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AN ABSTRACT OF THE DISSERTATION OF

Beverley Coghill Wemple for the degree of Doctor of Philosophy in Forest Science presented on November 30, 1998. Title: Investigations of Runoff Production and Sedimentation on Forest Roads.

Abstract Approved:_____

Julia Allen Jones

Forest roads constructed in steep mountain landscapes have been associated with a number of effects on hydrologic and geomorphic processes. This research examined the effects of forest roads on the flow of water and sediment in drainage basins in the Cascade range of western Oregon. A study conducted at the hillslope scale (< 0.1 km^2) during the 1996 water year examined the factors controlling runoff production on forest roads. Runoff response was related to climatic conditions (storm size and soil moisture) and to the hillslope setting (size of the contributing hillslope, hillslope gradient, and soil depth on contributing hillslopes) on which roads were located. These observations were consistent with a theoretical model of runoff production on steep hillslopes. A study conducted at the large basin scale (181 km^2) examined erosion associated with forest roads during the February 1996 flood. Roads functioned both as initiation sites for erosion and as depositional sites, interrupting the flow of water and sediment along hillslopes and in channels. Roads constructed prior to 1960 in midslope and valley floor positions experienced the highest frequency of erosion and deposition, and these impacts were concentrated at elevations below 800 m, where storm precipitation was augmented by snowmelt. Both fluvial and mass wasting processes deposited sediment on roads and eroded sediment from roads, and multiple processes were linked in complex cascades at

many sites. Roads were a net source of sediment in the basins studied, although they functioned as both sources and storage sites for sediment, depending upon their location on hillslopes. The results point to the importance of roads in both modifying physical processes and in routing material through drainage basins. The findings have significant implications for the management of roads in forested landscapes.

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Investigations of Runoff Production and Sedimentation on Forest Roads

by

Beverley Coghill Wemple

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

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APPROVED:

Major Professor, representing Forest Science

Chair of Department of Forest Science

Dean of Graduate School

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

Beverley Coghill Wemple, Author

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Investigations of Runoff Production and Sedimentation on Forest Roads

Chapter 1

Introduction

In the western U. S., as in many parts of the world, much of the existing forested land is located in mountainous regions. Steep slopes, high relief and extreme climate conditions typical of mountain environments commonly result in high precipitation, rapid conversion of precipitation to runoff, and erosion rates that exceed most other subaerial environments (Hewitt, 1972). An understanding of hydrologic and geomorphic processes active in these environments is a critical component of ecosystem science and essential to sound land management. Water represents the greatest flow of any material substance through a forested ecosystem (Waring and Schlessinger, 1985). Geomorphic processes are important mechanisms for ecosystem disturbance and nutrient transport, create landforms that provide habitat for terrestrial and aquatic organisms, and influence water quality. In addition, land management activities that alter runoff and erosion regimes have important implications for ecosystem function.

Forested watersheds respond dynamically to precipitation, and runoff occurs by multiple flow processes. The dynamic nature of hydrologic response is perhaps best evidenced by the expansion and contraction of drainage networks. These changes occur over time scales ranging from individual storm events (Blyth and Rodda, 1973; Dunne, Moore et al., 1975; Rochelle and Wigington Jr., 1986) to thousands of years over which landscape evolution occurs (Smith and Bretherton, 1972; Abrahams, 1984; Dietrich and Dunne, 1993). Early studies in forest hydrology, motivated by a need to understand runoff generation processes, characterized dynamic changes in channel networks in response to storms and led to the notion that runoff is produced from dynamic source areas (Amerman, 1965; Ragan, 1968; Hewlett and Hibbert, 1967; Betson and Marius, 1969).

Considerable progress has been made in recent decades in understanding the processes and mechanisms of runoff generation in steep, upland watersheds. While runoff by infiltration-excess overland flow (e.g. Horton, 1933) is rare in forested settings, detailed field studies have provided considerable insight into runoff by saturation-excess overland flow (Dunne and Black, 1970) and subsurface flow (Whipkey, 1965; Weyman, 1973; Anderson and Burt, 1978). Recognition of the importance of subsurface flow has led to numerous studies investigating mechanisms of runoff production by subsurface-flow processes. Hewlett and Hibbert (1967) originally asserted that moisture would be delivered downslope as stored water in the soil was displaced by new precipitation, producing a piston-type mechanism that they termed "translatory flow." Other studies point to the importance of groundwater contributions in the near-stream zone (Sklash and Farvolden, 1979; Poinke et al., 1988). The role of rapid pressure changes in the unsaturated (Torres et al., 1998) or saturated (Sklash and Farvolden, 1979) zone has been invoked to explain runoff contributions from the subsurface. Rapid, downslope delivery of water via preferential subsurface flowpaths (e.g. macropores) has also been recognized as an important mechanism of runoff production in forested watersheds (Aubertin, 1971; Jones, 1971; Beven and Germann, 1982; Roberge and Plamondon, 1987; McDonnell, 1990; Tsuboyama et al., 1994), although the spatial distribution and connectivity of macropores is poorly understood. In most environments, runoff is probably produced by the interaction of multiple mechanisms, and these interactions have received recent attention in field studies (Mulholland, 1993; Montgomery and Dietrich, 1995).

The suite of geomorphic processes operating in steep, forested environments is complex, involving multiple mechanisms of material transfer. This complex nature is perhaps best evidenced by the variety of landforms and channel structures present in forested settings. These landforms are produced by processes operating at varying temporal and spatial scales (Hack and Goodlett, 1960; Dietrich and Dunne, 1978; Swanson et al., 1982a), with frequencies that range from continuous to episodic, and rates of soil and sediment movement that range from relatively slow (10^{-3} - 10^{0} m/year) to relatively fast (10^{1} - 10^{2} m/s) (Swanson et al., 1982a).

The literature on geomorphic processes in upland, forested settings is extensive. Considerable work has focused on examining the mechanics of individual processes (Varnes, 1978; Iverson and Denlinger, 1987; Wilson and Dietrich, 1987; Komar and Shih, 1992, and many others). Sediment budget and routing studies (Dietrich and Dunne, 1978; Swanson et al., 1982b; Swanson et al., 1987). have identified the range of geomorphic processes active in forested watersheds, rates of material transport, and factors controlling material storage. Within an ecological context, geomorphic processes may be viewed as important agents of nutrient and material export from watersheds (1982a) and as disturbance agents with variable effects on modifying terrestrial vegetation and aquatic habitat (Swanson et al., 1998).

Geomorphic processes that operate in steep, forested settings may be broadly grouped into those that operate on hillslopes and those that are active in channels (Swanson et al., 1982a). On hillslopes, material transfer may include particle-by-particle transport by surface erosion, slow, continuous downslope movement of soil by creep, rapid detachment and transport of soil *en mass* -- alternately termed debris slides or debris avalanches (Swanson et al., 1982a; Dietrich et al., 1982), and slow, deep-seated displacement of soil masses as earthflows. In channels, material transfer occurs in solution, in suspension, or as bedload. Transport of material in solution or in suspension typically occurs continuously, while transport of larger size classes of material typically occurs episodically during storms. Large pulses of organic and inorganic material may also be transported in channels by debris flows. Bank erosion occurs by lateral channel migration. Many of these processes work together and are inherently linked (Swanson et al., 1982a; Dietrich et al., 1982). Processes supply sediment to depositional environments, where it is stored and subsequently subject to transport by other processes. In addition, one process may initiate another. Finally, soil transported by slow, continuous processes may become vulnerable to rapid transport during large storm events.

This dissertation examines the effects of forest roads on hydrologic and geomorphic processes in a steep, mountain environment. It is now generally understood that forest practices, including harvesting and road construction, affect hydrologic and geomorphic processes (Figure 1.1). Forest roads can generate overland flow (Reid, 1981;

Ziegler and Giambelluca, 1997), which is rare in undisturbed forested settings (Dunne, 1978), and can intercept subsurface flow along road cuts (Megahan, 1972). This runoff may be rapidly routed downstream when road drainage discharges directly to channels, effectively extending the channel network (Wemple et al., 1996). Forest roads can also increase rates of fine sediment production (Reid and Dunne, 1984; Bilby et al., 1989) and increase rates of landsliding relative to forested conditions (Swanson and Dyrness, 1975). The contributions of road sediment to channels may adversely affect aquatic habitat (Duncan et al., 1987; Bilby et al., 1989). In addition, complex process interactions, or disturbance cascades, may occur during storms when material from hillslopes and channels is intercepted by roads, diverted by road drainage structures, and triggers additional erosion on roads (Swanson et al., 1998).

The research presented in this dissertation was conducted in forested watersheds of the western Oregon Cascades. Logging and road construction have produced a mosaic of harvest units covering approximately 25% of the land area and road densities of roughly 3 km/km^2 (Jones and Grant, 1996). Details of the road network development in these watersheds is given elsewhere (Wemple, 1994). Previous studies of hydrology and geomorphology in these watersheds have examined the effects of logging and road construction on peak streamflows (Rothacher, 1970b; Harr, 1976; Harr and McCorison, 1979; Jones and Grant, 1996; Thomas and Megahan, 1998), water yield (Rothacher, 1970a), sediment yield (Swanson et al., 1982a; Grant and Wolff, 1991), and erosion during flood events (Dyrness, 1967; Swanson and Dyrness, 1975). While logging roads have been implicated in changes in streamflow and increased rates of erosion, little process-based information details how roads modify key processes.

The central question addressed in this research is, how do roads modify the flows of water and sediment in a forested landscape? Chapter 2 presents findings of a study, conducted at the hillslope scale (10^{-3} - 10^{-2} km^2) during one water year, aimed at examining factors controlling runoff generation on forest roads (Figure 1.2). Chapter 3 presents findings of a study, conducted at the large watershed scale (10^2 km^2), aimed at examining how roads modify the transfer and storage of sediment during a flood of

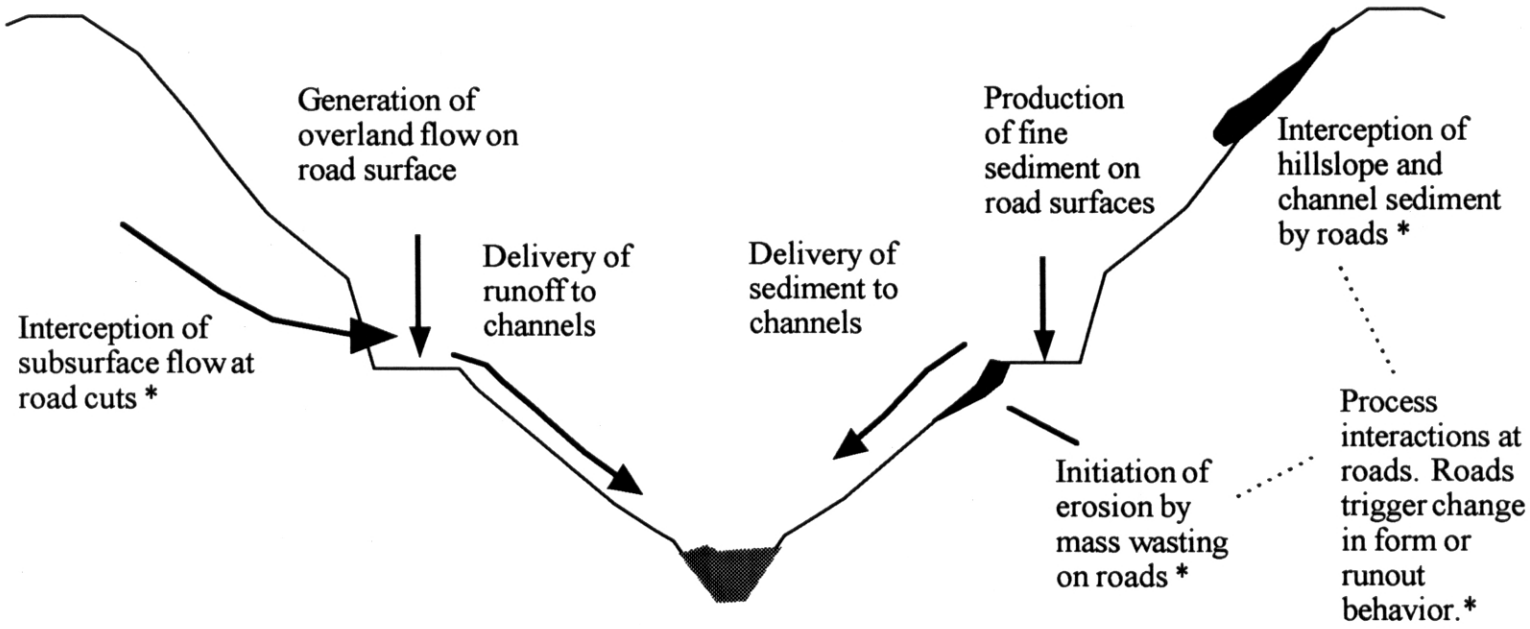
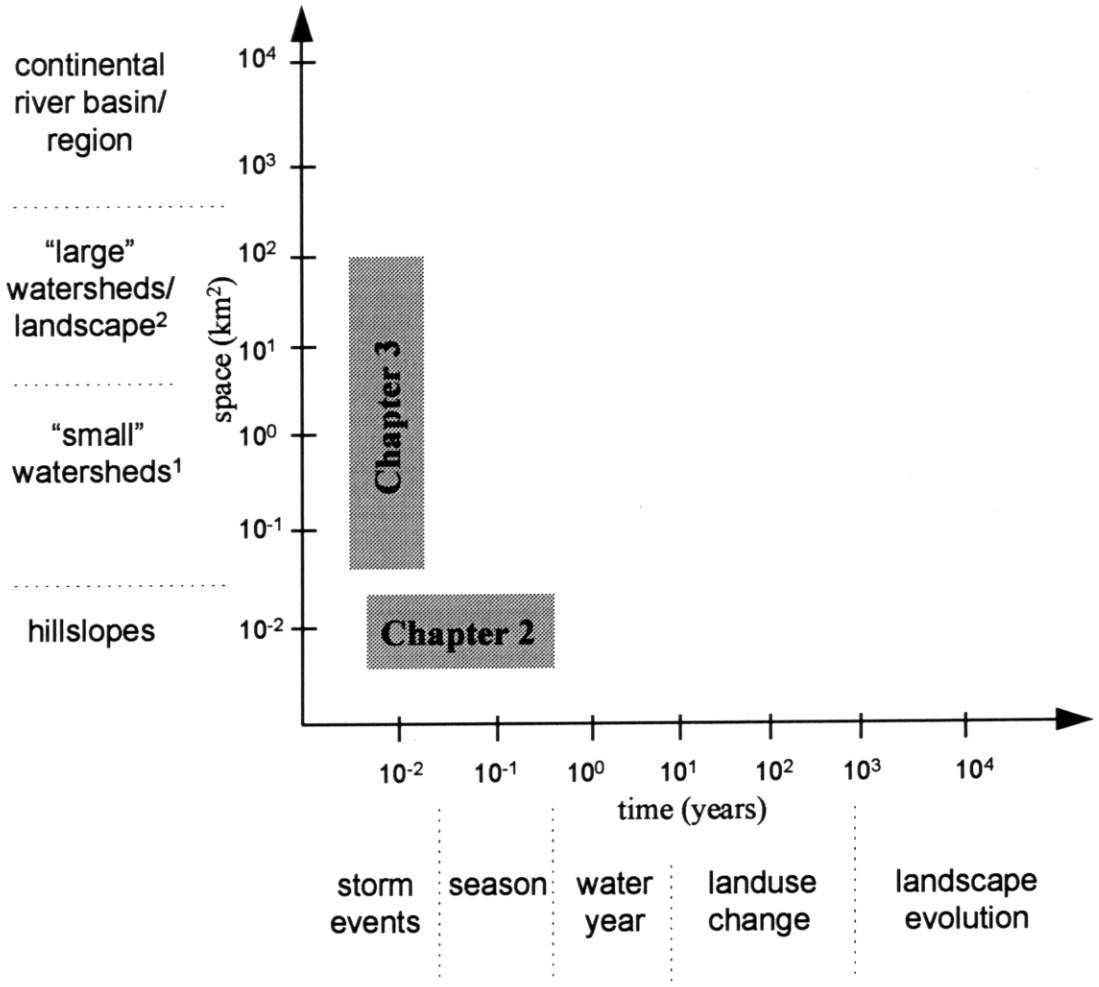


Figure 1.1 Schematic diagram of a hillslope showing possible hydrologic and geomorphic effects of forest roads. Stars (*) indicate effects examined in this study.



Notes:

[1] Refers to watershed scale typically examined in paired-watershed studies of effects of landuse on water and sediment (Brooks et al., 1991).

[2] Refers to scale relevant to management of public lands and important to biological integrity of key terrestrial and aquatic organisms (FEMAT, 1993).

Figure 1.2 Relevant scales in time and space for studies in hydrology and geomorphology. Temporal and spatial scales of investigation for Chapters 2 and 3 of this study are shown.

record in the region (Figure 1.2). A central goal is to develop conceptual models for understanding how roads function in this steep, forested landscape. Chapter 4 provides a summary of findings, points to future research needs, and comments on management implications of this research.

Chapter 2

Hillslope and Climatic Controls on Runoff Production on Forest Roads

Beverley Coghill Wemple

in preparation for journal submission

2.1 Introduction

Forest roads constructed in steep, mountainous terrain influence hydrology through several mechanisms. Roads generate runoff by intercepting precipitation on compacted road surfaces and subsurface flow along road cuts. The network of road ditches and culverts concentrates runoff into channelized flowpaths. Where concentrated surface runoff is routed to streams, roads effectively extend the channel network. These factors alter pre-existing flowpaths, modify the routing of water through a basin, and potentially alter the timing and magnitude of runoff peaks.

By concentrating runoff and routing it to channels, roads may substantially increase drainage density. Wemple et al. (1996) estimated increases in drainage density ranging from 20 to 50% for two basins in the western Oregon Cascades, based on portions of the road network assumed to be connected to channels. Bowling and Lettenmeier (1997) estimated increases in drainage density of 64 and 52% in two basins in western Washington. Earlier studies in the Pacific Northwest documented the connection of roads and streams as an important factor in the delivery of fine sediment to streams (Duncan et al., 1987; Bilby et al., 1989).

Compaction of the road surface reduces infiltration capacity, producing overland flow which is rare on undisturbed forest soils (Harr, 1977). Documented overland flow rates and associated sediment production on roads is available for field studies in the western U.S. (Reid, 1981; Foltz and Burroughs, 1990), equatorial Africa (Dunne and Dietrich, 1982), and the humid tropics (Harden, 1992). Factors influencing overland flow production on roads include antecedent moisture conditions on the road surface, quality of road surfacing material and associated roughness, and degree of compaction (Foltz and Burroughs, 1990), as well as the slope and surface area of an individual road segment (Reid, 1981; Bilby et al., 1989). Modeling studies have produced predictive tools for estimating overland flow on roads. Luce and Cundy (1994), using results of rainfall-sprinkling experiments, identified infiltration parameters for roads that produced good predictions of surface runoff for a range of conditions. Ziegler and Giambelluca (1997)

estimated infiltration rates on road surfaces, agricultural fields and forested areas and made predictions of the conditions under which roads would be expected to generate surface runoff.

Road cuts incised into the soil profile may intercept shallow subsurface flow on hillslopes. Empirical studies have documented subsurface-flow interception far in excess of overland flow volumes from road surfaces (Burroughs et al., 1971; Megahan, 1972; Sullivan and Duncan, 1981), although the occurrence may be highly variable in space and time. In studies in Idaho, Megahan (1972) estimated that subsurface flow intercepted at a road cut was more than seven times larger than direct runoff from the road surface. Megahan and Clayton (1983) showed that the volume of subsurface flow intercepted by a road was related to the volume of stored soil water in the hillslope. No empirical study has attempted to describe the range of conditions necessary for the interception of subsurface flow along road cuts. While several attempts have been made to model transient saturated subsurface flow on hillslopes (Freeze, 1972; Freeze, 1972; Beven, 1977; Beven, 1981; Beven, 1982a; Beven, 1982b) and to apply these to forested settings (Stephenson and Freeze, 1974; Dietrich et al., 1986; Wilson et al., 1989; Brown, 1995), I know of only one attempt to date, which met with limited success, to model the occurrence of subsurface flow at a road cut (Mohsenisaravi, 1981).

In this study, I report findings of detailed field measurements of runoff on forest roads. I evaluate the relative importance of surface runoff and subsurface-flow interception as components of measured runoff on roads in a small (1 km^2) instrumented watershed. I present a theoretical model for predicting runoff behavior on roads and examine the relationship between runoff and the climatic conditions and hillslope setting on sites studied.

2.2 Theory

Studies have shown that the storm response of steep forested hillslopes is typically dominated by saturated subsurface flow (Dunne, 1978; Harr, 1977; Beven, 1981; Montgomery and Dietrich, 1995). Hydraulic conductivity of surface soils usually exceeds

rainfall rates, and overland flow is rare on undisturbed soils (Dunne, 1978). High organic matter content, low weathering rates and high rates of soil turnover due to erosion by mass movements conspire to produce thin, highly porous soils, overlying less permeable subsoil or bedrock (Dyrness, 1969; Dietrich et al., 1995). Numerous flowpath studies have confirmed that precipitation typically infiltrates the soil profile and produces surface runoff via one or more hydrologic mechanisms, including saturated subsurface flow and preferential macropore flow (Dunne and Black, 1970; Jones, 1971; Anderson and Burt, 1978; McDonnell, 1990; Tsuboyama et al., 1994; Mulholland, 1993; Montgomery and Dietrich, 1995, and many others).

In managed forests, overland flow may occur on disturbed soils and road surfaces, where compaction limits infiltration capacities. The rate of runoff originating on compacted road surfaces (Q_{rs}) may be estimated from the contributing road area (A_r) using the standard rational method (Pilgrim and Cordery, 1993)

$$Q_{rs} = ciA_r \qquad (2.1)$$

where i is the rainfall intensity and c is a runoff coefficient. Although it was developed for peak flow estimation, this method provides a reasonably good estimate of overland flow production on compacted road surfaces, assuming that runoff is immediately delivered to a measurement station.

Runoff production by subsurface flow is considerably more complex, particularly on steep hillslopes common in upland forested environments. On steeply inclined slopes with thin, highly porous soils overlying less permeable bedrock, conditions often favor the formation of a perched water table and lateral subsurface flow (Figure 2.1). Assuming flow is parallel to the slope ($\sin \alpha$) and neglecting capillary

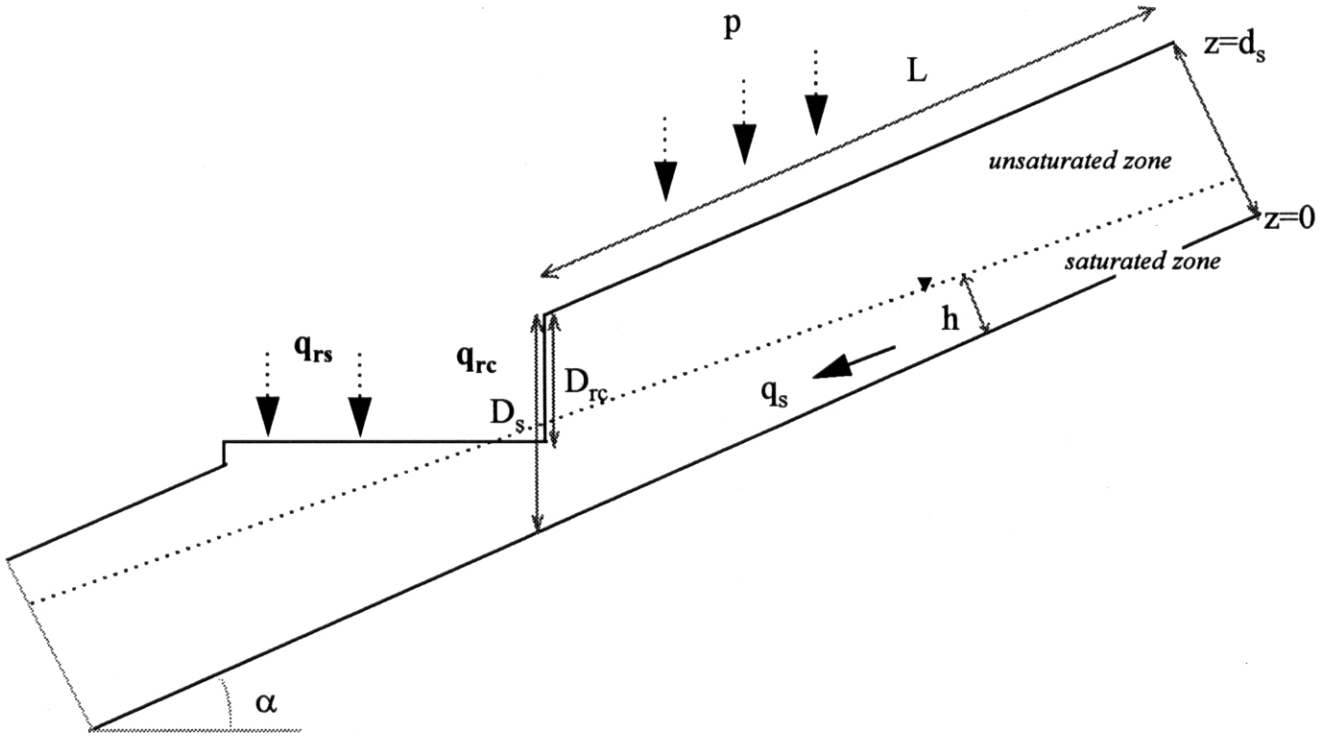


Figure 2.1: Definition diagram for a hillslope inclined at angle α of constant soil depth d_s, measured orthogonal to the slope. Under certain conditions, precipitation (p) promotes the formation of a pearched water table of height h, driving lateral subsurface flow (q_s). Runoff generated on roads may originate from subsurface flow intercepted at the road cut (q_{rc}) or precipitation intercepted on the compacted road surface (q_{rs}). The occurrance of the former is controlled in part by the hillslope length (L) or upslope drainage area and the ratio of the depth of the road cut (D_{rc}) to the total soil depth (D_s) (measured orthogonal to the road bed, e.g. $D_s \cos \alpha = d_s$).

forces, subsurface flow can be approximated by

$$q_s = K_s \sin\alpha \tag{2.2}$$

where K_s is the saturated hydraulic conductivity and q_s is the (two-dimensional) flow rate through a hillslope profile.

Numerous field studies conducted in forested settings confirm that hydraulic conductivity of soils is not constant, but varies with depth into the profile and can be expressed as a function of water table height (h) as

$$K_s(h) = K_o h^n \tag{2.3}$$

where K_o is the conductivity at the base of the profile and the parameter n describes the change in conductivity as the height of the water table changes (see table in Beven, 1982b). Combining (2.2) and (2.3) gives a simple form for estimation of subsurface flow on a hillslope as a function of water table height

$$q_s(h) = \int_0^h K_0 h^n \sin\alpha \, dz \tag{2.4}$$

Beven (1982a, 1982b) showed that on steeply inclined hillslopes, the water table height at steady state is controlled by the precipitation rate (p), the slope length (L), the hillslope gradient (sin α), and the form of the hydraulic conductivity of the soil, and is given by

$$h = \left[\frac{(n+1)pL}{K_o \sin\alpha} \right]^{\frac{1}{1+n}} \tag{2.5}$$

Antecedent moisture conditions also influence both the magnitude and timing of subsurface flow. In the unsaturated zone, hydraulic conductivity is a function of soil moisture content (θ), and wetter conditions lead to more rapid transmission of precipitation to the saturated zone and an associated rise in the water table. Antecedent precipitation and soil moisture may also correlate with the height of the hillslope water table, and influence the rate and timing of flow in the saturated zone.

The timing of runoff response is governed by the movement of water through the soil profile and includes two components, a lag time (T_l) controlled by the flux of moisture through the unsaturated zone, and a concentration time (T_c) controlled by the transmission

of water through the saturated zone (Figure 2.1, Figure 2.2). Beven (1982b) demonstrated that these two components would be most sensitive to soil depth, the precipitation input rate, and the initial soil moisture conditions.

This theoretical model of subsurface flow provides a context for characterizing subsurface flow interception by roads constructed on steep slopes. Neglecting drawdown effects at the cutface, interception of subsurface flow would be expected to occur as the water table rises above the depth of the road cut. Hence, subsurface flow at the road (q_{rc}) would be

$$q_{rc}(h) = \int_{z=d_{rc}}^{z=h} K_0 h^n \sin\alpha \, dz \qquad (2.6)$$

where $d_{rc} = D_{rc} \cos \alpha$ (Figure 2.1).

This discussion suggests that several key factors control runoff in space and time. Temporal variation in runoff should be controlled by the precipitation rate (equations 2.1, 2.5), although soil moisture conditions may influence the magnitude and timing of the response. Spatial variation in runoff should be related to contributing area, the slope gradient, and characteristics of the soil profile (equations 2.1, 2.5). Following equation 2.6, I expect subsurface flow interception by roads to be influenced by the depth to which the road cut intersects the soil profile. Furthermore, the above model suggests that there is a threshold precipitation rate or depth below which the water table does not reach the road cut and subsurface flow is not intercepted.

Accordingly, I examine the behavior of runoff generated on a series of road segments, constructed on steep hillslopes in a forested setting. Using the theoretical model set forth above, I examine the influence of climatic conditions (precipitation rate and depth, antecedent soil moisture conditions) and hillslope setting (drainage area, slope gradient, soil depth, and depth of the road cut) on the magnitude and timing of road runoff and develop a framework for understanding how roads function hydrologically in this environment.

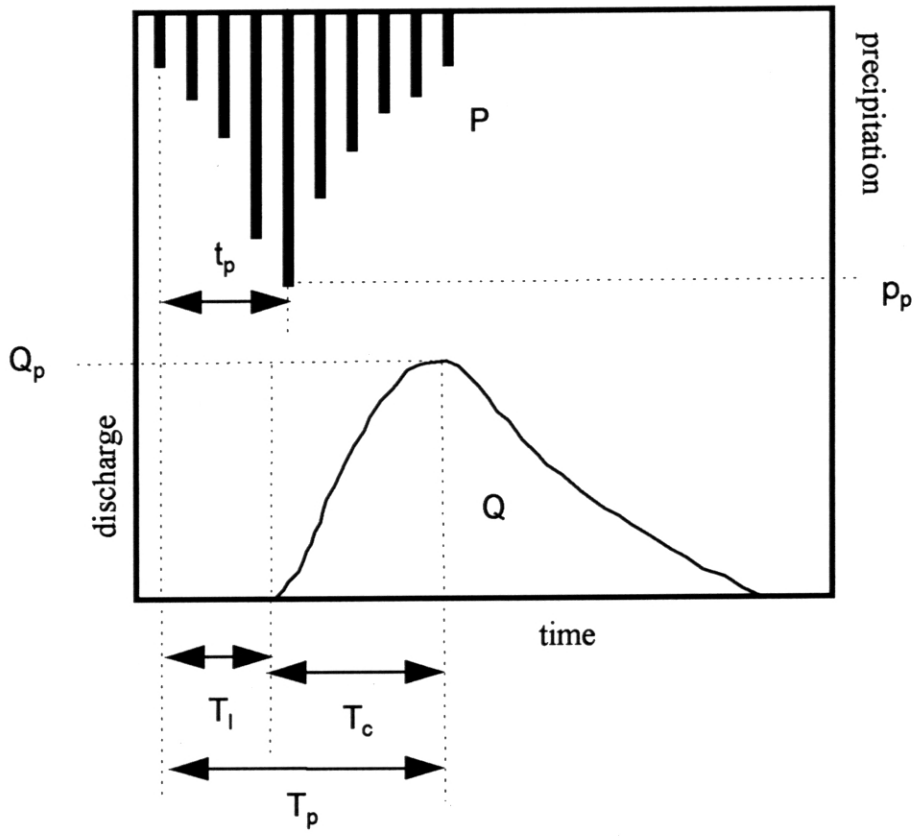


Figure 2.2: Definition diagram for components of precipitation hyetograph and runoff hydrograph. Precipitation events are characterized by total precipitation depth (P), a peak precipitation intensity (p_p), and a time to peak precipitation (t_p). Runoff is characterized by a total discharge volume (Q), a peak discharge rate (Q_p), and a time to peak runoff (T_p). The time to peak runoff includes two components: a lag time (T_l) from the start of precipitation until runoff begins, and a concentration time (T_c) from the start to the peak of runoff (Beven, 1982b).

2.3 Methods

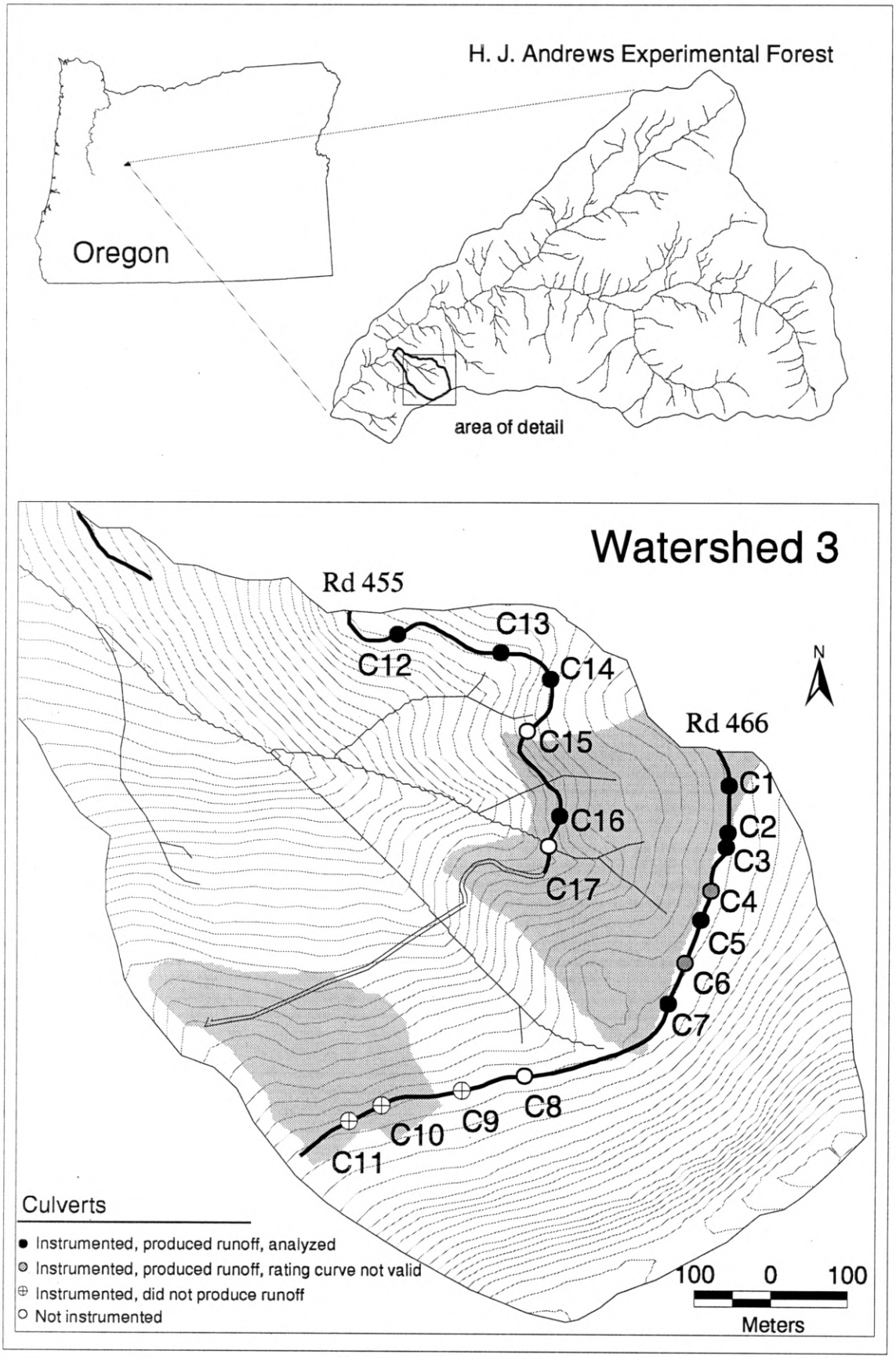
The study was conducted in Watershed 3 in the Lookout Creek watershed, located approximately 70 kilometers east of Eugene. Road runoff and precipitation were measured during the 1996 water year. Field mapping was used characterize hillslopes and road surfaces contributing runoff to monitoring stations.

2.3.1 Study area

Watershed 3 is a 1.01 km^2 basin in the Lookout Creek watershed in the western Oregon Cascades. Located within the H. J. Andrews Experimental Forest, the basin is part of a paired-watershed study, established in 1952, to examine the effects of forest practices on streamflow and sedimentation (Rothacher et al., 1967) (Figure 2.3). The experimental treatment in Watershed 3 included roads and clearcuts. Approximately 3 kilometers of logging road were constructed in 1959. Three small patch cuts, covering approximately twenty-five percent of the basin area, were harvested and broadcast burned in 1963. Continuous streamflow monitoring since November 1952 provides a record of the pre- and post-treatment hydrology of the basin.

The basin is underlain by geomorphically unstable, volcaniclastic rocks of Oligocene to late Miocene origin (Swanson and James, 1975). The uppermost ridge is comprised of more stable andesite. Topographic development of the upper hillslopes in the basin is pronounced with evidence of periodic failure of colluvium. Soils derived from volcanic parent material are loams to clay loams with variable stone contents. Infiltration rates and saturated hydraulic conductivities are high, and overland flow rarely occurs on undisturbed soils (Harr, 1977). Soil depths range from less than 1 meter to more than 8 meters in some locations (Dyrness, 1969). Vegetation cover includes old- growth Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) (Rothacher et al., 1967).

Figure 2.3: Study area, Watershed 3 in the H. J. Andrews Experimental Forest, and locations of instrumented sites. Heavy black line represents functional roads; open line represents abandoned road. Shaded gray zones are locations of harvested units in Watershed 3. Locations of culverts are shown as circles with information regarding instrumentation status shown in the map legend.


H. J. Andrews Experimental Forest
Oregon
area of detail
Watershed 3
Rd 455
Rd 466
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
C11
C12
C13
C14
C15
C16
C17
N
Culverts
Instrumented, produced runoff, analyzed
Instrumented, produced runoff, rating curve not valid
Instrumented, did not produce runoff
Not instrumented
100 0 100
Meters

Elevations in Watershed 3 range from 480 to 1080 meters. Mean annual precipitation is 2300 mm, with roughly 80% occurring between October and April (Greenland, 1994). Precipitation occurs most frequently in the form of rain at this elevation, although a transient snowpack develops during some winter storms (Perkins, 1997). Snowmelt concurrent with large rain storms, so-called "rain-on-snow" events, has produced the highest runoff events of record (Harr, 1981).

Total annual precipitation during the study period (Water Year 1996) is among the highest on record (D. Henshaw, personal communication). Between the months of October 1995 and January 1996, precipitation in Watershed 3 occurred as rainfall. A period of snow accumulation began in mid-January and lasted approximately three weeks. By early February, snowpack for the Willamette River basin in western Oregon was recorded at 112% of the long-term average (Swanson et al., 1998). Between February 6-8, 1996, a flood of record occurred in the region. The three-day precipitation recorded during this period at the Primary Meteorological Station (H. J. Andrews Forest) exceeded 250 mm. A debris flow initiated below the 455 road in Watershed 3 (Figure 2.3) destroyed the stream gage at the mouth of the basin. Following the February flood, a series of mixed rain and snow events occurred through early April, when rainfall and warmer weather resulted in melting of the accumulated snowpack in the upper elevations of the basin. A final rain event was recorded in late April 1996 near the end of the monitoring period for this study.

2.3.2 Road runoff measurements

Watershed 3 has 17 functional culverts on two roads located in the upper portion of the basin (Figure 2.3). Fourteen of these culverts were instrumented to collect storm hydrographs from road segments (Figure 2.3). Twelve of the instrumented culverts had standard 18-inch (45.7 cm) inlets, and two culverts had 9-inch (22.9 cm) inlets. Measurements were not taken at the primary channel (C17) and two blocked ditch-relief culverts (C8 and C15).

Discharge at the culverts was determined through continuous stage measurements taken at culvert inlets and rating curves constructed from field measurements. A V-notch weir with a double 60-degree to 120-degree notch, constructed from aluminum plate, was attached to the inlets of 18-inch culverts to improve resolution in the stage-discharge relations (Figure 2.4). Weirs were not used on the 9-inch culverts at sites C4 and C6. Stage at the weir was measured by 2.5-psi pressure transducers (Electronic Engineering Innovations, Las Cruces, NM) installed in stand pipes. Calibration equations, established in laboratory water-tank measurements over temperature ranges of 2° to 15°C, were used to convert millivolt output of the transducer to water height above datum. Stage readings were recorded at 5-minute timesteps using CR10 dataloggers (Campbell Scientific, Logan, UT) throughout the monitoring period from November 1995 - April 1996. Peak stage at each installation was verified using manual crest-stage recorders of one-inch diameter PVC pipe with floating cork. To assure quality control of the continuous record, digital measurements of stage were compared against observed measurements taken during weekly field visits.

Stage records were converted to discharge using rating curves based on measurements of culvert discharge during winter storms. One rating curve was developed for each culvert dimension (18-inch and 9-inch) (Figure 2.5). The rating curve for 18-inch culverts was based on 24 stage-discharge measurements over stage heights ranging from 1.75 to 19 cm. The rating curve for 9-inch culverts was based on only six stage-discharge measurements, over stage heights ranging from 1 - 5.5 cm. The inlets of these 9-inch culverts experienced frequent overtopping during storm events. Each stage-discharge measurement was made by measuring stage height at the culvert inlet and timing flow into a bucket at the culvert outlet. The discharge measurement interval varied depending upon the flow rate, with intervals of up to 60 seconds possible during lower-flow periods. All discharge measurements exceeded five seconds. Buckets were sealed and returned to the lab where they were weighed to determine volumes.

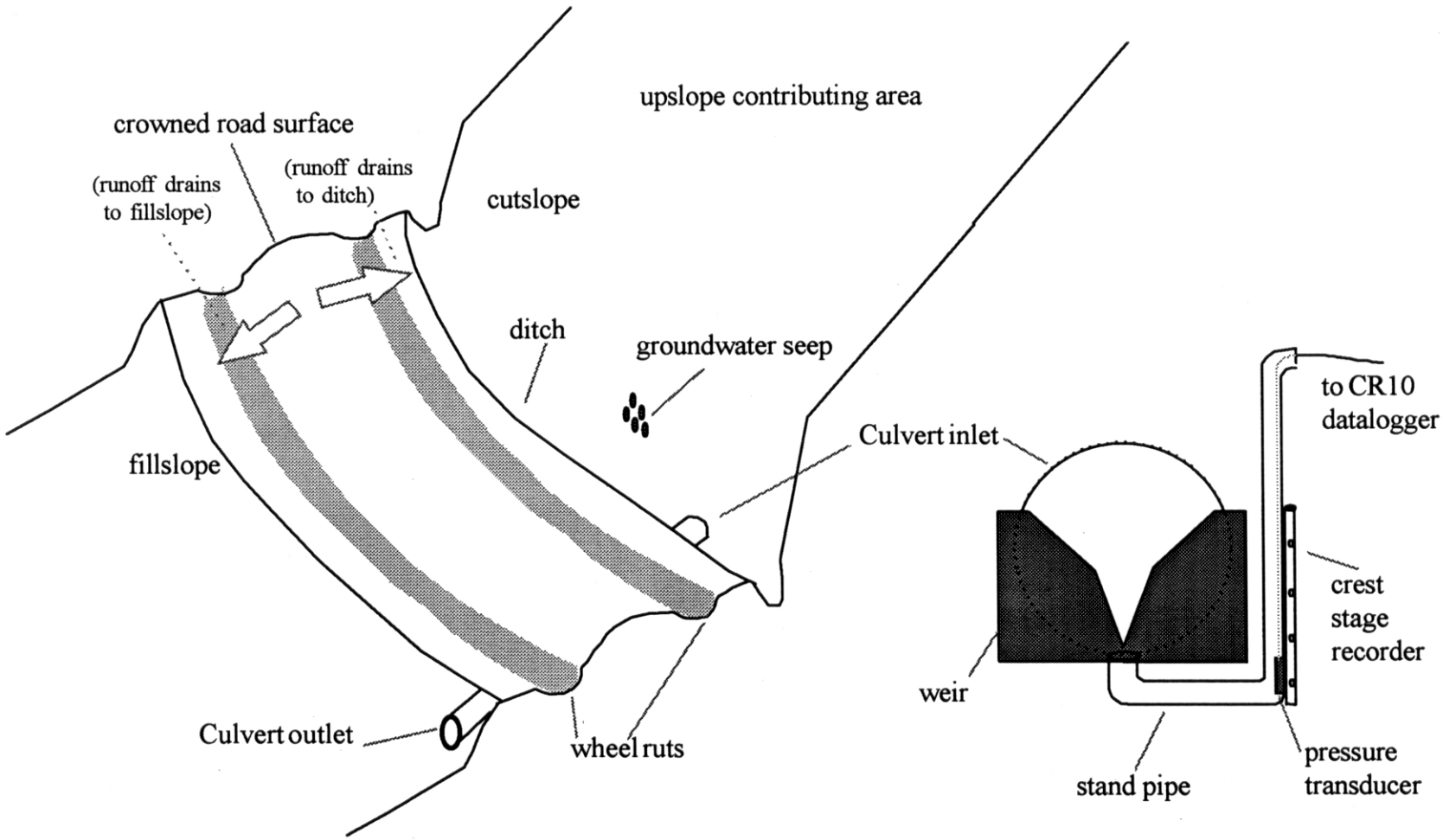


Figure 2.4: Schematic of road features and instrumentation design. Runoff from road surface and subsurface-flow seeps was measured at culvert inlets. Measurement instrumentation included weirs attached to culvert inlets and pressure transducers installed in stilling wells. Stage at the weir was recorded on dataloggers at 5-minute intervals.

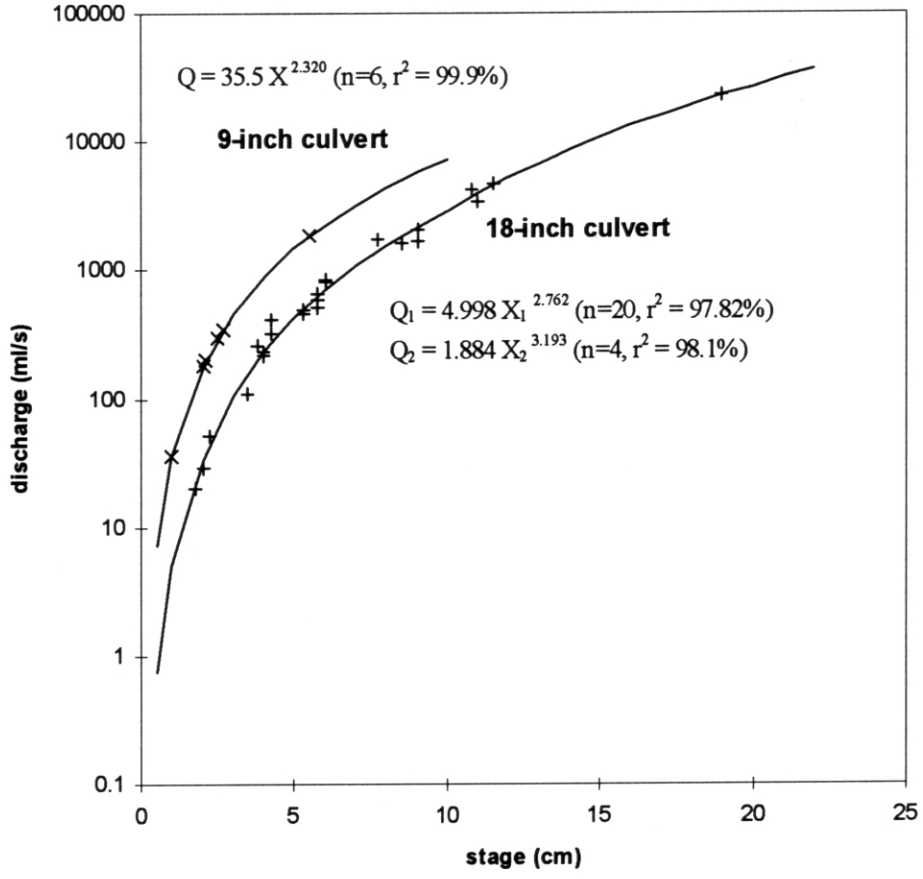


Figure 2.5: Rating curves for 9-inch and 18-inch culverts instrumented for this study. Lines represent fitted curves. Points are measured values. Equations are of the form $Q = aX^b$, where Q is discharge in ml/s and X is stage in cm (for 18-inch culverts, X_1 is stage < 10 cm and X_2 is stage => 10 cm). Parameters a and b are obtained by regression.

Among the fourteen instrumented culverts, two culverts (C4 and C6) were omitted from the analysis, since the 9-inch culvert inlets at these sites were frequently blocked or overtopped during the monitoring period and rating curves were deemed unreliable during these periods. Three culverts (C9, C10, C11) produced no measurable runoff between November 1995, when monitoring began, and late January 1996, when access to the site was impaired by extensive treefall. The remaining nine culverts (C1, C2, C3, C5, C7, C12, C13, C14, C16) provide the primary dataset for analysis of runoff behavior on roads in this study. Monitoring at C5, C9, C10, C11, C12, C13, and C16 was discontinued after the February 5-8, 1996 flood event, due to site-access difficulty or damage to instruments.

Storm hydrographs were extracted from the continuous runoff record collected at each culvert when stage height rose by more than 1.5 cm and ended either when stage height fell to 20% of the peak height or after 72 hours elapsed with steadily declining flow. Hydrographs were described by the runoff volume, Q, defined as

$$Q = \int_{t_{start}}^{t_{end}} q(t)dt \qquad (2.7)$$

where q(t) is the instantaneous runoff rate integrated from the start to the end of the storm, the peak runoff rate, q_p, and the time to peak runoff, T_p (Figure 2.2)

2.3.3 Climatic conditions

Precipitation measurements for storms during the monitoring period were taken from the Primary Meteorological Station (Primet), located approximately 1.4 km from the gaging station at Watershed 3 and maintained by the H. J. Andrews Experimental Forest. Precipitation is measured in a tipping bucket gage and recorded at a 5-minute time step. All precipitation events that lasted at least 12 hours with average precipitation intensity exceeding 0.5 mm/hour were selected from the continuous record for analysis of precipitation-runoff relations. A precipitation event was defined to have ended when

rainfall ceased for six or more hours. Precipitation events were described by the total storm precipitation, P, defined as

$$P = \sum_{n_{start}}^{n_{end}} p_n \qquad (2.8)$$

where p_n is the precipitation intensity at time n (using a 15-minute timestep) summed over the storm period, the peak precipitation intensity, p_p, and the time to peak precipitation, t_p (Figure 2.2). Precipitation events were manually matched to runoff events to create coupled hyetograph-hydrograph records of storms.

Precipitation form was described as rain, mixed rain/snow, or snow according to the following criteria, based largely on field observations made during the study period. Events were classified as rain if the minimum air temperature was above 1°C for the period during which precipitation fell. Events were classified as mixed (e.g. rain-on-snow, mixed rain and snow, or mixed on snow, sensu Perkins, 1997) when the minimum temperature fell below 1°C and the maximum temperature was above 1°C for the precipitation period. Snow events were those that occurred when the maximum temperature during the precipitation period was below 1°C. Field observations (prior to February 8 and after April 13, 1996) and reports from the H. J. Andrews field staff confirmed classification of precipitation for all events.

A soil moisture index θ^* was developed for each culvert and for Watershed 3 following the method of Fedora and Beschta (1989). At the temporal scale of an individual storm event, the method assumes that the influence of antecedent precipitation on streamflow decays at the same rate as the recession limb of the hydrograph. The method was applied to develop a general index of soil moisture conditions at a given site. Six storms (Nov. 30, Dec. 8, Dec. 14, Dec. 28, Jan. 7, and Apr. 21), produced by rain events and having a single, well-defined recession limb, were used to derive recession coefficients as follows. For each storm at each site, runoff values on hydrograph recession limbs were plotted against values preceding those observations by one hour. The recession coefficient r_h is the slope of this plot. The average recession coefficient r_h for each site (Figure 2.6), determined from the hourly runoff timeseries, was converted to a daily coefficient r_d according to

$$r_d = r_h^{24} \quad (2.9)$$

(Appendix 1). This value was used to index the relative soil moisture conditions at the time of each storm. The daily recession coefficient at each site was used to calculate the soil moisture index θ* from the continuous precipitation record as follows

$$\theta^*_t = (\theta^*_{t-\Delta t} * r_d) + P_t \quad (2.10)$$

where P_t is the precipitation (in mm) at time t.

