothesized that ephemeral ditch flow was governed by road surface runoff, area-normalized runoff depths were similar to confirmed road surface runoff from this study (Figure 6.6).

Ditch flow normalized by the road surface area for sites with intermittent flow was much greater than the rainfall that caused the runoff (Figure 6.6). For example, a 100 to 150 mm storm resulted in the 1000 mm of runoff from ditch flow. The source of this much runoff was more than just the road surface. Study sites with ephemeral flow had runoff volumes that, when normalized by road surface area, were less than rainfall depth. However, Gilbert's ephemeral sites had greater runoff depth at a given rainfall depth than the road surface runoff in this

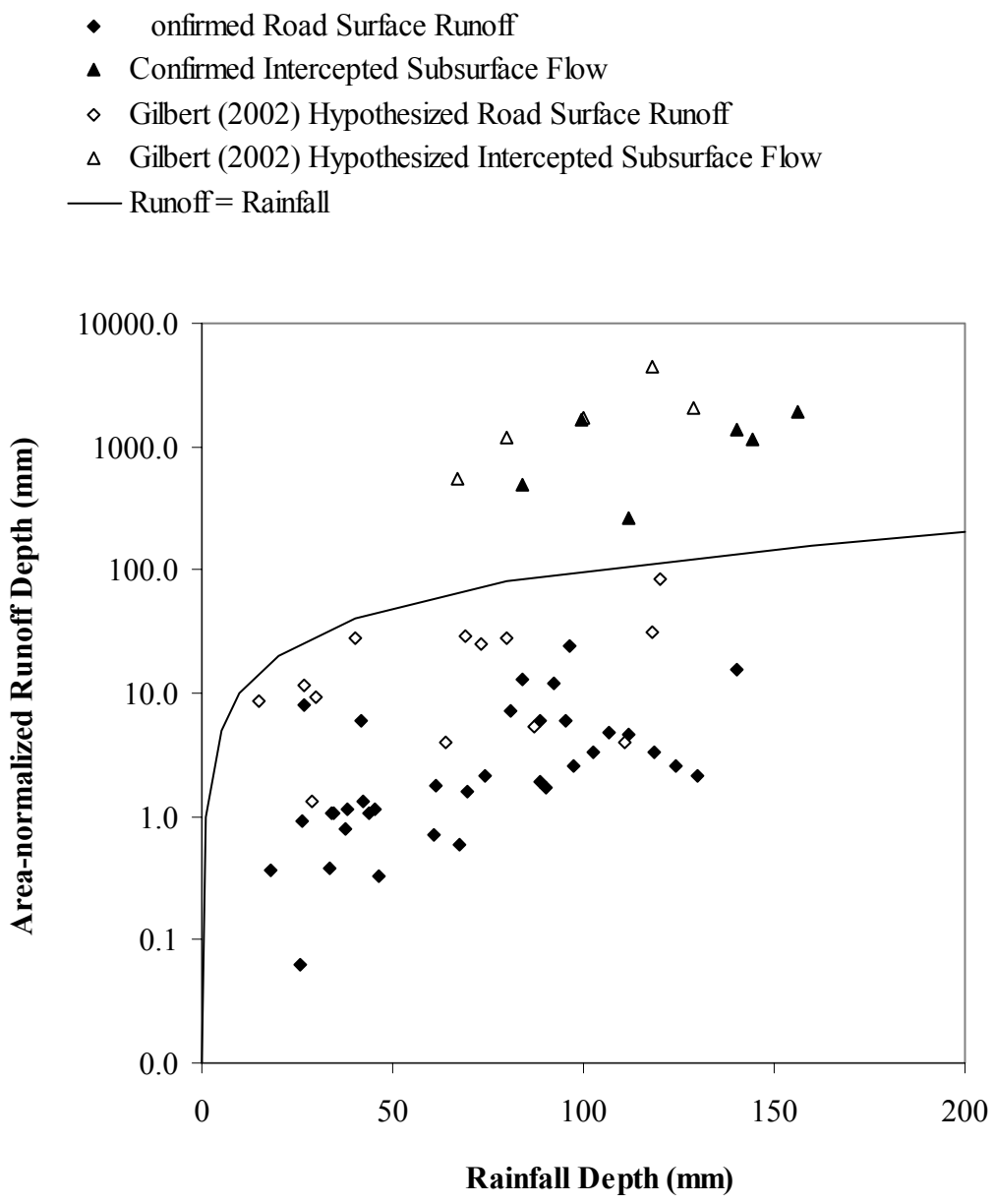

Figure 6.6. Area-normalized runoff vs. rainfall depth for Gilbert's (2002) study road segments and for the current study. Area-normalized runoff is runoff volume divided by road surface area. The hollow symbols represent sites where Gilbert hypothesized the source of ditch flow. The solid symbols represent sites from this study where the source of ditch flow was confirmed. The line indicates where runoff depth = rainfall depth.

study. It is possible that some of Gilbert's ephemeral flow sites that were hypothesized to have been dominated by road surface runoff most likely had mixed flow pathways contributing road surface runoff and intercepted subsurface flow to the ditch flow.

I compared runoff ratios from this study to runoff ratios from Gilbert's (2002) study (Table 6.7). Runoff ratios in Table 6.7 are based on quickflow volumes. In both studies, ditches with ephemeral flow had runoff ratios less than 1. In other words, the amount of ditch flow was always less than the amount of rain that fell on the road surface. This study confirmed that the primary source of ephemeral ditch flow was the road surface. Ditches with intermittent flow had runoff ratios much greater than 1. That is, the amount of ditch flow was always much greater than the amount of rain that fell on the road surface. This study confirmed that the primary source of intermittent ditch flow was most likely intercepted subsurface flow.

Table 6.7. Runoff ratios for study sites in Gilbert's (2002) study (hypothesized) and this study (confirmed).

