AN ABSTRACT OF THE THESIS OF

Erin H. Gilbert for the degree of Master of Science in Forest Engineering presented on August 30, 2002.

Title: A Characterization of Road Hydrology in the Oregon Coast Range.

Abstract approved: Arne Skaugset

Arne Skaugset

Forest roads alter hillslope hydrologic processes by intercepting, concentrating, and rerouting storm runoff. Current road drainage guidelines are based on minimizing erosion and do not take into account the impact of forest roads on hillslope hydrology. This work monitors ditch flow and rainfall for 10 road segments over the course of one winter in the central Oregon Coast Range. The objective was to determine rainfall/runoff relationships and quantify metrics of runoff for the flow of water in roadside ditches. Road and hillslope characteristics were also recorded and related to the metrics of runoff of ditch flow.

Five large discrete storms were selected from the record for analysis. Two distinct ditch flow behaviors were identified from field observations and hydrograph inspection and were termed intermittent and ephemeral flow. Road segments that had intermittent flow had higher peak flows and greater storm runoff volumes than road segments with ephemeral flow. Rainfall/runoff relationships such as the lag time from the maximum rainfall intensity to the peak flow and the percent of rainfall seen as ditch flow were also significantly different between the two flow behaviors. Road and hillslope characteristics were not related to runoff peak flows or storm volumes. The best predictors of runoff were rainfall intensities and amounts. Evidence suggested that road segments with intermittent flow were being driven by the interception of upslope subsurface flow and that road segments with ephemeral flow were being driven by road surface runoff.

A CHARACTERIZATION OF ROAD HYDROLOGY IN THE OREGON COAST RANGE

by

Erin H. Gilbert

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 30, 2002
Commencement June 2003

Master of Science thesis of Erin H. Gilbert presented on August 30, 2002.

APPROVED:

Arne Skaugset

Major Professor, representing Forest Engineering

Chair of Department of Forest Engineering

Dean of Graduate School

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.

Erin H. Gilbert, Author

ACKNOWLEDGEMENTS

This research project was funded by a Center For Wood Utilization Grant through the Department of Forest Engineering.

I would like to thank my committee members, Drs. Fred Swanson, Stephen Schoenholtz, and Darrell Ross. I would especially like to thank my major professor Dr. Arne Skaugset who helped guide me through this challenging process.

There were many who helped me in the field and in data analysis. Erica Briese was an inspiring source of creative energy, and helped me immensely in my fieldwork. Erica, I still owe you for the hours we spent pounding steel pipe into the soil, only to pull it back out again. Melissa Clark and Richard Keim were a great help whenever I hit a brick wall in my data analysis, or couldn't quite get a computer to do what I wanted. Rob Tanner, Michelle Reba, Tracie Kirkham, K.K. McGee – thanks for your help in the field, I truly appreciated the input and most of all the company. And to all those who shared the Forest Engineering computer lab, through many a dark and wet Oregon winter, thanks for keeping me sane.

I would like to thank my family, my mother Judy and my father Jim, my brother Taavi, and my sisters Verity, Meighan, and Emmy. Thanks for believing in me. I would also like to apologize to all my friends and family who had to listen to me complain about my thesis for far too long (yes, I really DID finish it!). And lastly, to my greatest believer, thank you Tara.

TABLE OF CONTENTS

Page

1. Introduction 1
2. Study Objectives 3
3. Literature Review 4
    3.1. Road Drainage 4
    3.2. Sediment Generation and Transport 5
    3.3. Hillslope Runoff Processes 6
    3.4. Subsurface Flow Interception 8
    3.5. Peak and Low Flows 9
4. Study Area 11
    4.1. Geology 13
    4.2. Soils 13
    4.3. Climate 14
5. Methods 15
    5.1. Field Methods 15
        5.1.1. Selection of Individual Road Segments 15
        5.1.2. Equipment 17
        5.1.3. Road Segment Design 21
        5.1.4. Road and Hillslope Measurements 23
    5.2. Analysis Methods 24
        5.2.1. Storm Definition 24
        5.2.2. Summarizing Rainfall and Runoff 24
6. Results 26
    6.1. Road and Hillslope Characteristics 28

TABLE OF CONTENTS (Continued)

Page

6.2. Quality Checking the Data 29

6.2.1. Ditch Flow 29
6.2.2. Rainfall 31
6.2.3. Summary 34

6.3. Rainfall Summary 35

6.4. Ditch Flow Summary 38

6.4.1. Initial Results and Observations 38
6.4.2. Instantaneous Peak Flows 43
6.4.3. Total Storm Volumes 48

6.5. Rainfall/Runoff Relationships 53

6.5.1. Peak Lag Times 60
6.5.2. Percent Quickflow 62

6.6. Road and Hillslope Predictors 66

7. Discussion 69

8. Conclusions 76

Bibliography 78

LIST OF FIGURES

Figure Page

1. Location map of study area within the Oregon Coast Range............................12

2. Rating curve used to convert stage height to flow for a Large 60-degree "V" flume...18

3. Flume installation at road segment 16-6-8...20

4. Flume installation at road segment 15-8-1.2..20

5. Schematic of road segment design...22

6. Locations of individual road segments in the study area..................................27

7. Example of the stepping phenomena found in some of the road segment hydrographs, and the subsequent reconstruction of those hydrographs. 30

8. Cumulative rainfall for the five raingages used in analysis for a period with no snowfall..32

9. Cumulative rainfall for two raingages. The evidence of snowfall is shown in the lighter line.. 33

10. Total rainfall for four storms showing an increase in rainfall with increasing elevation. 36

11. A comparison of maximum 6-, 12-, and 24-hour rainfall intensities between the Lobster Creek raingage and the raingages from the study sites. ..37

12. The hydrograph of the five selected storms from road segment 15-8-1.2 with intermittent flow. 39

13. The hydrograph and cumulative rainfall of Storm 1 (11/26/99) from road segment 15-8-1.2 with intermittent flow. 40

14. The hydrograph of the five selected storms from road segment 14-8-1.4 with ephemeral flow...41

15. The hydrograph and cumulative rainfall of Storm 1 (11/26/99) from road segment 14-8-1.4 with ephemeral flow. 42

LIST OF FIGURES (Continued)

Figure Page

16. Instantaneous peak flows for all road segments and storms included in the analysis...45

17. Instantaneous peak flows normalized by road segment length for all road segments and storms included in the analysis...46

18. Instantaneous peak flows normalized by upslope contributing area for all road segments and storms included in the analysis. ...47

19. Total runoff volumes for all road segments and all storms analyzed. ...50

20. Total runoff volumes normalized by road segment length for all road segments and all storms analyzed.. ...51

21. Total runoff volumes normalized by upslope contributing area for all road segments and all storms analyzed. ...52

22. A graph showing the relationship between the maximum 24-hr rainfall intensity and total storm rainfall for all storms and road segments analyzed...54

23. The relationships between a) maximum 15-minute rainfall intensity and instantaneous peak flow, b) maximum 15-minute rainfall intensity and runoff volume, c) total storm rainfall and instantaneous peak flow, and d) total storm rainfall and runoff volume for all road segments. ...55

24. The relationships between a) maximum 15-minute rainfall intensity and instantaneous peak flow, b) maximum 15-minute rainfall intensity and runoff volume, c) total storm rainfall and instantaneous peak flow, and d) total storm rainfall and runoff volume for all road segments...56

25. Relationships between maximum 15-minute rainfall intensity and instantaneous peak flow and between total storm rainfall and instantaneous peak flow for four road segments with ephemeral flow. ...58

26. Relationships between maximum 15-minute rainfall intensity and runoff volume and between total storm rainfall and runoff volume for four road segments with ephemeral flow...59

LIST OF FIGURES (Continued)

Figure Page

27. Lag times between the maximum 15-minute rainfall intensity and the associated instantaneous peak flow for all storms and road segments. 61

28. Percent of total storm rainfall falling on the road area that was quickflow in the road ditch..64

29. Percent of total storm rainfall falling on the upslope contributing area that was quickflow in the road ditch. 65

30. Instantaneous peak flows compared with road and hillslope characteristics for four storm events 67

31. Total storm volumes compared with six road and hillslope characteristics for four storm events 68

32. A graph showing the lack of relationship between upslope contributing area and road segment length for the six road segments used in the analysis..73

LIST OF TABLES

Table Page

1. Road and upslope contributing area characteristics for the 10 road segments. .28

2. Road segments and storms included in the final analysis. 34

3. A summary of maximum rainfall intensities and total rainfall for five storms and six road segments in the vicinity of Prairie Peak in the central Oregon Coast Range during the winter of 1999-2000. 35

4. Instantaneous peak flows for all road segments and storms included in the analysis. 44

5. Total runoff volumes for all road segments and all storms analyzed. 49

6. The lag time between the maximum 15-minute rainfall intensity and the associated instantaneous peak flow for all storms and road segments. 60

7. Percent quickflow (using road area and the upslope contributing area) for all storms and road segments analyzed. 63

A Characterization of Road Hydrology in the Oregon Coast Range

1. INTRODUCTION

Forest roads have historically been constructed in Oregon for the purpose of accessing and extracting timber. Once in place, these roads are also used for fire detection and suppression and provide access for recreational and silvicultural purposes. Historical trends in forest road design and location are responsible for the complex road system that must be managed today. It wasn't until after World War II that timber harvesting in Oregon became truly mechanized and rates of road construction increased dramatically. Around the 1970's, the use of more powerful logging trucks and the introduction of skyline logging allowed engineers to design roads with steeper grades and to place roads in ridge-top locations, thus reducing the number and length of roads needed for timber extraction. Forest roads have recently come under increased scientific and public scrutiny due to their potential impact on hillslope hydrologic and geomorphic processes. Past and present research involving forest roads has focused on landslides (Swanson and Dyrness, 1975), sedimentation (Reid and Dunne, 1984), surface and subsurface flow interception (Wemple, 1999), stream connectivity (Wemple et al., 1996), and peak flows (Jones and Grant, 1996).

Current road drainage guidelines are based on minimizing erosion and do not take into account the impact of forest roads on hillslope hydrology. Some studies have addressed the temporal changes in flow of road drainage in response to precipitation (Wemple, 1999, MacDonald et al., 2001), but this research needs to be applied to different climatic and geologic settings, and fine scale spatial and temporal variability in rainfall must be accounted for. A better understanding of temporal and spatial variability in road runoff response to rainfall will help improve the efficiency and effectiveness of drainage design. With this study we hope to add to existing knowledge of forest roads and their effect on watershed hydrology.

Forest roads present a unique challenge to land managers attempting to minimize management impacts on watershed ecosystems. While the harvesting of trees can be related to disturbances in the natural environment such as fire or disease, forest roads have no natural analogue. This makes roads especially difficult to manage, if the goal is to make them "invisible" to natural watershed processes.

2. STUDY OBJECTIVES

The overall goal of this study is to characterize the hydrology of individual road segments in the central Oregon Coast Range. There were two specific objectives: 1) Determine rainfall/runoff relationships and quantify metrics of runoff for the flow of water in roadside ditches. 2) Relate the metrics of runoff of ditch flow to hillslope and road characteristics.

The timing and magnitude of precipitation and ditch flow response will be measured at a site-specific scale and a relationship between rainfall and runoff will be developed. Ditch flow hydrology will also be characterized in order to better understand the temporal and spatial variability of runoff present in the natural environment. Additionally, road and hillslope characteristics will be compared to ditch flow response to determine what, if any, relationships may exist.

3. LITERATURE REVIEW

The impact of forest roads on hydrologic processes in watersheds is unclear to researchers and land managers. Interception of surface and subsurface flow by roads may play a key role in rerouting storm runoff. An understanding of hillslope runoff flow pathways may help to predict where road cutslope interception will occur. The routing of subsurface runoff to surface flow by roads may potentially affect the timing and magnitude of peak flows as well as the amount of sediment transported to streams.

3.1. ROAD DRAINAGE

The goal of forest road drainage is to minimize erosion. Inadequate road drainage can result in excessive road surface and ditch erosion (Packer, 1967) and increased rates of landslides (Dyson et al., 1966; Dyrness, 1967; Burroughs, 1984; Krag et al., 1986). Improved road drainage helps to minimize road maintenance costs and reduce sedimentation into streams. Ditch relief culverts are used to move water under the road prism. Proper spacing, location, sizing, and installation of these culverts are required to minimize ditch and road surface erosion (Packer, 1967; Donahue and Howard, 1987; Piehl et al.,1988). Arnold (1957) presented culvert spacing guidelines based on soil erodibility and road grade. These guidelines were revised by Baeder and Christner (1981) to include slope position, aspect, and cutbank failure probability. Inadequate culvert spacing and maintenance can result in excessive ditch erosion and erosion at culvert outlets (Piehl et al., 1988). Poorly located ditch relief culverts can result in road instability due to erosion and saturation of soils at the culvert outlet (Packer, 1967; Krag et al., 1986). Pipes that are undersized or improperly installed can be overtopped or plugged during peak runoff events, resulting in inlet and road surface erosion and road failures (Donahue and Howard, 1987; Piehl et al., 1988).

3.2. SEDIMENT GENERATION AND TRANSPORT

Forest roads generate and transport sediment by surface erosion and landslides (Swanson and Dyrness, 1975; Beschta, 1978; Reid and Dunne, 1984; Bilby et al., 1989; Megahan and Ketcheson, 1996). Forested roads are compacted surfaces that have infiltration capacities that are an order of magnitude or two lower than the surrounding forest floor (Ziegler and Giambelluca, 1997). Erosion occurs when rainfall is intercepted by road surfaces and is channeled into ditches as surface flow. Factors influencing sediment production include traffic rate, depth of road ballast and type of surfacing material, and road gradient (Reid and Dunne, 1984; Bilby et al., 1989). Soil type, length of road between drainage features, and vegetation in the ditch and on the cutslope has also been associated with increased rates of erosion (Luce and Black, 1999). Immediately following road construction, the cutslope, ditch, and fillslope, not the road surface, are probably the major sources of sediment (Fahey and Coker, 1989). Connectivity must exist between the road drainage systems and streams if sediment generated by road surface erosion is to reach the streams. These surface flow paths may be ditches draining directly into streams or incised gullies below cross drain culverts (Megahan and Ketcheson, 1996; Wemple et al., 1996).

Road-related landslides can produce erosion rates up to three orders of magnitude greater than surface erosion rates (Sidle et al., 1985; Fransen et al., 2001). Mass-movement erosion is influenced by a number of factors, including road location, design, and age, and hillslope geology, topography, and soil type (Swanson and Dyrness, 1975; Sessions et al., 1987; Beschta et al., 1995; Fransen et al., 2001). Roads constructed using steep grades and full bench end-haul techniques were associated with a significant decrease in landslide size and frequency compared to roads constructed using techniques typical of the late 1960's and early 1970's (Sessions et al., 1987). Road related landslides rates were shown to decrease with increasing road age in a study conducted in New Zealand (Fransen et al., 2001). Swanson and Dyrness (1975) found that a difference in geology within a single watershed was associated with an order of magnitude difference in road-related landslide frequency. Mass soil erosion from roads was found to be the primary cause for increased sediment production to streams following harvest activity in the Oregon Coast Range (Beschta, 1978).

3.3. HILLSLOPE RUNOFF PROCESSES

Little is known about the mechanisms that dictate subsurface flow of water in forested basins. It is generally accepted that overland flow rarely occurs in undisturbed forests of western Oregon. This is due to the fact that infiltration capacities of most forest soils are almost always greater than the maximum rainfall intensities (Horton, 1933; Hewlett and Hibbert, 1967; Chamberlin, 1972). Soil in a watershed can be thought of as a reservoir that will fill and empty in a manner dictated by a soil's characteristic curve. This reservoir concept is incorporated into models such as the Thornthwaite water balance equation, in which soil maps are used to calculate the available soil moisture holding capacity for a watershed. In this model it is assumed that a soil must reach saturation before surface runoff can occur (Thornthwaite and Mather, 1957).

To further explore hillslope runoff processes, other studies have introduced the concepts of preferential pathways and translatory flow (Hewlett and Hibbert, 1967; Keppler and Brown, 1997). Water can move through a soil via two pathways, either through micropores or macropores. Micropores transmit water slowly compared to macropores, and there is a certain pore pressure that must be reached before micropores will release water to macropores. This creates an environment in which macropores are able to transport water only when soils are near saturation.

Keppler and Brown (1997) describe a mechanism known as “pipe flow”, where subsurface macropore flow pathways are created by roots or animals and are connected and lengthened by erosion as water flows through them. These “pipes” create a mechanism for the rapid movement of water through the soil. Shallow fractured bedrock in the Oregon Coast Range also is thought to be a pathway for the rapid movement of subsurface waters (Montgomery et al., 1997). Water exiting these bedrock pathways has been shown to create local subsurface saturated areas, which can divert vertically penetrating vadose zone water to runoff (Montgomery et al., 1997).

There is evidence that stored water in the soil is displaced by "new" water entering as precipitation. This process (described as translatory or "plug" flow) may be another explanation for the relatively quick rates of runoff observed via subsurface flow (Hewlett and Hibbert, 1967; Anderson et al., 1997). This has been observed not only for translatory micropore flow, but also for macropore processes (McDonnell, 1990).

Topography has been shown to play a role in subsurface flow pathways as well (Anderson and Burt, 1978). McDonnell (1990) hypothesized that matrix flow paths can be predicted by soil surface topography, while macropore or “pipe” flow can be predicted by bedrock topography. Many studies also have shown that saturated conditions are rare in steep, humid forests, even at high rates of precipitation (Yee et al., 1977). This has resulted in the concept of transient saturated zones, variable in time and space (Yee et al., 1977; Harr, 1979). The interaction of all of these previously mentioned processes illustrates the complexity of subsurface flow pathways in steep, forested landscapes.

3.4. SUBSURFACE FLOW INTERCEPTION

Whether water is flowing down a hillslope as surface or subsurface flow, a road traversing the landscape can capture and concentrate that water. Road cutslopes have been shown to intercept subsurface flow and convert this into surface runoff (MacDonald et al., 2001). Subsurface interception by road cutslopes occurs primarily during large storm events when soils are receiving relatively large amounts of rainfall (Megahan, 1972), and differences in subsurface flow interception between roads can be related to differences in upslope contributing areas (MacDonald et al., 2001). A study conducted in Idaho found the annual subsurface flow interception by a road segment in a single watershed to be 21.3 area-cm of the upslope contributing area. This was in response to 102 cm of precipitation for the same year (Megahan, 1972). Megahan also found evidence of flow concentrating in drainage bottoms, but not exclusively. He estimated that the road cut was intercepting only about 35% of the total hillslope runoff, in spite of the fact that a majority of the road was constructed below the bedrock layer. The reason for this may be the subsurface flow of runoff under the road through weathered granitic bedrock (Megahan, 1972).

The topic of subsurface flow interception was addressed most recently in studies conducted in the Oregon Cascades by Wemple (1999), and in Southeast Alaska by McGee (2000). Wemple measured runoff from road segments that were located within a 101-hectare watershed. The road segments varied in characteristics such as upslope drainage area, slope gradient, soil depth, and depth of road cut. She also examined the influence of climatic variables such as precipitation rate and depth, and antecedent soil moisture conditions. Runoff was dependent on rainfall and soil moisture conditions, as well as hillslope contributing area, hillslope gradient, soil depth, and roadcut depth. Rainfall events greater than 40 mm with average intensities of 2 mm/hr were typically required to produce runoff in her study area. Roads located on convergent topography exhibited higher unit-area runoff values than roads on planar topography.

Subsurface and surface flow were monitored for two roads in southeast Alaska (McGee, 2000). Well water levels above and below an existing road were measured before and during a storm. Low water levels before the storm were significantly different above and below the road, but peak water levels during the storm were not. Subsurface water levels were also measured before and after road construction. Following road construction, pre-storm low water levels were not significantly different, but peak water levels had a small but significant change. Ditch flow measured on these roads accounted for roughly 100% of the area precipitation from the upslope contributing areas. Although the intercepted flow seemed significant, it did not translate into a change in subsurface water levels below the road. When changes do occur in subsurface water levels, they tend to occur directly above the road cutbank and below the road fillslope (McGee, 2000).