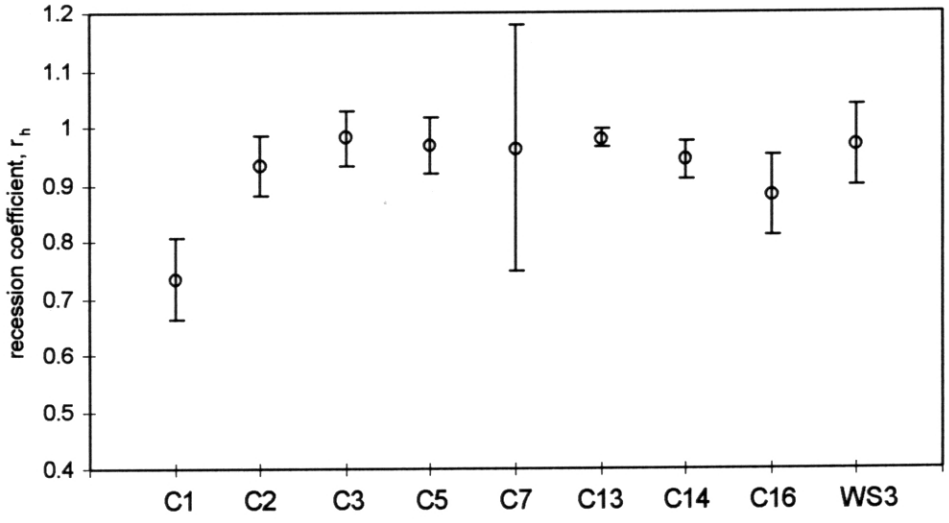


Figure 2.6: Average values and standard deviations of the hourly recession coefficient r_h for each culvert and Watershed 3, derived according to the method of Fedora and Beschta (see text) from recession limbs of hydrographs at each site. Values not calculated at C12, where runoff was only recorded during mixed rain/snow events. Recession coefficients were used to calculate a soil moisture index (θ*) for each site.

The seasonal soil moisture conditions were indexed by the cumulative precipitation during the monitoring period. Indexing soil moisture by cumulative precipitation is based on the presumption that soil moisture gradually increases throughout the runoff season, despite finer temporal-scale fluctuations in soil moisture over individual storms. The cumulative precipitation index P* is presumed to be a relative measure of the seasonal soil moisture conditions at a site.

2.3.4 Field mapping

Field mapping was used to characterize the hillslopes and road surfaces contributing runoff to road segments. Road surface maps were constructed by mapping maximum potential and actual contributing areas. Because road surface drainage is typically confined to rills or anastomising channels that develop on the road surface, the contributing surface area may be difficult to define (Reid, 1981). I estimated maximum potential contributing area by demarcating the entire road length in 10 meter segments and measuring surface areas, delineated by drainage divides or adjacent drainage structures, that drain to a given culvert. This area typically included only the inboard section of the road on crowned road surfaces (Figure 2.4). During storm periods, maps of the actual road surface areas channeling surface runoff to each culvert were constructed by introducing dye to surface flow, observing flow paths, and mapping runoff areas in a methods similar to that employed by Reid (1981).

Maps of the hillslopes above roads were constructed by means of tape-, compass- and clinometer surveys, using topographic features and culverts to delineate the boundaries of each site. These hillslope maps were digitized into a geographic information system in order to calculate contributing drainage area to each monitoring station.

Soil maps constructed by Dyrness (1969) were used to identify the predominant soil unit at each site. Five mapped soil series (Limberlost, Budworm, Frissell, Slipout, and soil derived from andesite colluvium) intersect the portion of the road network monitored for this study (T. Dyrness, personal communication and field reconnaissance). Full

descriptions of the soil series are given in Hawk and Dyrness (unpublished report) and illustrated schematically in Figure 2.7.

Maps of cutbank height along the entire road network were constructed by recording level readings on a stadia rod held in the ditch at 25-meter intervals along the entire road network. Soil depth at the base of the hillslope, immediately upslope of the road cut, was probed using a standard drive probe at approximately 50-meter spacings and at culvert locations.

A classification system to group sites based on the ratio of road cut depth (D_{rc}) relative to the soil depth (D_s) was developed based on soil depth and slope gradient (Figure 2.8). Soils were classified as shallow when they were less than or equal to 2 meters, and deep when they exceeded 2 meters, based on descriptions of soil profile development by Dyrness (1969). Division of slopes into gentle and steep was somewhat subjective, but based on field observations that roads on slopes of less than 20 degrees had little or no cutbank excavation.

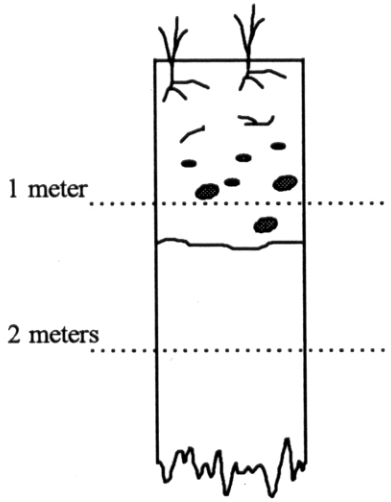
2.3.5 Analysis

Analysis of runoff was conducted in two phases. Runoff originating from road surfaces was estimated by calculating maximum contributions based on the preciptation record and mapped road surface area. Statistical and graphical analyses were used to evaluate total measured runoff relative to predicted controls on runoff production.

2.3.5.1 Road-surface runoff

Estimates of the fraction of total measured runoff derived from the road surface were calculated using the rational runoff method (equation 2.1). Precipitation intensity values were taken from the Primet station. The contributing road-surface area for runoff

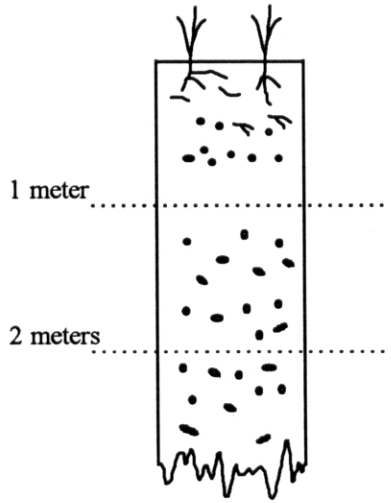
fine-textured to moderately coarse soils with saprolite at 0.75 - 2 meters



(Limberlost, Budworm, Frissell)

C1, C2, C3, C4, C13, C14, C16

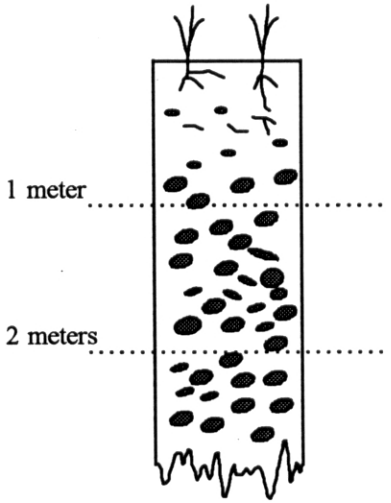
fine-textured to moderately-coarse deep soils with buried horizons, imperfectly drained



(Slipout)

C12

stony soils >2 to over 8 meters deep



(Andesite Colluvium)

C5, C6, C7, C9

Figure 2.7: Descriptions of soil profiles present on hillslopes above instrumented culverts, showing relative textural and depth differences between soil types. Sites occurring on each soil type are noted. Sites C10 and C11 are located on talus deposits, with little soil development.

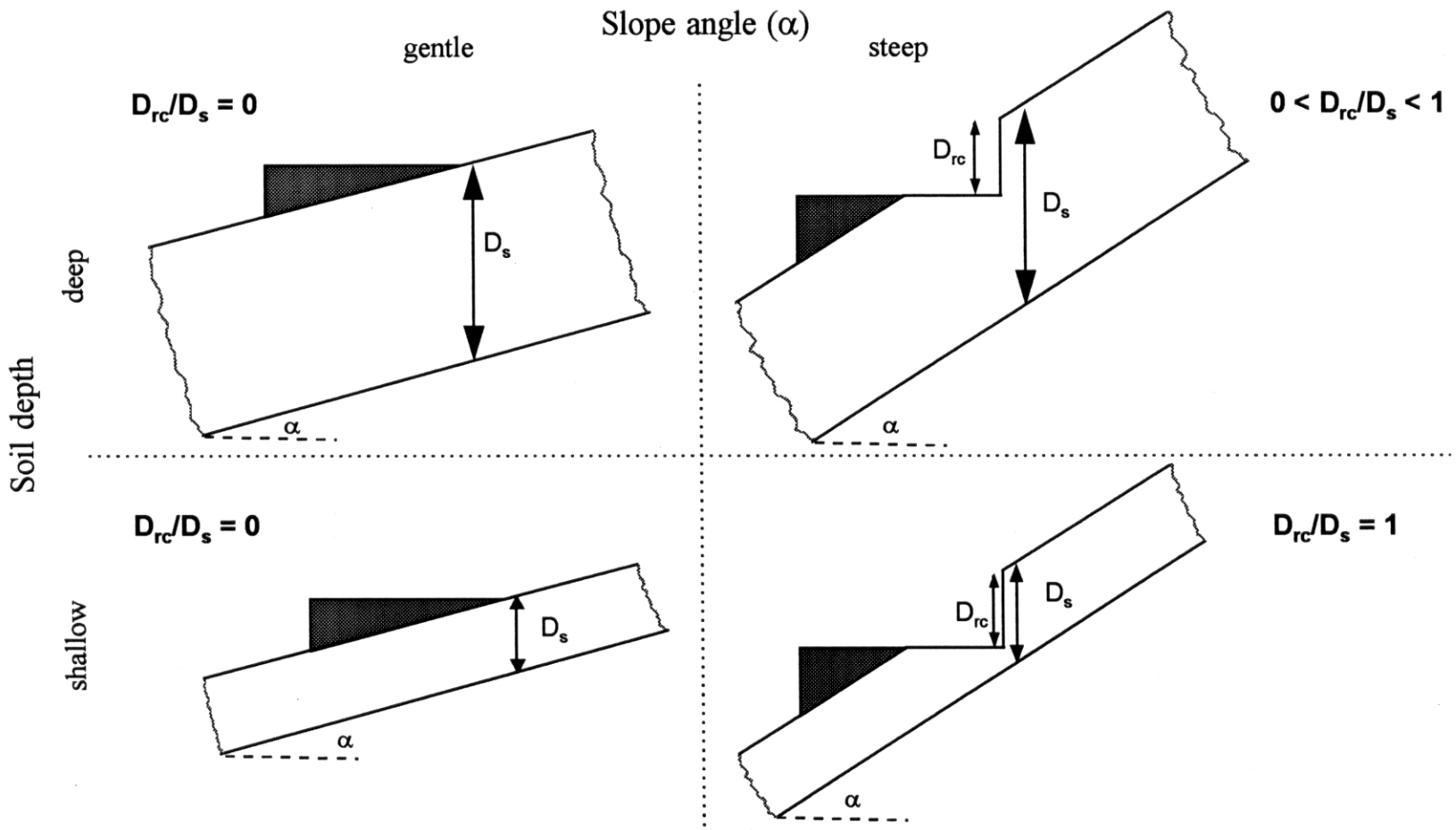


Figure 2.8: Schematic representation of the relationships among soil depth (D_s), slope angle (α), and depth of the road cut (D_{rc}). Sites on gentle slopes do not have cutbanks, and the ratio d_{rc}/d_s is equal to zero. Sites on steep slopes with deep soil profiles have d_{rc}/d_s ratios between zero and one, while sites on steep slopes with shallow soils have ratio d_{rc}/d_s approximately equal to one.

measurements was taken as the area observed to produce runoff during the monitoring period. A runoff coefficient of one (e.g. c = 1) was used, assuming that road surfaces were perfectly impervious. This assumption provides an upper estimate of the fraction of total runoff generated on road surfaces. Any infiltration into the road would reduce the actual runoff from this source.

2.3.5.2 Runoff by subsurface flow

The remaining analysis examined the influence of climatic conditions and hillslope setting on the interception of subsurface flow by roads. These analyses were performed on total measured flows collected at road monitoring stations. While these flows include contributions of road surface areas, the predominant source of runoff is presumed to originate from subsurface flow interception, based upon estimates of minimal contributions of road surface areas to total measured runoff.

Climatic controls on runoff behavior were examined using graphical and regression analysis. All storms that produced measurable hydrographs at instrumented road sites were selected to examine trends in precipitation-runoff relations (Table 2.1). Regression analysis was performed on rain events only, since storage and release of water in snowpacks were not expected to produce a simple relationship between precipitation and runoff for mixed rain/snow and snow events. Regressions were performed using the SAS statistical analysis software (SAS Institute, Chapel Hill, NC).

Hillslope controls on runoff behavior were examined by graphical analysis of runoff response across multiple sites. Seven rain events that produced measurable runoff hydrographs at multiple sites were used for the analysis (Table 2.1). I grouped sites into classes of road cut depth relative to total soil depth (D_{rc}/D_s), based on differences in soil depth and slope gradient (Figure 2.8), and examined how the magnitude of runoff generated on instrumented roads was influenced by the size of the contributing hillslope area above the road, expressed as a functional relationship of the

Table 2.1: Summary of storm events during the study period November 1995 - April 1996 and storm hydrographs recorded at instrumented culverts. Shaded areas refer to periods during which monitoring occurred at culverts[1]. Solid points (•) indicate hydrographs selected for analysis of runoff. Open points (°) indicate hydrographs that were omitted from analysis due to suspected errors. No point indicates storms that did not produce a runoff response that met the selection criteria for analysis (see text). Storms selected for cross site analysis are listed in bold font.

	Storm date[2]	Total precip. depth[3] (mm)	Average precip. intensity[3] (mm/hr)	Max. 1/2 hour precip. intensity[3] (mm/hr)	Min/ Max temp.[3,4] (°C)	Form[5]	Storm hydrographs recorded at instrumented culverts
							C1 C2 C3 C5 C7 C9 C10 C11 C12 C13 C14 C16
1	**Nov. 25, 0030[6]**	103	1.5	7.1	2.8/9.4	r	• • • • • • • • •
2	Nov. 27, 0630	55	1.6	7.1	7.8/10.1	r	• • •
3	**Nov. 29, 0900[6]**	51	2.5	6.1	7.3/9.5	r	• • • • • • • • •
4	**Nov 30, 1200[6]**	41[8]	1.7	4.6	2.5/9.3	r	• • • • • • • • •
5	Dec 1, 1800	23	0.7	3.3	1.5/4.0	r	•
6	Dec 3, 1200	20	1.1	4.2	1.3/7.3	r	° •
7	Dec 5, 0330	24	1.7	7.6	0.5/2.6	r	• •
8	**Dec. 8, 0300[6]**	44	1.6	6.6	0.9/9.1	r	• • • • • • • •
9	Dec 10, 1200	82	1.3	6.6	2.5/8.4	r	° ° ° ° ° ° ° °
10	Dec. 14, 0600	25	1.3	6.6	1.3/4.9	r	• • • ° • °
11	**Dec. 28, 1200[6]**	165	2.6	9.1	2.8/10.2	r	• • • • • • •
12	Jan 2, 2030	25	1.3	3.3	5.4/9.7	r	• • ° •
13	Jan 4, 0030	29	0.8	3.0	1.4/3.7	r	•
14	**Jan. 7, 0500[6]**	45	2.1	5.1	5.2/6.7	r	• • • • • •
15	Jan 9, 0100	28	1.5	4.0	2.9/6.2	r	•
16	Jan 14, 1200	79	1.4	8.6	-0.6/7.2	m	• • • •
17	Jan. 18, 0830	172	1.9	7.6	-0.7/1.3	m	• • • • • • • • •

Table 2.1 (continued)

	Storm date[2]	Total precip. depth[3] (mm)	Average precip. intensity[3] (mm/hr)	Max. 1/2 hour precip. intensity[3] (mm/hr)	Min/ Max temp.[3,4] (°C)	Form[5]	Storm hydrographs recorded at instrumented culverts											
							C1	C2	C3	C5	C7	C9	C10	C11	C12	C13	C14	C16
18	Jan 22, 1700	98	1.2	5.1	-1.5/0.2	s												
19	Jan 26, 2000	75	1.3	6.1	-1.9/0.3	s												
20	Feb. 4, 2200	259	4.5	12.2	1.8/8.1	m	○	○	○	○	○				○	○	○	○
21	Feb 8, 0030	47	2.1	10.5	5.8/8.8	m	○	○	○		○				○		○	
22	Feb. 17, 1500	55	1.8	3.5	1.6/8.5	m	●	●	●		●				●		●	
23	Feb 20, 0030	73	1.3	6.1	-2.3/8.1	m												
24	Mar. 3, 0230	34	1.0	4.1	0.6/5.2	m	●	●	●		●				●		●	
25	Mar 10, 1200	9	1.2	5.1	7.6/9.5	r												
26	Mar 11, 0630	9	0.7	1.8	4.5/8.9	r												
27	Mar 21, 1900	14	0.8	3.7	-	-												
28	Mar 30. 2100	69	1.4	4.0	-	-												
29	Apr 9, 1400	59	1.0	4.0	0.6/9.2	m	●	●										
30	Apr 15, 1700	23	1.1	3.6	0.8/13.3	r												
31	Apr 17, 0930	23	1.1	11.7	1.0/5.1	r	●	●	○									
32	Apr 19, 0630	19	0.8	3.2	0.5/5.6	r												
33	**Apr. 21, 0800**[6]	114	1.6	9.7	2.2/9.5	r	●	●	●		●						●	
					rain events	n[7] =	10	10	8	4	8	0	0	0	0	6	8	13
					mixed rain/snow events	n[7] =	5	5	4	1	4	0	0	0	3	1	3	1

Table 2.1 (continued)

[1] Periodic instrument malfunction and damage associated with the February 1996 flood resulted in failure to record during some periods.

[2] Storm date listed is the day and time on which precipitation began.

[3] Storm statistics, including total precipitation depth, average precipitation intensity, maximum 1/2-hour precipitation intensity, and maximum/minimum temperatures are given for the storm period, defined by the begin time and end time of precipitation.

[4] Minimum and maximum temperatures recorded on CR10 datalogger at the 466 road.

[5] Precipitation form, classified as rain (r), mixed rain and snow or rain-on-snow (m), or snow (s) (see text).

[6] Denotes storm events selected for cross-site comparisons, based on occurrance as rain event that produced runoff hydrographs at five or more sites to allow comparisons between site categories, as depicted in Figure 9.

[7] Number of recorded hydrographs selected to examine the relationship between precipitation and runoff at each culvert (does not included hydrographs that were excluded from analysis due to suspected errors).

[8] Hydrographs at C3 and C5 had recession limbs that extended through December 1, 1995. Precipitation associated with these hydrographs was taken as 64.35 mm (sum of November 30 and December 1 precipitation events).

form

$$Q_i = f(A_{h(i)}) \tag{2.11}$$

where Q_i is the total measured runoff and $A_{h(i)}$ is the upslope contributing area for the road segment at site i.

A series of composite variables was developed to examine the joint influence of climatic and hillslope controls on road runoff. The influence of storm precipitation on runoff volume was examined by controlling for drainage area, using a functional model of the form

$$\frac{Q_i}{A_{h(i)}} = f(P) \tag{2.12}$$

where $Q_i/A_{h(i)}$ is the unit area runoff (U_i). The influence of soil moisture on runoff was examined using a model of the form

$$\frac{U_i}{P} = f(I) \tag{2.13}$$

where U/P is commonly referred to as the runoff ratio and I is an index of soil moisture conditions. In this study the storm-scale soil moisture index θ^* and a seasonal soil moisture index P* were used as indices of soil moisture.

2.4 Results

2.4.1 Road surfaces and contributing hillslopes

Only a small fraction of the maximum potential contributing road-surface area at instrumented sites actually generated and routed overland flow to culverts. Most of the road length in Watershed 3 is crowned and has deep wheel ruts (Figure 2.4), and only a small fraction of the road surface drains to the inboard ditch and culvert. During storms, I observed that road-surface runoff was held in detention storage or channeled into wheel ruts and ultimately routed onto fillslopes over much of the road length in Watershed 3. While maximum potential contributing road-surface areas ranged from 60 to 500 m^2, the

surface area mapped as contributing runoff to culverts during storms was, in most cases, substantially smaller, ranging from 12 to 280 m^2 (Table 2.2).

Hillslope areas above roads were an important source of runoff to instrumented road segments. On road 466 (Figure 2.3), slope lengths from the drainage divide to the road range from 65 meters at C1 to 400 meters at C9, with contributing areas ranging from 0.25 to 3.6 hectares. Slope lengths above instrumented sites on road 455 range from 100 meters at C12 to 150 meters at C16, with contributing areas ranging from 0.75 to 3.0 hectares (Figure 2.3). Convergent topography on these hillslopes develops at slope lengths of roughly 150 meters below the drainage divide, although the exact slope length required to produce convergent slopes probably also depends on soil properties. Most road segments less than 150 meters from ridges are located on hillslopes that show little topographic convergence and are generally planar. Road segments located more than 150 meters from the ridge have upslope areas characterized by convergent slopes. Average slope gradients range from 15 to 35 degrees. Slopes are typically steepest near the ridge and decline in gradient with increasing distance from the drainage divide.

Soils in the study area range from shallow, fine-textured profiles with weathered bedrock at depths of 0.75 - 2 meters, to deep, rocky profiles developed in weathered colluvium (Figure 2.7), ranging from more than 2 to over 8 meters in depth (Hawk and Dyrness, unpublished report). The shallowest soils are those of the Limberlost series on the hillslope above C1. This series grades into the Budworm series, generally 1.5 - 2 meters in depth overlying relatively impermeable saprolite. Sites C2, C3, C4, C13 and C14 are located on the Budworm series. Soils derived from andesite colluvium occur on the slopes above C5, C6, C7 and C9. These soils have very high rock content and are typically more than 6 meters deep. The hillslopes above C10 and C11 are mantled with rocky talus deposits and have little or no soil development. Soils on hillslope above C12 are mapped as the Frissel series; however, runoff contributed to the culvert emerges from a seep located at the contact with a Slipout soil, a poorly drained soil with high clay content. At C16, a thin (approx. 0.5 m) soil mantle, mapped as the Limberlost

Table 2.2: Characteristics of instrumented sites

	C1	C2	C3	C4	C5	C6	C7	C9	C10	C11	C12	C13	C14	C16
Drainage area														
road surface (m^2) - maximum[1]	200	204	135	355	280	185	212	300	423	383	500	60	150	113
road surface (m^2) - observed [1]	32	42	122.5	280	50	35	20	5	5	7	100	12	30	35
hillslope (ha)	0.25	1.2	2.02	1.01	1.57	0.93	1.37	3.6	1.1	0.45	0.75	0.9	3.0	3.0
Hillslope length (m)	65	150	230	230	240	255	275	400	225	150	100	120	150	150
Slope form [2]	P	C	C	P-C	C	C	P-C	C	P	P	P	P	C	C
Average slope angle (degrees)	35	30	20	25	30	30	35	15	25	25	35	15	30	30
Soil type [3]	L,B	L,B	L,B	B	Ac	Ac	Ac	Ac	n/a	n/a	S,F	B	B	L
Soil depth (m) [4]	0.75	1.5	2	>4	>4	>4	>4	>4	<0.25	<0.25	1	>4	>4	0.5
Depth of road cut (m)	8.4	3.1	2.9	2.4	1.7	4.1	5.4	0	2.5	1.5	4.5	0	0.3	2
Surface runoff observed at instrumented station in WY96	yes	yes	yes	yes	yes	yes	yes	no	no	no	yes	yes	yes	yes

[1] Road surface drainage areas include mapped areas observed to contribute runoff to instrumented culverts during storms in WY96 and a maximum possible contributing area draining to the culvert (see text).

[2] Slope forms include planar (P) and concave (C) slopes.

[3] Soil types are taken from the series names mapped by Hawk and Dyrness (unpublished internal report) and include Limberlost (L), Budworm (B), Frissel (F), Slipout (S) and unnamed soils on andesite colluvium (AC). Slopes above C10 and C11 are mantled with talus deposits and little soil development is evident. Differences in relative depth and texture of soils are shown in Figure 2.7.

[4] Soil depth immediately above the road cut as determined by drive probe measurements in the field. Maximum depth of penetration was 4 meters. Soil depths exceeding 4 meters are noted and may be as deep as 8 meters (Hawk and Dyrness, unpublished internal report).

series, overlies bedrock, and subsurface runoff during storms emerges at the soil-bedrock contact, forming a waterfall on the cutbank draining to this site.

Instrumented sites spanned a range of slope gradients, soil profile depths, and roadcut depths. Roads located on hillslopes with gentle slope gradients have little or no road cut, while roads on steep slopes have deep cuts that may or may not penetrate the entire soil profile, depending upon soil depth. A plot of soil depth at the road cut versus slope angle on hillslopes above roads for the instrumented sites is shown in Figure 2.9. The road segments examined fell into three classes: sites located on gentle (≤15°) slopes and deep (≥3 meters) soils (C9, C13), sites located on steep slopes (≥20°) and deep soils (C5, C7, and C14), and sites located on steep slopes with shallow (≤2 meters) soils (C1, C2, C3, C10, C11, C12, C16).

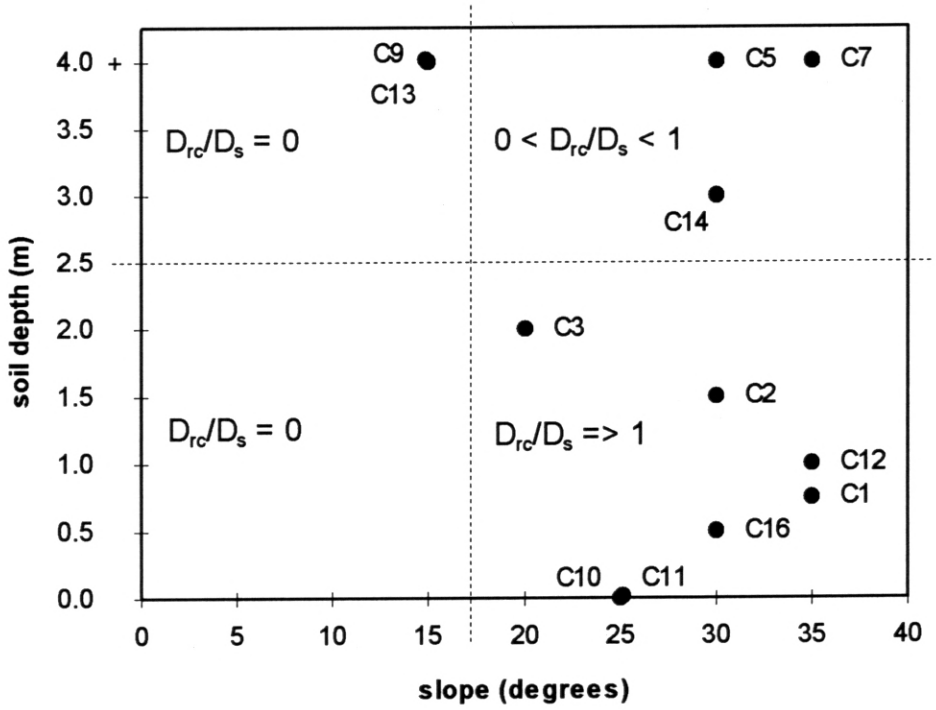


Figure 2.9: Graph of slope angle and soil depth for sites instrumented in this study. Dotted lines indicate divisions between low (< 15°) and high (> 20°) slopes and shallow (< 2.5 m) and deep (>2.5 m) soils. Categories delineated by these divisions are used in cross-site analysis. See also Figure 2.8.

2.4.2 Climatic conditions and runoff hydrographs

Thirty-three storm events occurred during the study period (Table 2.1). Observed precipitation depths ranged from 10 mm for short duration spring storms to over 100 mm for winter storms. Average precipitation intensities ranged from 0.36 to over 2.5 mm/hour, with maximum precipitation intensities from 1 to over 10 mm/hour. Between January 14 and February 4, 1996 over 400 mm of precipitation was recorded at the Primet precipitation gage. Field observations during this time confirm that precipitation occurred as snow beginning on January 15. Between February 5-8, 1996 a flood of record occurred in the region, triggering numerous landslides and erosion of hillslopes, roads and channels (Swanson et al., 1998). In the upper portions of the basin where the two instrumented roads are located, a snowpack persisted until early April.

Indices developed from the precipitation record show patterns of short-term (storm-scale) and long-term (seasonal) fluctuations in moisture conditions that probably approximate fluctuations in the soil moisture conditions influencing runoff (Figure 2.10). The storm-scale soil moisture index θ^* for Watershed 3 ranges from 0 to almost 200 mm over the monitoring period, with particularly high values for November 8-15, November 25-December 3, December 28-31, January 19-28, and February 6-10. In fact, four of the five largest precipitation events, each with total precipitation exceeding 100 mm, occurred early in the season. Cumulative precipitation, an index of the relative soil moisture conditions throughout the runoff season, ranges from 0 to over 2500 mm over the study period. Before the period of snow accumulation in mid-January, cumulative precipitation in Watershed 3 was less than 1300 mm. By late April, when the final storm was recorded on the instrumented road segments, cumulative precipitation was over 2400 mm.

Only a subset of the precipitation events produced measurable runoff at the instrumented sites (Table 2.1), although the threshold precipitation depth and intensity required to produce runoff varied by site (Figure 2.11). Only storms occurring as rain and as mixed rain/snow produced measurable runoff. Snow events on January 22 and January 26 produced no measurable storm response at the instrumented sites. Average

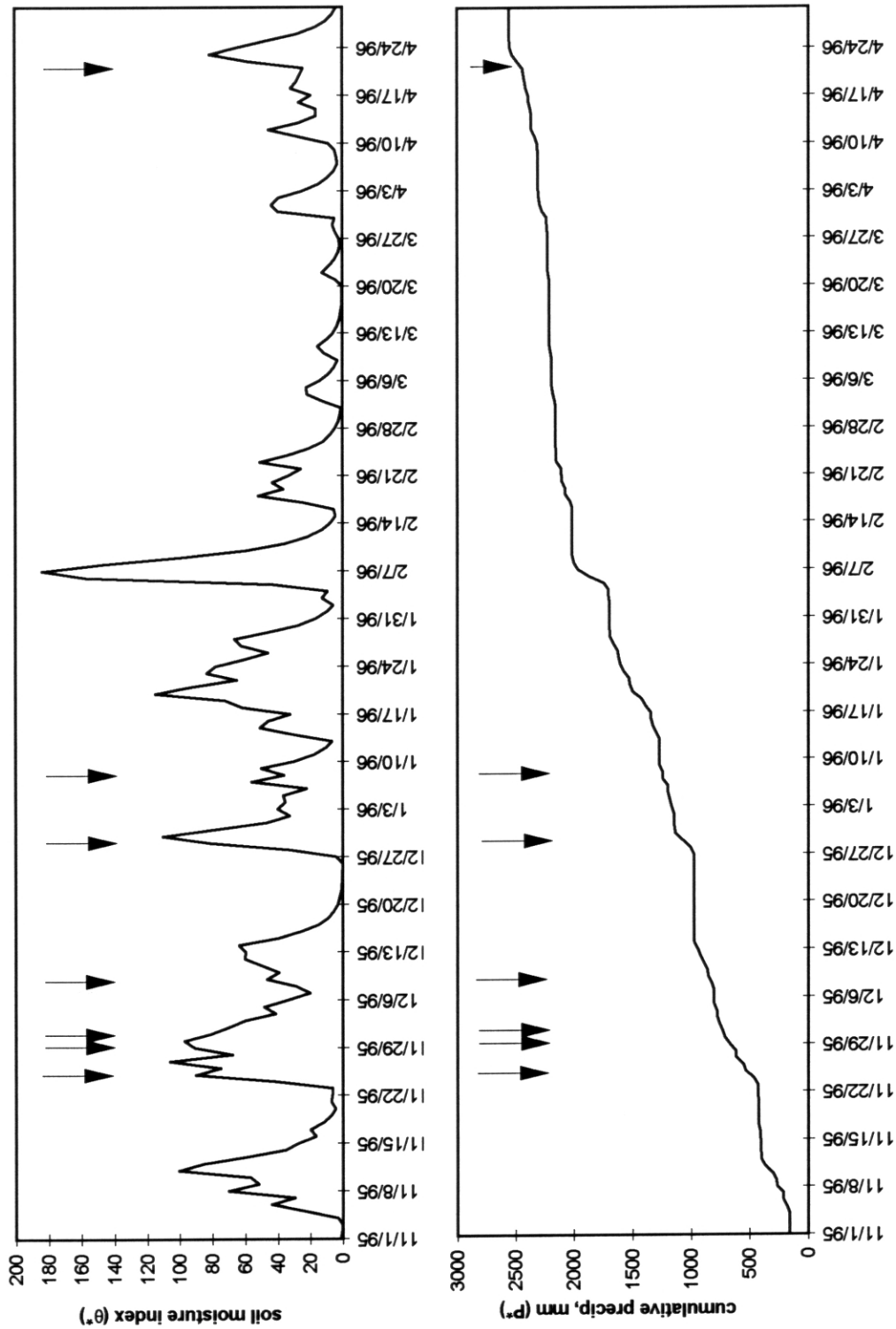
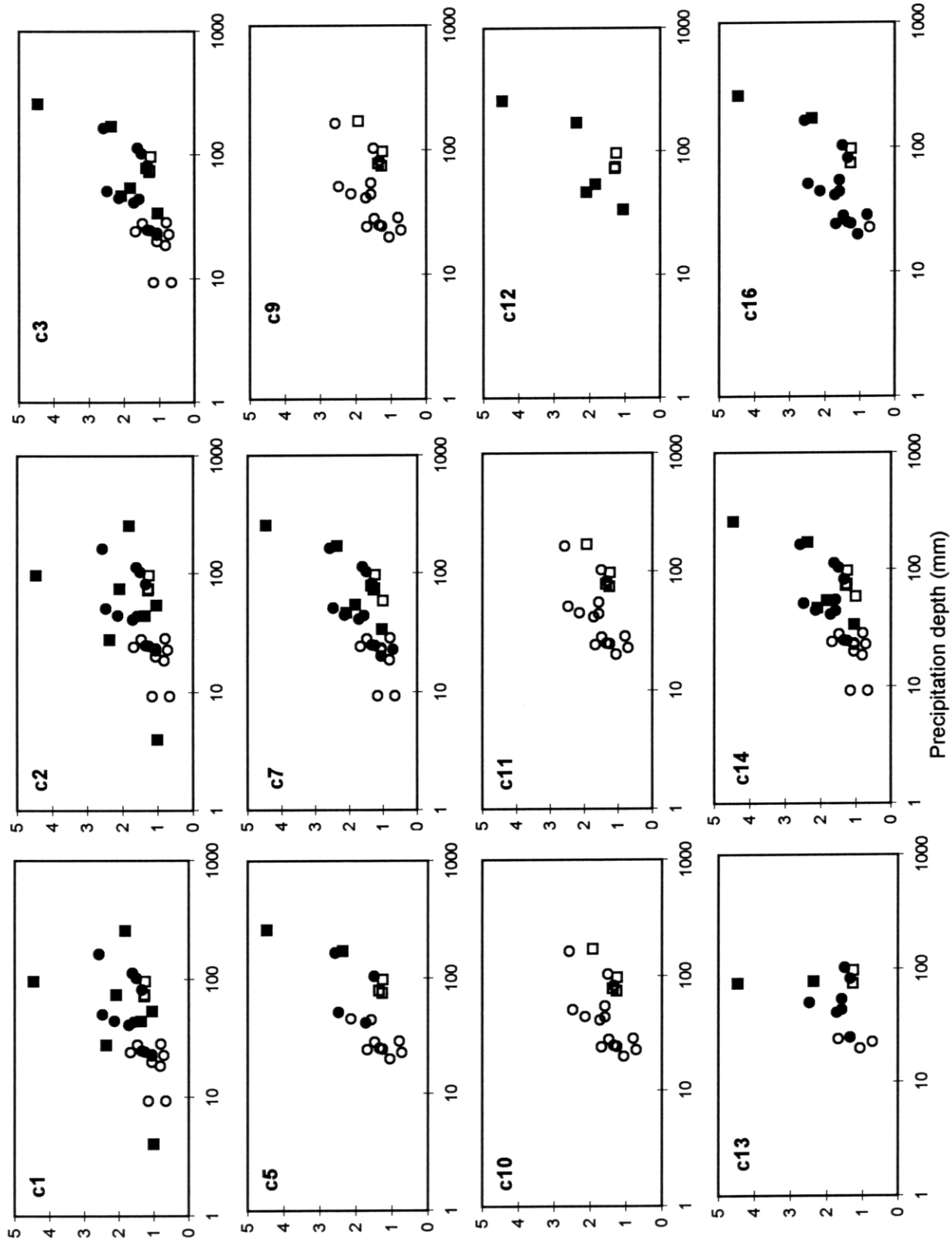


Figure 2.10: Values of the soil moisture index (θ*) for Watershed 3 and the cumulative precipitation (P*) between November 1, 1995 and April 30, 1996. Arrows indicate storms compared in cross-site analysis.

Figure 2.11: Plots of precipitation depth versus average precipitation intensity for storms. Symbols graphed for each site indicate precipitation events that occurred during monitoring of road runoff at each installation. Circles represent rain events, squares represent mixed rain/snow events. Closed symbols represent precipitation events that produced measurable runoff hydrographs at instrumented road sites. Open symbols represent precipitation events that did not produce detectable storm runoff hydrographs (see text).


c1
c2
c3
c5
c7
c9
c10
c11
c12
c13
c14
c16
Average precipitation intensity (mm/hr)
Precipitation depth (mm)

precipitation intensities above 2 mm/hour and total precipitation depths of ≥ 40 mm were required to produce runoff hydrographs at most sites. At C16, all but one rain event and the two snow events produced runoff hydrographs during the monitoring period. At C9, C10 and C11, runoff was not detected at any time between early November 1995 and mid January 1996.

Both the timing and magnitude of runoff response varied by site (Figure 2.12, see also Appendix 2). At most sites, discharge rose within hours of the onset of precipitation and was closely synchronized with the runoff response of Watershed 3. The exception to this pattern was seen at C5 and C7, where runoff was less responsive to precipitation and delayed in time. At some sites, discharge receded rapidly following cessation of rainfall, while recession of the hydrographs at other sites was slow, leading to substantial baseflow between storm events. In addition, baseflow was a considerable component of discharge at some sites (C2, C3, C5, C7, C14, C16), but a minor component of discharge at other sites (C1, C12, C13) (Figure 2.12, Appendix 2).

2.4.3 Road-surface runoff

Calculations of surface runoff using equation 2.1 indicate that road surfaces are a negligible source of total measured runoff at these sites. At C1, where some of the lowest discharge rates during storms were recorded, estimated road-surface runoff calculated from equation 2.1 was less than 10% of the total storm runoff for a small storm (December 14, 1995, precipitation depth = 25 mm) and an intermediate-size storm (November 29, 1995, precipitation depth = 51 mm) (Figure 2.13). Even when the maximum possible contributing area is used, estimates of road-surface runoff were considerably less than the total measured runoff at this site.

Other sites showed a similar pattern of minor contributions attributed to road surface runoff (Figure 2.14). For most storms at each site, the estimated road-surface runoff was less than 10% of total measured runoff. Higher estimates of the road-surface runoff component were calculated for three small storms at four sites, including the

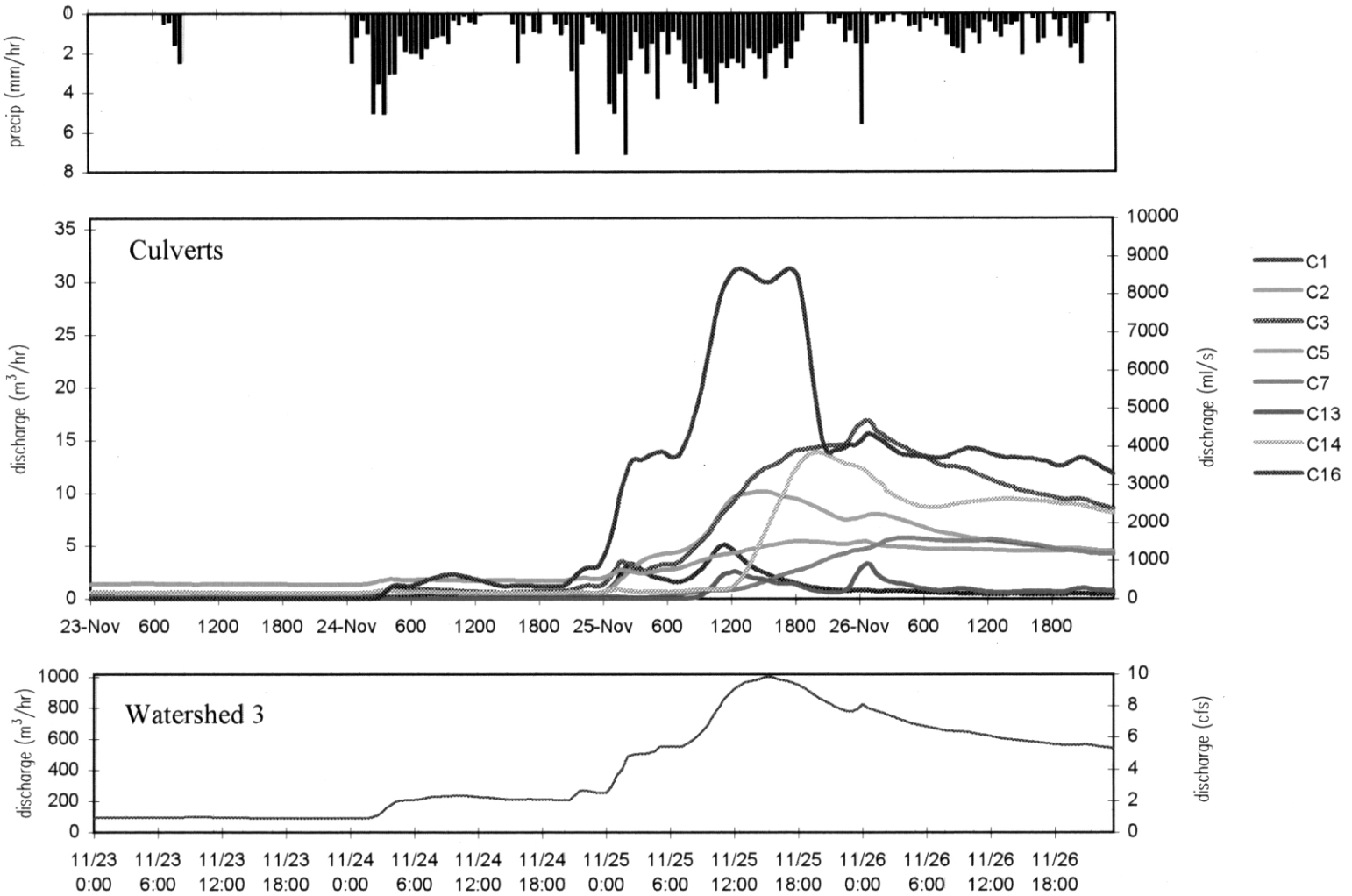


Figure 2.12: Precipitation hyetographs (Primet) and storm hydrographs from instrumented culverts and Watershed 3. (a.) November 24, 1995 storm