	Runoff Ratio	
Runoff Type	Confirmed	Hypothsized
Ephemeral, Surface Flow	0.002 - 0.3	0.07 - 0.7
Intermittent, Subsurface Flow	2.3 - 17	8 - 37

Instantaneous peak flow, normalized by road surface area, was not a good metric for distinguishing between intermittent and ephemeral sites. The study site where the source of intermittent ditch flow was confirmed (Prairie Mountain) had the greatest peak flows (Figure 6.7). Likewise, the study sites where the source of ephemeral ditch flow was confirmed had the lowest peak flows. However, in between these two extreme values, some of Gilbert's (2002) study sites with

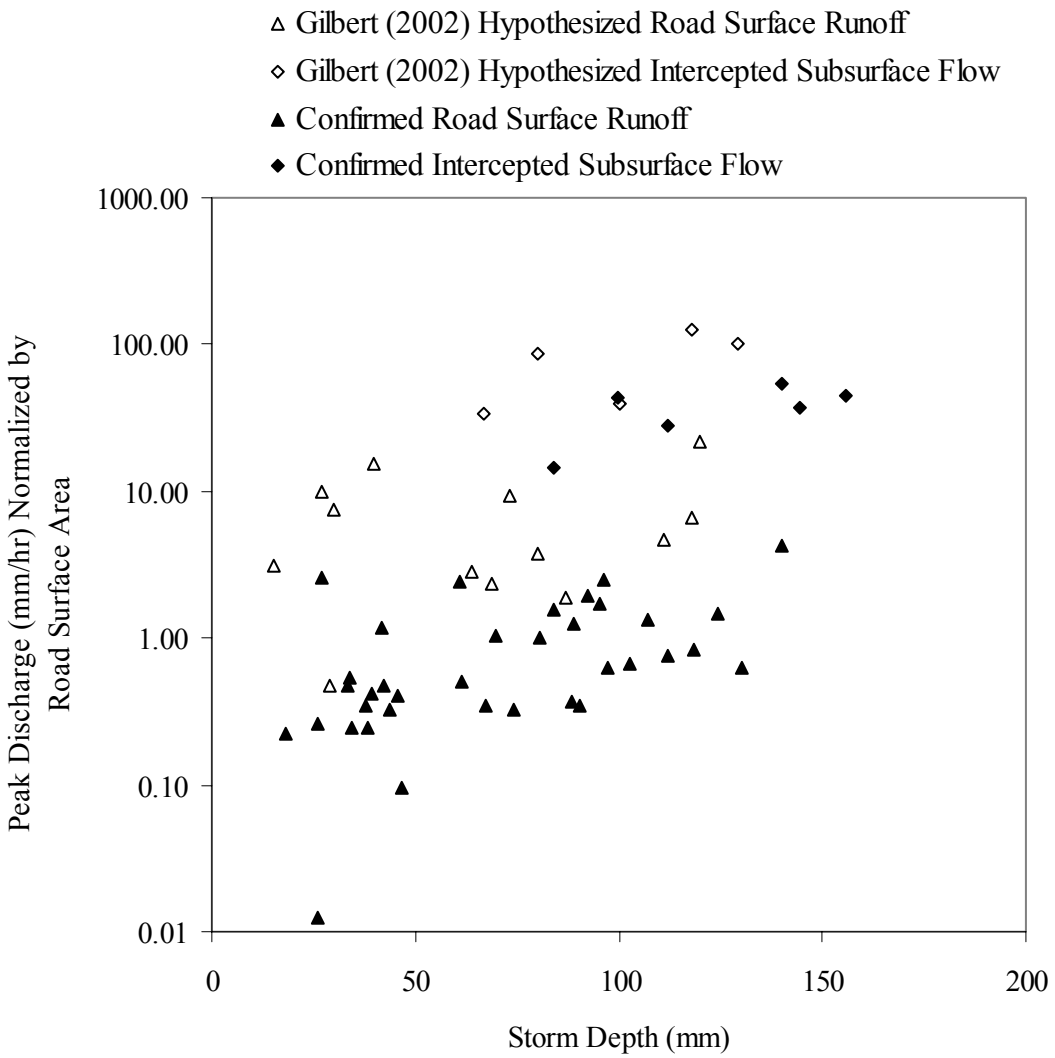

Figure 6.7. Peak discharges from storm hydrographs for Gilbert's (2002) study road segments and for the current study. Discharge is normalized by road surface area. The hollow symbols represent sites where Gilbert hypothesized the source of ditch flow. The solid symbols represent the sites from this study where the source of ditch flow was confirmed.

ephemeral hydrology had peak flows approaching the same magnitude found for some of the sites with intermittent hydrology.

These results suggest that there may have been intercepted subsurface flow in ephemeral ditches in Gilbert's (2002) study. However the hydrology of flow in these ditches was similar to the flow in the ditches governed by road surface runoff from this study. The results do confirm that the ditch flow at the Prairie Mountain study site was mainly intercepted subsurface flow, as was hypothesized by Gilbert. It is reasonable to assume that the ditch flow from the second study site that had intermittent behavior in Gilbert's study was also dominated by intercepted subsurface flow.

In summary, the hydrology of ten road segments was studied during these two master's projects. Roads that intercepted subsurface flow were intentionally sought out, however only two of the ten road segments showed evidence that subsurface flow was intercepted. These two sites flowed continuously during the winter season, and we labeled their hydrology intermittent. We gatherered evidence to show that the source of the flow for these two sites was intercepted subsurface flow. For the other eight sites, ditch flow was dominated by surface runoff from the road. We labeled the hydrology of these sites ephemeral. We confirmed that infiltration-excess overland flow, or road surface runoff, was the primary source of runoff for the four sites with ephemeral flow in this project.

6.4.4. The Source of Ditch flow in Other Studies

The sites with ephemeral flow in this project are similar to those observed in studies by Reid and Dunne (1984), Vincent (1985), and Kahklen (1993) (Section 3.3.1). Ditch flow from these sites came from the road surface, was directly related to the rainfall rate, and could be easily modeled with a unit hydrograph, WEPP(Water Erosion Prediction Project (Flanagan et al. 1995)), or KINEROS2 (A Kinametic Runoff and Erosion Model (Smith et al. 1995)). The site with

intermittent flow (Prairie Mountain hillside flume) in this project is similar to road segments in Megahan (1972), Wemple (1998), and McGee (2000). Large volumes of intercepted subsurface flow were observed at road segments in these studies. The most recent models used to predict interception of subsurface flow by roads are described in Section 3.3.2 ((DHSVM (Distributed Hydrologic Soil and Vegetation Model) and RHESSys (Regional Hydro-Ecological Simulation System) (La Marche and Lettenmaier 1998, Tague and Band 2001). Those models simulate a transient water table through permeable soil, over an impermeable layer, in response to storms, which is then intercepted by the road. McGee's (2000) road segments had these characteristics. A residual soil sat on top of an impermeable glacial till, and the road cutslope intercepted the entire soil profile. Subsurface flow ceased between storms, so the road ditches did not flow between storms (MgGee 2000). Use of DHSVM or RHESSys to simulate interception of subsurface flow from the Prairie Mountain hillslope might be difficult. At the Prairie Mountain site, the road ditch flowed in response to storms, but it also flowed between storms and well into the dry season. The source of the ditch flow was possibly the regional groundwater reservoir as well as a transient soil water table. Also, a sharp transition from permeable soil to an impermeable layer did not occur at Prairie Mountain or any of the other road segments in this study. Concentrated flow along an impermeable boundary was never seen at these sites during storms. Rather, the permeable forest soil made a gradual transition (over 1m to 3m) to weathered, fractured, and permeable bedrock. Preferential flow through bedrock fractures, as described for the Oregon Coast Range in Montgomery et al. (1997), may be a more common a pathway of subsurface flow than a ubiquitous transient water table.

