# Geomorphology and Hydrology of the H.J. Andrews Experimental Forest, Blue River, Oregon

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## INTRODUCTION

The H.J. Andrews Experimental Forest is the Lookout Creek watershed (6400 ha ) draining westward from the western Cascade Range about 80 km east of Eugene, Oregon. The experimental forest has been the site of applied forestry research since its establishment in 1948. During the 1970s , research on forest and stream ecosystems flourished as the Andrews Forest served as one of the Coniferous Forest Biome sites within the International Biological Program (IBP). In 1980 the forest became one of the first Long-Term Ecological Research (LTER) sites funded by the National Science Foundation. The central question of the LTER program has been: How do land use (principally roads, forest cutting, and regrowth), natural disturbances (principally wildfires and floods), and climate variability affect key ecosystem properties, mainly carbon dynamics, hydrology, and elements of biologic diversity?

Research at the forest spans many disciplines, including forest and stream ecology, entomology, social science, and many aspects of the earth sciences. Much of the work is focused within the confines of a disciplinary view of the world, yet synthesis and interaction occurs among the disciplines. Consideration of ecosystem structure and function in the context of long-term change imposed by land use, natural disturbances, and recovery processes such as biotic succession, has been an important medium for interdisciplinary thinking (Swanson et al., 1997).

Andrews Forest has been a base of hydrology, geomorphology, and biogeochemical cycling research since the 1960s. The initial stage for these studies was set in 1953 with establishment of experimental watersheds 1, 2, and 3 (Table 1, Fig. 1) and the gauging of Lookout Creek and Blue River, which began in 1949. Over time, work on these topics intensified within the small watersheds and also shifted to finer scale plot experiments and broader scale whole-forest and regional watersheds. The present resurgence of interest in small, experimental watershed studies at the forest is accelerating and is modernizing work on each of these themes.

Hydrology research in the early years at the forest focused on quantifying components of the hydrologic system and assessing initial effects of roads and forest cutting on runoff (Rothacher, 1963, 1970). This work intensified during the IBP with modeling (Waring and Running, 1976), tree physiology (Waring et al., 1977), hillslope hydrology (Harr, 1977), and several other research topics. Recent work on long-term trends of peak flows in response to roads and forest cutting and regrowth (Jones and Grant, 1996; Jones, 2000) has stimulated study of road hydrology (Wemple et al., 1996). Two additional components of hydrology research concern the perennial topic of stream water temperature (Levno and Rothacher, 1969; Johnson and Jones, 2000) and the newer theme of floodplain groundwater systems—the hyporheic zone (Wondzell and Swanson, 1996a, b, 1999).