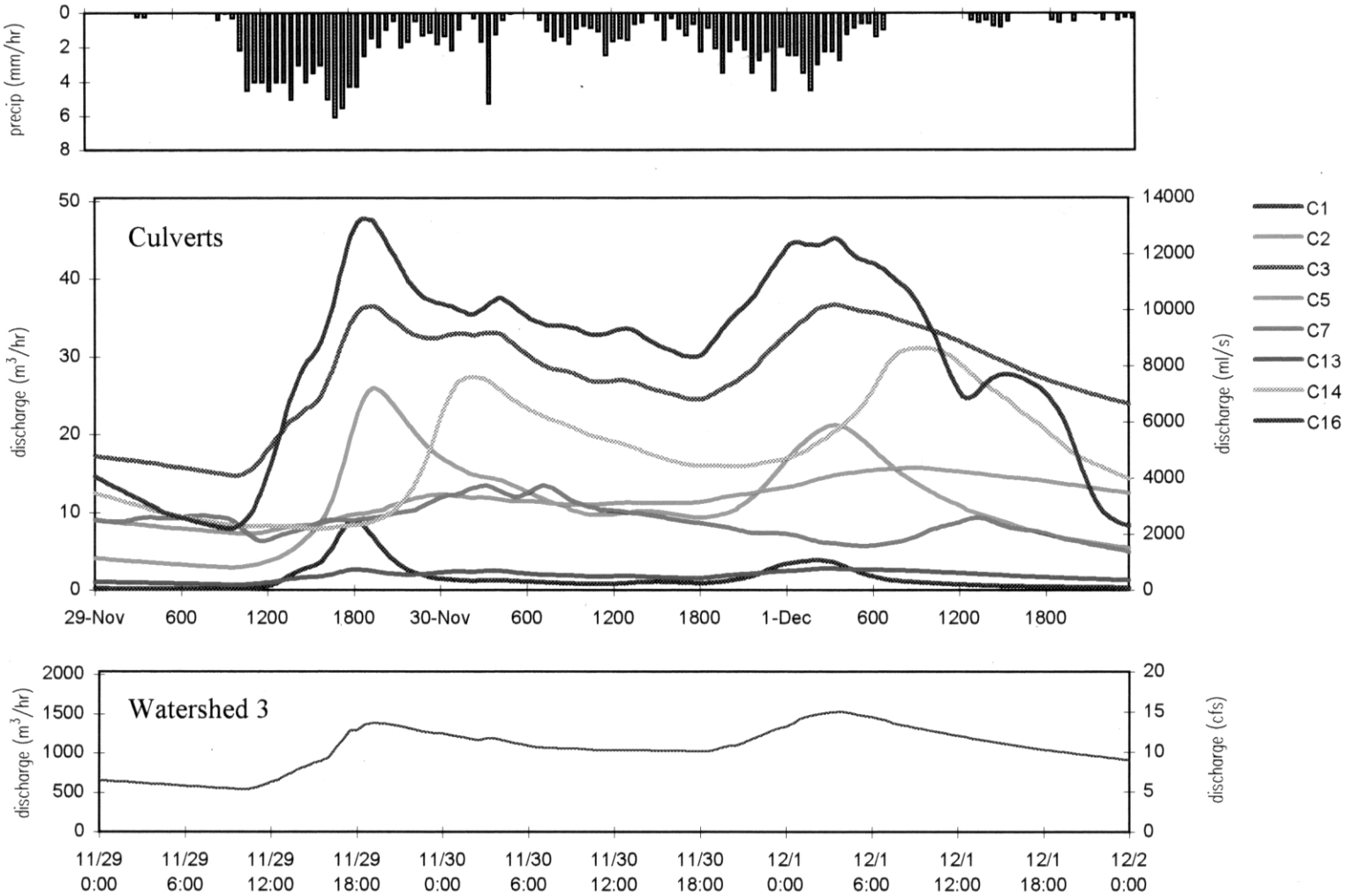


Figure 2.12: (continued)
(b.) November 29, November 30, 1995 storms

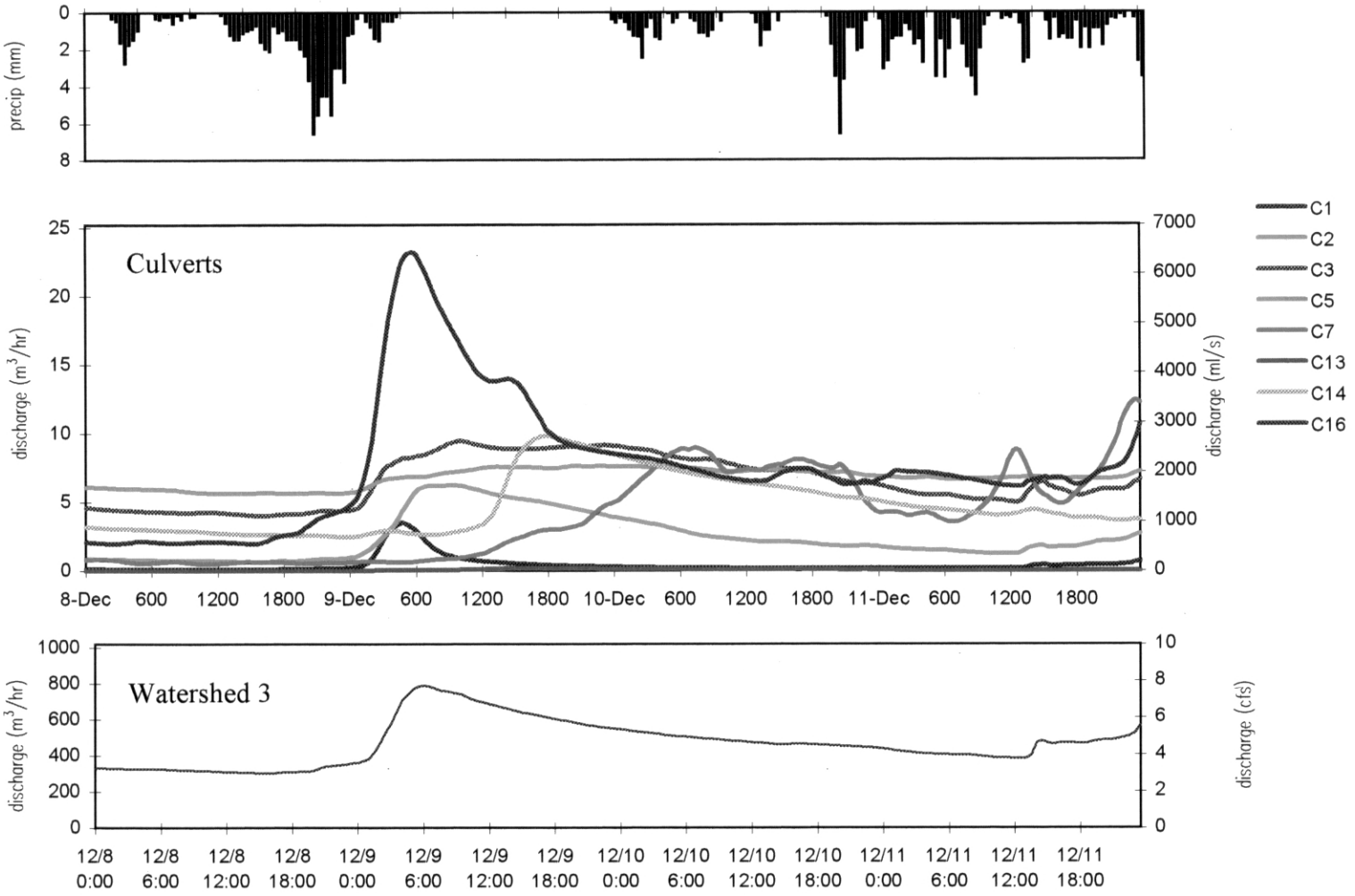


Figure 2.12: (continued)
(c.) December 8, 1995 storm

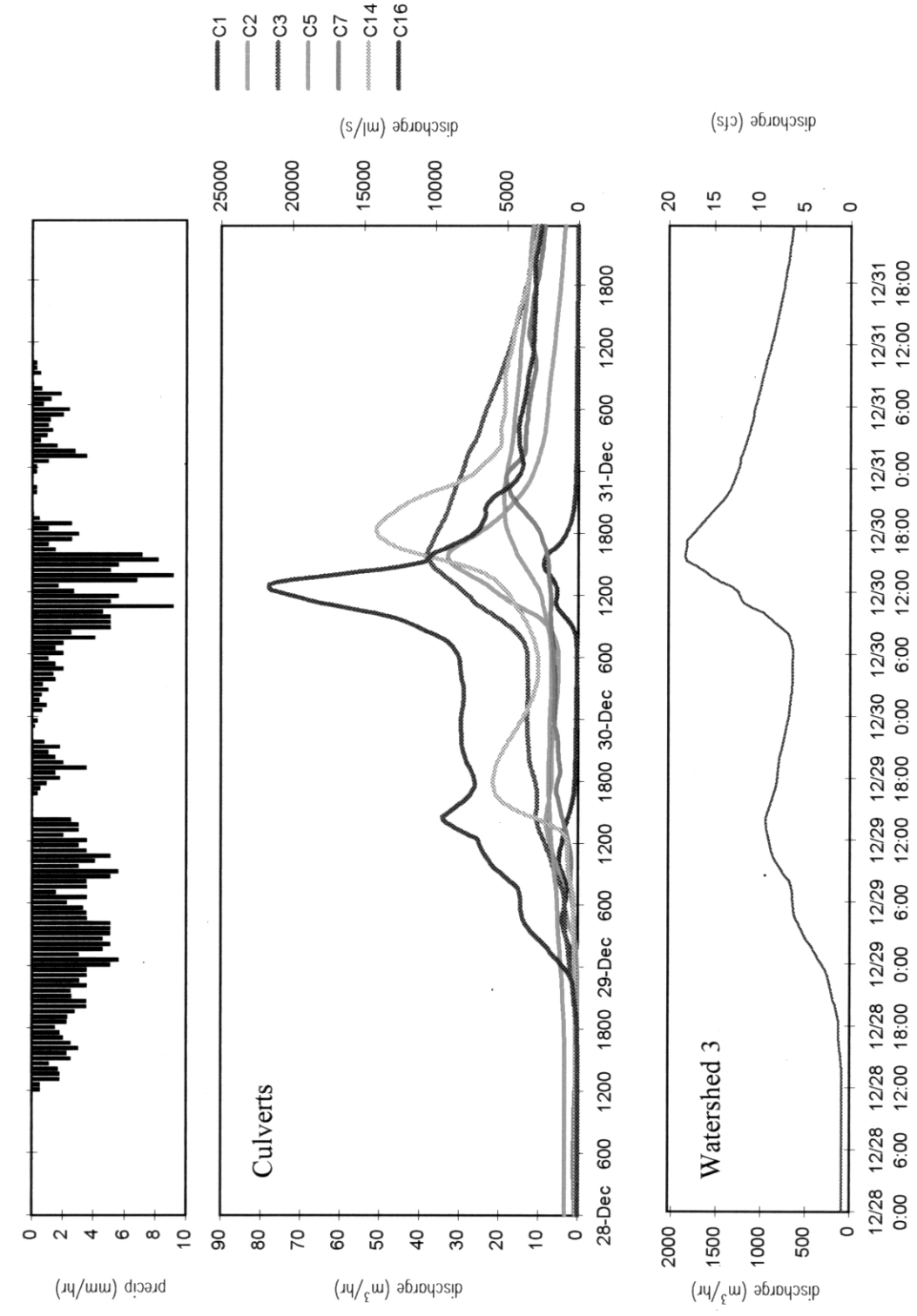


Figure 2.12: (continued)
(d.)December 28, 1995 storm

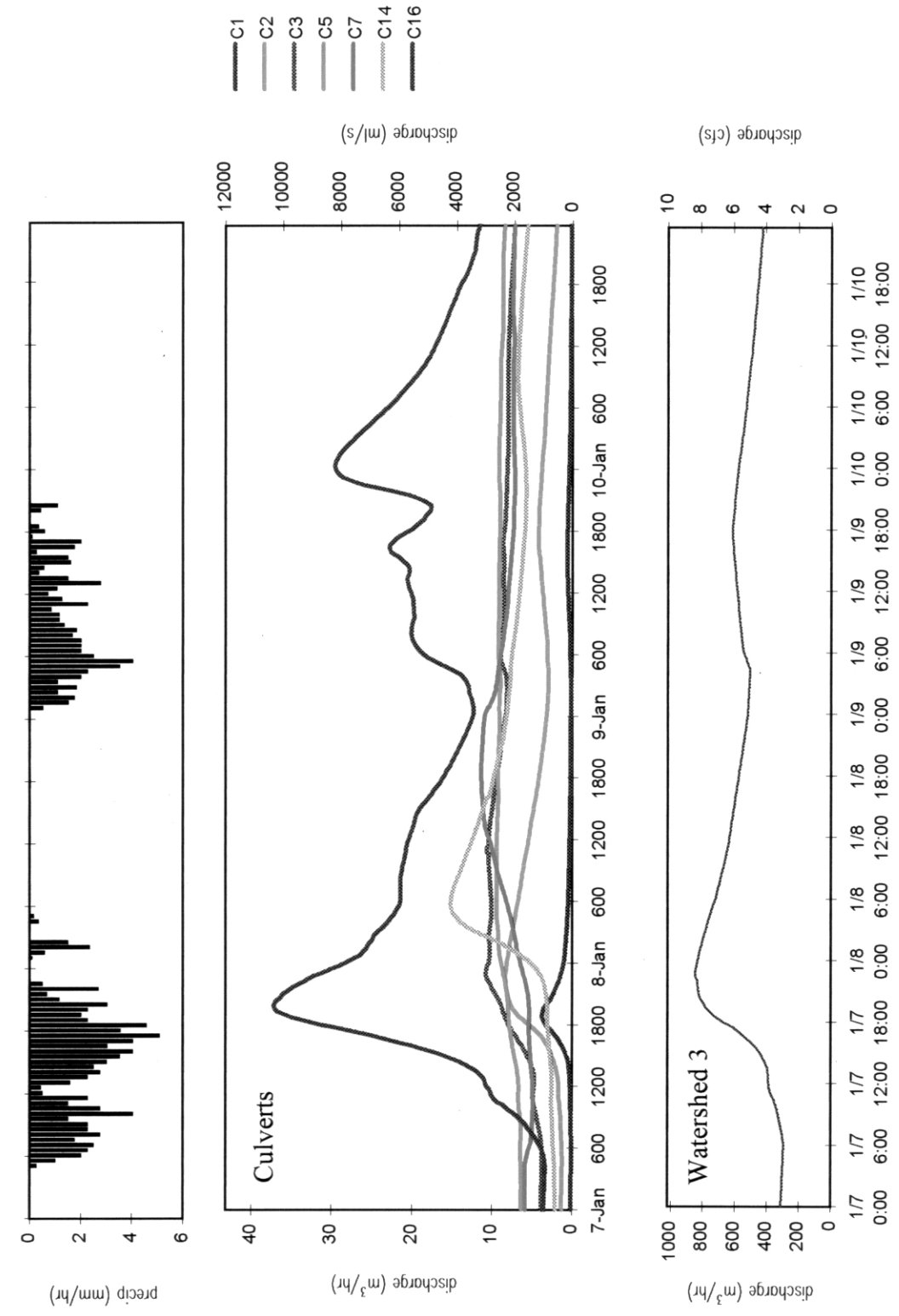
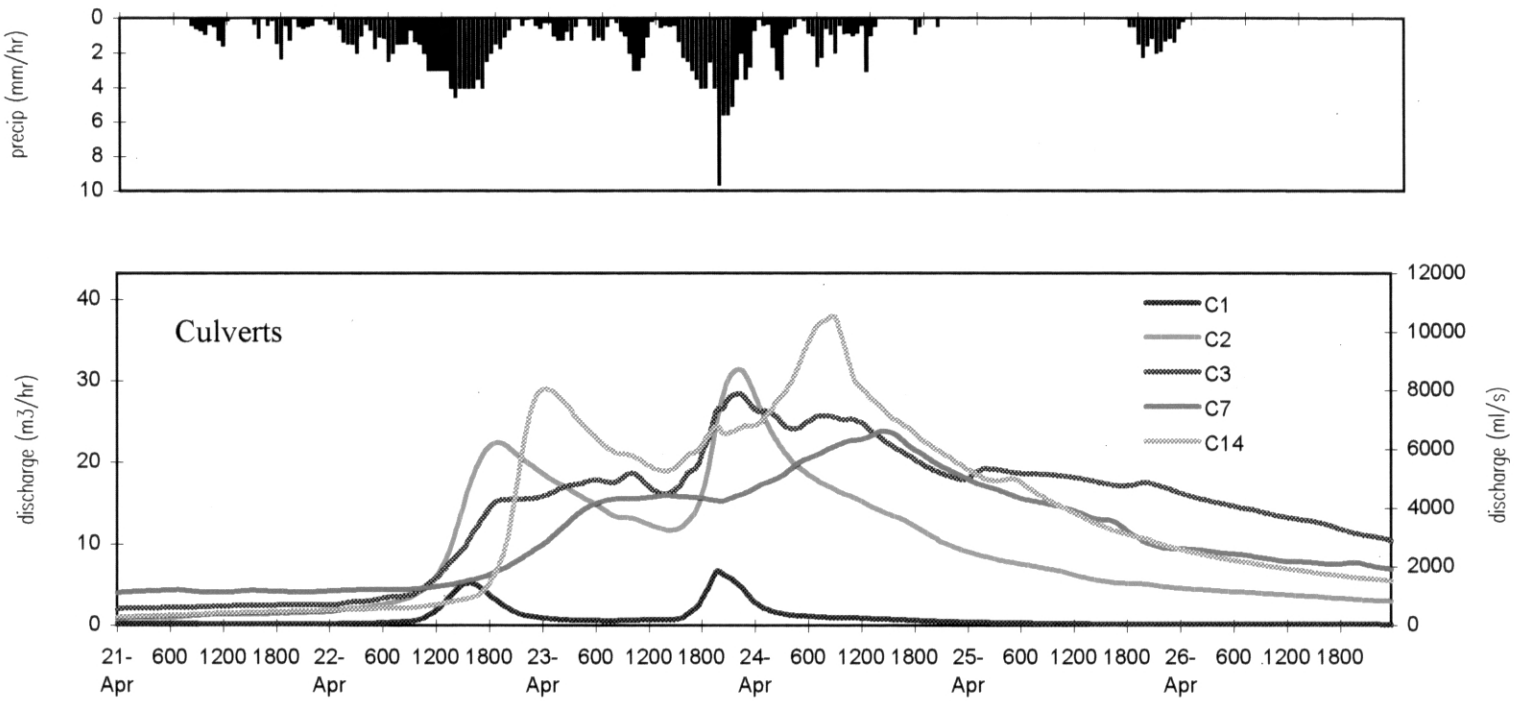


Figure 2.12: (continued)
(e.) January 7, 1996 storm



Watershed 3 hydrograph not available
(gaging station destroyed during February 1996 flood event)

Figure 2.12: (continued)
(f.) April 21, 1996 storm

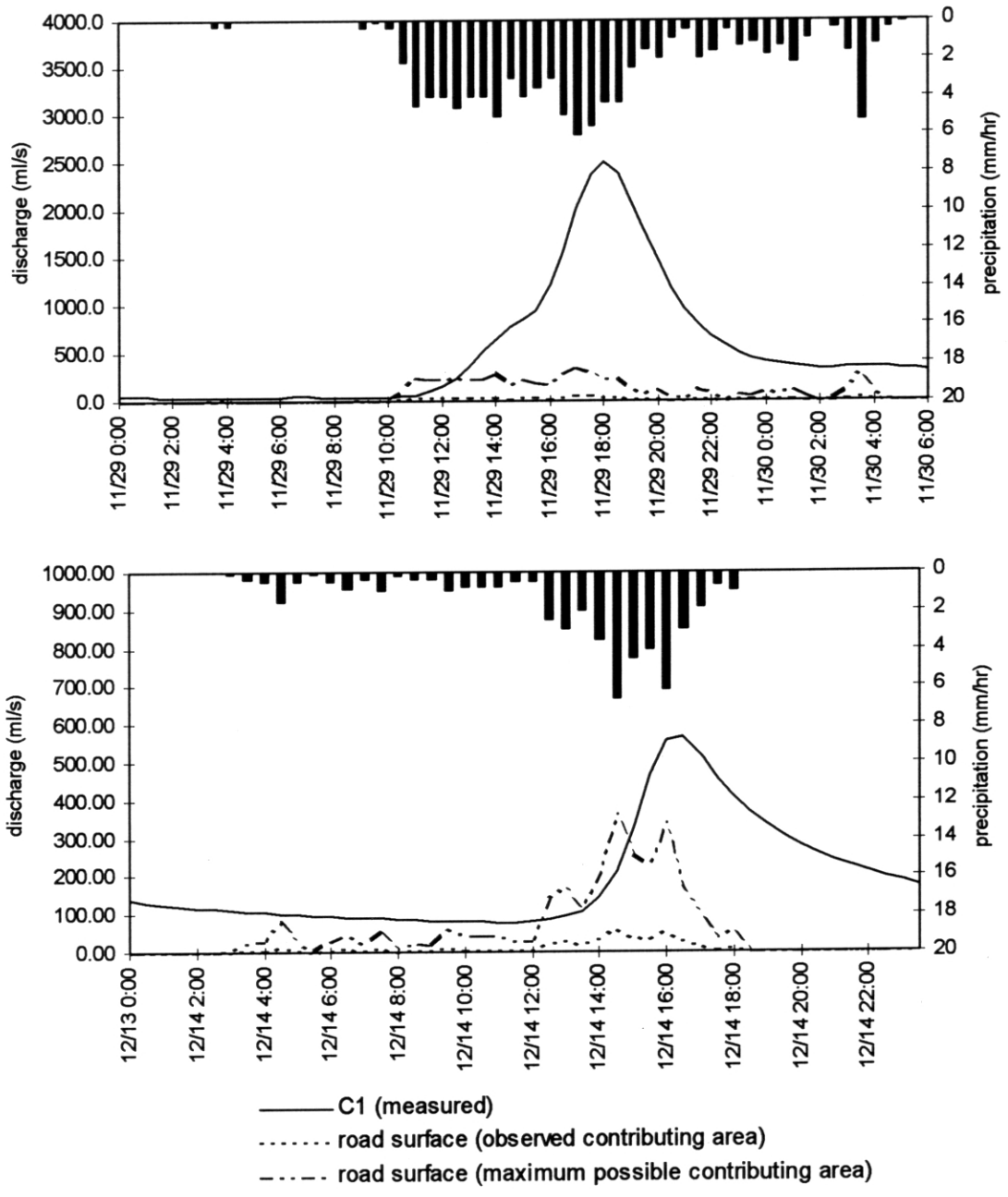


Figure 2.13: Measured hydrographs at C1 and estimated road surface runoff calculated from observed contributing area mapped during storms and maximum possible contributing area (see text and Table 2.2).

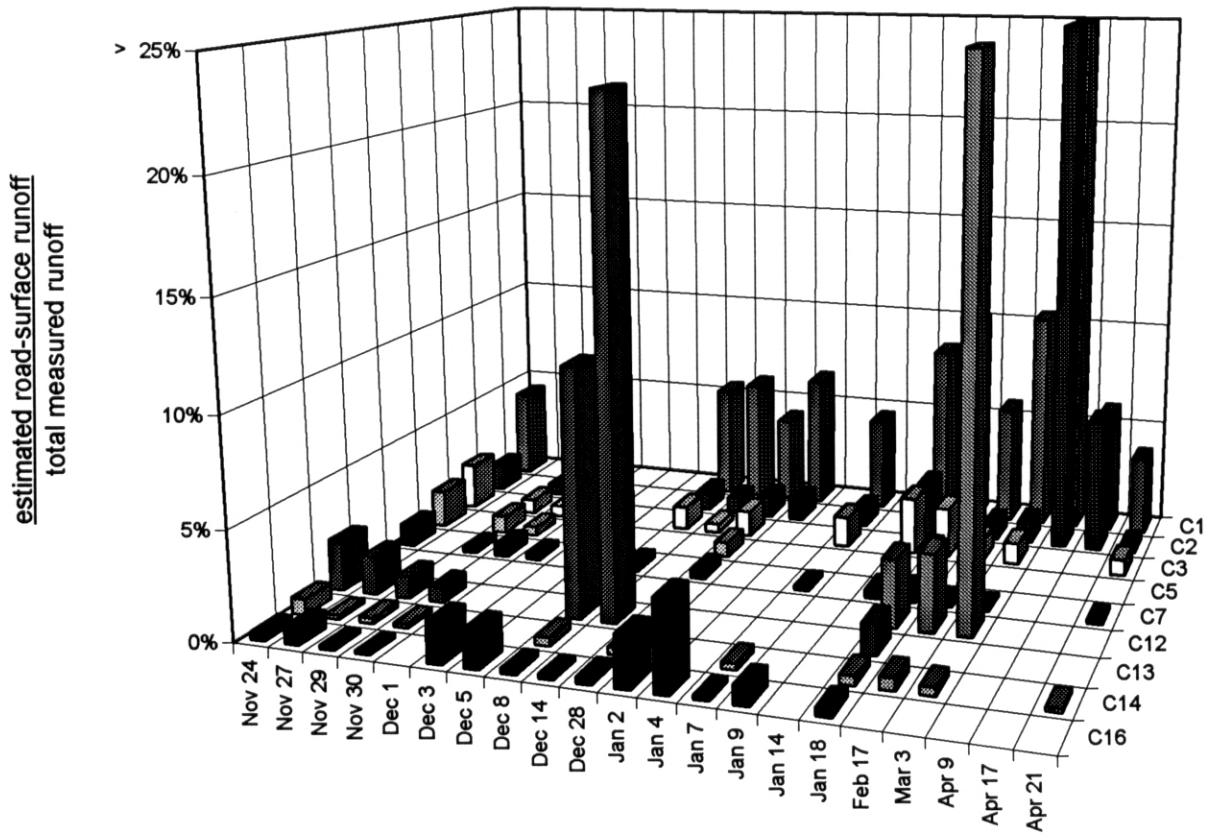


Figure 2.14: Estimated road surface runoff as a fraction of total measured runoff for storms during the monitoring period. Estimates of road-surface runoff are calculated from equation (2.1) using the road surface area observed to route runoff to culverts during storms (Table 2.2).

December 14 storm at C13 (23%), the March 3 storm (precipitation depth = 34 mm) at C12 (31%) and the April 9 storm (precipitation depth = 59 mm) at C1 (97%) and C2 (47%).

2.4.4 Runoff from subsurface flow

The time to peak runoff measured on roads (T_p) was positively related to time to peak precipitation (t_p), and the timing of precipitation and runoff were tightly coupled for rain events throughout the monitoring period (Figure 2.15a). Statistical models for the relationship between t_p and T_p were significant with high explanatory power (e.g. $r^2 > 0.79$ at all sites; all but one $r^2 > 0.86$) (Table 2.3a). The form of the timing relationship, however, varied between sites. For example, during a storm that reached peak precipitation after 24 hours, peak runoff occurred after roughly 28 hours at C1, after 35 hours at C5, and after 41 hours at C13. While theory predicts that the timing of runoff would also be controlled by soil moisture conditions, the addition of the soil moisture index θ^* provided little improvement in statistical models and was statistically significant only at C7 and C14 (Table 2.3a).

Peak precipitation intensity (p_p) and peak runoff magnitude (Q_p) were positively related at most sites (Figure 2.15b), but low explanatory power ($r^2 < 0.35$ for all but one culvert) and lack of statistical significance at most sites (Table 2.3b) indicate that other factors control the magnitude of peak runoff. Some of the variation in storm response over time was explained by soil moisture conditions. For example, the soil moisture index θ^* was relatively high for the events on November 27 (#2), November 29 (#3), November 30 (#4), December 28 (#11) and April 21(#33) (Figure 2.10), which consistently plot on or above regression lines for rain events (Figure 2.15b). Regression models that included the soil moisture index θ^* were significant ($p < 0.1$, $r^2 > 0.42$) at all sites except C5 and C13. Lack of fit of statistical models at C5 and C13 may in part be due to particularly small sample sizes ($n < 6$) (Table 2.3b). It is also possible that a combination of precipitation variables influence the magnitude of peak discharge on

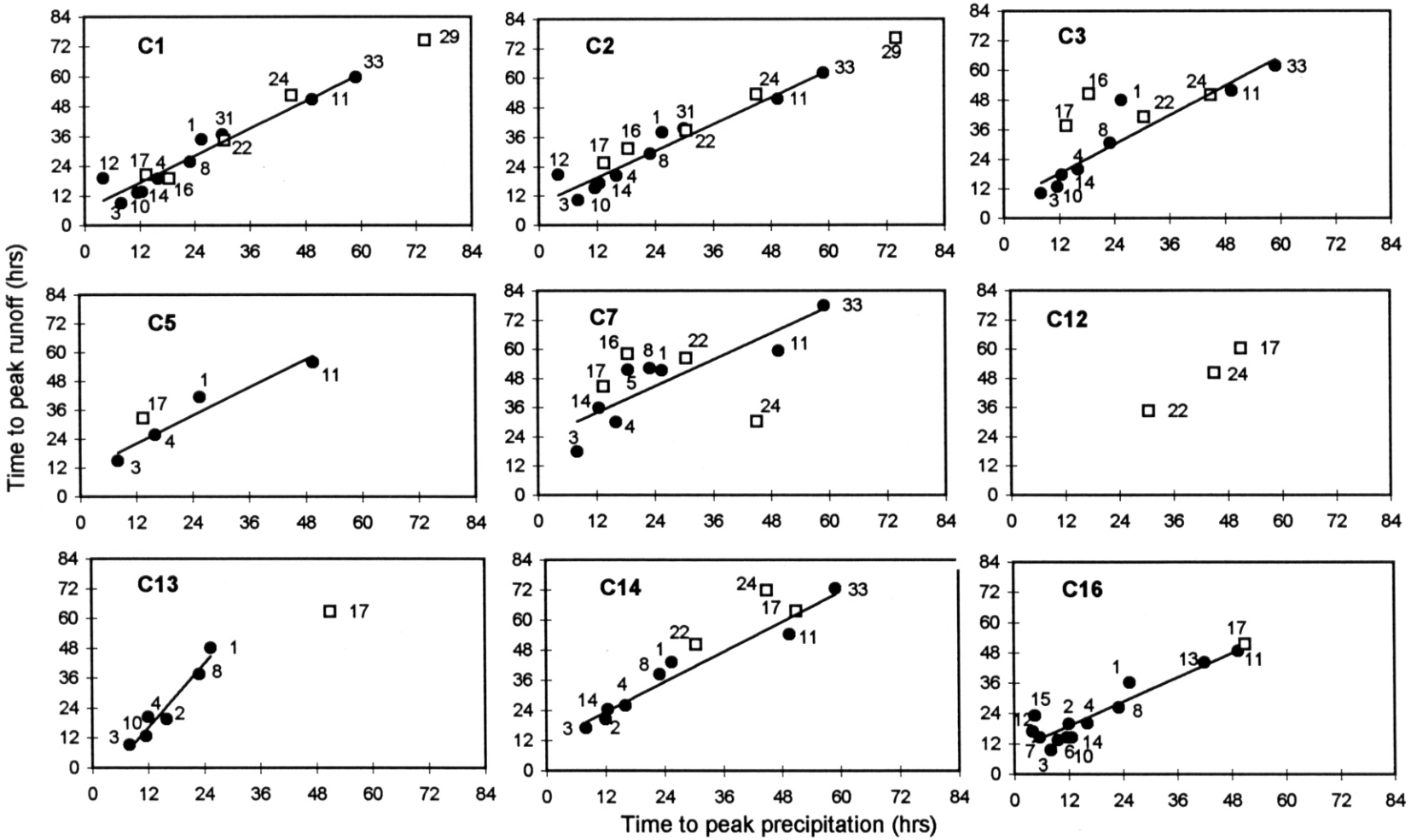


Figure 2.15: Rainfall-runoff relations for sites producing runoff during the monitoring period. Labels indicate storm numbers as listed in Table 2.1. Circles are rain events, squares are mixed rain/snow and snow events. Regression lines are for rain events only.

(a.) Time to peak runoff vs. time to peak precipitation. Regression equations are given in Table 2.3a.

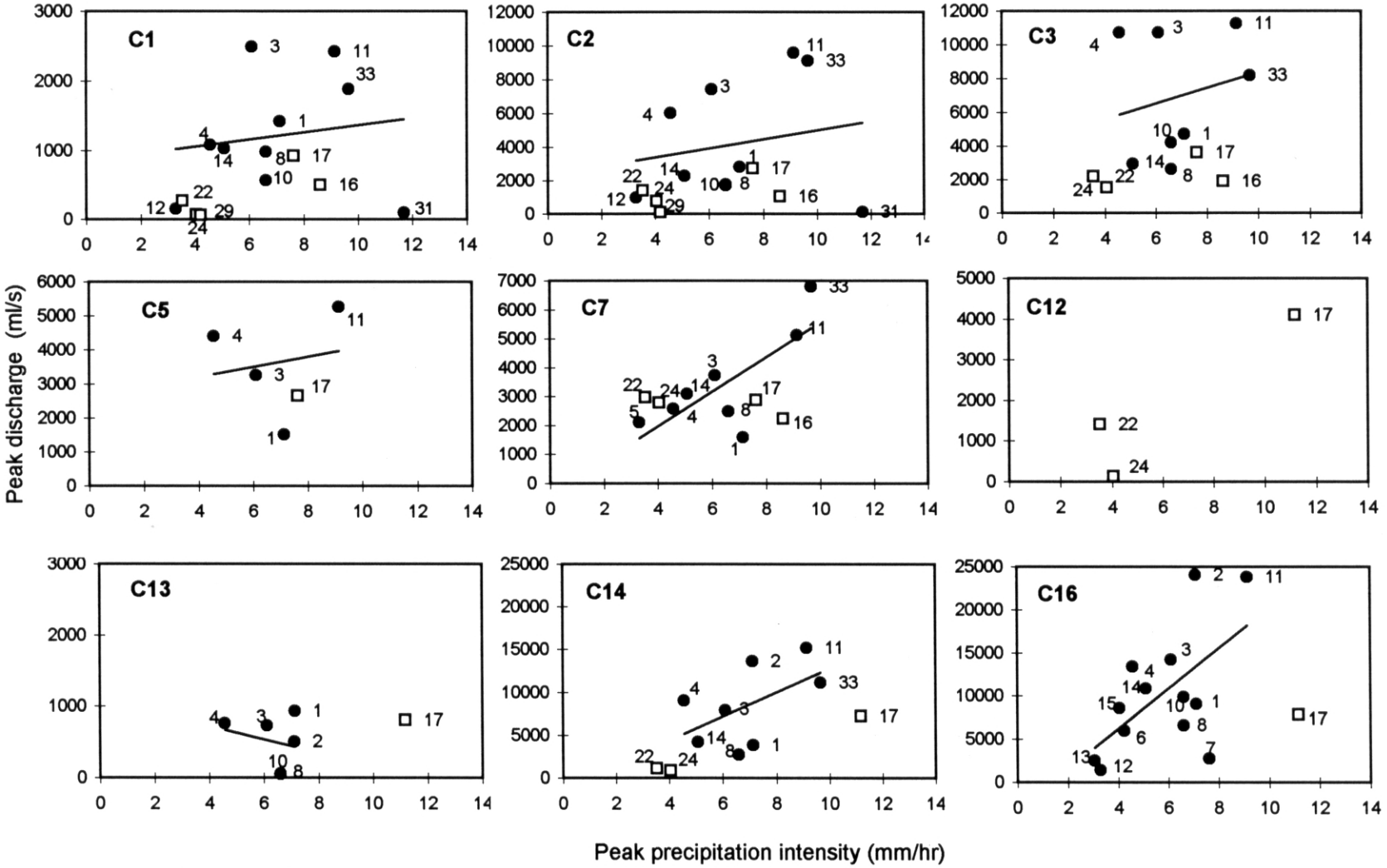


Figure 2.15: (continued)
(b.) Peak discharge vs. peak precipitation intensity. Regression equations are given in Table 2.3b.

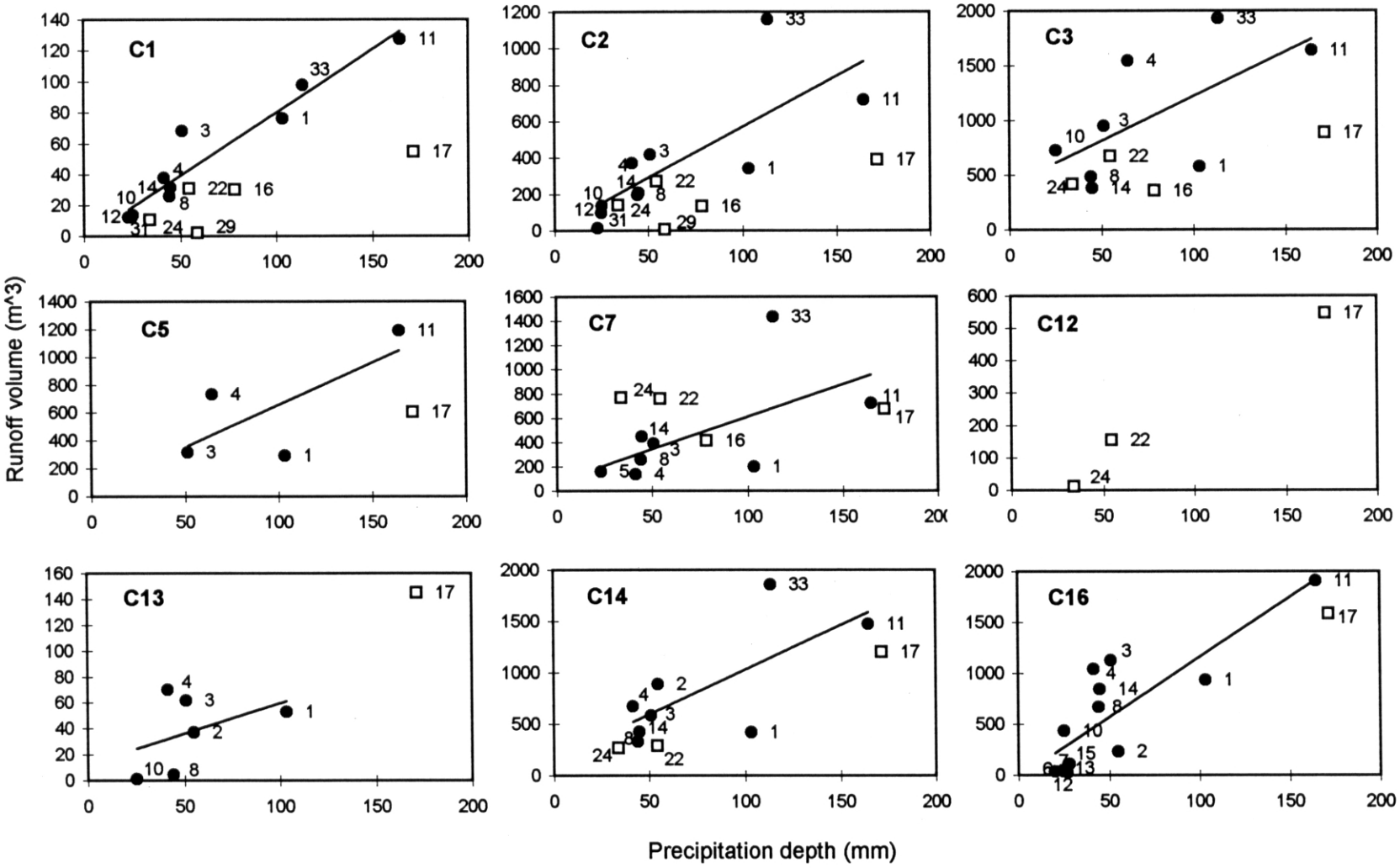


Figure 2.15: (continued)
(c.) Runoff volume vs. precipitation depth. Regression equations are given in Table 2.3c.

Table 2.3: Regression models (rain events only) for the relationship between runoff variables and storm conditions.

a. Time to peak runoff (T_p) vs. time to peak precipitation (t_p) and soil moisture index (θ^*)

Site[1]	n	Model [2]				Model + θ^* [2]				
		β_1	β_2	r^2	lev. sign.[3]	β_1	β_2	β_3	r^2	lev. sign.[3]
C1	10	6.5	0.9	0.93	<0.01	7.7	0.9	-0.04	0.91	<0.01
C2	10	8.8	0.9	0.93	<0.01	18.7	1.0	-0.2	0.94	<0.01
C3	8	6.5	1.0	0.88	<0.01	10.7	1.0	-0.1	0.83	<0.01
C5	4	10.6	1.0	0.94	<0.05	51.3	1.2	-0.5	0.92	n.s.
C7	8	22.9	0.9	0.79	<0.01	40.1	1.1	-0.5†	0.93	<0.01
C13	6	-9.3	2.1	0.94	<0.01	-17.0	2.2	0.07	0.92	<0.05
C14	8	11.4	1.0	0.95	<0.01	21.4	1.1	-0.2†	0.97	<0.01
C16	13	9.5	0.8	0.86	<0.01	10.5	0.8	-0.04	0.83	<0.01

[1] Models are not given for C12, where runoff was only recorded during mixed rain/snow events.

[2] Models are $T_p = \beta_1 + \beta_2 t_p$ and $T_p = \beta_1 + \beta_2 t_p + \beta_3 \theta^*$, where T_p is the time to peak discharge (in hours), t_p is the time to peak precipitation (in hours), and θ^* is the index of the soil moisture conditions on the day of the peak (in mm); β_1, β_2, and β_3 are regression parameters.

[3] Level of significance of the correlation coefficient, r (n.s. is not significant at an alpha level of 0.1 or less). Reported r^2 values are adjusted for degrees of freedom in Model + θ^*.

† Indicates that β_3 parameter is statistically significant at an alpha level of 0.1 or less.

Table 2.3 (continued)

b. Peak discharge (Q_p) versus peak precipitation intensity (p_p) and soil moisture index (θ^*)

Site[1]	n	Model [2]				Model + θ^* [2]				
		β_1	β_2	r^2	lev. sign.[3]	β_1	β_2	β_3	r^2	lev. sign.[3]
C1	10	855.2	51.4	0.02	n.s.	-313.5	-5.9	40.5†	0.54	<0.05
C2	10	2310.3	268.6	0.04	n.s.	-7321.6	7.9	165.0†	0.56	<0.05
C3	8	3801.6	456.2	0.05	n.s.	-9048.8	50.6	211.1†	0.71	<0.05
C5	4	2606.2	149.6	0.03	n.s.	-16928.8	-1762.3	339.2	0.55	n.s.
C7	8	-433.0	601.5	0.57	<0.05	-996.8	374.0	44.2	0.54	<0.1
C13	6	1093.8	-92.2	0.05	n.s.	-359.7	-32.3	12.7	0.38	n.s.
C14	8	-1257.8	1405.7	0.29	n.s.	-5792.3	72.6	273.6†	0.65	<0.05
C16	13	-3072.8	2327.5	0.35	<0.05	-377.2	688.6	191.2†	0.42	<0.05

[1] Models are not given for C12, where runoff was only recorded during mixed rain/snow events.

[2] Models are $Q_p = \beta_1 + \beta_2 p_p$ and $Q_p = \beta_1 + \beta_2 p_p + \beta_3 \theta^*$, where Q_p is peak discharge rate (in ml/s), p_p is peak precipitation intensity (in mm/hr), and θ^* is the index of the soil moisture conditions on the day of the peak (in mm); β_1, β_2, and β_3 are regression parameters.

[3] Level of significance of the correlation coefficient, r (n.s. is not significant at an alpha level of 0.1 or less). Reported r^2 values are adjusted for degrees of freedom in Model + θ^*.

† Indicates that β_3 parameter is statistically significant at an alpha level of 0.1 or less.

Table 2.3 (continued)

c. Runoff volume (Q) versus precipitation depth (P) and soil moisture index (θ^*)

Site[1]	n	Model [2]				Model + θ^* [2]				
		β_1	β_2	r^2	lev. sign.[3]	β_1	β_2	β_3	r^2	lev. sign.[3]
C1	10	-1.3	0.8	0.93	< 0.01	-11.5	0.8	0.5†	0.95	<0.01
C2	10	12.4	5.6	0.60	<0.01	-172.7	4.6	7.3†	0.67	<0.01
C3	8	409.3	8.1	0.41	<0.1	-671.4	10.5	14.2†	0.72	<0.05
C5	4	54.4	6.1	0.53	n.s.	-2350.5	17.7	19.1†	0.99	<0.1
C7	8	76.0	5.4	0.36	n.s.	-325.7	5.3	9.7	0.28	n.s.
C13	6	13.0	0.5	0.18	n.s.	-47.4	0.7	0.7	0.44	n.s.
C14	8	164.6	8.7	0.50	<0.05	-577.3	8.8	14.8†	0.75	<0.05
C16	13	-16.7	11.8	0.69	<0.01	-173.9	10.7	7.2	0.69	<0.01

[1] Models are not given for C12, where runoff was only recorded during mixed rain/snow events.

[2] Models are $Q = \beta_1 + \beta_2 P$ and $Q = \beta_1 + \beta_2 P + \beta_3 \theta^*$, where Q is runoff volume (in m^3), P is storm precipitation depth (in mm), and θ^* is the index of the soil moisture conditions on the day before precipitation began (in mm); β_1, β_2, and β_3 are regression parameters.

[3] Level of significance of the correlation coefficient, r (n.s. is not significant at an alpha level of 0.1 or less). Reported r^2 values are adjusted for degrees of freedom in Model + θ^*.

† Indicates that β_3 parameter is statistically significant at an alpha level of 0.1 or less.

these roads, although simple models using average precipitation intensity and total storm precipitation did not produce improved results, and small sample sizes prohibited robust statistical tests of complex models (Ramsey and Schafer, 1997).

Runoff volume was also positively related to total storm precipitation on the roads studied (Figure 2.15c), although some relationships were weak or statistically insignificant (Table 2.3c). Regression models for rain events were statistically significant at C1, C2, C3, C14, and C16 (Table 2.3c). The storm events of November 29 (#3), November 30 (#4), December 28 (#11), and April 21 (#33) plotted on or above regression lines for most sites, indicating that events with higher antecedent soil moisture produced higher than average runoff response. Regression models that included the soil moisture index θ^* were significant at all sites except C7 and C13, and provided improved explanatory power at C1, C2, C3, C5, and C14, with r^2 values ranging from 0.68 to 0.99 (Table 2.3c).

Variation in runoff response between sites was explained in part by drainage area, although the absolute volume of runoff generated on roads also apparently depended upon site class (e.g. D_{rc}/D_s, Figure 2.9), at least for early season storms (Figure 2.16). Runoff volumes for seven rain events that spanned the period from late November 1995 to late April 1996 followed a general trend of increasing magnitude with increasing drainage area. Data for early season storms (November 24, 29 and 30) indicate that sites with shallow soils on steep slopes produced greater runoff volumes per unit area than sites on deep soils. Although only one instrumented culvert (C13) was located on deep soil and a gentle slope, this site yielded the lowest measured volume of runoff per unit area. These distinctions among site classes appeared to diminish over time and were indistinguishable by late December.

The magnitude of runoff per unit area varied over time according to the size of the storm, but precipitation depth alone only partly explained the amount of runoff generated at these sites (Figure 2.17). In general, larger storms produced higher unit-area runoff. The storms of November 29, December 8, and January 7 had precipitation depths ranging from 44 to 51 mm and produced unit-area runoff depths of less than 50 mm at all sites. Larger precipitation events, however, did not always produce higher

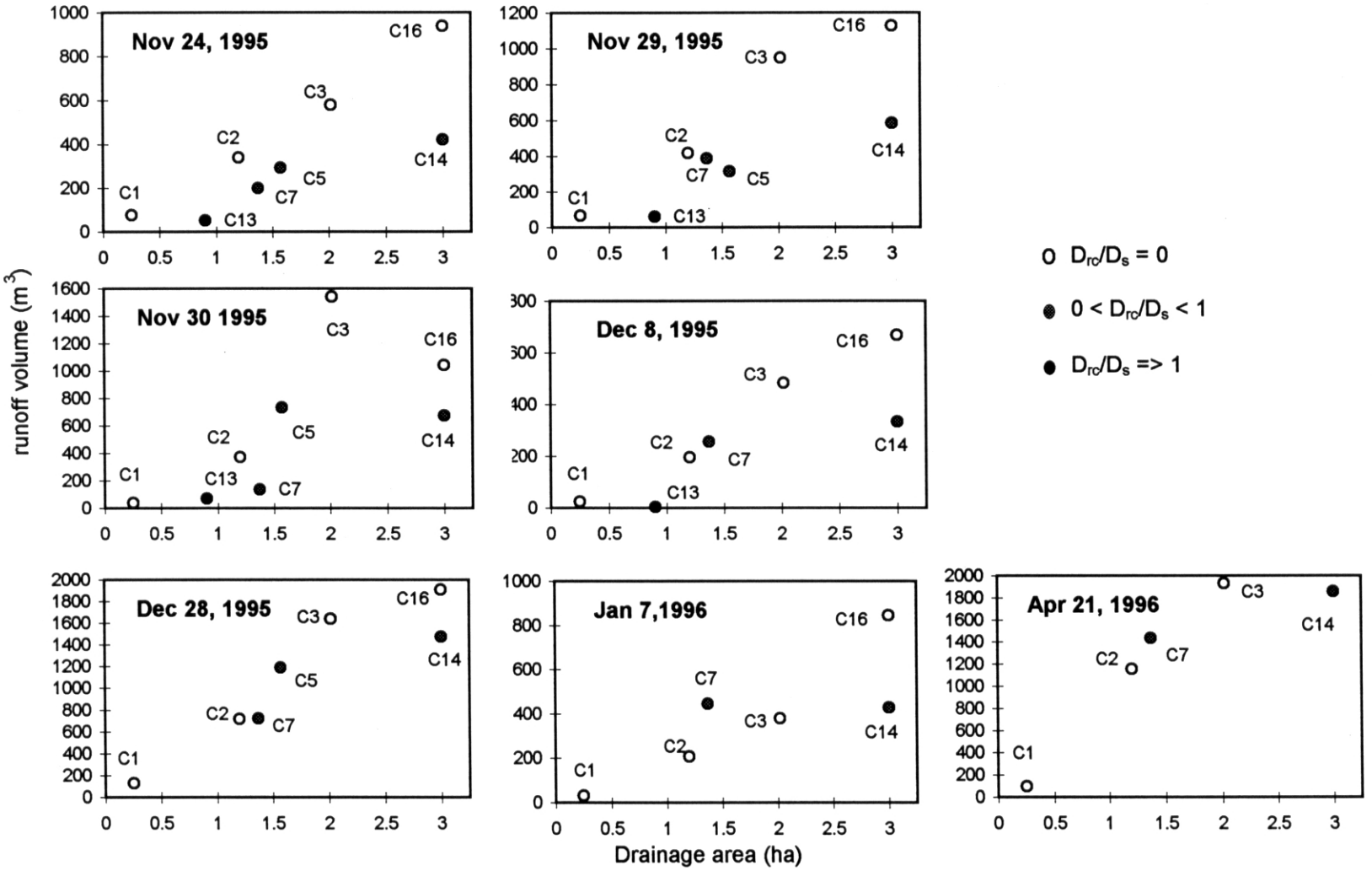


Figure 2.16: Plots of the drainage area (A) vs. runoff volume (Q) for seven rain events during the monitoring period. Symbols represent classes of the D_{rc}/D_s ratio.

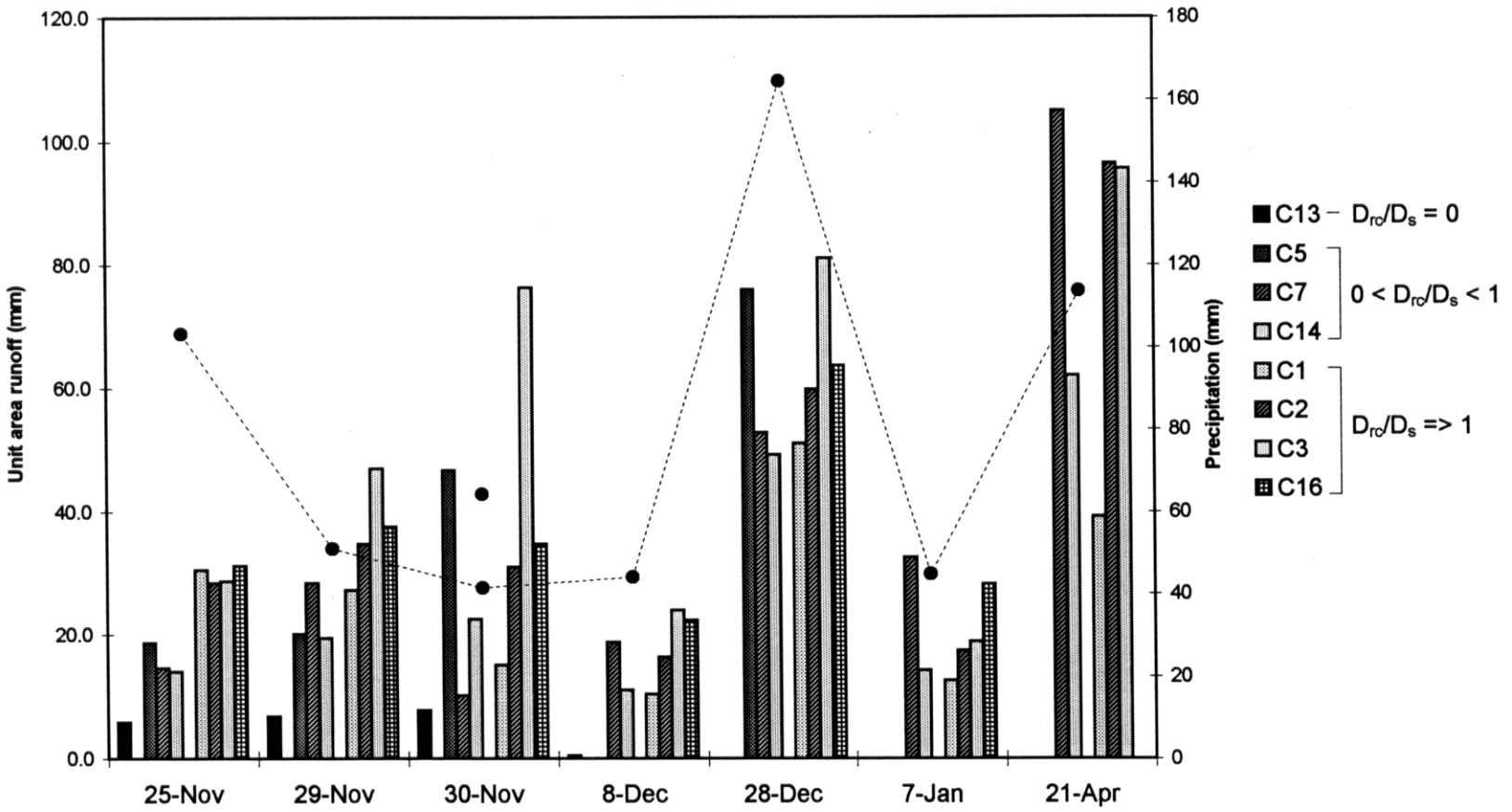


Figure 2.17: Unit area runoff (bars) and storm precipitation depth (circles) for seven rain events during the monitoring period. Bars are grouped by classes representing differences in the D_{ro}/D_s ratio. Note storm precipitation for November 30, 1995 event included 41.4 mm at all sites except C3 and C5, where precipitation is taken as 64.4 mm (see also Table 2.1).

unit-area runoff. The storms of November 24, December 28, and April 21 had precipitation depths of over 100 mm, but unit-area runoff was less than 35 mm at all sites for the November 24 storm and ranged from 40 to over 100 mm at all sites for the December 28 and April 21 storm.

Both short-term (storm-scale) and long-term (seasonal) soil moisture conditions contributed to observed runoff on roads (Figure 2.18). Short-term soil moisture conditions appeared to control runoff magnitude during fall events (Figure 2.18a). The runoff ratio, which controls for both drainage area and precipitation depth, was highest for the storms of November 29 and November 30, when the value of the short-term soil moisture index θ^* was highest. However, later season storms also produced relatively high runoff, despite lower values of the storm-scale moisture index θ^*. For example, at C7 the runoff ratio increased from 0.3 on December 28, to 0.7 on January 7, to 0.9 on April 21, but θ^* decreased from 33 mm on December 28 to 24 mm on April 21. Similarly, runoff ratios during these three storms increased at C14 from 0.3 to 0.6, at C2 from 0.4 to 0.8, and at C3 from 0.5 to 0.8. Cumulative precipitation correlates with the gradual trend in increasing runoff ratios for mid- to late-season storms (Figure 2.18b). Between December 28 and April 21, cumulative precipitation increased from 1133 mm to over 2500 mm. The interaction of short-term and long-term soil moisture indices fits the overall trend in runoff ratios throughout the monitoring period (Figure 2.19).

2.5 Limits of data and analysis

The data collected for this study span the runoff season in one water year, however climatic conditions and instrument failure constrained the period over which monitoring occurred. An extended period of snow between mid-January and late March, 1996 limited the number of runoff events that were available for analysis. In addition, the flood event of February 1996 resulted in the destruction of several monitoring stations and the Watershed 3 gaging station. Finally, failure of instruments to record data during several periods resulted a discontinuous record at some sites.