7. TEMPORAL VARIABILITY OF ROAD SURFACE RUNOFF

Two important conclusions from the previous chapters were that the infiltration capacities of road surfaces were low (<11 mm/hr), but runoff ratios from road surface runoff were also low (< 0.2). The first conclusion suggests that a road is a virtually impermeable surface that sheds rainfall, but the second conclusion indicates most rainfall infiltrates into the road. The spatial and temporal variability of rainfall and infiltration can help explain why these two conclusions can occur simultaneously. There are usually periods of high intensity rainfall during a storm, which I earlier called pulses of rainfall (Section 4.4.2). I analyzed 103 pulses of rainfall that occurred during three storms in November 2002 at four of my sites. I did not use data from the Prairie Mountain roadside flume because of measurement error (Section 6.4.1). The total depth of rainfall pulses ranged from 13 to 107 mm, and the duration ranged from 0.1 to 17.4 hours. The average intensity ranged from 2 to 14 mm/hr.

Rainfall depth or infiltration depth divided by duration of rainfall is an estimate of average rainfall intensity or infiltration rate for a road (Figure 7.1). Infiltration rate increased with rainfall rate with a slope of slightly less than one, because the majority of rainfall infiltrated into the road and ditch (Figure 7.1). For Eisele and Prairie Mountain, there was greater runoff to the roadside flumes, indicating less infiltration than at the other three study sites. If average infiltration rates were close to the infiltration capacity of the roads, then the relationship in Figure 7.1 would not be expected. Instead, the average infiltration rate of the road would remain constant as rainfall intensity increased. If there were data from higher rainfall intensities, then this trend might level out at a constant infiltration rate that would be the average infiltration capacity of the road. Eisele is the only study site where that situation may have occurred (Figure 7.1). Eisele's lower infiltration rates agree with the observation that it had higher runoff ratios than any other study site (Table 6.6). Lower infiltration capacities would result in more rainfall

becoming runoff in the road ditch. Otherwise, one could conclude that the infiltration capacity was seldom reached at the study sites. However, the infiltration capacity of the road had to be reached for some short time periods in order for runoff to occur.

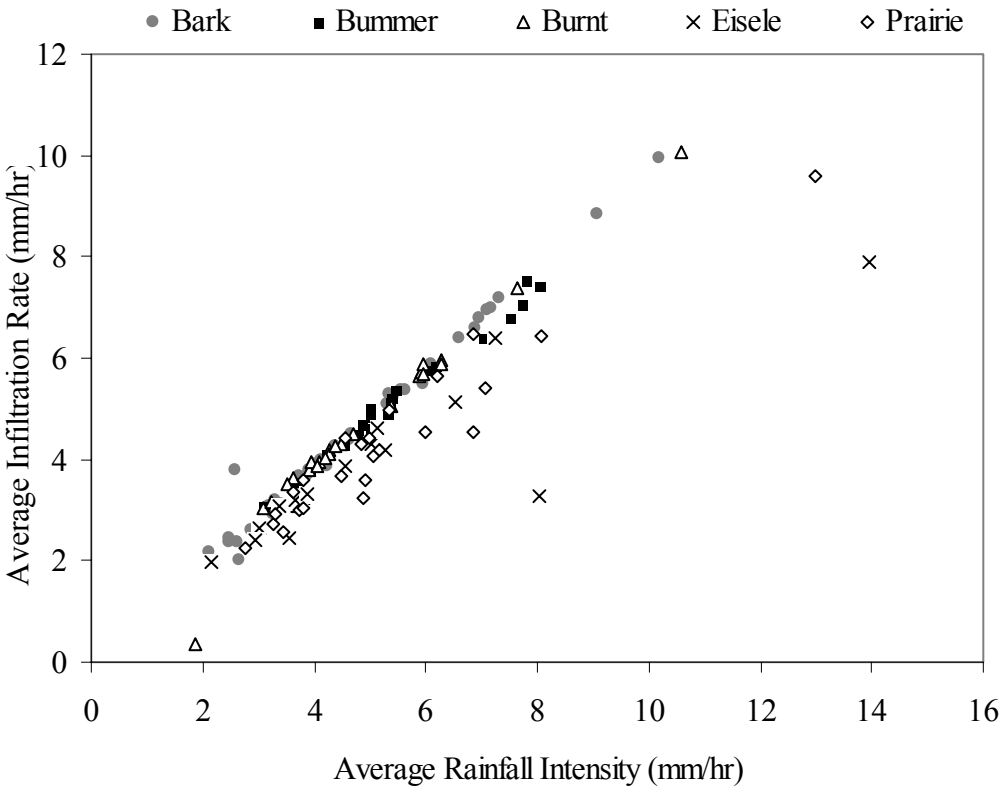

Figure 7.1. Average infiltration rate versus average rainfall rate for high and rainfall depths divided by the duration of the rainfall pulse.

7.1. WHEN RAINFALL INTENSITY IS GREATER THAN INFILTRATION CAPACITY

Stating average rainfall rates and infiltration rates implies that rainfall and infiltration are constant during the storms, but they are highly variable (Figure 7.2). Rainfall intensity infrequently exceeded the infiltration capacity of the road, which explained why storm runoff ratios were small for road surface runoff. Rainfall intensities were greater than the simulator-estimated infiltration capacities of the road surfaces for only 20 percent of the duration of storms, on average (Table 7.1). The importance of that figure is that most of the time during a storm, rainfall intensity is too low to produce surface runoff, and the infiltration rate of the road is the same as the rainfall intensity. Then, during a small portion of the storm, the rainfall intensity is high enough to produce surface runoff. Once the surface runoff is produced, it continues for some time after the high intensity rainfall has ceased until all the surface flow has drained off the road (Table 7.1).