3.5. PEAK AND LOW FLOWS

There are no known definitive answers concerning the effect of roads on peak flows in forested watersheds. Studies examining the impact of roads on peak flows have been conducted almost exclusively at the watershed scale. The results of these studies have varied widely, with observed peak flows reportedly increasing, decreasing, or not changing at all. Harr et al. (1975) found that peak flows were increased in a watershed following road construction, but only if roads occupied at least 12% of the watershed area. Jones and Grant (1996) report that roads combined with clearcutting increased peak flows to a greater extent than would roads or clearcutting alone. In a response to the Jones and Grant study, Thomas and Megahan (1998) reanalyzed the same data used by Jones and Grant, and reported an increase of 40% for the smallest peak flows in the roaded and patch cut watershed. This increase diminished and was not noticeable for peak flows with return intervals of greater than 2 years. Wright et al (1990) found no change in peak flows in response to road building. The variability in these studies may be due to the fact that they have focused primarily on the effects of timber removal and only secondarily on road effects (Beschta et al., 1995). The inconsistencies present in these studies support the need for a better understanding of road effects on peak flows at a process level.

4. STUDY AREA

This study was conducted in the Prairie Peak area of the central Oregon Coast Range (Figure 1). Created by uplift of the North American plate over the subducted Juan de Fuca plate, the Oregon Coast Range is a major topographic and climatic divide in the Pacific Northwest region of the United States. Elevations range from 450 to 750 meters in main ridge summits, with a maximum elevation of 1,249 meters at the top of Mary's Peak. Vegetation in this area consists primarily of a coniferous overstory of Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), with a vine maple (*Acer circinatum*), salal (*Gaultheria shallon*), and swordfern (*Polisticum munitum*) dominated understory. Moderate temperatures and high amounts of precipitation contribute to a highly productive growing environment (Corliss, 1973).

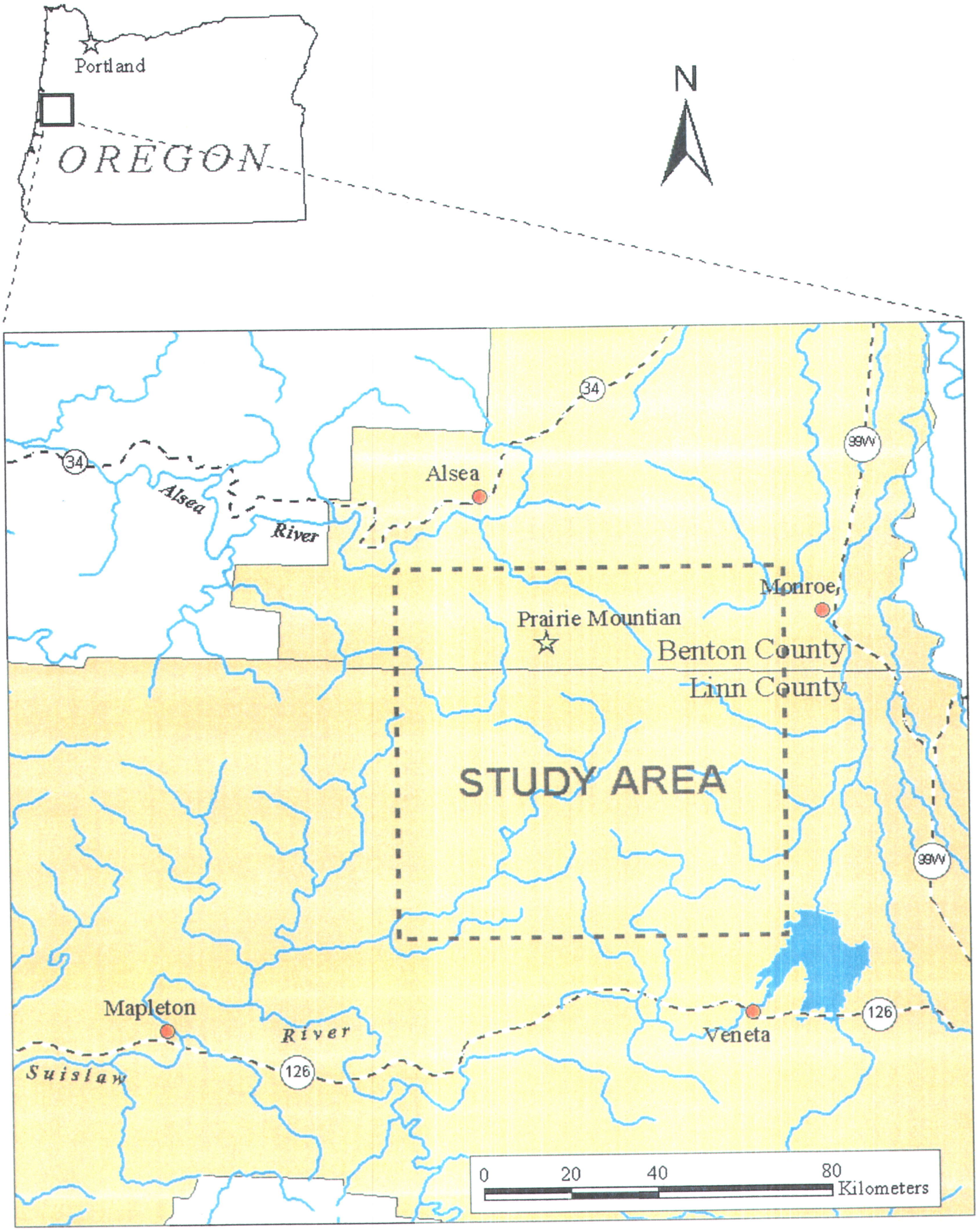

Figure 1. Location map of study area within the Oregon Coast Range.

4.1. GEOLOGY AND TOPOGRAPHY

Due to its origins beneath the ocean, the bedrock geology of the central Oregon Coast Range is primarily sedimentary sandstone and shale, with scattered areas of basalt, diorite, and gabbro. The Prairie Peak area consists primarily of arkosic sandstone, while Prairie Peak itself is capped with less easily weathered diorite and gabbro. High precipitation and mild temperatures characteristic of the area combine with easily weathered sandstone to create a topography highly dissected by streams. Stream networks in these sandstone areas typically follow a dendritic drainage pattern. Valleys tend to be narrow and steep sided (Corliss, 1973).

4.2. SOILS

Soils in the uplands of the Prairie Peak area possess low bulk density and high porosity. More specifically, soils for the study area fall into the gravelly-loams of the Bohannon, Slickrock, and Trask series, and the silty clay loam of the Honeygrove series. Bohannon, Slickrock, and Trask soils are all shallow and well-drained, formed in alluvial and colluvial materials derived from sandstone. Honeygrove soils are deep and well-drained, formed in colluvium and residuum derived from sandstone, siltstone, tuff, and basalt. Prairie Peak is capped by intrusive igneous rock, and soils in this area contain many coarse basaltic rock fragments (Corliss, 1973; Patching, 1987).

4.3. CLIMATE

The central Oregon Coast Range has a marine climate, winters are cool and wet and summers are dry and warm. Prolonged periods of daily temperatures below -7 degrees C or above 35 degrees C are uncommon. Frequent rain occurs during the winter, with 90 percent of the annual precipitation of 203 to 305 cm falling between October and May. Daily rainfall of 6.4 cm and monthly totals of 64 cm are not uncommon during this period, but intensities are low. Snowfall is usually restricted to the higher elevations and is not persistent. Summer precipitation is rare, typically less than one-tenth of the annual precipitation falls between the months of June and September (Corliss, 1973).

5. METHODS

5.1. FIELD METHODS

Forest road runoff is generated when precipitation falls on the cutslope, ditch, and road surface and by interception of subsurface flow by the road cutslope. Field methods for this study were designed to monitor ditch flow and precipitation and to characterize road and hillslope properties. Monitoring was conducted over the span of one winter, beginning in October of 1999 and ending March of 2000.

5.1.1. Selection of Individual Road Segments

Road segments were selected based on characteristics of the road and the adjacent hillslope. The desired road segment had a high potential for subsurface flow interception and ditch flow. Selected road segments were also required to fall within certain parameters necessary for flume installation and the accurate measurement of ditch flow.

The primary road characteristics used to select road segments were road grade and road location. Road grade needed to be sufficiently steep so that ditch flow would not infiltrate, however not so steep to compromise the accuracy of the flumes. A road grade of 10 percent was selected as optimum, and the actual road grades were greater than and less than that value. Selected road segments were all located at the mid-slope of the adjacent hillside, not at the valley bottom or near the ridge. Additional characteristics of the road segment considered to be desirable were cutslope height and evidence of previous ditch flow. Cutslope height and the associated soil depth have been reported to be associated with subsurface flow interception in previous studies (Wemple, 1999), however, it was not considered a primary factor in site selection for this study for several reasons. First of all, it was observed that cutslope height was dependent on whether the hillslope was convex or concave as the road traversed into and out of drainages and around ridges. Cutslopes are higher where roads go around the nose of a ridge and lower where roads pass through a drainage. This pattern in cutslope height is counter-intuitive to the concept that high cutslopes with shallow soils intercept more subsurface water because high cutslopes and shallow soils are located on ridges where subsurface flow is dissipated and contributing areas are smaller. Conversely, low cutslopes with deep soils are found in the drainages where subsurface flow is focused and contributing areas are larger. This relationship is important in the Oregon Coast Range, because the topography is highly dissected by streams and a long stretch of road on planar topography is rare. Given the difficulty finding road segments that possess several desired characteristics and the problem of isolating cutslope height from other contributing factors, cutslope height was not used as a factor in road segment selection. Finally, with regard to road characteristics, the variability in road age, surface material, and level of use was also minimized.

The primary hillslope characteristics used in road segment selection were slope and topography. Road segments were selected on steep slopes that have shallow soils and thus increase the potential for interception of subsurface flow. Road segments constructed through concave or convex topography were avoided to simplify hillslope subsurface flow processes as much as possible. Planar topography and road segments without curves were selected wherever possible. To the degree practicable, differences in vegetation age and type, geology, and soil types were minimized.

Ultimately, due to the high variability in road types and locations across the landscape, it was impossible to meet all criteria for all road segments. Thus, the road segments selected possess the maximum number of desirable characteristics. When deciding between two road segments of similar qualifications, the road with the greatest perceived potential to intercept subsurface flow was always chosen.

5.1.2. Equipment

Runoff was measured in the ditch of each road segment using a trapezoidal flume and water level recorder. The flumes, fabricated by Composite Structures Inc., were large 60-degree "V" flumes made of fiberglass. This type of flume was selected because its shape conforms to the normal shape of the ditch and the opening passes debris and sediment. These flumes have a maximum capacity of 9.34 liters per second (l/sec). A stilling well made of PVC pipe 15.2 cm in diameter was attached to the flume via a 1.3 cm port. Water level in the stilling well was measured using a Unidata 6541 Precision Water Level Instrument. This device uses a float and counterweight system to provide continuous monitoring of water level at a resolution of 0.2 mm. Water levels were measured or scanned every 15 seconds and averaged and recorded at 30-second intervals. Recorded data were stored on an attached Unidata data logger and downloaded to a laptop every 20 days. The flumes were factory calibrated and converted stage height to flow using the power function

$$q = 1.55h^{2.58} \tag{1}$$

where q is the instantaneous flow rate in units of cubic feet per second, and h is the stage height in units of feet. The rating curve resulting from equation 1 is seen in figure 2.

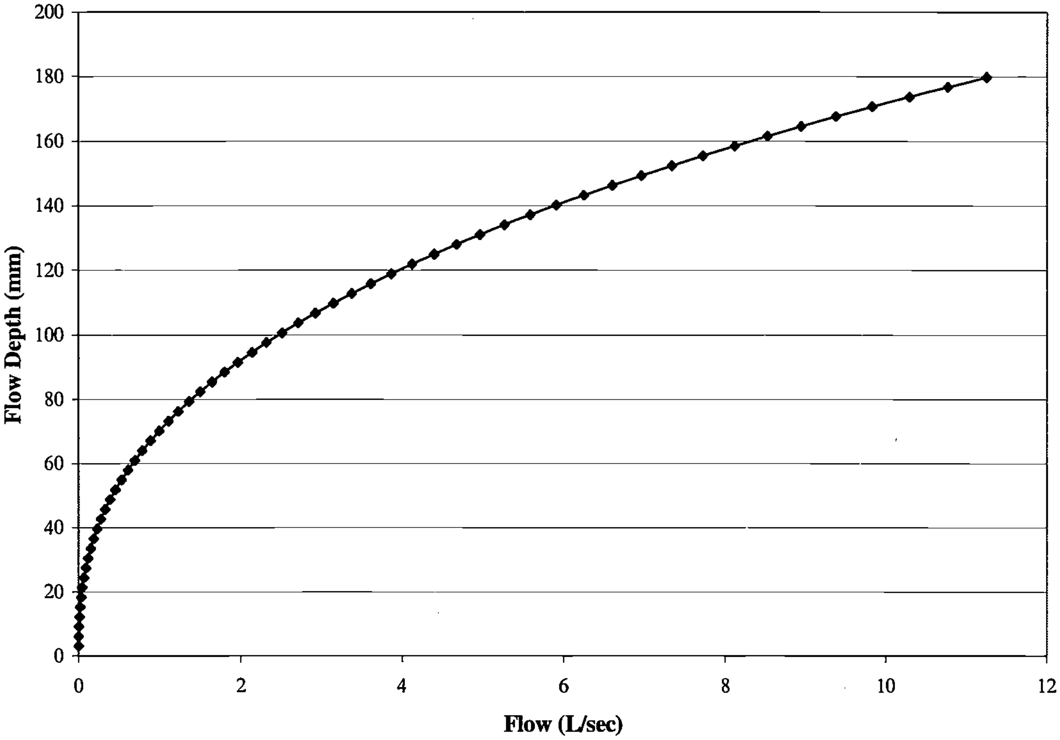

Figure 2. Rating curve used to convert stage height to flow for a large 60-degree "V" flume.

Values of stage measured using the water level recorder and the associated values of discharge that were calculated were compared with independent measurements of stage and discharge measured in the field. Discharge was measured at the outflow of the flume using a bucket, a timer, and graduated cylinders. Water height was measured at the entrance of the flume using a metal ruler.

Flumes were placed in the ditch with a 1.9 cm thick piece of plywood attached to the front flange of the flume that was buried 15 cm to seal it into the bottom of the ditch. The flume was leveled and secured at the outflow by two fence posts. A plywood cover was attached to the flume to prevent leaves and debris from falling into the flume. A wire screen (1.3 cm mesh) was installed across the mouth of the flume to keep leaves and debris out of the throat of the flume (Figures 3 and 4).

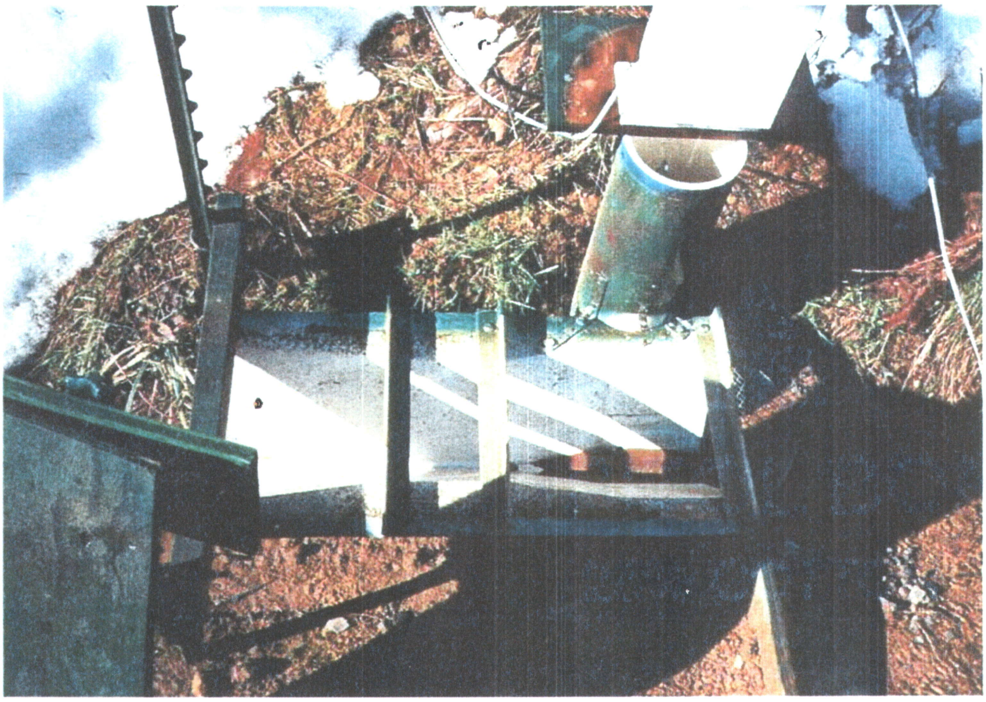

Figure 3. Flume installation at road segment 16-6-8.

Figure 4. Flume installation at road segment 15-8-1.2.

Rainfall was measured using NovaLynx tipping bucket rain gages that have a 20.3 cm orifice and record a tip for every 0.25 mm of rain. Data were stored on Hobo event data loggers made by Onset and were downloaded every 30 days. Data loggers were placed in the raingage to protect them from moisture and vandalism. The raingages were no less than one meter above the ground. The raingages were factory calibrated when installed and calibration was checked following the field season. Of the ten gages, six were within 5 percent accuracy, three exceeded 5 percent accuracy, and the data from one gage was not used and replaced with data from a nearby gage.

5.1.3. Road Segment Design

Surface flow in the roadside ditch was measured by the flume and originated, nominally, from one of two sources: Intercepted subsurface flow from the upslope contributing area and runoff from the road surface. Road segments that were studied were isolated from adjacent road segments. A ditch relief or a stream crossing culvert was located at the upper end of the road segment and the lower end was the flume. The sampled road length was measured between these two structures. All the roads used in this study were crowned, so the drainage was divided with half flowing into the ditch and the other half flowing off the outside of the road. The road surface was not hydrologically isolated at the upper and lower bounds of the road segment, meaning that water flowing down the road surface could enter or leave the road segment that was studied. The chances of this occurring increase when the road surface has wheel ruts that can divert water and not allow it to flow to the ditch. The contributing area upslope of the road may also contribute water to the ditch. Less is known about the boundaries of this source of subsurface flow due to complex flow pathways and processes. The flume measured only the flow that drained from the cutslope between the upper and lower bounds of the road segment (Figure 5).

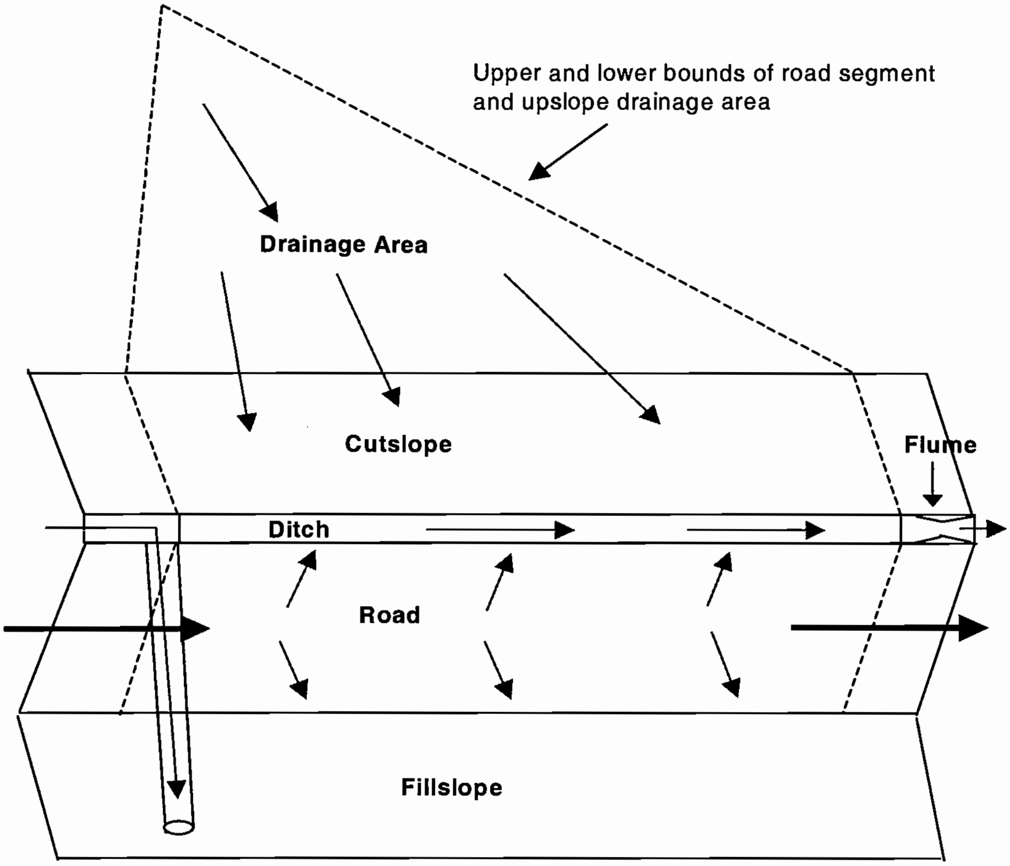

Figure 5. Schematic of road segment design. Arrows indicate the potential flow pathways of surface and subsurface runoff. The dashed lines are the hydrologic boundaries for the areas contributing to ditch flow.