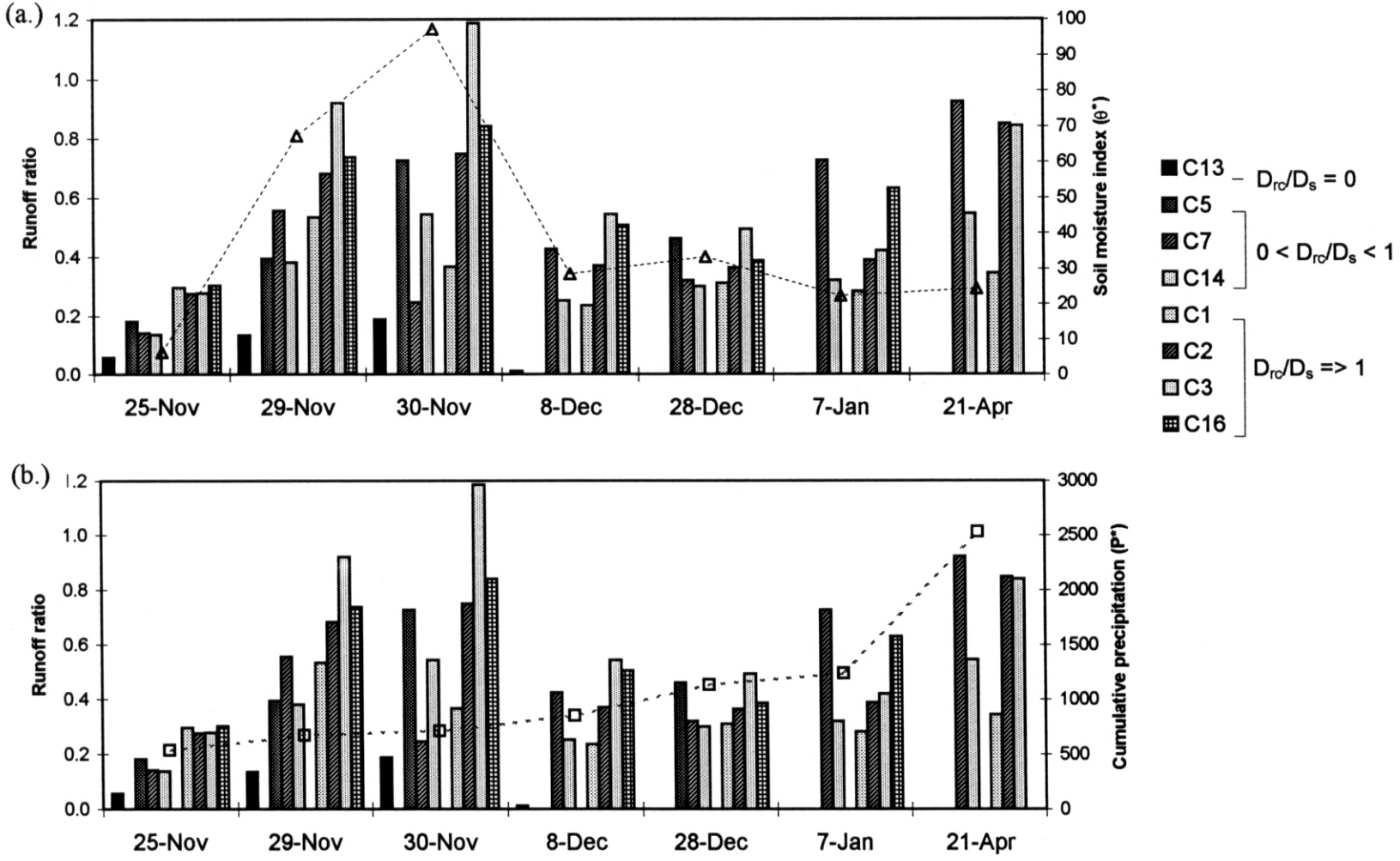


Figure 2.18: Runoff ratios (bars) and indices of soil moisture (open symbols) for seven rain events during the monitoring period: (a.) soil moisture index (θ*) for Watershed 3, and (b.) the value of cumulative precipitation (P*) for

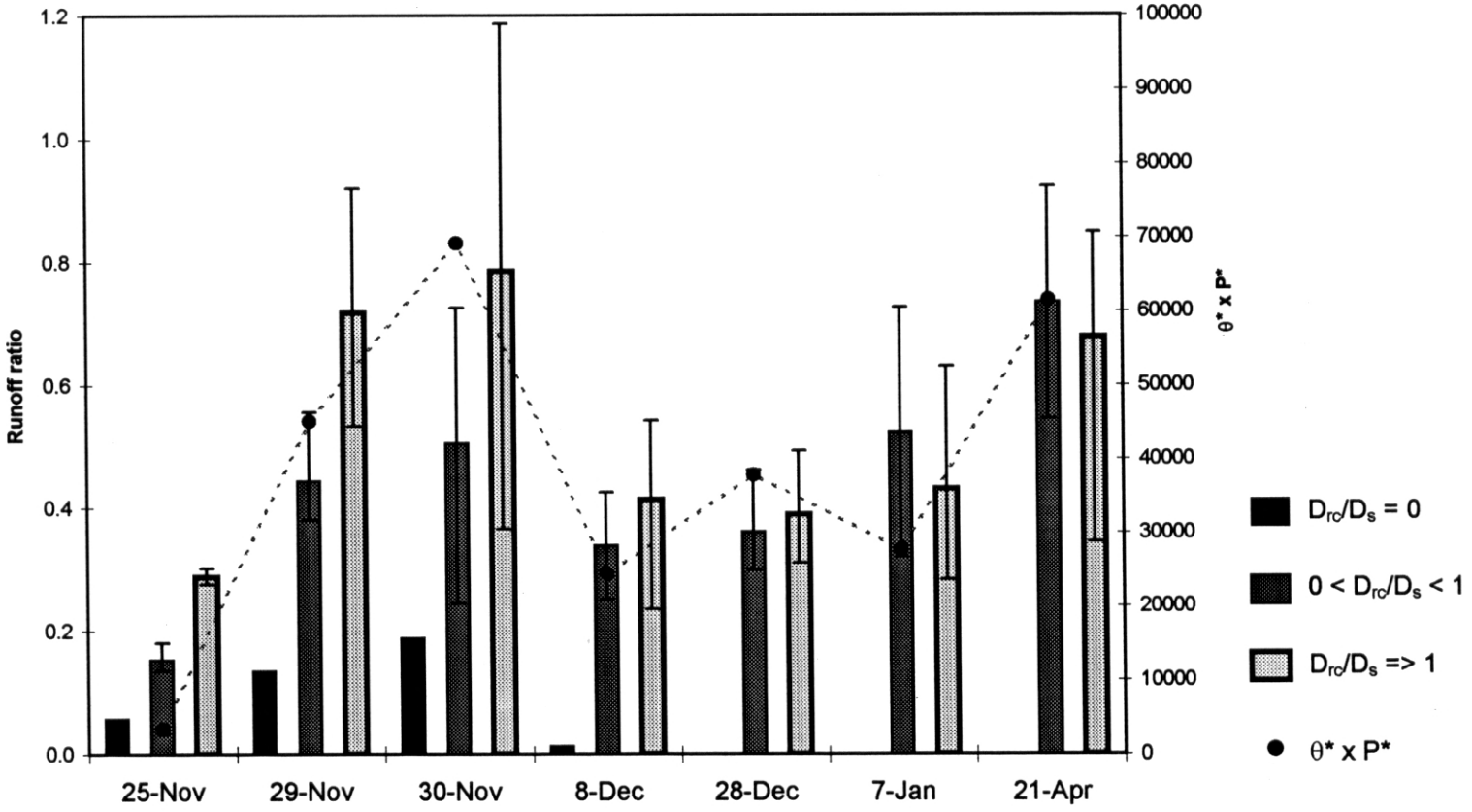


Figure 2.19: Average runoff ratios (bars) for seven rain events during the monitoring period. Error bars indicate the high and low values in the runoff ratio among sites in each category. The pattern over time is closely correlated with an index that represents the interaction of event-scale soil moisture conditions (θ*) and seasonal soil moisture conditions (P*).

At least three factors contribute to possible sources of error and uncertainty in this study. First, recorded values of stage at each monitoring site were subject to measurement error when electronic instruments failed to record true stage heights. To minimize this factor, recorded stage values were validated against field observations during weekly site checks, and manual crest stage recorders at each culvert provided a cross-validation of peak stages during storms. Second, conversion of stage records to a continuous discharge series was subject to error if the rating curve does not accurately reflect the stage-discharge relationship. In this study, discharge values for certain high flow events have a greater degree of uncertainty, since the rating curve for the highest discharge values is based on very few observations. This problem is not unusual in hydrology, where high flow events occur rarely and therefore provide limited opportunity for calibration of measurement stations. Finally, the extraction of discrete storm events from the continuous discharge record may have introduced error based on the subjective criteria used to define the beginning and end of a runoff event. Alternative rules for selection of storm hydrographs from the continuous record might result in different values for cumulative storm runoff at a given site.

2.6 Discussion

The findings presented in this study provide a foundation for a process-based understanding of runoff production on roads constructed on steep forested hillslopes. Climatic conditions, particularly storm size and soil moisture conditions, and the hillslope setting, namely size of the contributing hillslope, hillslope gradient, soil depth, and roadcut depth, influenced the magnitude and timing of runoff generated on roads. These observations are consistent with a theoretical model of runoff production on steep hillslopes. The findings presented here are expected to be generally applicable in humid, steep, upland environments where undisturbed soils are highly permeable and precipitation rates are sufficient to generate a transient saturated zone on hillslopes.

Runoff production on roads in Watershed 3 is strongly dependent on soil moisture conditions. The importance of soil moisture suggests key hydrologic controls on runoff

production and subsurface flow interception along roads. First, wetter conditions provide for the rapid transmission of precipitation through the unsaturated zone (e.g. Torres et al., 1998) and an associated rapid runoff response. Second, the soil moisture index probably correlates to the height of the hillslope water table (e.g. Beven, 1982a) and reflects the importance of saturated zone contributions to both baseflow and quickflow during storms.

Theoretical models (Toth, 1963; Salvucci and Entekhabi, 1995) and field studies (Anderson and Burt, 1978; Beven, 1978; Pierson, 1980; Anderson and Kneale, 1982) demonstrate that slope convergence influences water table elevations and may enhance the potential for subsurface flow interception when roads traverse convergent, unchanneled hillslopes. Among the sites studied here, a site located on a planar hillslope (C1) generated a lower unit-area runoff during most storms than sites located on convergent slopes (C2 and C3), despite the fact that soils are similar on these slopes (Table 2.2). A site with a shallow roadcut located on a gently-sloping planar hillslope (C13) had the lowest measured unit area runoff (Figure 2.17).

This study focused on examining runoff production on roads at the hillslope scale. Whether runoff generated on roads results in modification of downstream hydrographs depends on at least three factors: the volume and timing of road runoff, the extent to which roads concentrate runoff by collecting and routing water through a system of ditches and culverts, and the connectivity of roads to the channel network. This study demonstrated that the first of those factors is highly variable in space and time. Subsurface flow interception occurred along much of the road length in Watershed 3 where road cuts are excavated into the soil profile. In general, rainfall events exceeding 40 mm precipitation with intensities exceeding 2 mm/hr were required to initiate subsurface flow interception along roads, although this threshold was lower at some sites, and subsurface flow interception never occurred at three of the monitored sites. On the road segments studied, runoff was routed into ditches and discharged at discrete points below culverts. At some of these locations, concentrated surface runoff reaches downstream channels by overland flow (Figure 2.20), although this phenomenon is clearly a function of antecedent soil moisture conditions and size of the runoff event. Roads in Watershed 3 are not highly connected to the stream network via stream crossings, as only

one perennial stream intersects the functional road system. Temporal and spatial variation in the generation and routing of road runoff in this basin very likely determines the extent to which roads modify downstream hydrographs. This observation might explain why statistical analysis of watershed hydrographs (e.g. Jones and Grant, 1996; Thomas and Megahan, 1998) do not clearly demonstrate the range of conditions under which roads in this basin have modified basin hydrographs.

Regardless of the effect of roads on downstream hydrographs, the conversion of subsurface flow to surface runoff by roads may influence slope stability. Modification of hillslope drainage, concentration of water, and diversion of surface runoff onto unstable hillslopes or into channels may increase the potential for mass slope failure and other forms of erosion. During the February 1996 flood event, a cutslope failure occurred at the C5 monitoring station and fillslope slides occurred at the C12 and C16 stations (Figure 2.20). The role of roads in initiating these failures cannot be conclusively known, although previous studies have documented increased rates of slope failure associated with roads relative to forested conditions (Dyrness, 1967; Swanson and Dyrness, 1975; Megahan, 1987). The following chapter documents the extent of road-related landslides and other forms of sedimentation associated with roads that occurred during the February 1996 flood.

Future research is needed to validate these findings in other regions and to investigate the implications of road runoff on basin hydrology and slope stability. Additional field studies in other geologic terrains are needed to test the concepts developed in this study. Modeling studies may be most useful in determining the on-site effects of roads on slope stability and the downstream effects of roads on altering peak streamflows.

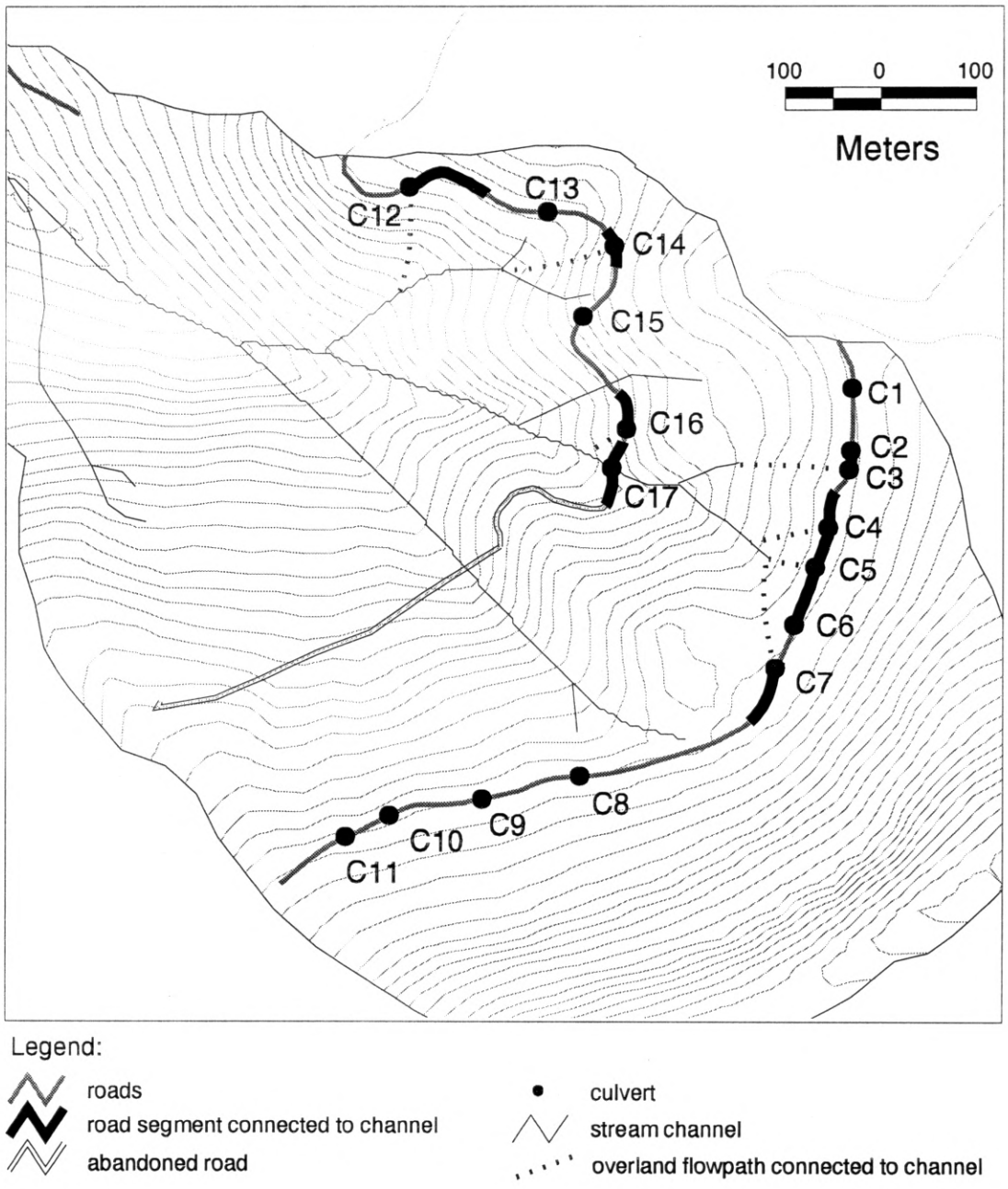


Figure 2.20: Map of the upper hillslope in Watershed 3 showing locations of culverts and connectivity of road segments to the channel network. Connected road segments are defined as those that discharge runoff to the channel network and are indicated by heavy black lines. Road segments draining to C17 are directly connected to the channel via a stream crossing culvert. Other road segments are connected to the channel network via overland flowpaths (dotted lines) below ditch relief culverts. Much of the road length in Watershed 3 is not hydrologically connected to the channel network.

Chapter 3

Road-related Sedimentation in the Western Oregon Cascades During the February 1996 Flood

Beverley Coghill Wemple

in preparation for journal submission

3.1 Introduction

Processes controlling the production, transport and deposition of sediment in forested settings are a key concern to scientists and land managers. These processes affect landform evolution, soil productivity, nutrient transfer and the quality of aquatic habitat. The analysis of sedimentation processes has therefore been the focus of considerable study.

Many previous studies have examined the mechanics of detachment, transport and deposition of individual geomorphic processes (Varnes, 1978; Iverson and Denlinger, 1987; Wilson and Dietrich, 1987; Komar and Shih, 1992, and many others). These studies, while critical, provide little insight into the movement of sediment through whole drainage basins. Sediment budget and routing studies have been used extensively in recent decades to construct a framework for understanding the range of processes and process linkages involved in sediment movement at the watershed scale (Dietrich and Dunne, 1978; Dietrich et al., 1982; Swanson et al., 1982b). More recently, the concept of disturbance cascades has been introduced to ecosystem science as a framework for understanding the dynamics of material flow through ecosystems and the implications for terrestrial and aquatic biota (Swanson et al., 1998).

In February 1996, a flood of record occurred in western Oregon. Monitoring stations at the H. J. Andrews Experimental Forest in the western Oregon Cascades recorded total precipitation depth for the three-day period between February 6-8 exceeding 250 mm. Unit area peak discharges at gauged watersheds in the Andrews Forest averaged 2.15 $m^3/s/km^2$ and were among the highest on record for the 50-year monitoring period (Dyrness et al., 1996). Recent studies of the effects of forest roads on mountain watersheds (e.g. Jones and Grant, 1996; Wemple et al., 1996) led me to ask how sedimentation processes were affected by roads during the flood. Of interest were how roads influenced erosional processes and how flood-induced erosion affected the transportation network. By employing concepts of sediment budgeting and disturbance

cascades, I aim to create a landscape context for understanding the impact of an extensive road network on the geomorphic imprint left by this flood of record.

3.2 Methods

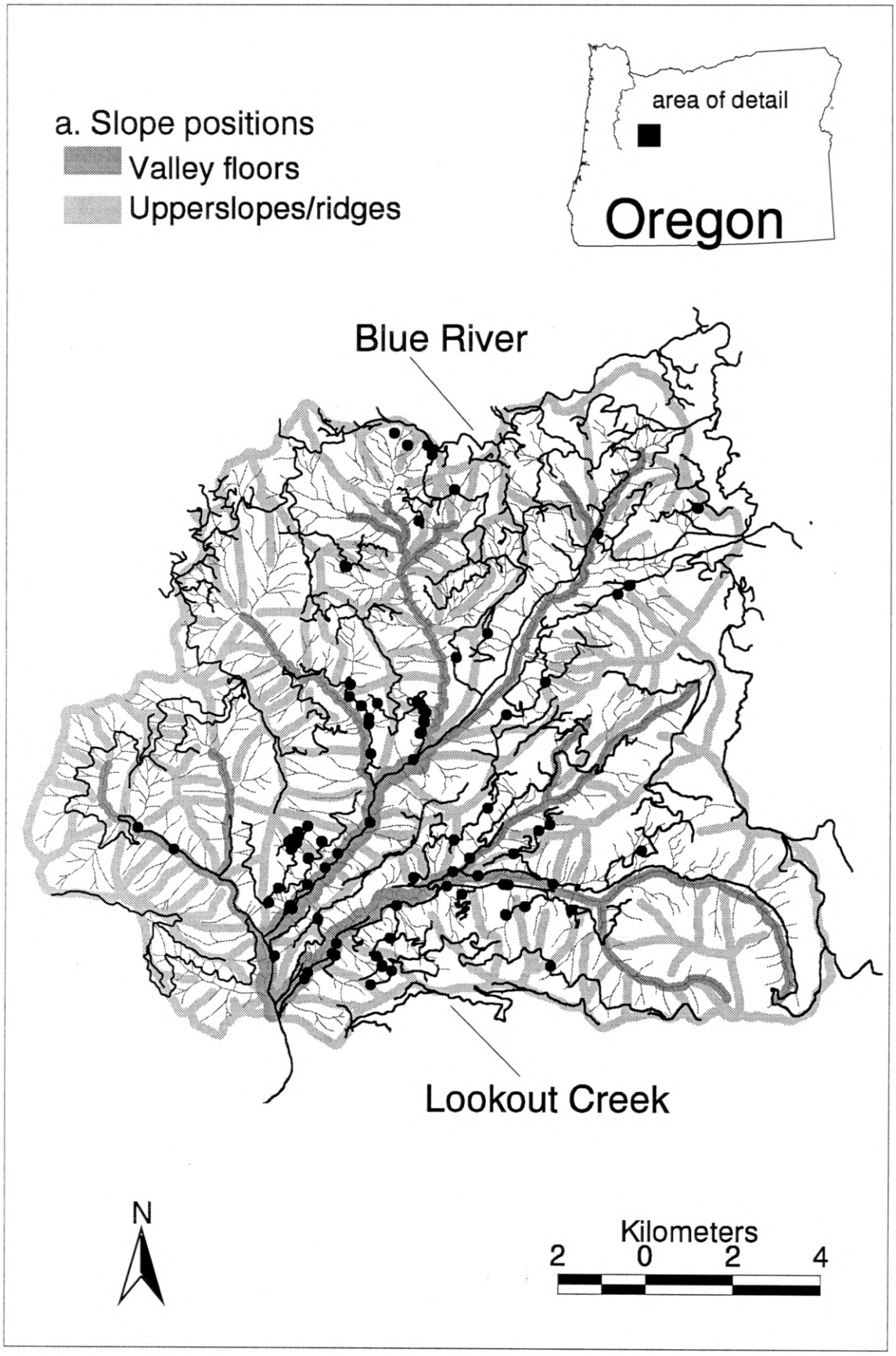
Following the February 1996 flood, I conducted a survey in two watersheds in the western Oregon Cascades to examine flood impacts associated with roads. The approach to this study included four components: (1) an inventory of road-related sedimentation features, (2) an analysis of landscape position of these features, (3) an analysis of process complexity and disturbance cascades, and (4) a mass balance of sediment relative to the zone of road influence.

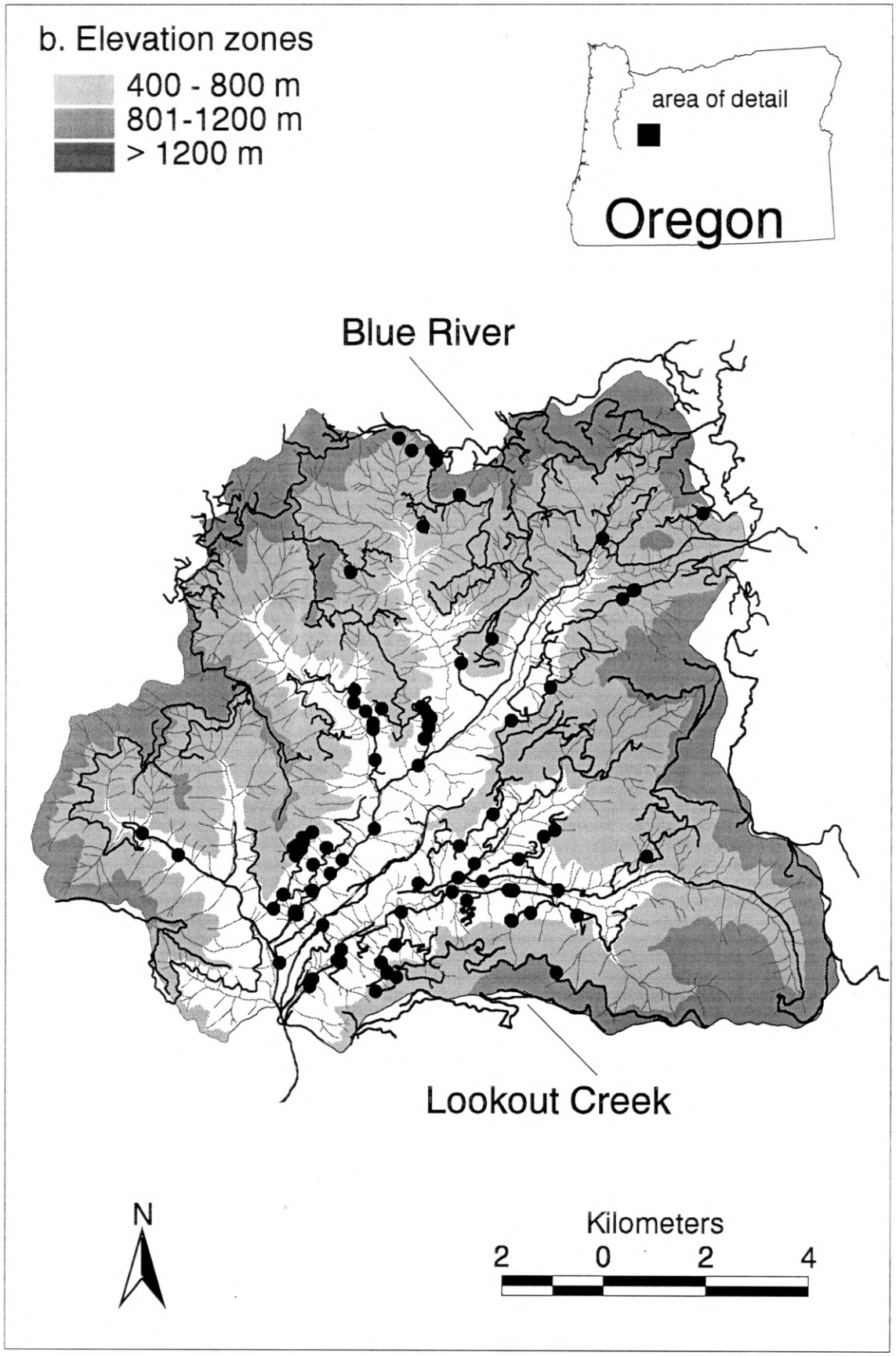
3.2.1 Study site description

The study was conducted in the Lookout Creek and Blue River watersheds, located approximately 70 km east of Eugene in the western Oregon Cascades (Figure 3.1, Table 3.1). Elevations in the basins range from 400 meters to over 1500 meters, with slopes ranging from 0 to 80 percent. The basins are underlaid by Tertiary and early Quaternary volcanic rocks, primarily ash flows, mudflows and pyroclastic flows at the lower elevations (below 800 meters) and andesite and basalt lava flows in the higher elevations. The geomorphic history of the basins is shaped by glacial, fluvial and mass wasting processes. Glacial deposits are evident in the southeast portion of the Blue River drainage. Lacustrine sediments and varve deposits are found along the banks of lower Blue River and Lookout Creek. Geologic mapping (Swanson and James, 1975) and landslide inventories (Dyrness, 1967; Swanson and Dyrness, 1975) document the history of deep-seated earthflows and shallow landsliding in the area.

Mean annual precipitation ranges from 2300 to over 2500 mm at the upper elevations (Greenland, 1994). Over 80% of the precipitation falls between November to April, typically as rain below 400 meters. Elevations between 400 and 1200 meters

Figure 3.1: Study area, Lookout Creek and Blue River watersheds in the western Oregon Cascades, showing extents of (a) slope position polygons and (b) elevation zones. Light gray lines symbolize stream network. Black lines are roads. Road-related sedimentation features are shown on each map as dots.


a. Slope positions
Valley floors
Upperslopes/ridges
area of detail
Oregon
Blue River
Lookout Creek
N
Kilometers
2 0 2 4


b. Elevation zones
400 - 800 m
801-1200 m
> 1200 m
area of detail
Oregon
Blue River
Lookout Creek
N
Kilometers
2 0 2 4

have been termed the "transient snow zone" (Harr, 1981) where precipitation falls alternately as rain and snow. A permanent snow zone develops during most winters above 1200 meters. Floods in the region often result from relatively warm rain events on an accumulated snowpack (Harr, 1981).

Table 3.1: Summary of characteristics of study basins

	Lookout Creek	Blue River
Watershed area (km^2)	62	119
Harvested area (%)	22	25
Drainage density (km/km^2)[a]	3.0	2.9
Road length (km)	118	230
Road density (km/km^2)	1.9	1.9
Area of basin in roads (%)[b]	3.1	3.1

Notes:

[a] Estimated winter baseflow drainage density (see Wemple et al., 1996).
[b] Computed using an average width of road cut, surface, and fill of 16 meters from Silen and Gratkowski, 1953.

Vegetation in the basins consists of Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). Stands of Pacific silver fir (*Abies amabilis*) occur above 800 m. Forest harvesting and road construction have occurred in both basins since the late 1930's (Jones and Grant, 1996). Harvesting and road construction in the Lookout Creek watershed occurred primarily in the 1950's

and 1960's. Most of the harvesting and road construction in the Blue River watershed occurred between 1960 and 1985.

3.2.2 Survey and field methods

A survey of the road network in the Lookout Creek and Blue River watersheds was conducted to inventory road-related sedimentation resulting from the February 1996 flood. During the spring and summer of 1996, the entire road network in both basins was inventoried for erosional and depositional features associated with roads. Each feature was field located on 7.5' topographic maps and later digitized into a geographic information system (GIS).

To distinguish among forms of erosion and deposition associated with roads, a typology of features, based on the process type and the point of origin relative to the road zone (defined as the cutslope, road surface and ditch, and fillslope), was developed (Figure 3.2). Two general process types were considered: mass wasting and fluvial. Mass wasting involves *en masse* detachment and transport of sediment and organic debris on hillslopes (debris slides) and in channels (debris flows). Mass wasting can also involve displacement of soil without evacuation from the site (e.g. slumps). The features produced by these processes are referred to in this paper as mass movements. Fluvial processes involve particle by particle transport of sediment by flowing water in channels (bedload transport) and on hillslopes or roads (incision and gullying), and produce what are generally refer to here as fluvial features. Four points of origin were considered (Table 3.2): above the road, the cutslope, the road surface and ditch, and the fillslope. Three types of debris slides were distinguished for this study: those initiated on hillslopes above roads were termed hillslope slides, those originating on cutslopes were termed cutslope slides, and those from road fills were termed fillslope slides. Other processes originating above roads included debris flows and bedload transport that plugged culverts. Processes originating within the road zone included slumps, ditch incision, and gullying.

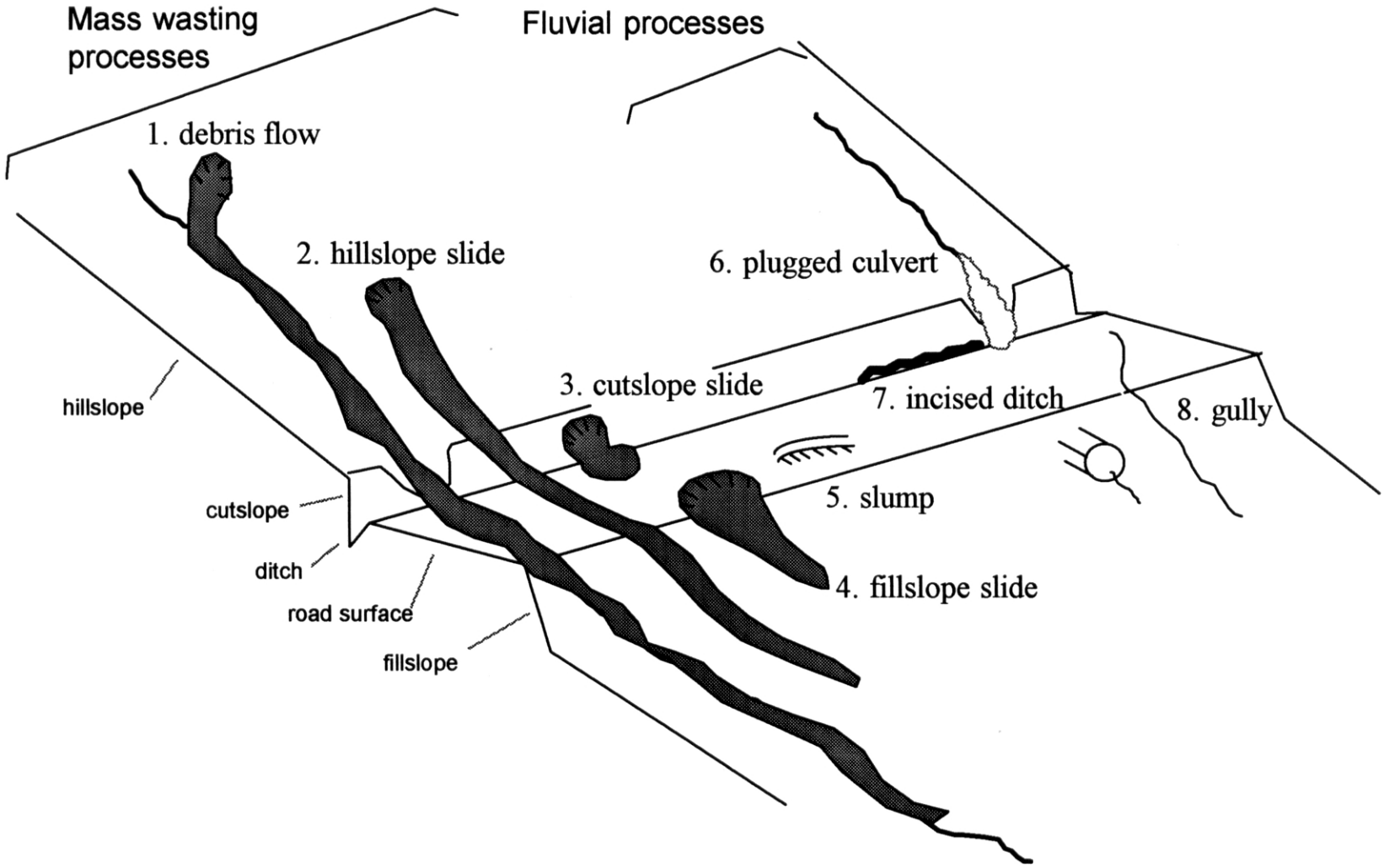


Figure 3.2: Eight types of features inventoried on roads in Lookout Creek and Blue River.

Table 3.2: Eight types of erosional and depositional features identified on the road network with point of origin, point of deposition and components considered in sediment mass balance.

	feature type	Volumes estimates taken from	point of origin relative to road [2] (above/ inside)	point of deposition relative to road [2] (inside/ below)	Components of sediment volume Vh	Vr
1	debris flow	erosional scar[3]	above	inside/ below	x	x
2	hillslope slide	erosional scar	above	inside/ below	x	x
3	cutslope slide	deposit[4]	inside (*cut*)	inside		x
4	fillslope slide	erosional scar	inside (*fill*)	below		x
5	slump [1]	n/a	inside (*surface*)	inside	-	-
6	plugged culvert	deposit	above	inside	x	
7	ditch incision	erosional scar	inside (*ditch*)	inside		x
8	gully	erosional scar	inside (*surface, fill*)	inside/ below		x

[1] Sediment volumes not applicable for slumps, which involve only in situ displacement of soil.
[2] "Road" refers to cutslope, road surface and ditch, and fillslope (see Figure 3.2).
[3] Debris flow volumes were estimated from the volumes of hillslope slide(s) that triggered debris flows.
[4] Cutslope slide volumes were measured from the geometry of the deposit, plus a visual estimate of the volume transported below roads in two cases.

The length, width and depth of erosional scars and deposits were measured as appropriate for each feature to determine sediment volumes (Table 3.2). Volumes are reported here to the nearest 5 m^3. The accuracy of volume estimates, however, varies by the size of the feature, and reported volumes are considered to be precise only to two significant figures.

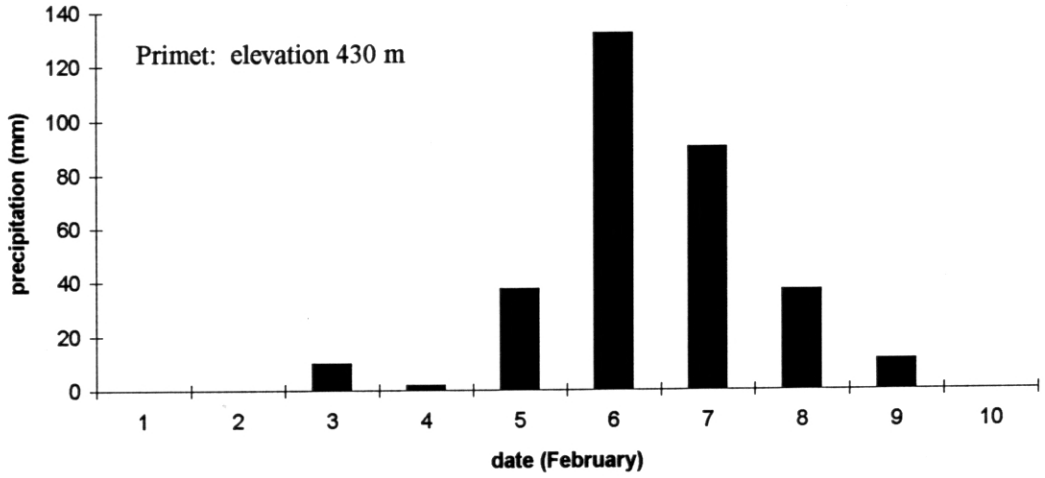
3.2.3 Analysis of landscape position of features

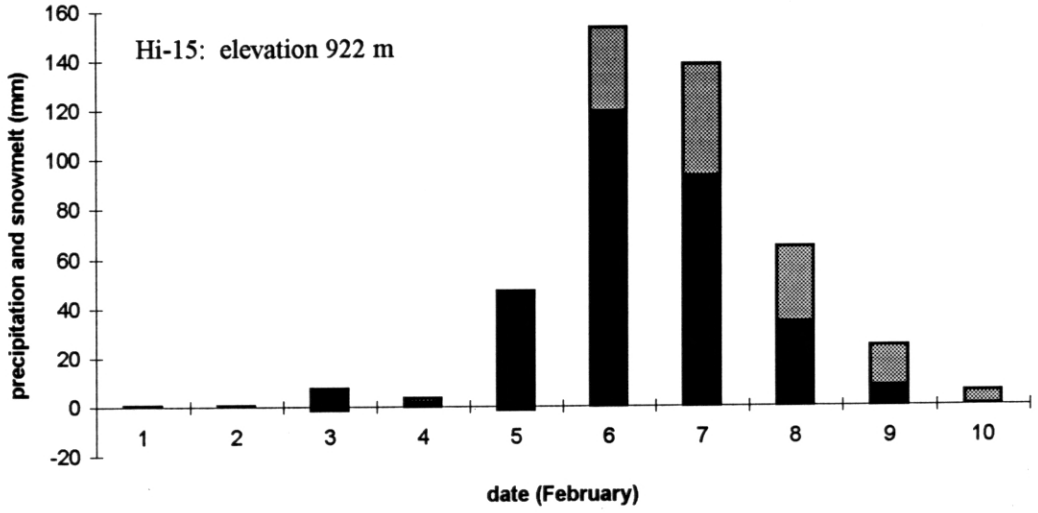
Analysis of the landscape position of inventoried features was accomplished using GIS. A series of overlay analyses were used to determine the road age, elevation and hillslope position for the road network and for the features inventoried in this study.

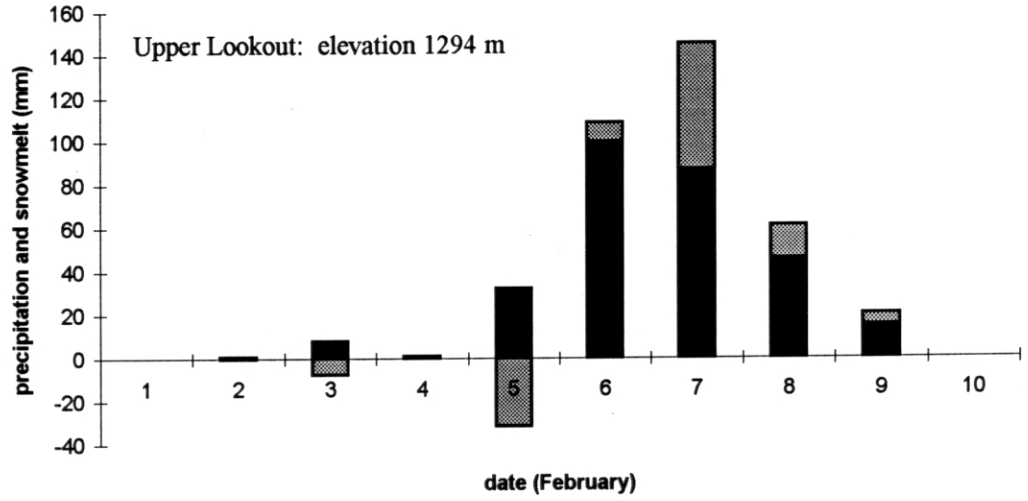
The decade of construction for roads in the study area was determined for a previous study (Jones and Grant, 1996) using aerial photographs and historical records of timber harvesting. Road networks in the Lookout Creek and Blue River watersheds were digitized from stereo-photo pairs using an analytical stereoplotter. Each road segment was assigned a year of construction corresponding to the year prior to timber harvesting of the nearest adjacent cutting unit. The datalayer of inventoried features was overlaid on the road network to determine the distribution of features by age of the road segment on which it occurred.

Three elevation classes were defined, based on elevational distinctions in geologic substrate and precipitation-snowmelt gradients observed during the flood (Figure 3.1b). The lowest elevation zone, from 400 - 800 meters, covers the extents of relatively unstable rock types in the basins, mainly those derived from mudflows, ashflows and pyroclastic flows (Swanson and James, 1975). The most intense rainfall and snowmelt were also synchronized at this elevation during the flood event (Dyrness et al., 1996). A second elevation zone between 800 - 1200 meters includes more stable soils derived from andesite and basalt. In this zone, rainfall and snowmelt were desynchronized in time, with the period of most intense rainfall preceding snowmelt by almost 24 hours (Figure 3.3). Above 1200 meters, little snowmelt occurred during the

Figure 3.3: Summary of precipitation and snowmelt for the period February 1-10, 1996 as recorded at meteorological stations at the H. J. Andrews Experimental Forest. Black bars represent rainfall, gray bars represent snowmelt (snowmelt data not available for Primet station). Negative snowmelt values indicate snowpack storage of water. Rainfall during the flood event was concentrated on February 5-7. Snowmelt recorded at the Hi-15 station (elevation 922 meters) began on February 6. At the Upper Lookout station (elevation 1294 meters), precipitation was absorbed into the snowpack early in the storm, and appreciable snowmelt did not occur until February 7. Adapted from Dyrness et al. 1996.


Primet: elevation 430 m
precipitation (mm)
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
date (February)


Hi-15: elevation 922 m
precipitation and snowmelt (mm)
160
140
120
100
80
60
40
20
0
-20
1
2
3
4
5
6
7
8
9
10
date (February)


Upper Lookout: elevation 1294 m
precipitation and snowmelt (mm)
160
140
120
100
80
60
40
20
0
-20
-40
1
2
3
4
5
6
7
8
9
10
date (February)

flood and much of the precipitation was absorbed by the snowpack. Elevation values derived from a digital elevation model of the basins were classified into these three zones using a GIS. The datalayer of sedimentation features was overlaid with the elevation coverage to determine the elevation zone of each feature.

Three hillslope position classes were delineated from topographic maps and GIS datalayers (Figure 3.1). Valley floors were delineated with a 200 meter buffer around fifth-order streams and a 100 meter buffer around fourth-order streams. The extents of the upperslopes and ridges were defined with a 100 meter buffer on a linear network of ridges digitized from 7.5' topographic maps. The remainder of the watershed area was defined as midslopes. Overlays of the inventoried features on these three zones provided the attributes for hillslope position of each feature.

3.2.4 Analysis of process complexity and disturbance cascades

Field evaluation and mapping of the location and runout paths of inventoried features were used to assess process complexity and the occurrence of disturbance cascades associated with roads. Here, a road-related disturbance cascade is defined as a sequence of associated erosional or deposition processes that occurs on hillslopes, in channels or along roads, in which the road functions to alter the form (type of mass movement or fluvial process) or behavior (e.g. runout length, deposition) of sedimentation processes.

Accordingly, each inventoried feature was classified according to process type, complexity, number of road tiers affected and evidence of multiple, associated forms of erosion and deposition. Process complexity was evaluated based on the number of individual features at a given location. Simple sites included locations where only one feature was inventoried. Complex sites were characterized by multiple, associated sedimentation features at a given location. Processes that affected only one road location were classed as single-tier, whereas processes that traversed more than one road along a hillslope were classed as multi-tier. Maps of flowpaths of individual features were used to trace the runout path and impact of individual features.

At complex sites, where more than one feature was inventoried, field evidence for association between features was assessed. Process associations were indicated by (1) deposition of sediment that diverted surface runoff or was available for transport by another process, (2) evidence of surface runoff diversion that appeared to trigger additional erosion, or (3) transport of sediment in debris slides to channels where transformation to debris flows occurred.

3.2.5 Sediment mass balance

To evaluate the role of roads as a source or storage site for sediment, I constructed a sediment mass balance from the inventoried features. Volumes of sediment mobilized on hillslopes (Vh) above roads and within the road zone (e.g. cutslope, ditch, road surface and fillslope) (Vr) were used to calculate inputs (Vin), outputs (Vout), and changes in storage (ΔS) as follows. Sediment volumes from hillslopes and roads were partitioned into the fraction stored on roads (V_s) and the fraction transported to hillslopes below roads (V_t) according to (Figure 3.4)

$$Vh = Vh_s + Vh_t$$
$$Vr = Vr_s + Vr_t \qquad (3.1)$$

Inputs of sediment to roads are represented by material originating on hillslopes above roads, while outputs are represented by the transported fractions of sediment from hillslopes and roads, e.g.

$$Vin = Vh$$
$$Vout = Vh_t + Vr_t \qquad (3.2)$$

Combining (1) and (2), the mass balance of sediment was computed as

$$\Delta S = Vin - Vout$$
$$= (Vh_s + Vh_t) - (Vh_t + Vr_t)$$
$$= Vh_s - Vr_t \qquad (3.3)$$

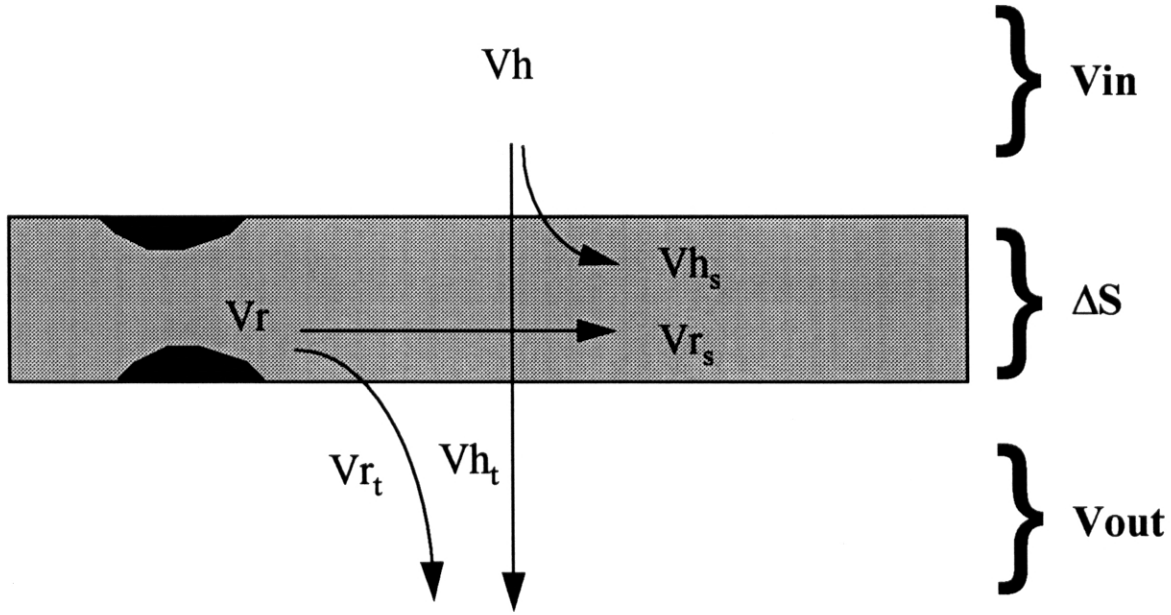


Figure 3.4: Volumes used to compute sediment mass balance. Sediment is mobilized on hillslopes above roads (Vh) or within the road zone (Vr) and may be stored on roads (V_s) or transported through the road zone to hillslopes below (V_t). The effect of roads on sediment storage (ΔS) is determined by the difference between inputs (Vin) to and outputs (Vout) from the road.

where ΔS represents the net change in sediment storage by roads, equal to the volume of hillslope material stored on roads less the volume of road material transported to hillslopes below. Positive values indicate that roads function as a net sink, or storage site, for sediment. Negative values of ΔS indicate that roads function as a net source of sediment to hillslopes.

3.3 Results

3.3.1 Number and types of sedimentation features

Erosion by mass wasting and fluvial processes during the February 1996 flood resulted in eight distinct types of features associated with roads (Figure 3.2). Mass wasting processes included slumps, debris flows, and debris slides, including those termed hillslope slides, cutslope slides and fillslope slides for the purposes of this study. Fluvial processes included bedload transport that was trapped at culvert inlets (plugged culverts), and erosion by concentrated surface runoff that resulted in gullying of road surfaces and hillslopes or incision of roadside ditches.

I inventoried 103 features along the 348 km of road in the Lookout Creek and Blue River watersheds (Figure 3.1, Table 3.3). As many as 30% of these features were fillslope slides, while hillslope slides that intersected roads were inventoried at only five locations, and only three sites of ditch incision were found. Other features mapped on the road network included 12 cutslope slides, 13 slumps, 13 culverts plugged by bedload, 10 sites where gullying of the road surface and hillslope was evident, and 16 sites where debris flows intersected roads. Although roughly 60% of these features were mapped in the Blue River watershed, the frequency of impact was lower in the Blue River watershed (0.27 features/kilometer) than in the Lookout Creek watershed (0.36 features/kilometer), which is roughly half the size with half the total road length relative to the Blue River watershed (Table 3.1).

Table 3.3: Distribution and frequency of inventoried features in the Lookout Creek and Blue River watersheds.

	Lookout Creek Watershed		Blue River Watershed		total	
	No.	No./km.	No.	No./km.	No.	No./km.
1. debris flow	9	0.08	7	0.03	16	0.05
2. hillslope slide	4	0.03	1	0.004	5	0.01
3. cutslope slide	1	0.01	11	0.05	12	0.03
4. fillslope slide	18	0.15	13	0.06	31	0.09
5. slump	1	0.01	12	0.05	13	0.04
6. plugged culvert	3	0.03	10	0.04	13	0.04
7. ditch incision	1	0.01	2	0.01	3	0.01
8. gully	5	0.04	5	0.02	10	0.03
total	42	0.36	61	0.27	103	0.30

The features inventoried on the road network were not evenly distributed between the two basins (Table 3.3). Hillslope slides occurred seven times more frequently, and fillslope slides and debris flows occurred roughly 2.5 times more frequently in the Lookout Creek watershed than in the Blue River watershed. In contrast, cutslope slides and slumps occurred five times more frequently in Blue River. Among features produced by fluvial erosion and deposition, culverts plugged by bedload occurred more frequently in Blue River, while gullying occurred twice as frequently in Lookout Creek.

In general, mass wasting processes mobilized larger volumes of sediment than fluvial processes (Figure 3.5). Debris slides were skewed toward the larger size classes. Hillslope slides and all but two of the 31 fillslope slides ranged from 100 - 10,000 m^3. The volumes of cutslope slides were slightly smaller, with most of these features ranging from 10 - 1000 m^3. In contrast, most of the fluvial features ranged from <10 m^3 - 100 m^3. Eleven of the 13 plugged culverts and seven of the 10 gullies had sediment volumes of 10 - 100 m^3. Debris flows ranged from < 100 m^3 to over 5000 m^3.

3.3.2 Landscape position of sedimentation features

There are some important differences in the distribution of roads by time of construction, hillslope position and elevation in the two basins. While road densities are similar in the Lookout Creek and Blue River watersheds (Table 3.1), more than 60% of the road length in Lookout Creek was constructed prior to 1960, while roughly 70% of the road length in Blue River was constructed between 1961 - 1980 (Table 3.4). Both basins have only a small proportion (< 25%) of the total road length constructed above 1200 m, but in Lookout Creek almost 50% of the total road length is concentrated in the lowest elevations (400 - 800 m) while in Blue River 50% of the road network is in the mid elevations (801 - 1200 m). Finally, roughly 60% of the total road length in both basins is located in midslope positions, but in Lookout Creek, 15% of the road length is in valley floor positions and 23% is in upperslope/ridge positions, while in Blue River

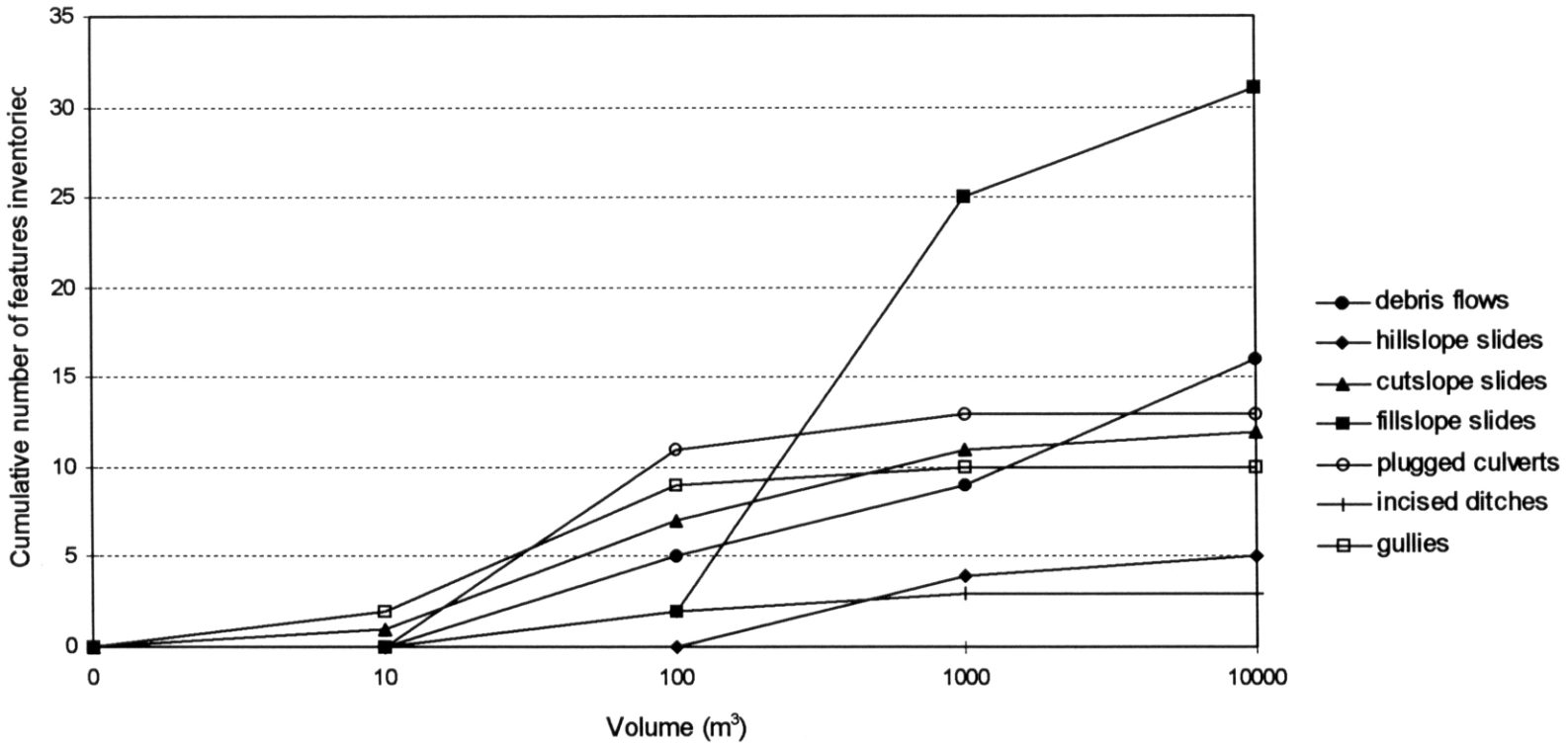


Figure 3.5: Distribution of size classes of sediment for inventoried features (slumps not included). Volumes are material mobilized on hillslopes (V_{in}) and within the road prism (V_r) as applicable (see Table 3.2).