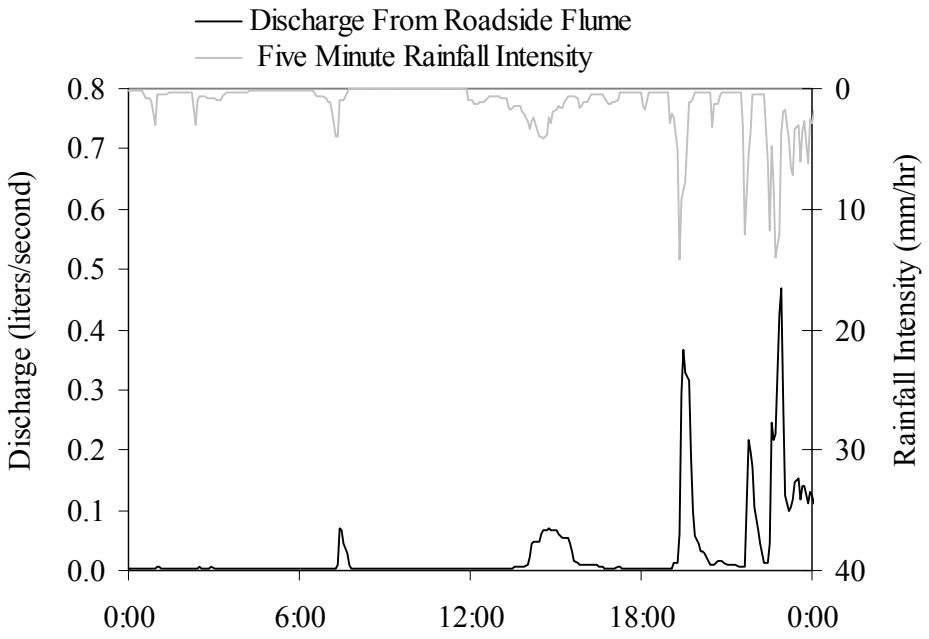

Figure 7.2. Five-minute rainfall intensity and discharge from the

Table 7.1. Infiltration rates in comparison to rainfall intensities during three storms, November 2001. Data from the Prairie Mountain study site were not included in this analysis.

Site	Storm	Infiltration Capacity (mm/hr)[A]	Infiltration Rate (mm/hr)[B]	Intensity > Infiltration Capacity (%)[C]	Runoff Occurrence (%)[D]
Bark Creek	1	3.2	1.2	7	21
Bark Creek	2	3.2	2.8	9	78
Bark Creek	3	3.2	2.3	28	92
Bummer Creek	1	5.4	1.2	3	18
Bummer Creek	2	5.4	3.9	25	60
Burnt Woods	1	4.8	3.3	21	60
Burnt Woods	2	4.8	3	20	67
Burnt Woods	3	4.8	2.1	11	35
Eisele	1	2.5	1	9	33
Eisele	2	2.5	2.5	54	90

A- Average infiltration capacity of the road as measured by a rainfall simulator.
B- Average infiltration rate over the duration of the storm (Infiltration Depth / Storm Duration)
C- Percent of time during the storm when 5-min rainfall intensity is greater than infiltration capacity.
D- Percent of time when runoff actually occurred in the ditch.

7.2. LAG TIMES

Lag times between the start of rain and start of ditch flow and also the lag times between the peak rainfall intensity and the peak discharge of ditch flow illustrated the responsiveness of ditch flow to rainfall. Start-to-start lag times ranged from 5 to 90 minutes, and median start-to-start lag time was 15 minutes. The large range of lag times could be attributed to the difference in antecedent moisture on the road at the onset of rain and to rainfall intensity. If the road were dry, then the expected lag time would be longer. If the rainfall intensity were high, then runoff would be produced more quickly, and therefore lag time would be shorter. Peak-to-peak lag times ranged from less than 5 minutes to 65 minutes. The median peak-to-peak lag time was 10 minutes, and 95 percent of lag times were less than 20 minutes (Figure 7.3).

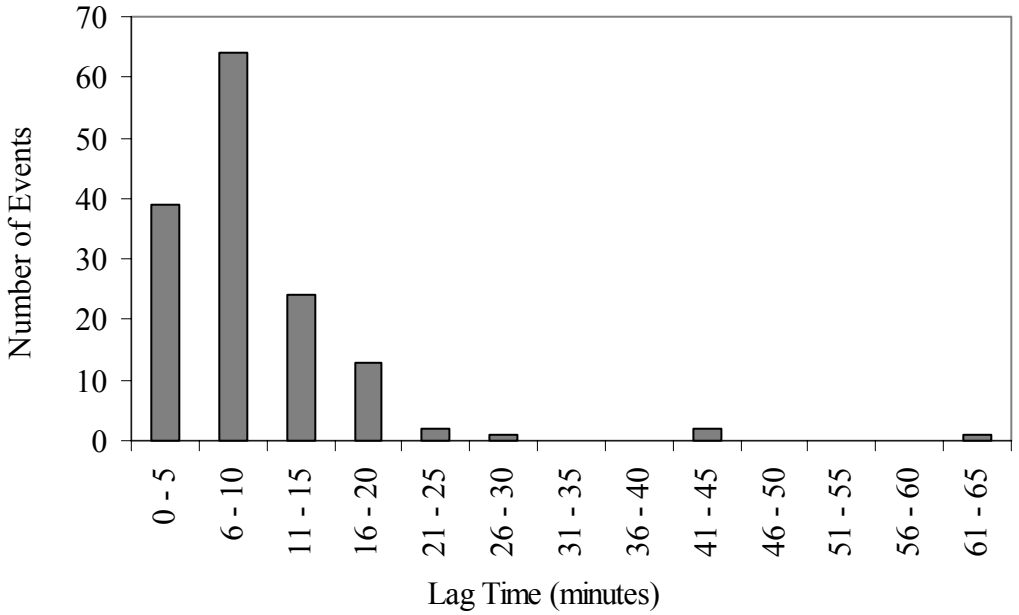

Figure 7.3. A frequency distribution of lag time between peak 5-minute rainfall intensity and peak runoff in roadside flumes for a total of 146 rainfall pulse events.

7.3. USE OF FLUME DATA TO CALCULATE INFILTRATION CAPACITIES

Given the close temporal relationship between rainfall and runoff described in the previous sections, the infiltration capacity of the road could be estimated by determining the maximum 5-minute peak rainfall intensity that does not produce runoff or the minimum 5-minute peak rainfall intensity that does produce runoff (Reid and Dunne 1984, Vincent 1985, and Kahklen 1993). The infiltration capacity should be between these values. The infiltration capacity, as determined from maximums and minimums, was similar to the infiltration capacity estimated by the rainfall simulator (Figure 7.4). Maximums and minimums are certainly affected by antecedent moisture on the road. Unless I characterize each peak with an estimate of antecedent moisture, this type of analysis will remain imprecise. Use of the maximum and minimum rainfall intensities as boundaries for the range of infiltration capacity added no precision to the estimates of the infiltration capacities derived from rainfall simulation. However it did confirm that the rainfall simulator estimates of infiltration capacity were reasonable. In other words, these estimates could be used in place of a rainfall simulator to give a reasonable estimate of infiltration capacity of a road.