5.1.4. Road and Hillslope Measurements

The characteristics of the road and upslope contributing area are hypothesized to affect the timing and magnitude of ditch flow. The characteristics of the road are length, width, surface area, cutslope height, and gradient. The characteristics of the hillslope include contributing area and hillslope gradient.

Road length was measured from the entrance of the flume to the next culvert up the road. Road widths were measured at five or six points along the road segment and were averaged and multiplied by road length to determine the road area. Road grade was measured with a clinometer. If a break in the road grade occurred within the road segment, a weighted average was used to determine the average road grade. Cutslope height was measured with a tape and clinometer at ten evenly spaced points along each road segment. Cutslope height was measured from the base of the ditch to the top of the cutslope and converted to a vertical height using the slope of the cutslope.

The area and slope of the contributing drainage above the road were determined using a tape, compass, and clinometer. The drainage divide was followed upslope above the upper and lower bounds of the road segment until meeting at some point upslope where the drainage area was isolated. Slope, distance, and the bearing were measured at each grade break or change in direction. Determining the drainage divide was difficult, and thus calculated drainage areas are approximate. The uncertainty in the drainage areas determined using surface topography becomes less important when the flow is primarily subsurface and thus may be dictated by unknown subsurface bedrock topography and flow pathways. Slope of the contributing drainage was calculated using a weighted average of slope and distance taken from the drainage area surveys. A topographic index similar to one in used in models of watershed hydrology was also calculated by dividing the area of the hillslope by the average gradient of the hillslope (Beven et al., 1995).

5.2. ANALYSIS METHODS

5.2.1. Storm Definition

Isolated storms were selected from the record using ditch flow hydrographs first and associated rainfall hyetographs second. The same storms were analyzed for all road segments. Using the hydrographs of the ditch flow, the start of a storm was defined as the point of initial rise in stage following prolonged steady base-flow or no-flow or following the end of a recession limb of a previous storm. The end of the storm was defined at the point where the recession limb of the storm hydrograph returned to steady base-flow or no-flow. Precipitation corresponding with ditch flow response was defined by hyetographs and the associated tabular data. The start of a storm was defined as the first precipitation that preceded the start of ditch flow for an identified storm after two hours without rain. The end of the storm was defined by a 2-hour absence of rainfall also. The data were analyzed on a storm basis to focus on the largest hydrologic events that are of greatest concern to land managers.

5.2.2. Summarizing Rainfall and Runoff

Rainfall and runoff parameters were summarized separately for each storm and then combined to explore rainfall/runoff relationships. Rainfall and runoff duration, rainfall depth and intensity, runoff flow volume, and peak flows were calculated using storm hyetographs and hydrographs. The duration of rainfall and runoff, depth of rainfall, and total volume of runoff were reported as total values for each storm. Maximum rainfall intensities and peak flows occurred for brief periods of time and potentially many times during a storm. For comparison between road segments, peak flows and total flow volumes were normalized by road segment length, road surface area, and upslope contributing area.

The rainfall/runoff relationships used to describe the hydrology of the roads were percent quickflow and peak-to-peak lag time. These parameters were calculated for all road segments and storms. Percent quickflow is defined as the total volume of ditch flow expressed as a percent of the total volume of precipitation that fell on the contributing area above the road segment and surface area of the road. Total rainfall volume was calculated by multiplying the rainfall depth by the upslope contributing area or the surface area of the road. Peak-to-peak lag time is defined as the length of time between the maximum 15-minute rainfall intensity and the maximum instantaneous peak flow in the ditch. Maximum rainfall intensities or peak ditch flows that lasted for more than one time increment (5 minutes for ditch flow, variable for rainfall depending on the time between tips) were assigned the median time between the beginning and end of the peak event. For storms with multiple peaks in ditch flow, the maximum 15-minute rainfall intensity associated with each peak in ditch flow was used and multiple peak-to-peak lag times were averaged for a single storm. If multiple peak rainfall intensities of the same value were associated with a single peak in ditch flow response, the multiple lag times were averaged to obtain a single value.

6. RESULTS

Ten road segments were selected for analysis. Nine road segments were located within 11 kilometers of one another on the north face of Prairie Peak at elevations ranging from 244 to 777 meters. A tenth road segment was located 13 kilometers southeast of Prairie Peak at an elevation of 402 meters (Figure 6). Five storms were selected from the winter of 1999-2000. These storms had the highest peak flows, the largest volumes of runoff, and were isolated from the other storms. Rainfall always began prior to ditch flow, and ended prior to the cessation of ditch flow.

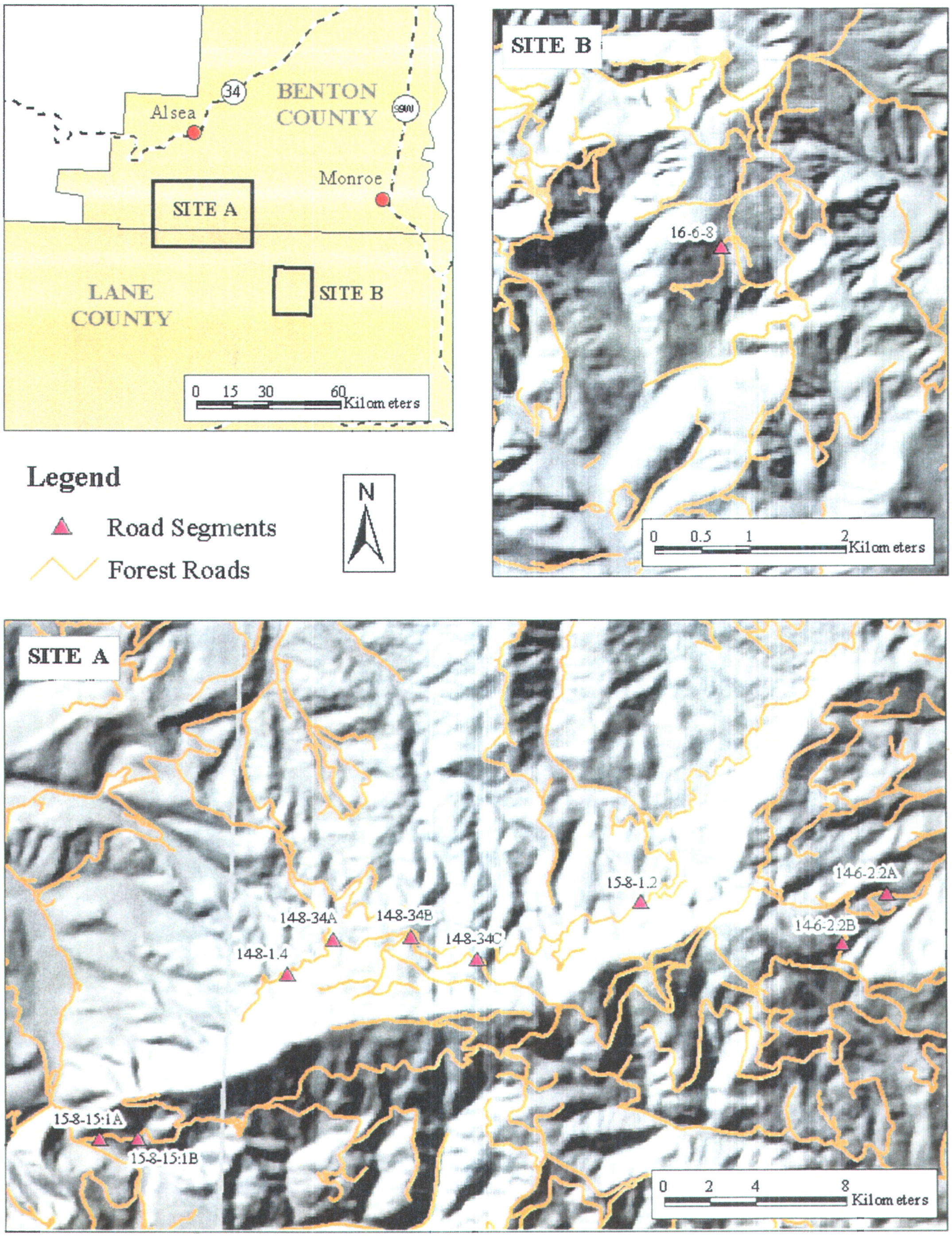

Figure 6. Locations of individual road segments in the study area.

6.1. ROAD AND HILLSLOPE CHARACTERISTICS

Characteristics of the roads and upslope contributing areas are hypothesized to influence the response of ditch flow. Characteristics of the ten selected road segments were road grade, segment length, road surface area, and cutslope height. Upslope characteristics included hillslope gradient and area. Road grades ranged from 7.4 to 16 percent and 9 out of 10 of the road segments had a grade of 10 percent or greater. The average road grade was 12.5 percent. Road length ranged from 41 to 181 meters and road surface area ranged from 184 to 769 square meters. Cutslope heights ranged from 0.9 to 6.6 meters. Contributing area slopes ranged from 16 to 69 percent for all road segments. For the segments used in the analysis, the range was from 19 to 49 percent. Areas of contributing drainages ranged from 0.26 to 4.02 hectares (Table 1).

Road Segment ID	Average Road Grade (%)	Road Length (m)	Road Area (m^2)	Average Upslope Drainage Grade (%)	Upslope Drainage Area (ha)	Average Cutslope Height (m)
15-8-15.1A	16.0	97	443	68.9	0.94	3.7
15-8-15.1B	14.5	181	760	49.4	4.02	4.1
14-8-34A	13.3	178	769	37.9	0.94	2.3
14-8-34B	12.3	153	633	16.3	0.89	4.0
14-8-34C	14.0	52	200	21.3	1.63	4.5
14-6-2.2A	15.0	80	363	55.2	0.69	5.7
14-6-2.2B	12.5	117	565	61.9	0.51	4.4
15-8-1.2	10.0	41	184	39.2	0.95	1.8
16-6-8	10.0	79	352	19.2	0.76	0.9
14-8-1.4	7.4	131	761	44.6	0.26	6.6

Table 1. Road and upslope contributing area characteristics for the 10 road segments.

6.2. QUALITY CHECKING THE DATA

6.2.1. Ditch Flow

Stage data from the flumes were quality checked with observations from field logbooks and with graphical analysis. Several problems occurred during the winter that affected the quality of the data. The screens placed to protect the flumes from leaves on occasion lowered the water level in the flume and, in extreme cases, caused the flow to overflow and bypass the flume. Even though the leaves were cleaned from the screens during each site visit and the screens were modified to be more efficient, some data were lost due to clogged screens. Some hydrographs were reconstructed if the screen was cleared before the peak flow occurred, but reconstruction was not possible if the peak flow was affected. Also, hydrograph reconstruction was not possible if the clogged screen caused the flume to be overtopped. On one occasion the flume was simply too small and the peak flow overtopped it even without a clogged screen. One road segment lost a significant amount of runoff to a hole in the ditch just above the flume (at low flows, 100 percent of the runoff was diverted). The loss of flow was large enough that the segment was removed from the analysis.

While reducing and analyzing the flow data, a stepping phenomenon was observed in the hydrographs for some road segments (Figure 7). Stage values for these segments changed abruptly from 5 to 15 mm over a period of 30 seconds. This occurred throughout the winter and only for road segments that exhibited steady and continuous ditch flow. The water level recorders and flumes were tested following the field season and failed to reproduce the phenomena. However, it seems unlikely that the stepping was due to actual variations in water height. A potential explanation could be that low temperatures affected the equipment and increased friction between moving parts. To account for these phenomena the hydrographs were reconstructed manually using data points that were thought to be accurate (Figure 7). If the steps were due to a catch and release in the float, weight, and pulley system, then on the rising limb of the hydrograph the float would be briefly submerged before releasing to the true water level. In this case, the point at the end of a quick rise or step would be the true water level. For the receding limb of the hydrograph, the float would be artificially suspended above the water level before quickly falling to true stage height. In this case the point at the bottom of a quick fall would be the true water level. By drawing lines that connect these points, the hydrographs for some storms were reconstructed. Flows are reported for the original and reconstructed hydrographs.

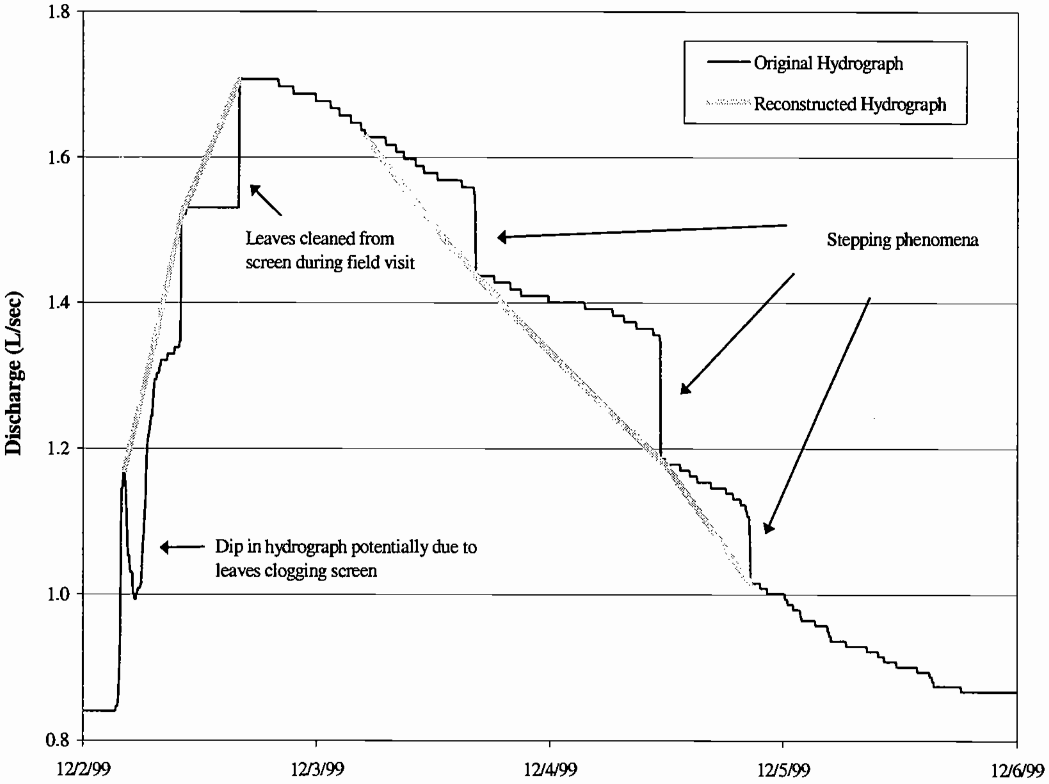

Figure 7. Example of the stepping phenomena found in some of the road segment hydrographs, and the subsequent reconstruction of those hydrographs.

6.2.2. Rainfall

Rainfall data were checked for snowfall and mechanical malfunctions. Periods of snowfall in the record were determined by observations in the field and graphical analysis. Snowfall was observed on numerous occasions during the field season and raingages were cleared of snow whenever possible. Graphs of cumulative rainfall were inspected for patterns that indicated snowfall. Also, cumulative rainfall was compared between raingages and the gage at the lowest elevation (244 m) was used as a reference gage with the assumption that little or no snow fell there during the winter. Rainfall intensities from 5 of the 9 raingages correlated quite closely (Figure 8) and the differences in rainfall between the low elevation gage and the other gages clearly showed when snowfall occurred (Figure 9). Rainfall intensities from the remaining 4 raingages also correlated closely, although the data from these gages were not used in the final analyses. As a result of episodic snowfall throughout the study period, it was not possible to analyze one storm for all the road segments, and a second storm was removed for two of the road segments at higher elevations because of snow during the rising limb of the hydrograph.

Rainfall data were also lost because the raingages malfunctioned sporadically throughout the winter. Most of these problems were detected during field visits and were fixed. However, data from one raingage for the entire winter was lost due to inconsistencies discovered during analysis. Fortunately, it was possible to use flume data from this road segment by analyzing rainfall data from a nearby road sedimentation research site (Luce and Black, 1999). At other sites with short duration loss of data, raingages from nearby road segments were used to provide rainfall data. This was possible because rainfall patterns were similar for all the sites. Only one storm at one road segment was lost due to mechanical failure of raingages.

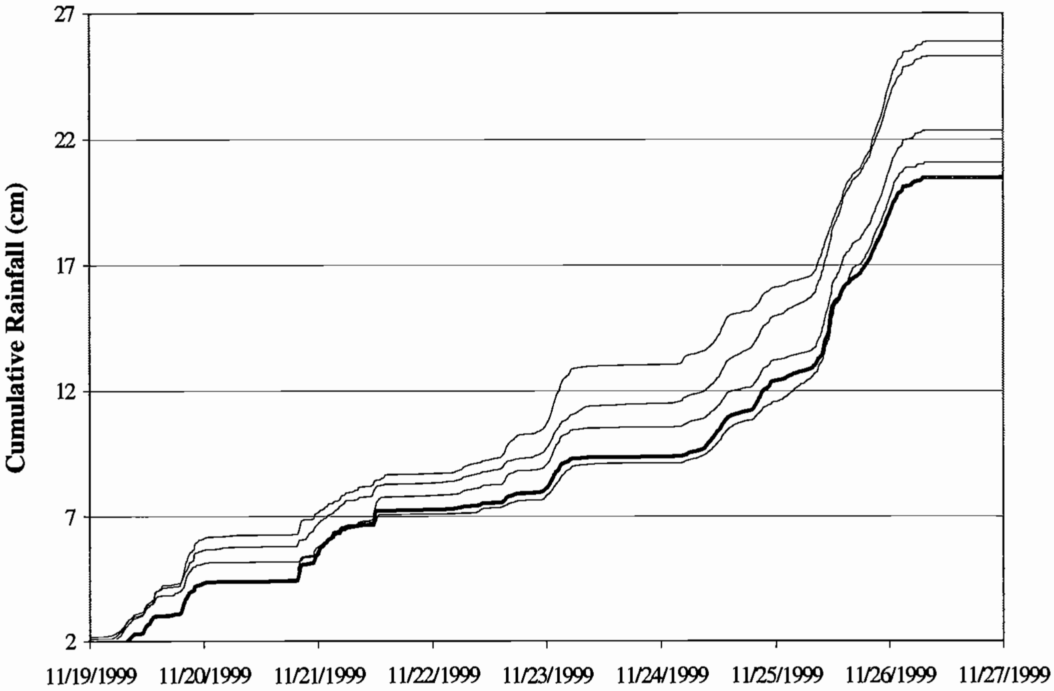

Figure 8. Cumulative rainfall for the five raingages used in analysis for a period with no snowfall. The heavier black line is the raingage of lowest elevation, used as a reference to detect the presence of snow at the other gages.

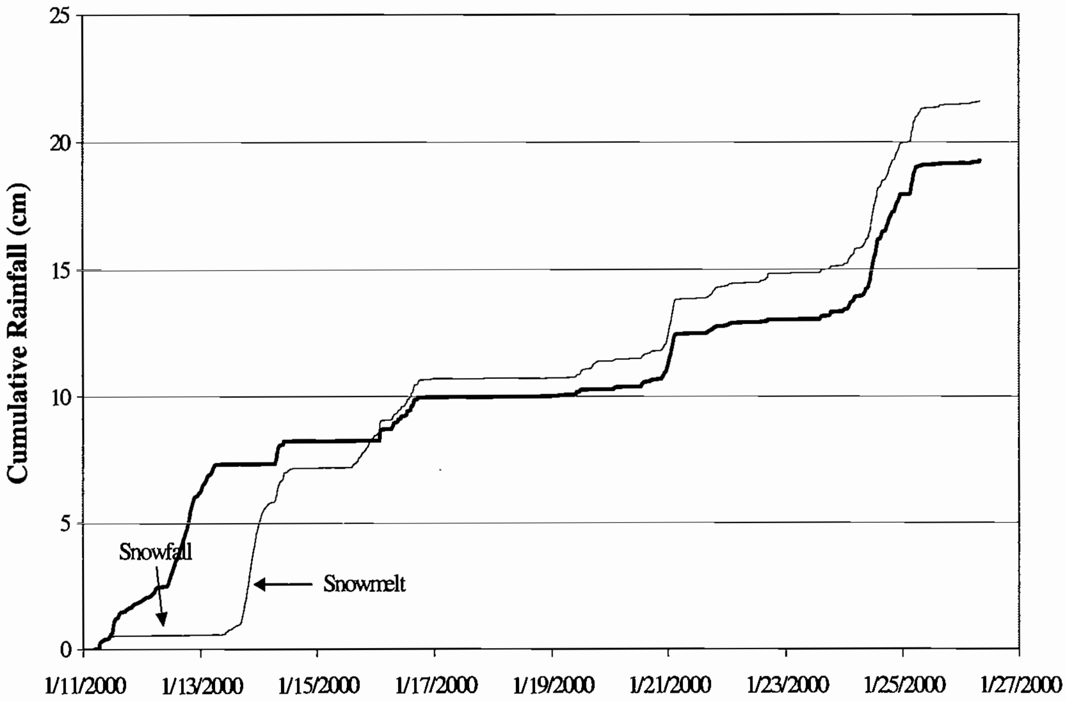

Figure 9. Cumulative rainfall for two raingages. The evidence of snowfall is shown in the lighter line. The heavier black line is the low elevation or reference raingage.