Table 3.4: Distribution of road length and inventoried features by road age, elevation and hillslope position in the Lookout Creek and Blue River watersheds.

	Lookout Creek Watershed					Blue River Watershed				
	road length		inventoried features			road length		inventoried features		
	km	%	no	%	per km	km	%	no	%	per km
Road Age (e.g. decade of road construction)										
<1960	72	61	35	83	0.49	41	18	26	43	0.63
1961-1970	42	35	6	14	0.14	76	33	13	21	0.28
1971-1980	2	2	1	3	0.5	86	37	16	26	0.19
1981-1990	2	2	0	0	0	27	12	6	10	0.22
total	118	100	42	100	0.36	230	100	61	100	0.27
Elevation										
400-800	58	49	38	90	0.66	61	27	36	59	0.59
801-1200	36	31	3	8	0.08	116	50	25	41	0.22
>1200	24	20	1	2	0.04	53	23	0	0	0
total	118	100	42	100	0.36	230	100	61	100	0.51
Hillslope Position										
valley	18	15	19	45	1.06	23	10	13	21	0.57
mid	73	62	21	50	0.29	132	57	45	74	0.34
upper	27	23	2	5	0.07	75	33	3	5	0.04
total	118	100	42	100	0.36	230	100	61	100	0.27

only 10% of the road length is located on valley floors and 33% is located on upperslopes and ridges.

The distribution of inventoried features is not a simple function of the length of road in a given landscape position (Table 3.4). Over 80% of the features in the Lookout Creek watershed and more than 40% of the features in the Blue River watershed occurred on roads constructed prior to 1960, although much of the total road length in Blue River was constructed after 1960. Ninety percent (90%) of the inventoried features in Lookout Creek and almost 60% of the features in Blue River occurred on roads in the lowest elevation zone (400 - 800 m), proportions that are significantly higher than the proportion of road length in this elevation zone. Finally, most (74%) of the features in Blue River occurred on midslope roads, whereas in Lookout Creek only half of the features occurred on midslope roads, and all but one of the remaining features occurred on valley floor roads.

The interactions between road age, elevation and slope position reveal important patterns in the frequency of inventoried features (Table 3.5). Of the 36 possible combinations of road age, elevation and hillslope position examined, roughly half of the road length in the Lookout Creek watershed falls into three classes: low-elevation, valley-floor and midslope roads constructed prior to 1960, and mid-elevation, midslope roads constructed prior to 1960 (Table 3.5a). Most of the inventoried features in Lookout Creek were found on these roads (Table 3.5b), particularly on roads constructed prior to 1960 in the lowest elevation zone (400 - 800 m), resulting in a high frequency of occurrence on these roads (Table 3.5c). In the Blue River watershed, roughly half of the road length falls into five classes: low-elevation, valley-floor roads constructed before 1960 and midslope roads constructed in the 1960's, and mid-elevation, midslope roads constructed between 1961-1980 plus ridge roads constructed in the 1970's (Table 3.5a). Most of the inventoried features in Blue River were found on these roads (Table 3.5b), but a high concentration of features on roads constructed prior to 1960 in the lowest elevation zone resulted in a high frequency of occurrence on these roads (Table 3.5c).

Table 3.5: Relation between decade of road construction, elevation, and hillslope position in the Lookout Creek and Blue River watersheds. (a) Kilometers of road. Bold font indicates classes with highest concentration of road length, totaling 50% of network length in each watershed (see text)

	Lookout Creek Watershed ----- decade of road construction -----					BlueRiver Watershed ----- decade of road construction -----				
	<1960	1961-1970	1971-1980	1981-1990	total	<1960	1961-1970	1971-1980	1981-1990	total
Elevation 400-800 m										
valley floor	**11.4**	2.8	0.3	0	14.5	**16.2**	2.6	1.6	0	20.4
midslope	**28.6**	5.3	0	0.3	34.2	9.0	**14.4**	9.3	0.8	33.5
upper slope	4.7	4.7	0	0	9.4	1.4	4.0	0.9	0.4	6.7
total	44.7	12.8	0.3	0.3	58.1	26.6	21.0	11.8	1.2	60.6
Elevation 801-1200 m										
valley floor	2.5	0	0	0	2.5	0	1.0	1.7	0	2.7
midslope	**16.8**	8.2	1.2	0.4	26.6	2.7	**25.3**	**31.8**	9.9	69.7
upper slope	4.7	1.7	0.6	0	7.0	1.4	10.7	**20.5**	11.0	43.6
total	24.0	9.9	1.8	0.4	36.1	4.1	37.0	54.0	20.9	116.0
Elevation >1201 m										
valley floor	0	0.9	0	0	0.9	0	0	0	0	0
midslope	1.8	10.6	0	0.8	13.2	7.3	13.4	7.0	2.3	30.0
upper slope	1.4	7.8	0	0.7	9.9	3.2	4.3	13.4	2.8	23.7
total	3.2	19.3	0	1.5	24.0	10.5	17.7	20.4	5.1	53.7
grand total	71.9	42.0	2.1	2.2	118.2	41.2	75.7	86.2	27.2	230.3

Table 3.5 (continued). (b) Number of features inventoried. Note inventoried features occurred in only eight of 36 possible classes in the Lookout Creek watershed and 15 of 36 possible classes in the Blue River watershed. Bold font indicates highest concentration of features.

	Lookout Creek Watershed ----- decade of road construction -----					BlueRiver Watershed --- decade of road construction ---				
	<1960	1961-1970	1971-1980	1981-1990	total	<1960	1961-1970	1971-1980	1981-1990	total
Elevation 400-800 m										
valley floor	**16**	2	1	0	19	**8**	2	1	0	11
midslope	**13**	4	0	0	17	**12**	5	5	3	25
upper slope	2	0	0	0	2	0	0	0	0	0
total	31	6	1	0	38	20	7	6	3	36
Elevation 801-1200 m										
valley floor	0	0	0	0	0	1	1	0	0	2
midslope	3	0	0	0	3	5	3	**10**	2	20
upper slope	0	0	0	0	0	0	2	0	1	3
total	3	0	0	0	3	6	6	10	3	25
Elevation >1201 m										
valley floor	0	0	0	0	0	0	0	0	0	0
midslope	1	0	0	0	1	0	0	0	0	0
upper slope	0	0	0	0	0	0	0	0	0	0
total	1	0	0	0	1	0	0	0	0	0
grand total	35	6	1	0	42	26	13	16	6	61

Table 3.5 (continued). (c) Number of features per kilometer of road. Bold font indicates highest frequencies in each basin (note frequencies > 1.0 that are not highlighted result in classes with < 3 kilometers of road and are considered inadequate sample sizes to assess susceptibility).

	Lookout Creek Watershed ----- decade of road construction -----					BlueRiver Watershed ----- decade of road construction -----				
	<1960	1961-1970	1971-1980	1981-1990	total	<1960	1961-1970	1971-1980	1981-1990	total
Elevation 400-800 m										
valley floor	**1.4**	0.7	3.3	0	1.3	0.5	0.8	0.6	0	0.5
midslope	0.5	0.8	0	0	0.5	**1.3**	0.3	0.5	3.8	0.7
upper slope	0.4	0.0	0	0	0.2	0	0	0	0	0
total	0.7	0.5	3.3	0	0.7	0.8	0.3	0.5	2.5	0.6
Elevation 801-1200 m										
valley floor	0	0	0	0	0	0	1.0	0	0	0.7
midslope	0.2	0	0	0	0.1	1.9	0.1	0.3	0.2	0.3
upper slope	0	0	0	0	0	0	0.2	0	0.1	0.1
total	0.1	0	0	0	0.1	1.5	0.2	0.2	0.1	0.2
Elevation >1201 m										
valley floor	0	0	0	0	0	0	0	0	0	0
midslope	0.6	0	0	0	0.1	0	0	0	0	0
upper slope	0	0	0	0	0	0	0	0	0	0
total	0.3	0	0	0	0	0	0	0	0	0
grand total	0.5	0.1	0.5	0	0.4	0.6	0.2	0.2	0.2	0.3

3.3.3 Process complexity and disturbance cascades

Flood impacts to the road network occurred as both simple, isolated events and as complex cascades of multiple erosional and depositional processes (Figure 3.6). Certain types of processes commonly occurred in isolation, while others typically occurred in association with other forms of erosion. All of the slumps occurred as simple, isolated features, whereas all of the incised ditches were associated with another feature. Four of the five hillslope slides and nine of the 13 plugged culverts occurred in isolation, while nine of the 10 gullies resulted when channelized surface runoff was diverted by deposition of sediment from an another feature.

Of the 103 features mapped in the study area, 58 were simple features affecting roads in only one hillslope position (Figure 3.6). Most of these features were mass movements that occurred within the road zone. Only five of these features occurred on ridge roads, and the remainder were found on midslope (38 features) and valley-floor roads (15 features).

The remaining 45 features inventoried in this study resulted from complex cascades of erosion and deposition (Figure 3.6). These cascades fell into two general classes: (1) debris flows, cutslope slides or plugged culverts that deposited sediment at roads, caused diversion of channels or ditchflow, and triggered fillslope slides, gullying or ditch incision, and (2) hillslope or fillslope slides that entered channels and became debris flows. Most of these complex features affected roads in only one hillslope position, although one hillslope slide and one debris flow affected midslope and valley-floor roads, and five fillslope slides initiated on midslope roads became debris flows that impacted valley-floor roads. No complex associations occurred on upperslope/ridge roads. These complex features were concentrated on midslope roads, and all but four of the complex features on valley floor roads were triggered by erosion that also affected midslope roads.

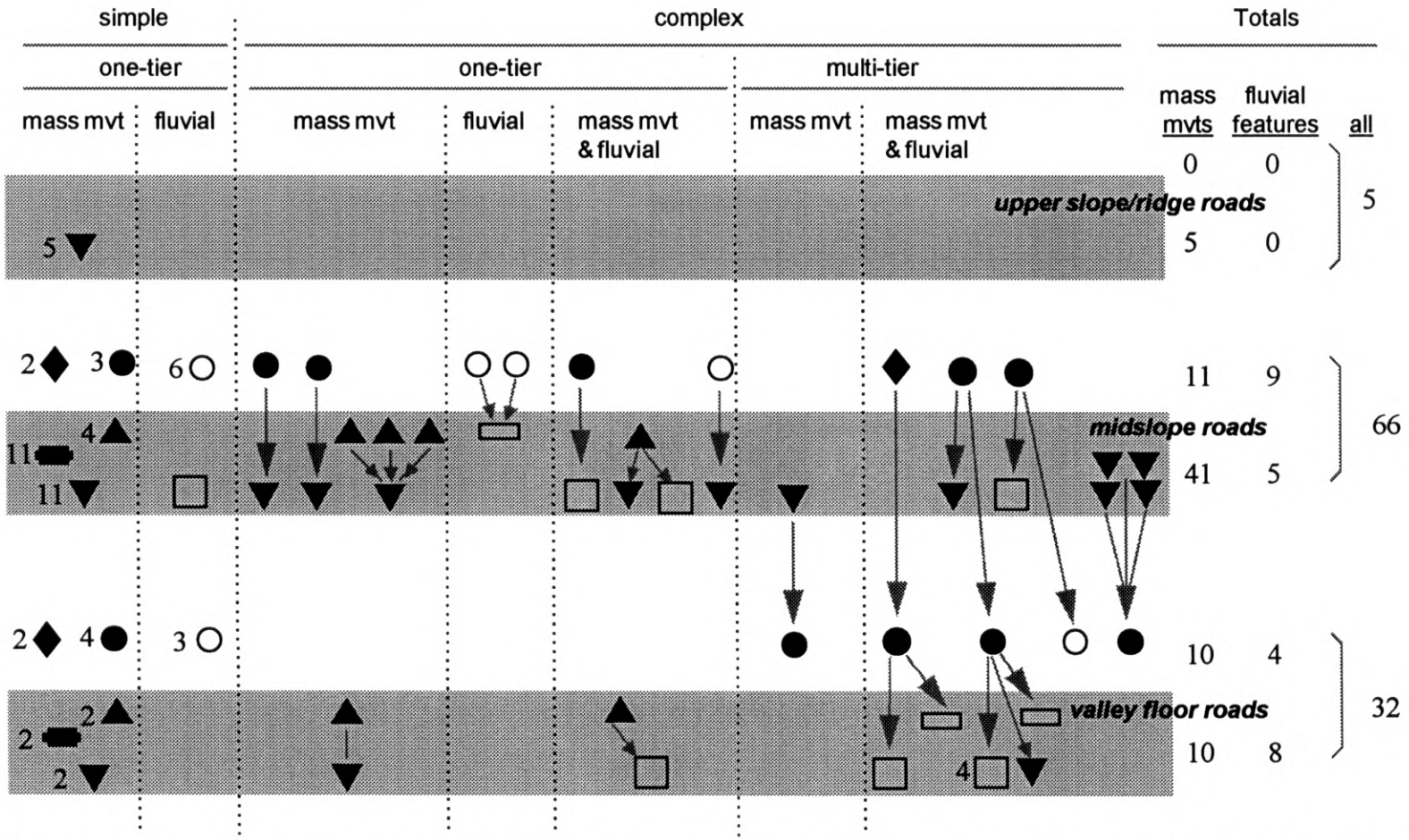


Figure 3.6: Schematic representation of the distribution and spatial complexity of features inventoried in this study. Closed symbols represent mass movements (●debris flows, ◆hillslope slides, ▲cutslope slides, ▼fillslope slides, and ▬ slumps). Open symbols represent fluvial features (○plugged culverts, ▭ incised ditches, and □ gullies). Features are positioned relative to point of origin, on hillslopes above roads or within the road zone(represented by gray bars). Arrows indicate features that triggered erosion of associated feature, and show impacts to multiple tiers of roads where applicable.

While most of the features were a result of erosion that occurred within the road zone, one-third (34 features) of the inventoried features were the result of erosional processes that began on hillslopes outside the road zone. The importance of these features increased from ridge to valley floor. None of the features inventoried in the uppermost hillslope position resulted from sediment transported into roads from above. However, on midslope roads, roughly one-third (20 of 66 features) of the inventoried features were hillslope slides, debris flows or plugged culverts that resulted from erosion on hillslopes above roads. On valley-floor roads, almost half (14 of 32 features) of the inventoried features originated on hillslopes or in channels above roads. Many of these were the result of erosion on midslope roads and were involved in complex associations of erosion and deposition on valley-floor roads.

3.3.4 Sediment volumes and mass balance

Sediment volume measurements indicate that over 32,000 m^3 of sediment was mobilized by the processes that occurred within the road zone (cutslope slides, fillslope slides, incised ditches and gullies) (Figure 3.7). Of this volume, over 80% was mobilized by fillslope slides and 60% was from fillslope slides on midslope roads. Cutslope slides accounted for 14% of the sediment mobilized from roads, predominantly from midslope roads; however, most of this sediment remained within the road zone, with little net contribution to hillslopes. Less than 5% of the total sediment volume eroded from road cuts, surfaces or fillslopes was mobilized by ditch incision or gullying.

In addition to the sediment mobilized from roads, over 25,000 m^3 of sediment eroded on hillslopes and in channels (e.g. hillslope slides, debris flows and bedload that plugged culverts) intersected roads (Figure 3.7). Of this volume, roughly 67% was from debris flows, and almost 50% was from debris flows that intersected valley-floor roads. The remaining volume of hillslope material was transported onto roads via hillslope slides (30%) and bedload that plugged stream-crossing culverts (3%). These processes

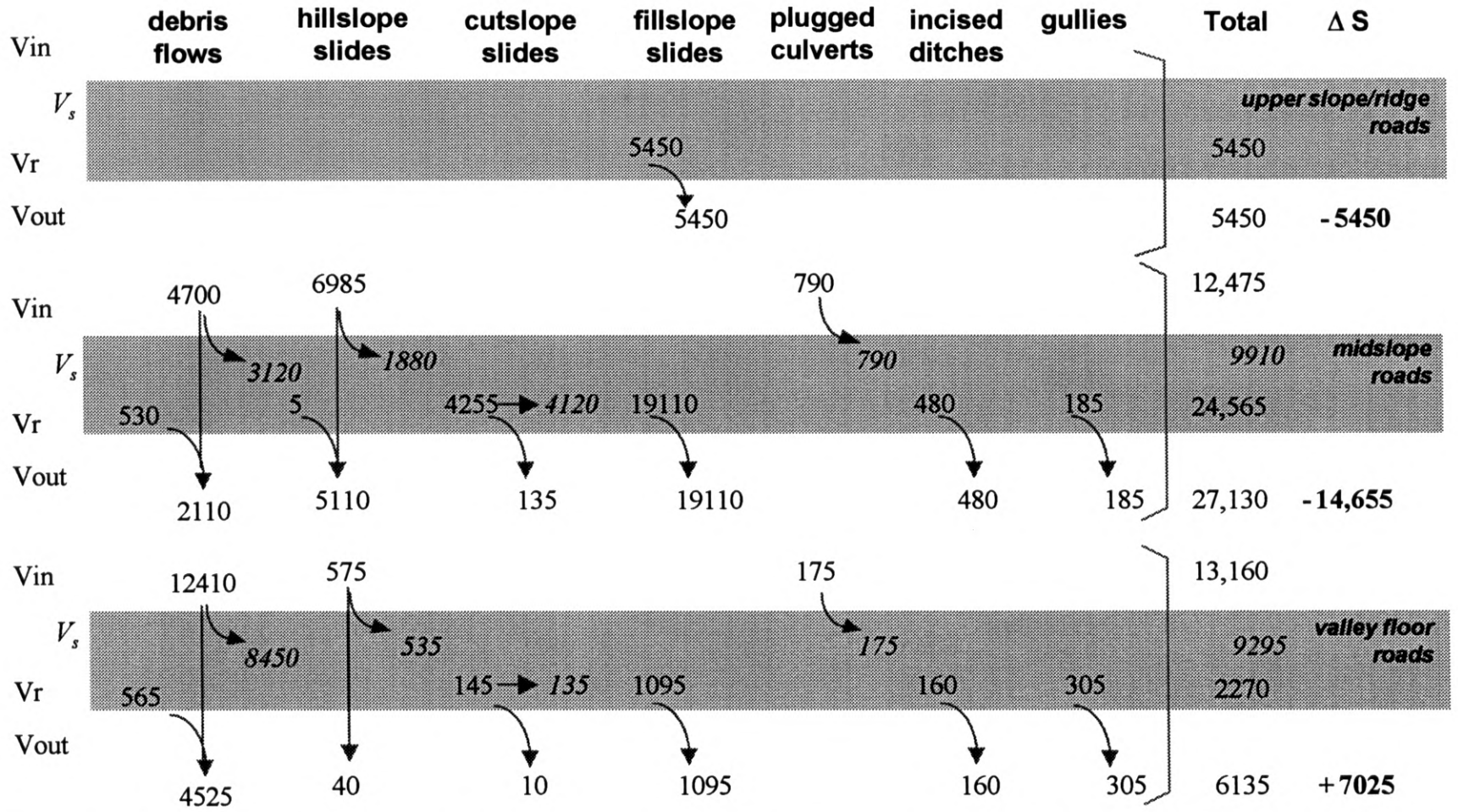


Figure 3.7: Schematic representation of sediment mass balance for sedimentation features inventoried in Lookout Creek and Blue River. Sediment volumes are partitioned into volumes transported into the road zone from hillslopes (Vin), volume of material eroded within the road zone (Vr) from cutslopes, ditches, and road fill, and volume of material transported to hillslopes below roads (Vout). Volumes of sediment stored on roads (*Vs*) are italicized. Changes in storage of sediment by roads are calculated from (3.3).

resulted in at least partial deposition of sediment on roads, although hillslope slides and particularly debris flows also triggered additional erosion on roads.

The role of roads as sources or storage sites for sediment varied from ridge to valley floor (Figure 3.7). Upperslope/ridge roads were a net source of sediment, although a modest one. Midslope roads were a considerably more important source of sediment, producing almost 2.5 times the volume of sediment than was trapped from hillslope and channel erosion above these roads. Valley-floor roads, however, trapped four times the volume of sediment than was eroded on roads and served as a net storage site for sediment. In total, more sediment was eroded from roads than was stored on roads, and the entire road system functioned as a net source of sediment in the basins studied.

3.4 Discussion

The flood of February 1996 resulted in considerable erosion in the Lookout Creek and Blue River watersheds, and various types of erosion and deposition were associated with forest roads. Maps of the locations of road-related sedimentation indicate that there were "hot-spots" of erosion concentrated below 800 m on certain midslope and valley floor roads, where the road was involved in complex cascades of erosion and deposition. Mass wasting accounted for the greatest number of inventoried features and most of the mobilized sediment in road-related erosion, but the consequences of erosion and deposition by fluvial processes is important for at least two reasons. First, bedload that plugged stream-crossing culverts resulted in complete blockage of channels. Second, ditch incision and gullying created new surface channels that could divert flow during future storms and possibly contribute to future slope instability. These findings show that fillslope slides represented the most common form of road-related erosion in these basins. Furthermore, if the associated forms of erosion that were linked to fillslope slides are considered, the importance of this process to the overall impact of roads during the flood is even more significant. These findings also show that erosional processes occurred in large numbers on midslope roads, but the relatively small proportion of road length on the valley floor of these basins was heavily impacted. Finally, while the overall effect of roads

was to serve as a net source of sediment in these basins, roads functioned as both sources and storage sites for sediment depending upon their location on hillslopes.

Certain types of processes may be under-represented in this study, either because they do not commonly occur in these particular basins or because I failed to identify them in the inventory. One erosional feature along a tributary to Lookout Creek was classified as a fillslope slide, although field evidence suggested that it may have been caused by lateral migration of the channel and undercutting of road fill, rather than the typical failure mechanism of most fillslope slides. Lateral channel migration and undercutting of road fill may be common along channels in other sites, especially in places where roads are adjacent to less constrained streams. One fillslope slide that was inventoried appeared to be associated with road drainage, since the point of initiation was tens of meters below a culvert, although the slide was not technically on road-fill material. Association of such features with the road does involve some subjective judgment. Finally, failures at stream crossings that were inventoried as plugged culverts included only those where deposition of sediment was sufficient to divert of surface runoff and visibly effect the road. Many other culverts may have been partially blocked during this event, and other fully-blocked culverts may have had little erosional consequence to the road and surrounding hillslope.

Several factors may limit the generality of the findings presented in this study. The basins examined were subject to a specific landuse history that includes roads constructed according to practices that pre-date current standards, with considerable length in midslope positions. Many of these older roads were also constructed in the most geologically unstable portions of the basins. In addition, in the last 30 years, these basins have experienced two significant flood events that have tested the effectiveness of road location and construction practices. The flood of 1964 resulted in numerous road-related landslides in this area (Dyrness, 1967; Swanson and Dyrness, 1975). Finally, there are unique characteristics of this storm that may have contributed to the pattern of erosion found. Snowmelt was synchronized with the period of most intense rainfall only in the lowest elevation zone. More extensive snowmelt might have produced more erosion in these basins. The duration of precipitation during this event was shorter than the 1964 flood, when higher rates of road-related debris slides (e.g. cutslope slides and fillslope

slides) were recorded. Longer-duration precipitation during this storm might have resulted in fillslope slides where slumps occurred, and would have elevated the erosion rate attributed to roads.

The findings presented in this study should, however, be generally applicable to publicly-owned forested lands under federal management in the Pacific Northwest. Road construction on these lands has typically included main-entry roads along the valley floors of most drainage basins and midslope roads that were constructed during a period when harvesting and yarding practices required multiple points of access on hillslopes, with construction practices that have been improved in recent decades (Ruth and Silen, 1950; Silen, 1955; Sessions et al., 1987). The practice of constructing roads on or near ridges has evolved over the last two to three decades with improvements in harvesting technology and a recognition of adverse environmental effects of midslope roads (Sessions, Balcom et al., 1987). The frequency of road-related sedimentation recorded in this study is similar to that found in other studies conducted in the region following this flood. Skaugset et al. (1997) inventoried road-related landslide (e.g. cutslope and fillslope slides) rates that were typically between 0.1 to 0.5 slides/kilometer, although rates ranged from 0 to 1 slide/kilometer in the areas they studied throughout western Oregon. Thiesen et al. (unpublished draft) found similar rates of landsliding and surface erosion on roads in the Klamath River basin in northern California, and noted similar patterns of erosion along a gradient from upper to lower hillslope positions.

Key implications of this study for road engineering and watershed management may be summarized as follows. First, high rates of erosion on midslope roads indicate that these roads constitute a significant concern for erosion, slope stability and associated ecological impacts. Second, the high frequency of failure on valley-floor roads is particularly important, not only because they lie in close proximity to mainstem channels, but also because these roads typically provide access to the entire road network in a drainage basin. In the Lookout Creek watershed, for example, access to most of the 118-kilometer road network was cut off by a debris flow that obliterated a valley-floor road at several sites. Third, the higher frequency of road-related erosion in the Lookout Creek watershed, coupled with the fact that this watershed experienced a higher frequency of

more catastrophic erosion in the form of hillslope slides, fillslope slides, and debris flows suggest that older road location and construction practices contributed to the form and impact of erosion in this basin.

These findings lead to several important interpretations of the geomorphic function and ecological effects of roads (Figure 3.8). Forest roads function both to interrupt flows of water and sediment along hillslopes and channels and to accelerate the rate of erosion in the basins studied. In some cases, the processes that affect roads originate on hillslopes above roads, and road design has little to no influence on their occurrence. In other cases, the types of erosion that occur on roads may be directly attributed to design factors, including oversteepened road cuts and fills placed on steep slopes with high failure potential, culverts undersized to pass water and sediment mobilized during large storms, and high diversion potential (e.g. Furniss et al., 1998) present at many stream crossings. The potential ecological effects of these impacts are an important consideration. When roads interrupt the natural downhill flows of water and sediment, channels may be deprived of sediment or, more importantly, of large wood that provides channel stability and habitat structure. When roads accelerate the rates of erosion, changes in the amount and size distribution of sediment delivered to channels may result.

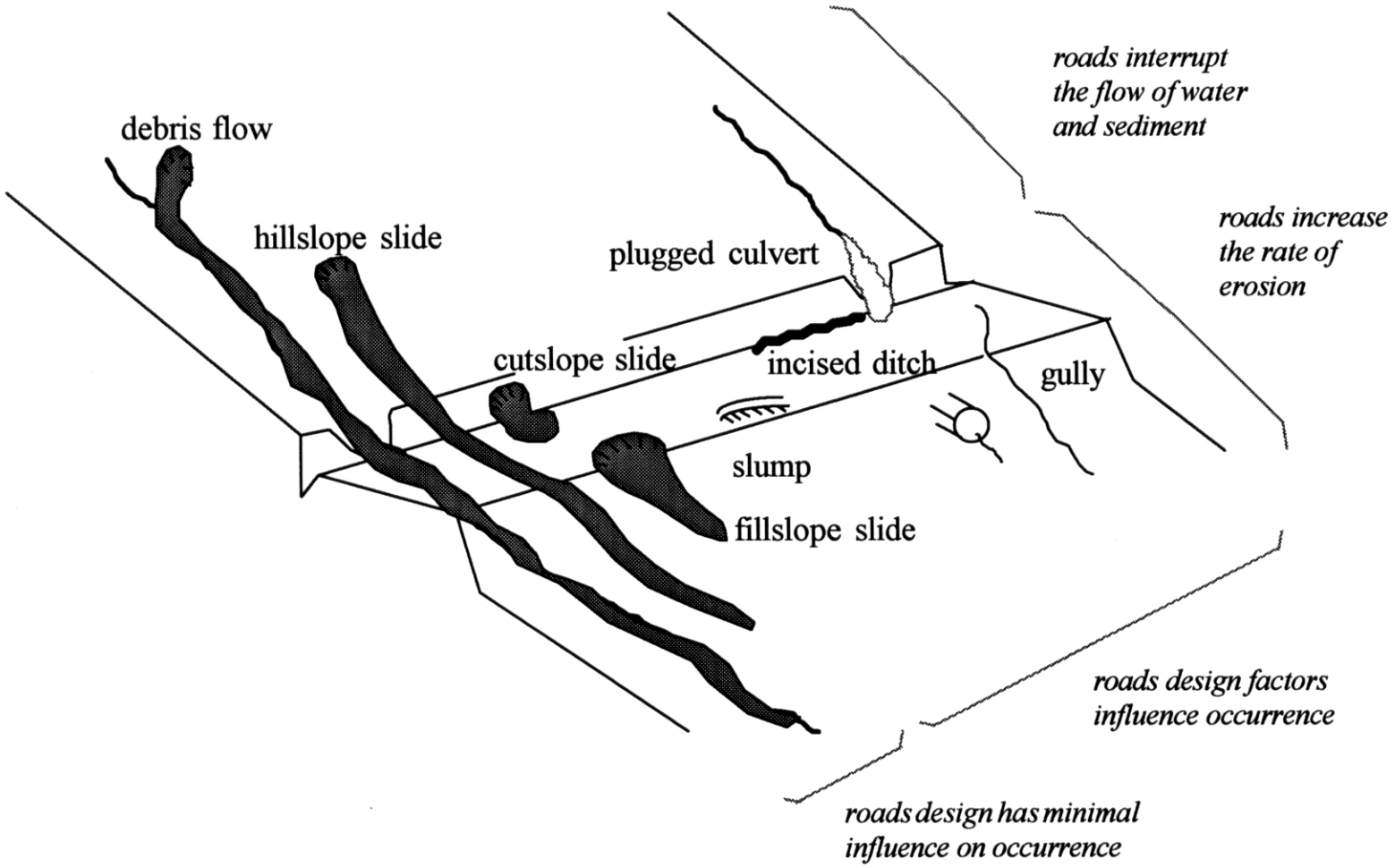


Figure 3.8: Function of forest roads relative to forms of erosion and deposition studied and influence of road design on occurrence of these features.

Chapter 4

Conclusions

4.1 Summary

The central question examined in this research is, how do roads modify the flows of water and sediment in a forested landscape? The studies described in Chapters 2 and 3 were conducted at spatial scales ranging from individual hillslopes (< 0.1 km^2) to large watersheds (181 km^2) and at temporal scales ranging from a single extreme flood to part of a water year.

The analysis presented in Chapter 2 supports a theoretical model of runoff production on roads, driven by subsurface flow intercepted along road cuts. In Watershed 3, a tributary to Lookout Creek, interception of subsurface flow dominated runoff generated on the roads examined, and the magnitude of intercepted runoff was controlled by the area of the contributing hillslope, soil depth, hillslope gradient, road-cut depth, the size of the precipitation event, and antecedent soil moisture conditions. Runoff generated on these roads has larger-scale implications, including possible modification of downstream hydrographs and contribution to slope instability.

The findings presented in Chapter 3 demonstrate the range of erosional processes affected by roads in the Lookout Creek and Blue River watersheds during the February 1996 flood. Roads were involved in eight distinct types of sedimentation, including erosion and deposition by both fluvial and mass wasting processes. Roads constructed prior to 1960 in midslope and valley floor positions experienced the highest frequency of erosion and deposition, and these impacts were concentrated at elevations below 800 m, where storm precipitation was augmented by snowmelt. Roads were involved in complex cascades of associated erosion and deposition that typically resulted from the transformation of debris slides into debris flows, or from the deposition of sediment on roads, diversion of surface runoff, and the initiation of new erosional processes. While

overall roads served as a net source of sediment in these basins, roads functioned as both sources and storage sites for sediment depending upon their location on hillslopes.

4.2 Management Implications

At least three distinct factors relevant to land management in the Pacific Northwest underscore the need for an improved understanding of how roads function in forested basins. First, legal imperatives associated with the protection of threatened and endangered species and changing social values have focused considerable attention on ecosystem restoration and protection in recent years. Road restoration and road removal have received special attention, and guidelines for prioritizing road treatments are needed. Second, reduced maintenance budgets, equipment and staffing have limited the upkeep of currently existing road systems and dramatically reduced funds for new road construction. Finally, the record storms of 1996 highlighted the need to develop storm-proofing measures for existing road networks and to predict sites of likely future storm damage.

There are no simple management prescriptions for minimizing the effects of existing roads, although this research provides insight into important management considerations. Midslope roads deserve particular attention in maintenance or deconstruction efforts, since these roads appear most likely to intercept groundwater, increase erosion, and alter the routing of water and sediment during storms. Maintenance efforts might usefully focus on reducing the opportunity for diversion of water and sediment along roads and roadside ditches, and attention also should be given to reducing the connectivity of roads with streams. Designing drainage structures that can accommodate both wood and sediment, as well as water, is an important need. On valley floor roads, attention should be given to designing drainage structures that would allow for passage of debris flows or excessive bedload, since these roads are critically important for transportation access.

4.3 Future research

This research points to a number of areas for further study. Additional field data are needed to document the conditions leading to subsurface flow interception on roads in other areas. Field studies should be designed to assess the roles of topography, soil properties, and precipitation regimes in driving subsurface flow interception by roads. Field documentation of differences in subsurface flow drainage on hillslopes before and after road construction would be particularly beneficial. The conceptual model developed in Chapter 2 provides a foundation for physically-based numerical modeling of the conditions required to drive formation of perched water tables on steep hillslopes and the interception of subsurface flow along road cuts. Such efforts are likely to provide the most insight if models are used to assess the range of conditions that drive these phenomena and to assess sensitivities of road design and landscape condition to interception of subsurface flow. Finally, modeling efforts at the watershed scale are needed to test potential downstream effects on peak flow generation caused by the interception of subsurface flow along roads.

Additional work is needed to assess the effect of improved road design practices in minimizing the effects of roads on erosion during large floods. These studies should be conducted in a landscape context, in order to disentangle the potentially interactive influences of engineering practices and inherent landscape susceptibility in contributing to the patterns of erosion that result from severe storms. In the Lookout Creek and Blue River basins, more work is needed to assess the delivery of road-derived sediment to channels during the February 1996 flood. Finally, collaborative studies with ecologists should be undertaken to assess the ecological effects of erosional and hydrologic impacts associated with roads.

A management-oriented analytical framework is needed for assessing risks of road-related impacts on hydrologic, geomorphic, and ecological resources. The framework should be adaptable to varied environments and should include tools that allow measurement and quantification of potential road effects. Such tools might include indices

that can be measured in the field and extrapolated spatially using GIS in order to develop objective criteria for road maintenance or deconstruction.

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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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Primary Meteorological Station
ppt (mm/hr)
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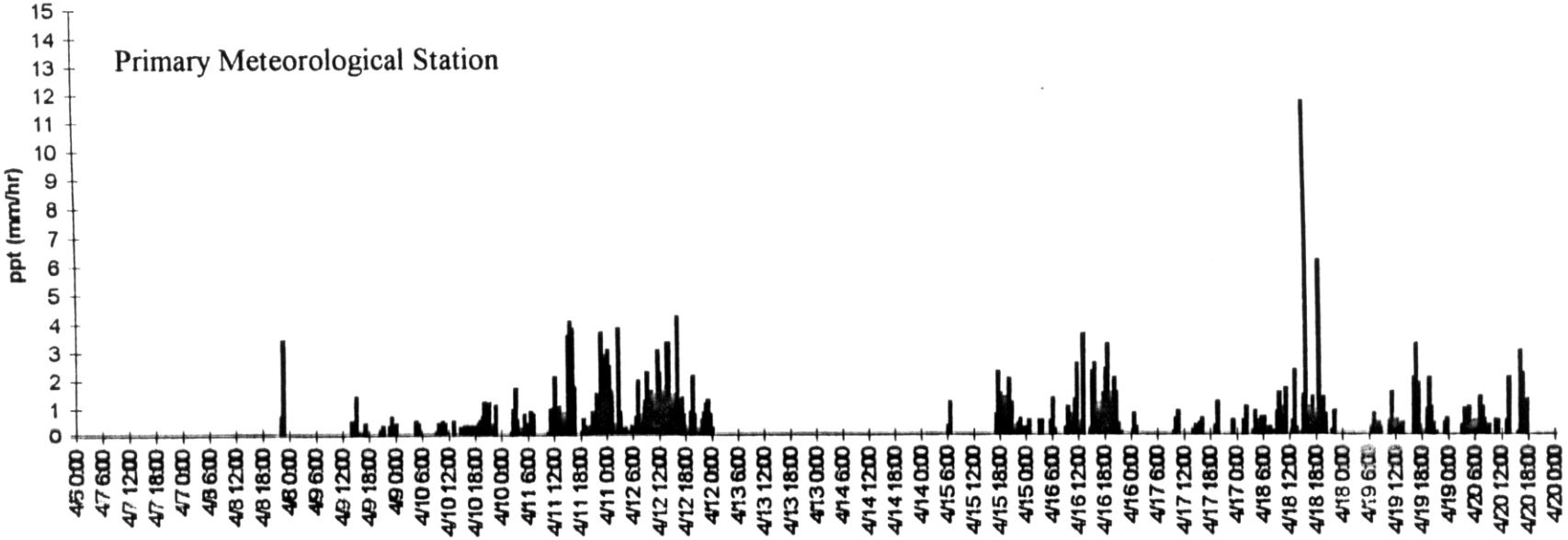
Primary Meteorological Station
ppt (mm/hr)
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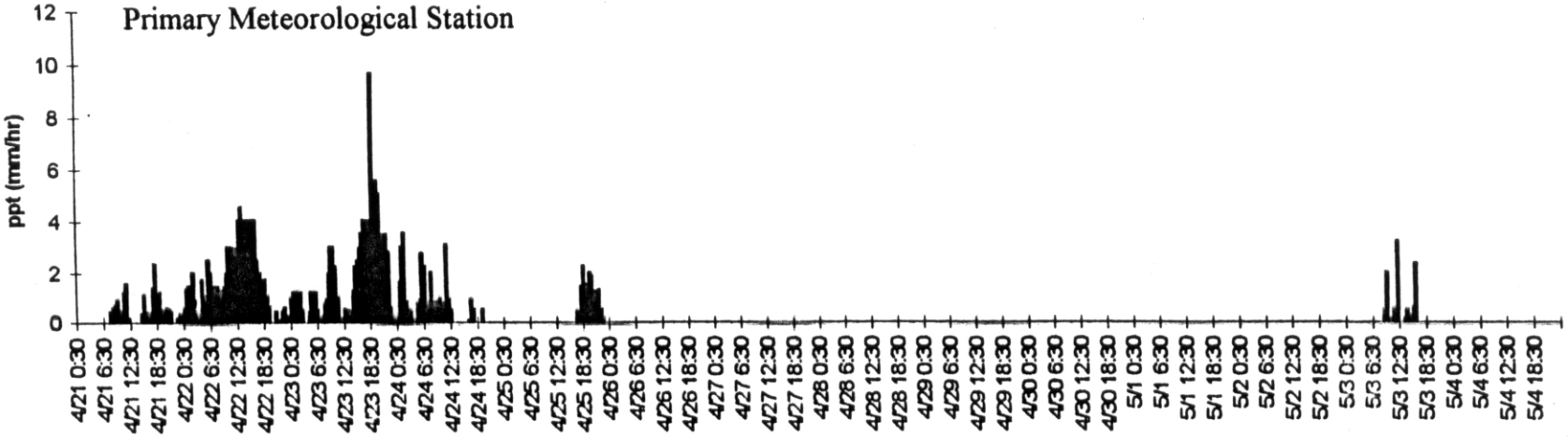
Primary Meteorological Station
ppt (mm/hr)
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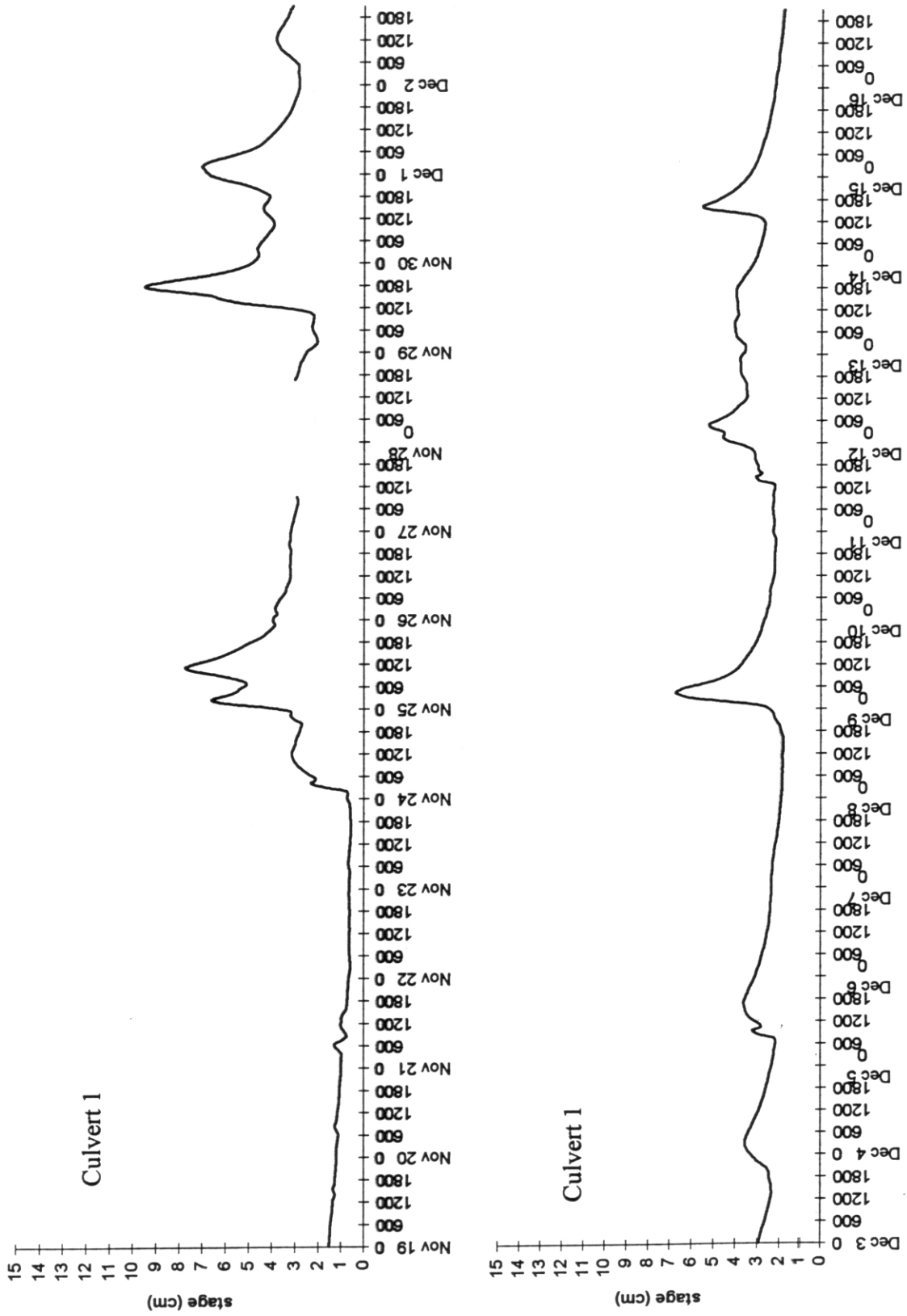
Culvert 1
stage (cm)
0
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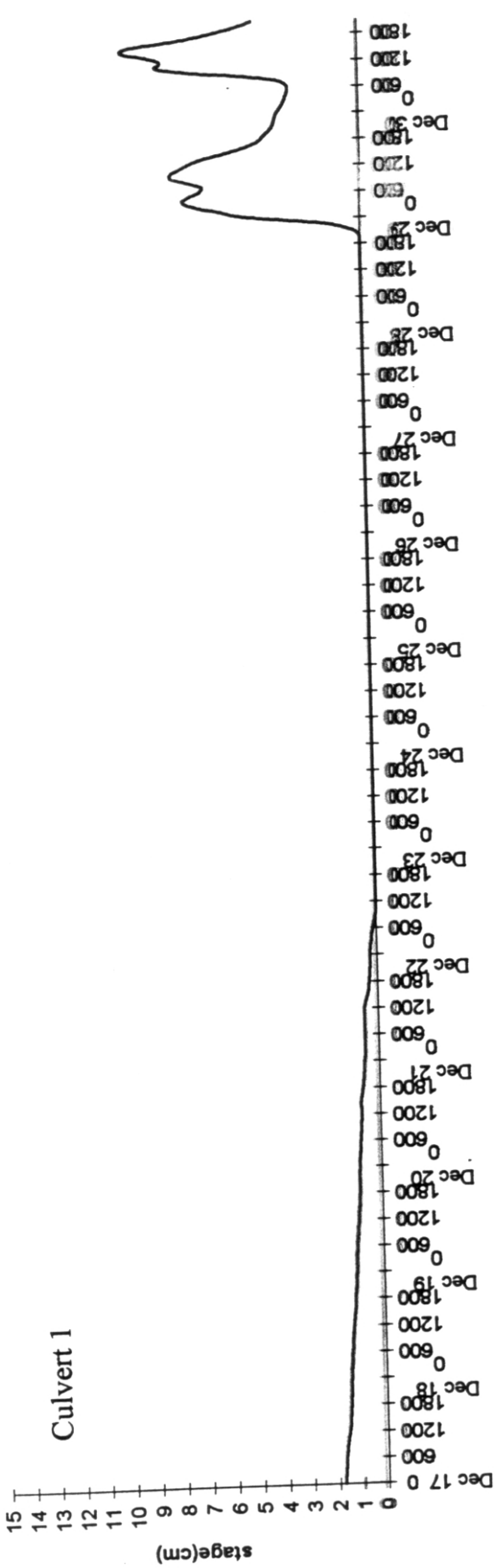
Nov 19 0
Nov 20 0
Nov 21 0
Nov 22 0
Nov 23 0
Nov 24 0
Nov 25 0
Nov 26 0
Nov 27 0
Nov 28 0
Nov 29 0
Nov 30 0
Dec 1 0
Dec 2 0
Culvert 1
stage (cm)
Dec 3 0
Dec 4 0
Dec 5 0
Dec 6 0
Dec 7 0
Dec 8 0
Dec 9 0
Dec 10 0
Dec 11 0
Dec 12 0
Dec 13 0
Dec 14 0
Dec 15 0
Dec 16 0


Culvert 1
stage(cm)
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Dec 17 0
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1200
1800
Dec 18
Dec 19
Dec 20
Dec 21
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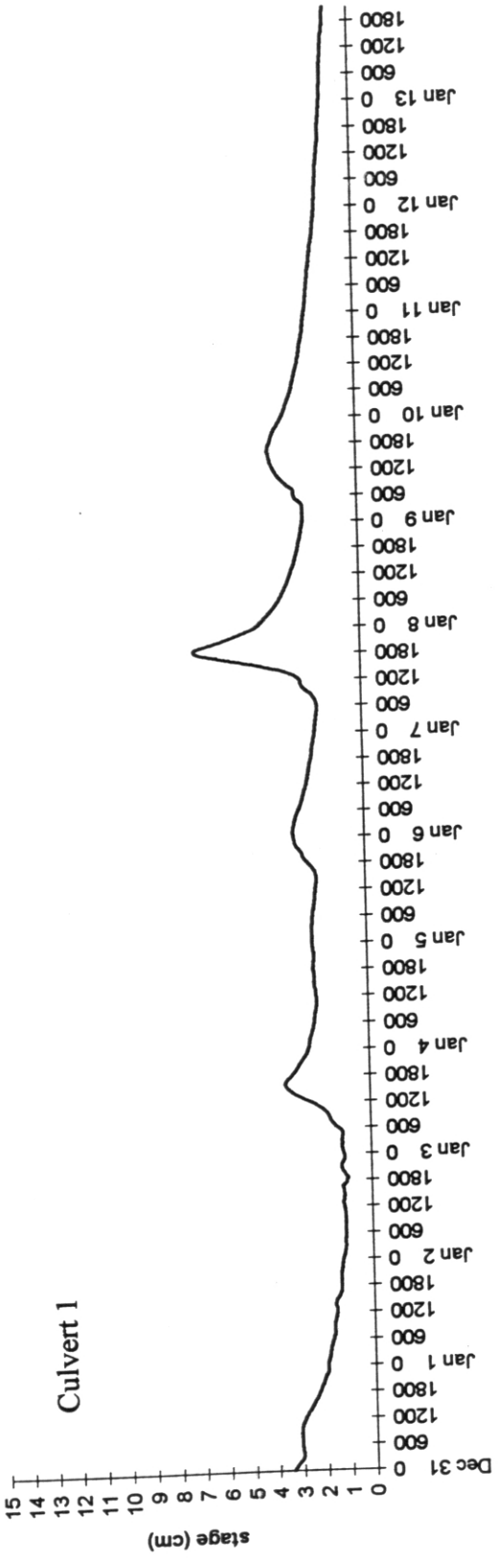
Dec 29
Dec 30


Culvert 1
stage (cm)
0
1
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14
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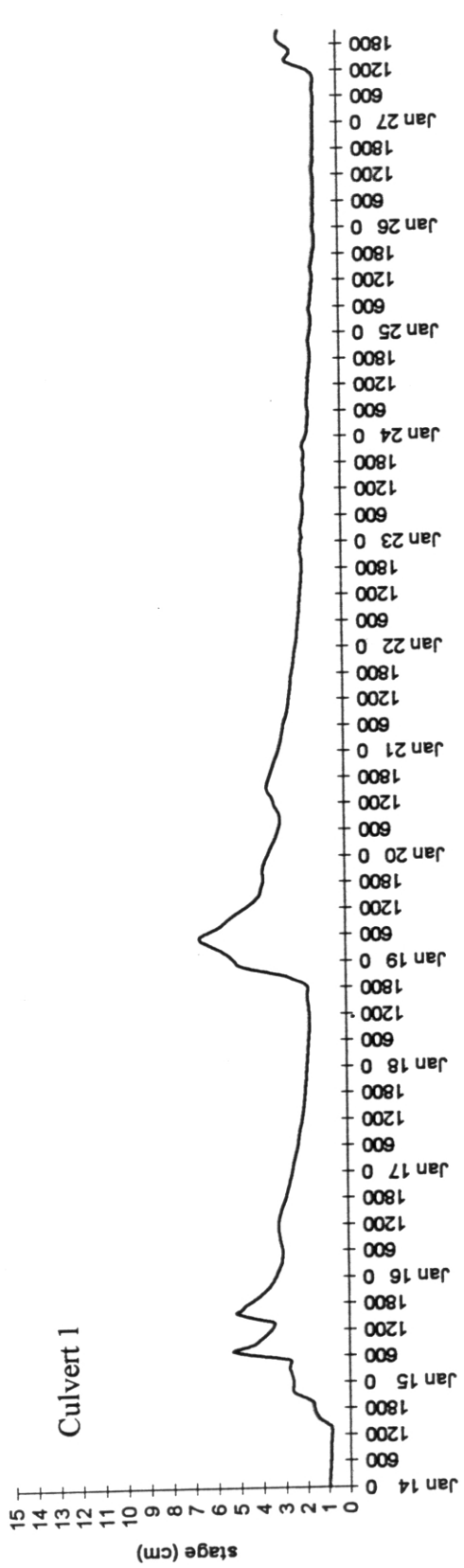
Dec 31 0
600
1200
1800
Jan 1 0
Jan 2 0
Jan 3 0
Jan 4 0
Jan 5 0
Jan 6 0
Jan 7 0
Jan 8 0
Jan 9 0
Jan 10 0
Jan 11 0
Jan 12 0
Jan 13 0