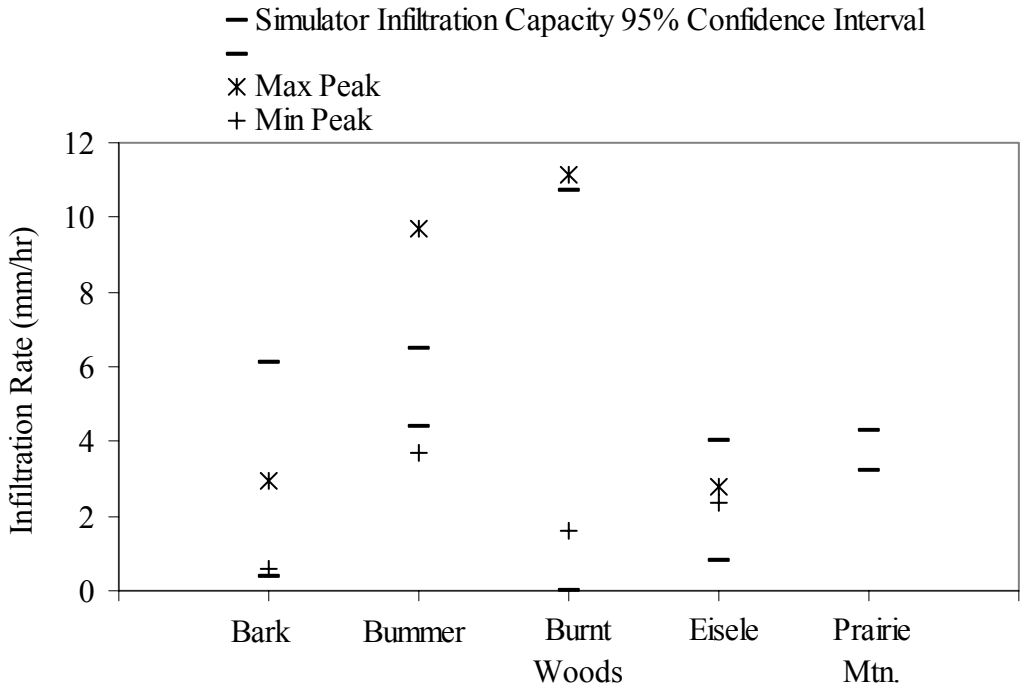

Figure 7.4. Estimates of infiltration capacities of the road study segments. The

simulator. The stars are the maximum peak 5-minute rainfall intensities that did not produce runoff. The crosses are the minimum peak 5-minute rainfall intensities that did produce runoff. No runoff data were included for Prairie Mountain.

8. CONCLUSIONS AND IMPLICATIONS FOR ROAD MANAGEMENT

Environmental regulations require forest landowners to minimize road building and limit road use, because the negative impacts of roads have been observed and documented (Beschta 1978, Lewis 1998). Yet the impact of a road system on any given watershed is hard to predict due to diverse geology, soils, climate, and road construction practices. This thesis demonstrates the utility of monitoring road ditch flow by illustrating that road hydrology is variable in sedimentary material of the Oregon Coast Range. Some roads exhibit ephemeral ditch flow. That is, they remain dry most of the year except during high intensity rainfall. Other roads exhibit intermittent ditch flow. That is, they flow continuously during the rainy season. Road management practices should accommodate these two types of flow.

The ephemeral ditch flow documented in this thesis was overland flow with minimal erosive power during low return interval storms. Previous authors of ditch relief culvert spacing tables probably expected that this type of flow was the only flow occurring in ditches where they collected empirical data (Arnold 1957, Copstead et al. 1998). Intermittent ditch flow was intercepted subsurface flow from the hillslope by the road cutslope and ditch, often from a seep. The greatest difference between the two types of flow was volume. Ephemeral flow in the ditch of this site produced minimal runoff volume, no more than 4.5 m^3 (16 mm / m^2 of road), for storms up to 140 mm in depth. In contrast, intermittent ditch flow intercepted from the hillslope produced up to 801 m^3 (2800 mm / m^2 of road) for similar storms, 20 times more flow than all of the rainfall that had occurred on the road surface. Any ephemeral ditch flow derived from subsurface flow on the hillslope was not observed in this study, though it may exist. Given current road drainage practices, ephemeral and intermittent ditch flow could be passing through the same size culvert and falling on to the same steep hillslope below, even though erosive power of intermittent flow is much greater. Road managers looking for

sources of road prism failures and road related landslides would do well to monitor flow volumes through road ditches.

Other ditch flow characteristics that were calculated in the thesis were peak flows and concentration times. Peak flows should not be the only measured ditch flow characteristic. Ephemeral runoff from the road surface had peak flows of no more than 0.3 liters/second from a road area of 286 square meters of road. Intermittent ditch flow peaked at a maximum of 4.3 liters/second. However, ephemeral and intermittent peak flows were similar and indistinguishable at times. Ephemeral and intermittent flow were distinguishable by concentration time, which was the time from beginning of storm flow to peak flow. Median concentration time was 48 minutes for ephemeral flow and 38 hours for intermittent flow.

It is possible that subsurface flow intercepted by road cuts could be ephemeral in behavior but still much greater in volume than road surface runoff. It wasn't documented in the sedimentary soils of study sites in thesis, but it could be common on hillslopes with different geology. A shallow, highly permeable forest soil over an impermeable bedrock or till in steep terrain could transmit soil water rapidly, resulting in short concentration times yet large ditch flow volumes. Regardless, the type of ditch flow cannot be determined by simple observation of a road system at one point in time. Ditch flow and rainfall must be continuously monitored.

Another product of this thesis was detailed information on runoff from five road study segments in the Oregon Coast Range. Road surfaces were crushed basalt surface rock on top of compacted sandstone soils. A rainfall simulator was used to measure road infiltration capacities, which averaged 4 mm/hr (95% confidence interval of individual experimental plots ranged from 0 mm/hr to 11 mm/hr). Despite the low infiltration capacities, rainfall and ditch flow data indicated that runoff volumes averaged only 5 percent of the rainfall that had occurred over the road surface area. This was primarily because rainfall intensity remained lower than infiltration capacity during most of the duration of storms.

Periodically, pulses of high intensity rainfall overwhelmed the infiltration capacity of the road and produced surface runoff. The median lag time from the peak of rainfall intensity to peak discharge of surface runoff was 10 minutes. A reasonable estimate of the infiltration capacity of a given road was obtained by finding the maximum rainfall intensity that did not produce runoff or the minimum rainfall intensity that did produce runoff. This exercise produced estimates of infiltration capacity that ranged from 0.5 mm/hr to 11 mm/hr.