6.2.3. Summary

Runoff hydrographs of ditch flow in response to rainfall were produced at 8 of 10 of the road segments. One road segment produced no measurable runoff for the entire period of record and data from the other road segment could not be used because of equipment failure. In addition, data from two road segments were removed from analysis because of suspected mechanical failure and irregularities in the data. In total, 6 road segments were included in the final analysis (Table 2). Occasional snow combined with mechanical failure of some raingages caused individual storms to be removed from the analysis. Data from five storms were removed from analysis because of snow (Table 2).

Road Segment	**Storm 1** 11/26/99	**Storm 2** 12/3/99	**Storm 3** 12/15/99	**Storm 4** 1/11/00	**Storm 5** 2/2/00
14-6-2.2A	▨ Large hole in ditch directly above flume eliminated data for this segment for entire winter	▨	▨	▨ Snow	▨
14-6-2.2B	▨ Faulty wiring of water level recorder eliminated data for this segment for entire winter	▨	▨	▨ Snow	▨
14-8-1.4				▨ Snow	
14-8-34A				▨ Snow	
14-8-34B	▨ Unexplained inconsistancies in runoff hydrograph eliminated data for this segment for entire winter	▨	▨	▨ Snow	▨
14-8-34C	▨		▨ Snow	▨ Snow	
15-8-1.2			▨ Snow	▨ Snow	
15-8-15.1A	▨	▨ No recorded flow for entire winter, dry ditch	▨	▨ Snow	▨
15-8-15.1B				▨ Snow	
16-6-8				▨ Snow	▨ No rain data

☐ = included ▨ = removed

Table 2. Road segments and storms included in the final analysis.

6.3. RAINFALL SUMMARY

Precipitation for the winter of WY 2000 was primarily rain. Snowfall did occur periodically and was more persistent at higher elevations. Patterns of rainfall intensity for individual storms were similar throughout the network of gages (Figure 8), however cumulative rainfall did vary (Table 3). As expected, a trend was observed of increasing rainfall with elevation for most storms (Figure 10).

Raingage	**Elevation (m)**	**Storm**		**Peak Intensities**					
		Duration (hrs)	**Amount (cm)**	**15 min (cm/hr)**	**1 hour (cm/hr)**	**2 hour (cm/hr)**	**6 hour (cm/hr)**	**12 hour (cm/hr)**	**24 hour (cm/hr)**
Storm 1									
15-8-15.1	244	51	11.1	1.93	1.17	0.93	0.52	0.39	0.32
16-6-8	402	52	12.0	1.67	1.17	0.89	0.58	0.45	0.36
14-8-1.4	543	51	11.8	1.83	1.02	0.86	0.60	0.44	0.37
15-8-1.2	646	53	12.9	1.12	0.81	0.72	0.61	0.47	0.39
Storm 2									
15-8-15.1	244	24	6.4	1.73	1.14	0.88	0.65	0.44	0.27
16-6-8	402	30	4.0	1.05	0.57	0.44	0.38	0.26	0.15
14-8-1.4	543	36	7.3	1.93	1.22	0.90	0.61	0.42	0.27
15-8-1.2	646	42	6.7	1.73	1.02	0.85	0.57	0.41	0.25
14-8-34BC	768	49	8.0	1.73	1.12	0.81	0.59	0.44	0.27
Storm 3									
15-8-15.1	244	14	2.9	1.02	0.61	0.56	0.38	0.23	0.14
16-6-8	402	13	1.5	0.57	0.38	0.27	0.21	0.13	0.07
14-8-1.4	543	13	3.0	1.73	0.91	0.69	0.41	0.25	0.13
14-8-34A	555	12	2.7	1.73	0.94	0.67	0.39	0.23	0.12
Storm 5									
15-8-15.1	244	34	8.7	1.12	0.86	0.76	0.62	0.48	0.33
14-8-1.4	543	34	8.0	1.02	0.76	0.69	0.55	0.46	0.30
14-8-34A	555	39	6.9	0.91	0.74	0.65	0.52	0.42	0.26
15-8-1.2	646	43	10.0	1.22	0.94	0.84	0.69	0.57	0.38
14-8-34BC	768	41	11.8	1.22	1.04	0.94	0.81	0.66	0.44

Table 3. A summary of maximum rainfall intensities and total rainfall for five storms and six road segments in the vicinity of Prairie Peak in the central Oregon Coast Range during the winter of 1999-2000. Only raingages and storms used in the final analyses are included.

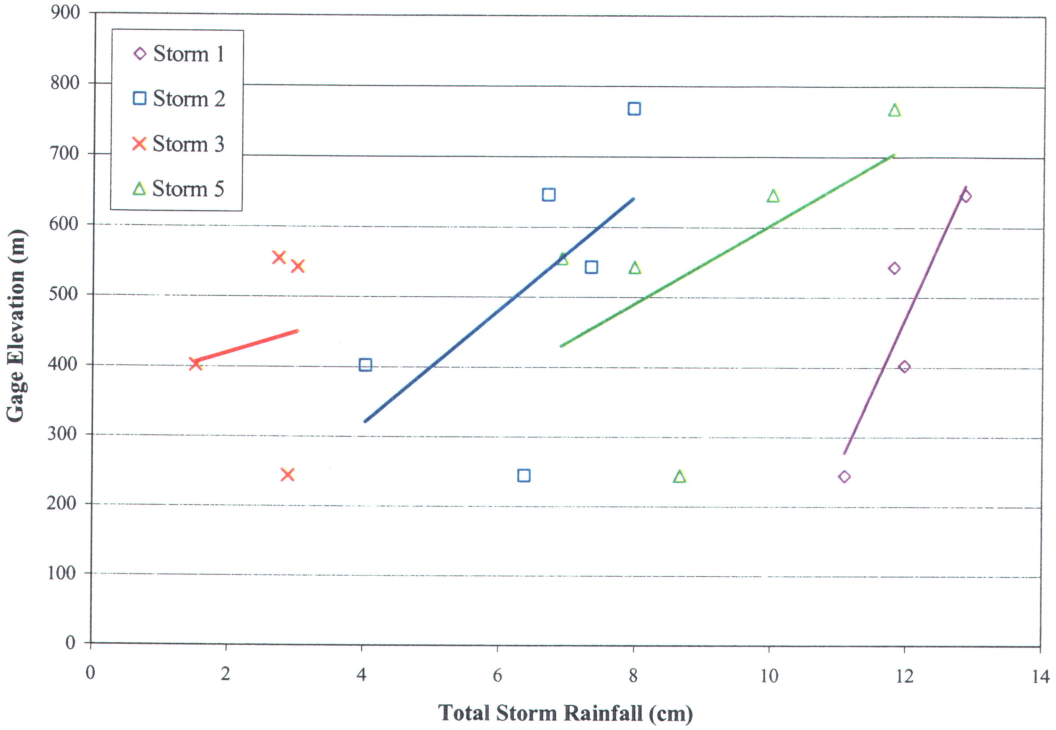

Figure 10. Total rainfall for four storms showing an increase in rainfall with increasing elevation.

Annual precipitation at Corvallis, Oregon, located in the Willamette Valley approximately 70 km northeast of the study sites was greater than average for the winter of 1999-2000. The average rainfall for the months of October through February from 1961 to 1990 was 111.6 cm. The total rainfall for the same months in 1999-2000 was 125.7 cm. Although Corvallis rainfall was greater than the long-term average for the winter of 1999-2000, rainfall intensities never exceed a 2-year recurrence interval. Using an existing raingage network in the Oregon Coast Range, the raingage closest to the study sites (Lobster Creek raingage) had a rainfall record of 4 years. The 6-, 12-, and 24-hour maximum intensities from the storms in this study do not exceed a 2-year recurrence interval when compared to maximum intensities from the Lobster Creek raingage (Figure 11). This finding may lack significance due to the short period of record for this gage and the high amount of spatial variability in rainfall intensities for the Oregon Coast Range; however, it is an attempt to place the rainfall intensities for the period of study in some historical context.

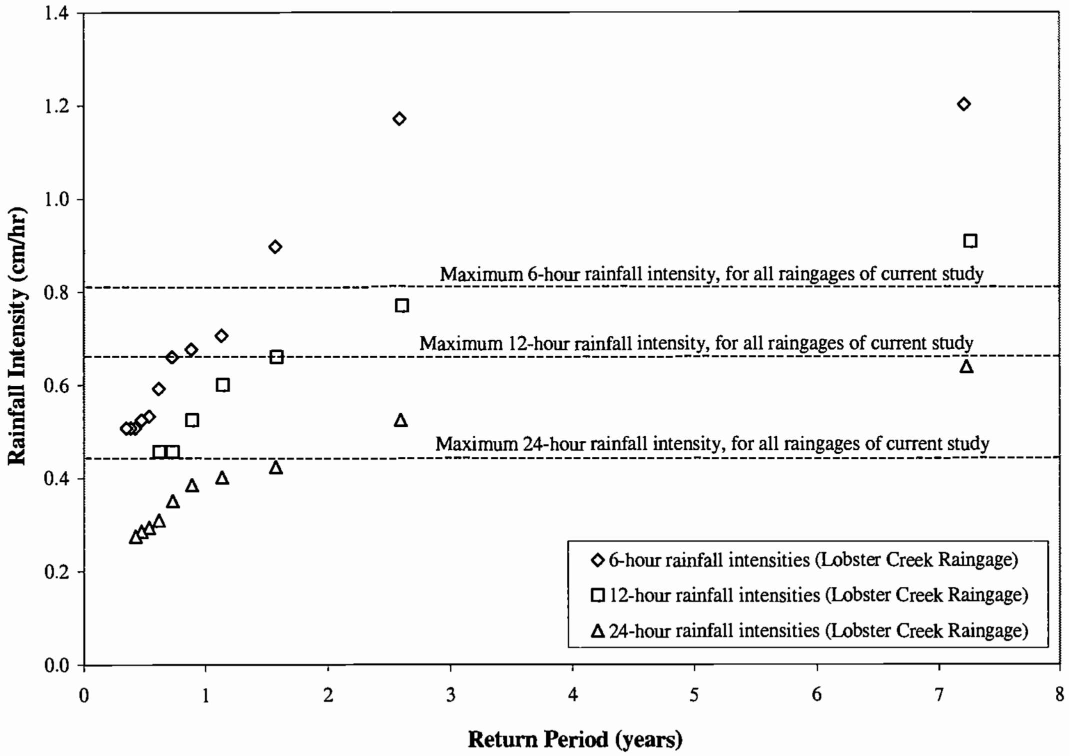

Figure 11. A comparison of maximum 6-, 12-, and 24-hour rainfall intensities between the Lobster Creek raingage and the raingages from the study sites. Frequency analysis for Lobster Creek was conducted as a partial series on a rainfall record of 4 years.

6.4. DITCH FLOW SUMMARY

6.4.1. Initial Results and Observations

Initial analyses of ditch flow hydrographs, combined with field observations throughout the winter, revealed two distinct flow responses among the road segments. For four of the road segments the flow was characterized as intermittent (Figures 12 and 13) and for the other four road segments the flow was characterized as ephemeral (Figures 14 and 15). The terms intermittent and ephemeral are typically used to describe streams. Intermittent streams flow only at certain times of the year, during the rainy season or in response to snowmelt, and have no flow during the dry season. Ephemeral streams flow only in direct response to storm precipitation. Road segments that had intermittent flow began to flow at the beginning of the rainy season and flowed throughout the winter. They exhibited a muted response to rainfall and had high, constant flows. Road segments that had ephemeral flow had ditch flow only in direct response to rainfall and they rapidly become dry when rainfall ceased. Hydrographs of storms from ephemeral road segments had multiple peaks with steep rising and falling limbs. Hydrographs of storms from intermittent road segments had a single, higher peak flow and longer and less steep rising and falling limbs. Of the four road segments that had intermittent flow, two were removed from analysis because of problems discussed in previous sections of this document.

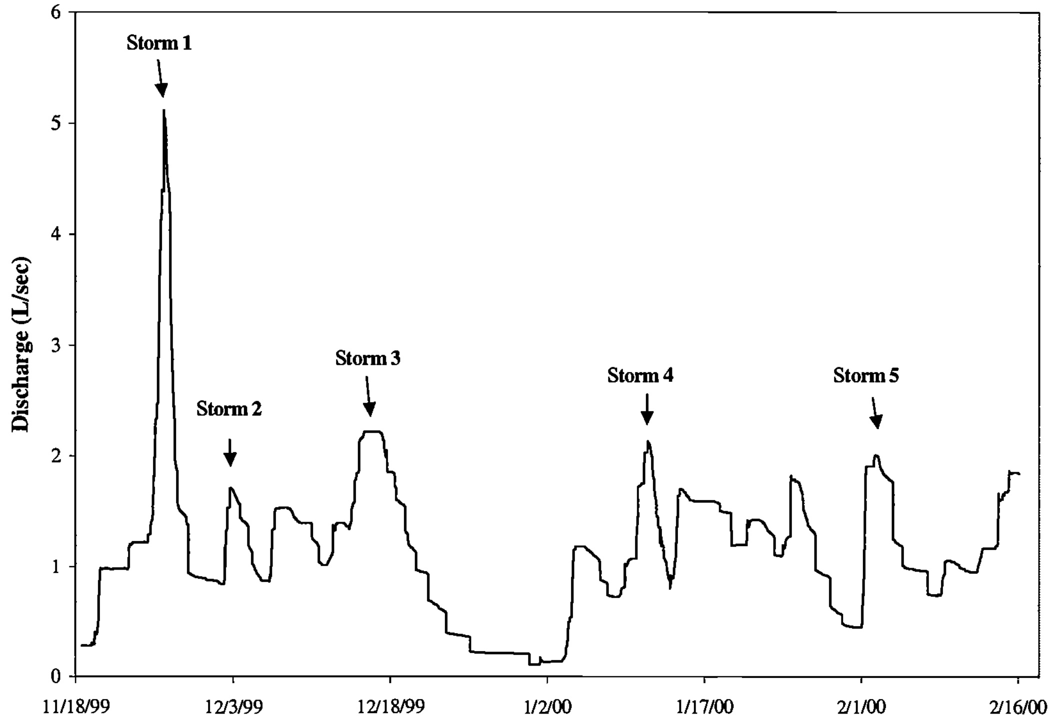

Figure 12. The hydrograph of the five selected storms from road segment 15-8-1.2 with intermittent flow.

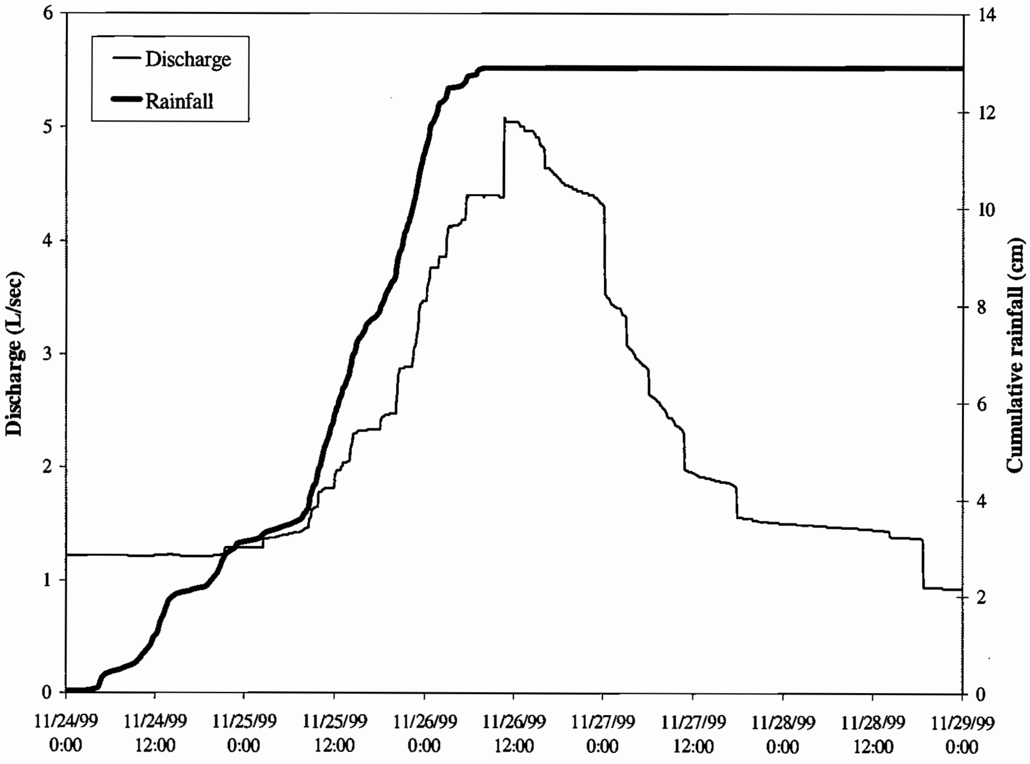

Figure 13. The hydrograph and cumulative rainfall of Storm 1 (11/26/99) from road segment 15-8-1.2 with intermittent flow.

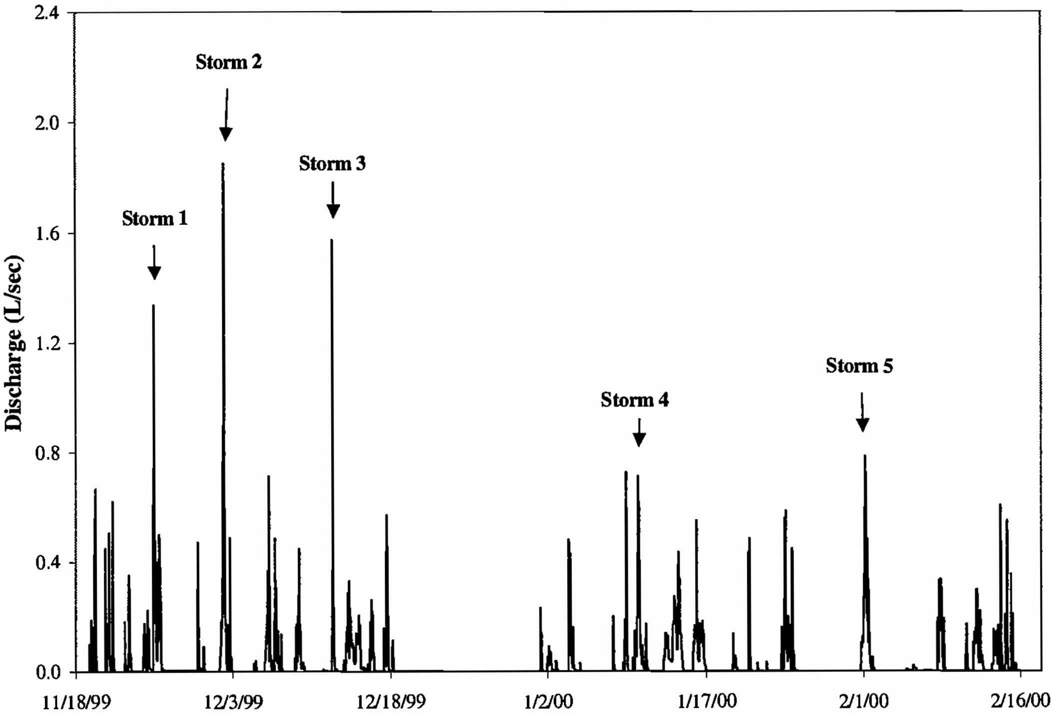

Figure 14. The hydrograph of the five selected storms from road segment 14-8-1.4 with ephemeral flow.