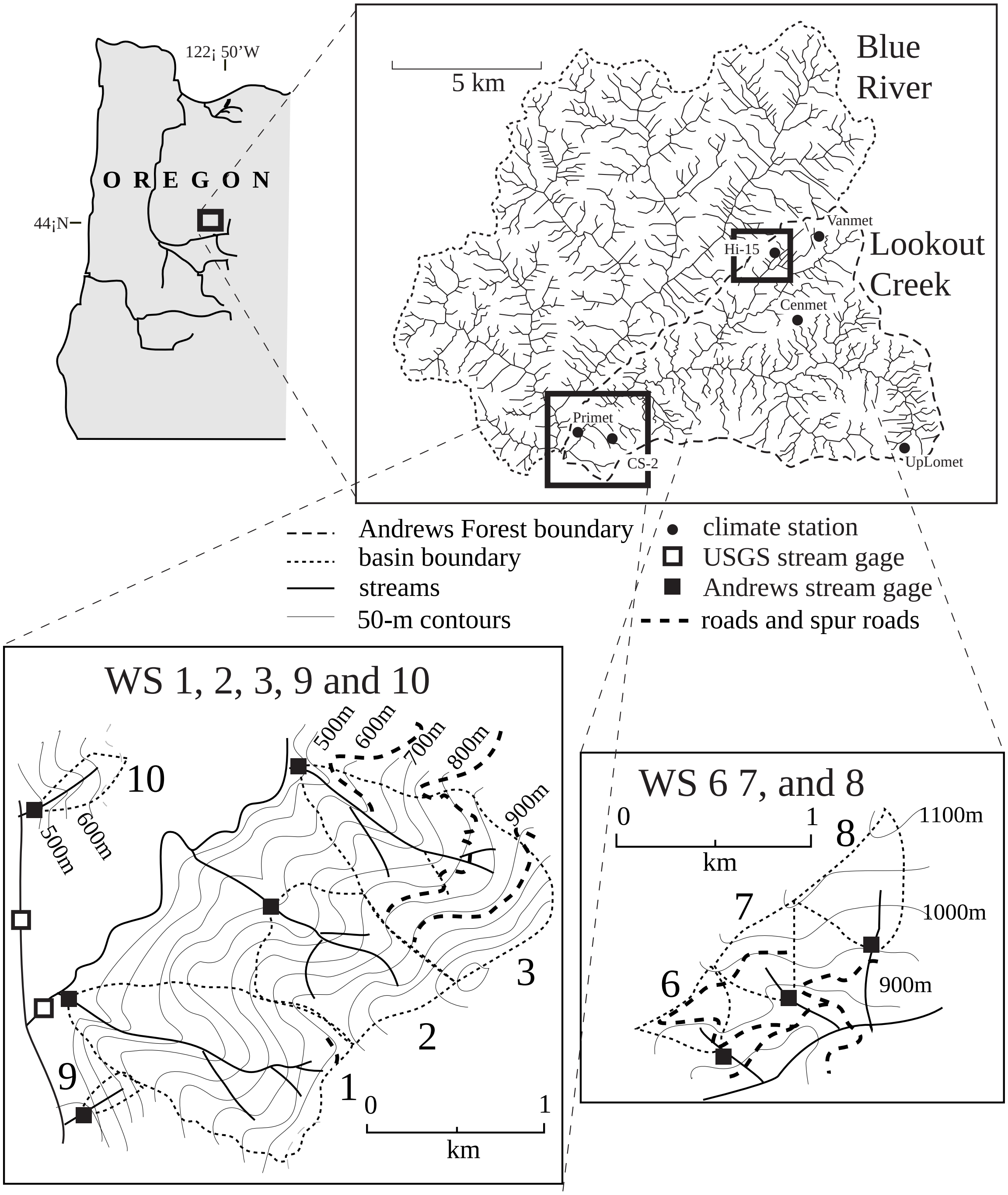

Figure 1. Andrews Forest and upper Blue River watershed stream network and experimental watersheds (noted WS). Primet, Vanmet, Cenmet, and UpLomet are locations of meteorological stations.

Table 1. Experimental watersheds in the H.J. Andrews Experimental Forest. Prior to treatments, forests were 400 to 500 year old Douglas-fir/western hemlock stands in watersheds 1, 2, 3, 9 and 10, and 130-yr old Douglas-fir stands in watersheds 6, 7, and 8.

| Basin no. | Area (ha) | Elev (m) Min | Max | Management history | Water, stream chemistry, and sediment records, start date[1] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | W[2] | C[3] | S | B |
| 1 | 96 | 460 | 990 | 100% clearcut, 1962-66; prescribed burned 1967 | 1953 | – | 1957 | 1957 |
| 2 | 60 | 530 | 1070 | control | 1953 | 1981 | 1957 | 1957 |
| 3 | 101 | 490 | 1070 | 1.5 km (6%) roads, 1959; 25% clearcut in 3 patches, 1963 | 1953 | – | 1957 | 1957 |
| 6 | 13 | 880 | 1010 | 100% clearcut, 1974 | 1964 | 1972 | 1972 | – |
| 7 | 15 | 910 | 1020 | 50% selective canopy removal, 1974; remaining canopy removed 1984 | 1964 | 1972 | 1972 | – |
| 8 | 21 | 960 | 1130 | control | 1964 | 1972 | 1972 | – |
| 9 | 9 | 425 | 700 | control | 1967 | 1969 | 1969 | 1973 |
| 10 | 10 | 425 | 700 | 100% clearcut, 1975 | 1967 | 1969 | 1969 | 1973 |

[1] W = continuous stream discharge; C and S = composited 3-weekly samples of streamwater collected with proportional sampler and analyzed for chemistry (C): N, P, Ca, Mg, K, Na, alkalinity, conductivity, pH, particulate N, and particulate P; and suspended sediment (S); B = bedload sampling in ponding basin.

[2] Streamflow records are continuous up to the present, except for Watersheds 6 and 7, where streamflow was not measured from 1987 to 1994. Records are based on water year, October 1 to September 30.

[3] Long-term records with 3-weekly sampling interval began on this date.