The measurements in this thesis could be useful to road managers and easily repeated in different forest road systems. Cross drain culverts are ubiquitous on a managed forest landscape. Their consistently engineered shapes allow that the volume of water passing through them at any given moment can be measured. Inexpensive devices can be placed in culverts all over road systems to measure the distribution of water across a watershed. At the same time, log truck traffic can be tracked with GPS systems, so the quantity of road use can be measured (Brown et al. 2002). The degree of connection between road and stream networks is easily calculated with field surveys and Geographic Information Systems. Since runoff and traffic combine to produce the erosion that causes damage to aquatic ecosystems, forest managers would benefit greatly from knowing their exact location and timing. This would allow them to more accurately measure their own impacts on aquatic systems, to focus road improvements in the locations where they are most needed, and to clearly demonstrate improvements to regulators.

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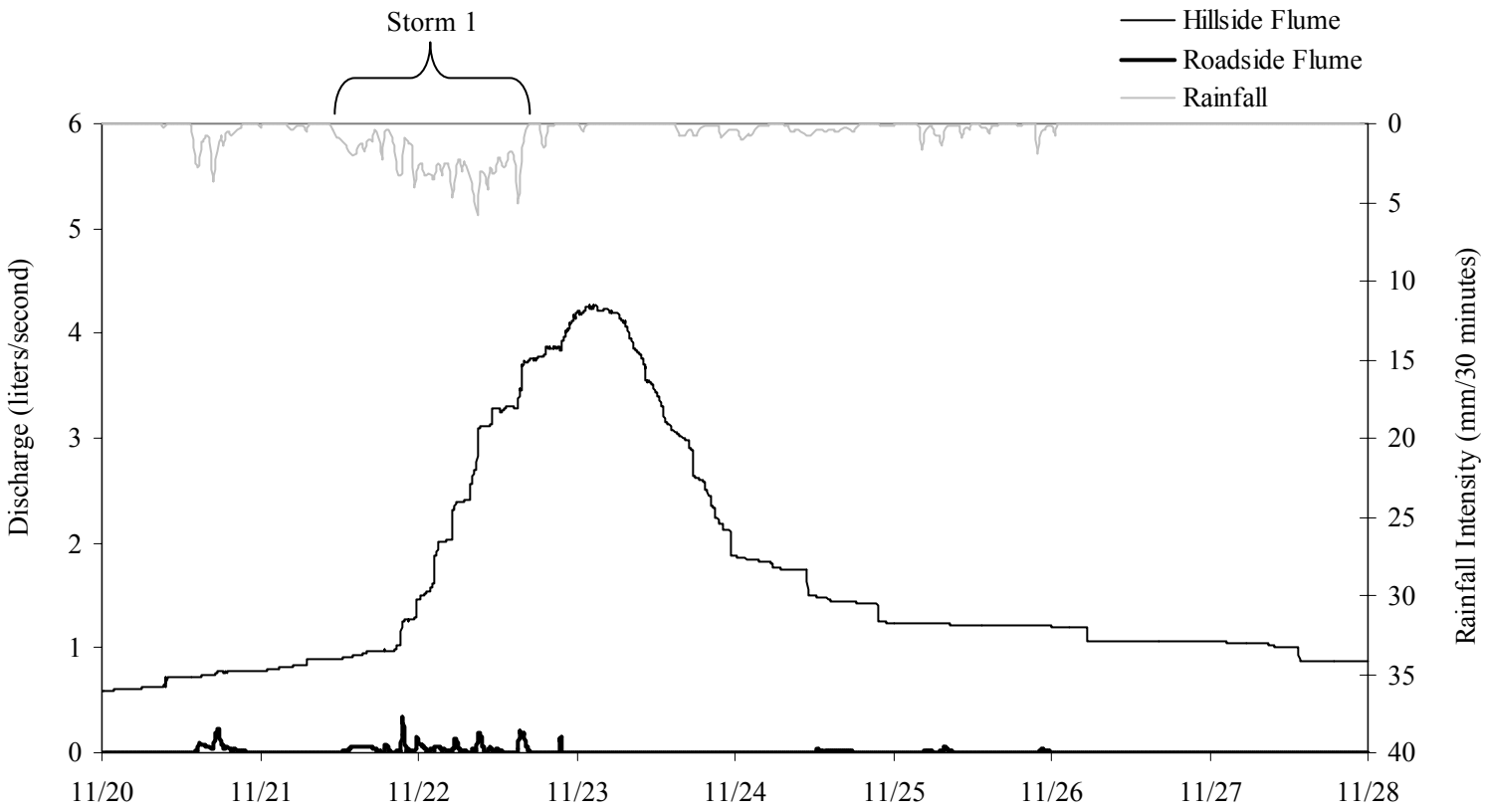
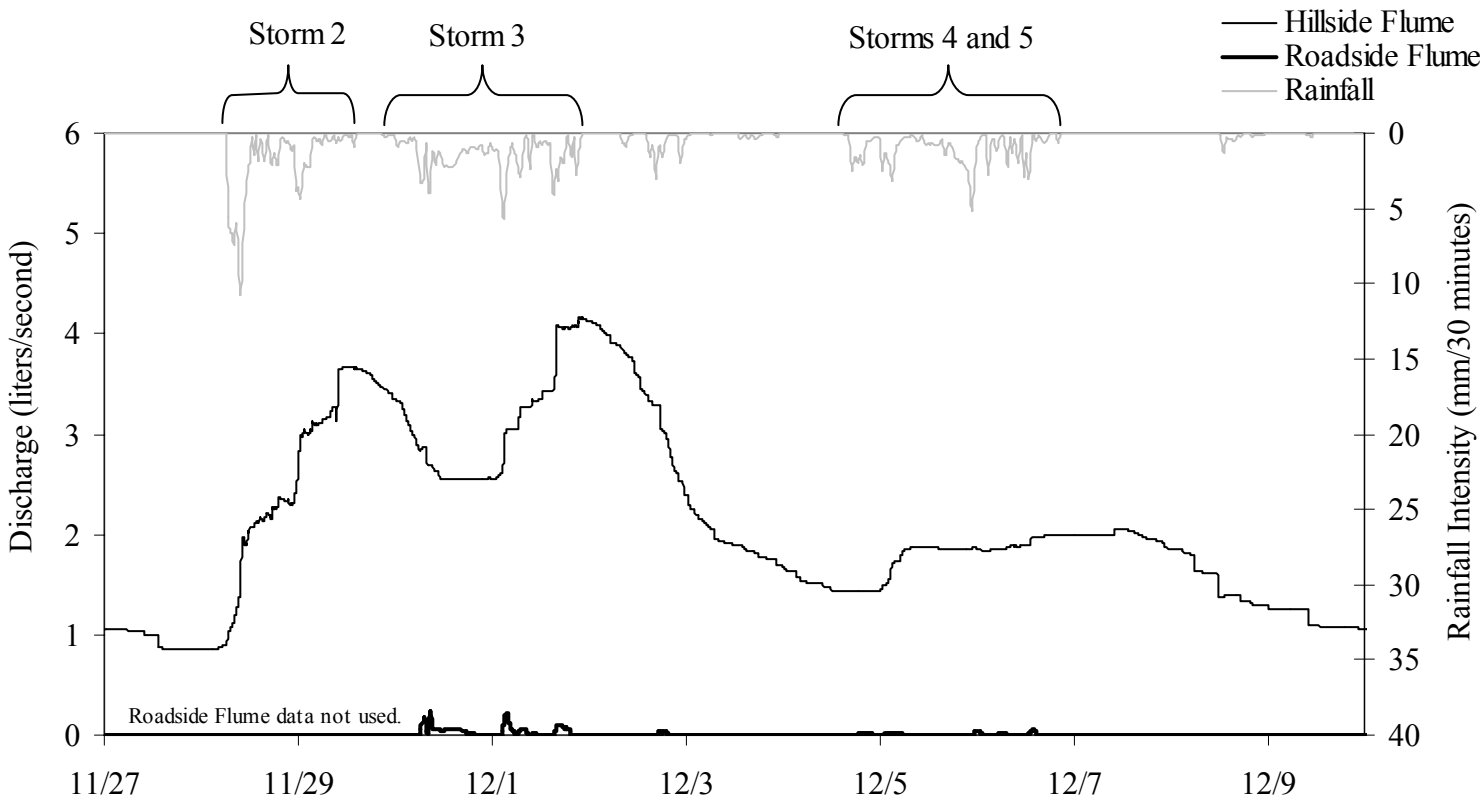
Appendix