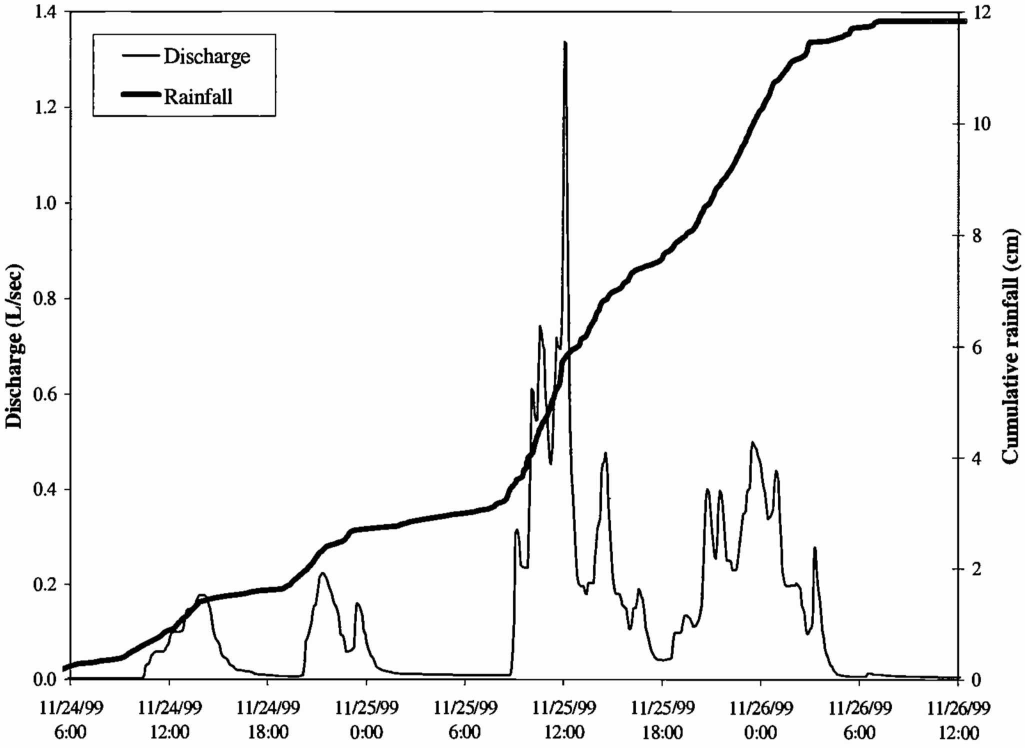

Figure 15. The hydrograph and cumulative rainfall of Storm 1 (11/26/99) from road segment 14-8-1.4 with ephemeral flow.

6.4.2. Instantaneous Peak Flows

Instantaneous peak flows varied significantly between road segments and between storms (Table 4). Without normalizing the data for road length or drainage area, instantaneous peak flows range from 0.1 to 7.0 L/sec for all road segments and all storms. Peak flows were greater for road segments that had intermittent flow (1.7 to 7.0 L/sec with an average of 4.1 L/sec) than for road segments that had ephemeral flow (0.1 to 2.1 L/sec with an average of 1.2 L/sec) (Figure 16).

When the data are normalized by road length, peak flows from road segments with ephemeral flow range from 0.8 to 26.5 L/sec/km and averaged 9.2 L/sec/km. Road segments with intermittent flow had peak flows greater than road segments with ephemeral flow. Peak flows ranged from 42 to 134 L/sec/km and averaged 88 L/sec/km (Figure 17). When the data are normalized by upslope contributing area, the differences between road segments with ephemeral or intermittent flow are no longer apparent (Figure 18). One reason for this is that road segment 14-8-1.4, which has ephemeral flow, has a drainage area much smaller than the other road segments. If the ditch-flow response for this road segment is driven by road surface runoff, peak flow normalized by upslope drainage area would not yield relevant comparisons.

Road Segment	Instantaneous Peak Flow (L/sec)				Peak Flow per Unit Road Length (L/sec/km)				Peak Flow per Unit Upslope Drainage Area (L/sec/ha)			
	Storm				Storm				Storm			
	1	2	3	5	1	2	3	5	1	2	3	5
Ephemeral Flow												
15-8-15.1B	1.0	0.6	0.1	0.4	5.3	3.5	0.8	2.0	0.2	0.2	0.04	0.1
14-8-1.4	1.4	2.0	1.6	0.8	10.9	14.9	12.2	6.0	5.5	7.5	6.2	3.0
14-8-34A	1.2	1.8	2.1	0.8	6.7	9.9	12.0	4.4	1.3	1.9	2.3	0.8
16-6-8	2.1	1.5	0.3	--	26.5	18.6	4.2	--	2.7	1.9	0.4	--
Intermittent Flow												
14-8-34C	--	4.8	--	7.0	--	91	--	134	--	2.9	--	4.3
15-8-1.2	5.2	1.7	--	2.0	127	42	--	49	5.5	1.8	--	2.1

Table 4. Instantaneous peak flows for all road segments and storms included in the analysis.

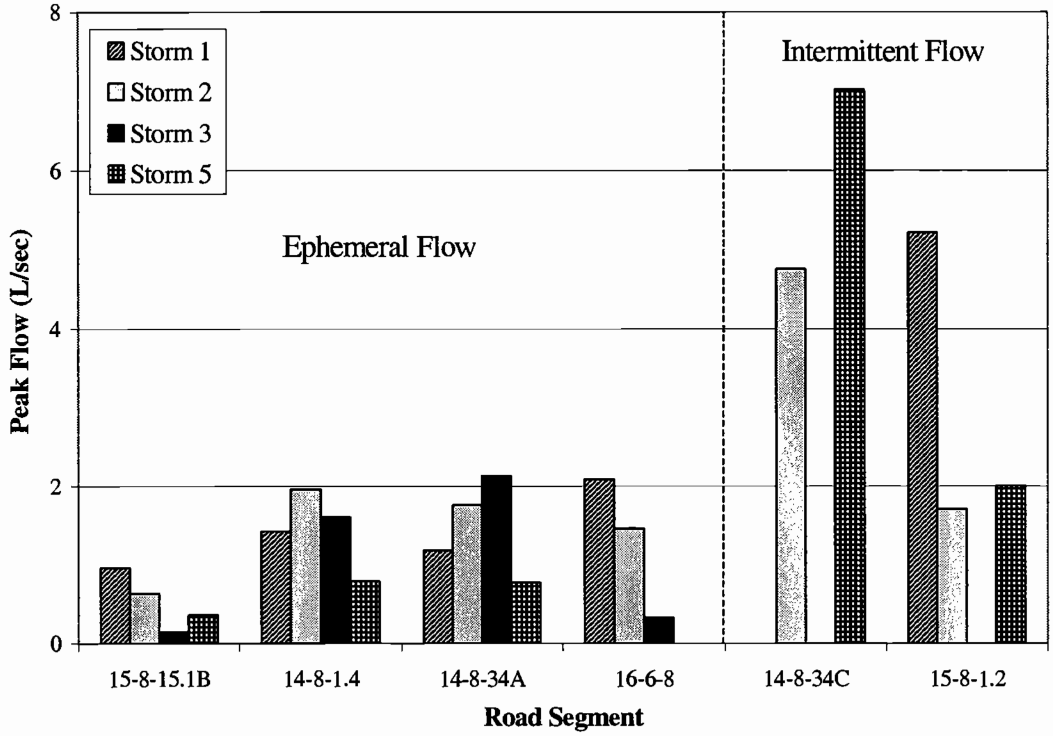

Figure 16. Instantaneous peak flows for all road segments and storms included in the analysis.

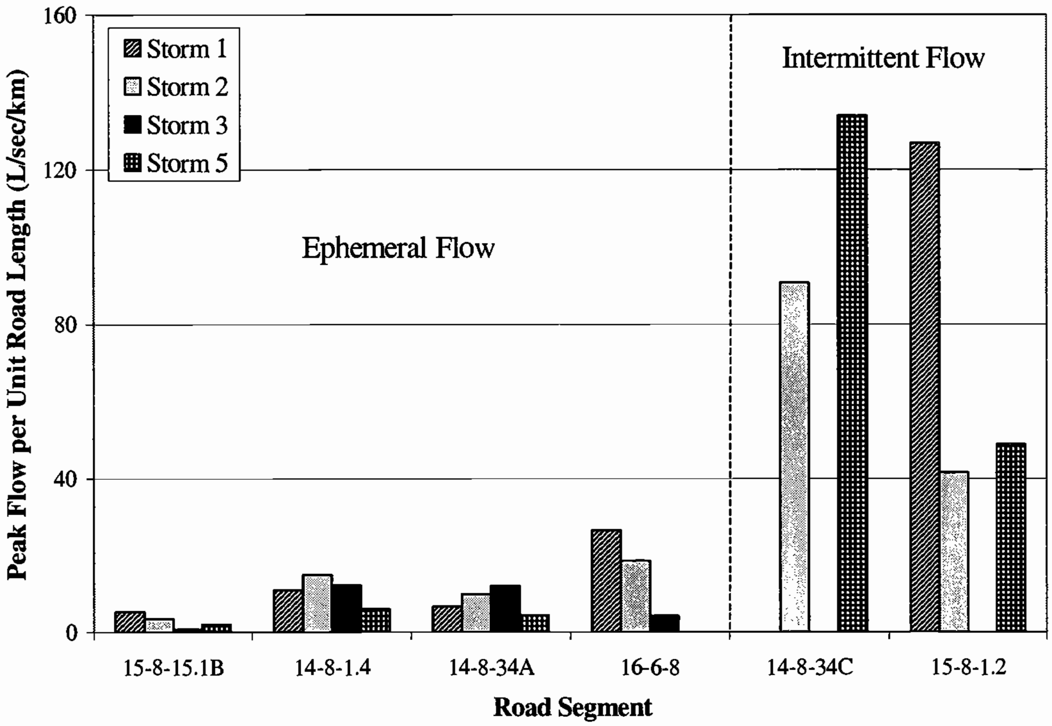

Figure 17. Instantaneous peak flows normalized by road segment length for all road segments and storms included in the analysis.

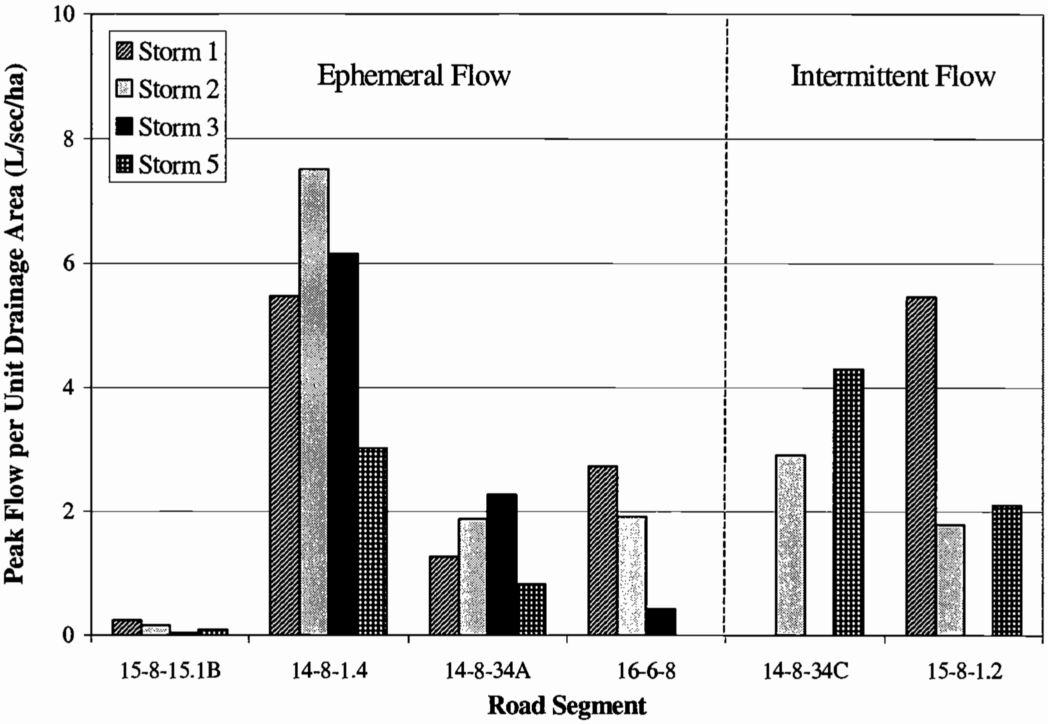

Figure 18. Instantaneous peak flows normalized by upslope contributing area for all road segments and storms included in the analysis.

6.4.3. Total Storm Volumes

The total volume of ditch flow in response to individual storms for the road segments with intermittent flow was determined using the base flow separation technique developed by Hewlett and Hibbert (1967). The slope of this base-flow separation line is .05 csm/hr (cubic feet per second per square mile per hour). For road segments with ephemeral flow, there was no base-flow, thus this technique was not used. The total volume of storm runoff was calculated for both types of flow responses by subtracting the volume of base-flow from the total volume under the hydrograph (base flow being zero for flashy-flow road segments). Road segments with stepping were analyzed for the original and the adjusted hydrograph as mentioned earlier (Figure 7). Adjusted flow volumes ranged from 18 percent greater than the unadjusted value to 8 percent smaller than the unadjusted value. The magnitude of these differences does not change the results or conclusions of this study. Thus, the adjusted values are not included in the following analyses.

The total volume of ditch-flow measured in response to each storm event was much greater for the road segments with intermittent flow than for the road segments with ephemeral flow. Storm runoff volumes for road segments with ephemeral flow ranged from 1 to 30 m^3 and from 102 to 879 m^3 for road segments with intermittent flow (Table 5, Figure 19). Storm runoff volumes per unit road length ranged from 3 to 383 m^3/km for road segments with ephemeral flow and from 2,476 to 16,759 m^3/km for road segments with intermittent flow (Figure 20). When normalized for upslope drainage area, storm runoff volumes ranged from 1 to 91 m^3/ha for road segments with ephemeral flow and from 107 to 538 m^3/ha for road segments with intermittent flow (Figure 21).

Road Segment	Total Runoff Volume (m^3)				Runoff Volume per Unit Road Length (m^3/km)				Runoff Volume per Unit Upslope Drainage Area (m^3/ha)			
	Storm				Storm				Storm			
	1	2	3	5	1	2	3	5	1	2	3	5
Ephemeral Flow												
15-8-15.1B	3	3	1	4	16	17	3	23	1	1	0	1
14-8-1.4	24	19	7	21	182	144	57	161	91	73	29	81
14-8-34A	29	24	9	22	163	133	50	122	31	25	9	23
16-6-8	30	10	3	--	383	122	34	--	39	13	4	--
Intermittent Flow												
14-8-34C	--	234	--	879	--	4465	--	16759	--	143	--	538
15-8-1.2	386	102	--	318	9374	2476	--	7723	404	107	--	333

Table 5. Total runoff volumes for all road segments and all storms analyzed.

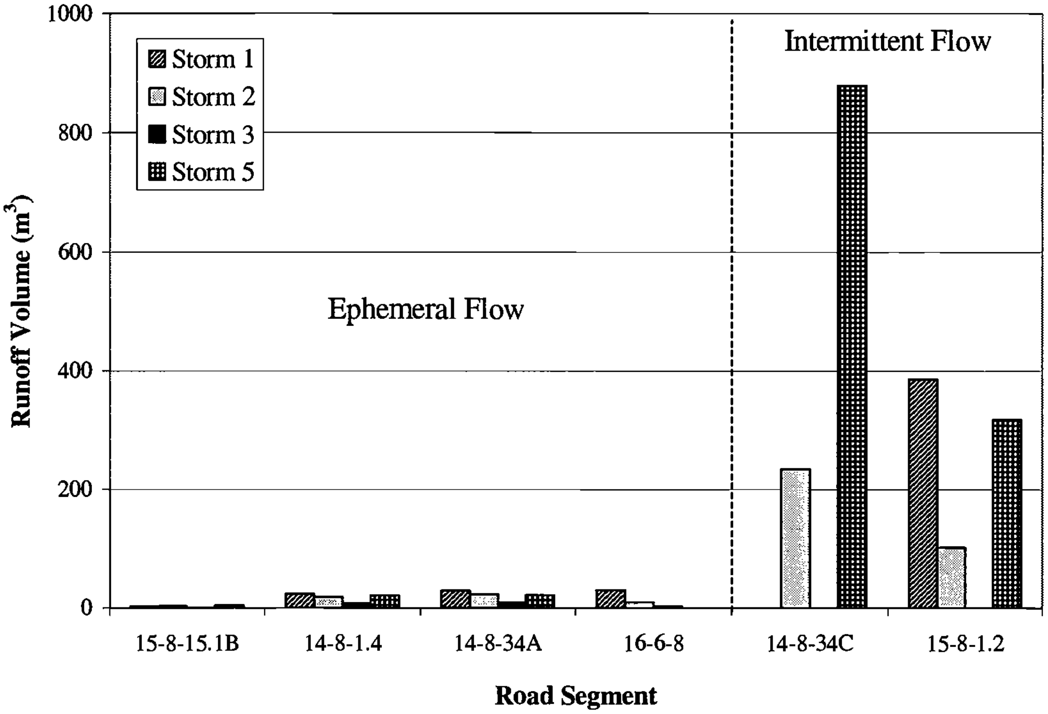

Figure 19. Total runoff volumes for all road segments and all storms analyzed.

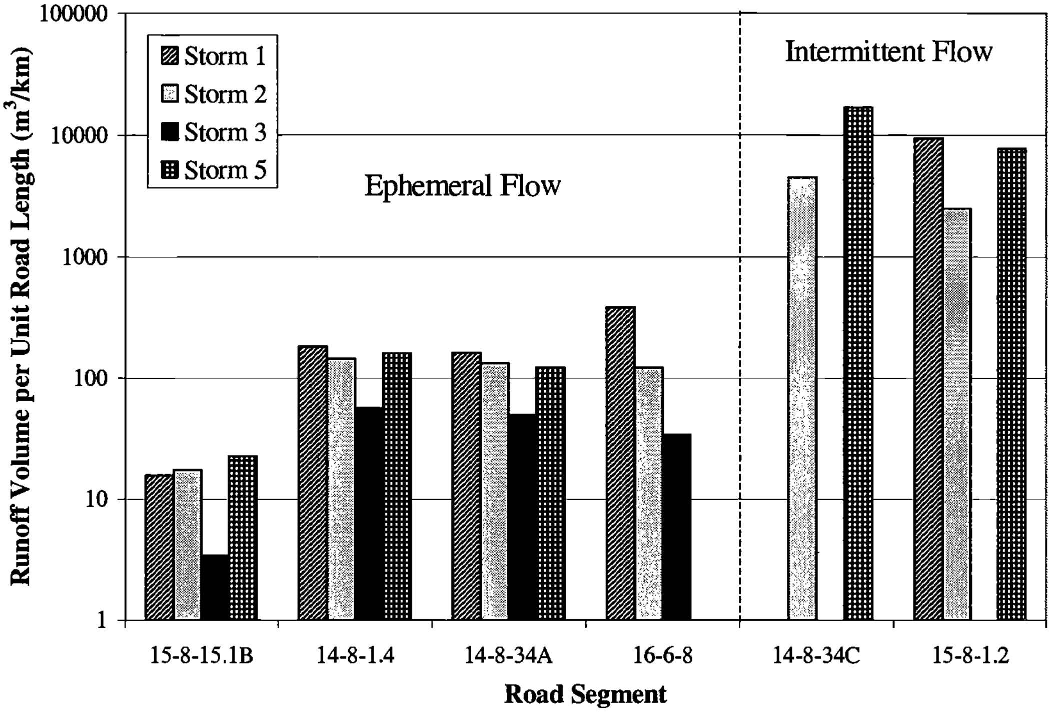

Figure 20. Total runoff volumes normalized by road segment length for all road segments and all storms analyzed. The y-axis is presented in logarithmic scale.