Culvert 1
stage (cm)
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Jan 14 0
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Jan 15 0
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Jan 16 0
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Jan 17 0
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Jan 18 0
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Jan 19 0
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Jan 20 0
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Jan 21 0
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Jan 22 0
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Jan 23 0
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Jan 24 0
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Jan 27 0
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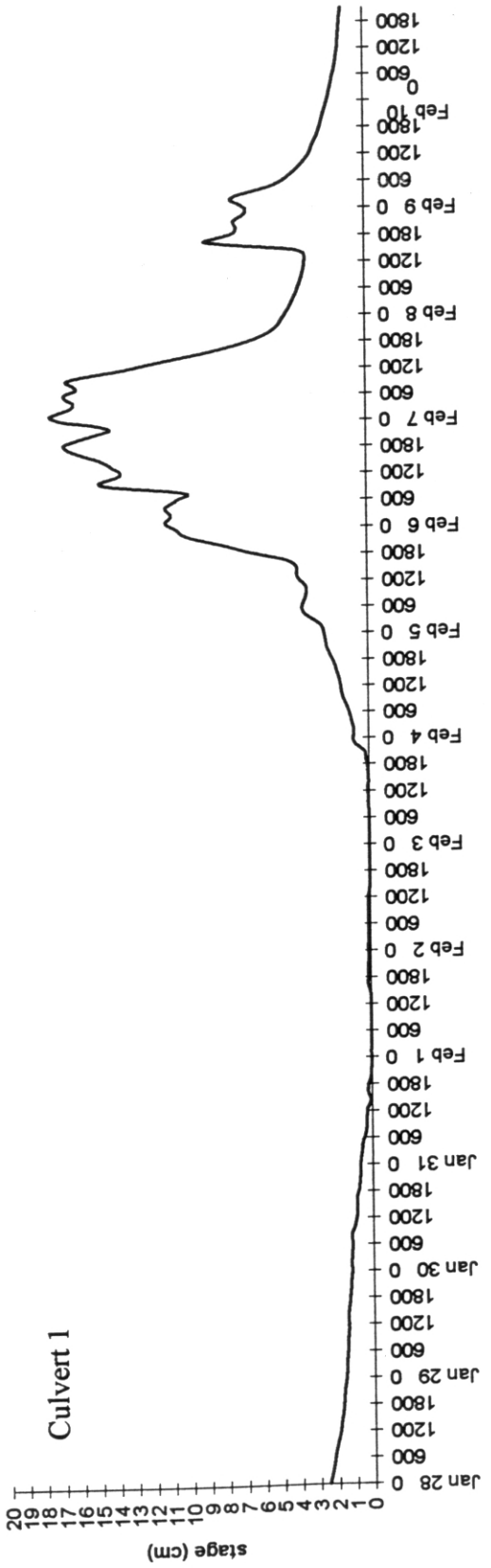
1800


Culvert 1
stage (cm)
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Jan 29 0
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Jan 30 0
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Jan 31 0
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Feb 1 0
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Feb 3 0
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Feb 7 0
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Feb 8 0
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Feb 9 0
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Feb 10
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600
1200
1800

Culvert 1
stage (cm)
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Feb 25 0
600
1200
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Feb 26 0
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1200
1800
Feb 27 0
600
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Feb 28 0
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Feb 29 0
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Mar 1 0
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Mar 2 0
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Mar 3 0
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Mar 4 0
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Mar 5 0
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Mar 6 0
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Mar 7 0
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Mar 8 0
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1200
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Mar 9 0
600
1200
1800

Culvert 1
stage (cm)
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Feb 11 0
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Feb 12 0
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Feb 13 0
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Feb 15 0
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Feb 19 0
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Feb 24 0
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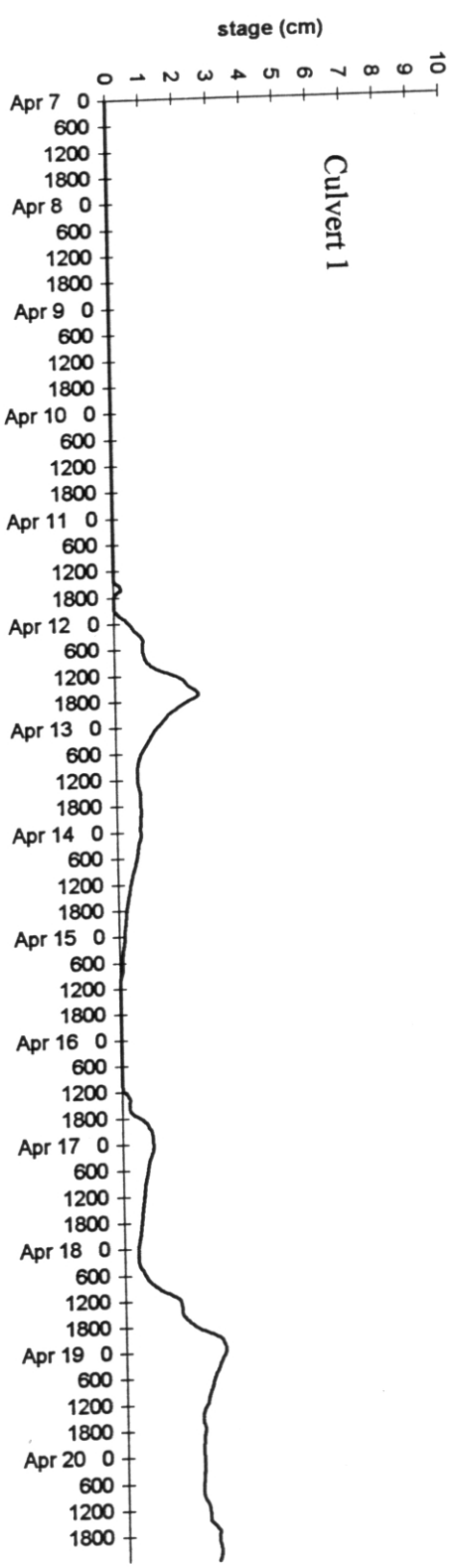
stage (cm)
0 1 2 3 4 5 6 7 8 9 10
Culvert 1
Apr 7 0
600
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1800
Apr 8 0
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Apr 9 0
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1200
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Apr 10 0
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Apr 11 0
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Apr 12 0
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Apr 13 0
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Apr 14 0
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Apr 15 0
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Apr 16 0
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Apr 18 0
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Apr 19 0
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Apr 20 0
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1200
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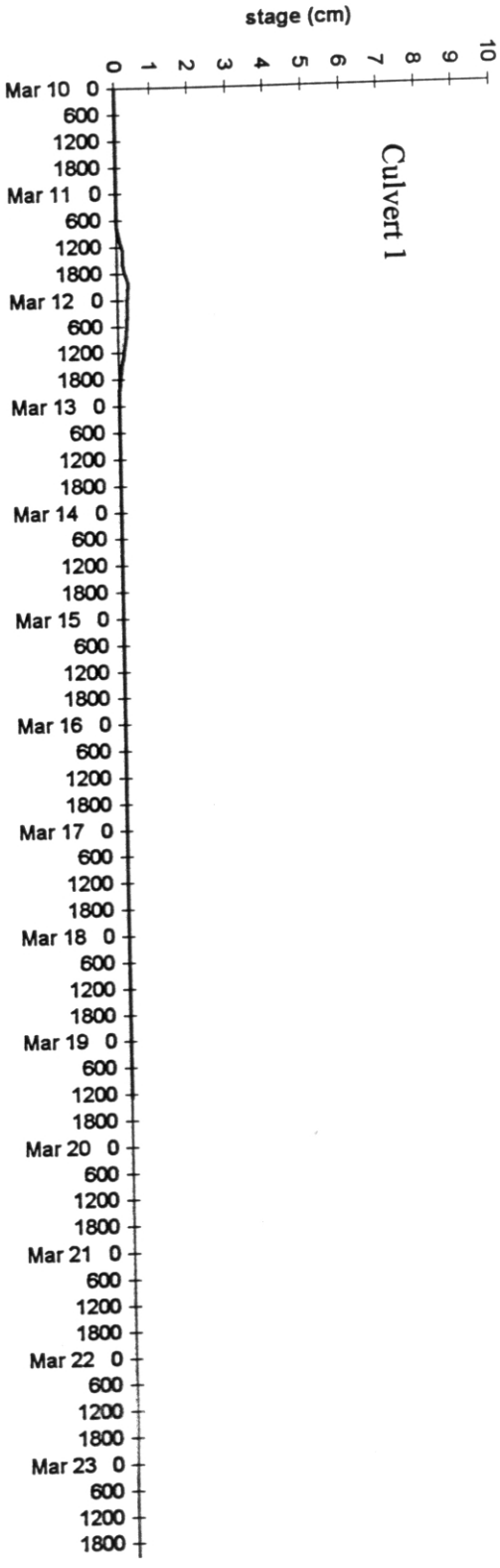
stage (cm)
0 1 2 3 4 5 6 7 8 9 10
Culvert 1
Mar 10 0
600
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Mar 11 0
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Mar 12 0
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1200
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Mar 13 0
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Mar 14 0
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Mar 15 0
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Mar 21 0
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Mar 23 0
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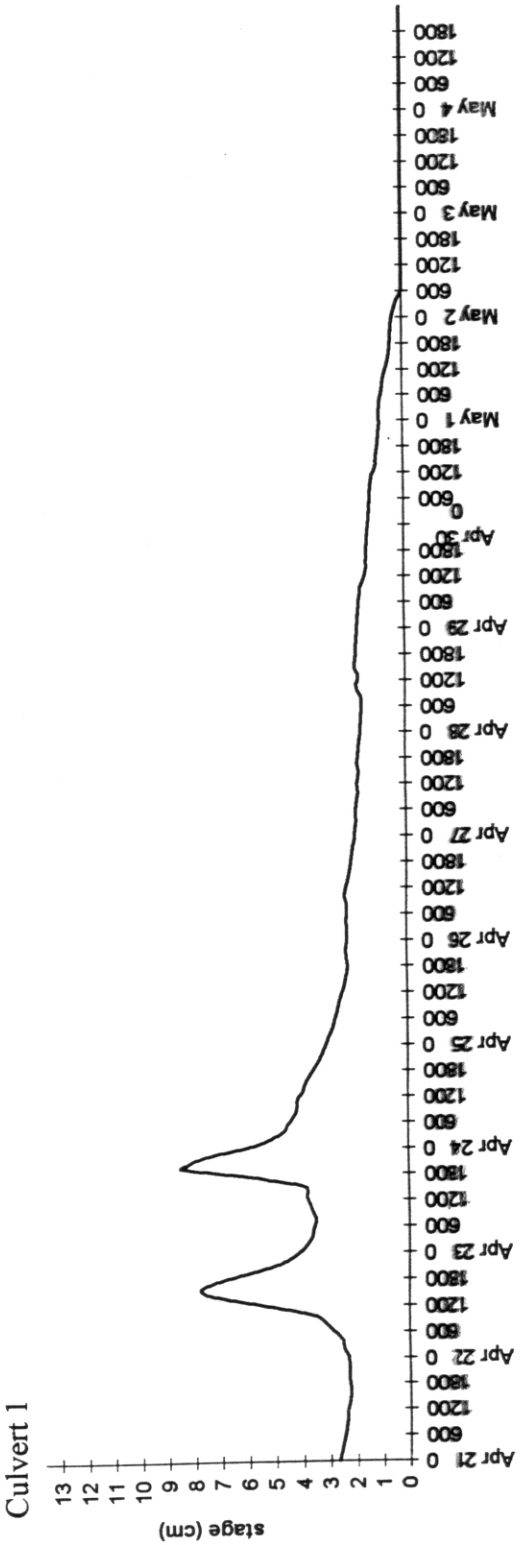
Culvert 1
stage (cm)
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11
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Apr 21 0
Apr 22 0
Apr 23 0
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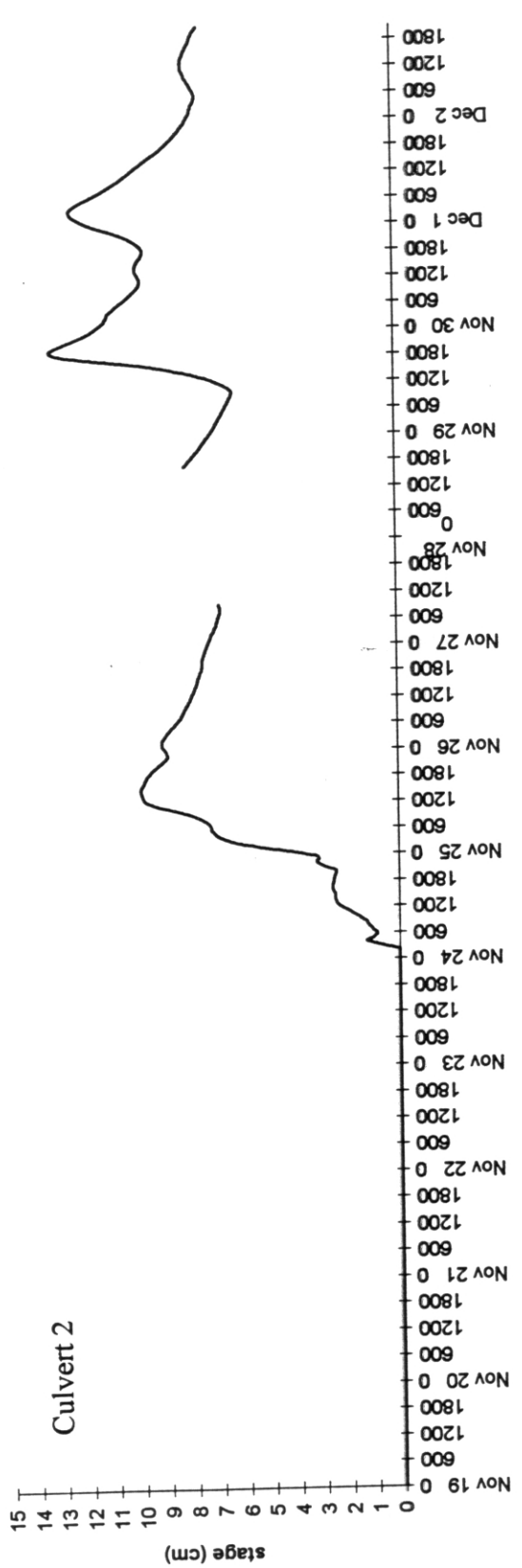
May 4 0
600
1200
1800


Culvert 2
stage (cm)
0
1
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11
12
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14
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Nov 19 0
Nov 20 0
Nov 21 0
Nov 22 0
Nov 23 0
Nov 24 0
Nov 25 0
Nov 26 0
Nov 27 0
Nov 28 0
Nov 29 0
Nov 30 0
Dec 1 0
Dec 2 0
600
1200
1800

Culvert 2
stage (cm)
0
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11
12
13
14
15
Dec 3 0
Dec 4 0
Dec 5 0
Dec 6 0
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Dec 10 0
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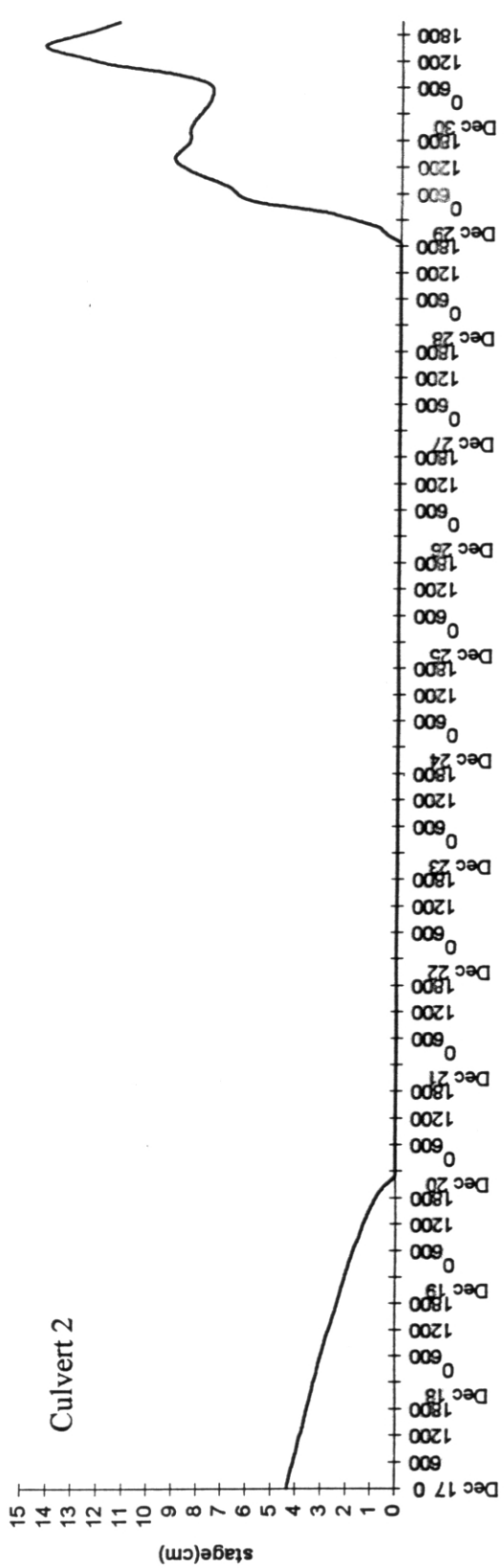
Dec 14 0
Dec 15 0
Dec 16 0
600
1200
1800


Culvert 2
stage(cm)
15
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Dec 17 0
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1800
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Dec 20
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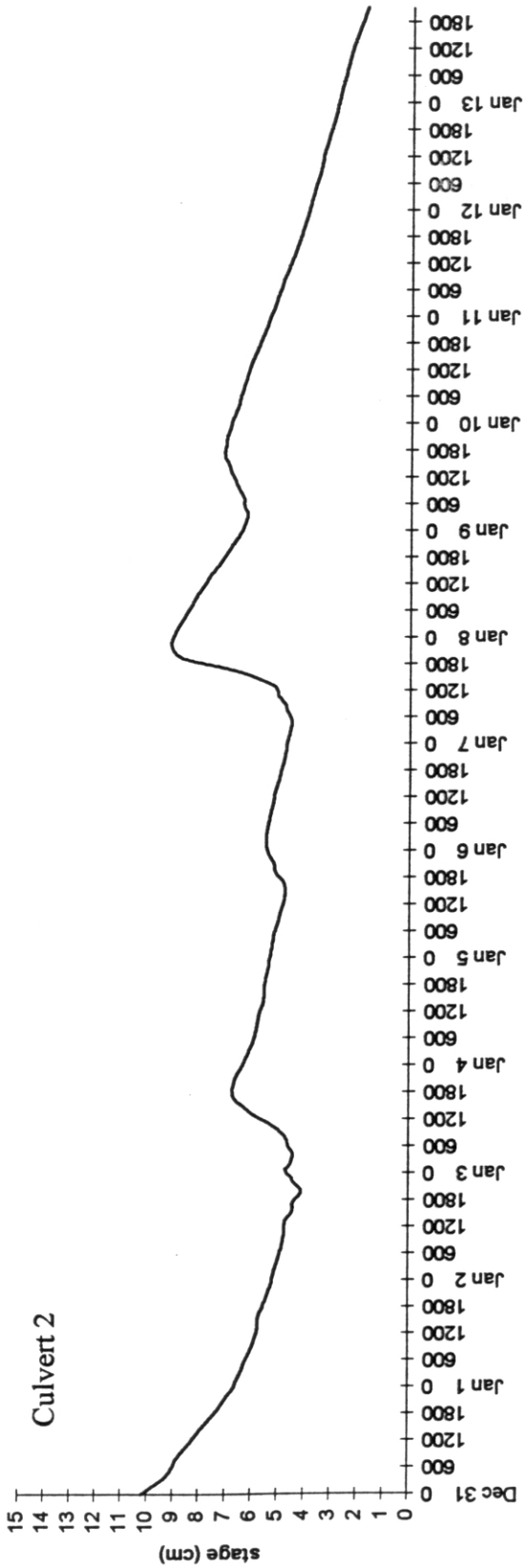
Culvert 2
stage (cm)
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Dec 31 0
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1200
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Jan 1 0
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Jan 5 0
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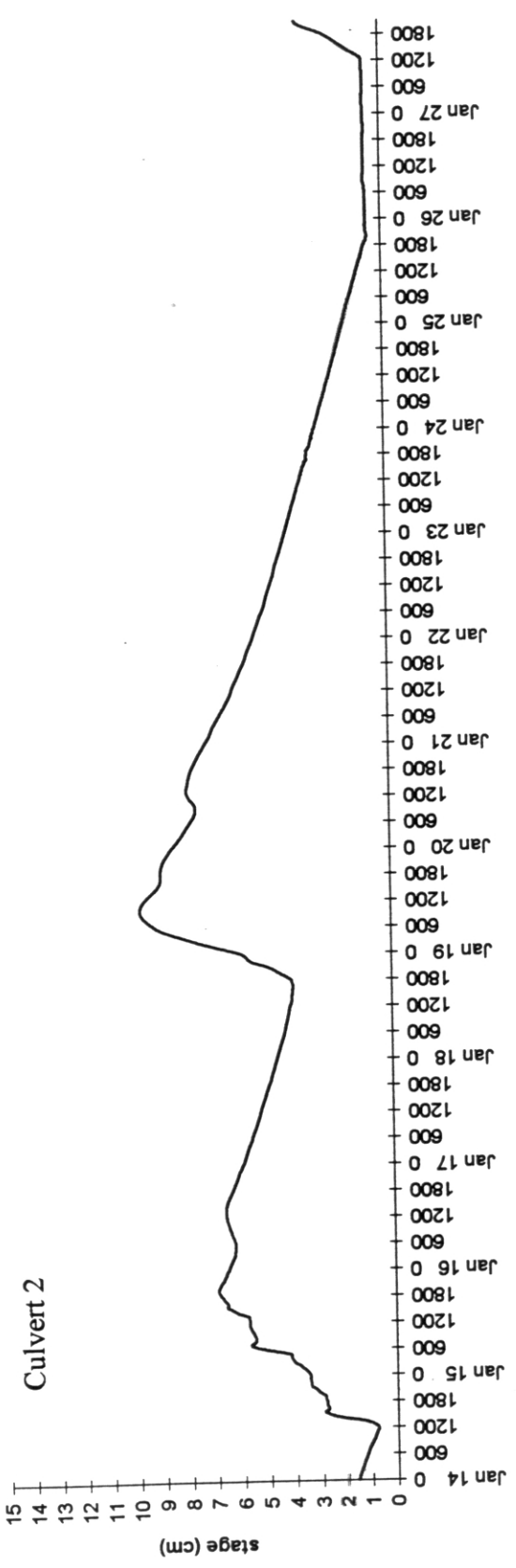
Jan 9 0
Jan 10 0
Jan 11 0
Jan 12 0
Jan 13 0


Culvert 2
stage (cm)
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Jan 14 0
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1800
Jan 15 0
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Jan 16 0
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Jan 17 0
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Jan 18 0
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Jan 19 0
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Jan 20 0
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Jan 21 0
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Jan 23 0
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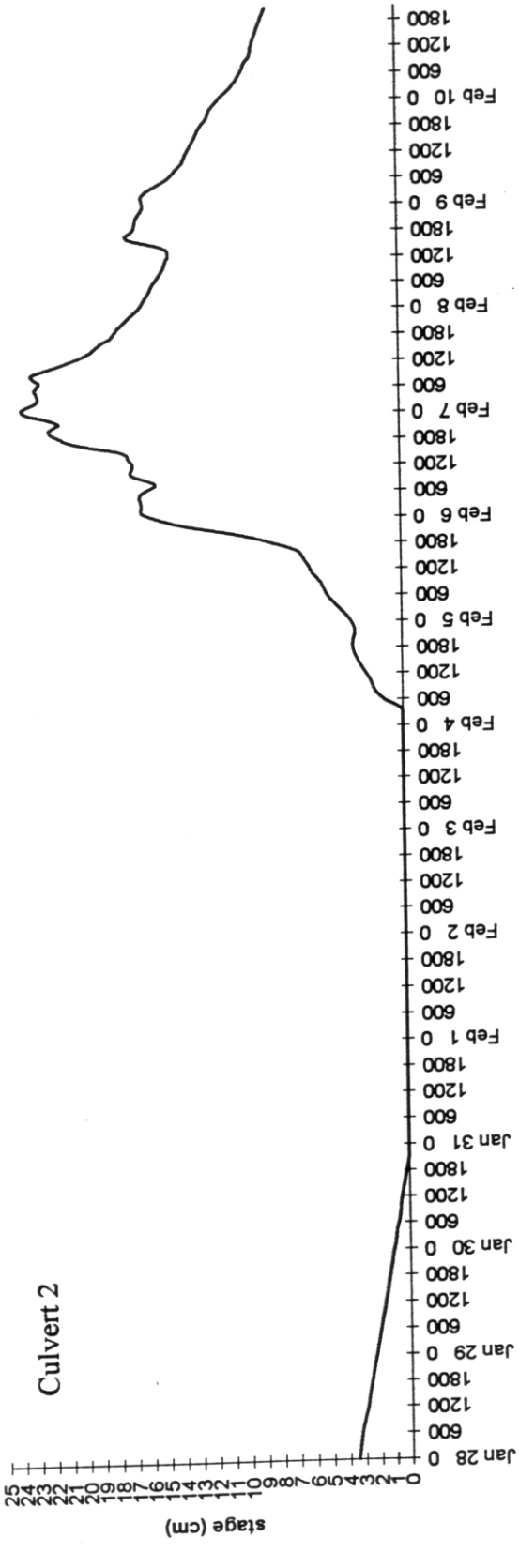
Culvert 2
stage (cm)
0
1
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23
24
25
Jan 28 0
600
1200
1800
Jan 29 0
600
1200
1800
Jan 30 0
600
1200
1800
Jan 31 0
600
1200
1800
Feb 1 0
600
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Feb 2 0
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Feb 3 0
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Feb 4 0
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Feb 5 0
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Feb 6 0
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Feb 7 0
600
1200
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Feb 8 0
600
1200
1800
Feb 9 0
600
1200
1800
Feb 10 0
600
1200
1800

Culvert 2
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
Feb 25 0
600
1200
1800
Feb 26 0
600
1200
1800
Feb 27 0
600
1200
1800
Feb 28 0
600
1200
1800
Feb 29 0
600
1200
1800
Mar 1 0
600
1200
1800
Mar 2 0
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1200
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Mar 3 0
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1200
1800
Mar 4 0
600
1200
1800
Mar 5 0
600
1200
1800
Mar 6 0
600
1200
1800
Mar 7 0
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1200
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Mar 8 0
600
1200
1800
Mar 9 0
600
1200
1800

Culvert 2
stage (cm)
0
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9
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12
13
14
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Feb 11 0
600
1200
1800
Feb 12 0
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Feb 13 0
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Feb 14 0
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Feb 15 0
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Feb 16 0
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Feb 20 0
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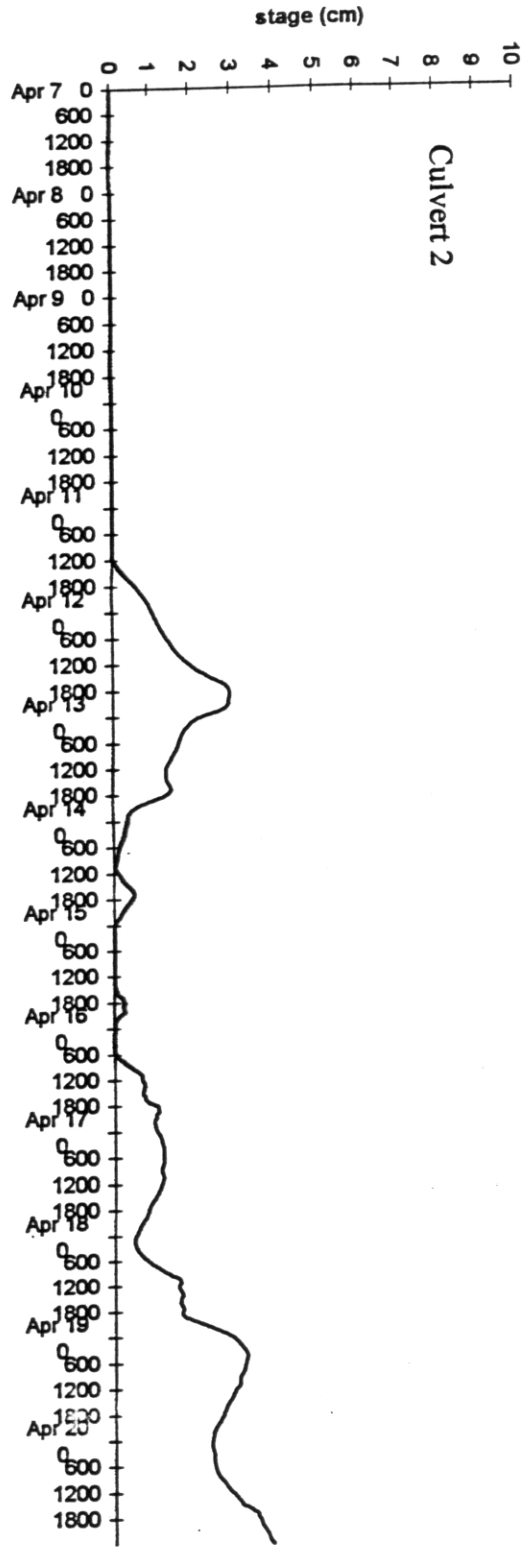
stage (cm)
0 1 2 3 4 5 6 7 8 9 10
Apr 7 0
600
1200
1800
Apr 8 0
600
1200
1800
Apr 9 0
600
1200
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600
1200
1800
Apr 11 0
600
1200
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Apr 12 0
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Apr 13 0
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Apr 14 0
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Apr 15 0
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Apr 16 0
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1200
1800
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1800
Apr 20 0
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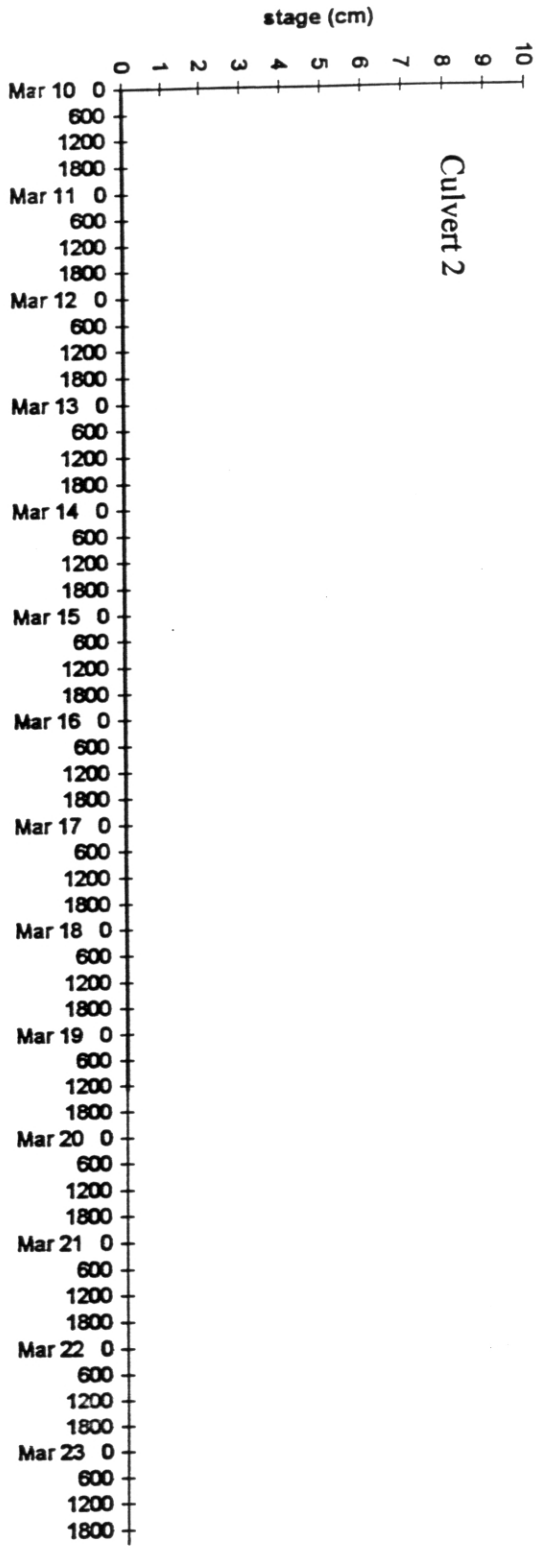
1200
1800
Culvert 2


stage (cm)
0 1 2 3 4 5 6 7 8 9 10
Mar 10 0
600
1200
1800
Mar 11 0
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1200
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Mar 12 0
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Mar 13 0
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Mar 14 0
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Mar 15 0
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Mar 16 0
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Mar 18 0
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Mar 19 0
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Mar 22 0
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Mar 23 0
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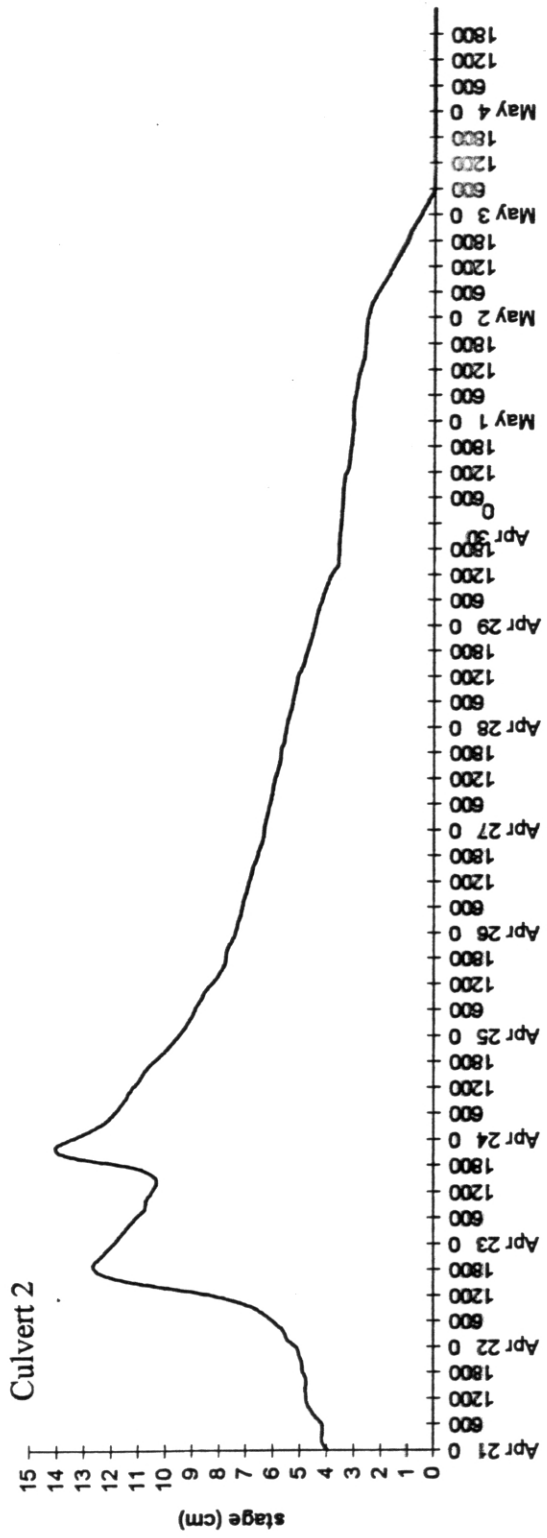
1200
1800
Culvert 2


Culvert 2
stage (cm)
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12
13
14
15
Apr 21 0
Apr 22 0
Apr 23 0
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May 2 0
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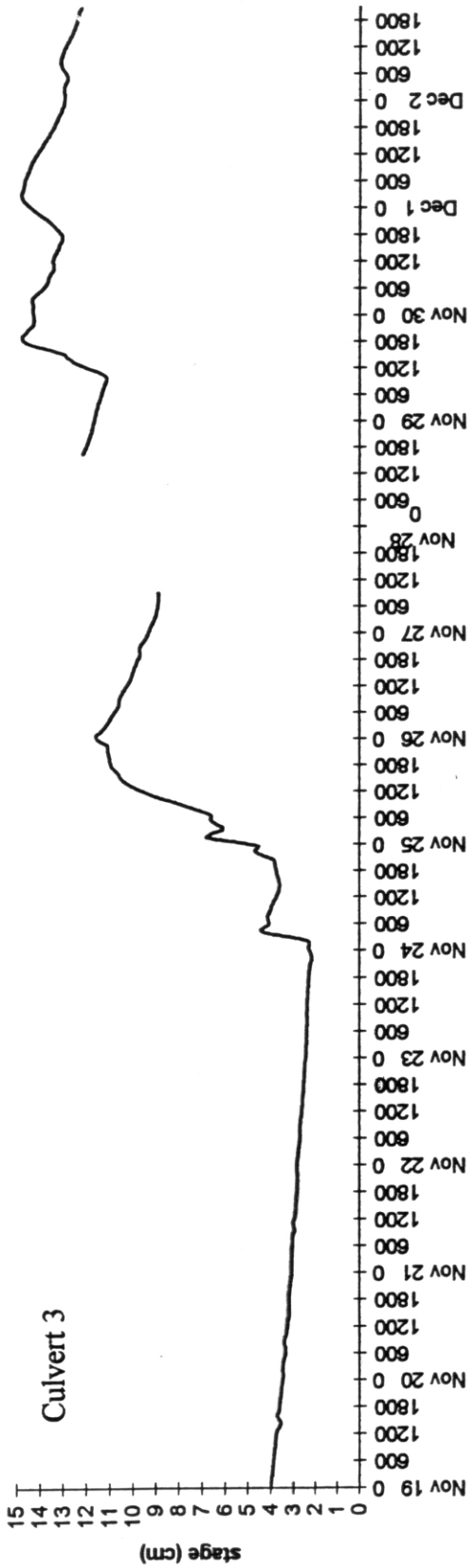
1200
1800


Culvert 3
stage (cm)
0
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Nov 19 0
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1200
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Nov 20 0
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Nov 21 0
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Nov 22 0
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Nov 23 0
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Nov 24 0
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Nov 27 0
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Nov 29 0
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Nov 30 0
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Dec 1 0
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1200
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Dec 2 0
600
1200
1800

Culvert 3
stage (cm)
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14
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Dec 3 0
600
1200
1800
Dec 4 0
600
1200
1800
Dec 5 0
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Dec 6 0
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Dec 7 0
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Dec 11 0
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Dec 12 0
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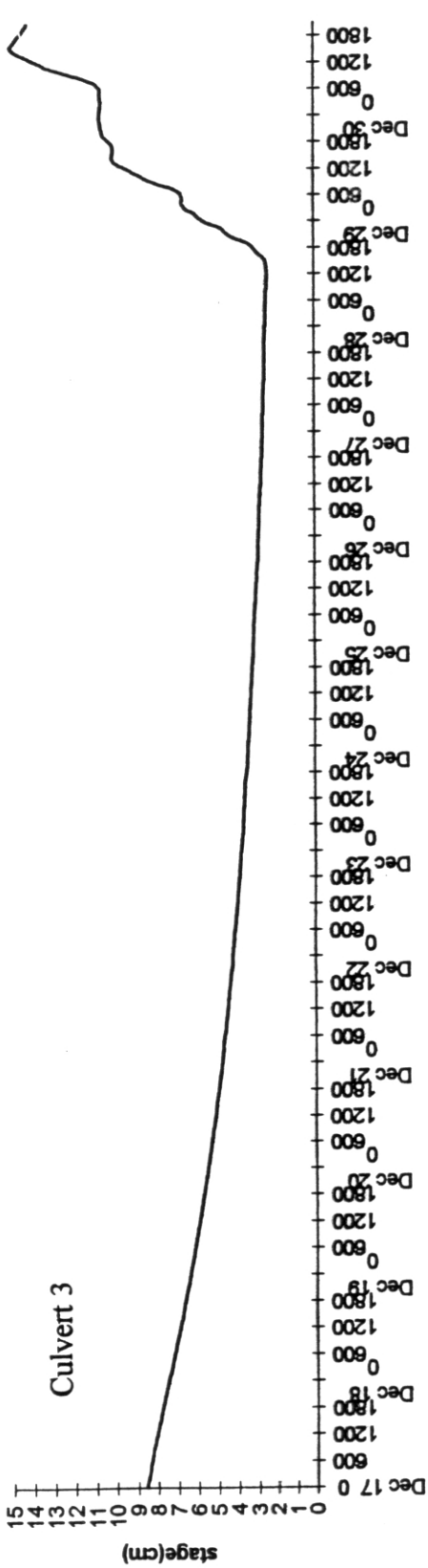
Culvert 3
stage(cm)
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Dec 17 0
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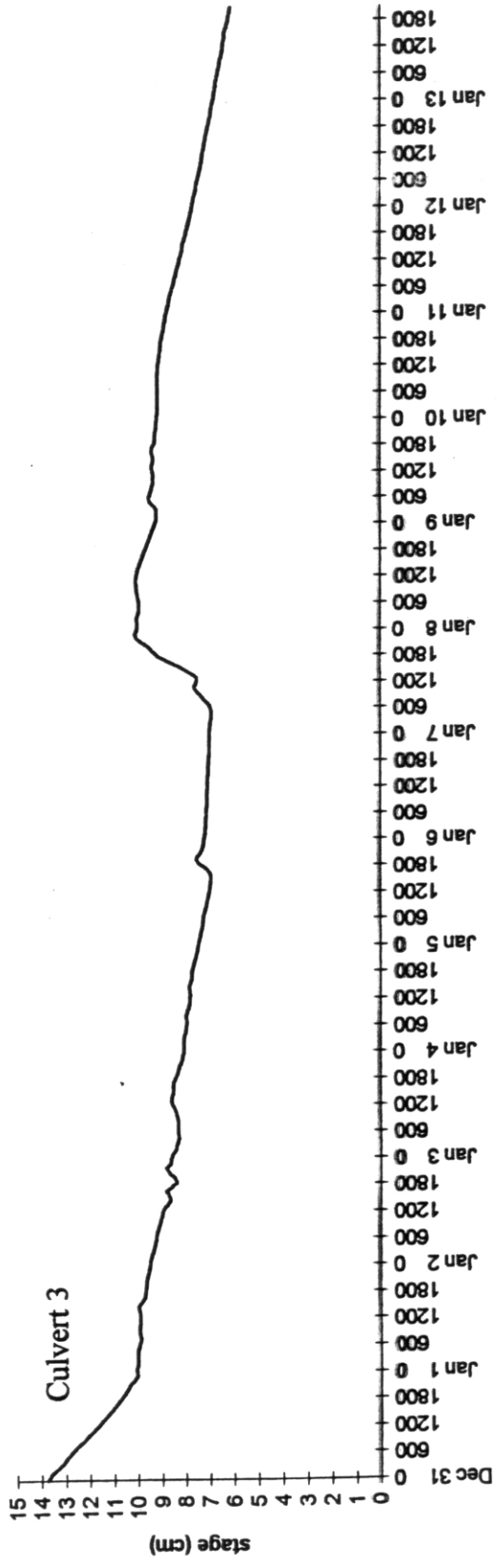
Culvert 3
stage (cm)
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14
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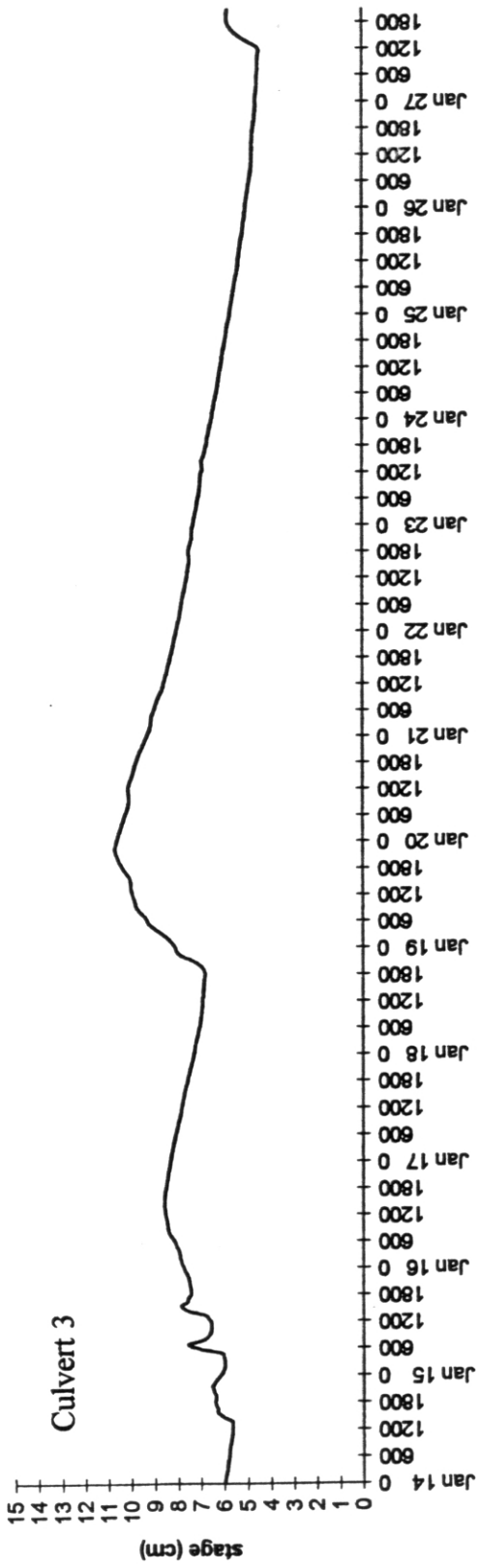
Dec 31 0
600
1200
1800
Jan 1 0
Jan 2 0
Jan 3 0
Jan 4 0
Jan 5 0
Jan 6 0
Jan 7 0
Jan 8 0
Jan 9 0
Jan 10 0
Jan 11 0
Jan 12 0
Jan 13 0


Culvert 3
stage (cm)
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Jan 14 0
Jan 15 0
Jan 16 0
Jan 17 0
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Jan 21 0
Jan 22 0
Jan 23 0
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Jan 25 0
Jan 26 0
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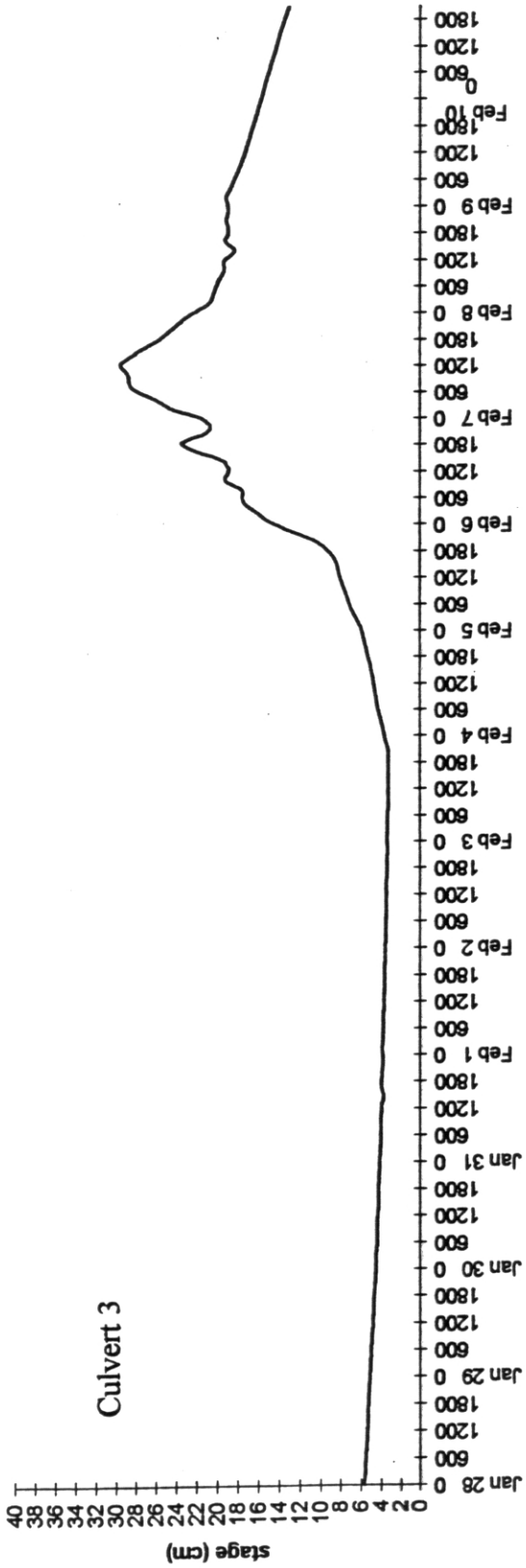
600
1200
1800


Culvert 3
stage (cm)
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Jan 28 0
Jan 29 0
Jan 30 0
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Feb 5 0
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Feb 8 0
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Feb 10
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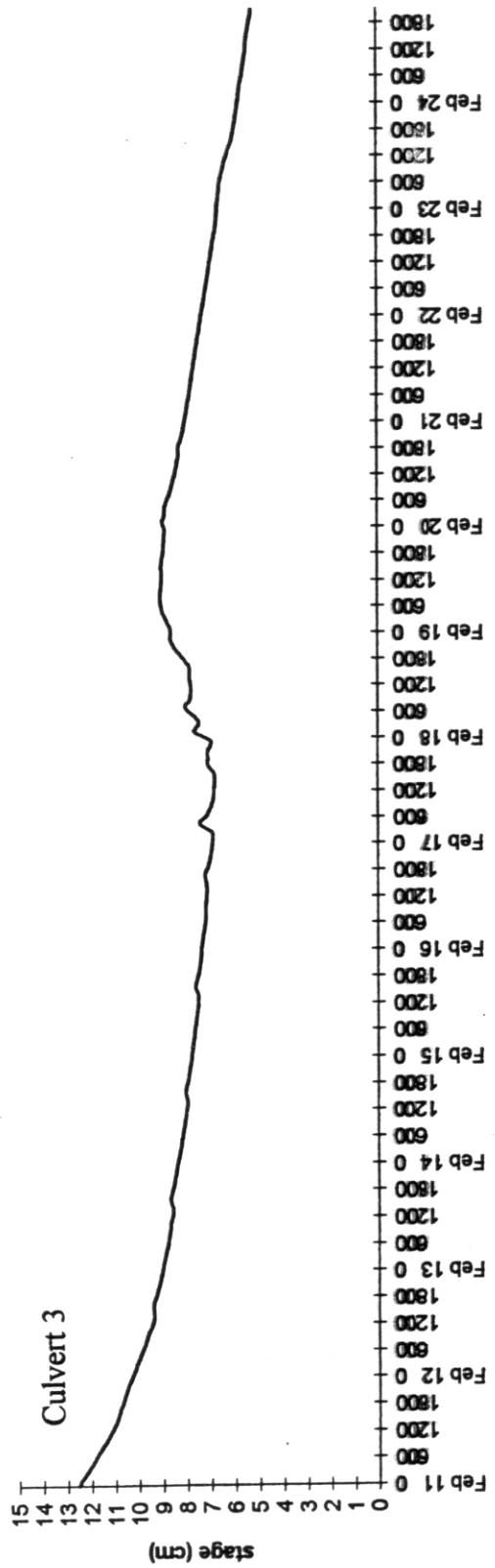
1200
1800