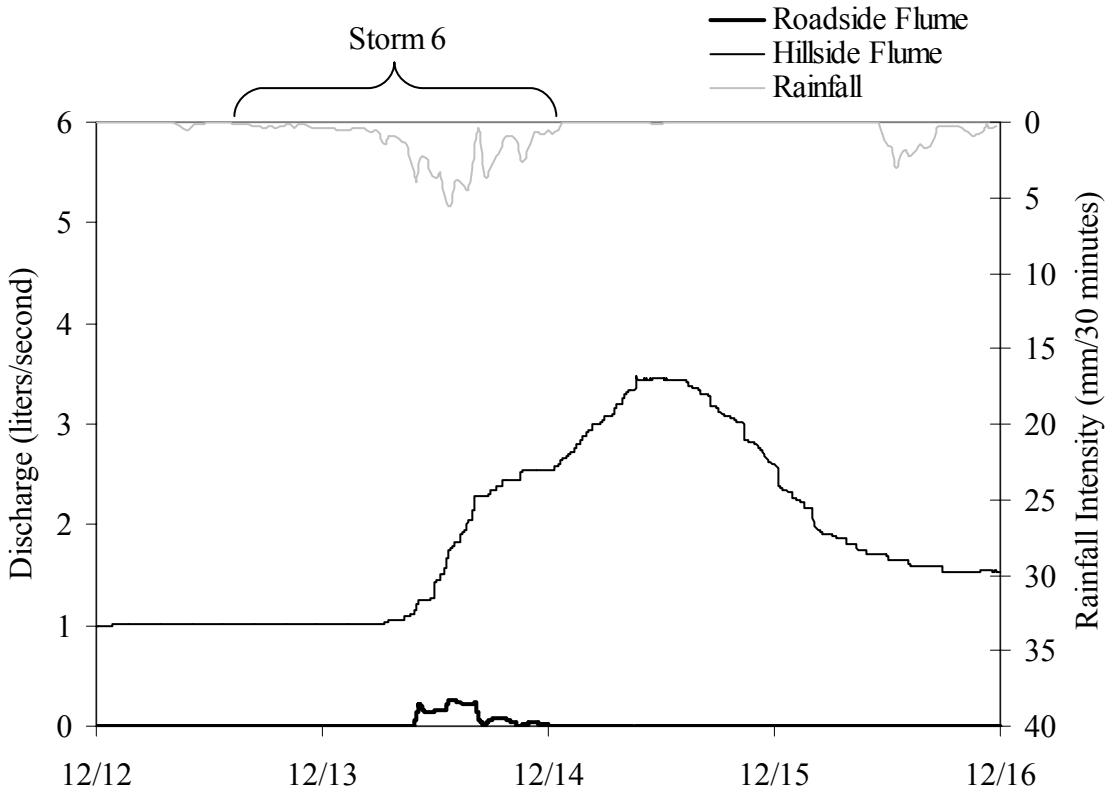
Rainfall and runoff at the Prairie Mountain study site
during the storms used in data analysis