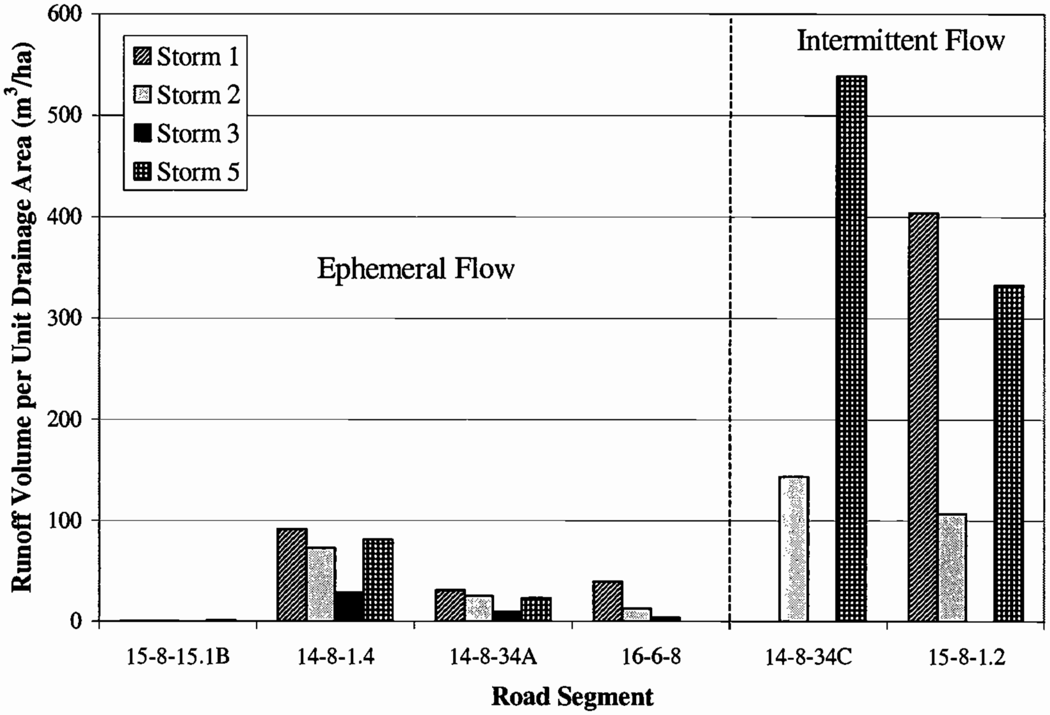

Figure 21. Total runoff volumes normalized by upslope contributing area for all road segments and all storms analyzed.

6.5. RAINFALL/RUNOFF RELATIONSHIPS

Maximum rainfall intensities and storm amounts were compared with runoff peak flows and storm volumes. The 15-minute maximum rainfall intensity was chosen for this analysis because of the rapid response of road segments with ephemeral flow. The 24-hr maximum intensities were not used because they correlated strongly with total storm rainfall (Figure 22). The relationships between total storm rainfall and maximum 15-minute rainfall intensity and total runoff and instantaneous peak flows were weak (r-squared values of 0.01, 0.03, 0.20, and 0.20) when all road segments were evaluated (Figure 23). The relationships between total storm rainfall and instantaneous peak flows and between total storm rainfall and runoff volume were strongest. The weak relationships are most likely due to the difference in runoff responses between road segments that had ephemeral versus intermittent flow. When the road segments that have ephemeral and intermittent flow are analyzed separately, the relationships between rainfall and runoff improve. For road segments with ephemeral flow, the best relationships are between the maximum 15-minute rainfall intensities and instantaneous peak flows and between total storm rainfall and runoff volume (Fig 24). For ephemeral hydrology, peak flows are expected to be correlated with short-term rainfall intensities and total storm runoff is expected to correlate with total rainfall. For road segments with intermittent flow, little correlation is expected between short-term rainfall intensities and instantaneous peak flows and between short-term rainfall intensities and runoff volume. That is the case in this study. Road segments with intermittent flow have the strongest positive relationships between total storm rainfall and instantaneous peak flows and between and total storm rainfall and runoff volume (Figure 24). There is a high chance for spurious correlations in these results because of the small population of road segments with intermittent flow.

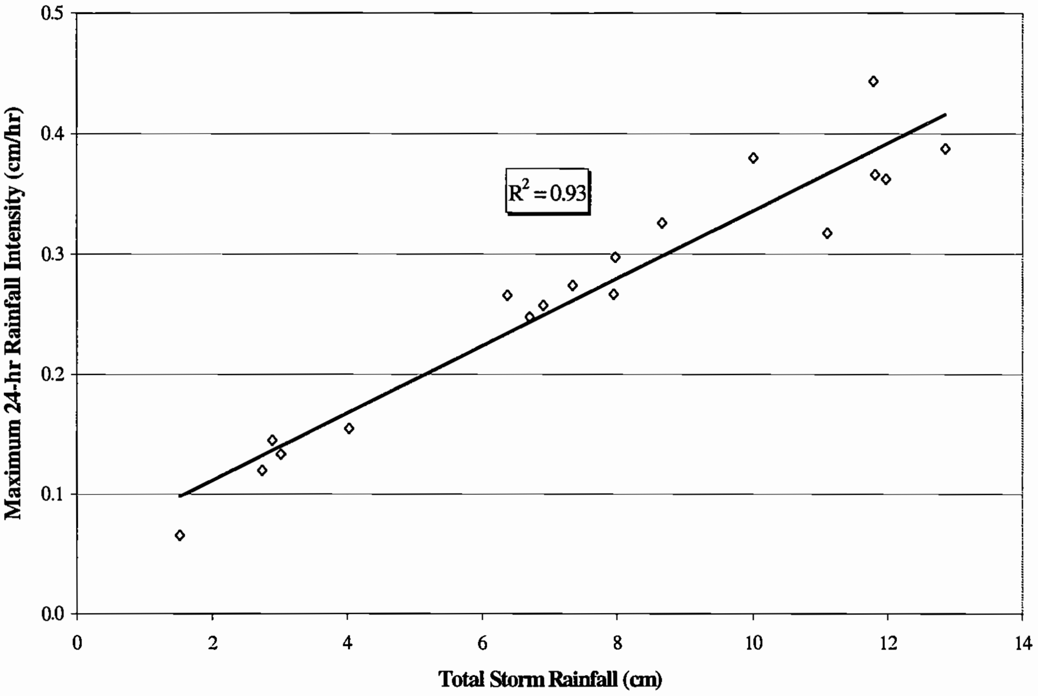

Figure 22. A graph showing the relationship between the maximum 24-hr rainfall intensity and total storm rainfall for all storms and road segments analyzed.

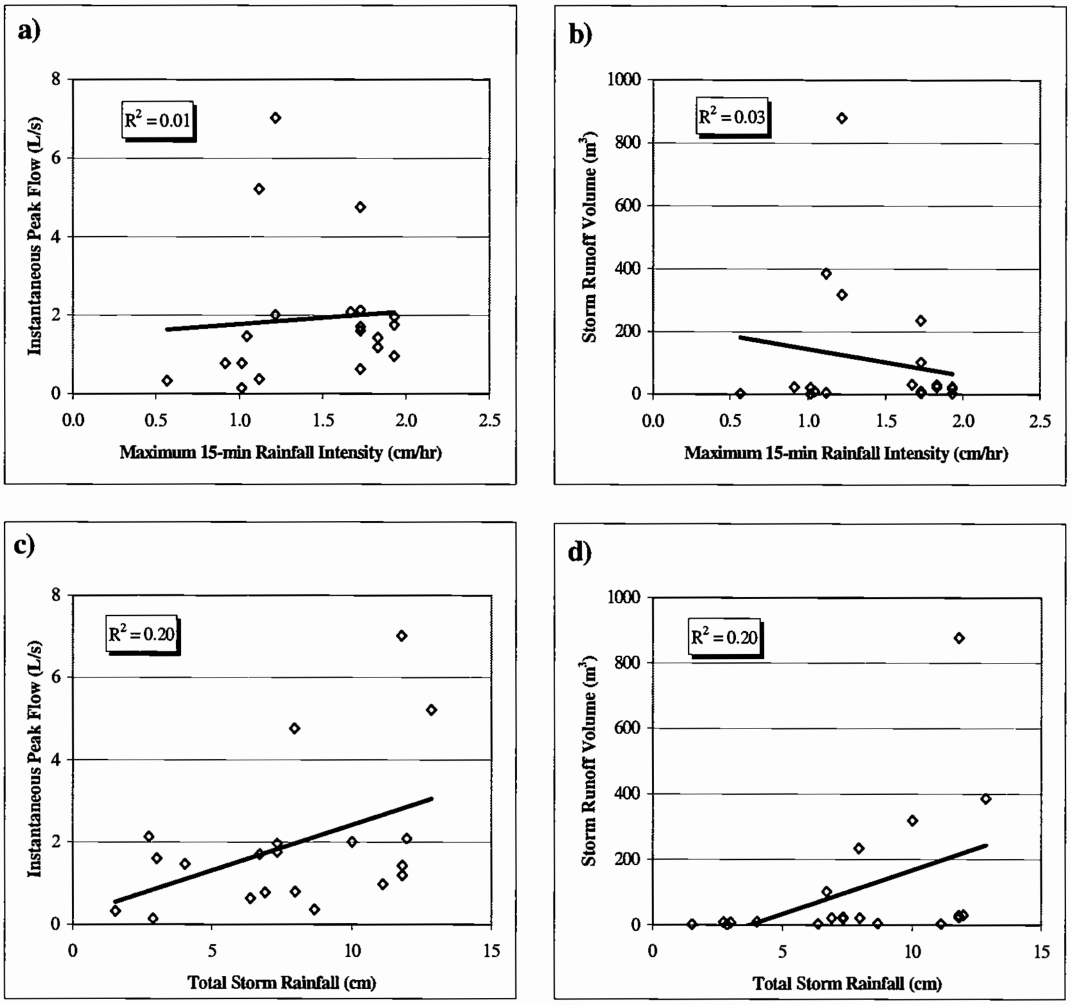

Figure 23. The relationships between a) maximum 15-minute rainfall intensity and instantaneous peak flow, b) maximum 15-minute rainfall intensity and runoff volume, c) total storm rainfall and instantaneous peak flow, and d) total storm rainfall and runoff volume for all road segments.

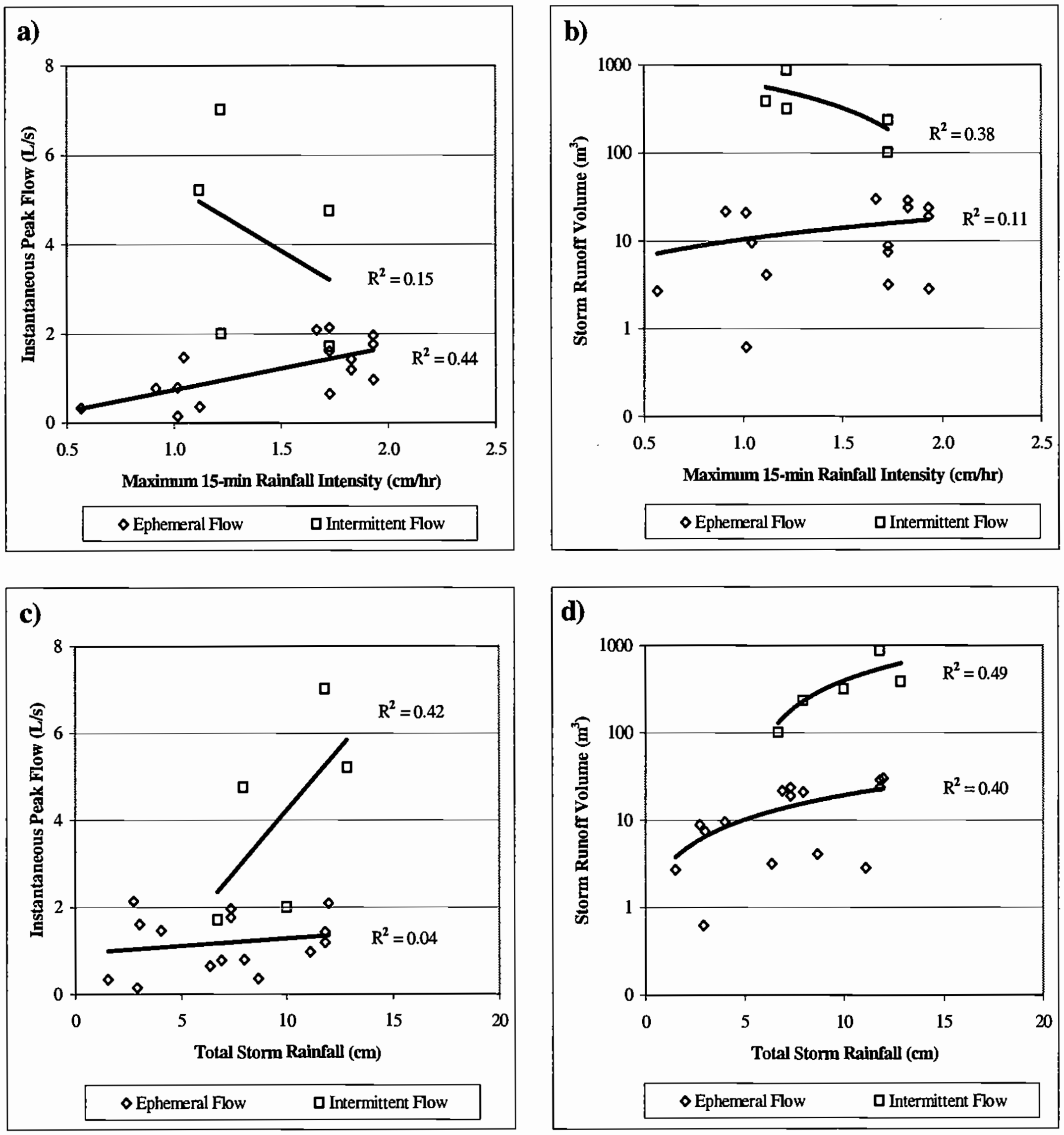

Figure 24. The relationships between a) maximum 15-minute rainfall intensity and instantaneous peak flow, b) maximum 15-minute rainfall intensity and runoff volume, c) total storm rainfall and instantaneous peak flow, and d) total storm rainfall and runoff volume for all road segments. Trend lines are linear. The y-axis for storm runoff volume is presented in log scale for some graphs to better illustrate the data.

Rainfall/runoff relationships were also analyzed for each separate road segment. This was only possible for the road segments with ephemeral flow because of the small number of road segments with intermittent flow. Only road segment 16-6-8 exhibited a strong positive correlation for all four comparisons of rainfall and runoff variables (r-squared values ranged from 0.80 to 1.00) (Figures 25 and 26). Road segment 15-8-15.1B also exhibited positive correlations between all four rainfall and runoff comparisons, however r-squared values ranged from 0.11 to 0.93, with the weakest relationship between total storm runoff and maximum 15-minute rainfall intensity (Figures 25 and 26). The strongest correlations for road segments 14-8-1.4 and 14-8-34A were in comparisons between instantaneous peak flows and maximum 15-minute rainfall intensities and between storm runoff volume and total storm rainfall (Figures 25 and 26). Instantaneous peak flows were positively correlated with maximum 15-min rainfall intensities for all road segments (r-squared values ranged from 0.50 to 0.93). Positive correlations were also found for all road segments when storm runoff volume and total storm rainfall were compared (r-squared values ranged from 0.53 to 1.00).

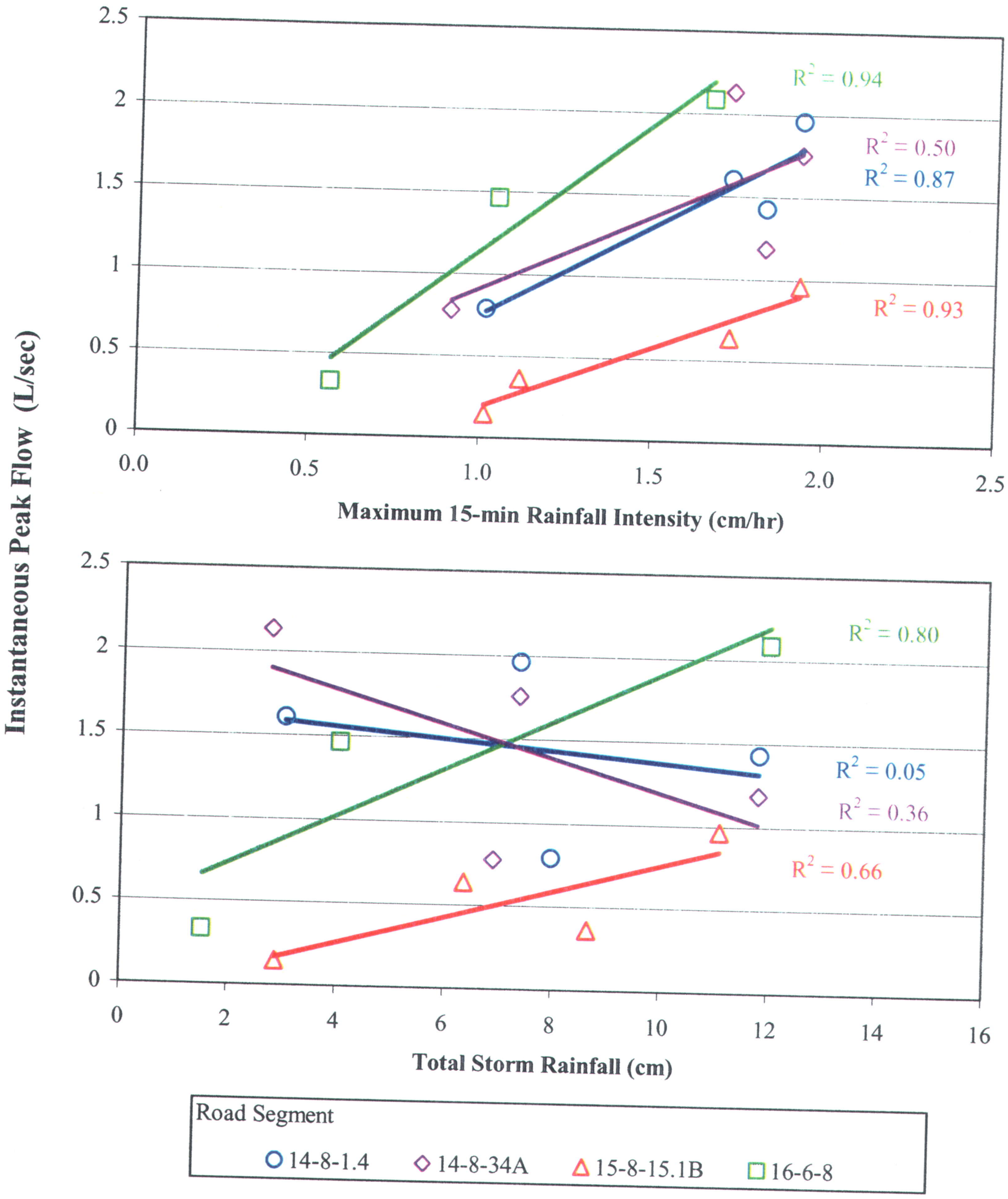

Figure 25. Relationships between maximum 15-minute rainfall intensity and instantaneous peak flow and between total storm rainfall and instantaneous peak flow for four road segments with ephemeral flow.

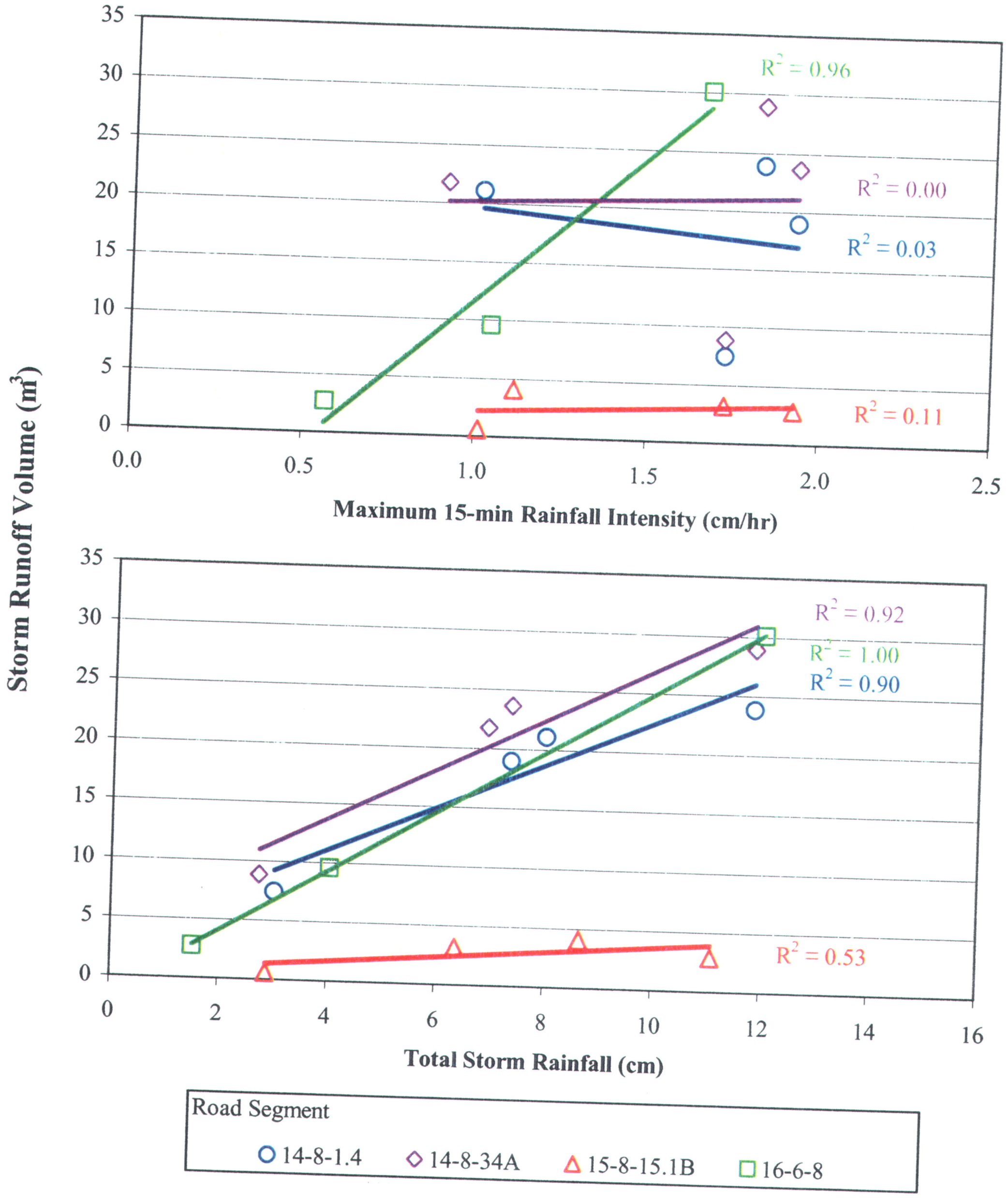

Figure 26. Relationships between maximum 15-minute rainfall intensity and runoff volume and between total storm rainfall and runoff volume for four road segments with ephemeral flow.