Culvert 3
stage (cm)
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Feb 25 0
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Feb 26 0
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Feb 27 0
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Feb 28 0
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Feb 29 0
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Mar 1 0
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Mar 2 0
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Mar 3 0
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Mar 4 0
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Mar 5 0
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Mar 6 0
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Mar 8 0
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Mar 9 0
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1200
1800

Culvert 3
stage (cm)
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Feb 11 0
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Feb 12 0
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Feb 13 0
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Feb 14 0
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Feb 15 0
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Feb 16 0
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Feb 20 0
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1200
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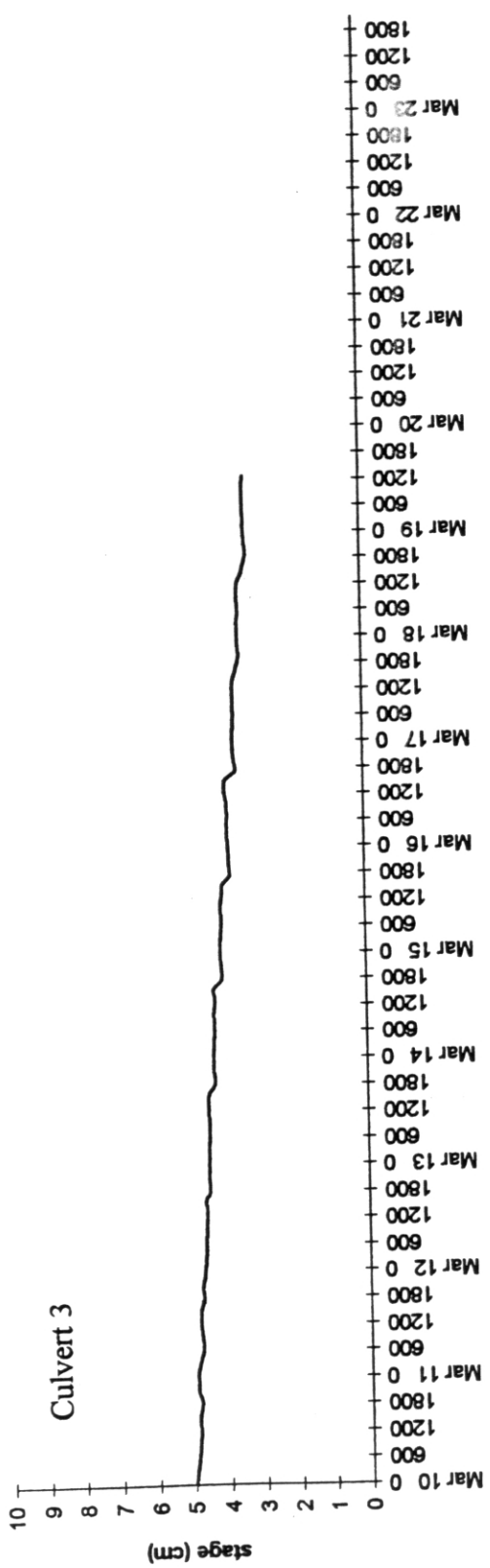
Culvert 3
stage (cm)
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Mar 10 0
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Mar 11 0
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Mar 12 0
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Mar 13 0
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Mar 14 0
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Mar 15 0
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Mar 19 0
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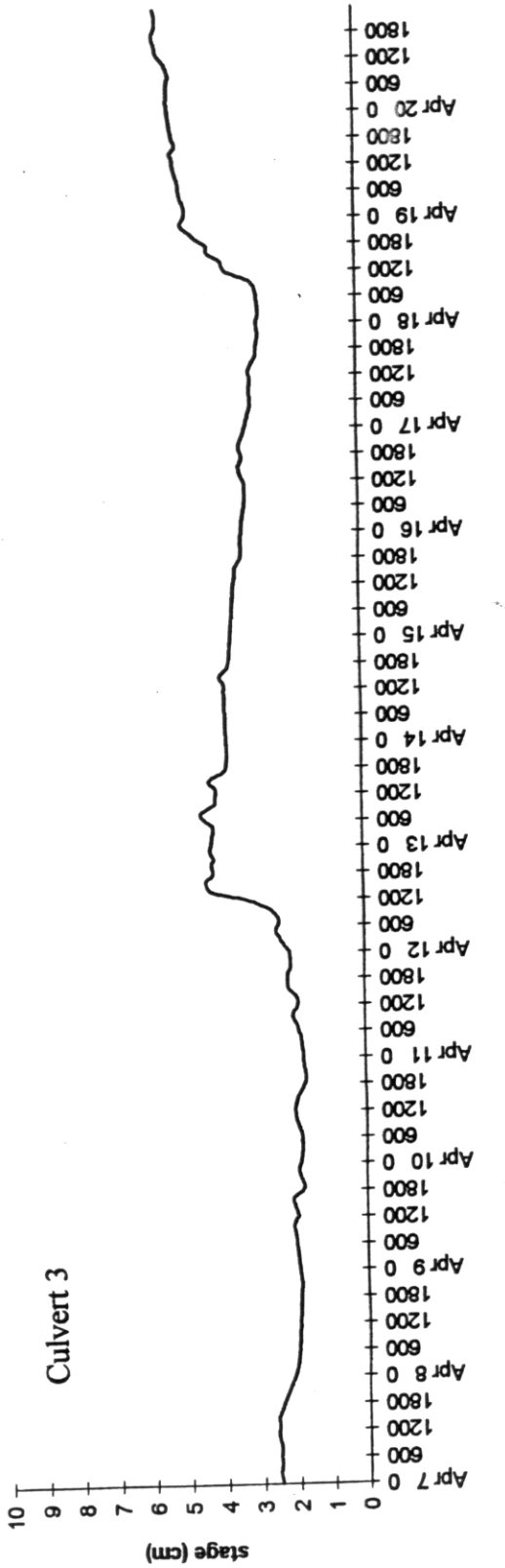
Culvert 3
stage (cm)
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Apr 7 0
1800
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600
Apr 8 0
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Apr 9 0
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Apr 10 0
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Apr 11 0
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Apr 12 0
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Apr 16 0
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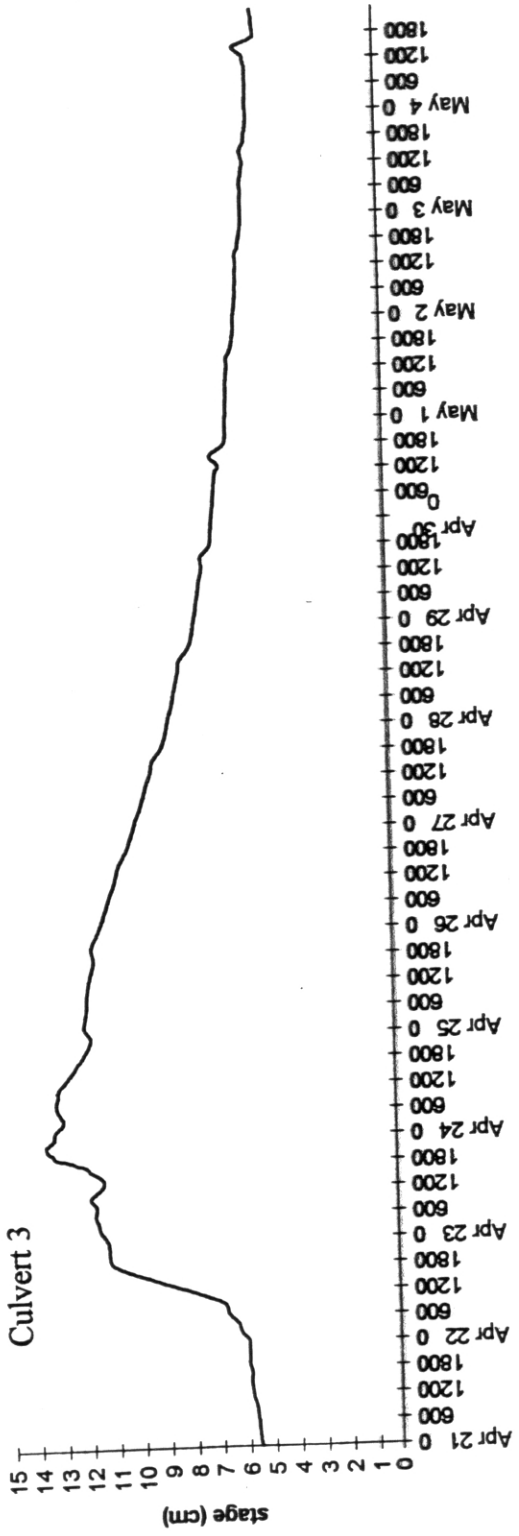
Culvert 3
stage (cm)
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Apr 21 0
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Apr 22 0
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Apr 26 0
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Apr 29 0
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Apr 30
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May 4 0
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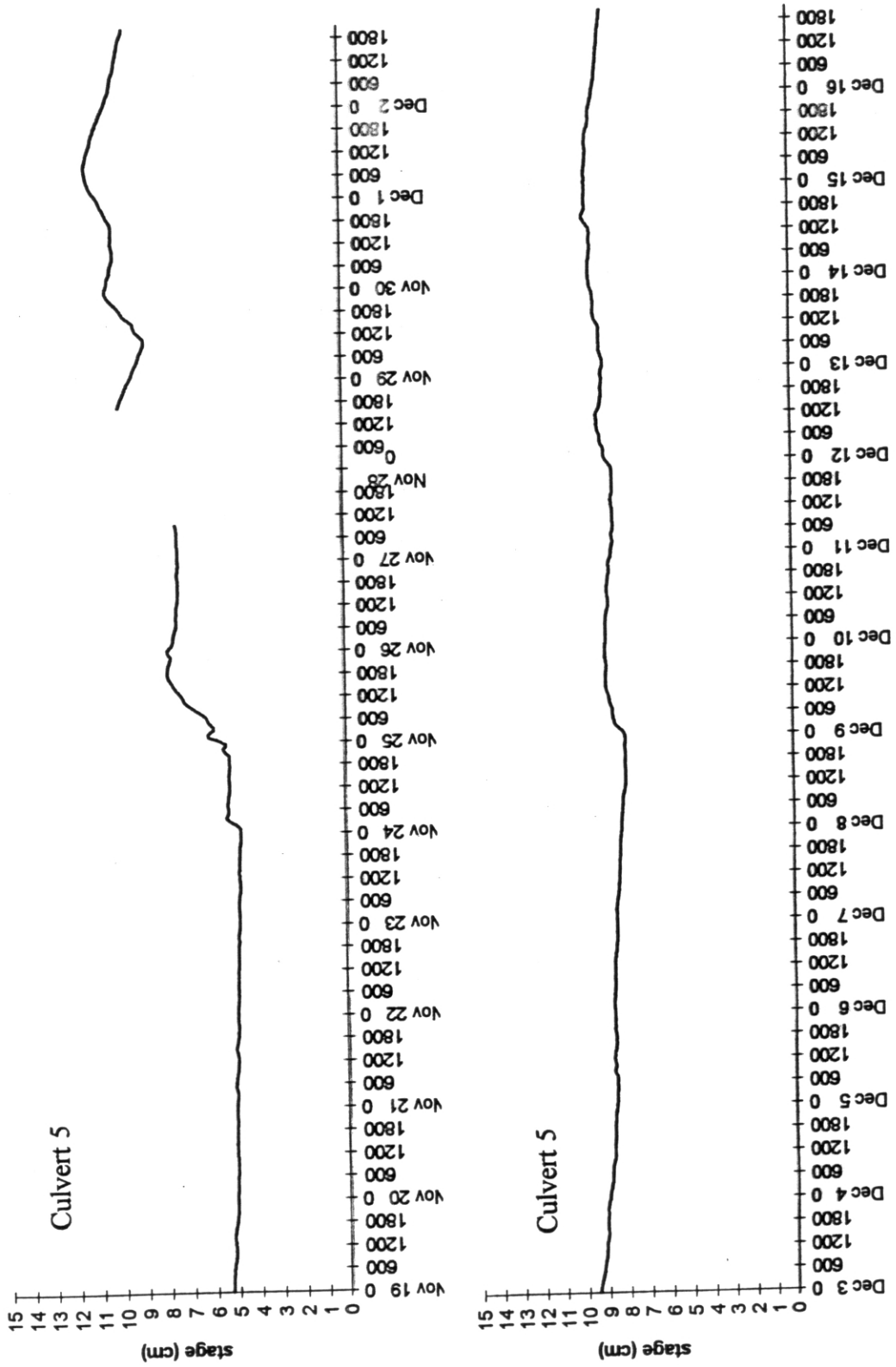
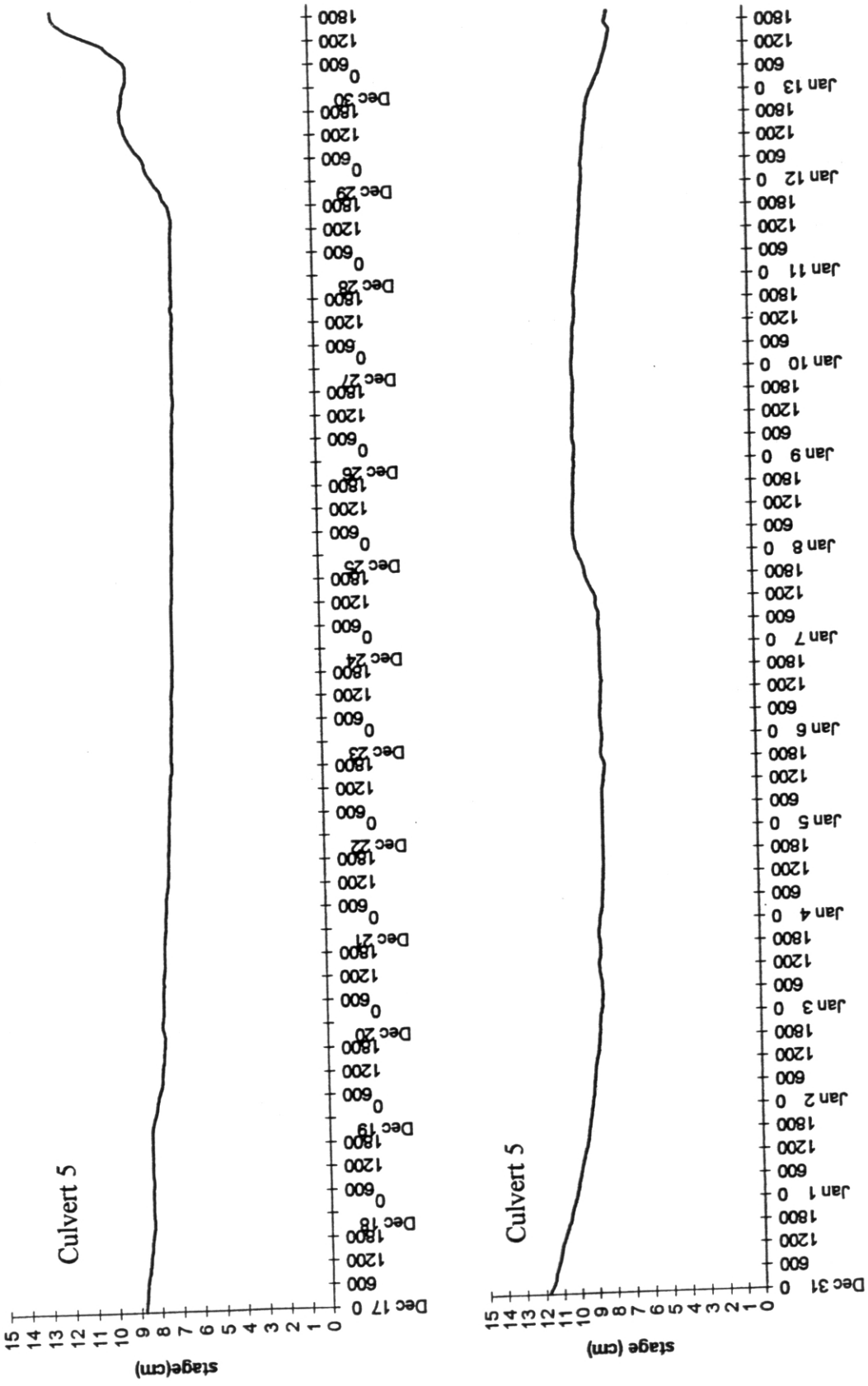
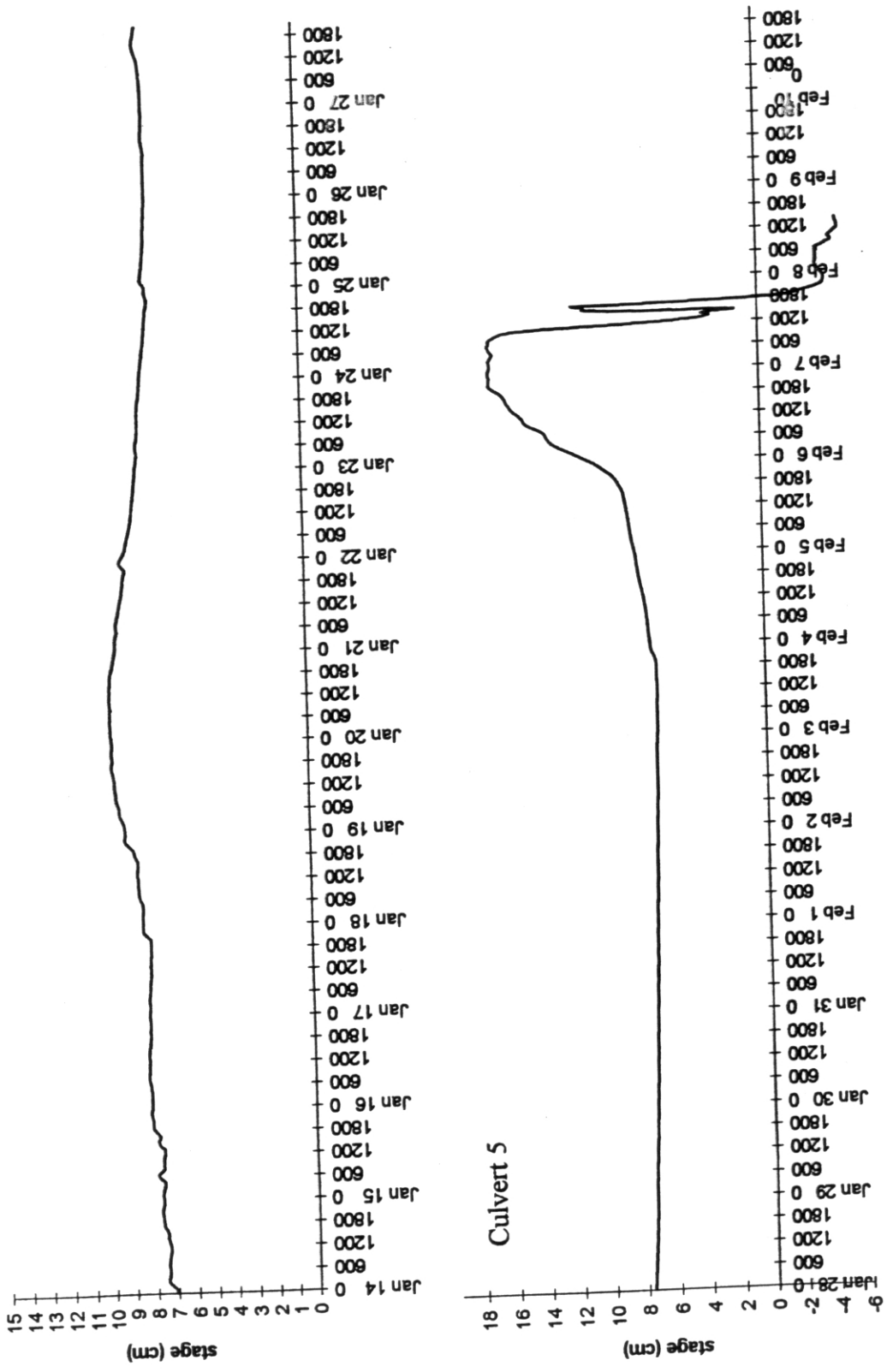
1800


Culvert 5
stage (cm)
Culvert 5
stage (cm)


Culvert 5
stage (cm)
Culvert 5
stage(cm)


Culvert 5
stage (cm)
stage (cm)

Culvert 7
stage (cm)
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14
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Nov 19 0
Nov 20 0
Nov 21 0
Nov 22 0
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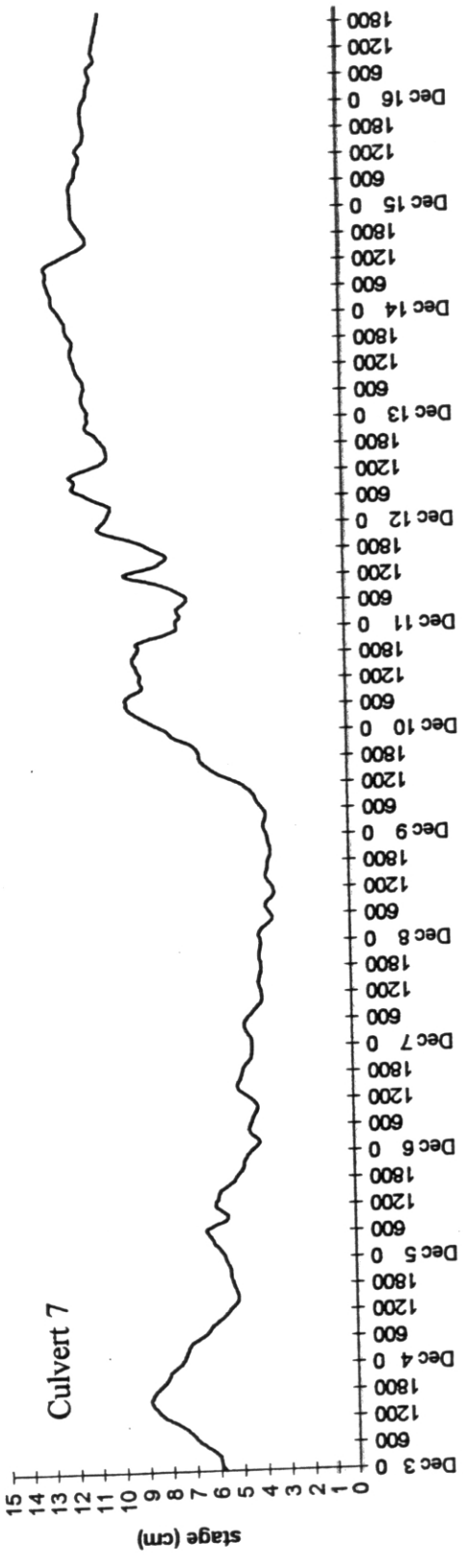
Nov 30 0
Dec 1 0
Dec 2 0
600
1200
1800


Culvert 7
stage (cm)
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Dec 3 0
Dec 4 0
Dec 5 0
Dec 6 0
Dec 7 0
Dec 8 0
Dec 9 0
Dec 10 0
Dec 11 0
Dec 12 0
Dec 13 0
Dec 14 0
Dec 15 0
Dec 16 0
600
1200
1800

Culvert 7
stage (cm)
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Dec 17 0
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Dec 18
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Dec 31
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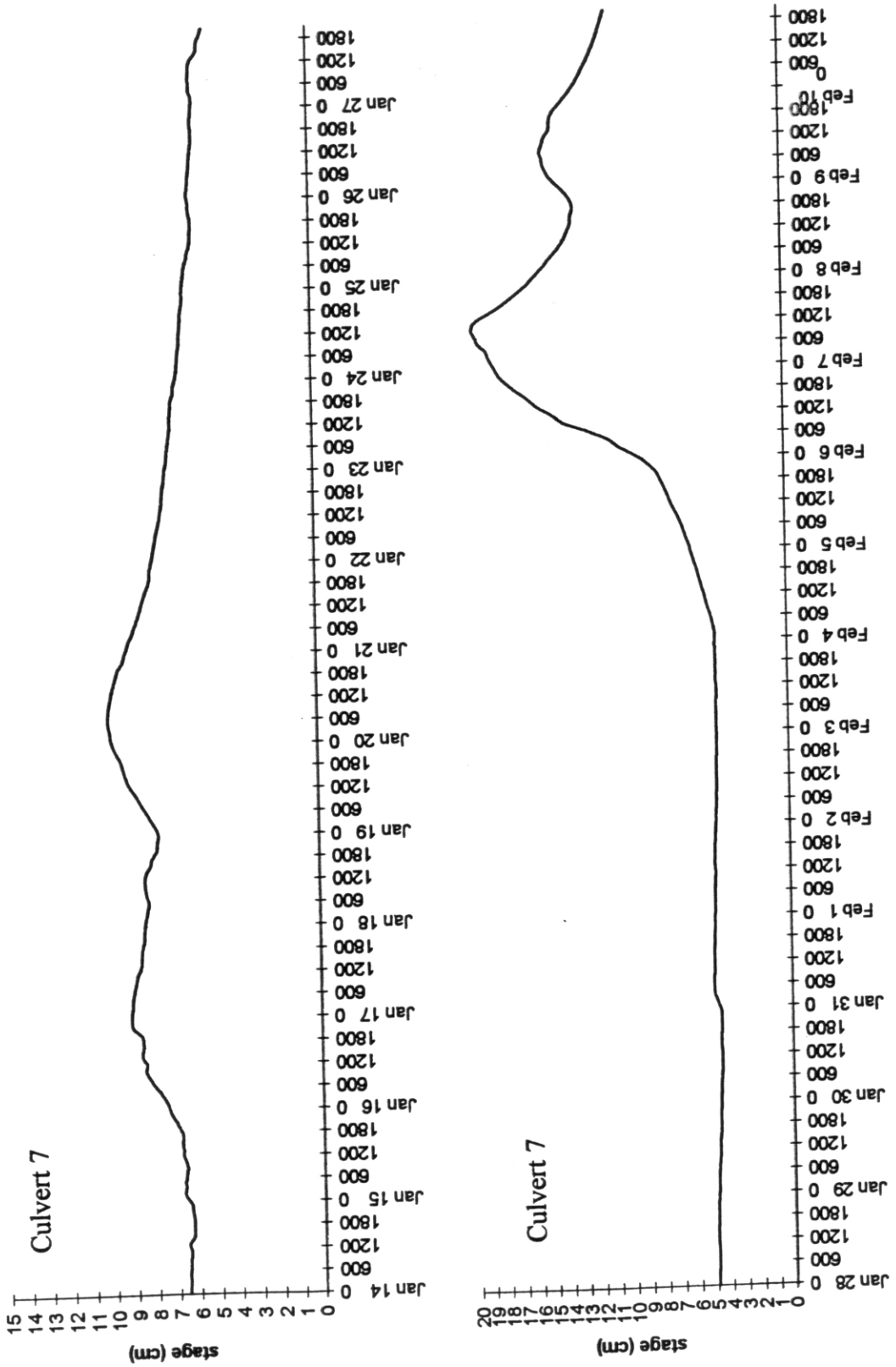
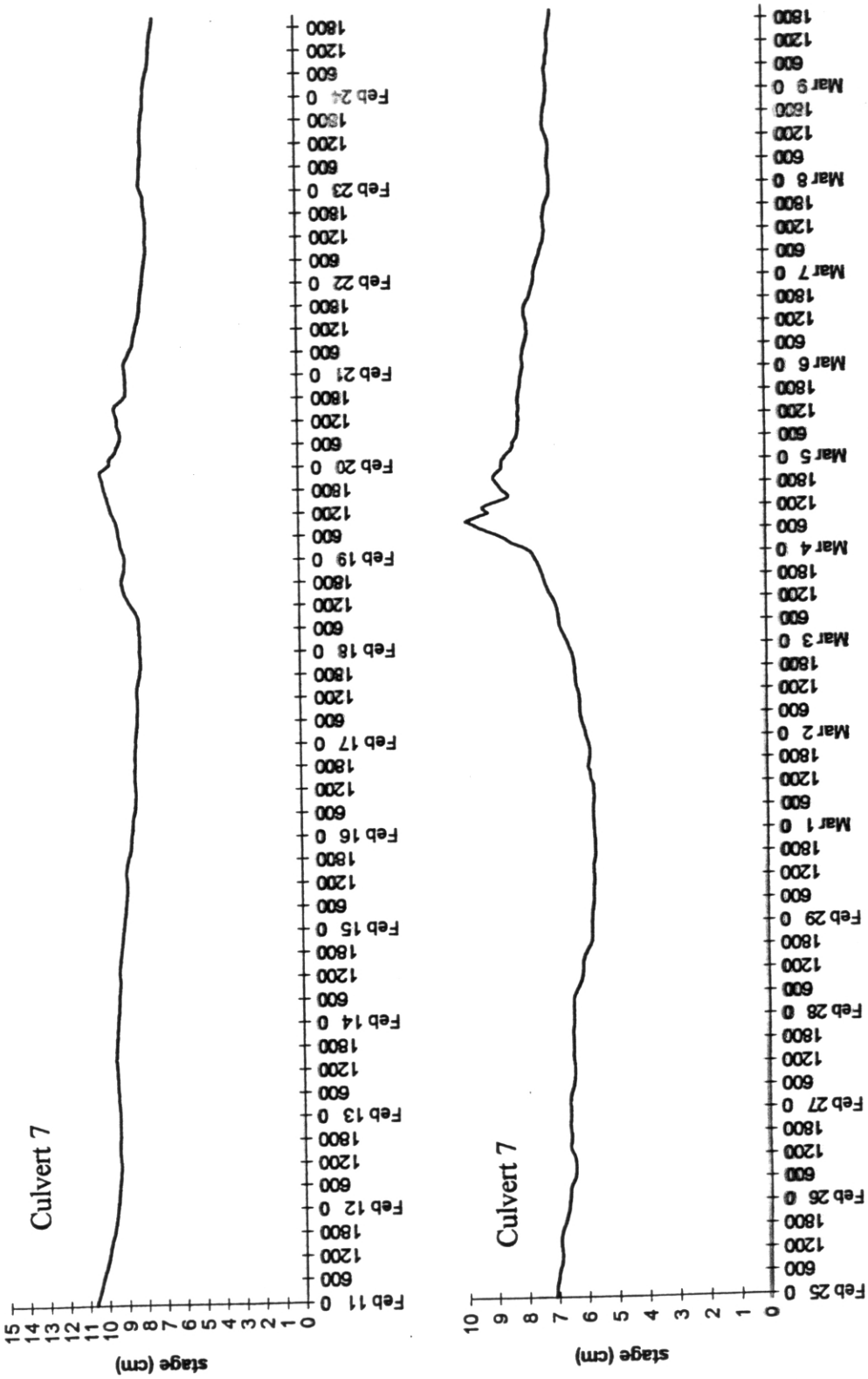
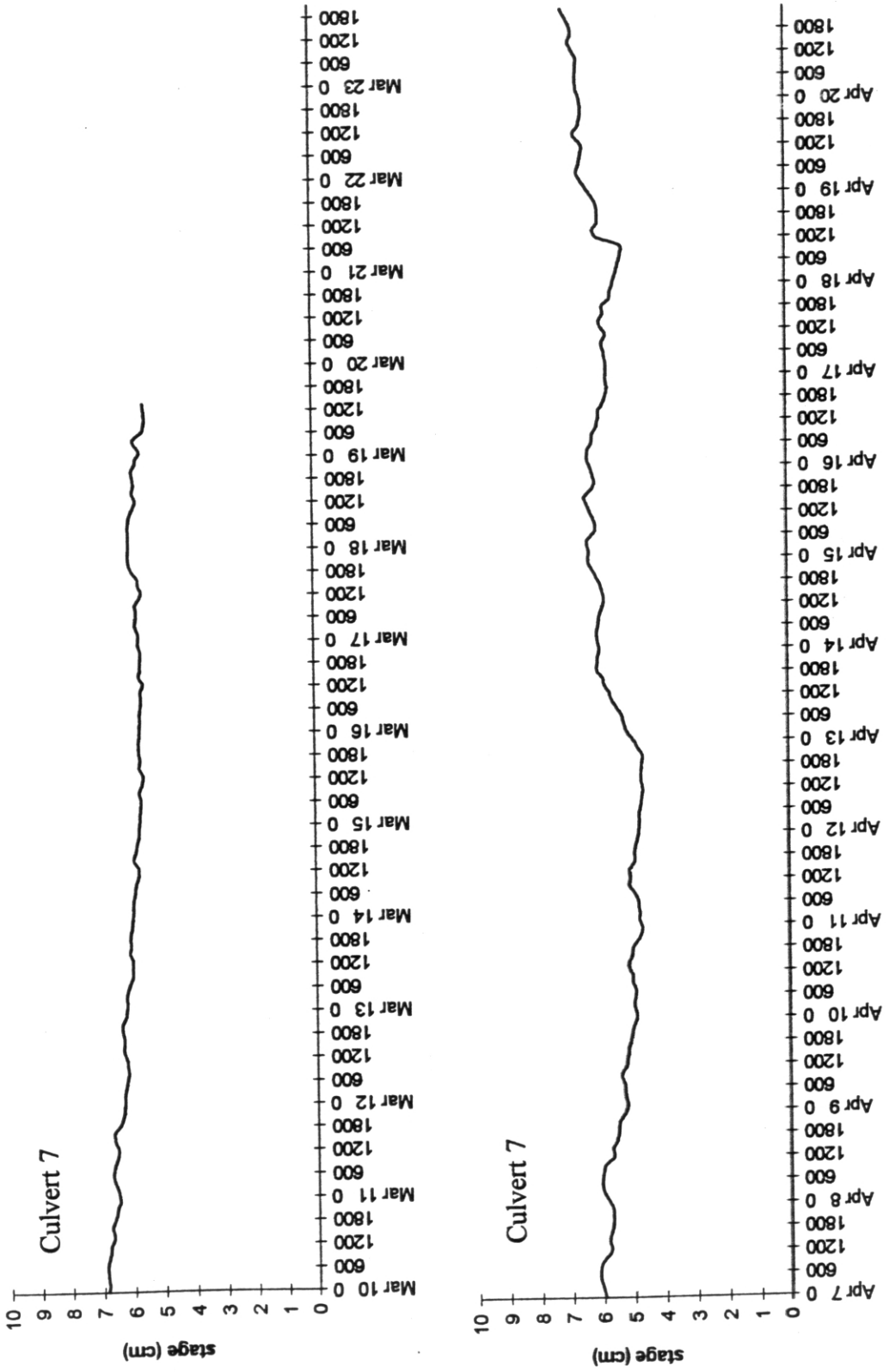
Jan 11
Jan 12
Jan 13


Culvert 7
stage (cm)
Culvert 7
stage (cm)


Culvert 7
stage (cm)
Culvert 7
stage (cm)


Culvert 7
stage (cm)
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Mar 10 0
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Mar 11 0
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Mar 22 0
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Mar 23 0
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1200
1800
Culvert 7
stage (cm)
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Apr 7 0
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Apr 8 0
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Apr 9 0
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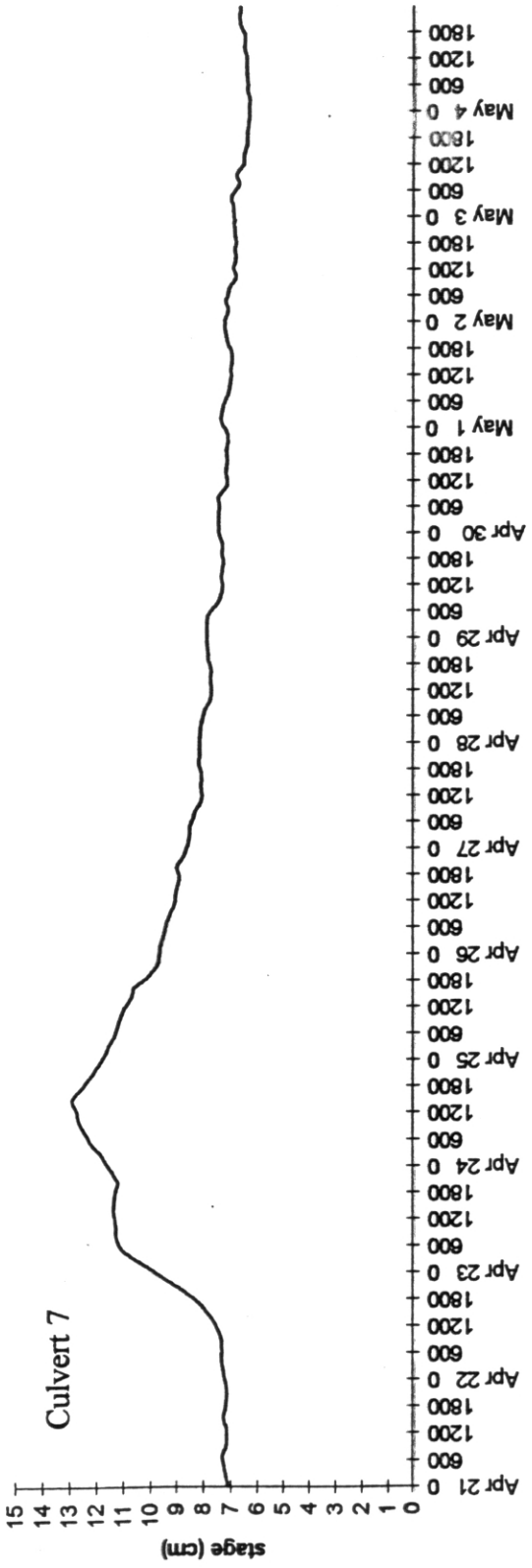
Culvert 7
stage (cm)
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Apr 21 0
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Apr 22 0
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May 4 0
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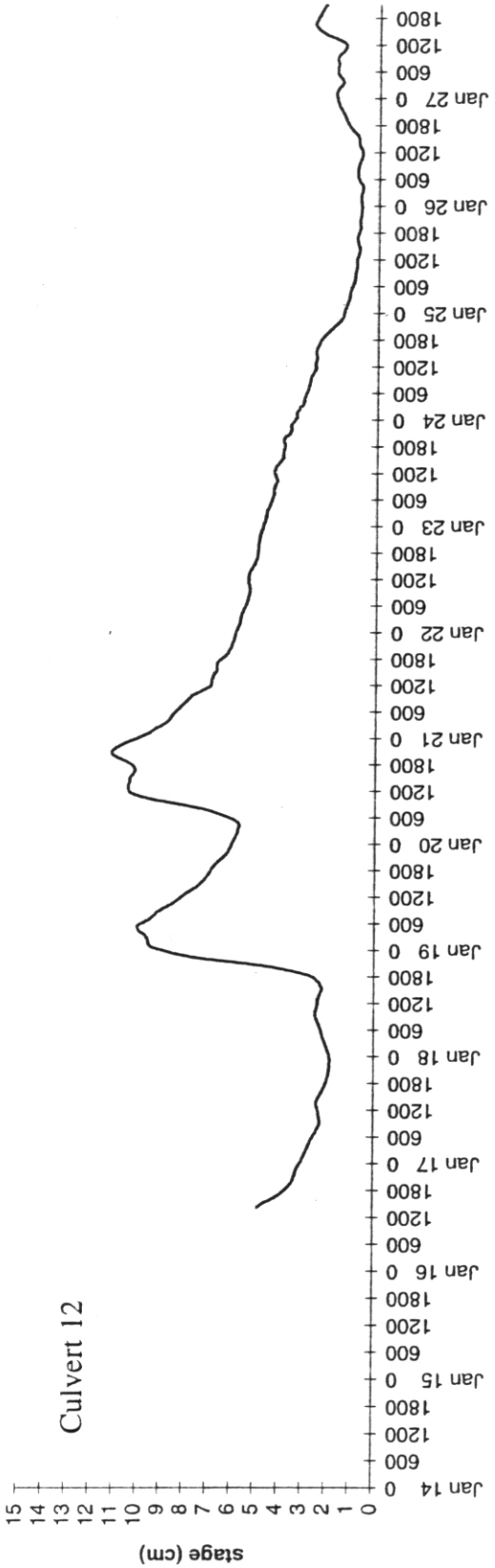
1200
1800


Culvert 12
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Jan 14 0
600
1200
1800
Jan 15 0
600
1200
1800
Jan 16 0
600
1200
1800
Jan 17 0
600
1200
1800
Jan 18 0
600
1200
1800
Jan 19 0
600
1200
1800
Jan 20 0
600
1200
1800
Jan 21 0
600
1200
1800
Jan 22 0
600
1200
1800
Jan 23 0
600
1200
1800
Jan 24 0
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1200
1800
Jan 25 0
600
1200
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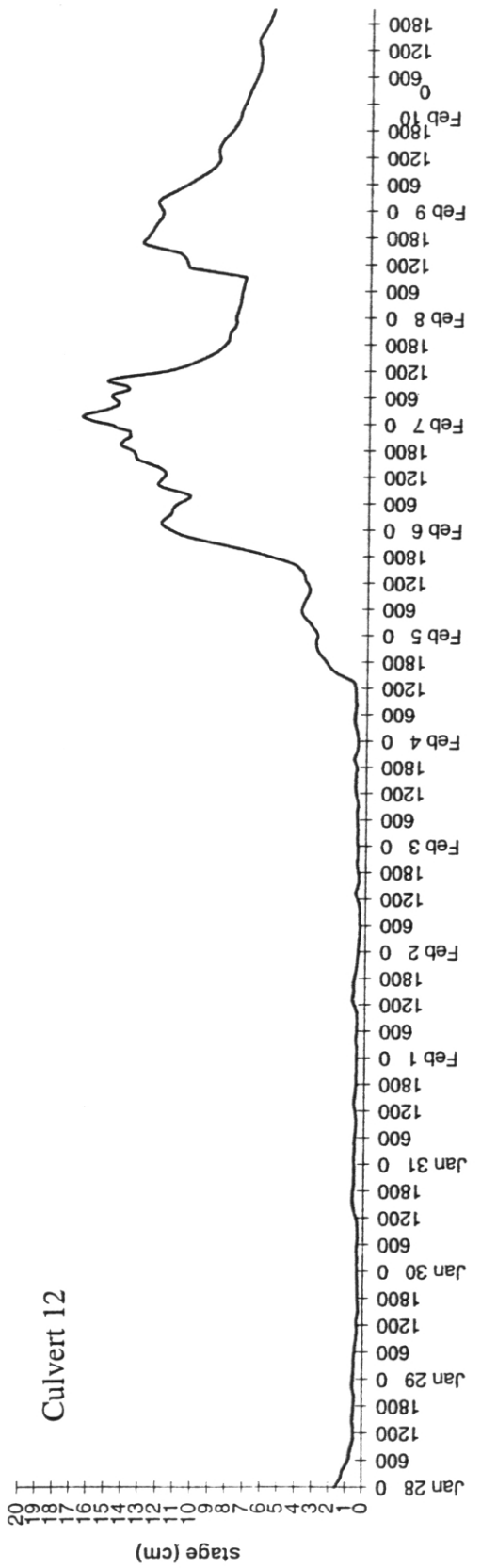
Jan 26 0
600
1200
1800
Jan 27 0
600
1200
1800


Culvert 12
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Jan 28 0
600
1200
1800
Jan 29 0
600
1200
1800
Jan 30 0
600
1200
1800
Jan 31 0
600
1200
1800
Feb 1 0
600
1200
1800
Feb 2 0
600
1200
1800
Feb 3 0
600
1200
1800
Feb 4 0
600
1200
1800
Feb 5 0
600
1200
1800
Feb 6 0
600
1200
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Feb 7 0
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Feb 8 0
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1200
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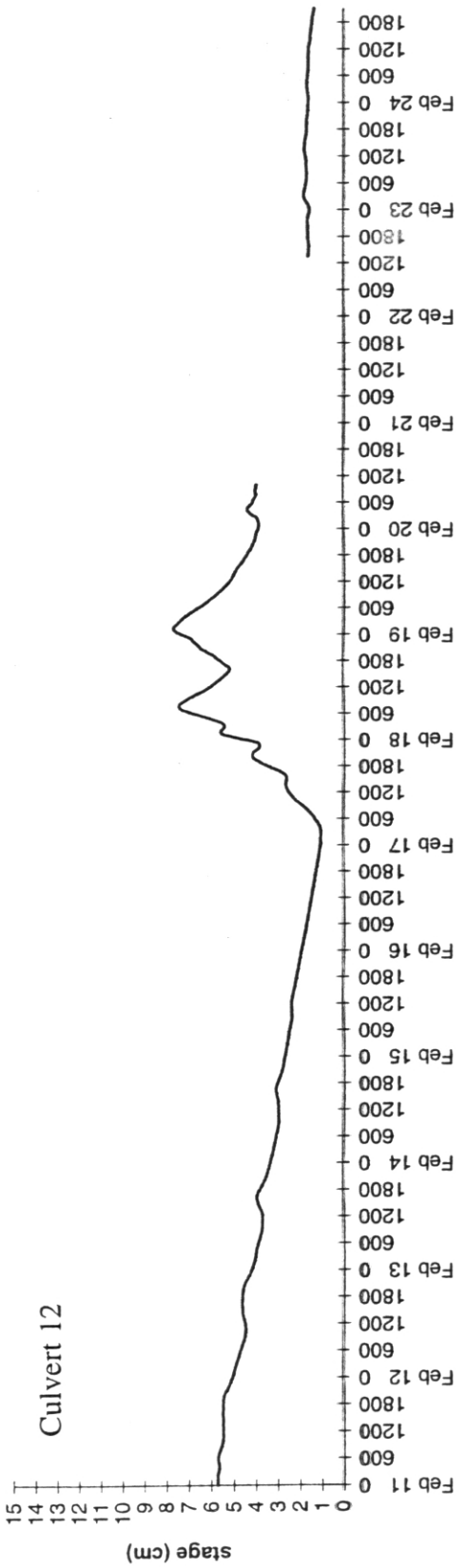
Feb 10
0
600
1200
1800


Culvert 12
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
Feb 25 0
600
1200
1800
Feb 26 0
600
1200
1800
Feb 27 0
600
1200
1800
Feb 28 0
600
1200
1800
Feb 29 0
600
1200
1800
Mar 1 0
600
1200
1800
Mar 2 0
600
1200
1800
Mar 3 0
600
1200
1800
Mar 4 0
600
1200
1800
Mar 5 0
600
1200
1800
Mar 6 0
600
1200
1800
Mar 7 0
600
1200
1800
Mar 8 0
600
1200
1800
Mar 9 0
600
1200
1800