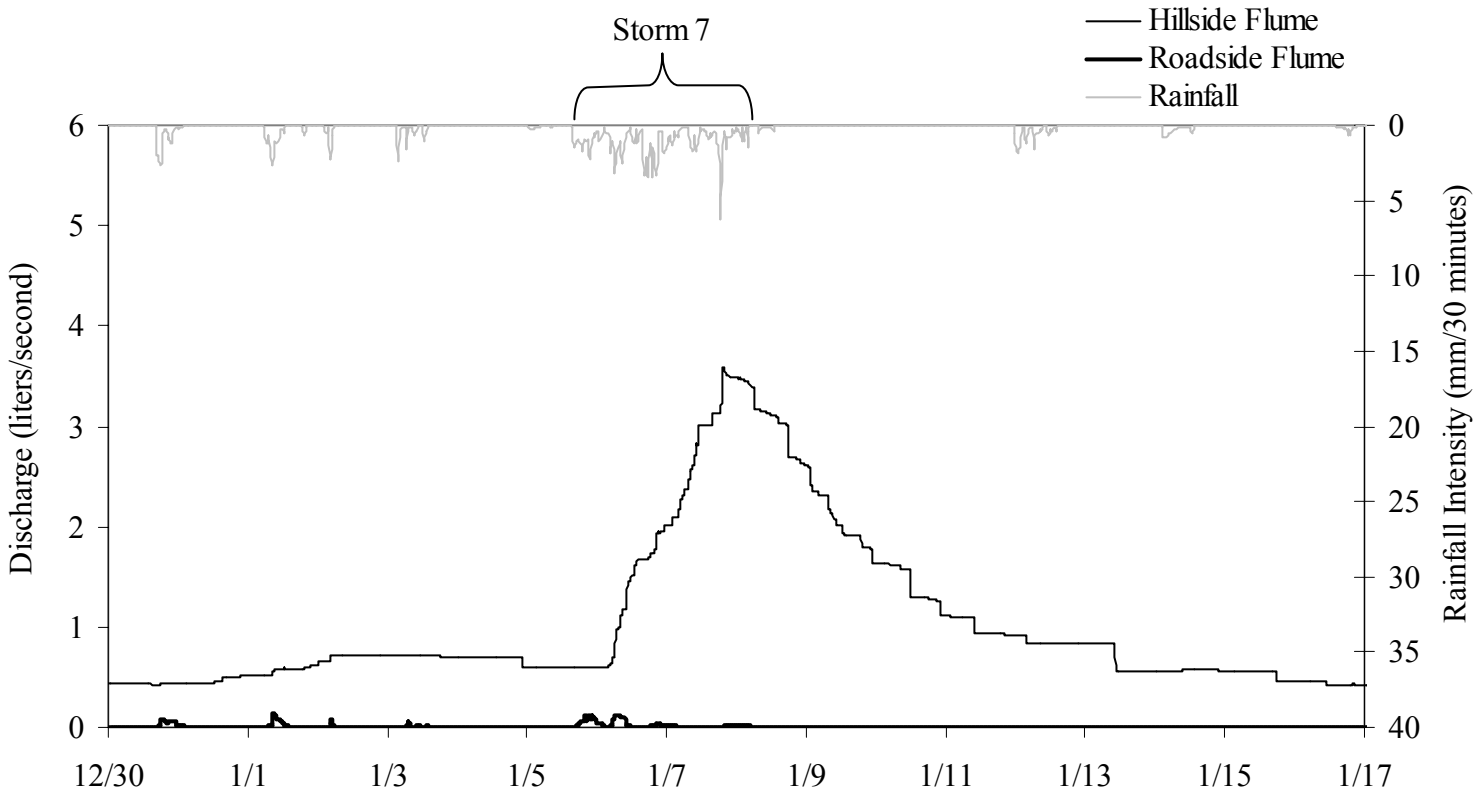
Appendix.1. Rainfall and runoff during Storm 1 at the Prairie Mountain study site in November 2001



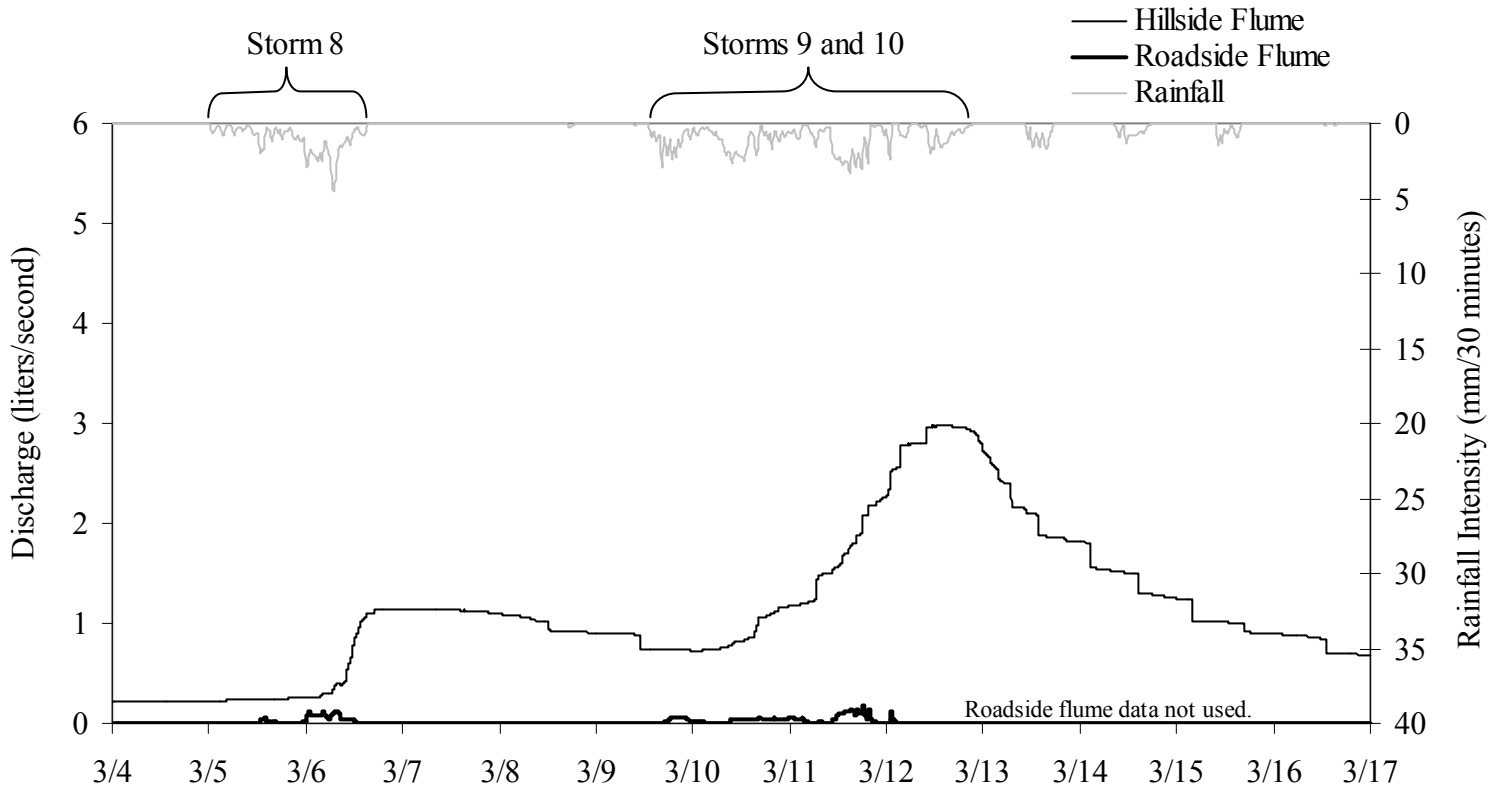
Appendix.2. Rainfall and runoff during Storms 2, 3, 4, and 5 at the Prairie Mountain study site in November and December 2001. Storms 2 and 3 were rain-on-snow events at the Prairie Mountain site and therefore not used in further data analysis.



Appendix.3. Rainfall and runoff during Storm 6 at the Prairie Mountain study site in December 2001



Appendix.4. Rainfall and runoff during Storm 7 at the Prairie Mountain study site in January 2002



Appendix.5. Rainfall and runoff during Storms 8, 9, and 10 at the Prairie Mountain study site in March 2002