6.5.1. Peak Lag Times

The lag time between the instantaneous peak flow and the associated maximum 15-minute rainfall intensity was calculated for road segments that had intermittent and ephemeral flow. Hydrographs of road segments that had ephemeral flow had multiple peaks per storm and lag times for all peaks within a storm were averaged. Road segments with intermittent flow had a single peak per storm. Lag times between instantaneous peak flows and maximum 15-minute rainfall intensities ranged from 0.10 to 0.42 hours for road segments that had ephemeral flow and from 12.4 to 28.7 hours for road segments that had intermittent flow (Table 6, Figure 27).

Road Segment	Peak to Peak Lag Time (min)			
	Storm			
	1	2	3	5
Ephemeral Flow				
15-8-15.1B	17	19	17	14
14-8-1.4	24	25	10	14
14-8-34A	24	25	11	13
16-6-8	6	7	7	--
Intermittent Flow				
14-8-34C	--	939	--	744
15-8-1.2	775	855	--	1722

Table 6. The lag time between the maximum 15-minute rainfall intensity and the associated instantaneous peak flow for all storms and road segments.

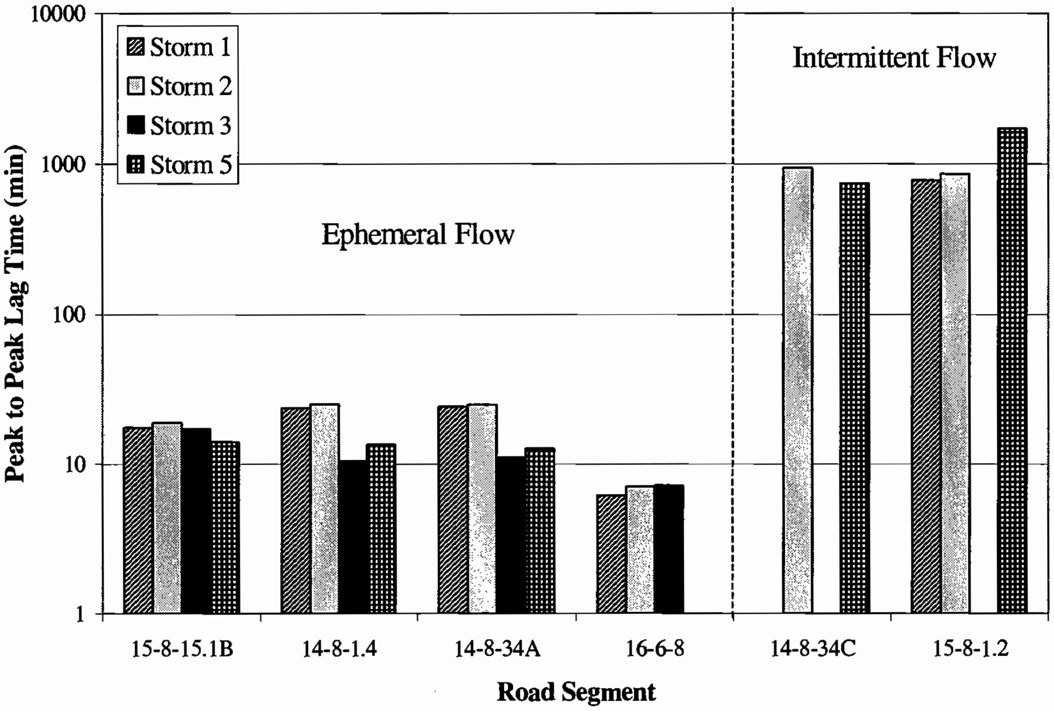

Figure 27. Lag times between the maximum 15-minute rainfall intensity and the associated instantaneous peak flow for all storms and road segments.

6.5.2. Percent Quickflow

The percent quickflow is the amount of ditchflow that runs off during a storm expressed as a percent of the total storm rainfall that fell on either the road surface or the upslope contributing area.

For total storm rainfall that fell on the road surface, percent quickflows were orders of magnitude greater for road segments that had intermittent flow than for road segments that had ephemeral flow. All of the road segments that had intermittent flow had much more than 100 percent of rainfall falling on the road surface show up as quickflow, which means that these road segments were likely intercepting subsurface flow. The road segments that had ephemeral flow had quickflow that ranged from 3 to 71 percent. Thus, it is possible that all quickflow came from the road surface (Table 7, Figure 28).

For total rainfall falling on the upslope contributing area, percent quickflow was under 50 percent for the road segments that had intermittent flow, and ranged from 16 to 46 percent with an average of 29 percent. The percent quickflow for road segments that had ephemeral flow was significantly less and ranged from less than 1 percent to 10 percent with an average of 4 percent (Table 7, Figure 29).

Road Segment	Percent Quickflow (of road area rainfall volume)				Percent Quickflow (of drainage area rainfall volume)			
	Storm				Storm			
	1	2	3	5	1	2	3	5
Ephemeral Flow								
15-8-15.1B	3	7	3	6	0.1	0.1	0.1	0.1
14-8-1.4	27	34	32	35	8	10	9	10
14-8-34A	32	42	42	41	3	3	3	3
16-6-8	71	68	50	--	3	3	2	--
Intermittent Flow								
14-8-34C	--	1474	--	3732	--	18	--	46
15-8-1.2	1628	824	--	1722	31	16	--	33

Table 7. Percent quickflow (using road area and the upslope contributing area) for all storms and road segments analyzed.

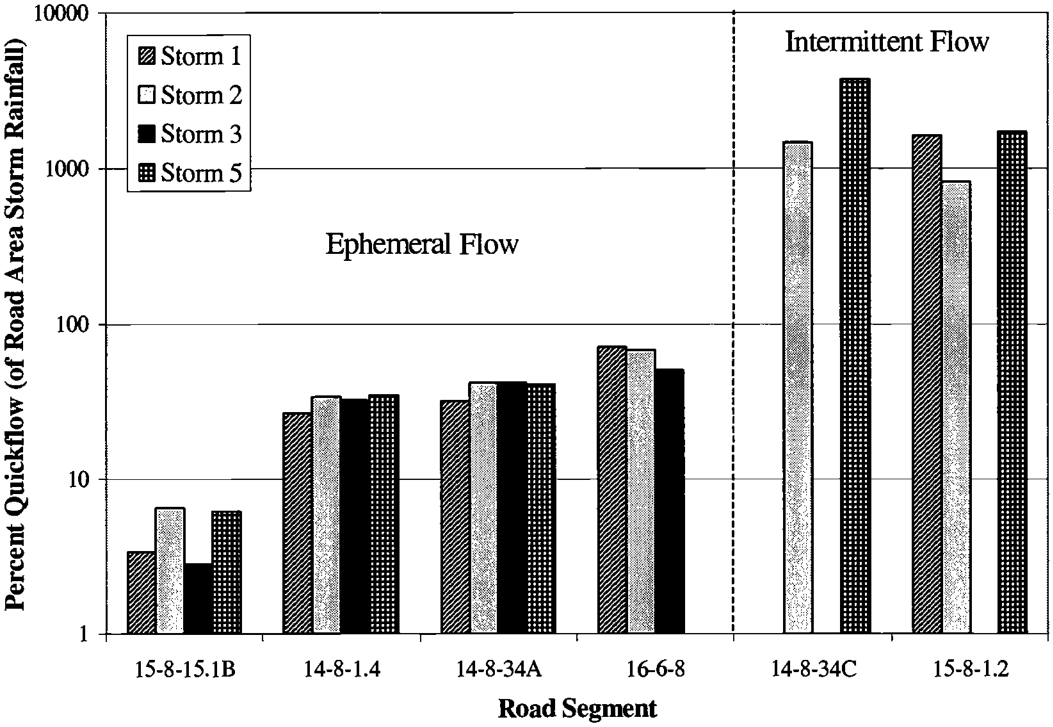

Figure 28. Percent of total storm rainfall falling on the road area that was quickflow in the road ditch.

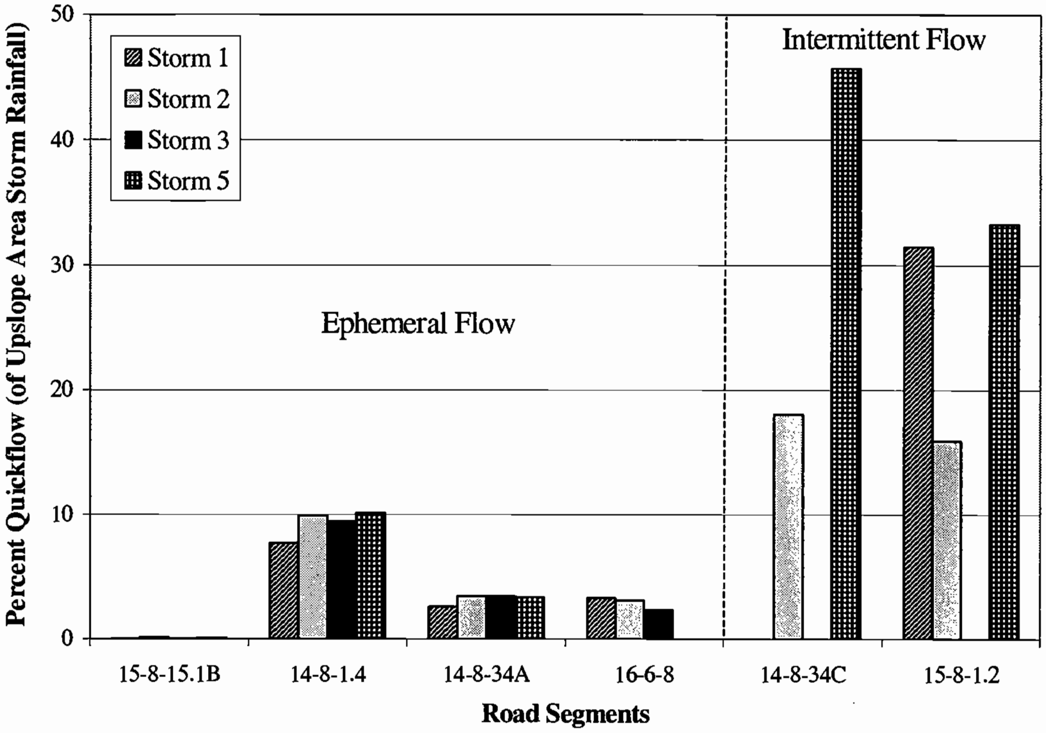

Figure 29. Percent of total storm rainfall falling on the upslope contributing area that was quickflow in the road ditch.

6.6. ROAD AND HILLSLOPE PREDICTORS

Instantaneous peak flows and total storm runoff were correlated with six road and hillslope characteristics: road length, average road grade, average cutslope height, hillslope drainage area, average hillslope gradient, and topographic index (Figures 30 and 31). For all combinations of ditch flow and road and hillslope characteristics, no significant correlation was found. Road length had no correlation with ditch flow, in fact the shortest road segments had the most of ditch flow. Road segment 15-8-15.1A had the largest hillslope area, the steepest average hillslope gradient, and an average cutslope height of 4.1 meters, and yet had the lowest peak flows and flow volumes of any of the road segments. Road segment 14-8-34C had one of the least steep average hillslope gradients but had the highest peak flows and flow volumes. Road segment 15-8-1.2 had the second shortest average cutslope height, yet had the second highest flow volumes and peak flows.

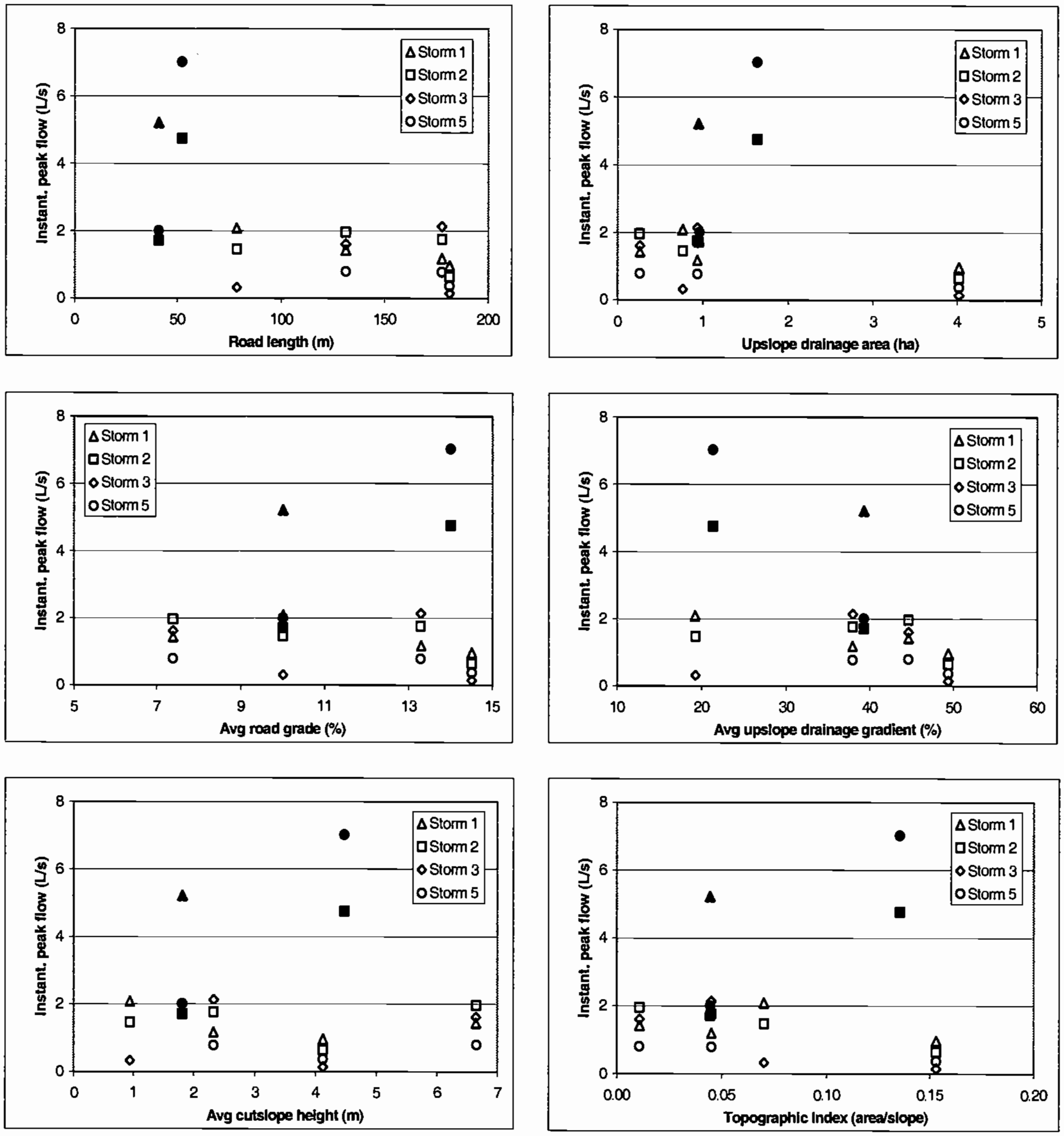

Figure 30. Instantaneous peak flows compared with road and hillslope characteristics for four storm events. Hollow symbols indicate roads with flashy-flow hydrology and solid symbols indicate roads with steady-flow hydrology. The topographic index is the area of the hillslope in hectares divided by the gradient of the hillslope in degrees.

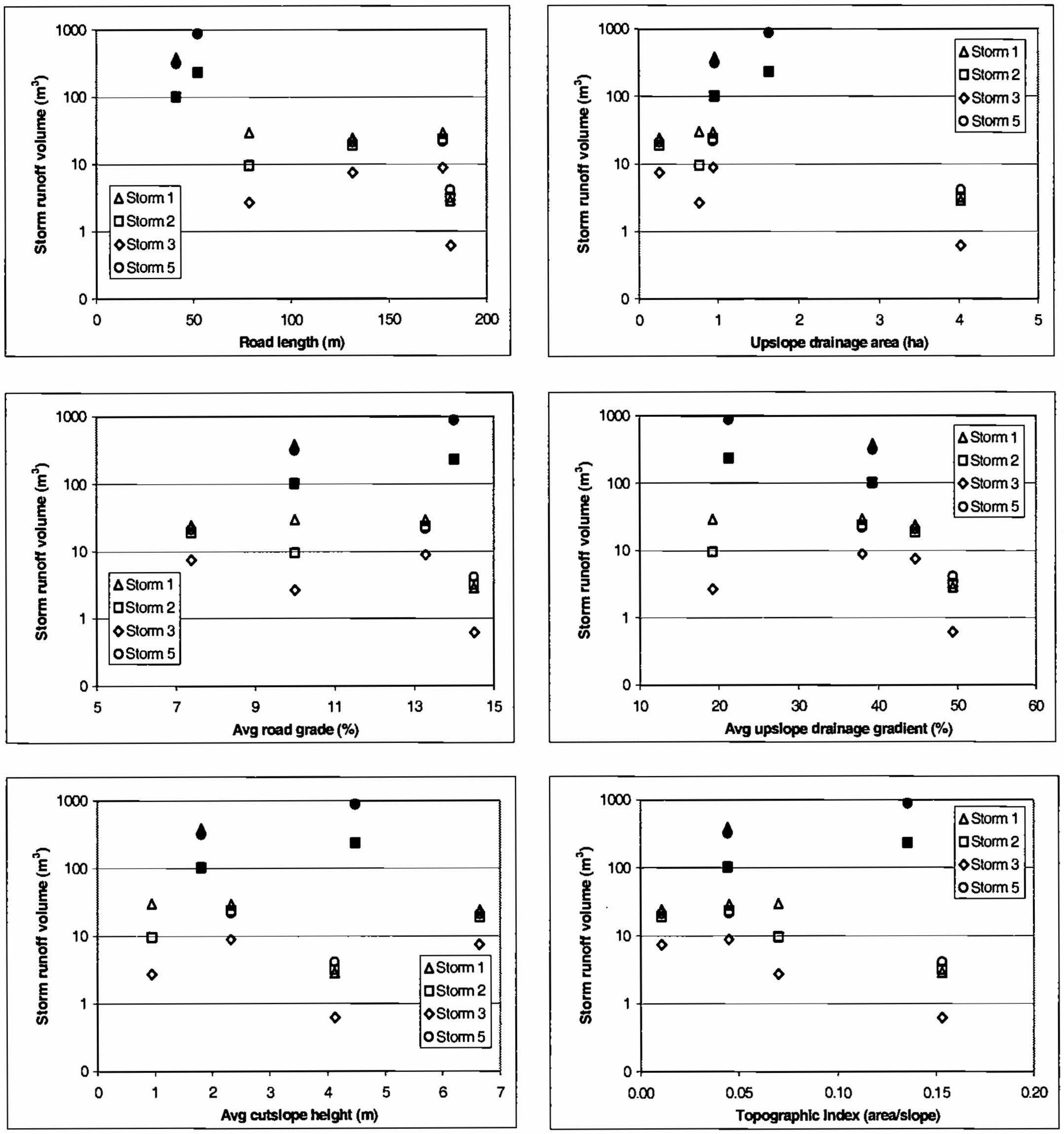

Figure 31. Total storm volumes compared with six road and hillslope characteristics for four storm events. Hollow symbols indicate roads with flashy-flow hydrology and solid symbols indicate roads with steady-flow hydrology. The topographic index is the area of the hillslope in hectares divided by the gradient of the hillslope in degrees. The y-axis is presented in logarithmic scale.