Culvert 12
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Feb 11 0
600
1200
1800
Feb 12 0
600
1200
1800
Feb 13 0
600
1200
1800
Feb 14 0
600
1200
1800
Feb 15 0
600
1200
1800
Feb 16 0
600
1200
1800
Feb 17 0
600
1200
1800
Feb 18 0
600
1200
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Feb 19 0
600
1200
1800
Feb 20 0
600
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1200
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600
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Feb 23 0
600
1200
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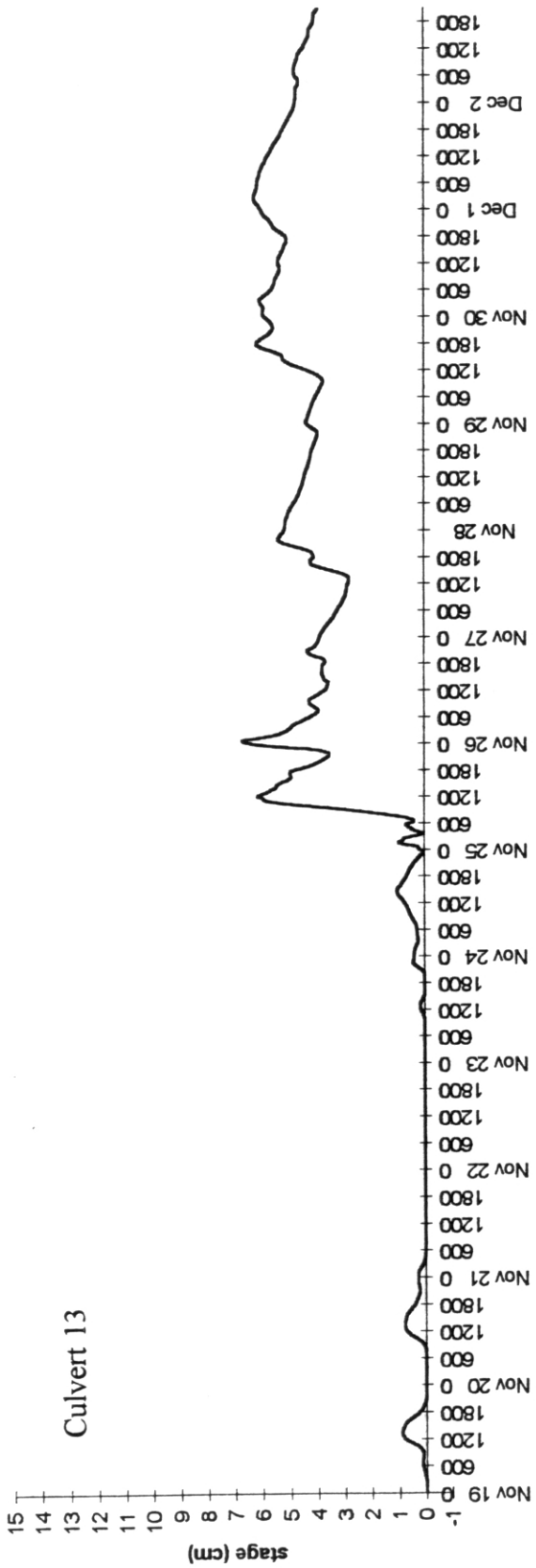
Feb 24 0
600
1200
1800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stage (cm)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
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-1
Nov 19 0
1200
1800
Nov 20 0
1200
1800
Nov 21 0
1200
1800
Nov 22 0
1200
1800
Nov 23 0
1200
1800
Nov 24 0
1200
1800
Nov 25 0
1200
1800
Nov 26 0
1200
1800
Nov 27 0
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1800
Nov 29 0
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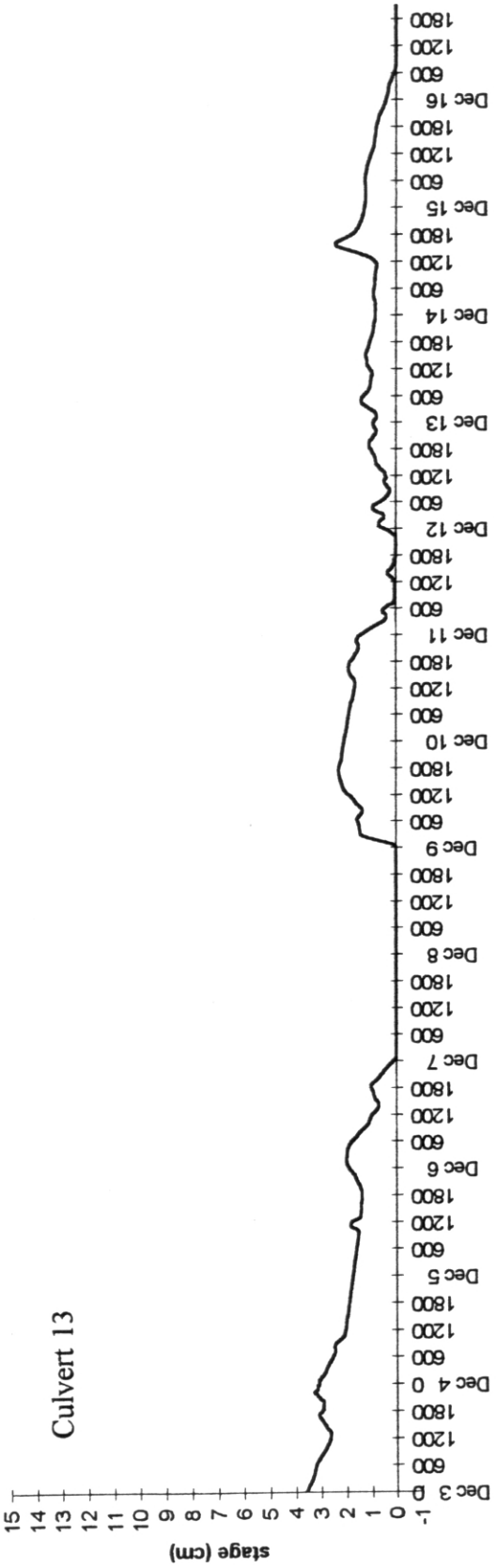
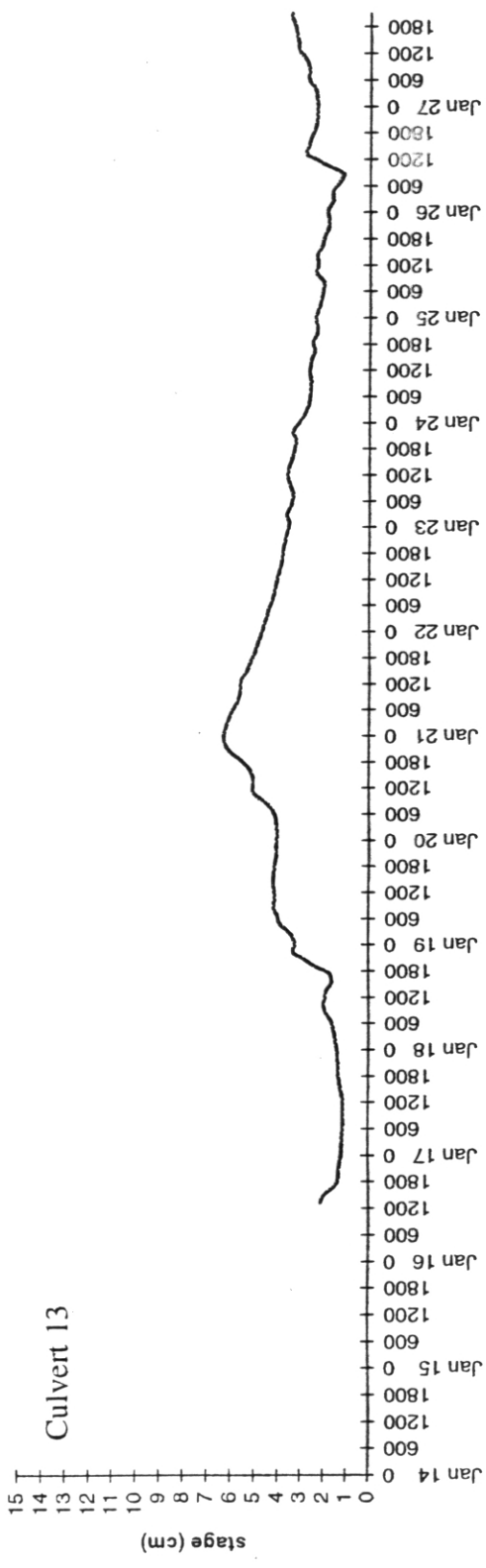
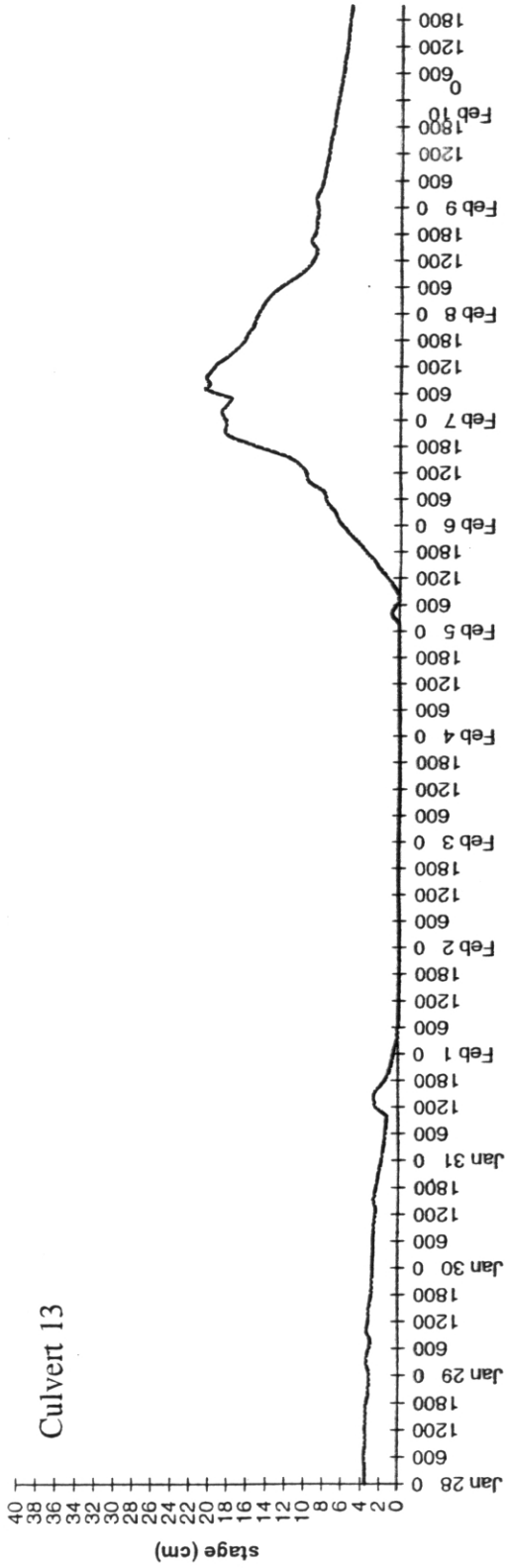
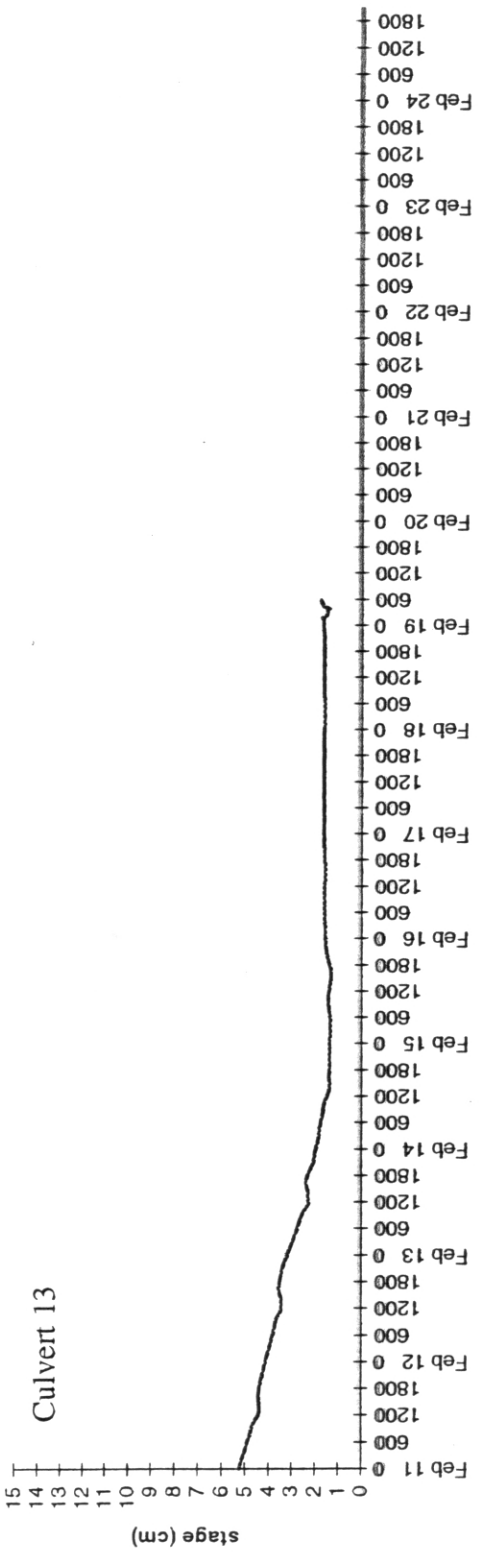
Nov 30 0
1200
1800
Dec 1 0
1200
1800
Dec 2 0
1200
1800


Culvert 13
stage (cm)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
Dec 3 0
1200
1800
Dec 4 0
1200
1800
Dec 5
1200
1800
Dec 6
1200
1800
Dec 7
1200
1800
Dec 8
1200
1800
Dec 9
1200
1800
Dec 10
1200
1800
Dec 11
1200
1800
Dec 12
1200
1800
Dec 13
1200
1800
Dec 14
1200
1800
Dec 15
1200
1800
Dec 16
1200
1800


Culvert 13
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Jan 14 0
Jan 15 0
Jan 16 0
Jan 17 0
Jan 18 0
Jan 19 0
Jan 20 0
Jan 21 0
Jan 22 0
Jan 23 0
Jan 24 0
Jan 25 0
Jan 26 0
Jan 27 0
600
1200
1800


Culvert 13
stage (cm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Jan 28 0
Jan 29 0
Jan 30 0
Jan 31 0
Feb 1 0
Feb 2 0
Feb 3 0
Feb 4 0
Feb 5 0
Feb 6 0
Feb 7 0
Feb 8 0
Feb 9 0
Feb 10
600
1200
1800


Culvert 13
stage (cm)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Feb 11 0
Feb 12 0
Feb 13 0
Feb 14 0
Feb 15 0
Feb 16 0
Feb 17 0
Feb 18 0
Feb 19 0
Feb 20 0
Feb 21 0
Feb 22 0
Feb 23 0
Feb 24 0
600
1200
1800

Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Nov 19 0
600
1200
1800
Nov 20 0
600
1200
1800
Nov 21 0
600
1200
1800
Nov 22 0
600
1200
1800
Nov 23 0
600
1200
1800
Nov 24 0
600
1200
1800
Nov 25 0
600
1200
1800
Nov 26 0
600
1200
1800
Nov 27 0
600
1200
1800
Nov 28
0
600
1200
1800
Nov 29 0
600
1200
1800
Nov 30 0
600
1200
1800
Dec 1 0
600
1200
1800
Dec 2 0
600
1200
1800

Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Dec 3 0
600
1200
1800
Dec 4 0
600
1200
1800
Dec 5
0
600
1200
1800
Dec 6
0
600
1200
1800
Dec 7
0
600
1200
1800
Dec 8
0
600
1200
1800
Dec 9
0
600
1200
1800
Dec 10
0
600
1200
1800
Dec 11
0
600
1200
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Dec 12
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600
1200
1800
Dec 13
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1200
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Dec 14
0
600
1200
1800
Dec 15
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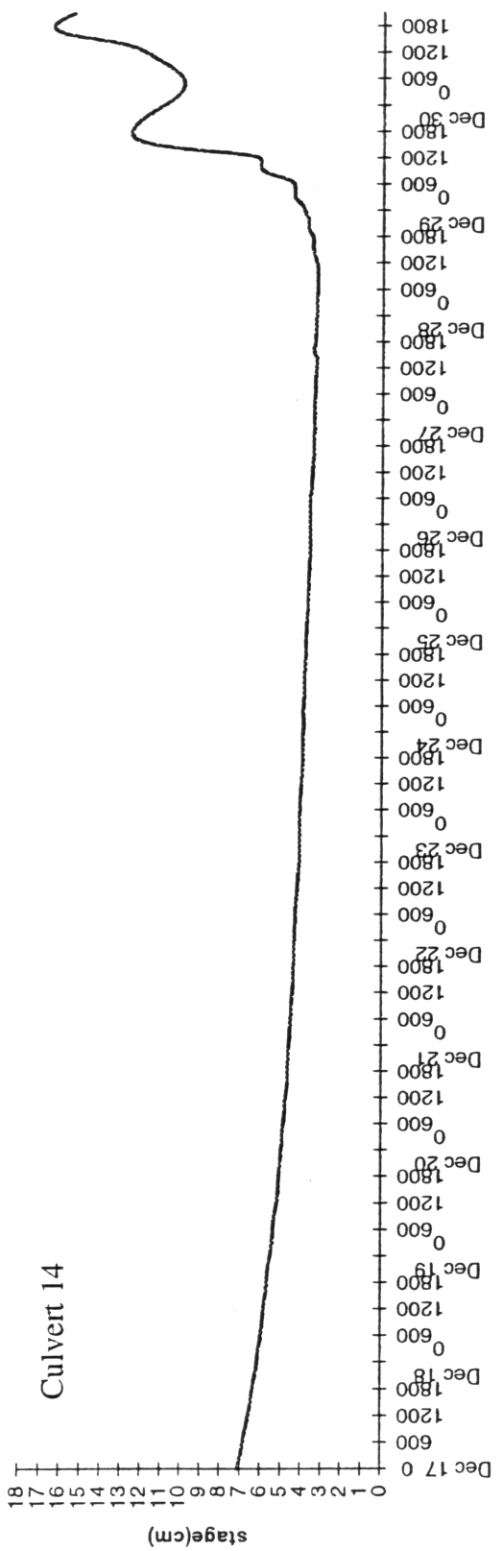
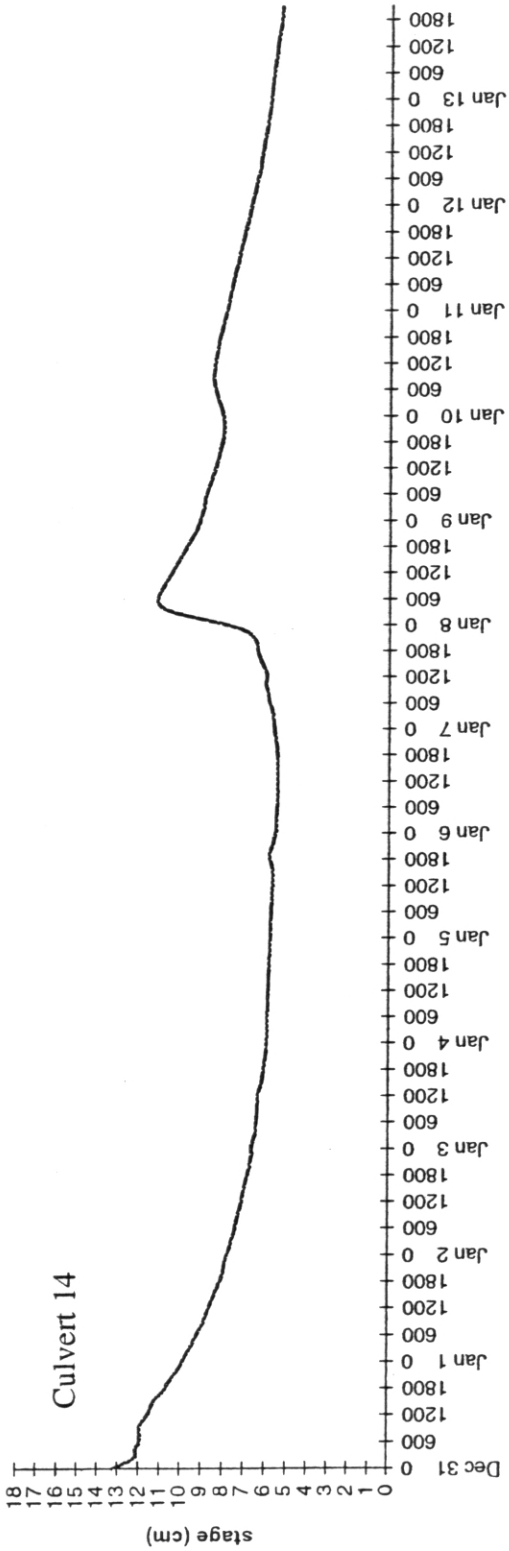
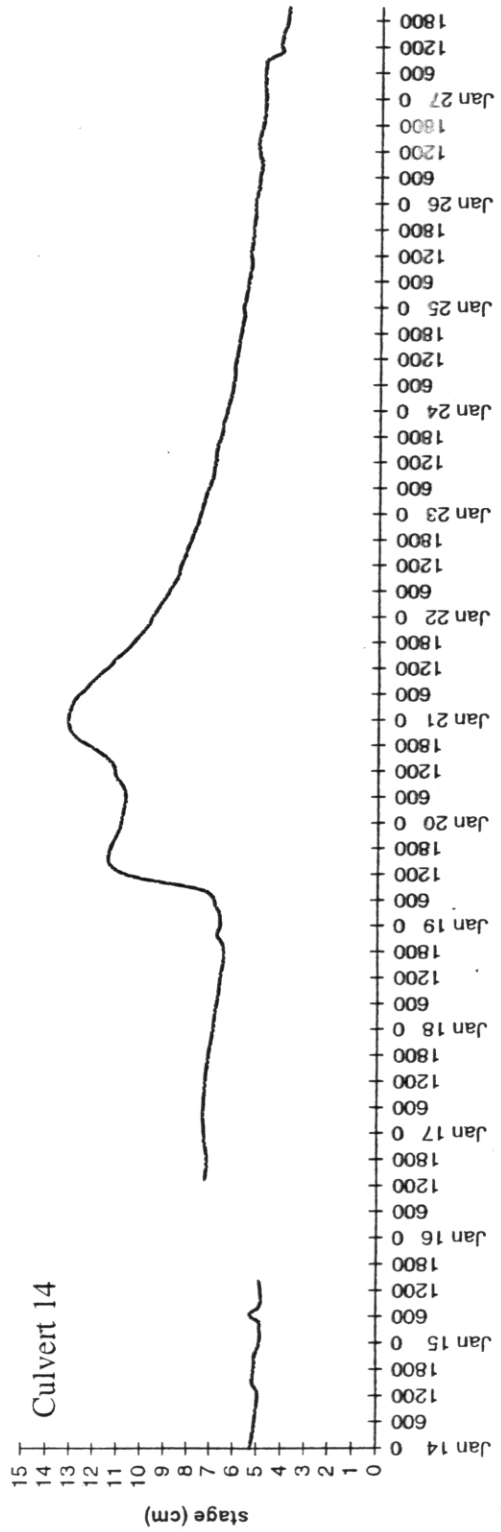
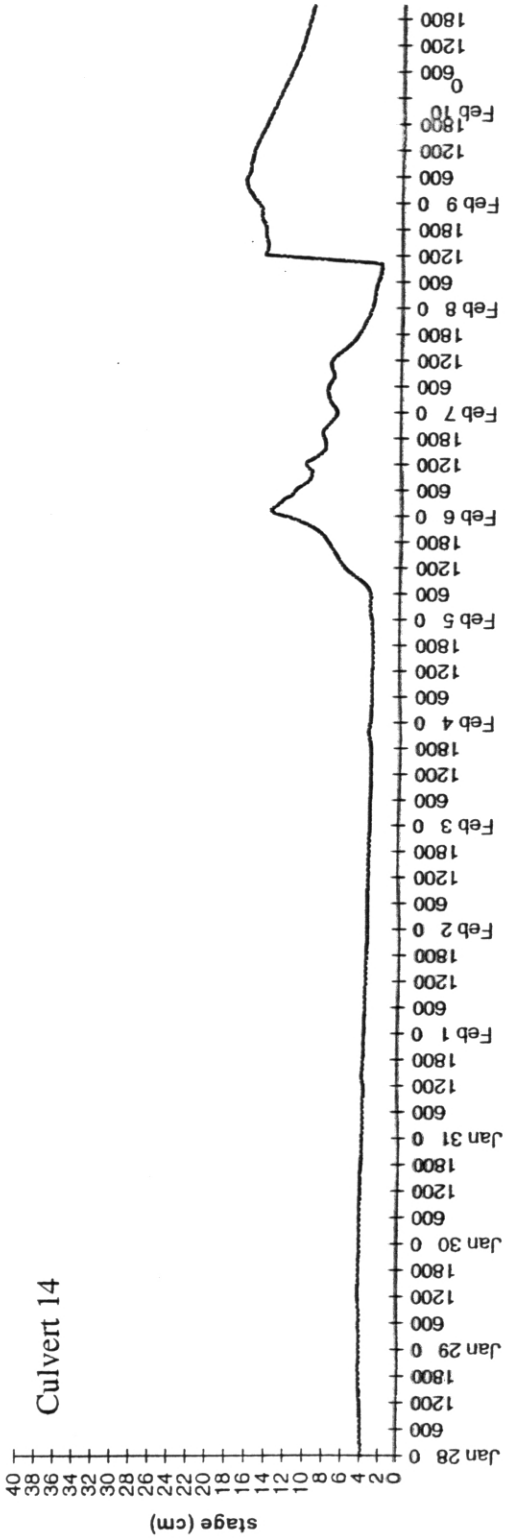
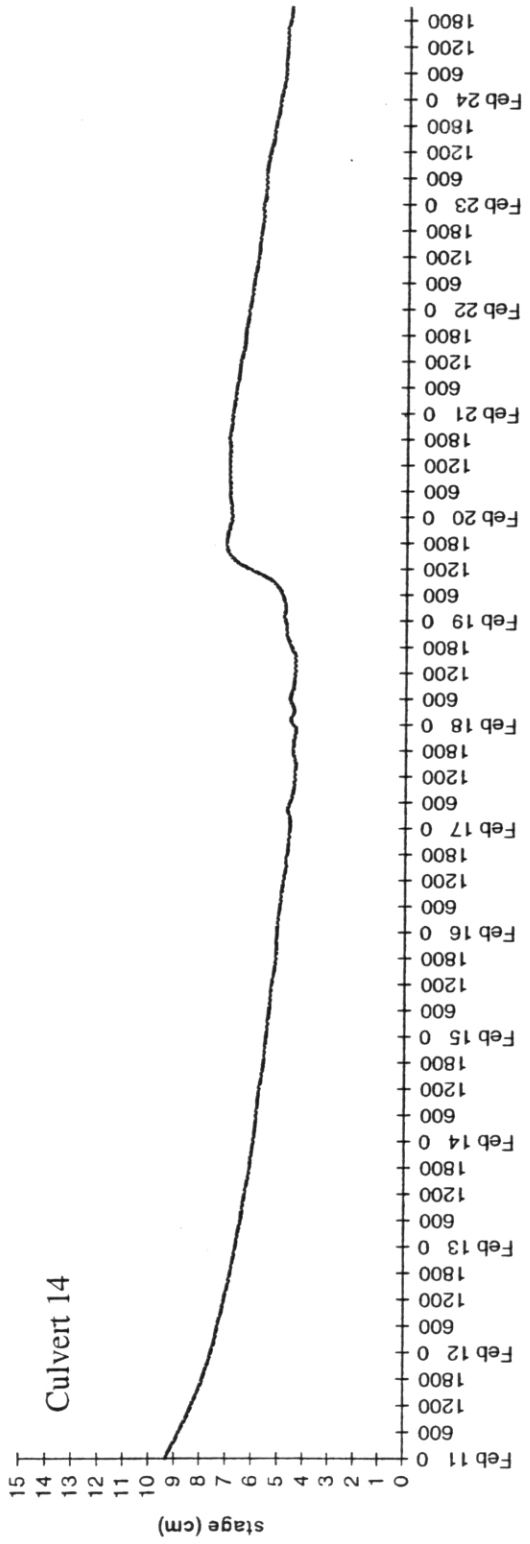
600
1200
1800
Dec 15
0
600
1200
1800


Culvert 14
stage(cm)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Dec 17 0
600
1200
1800
Dec 18
Dec 19
Dec 20
Dec 21
Dec 22
Dec 23
Dec 24
Dec 25
Dec 26
Dec 27
Dec 28
Dec 29
Dec 30


Culvert 14
stage (cm)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Dec 31 0
600
1200
1800
Jan 1 0
Jan 2 0
Jan 3 0
Jan 4 0
Jan 5 0
Jan 6 0
Jan 7 0
Jan 8 0
Jan 9 0
Jan 10 0
Jan 11 0
Jan 12 0
Jan 13 0


Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Jan 14 0
Jan 15 0
Jan 16 0
Jan 17 0
Jan 18 0
Jan 19 0
Jan 20 0
Jan 21 0
Jan 22 0
Jan 23 0
Jan 24 0
Jan 25 0
Jan 26 0
Jan 27 0
600
1200
1800


Culvert 14
stage (cm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Jan 28 0
Jan 29 0
Jan 30 0
Jan 31 0
Feb 1 0
Feb 2 0
Feb 3 0
Feb 4 0
Feb 5 0
Feb 6 0
Feb 7 0
Feb 8 0
Feb 9 0
Feb 10
600
1200
1800


Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
Feb 25 0
600
1200
1800
Feb 26 0
600
1200
1800
Feb 27 0
600
1200
1800
Feb 28 0
600
1200
1800
Feb 29 0
600
1200
1800
Mar 1 0
600
1200
1800
Mar 2 0
600
1200
1800
Mar 3 0
600
1200
1800
Mar 4 0
600
1200
1800
Mar 5 0
600
1200
1800
Mar 6 0
600
1200
1800
Mar 7 0
600
1200
1800
Mar 8 0
600
1200
1800
Mar 9 0
600
1200
1800

Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Feb 11 0
600
1200
1800
Feb 12 0
600
1200
1800
Feb 13 0
600
1200
1800
Feb 14 0
600
1200
1800
Feb 15 0
600
1200
1800
Feb 16 0
600
1200
1800
Feb 17 0
600
1200
1800
Feb 18 0
600
1200
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Feb 19 0
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1200
1800
Feb 20 0
600
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Feb 21 0
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Feb 23 0
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Feb 24 0
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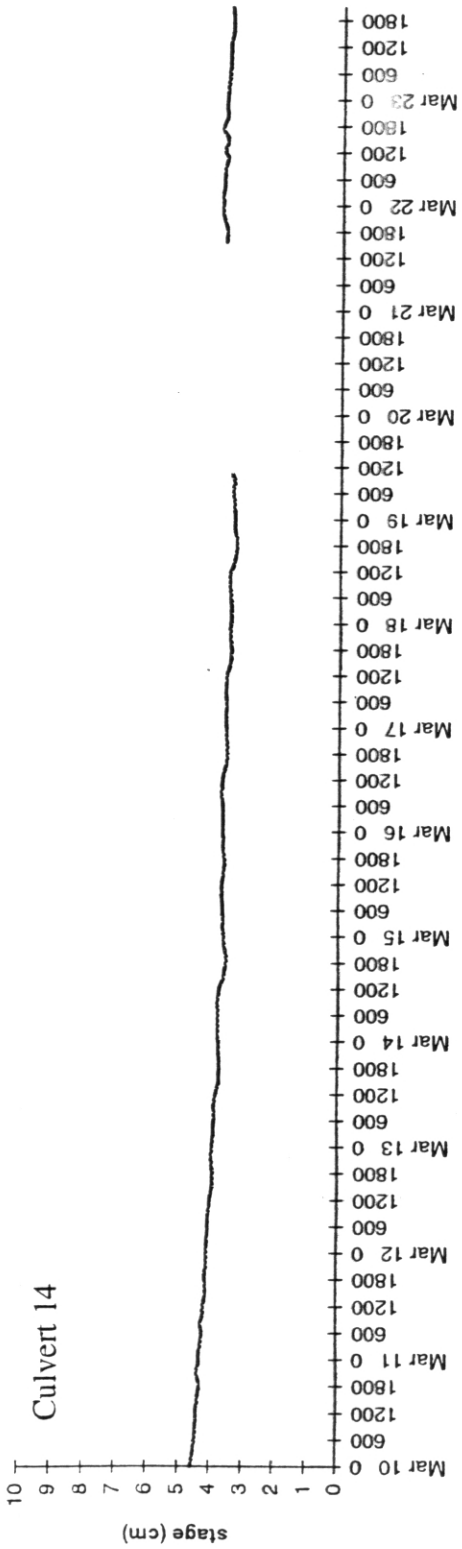
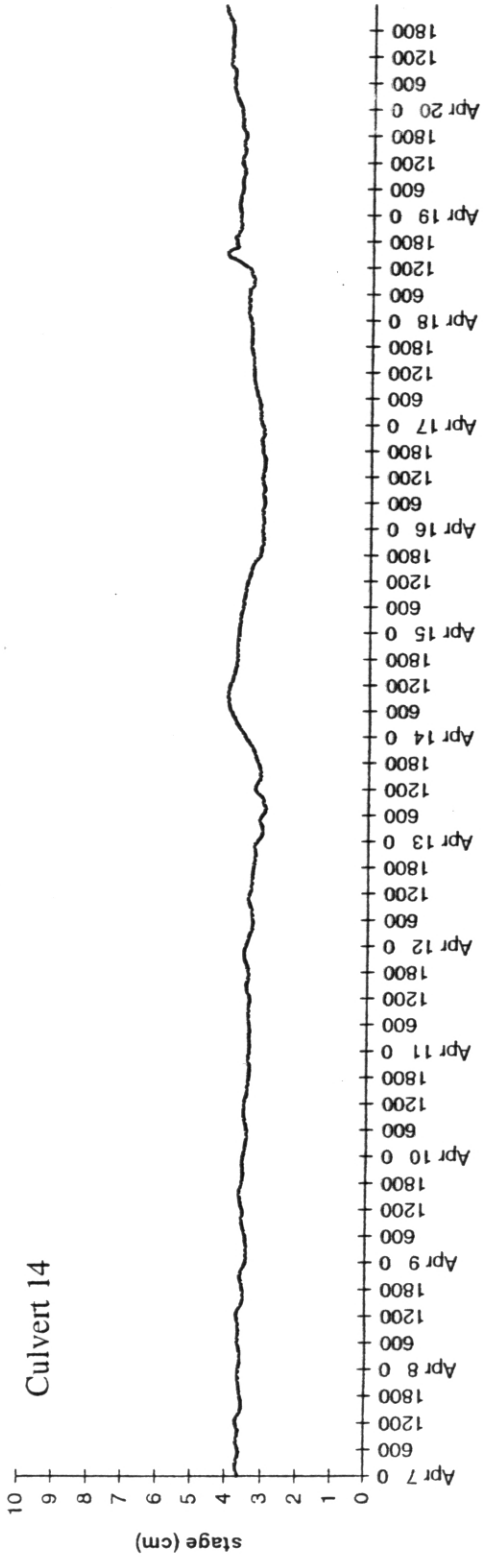
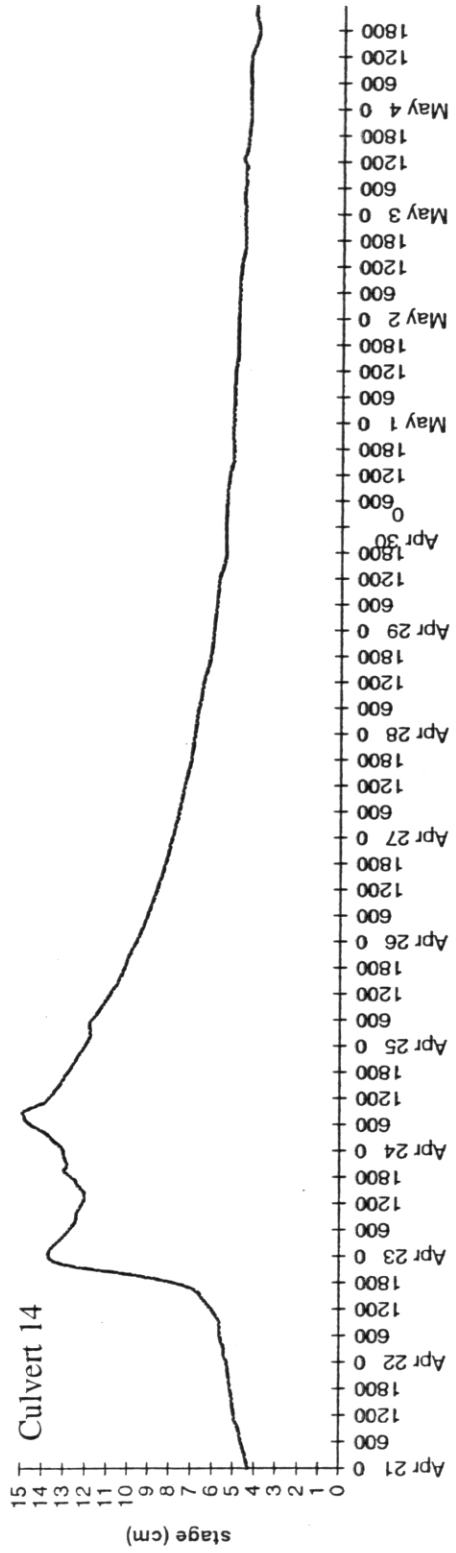
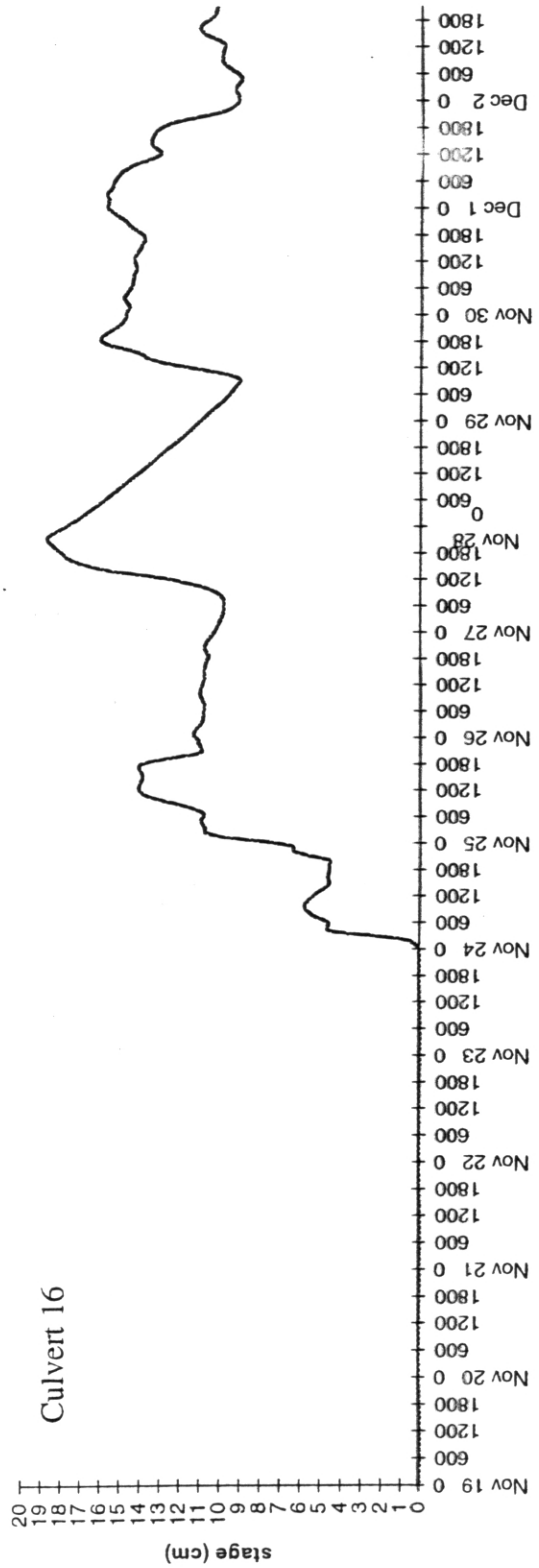
1200
1800


Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
Mar 10 0
Mar 11 0
Mar 12 0
Mar 13 0
Mar 14 0
Mar 15 0
Mar 16 0
Mar 17 0
Mar 18 0
Mar 19 0
Mar 20 0
Mar 21 0
Mar 22 0
Mar 23 0
600
1200
1800


Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
Apr 7 0
Apr 8 0
Apr 9 0
Apr 10 0
Apr 11 0
Apr 12 0
Apr 13 0
Apr 14 0
Apr 15 0
Apr 16 0
Apr 17 0
Apr 18 0
Apr 19 0
Apr 20 0
600
1200
1800


Culvert 14
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Apr 21 0
Apr 22 0
Apr 23 0
Apr 24 0
Apr 25 0
Apr 26 0
Apr 27 0
Apr 28 0
Apr 29 0
Apr 30
May 1 0
May 2 0
May 3 0
May 4 0
600
1200
1800


Culvert 16
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Nov 19 0
600
1200
1800
Nov 20 0
600
1200
1800
Nov 21 0
600
1200
1800
Nov 22 0
600
1200
1800
Nov 23 0
600
1200
1800
Nov 24 0
600
1200
1800
Nov 25 0
600
1200
1800
Nov 26 0
600
1200
1800
Nov 27 0
600
1200
1800
Nov 28
0
600
1200
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Nov 29 0
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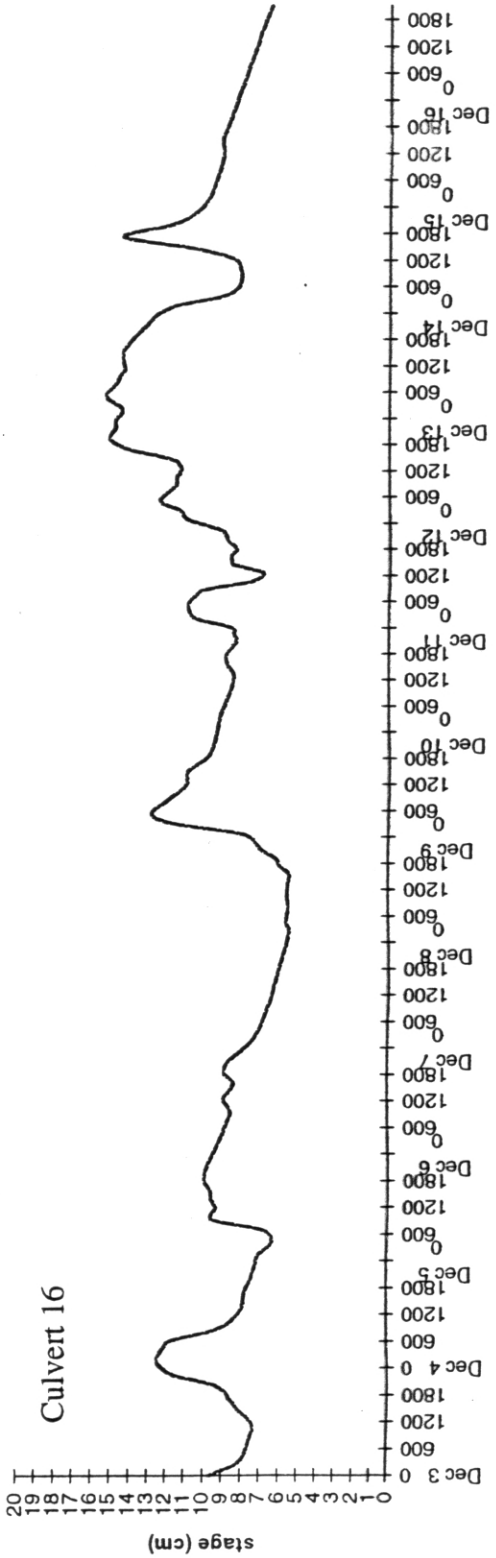
1200
1800
Nov 30 0
600
1200
1800
Dec 1 0
600
1200
1800
Dec 2 0
600
1200
1800


Culvert 16
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Dec 3 0
600
1200
1800
Dec 4 0
600
1200
1800
Dec 5
0
600
1200
1800
Dec 6
0
600
1200
1800
Dec 7
0
600
1200
1800
Dec 8
0
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Dec 9
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1800
Dec 10
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1200
1800
Dec 11
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Dec 12
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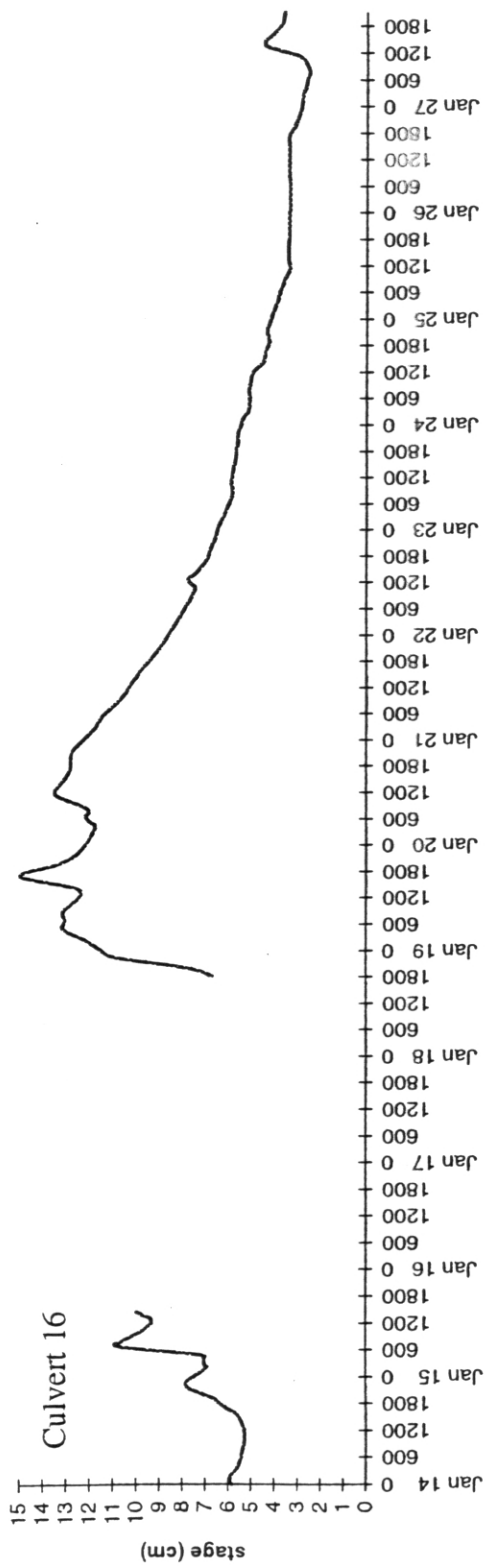
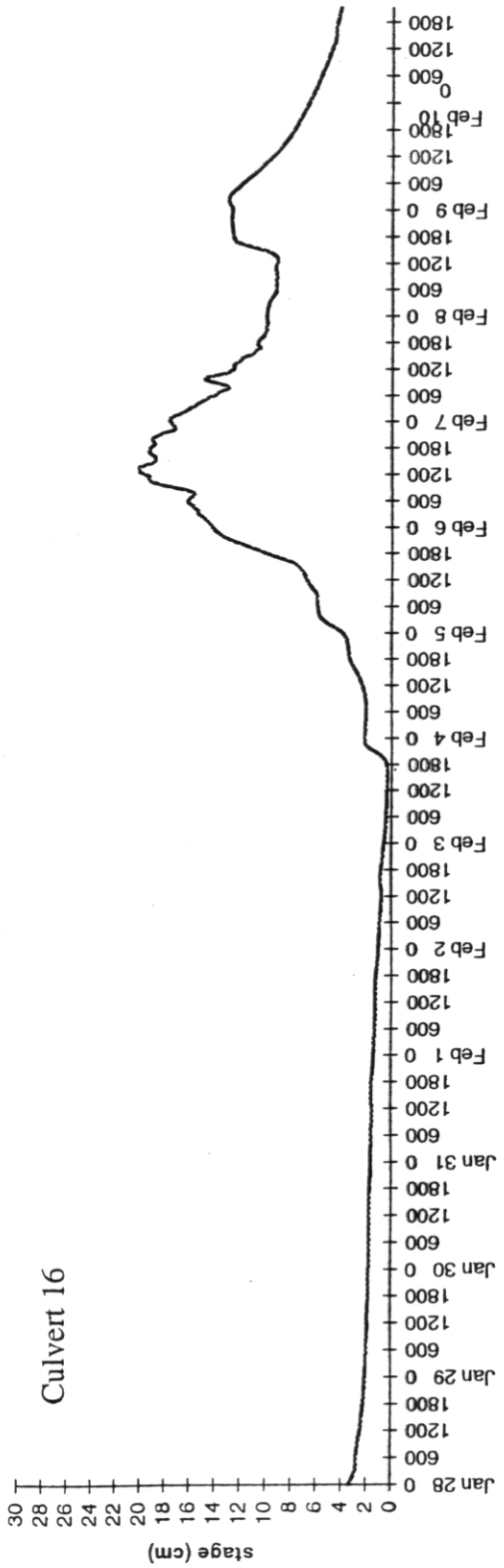
600
1200
1800
Dec 13
0
600
1200
1800
Dec 14
0
600
1200
1800
Dec 15
0
600
1200
1800
Dec 16
0
600
1200
1800

Culvert 16
stage(cm)
Dec 17 0
Dec 18
Dec 19
Dec 20
Dec 21
Dec 22
Dec 23
Dec 24
Dec 25
Dec 26
Dec 27
Dec 28
Dec 29
Dec 30
Culvert 16
stage (cm)
Dec 31 0
Jan 1 0
Jan 2 0
Jan 3 0
Jan 4 0
Jan 5 0
Jan 6 0
Jan 7 0
Jan 8 0
Jan 9 0
Jan 10 0
Jan 11 0
Jan 12 0
Jan 13 0


Culvert 16
stage (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Jan 14 0
Jan 15 0
Jan 16 0
Jan 17 0
Jan 18 0
Jan 19 0
Jan 20 0
Jan 21 0
Jan 22 0
Jan 23 0
Jan 24 0
Jan 25 0
Jan 26 0
Jan 27 0
600
1200
1800


Culvert 16
stage (cm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Jan 28 0
Jan 29 0
Jan 30 0
Jan 31 0
Feb 1 0
Feb 2 0
Feb 3 0
Feb 4 0
Feb 5 0
Feb 6 0
Feb 7 0
Feb 8 0
Feb 9 0
Feb 10 0
600
1200
1800

Appendix 3

Dataset of road-related sedimentation features inventoried in Lookout Creek and Blue River

feature#	type [1]	Islide [2]	Vh [3]	Vs [3]	Vt [3]	Vr [3]	Vout [3]	basin [4]	decade [4]	elev [5]	position [6]	assoc [7]
1	ff	23	0	0	0	180	180	lo	60	3	m	
2	hs	2	670	665	5	5	10	lo	60	1	m	
3	ff	22	0	0	0	1130	1130	lo	60	2	m	
4	cf		0	0	0	35	0	lo	60	2	m	
5	ff	21	0	0	0	215	215	lo	60	1	m	
6	ff	20	0	0	0	6255	6255	lo	60	1	m	
7	ff	19	0	0	0	290	290	lo	60	1	m	
8	hs	36	315	215	100	0	100	lo	60	1	m	
9	df	7,77	2010	1910	100	0	100	lo	60	1	v	
10	ff		0	0	0	225	225	lo	60	1	v	9
11	g		0	0	0	35	35	lo	60	1	v	9
12	g		0	0	0	50	50	lo	60	1	v	9
13	g		0	0	0	15	15	lo	60	1	v	9
14	g		0	0	0	30	30	lo	60	1	v	9
15	id		0	0	0	80	80	lo	60	1	v	9
16	pc		35	35	0	0	0	lo	60	1	v	
17	df	77	745	0	745	400	1145	lo	70	1	m	
18	ff	7	0	0	0	865	865	lo	70	1	m	17
19	df	6	50	50	0	0	0	lo	60	1	m	
20	ff	5	0	0	0	150	150	lo	60	1	m	19
21	ff	35	0	0	0	485	485	lo	60	1	m	
22	pc		290	290	0	0	0	br	80	2	m	
23	pc		270	270	0	0	0	br	80	2	m	
24	id		0	0	0	480	480	br	80	2	m	22,23
25	pc		65	65	0	0	0	br	80	1	m	
26	cf	40	0	0	0	90	0	br	60	2	m	
27	s		0	0	0	0	0	lo	60	1	m	
28	g		0	0	0	80	80	lo	60	1	m	29?
29	df	8,90	2085	1500	585	0	585	lo	60	1	v	
30	ff	17	0	0	0	180	180	lo	60	2	m	
31	hs	33	335	335	0	0	0	lo	60	1	v	
32	ff		0	0	0	70	70	lo	60	1	v	
33	hs	18	240	200	40	0	40	lo	60	1	v	
34	pc		100	100	0	0	0	lo	50	1	v	
35	df	19-21,8(	3000	0	3000	550	3550	lo	50	1	v	
36	df	1	15	10	5	0	5	lo	50	1	v	
37	pc		25	25	0	0	0	lo	70	1	v	
38	df	13	240	200	40	0	40	lo	70	1	m	
39	ff	12	0	0	0	225	225	lo	70	1	m	38
40	ff	10	0	0	0	600	600	lo	60	1	m	
41	ff	9	0	0	0	3910	3910	lo	60	1	r	
42	ff	4	0	0	0	415	415	lo	60	1	r	
43	df	52	40	35	5	5	10	lo	80	1	v	
44	s		0	0	0	0	0	br	80	2	m	
45	cf	82	0	0	0	385	135	br	80	2	m	
46	s		0	0	0	0	0	br	80	2	m	
47	s		0	0	0	0	0	br	60	2	m	
48	df	3	5000	4750	250	0	250	br	60	1	v	
49	g		0	0	0	170	170	br	60	1	v	48
50	ff	26	0	0	0	1915	1915	br	60	1	m	
51	hs	3	6000	1000	5000	0	5000	br	70	1	m	
52	df	94	1750	1250	500	90	590	br	80	1	m	
53	pc		20	20	0	0	0	br	60	2	m	
54	pc		25	25	0	0	0	br	60	1	m	
55	ff	81	0	0	0	220	220	br	60	1	m	100
56	s		0	0	0	0	0	br	70	1	v	
57	df	45	175	120	55	35	90	br	70	1	m	
58	ff	44	0	0	0	1980	1980	br	70	1	m	
59	df		90	90	0	5	5	br	70	1	m	

60	df	43	1310	1110	200	0	200	br	90	1	m	
61	g		0	0	0	5	5	br	60	1	m	60
62	s		0	0	0	0	0	br	90	2	m	
63	df	16	340	300	40	0	40	br	60	1	m	
64	cf	29	0	0	0	2085	0	br	60	1	m	
65	cf	30	0	0	0	580	0	br	60	1	m	
66	cf	31	0	0	0	505	0	br	60	1	m	
67	cf	32	0	0	0	505	0	br	60	1	m	
68	ff	28	0	0	0	155	155	br	90	1	m	64
69	ff	27	0	0	0	390	390	br	90	1	m	67
70	s		0	0	0	0	0	br	90	2	m	
71	s		0	0	0	0	0	br	70	2	m	
72	ff	74	0	0	0	250	250	br	70	2	r	
73	ff	73	0	0	0	700	700	br	90	2	r	
74	ff	75	0	0	0	175	175	br	70	2	r	
75	ff	71	0	0	0	240	240	br	80	2	m	
76	ff	37	0	0	0	755	755	br	60	2	v	97
77	ff	79	0	0	0	755	755	br	60	2	m	
78	pc		15	15	0	0	0	br	80	1	v	
79	g		0	0	0	5	5	br	70	1	v	81
80	ff	72	0	0	0	500	500	br	60	2	m	
81	cf		0	0	0	25	0	br	60	1	v	
82	cf		0	0	0	10	0	br	60	1	v	
83	cf		0	0	0	40	0	br	60	1	v	
84	df		100	100	0	0	0	br	60	1	v	
85	s		0	0	0	0	0	br	60	1	v	
86	g		0	0	0	20	20	br	60	1	m	67
87	s		0	0	0	0	0	br	60	1	m	
88	ff	60	0	0	0	110	110	br	80	1	m	
89	pc		20	20	0	0	0	br	70	1	m	
90	s		0	0	0	0	0	br	70	2	m	
91	pc		20	20	0	0	0	br	80	2	m	
92	s		0	0	0	0	0	br	80	1	m	
93	pc		20	20	0	0	0	br	80	2	m	
94	s		0	0	0	0	0	br	70	2	m	
95	cf		0	0	0	70	0	br	80	2	m	
96	id		0	0	0	80	80	br	60	1	v	48
97	cf		0	0	0	70	10	br	70	2	v	
98	df	1	160	145	15	10	25	lo	70	1	v	
99	ff		0	0	0	45	45	lo	60	1	v	
100	pc		60	60	0	0	0	br	60	1	m	
101	g		0	0	0	80	80	br	80	1	m	53
102	ff		0	0	0	2000	2000	lo	60	1	m	
103	ff		0	0	0	270	270	lo	60	1	m	

Notes:

[1] Type of feature, includes hillslope slides (hs), fillslope slides (ff), cutslope slides (cf), debris flows (df), slumps (s), plugged culverts (pc), incised ditches (id), and gullies (g).

[2] Refers to identification number in Swanson/Wallenstein inventory of landslides.

[3] Volume estimates for features, includes volume of hillslope material (Vh), volume stored on the road (Vs) and transported through the road (Vt), volume of road material (Vr), and volume yielded below the road (Vout).

[4] Refers to basin where feature was mapped: Lookout Creek (lo) or Blue River (br).

[5] Refers to decade of construction for road on which feature was mapped: before 1960 (60), 1961-70 (70), 1971-80 (80), 1981 - 90 (90).

[6] Refers to elevation zone in which feature was mapped: 400- 800 m (1), 801 - 1200 m (2), > 1200 m (3).

[7] Refers to number of associated feature.