7. DISCUSSION

The hydrologic parameters investigated in this study indicate that there are two different responses of ditch flow to rainfall. During storms, ditch flows can be either ephemeral or intermittent. These two different flow responses can be identified graphically. Road segments that have ephemeral flow have multiple peak flows during a storm and the peak flows have steep rising and falling limbs. Road segments that have intermittent flow have gradual rising and falling limbs of the hydrograph and a single peak per storm. The magnitude of peak flows and total storm runoff also illustrates these differences. Road segments that have intermittent flow have larger peak flows and greater runoff than road segments that have ephemeral flow. A hypothesis that might explain these different runoff responses is that they represent different flow pathways and runoff processes.

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 cut. Runoff from both of these sources was undoubtedly present at all the 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. The lag times between the maximum 15-minute rainfall intensities and instantaneous peak flows as well as hydrograph response factors from the road surface and upslope contributing areas also support these hypotheses.

Peak-to-peak lag times for road segments that exhibit the different types of flow response differ by two orders of magnitude. Instantaneous peak flows for road segments that had ephemeral flow occurred 6 to 25 minutes after the associated maximum 15-minute rainfall intensity. This short lag time results from the primary source of runoff being overland flow from the road surface. In contrast, the peak-to-peak lag times for the road segments that had intermittent flow ranged from 12 to 28 hours. The greater length of the lag times indicates that runoff from road segments that have intermittent flow comes from the upslope contributing area. This flow travels a greater distance via flow pathways that have, nominally, slower velocities.

The total volume of runoff from the ditch expressed as a percent of the total storm rainfall is another indicator of runoff origin. For road segments with ephemeral flow, 3 to 71 percent of the total rainfall landing on the road surface was measured as ditch flow. For road segments with intermittent flow, 8 to 37 times the amount of total storm rainfall that fell on the road was measured as ditch flow. This strongly suggests that road segments with intermittent flow are accessing water other than rainfall that falls on the road surface. Conversely, if the percent of runoff is based on the volume of rainfall that falls on the upslope contributing area, then road segments with intermittent flow generate 16 to 46 percent of the rainfall as ditch flow, and road segments with ephemeral flow generate as little as 0.1 to 10 percent of the rainfall as runoff. This does not eliminate runoff contribution to road segments from either flow pathway, however it does show that for road segments with intermittent flow, interception of subsurface flow is a much more important runoff mechanism.

In addition, direct comparisons of peak rainfall intensities and storm rainfall amounts with instantaneous peak flows and total storm runoff also help to indicate the different runoff processes. For the road segments that have intermittent flow, the best relationships are between total storm rainfall versus instantaneous peak flow and total storm runoff (Figure 24). Both relationships are positively correlated with r-squared values of .42 and .49. Conversely, the relationships between maximum15-minute rainfall intensity versus instantaneous peak flow and total storm runoff are negatively correlated with weaker r-squared values (Figure 24). These results support the hypothesis regarding flow paths for road segments that have intermittent flow. If ditch flow is dominated by subsurface flow from the upslope contributing area, maximum 15-minute rainfall intensities should have little effect on peak flows driven by processes dependent on soil moisture in the hillslope, pore-water pressure, and preferential flow paths.

For road segments that have ephemeral flow, the best relationships are maximum 15-minute rainfall intensity versus instantaneous peak flow, and total storm rainfall versus total storm runoff volume (Figure 24). Both relationships are positively correlated with r-squared values of .44 and .40 respectively. Conversely, maximum 15-minute rainfall intensity versus total storm runoff and total storm rainfall versus instantaneous peak flow are poorly correlated for roads that have ephemeral flow, with r-squared values of .11 and .04 respectively (Figure 24). When individual road segments that have ephemeral flow are analyzed, the best correlations are between the same parameters. Relationships for three of the four road segments have r-squared values greater than or equal to 0.87 for comparisons of instantaneous peak flow versus maximum 15-minute rainfall intensity and total storm runoff versus total storm rainfall (Figures 25 and 26). These results support the hypothesis regarding flow paths for road segments that have ephemeral flow. If ditch flow is dominated by overland flow from the road surface, runoff mechanisms should be quicker and correlate better with short-term rainfall intensities rather than overall storm rainfall. Total storm runoff should still be correlated with total storm rainfall because over the duration of a storm the effect of short-term intensities should be muted.

Given the differences in the magnitudes of instantaneous peak flow and total storm runoff between road segments that have ephemeral flow versus intermittent flow, it would be of great value to be able to predict the road segments where a certain type of flow is likely to occur. Predictive power of this sort remains elusive in this study. No correlation between road and hillslope characteristics and hydrology was found.

One reason for the lack of correlation between the hydrology of roads and the characteristics of the roads and adjacent hillslopes is that the two hypothesized runoff pathways are mutually exclusive. Thus, it is not possible to use a single road or hillslope to describe behavior from both runoff pathways. For example, a road segment whose hydrology is driven by the interception of subsurface flow from the upslope contributing area will not be described by road length or grade. Conversely, a road segment whose hydrology is driven by runoff from the road surface will not be described by upslope contributing area.

A second reason results from the combination of a small population of road segments and the presence of outliers within the population that possess large or small upslope contributing areas (road segments 14-8-1.4 and 15-8-15.1B are examples of this), or road lengths that are out of proportion with drainage area (road segments 14-8-34C and 14-8-1.4 are examples of this). The lack of relationship between road length and drainage area for the six road segments is shown in Figure 32.

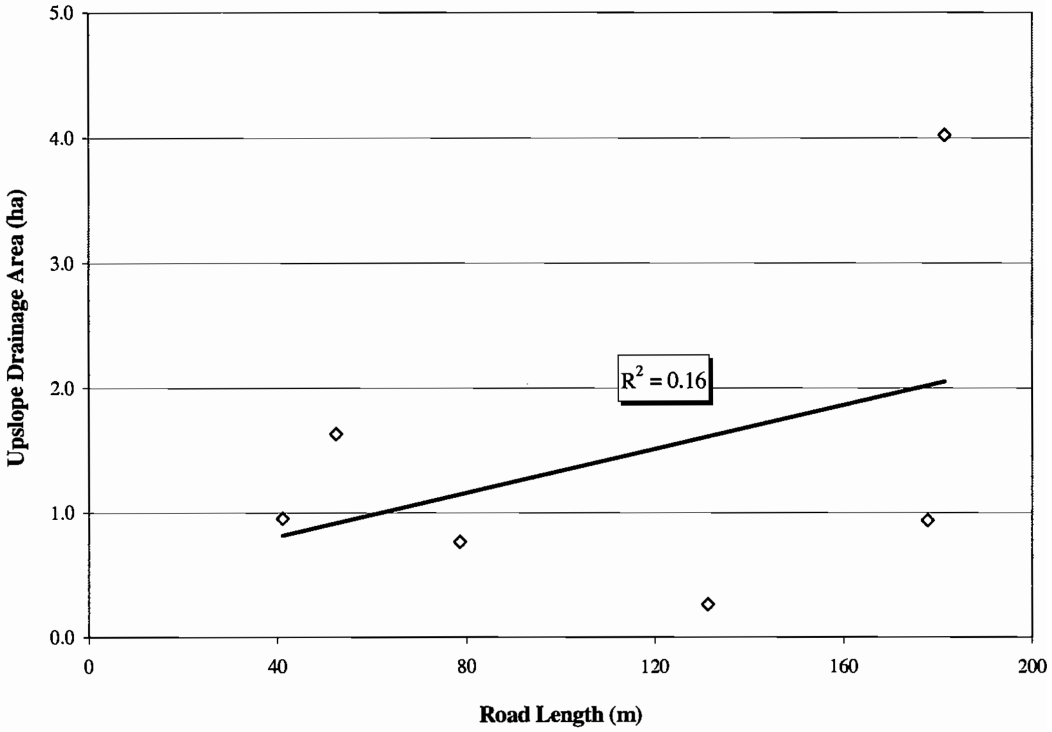

Figure 32. A graph showing the lack of relationship between upslope contributing area and road segment length for the six road segments used in the analysis.

These results can be compared with Wemple (1999) who also investigated rainfall/runoff relationships of segments of forest roads. Wemple found that estimated storm runoff from the road surface (calculated using total storm rainfall and contributing road surface area) was for most sites less than 10 percent of actual storm runoff captured in the ditch. Similarly, estimated road surface runoff for this study was less than 12 percent of actual runoff for all road segments that had intermittent flow. However, all road segments that had ephemeral flow produced less actual runoff than runoff estimated using contributing road surface area and total storm rainfall. Some differences between the two studies that could affect these results include the fact that Wemple only used the amount of road surface area observed to contribute runoff in her runoff calculations, while the maximum potential contributing road surface area was used in runoff calculations for this study.

Wemple (1999) found the relationship between maximum precipitation intensities and peak flows to be positively correlated, but with r-squared values less than 0.35 for all but one road segment. Only the road segments that had ephemeral flow exhibited a positive relationship for this study, however a much greater amount of variability was explained, with 3 of the 4 road segments having r-squared values greater than 0.87. Road segments that had intermittent flow exhibited a weak negative relationship with an r-squared value of 0.15. Wemple (1999) used 30-min peak intensities while 15-min peak intensities were used for this study. Both studies found positive relationships between total storm runoff and total storm rainfall for all road segments. R-squared values for this study were 0.49 for the combined intermittent road segments and ranged from 0.53 to 1.00 for individual ephemeral road segments. Wemple (1999) reported r-squared values from 0.18 to 0.93 for all road segments. It should be noted that Wemple (1999) had a larger population of road segments and analyzed more storms in her study.

Wemple (1999) did not observe different runoff responses of the nature that have been characterized as ephemeral or intermittent by this study. The comparisons discussed above indicate that the runoff behavior of road segments from Wemple's study is more similar to the runoff behavior exhibited by road segments with intermittent flow from this study, and less similar to the runoff behavior exhibited by road segments with ephemeral flow. Wemple (1999) found calculated runoff from the road surface to be a "negligible" component of total storm runoff for road segments in her study, similar to road segments that had intermittent flow from this study. These similarities between road segment runoff behavior support the hypothesis that runoff from road segments with intermittent flow is driven by the interception of subsurface flow from the upslope contributing area, the source of runoff that Wemple argued was dominant for most of her road segments. The fact that Wemple (1999) did not see road segments that had ephemeral flow behavior is possibly explained by differences in geology between the two studies, andesitic basalt versus uplifted marine sandstone, and by spatial proximity, all of Wemple's road segments are within a single 1.01 square kilometer basin while the road segments from this study are spread over a much larger area and thus are more variable in ditch flow behavior.

Wemple (1999) found that road and hillslope characteristics, such as upslope drainage area, drainage gradient, and cutslope height, influenced the magnitude and timing of runoff. Conversely, none of the parameters were predictors in determining runoff characteristics in this study. Again, this is undoubtedly due to the small populations of storms and road segments studied and this was compounded by the need to characterize two totally different runoff responses.

8. CONCLUSIONS

Storm-based analyses of precipitation and runoff have provided insight into the spatial and temporal variability of runoff magnitudes and rainfall/runoff relationships of forest roads in the central Oregon Coast Range. Peak flows and storm runoff volumes, as well as rainfall/runoff relationships such as peak-to-peak lag times and percent quickflow all varied considerably between road segments, but ultimately fell into two runoff behavior categories; intermittent and ephemeral. The hypothesized source of runoff driving these two flow types (road surface runoff for ephemeral flow and interception of upslope subsurface flow for intermittent flow) as well as the pronounced difference in the magnitude of peak flows and flow volumes are important factors to consider when designing efficient and low-impact road drainage systems. Road segments that have intermittent flow are at greater risk of excessive erosion of the road surface and at culvert outlets, and of fillslope and cutslope failure, due to the large peak flows and flow volumes that characterize this type of flow behavior. Because the primary source of runoff is the interception of upslope subsurface flow, road segments that have intermittent flow also have a greater potential to alter hillslope hydrologic processes by converting subsurface flow to surface flow and rerouting large amounts of runoff. Because of these runoff characteristics, additional effort should be exercised in locating and designing drainage for roads that exhibit intermittent types of runoff flow behavior.

The variability in runoff response to rainfall exhibited by road segments evaluated in this study was not explained by road and hillslope characteristics such as road grade and length, and hillslope gradient and upslope contributing area. This lack of relationship highlights the difficulty of predicting road runoff peak flows and volumes in the dry summer months when most new roads are built. Continued research would need to include a larger population of road segments and storms in order to increase the chances of discovering a relationship. Even the data set from this study could be analyzed to include more of the smaller storms. However, the high variability in fine scale topography and the lack of understanding of subsurface flow pathways of forested hillslopes will continue to complicate research seeking to predict the interception of subsurface flow by roads.

Bibliography

Anderson, M. G., and T. P. Burt. 1978. The Role of Topography in Controlling Throughflow Generation. Earth Surface Processes 3: 331-344.

Anderson, Suzanne P., W. E. Dietrich, D. R. Montgomery, R. Torres, M. E. Conrad, K. Loague. 1997. Subsurface flow paths in a steep, unchanneled catchment. Water Resources Research 33(12): 2637-2653.

Arnold, J. 1957. Chapter XIII. Engineering aspects of forest soils. In An introduction to forest soils of the Douglas-fir region of the Pacific Northwest. Western Forestry and Conservation Assoc., Portland, Oregon. Pp. 1-15.

Baeder, L., and J. Christner. 1981. Revision of the guide for spacing relief culverts for the Willamette National Forest. USDA For. Serv. Pac. Northwest Reg., Willamette Natl. For., Eugene, Oregon.

Beschta, R. 1978. Long Term Patterns of Sediment Production Following Road Construction and Logging in the Oregon Coast Range. Water Resources Research 14(6): 1011-1016.

Beschta, R., M. L. Reiter et al. 1995. Cumulative Effects of Forest Practices in Oregon: Literature and Synthesis. Prepared for The Oregon Department of Forestry. 185 pp.

Beven, K. J., R. Lamb, P. F. Quinn, R. Romanowicz, and J. Freer. 1995. TOPMODEL. IN: Computer Models of Watershed Hydrology. V. P. Singh Ed., Water Resources Publications, 1995, pp. 627-668.

Bilby, R. E., K. Sullivan, S. H. Duncan. 1989. The Generation and Fate of Road-Surface Sediment in Forested Watersheds in Southwestern Washington. Forest Science 35(2): 453-468.

Burroughs, E. R. 1984. Survey of slope stability problems on forest lands in the west. In Proceedings of a workshop on slope stability; problems and solutions in forest management. USDA For. Serv. Gen. Tech. Rep. PNW-180. Pp. 6-16.

Chamberlin, T. W. 1972. Interflow in the mountainous forest soils of coastal British Columbia IN: Mountain Geomorphology: Geomorphological Processes in the Canadian Cordillera, B. C. Geogr. Ser. 14, pp. 121-127. H. O. Slaymaker and H. J. McPherson, eds. Tantalus Research, Vancouver.

Corliss, John F. 1973. Soil survey, Alsea area, Oregon. 82 pp.

Donahue, J. P., and A. F. Howard. 1987. Hydraulic design of culverts on forest roads. Can. J. For. Res. 17: 1545-1551.

Dyrness, C. T. 1967. Mass soil movements in the H. J. Andrews experimental forest. Portland, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Dyson, E. L., J. R. Risher, H. E. Graham, T. B. Glazebrook, L. W. Murphy, and J. S. Rothacher. 1966. Part II: A report of the Region 6 storm damage evaluation committee (Storms of December 1964 and January 1965). USDA For. Ser. Pac. Northwest Reg., Portland, Oregon.

Fahey, B. D. and R. J. Coker. 1989. Forest Road Erosion in the Granite Terrain of Southwest Nelson, New Zealand. Journal of Hydrology (N.Z.) 28(2): 123-141.

Fransen, Pieter J. B., Chris J. Phillips, and Barry D. Fahey. 2001. Forest Road Erosion in New Zealand: Overview. Earth Surface Processes and Landforms 26: 165-174.

Harr, R. D., W. C. Harper, J. T. Krygier, and F. S. Hsieh. 1975. Changes in Storm Hydrographs After Road Building and Clear Cutting in the Oregon Coast Range. Water Resources Research 11(3):436-444.

Harr, R. D. 1979. Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific Northwest. Proceeding of a Workshop on Scheduling Timber Harvest for Hydrologic Concerns. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Hewlett, John D. and Alden R. Hibbert. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. IN: Sopper and Lulls, Eds., International Symposium on Forest Hydrology. pp. 275-290.

Horton, R. E. 1933. The role of infiltration in the hydrologic cycle. Transactions of the American Geophysical Union 14: 446-460.

Jones, J.A. and G.E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32(4): 959-974.

Keppeler, Elizabeth T. and David Brown. 1997. Subsurface Drainage Processes and Management Impacts. IN: Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story. Tech. Cord; R. R. Ziemer. USDA Forest Service, Pacific Southwest Research Station, General Technical Report, PSW-GTR-168. pp. 25-34.

Krag, R. K., E. A. Sauder, and G. V. Wellburn. 1986. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. Forest Engineering Institute of Canada, Land Management Report Number 43. 138 pp.

Luce, Charles H. and Thomas A. Black. 1999. Sediment production from forest roads in western Oregon. Water Resources Research 35(8): 2561-2570.

MacDonald, Lee H., Robert W. Sampson, and Donald M. Anderson. 2001. Runoff and Road Erosion at the Plot and Road Segment Scales, St John, US Virgin Islands. Earth Surface Processes and Landforms 26: 251-272.

McDonnell, Jeffrey J. 1990. A Rationale for Old Water Discharge Through Macropores in a Steep, Humid Catchment. Water Resources Research 26(11): 2821-2832.

McGee, Katherine E. 2000. Effects of Forest Roads on Surface and Subsurface Flow in Southeast Alaska. M.S. Thesis, Oregon State University, Corvallis. Pp. 66.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. National Symposium on Watersheds in Transition, Colorado State University, American Water Resources Association.

Megahan, W. F. and G. L. Ketcheson. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. Water Resources Bulletin 32(2): 371-382.

Montgomery, David R., W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, and K. Loague. 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. Water Resources Research 33(1): 91-109.

Packer, Paul E. 1967. Criteria for Designing and Locating Logging Roads to Control Sediment. Forest Science 13(1): 1-18.

Patching, William R. 1987. Soil survey of Lane County area, Oregon. 369 pp.

Piehl, Bradley T., Robert L. Beschta, and Marvin R. Pyles. 1988. Ditch-relief Culverts and Low-volume Forest Roads in the Oregon Coast Range. Northwest Science 62(3): 91-98.

Reid, L. M. and T. Dunne. 1984. Sediment Production from Road Surfaces. Water Resources Research 20:1753-1761.

Sessions, J., J. C. Balcom, and K. Boston. 1987. Road Location and Construction Practices: Effects on Landslide Frequency and Size in the Oregon Coast Range. Western Journal of Applied Forestry 2(4):119-124.

Sidle, R. C., A. J. Pearce, C. L. O'Loughlin. 1985. Hillslope stability and land use. Water resources monograph no. 11. 140 Pp.

Swanson, F. J., and C. T. Dyrness. 1975. Impact of Clearcutting and Road Construction on Soil Erosion by Landslides in the Western Cascade Range, Oregon. Geology 3: 392-396.

Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large; western Cascades, Oregon: A second opinion. Water Resources Research 34(12): 3393-3403.

Thornthwaite, C.W. and J.R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Institute of Technology Laboratory of Climatology: Publications in Climatology 5(3): 311

Wemple, Beverly C., J. A. Jones, G. E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32(6): 1195-1207.

Wemple, Beverly C. 1999. Investigations of runoff production and sedimentation on forest roads. PhD Dissertation, Oregon State University, Corvallis. Pp. 168.

Wright, K. A., K. H. Sendek, R. M. Rice, and R. B. Thomas. 1990. Logging effects on streamflow: Storm runoff at Caspar Creek in Northwest California. Water Resources Research 26(7): 1657-1667.

Yee, C. S., and R. D. Harr. 1977. Influence of Soil Aggregation on Slope Stability in the Oregon Coast Ranges. Environmental Geology 1: 367-377.

Ziegler, Alan D., and T. W. Giambelluca, 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. Journal of Hydrology 196:204-229.