Geomorphology studies began with examination of sediment yield from experimental watersheds (Fredriksen, 1970; Grant and Wolff, 1991) and mass movement associated with the 1964-1965 floods (Dyrness, 1967; Fredriksen, 1970). In the IBP sedimentation studies moved to a sediment-budgets and routing perspective (Swanson et al., 1982a, b) to parallel the ecologists' work on water and nutrient cycling. Another example of work at the ecology-geomorphology interface is the continuing study of woody debris in streams, which took off in 1975. A series of studies has addressed channel form-process relations over a hierarchy of scales of channel and valley-floor landforms (Grant et al., 1990; Grant and Swanson, 1995; Grant, 1997). The February 1996 flood catalyzed study of an integrated response of the hydrology, geomorphology, and ecology of a watershed to a major flood (Swanson et al., 1998; Wondzell and Swanson, 1999; Johnson et al., 2000; Nakamura et al., 2000; Wemple et al., 2001). Long-term monitoring activities are underway, including streamflow, sediment yield from experimental watersheds (Grant and Wolff, 1991), movement of the Lookout Creek Earthflow (Wong, 1991), and channel dynamics observed with repeat surveys of cross sections (Faustini, 2000).

Nutrient cycling and cation export studies have pursued the theme of coupling of geophysical and biological processes in forest-stream ecosystems. Studies in the early IBP period emphasized quality of water from control and treated watersheds (Fredriksen, 1971). Subsequent work in the IBP era focused on nutrient budgets, particularly nitrogen, in soil, forests, streams, and small watersheds (Sollins et al., 1980; Triska et al., 1984). Work in the early years on the Andrews LTER site examined precipitation and stream chemistry of undisturbed basins, and contrasted the chemistry of control basins with that of harvested basins (Martin and Harr, 1988, 1989). Recent studies have examined long-term trends of nitrogen budgets for small watersheds (Vanderbilt, 2000).

A close partnership between Andrews Forest scientists and land managers of the Willamette National Forest influences the science and ultimately the management and policy. This work occurs locally in the contexts of the Cascade Center for Ecosystem Management and the Central Cascades Adaptive Management Area, which is designated under the Northwest Forest Plan with the charge to develop innovative approaches to landscape management. A great deal of applied research, development, application, and management demonstration takes place at the interface of research and management. For example, research results are used in modification of roads for purposes of watershed restoration, in assessment of effectiveness of in-stream habitat structures, and in landscape management plans that recognize various types of landslide terrain in terms of hazards as well as their sediment and wood delivery functions. The engagement of land management provides media for synthesis (landscape management plans) and opportunity to conduct large-scale experiments, such as stream-habitat manipulations.

This guide supplements and updates guidebooks for the 1980 GSA Cordilleran Section meeting in Corvallis (Swanson et al., 1980) and an expanded version of that guide used for the 1987 International Symposium on Erosion and Sedimentation in the Pacific Rim held in Corvallis (Swanson et al., 1987). Those guides provide information on the following themes and field stops, which are not covered in this guide: geomorphology of lower Lookout Creek and Blue River reservoir area, Watershed 10 sediment budget, Lookout Creek earthflow, revegetation of debris slide and debris flow sites, dynamics of wood in Mack Creek, and channel and valley floor morphology of Lookout Creek. The 1987 guide also contains a road log from Corvallis to Andrews Forest. See also the Andrews Forest webpages for further information on a variety of topics of interest to scientists (http://fsl.orst.edu/lter) and land managers (http://fsl.orst.edu/ccem). A journalistic account of Andrews Forest science is offered by Jon Luoma (1999).

## GENERAL CHARACTERSITICS OF THE ANDREWS FOREST LANDSCAPE

The Lookout Creek watershed, equal to the Andrews Forest, ranges in elevation from 420-1615 m. Bedrock below about 850 m is composed of hydrothermally altered volcaniclastic rocks of late Oligocene to early Miocene age (Swanson and James, 1975). Middle elevations are underlain by ash flows and basaltic andesite lava flows of Miocene age. Upper elevation areas are underlain by andesite lava flows with K-Ar ages in the range of 3-6 million yr. Soils have loamy surface horizons, have aggregate structure bound by organic matter, and have porosity of 60-70%, over half of which is macropore space (Ranken, 1974). Subsoil porosity is also high (50-60%) of which about 20% is macropores. This accounts for the predominance of subsurface flow over streams (Harr, 1977), because infiltration capacity greatly exceeds precipitation intensity. The ability of these soils to retain 30-40 cm of water in the upper 120 cm of soil (Dyrness, 1969) helps sustain the massive forest vegetation through the dry summer (Waring and Franklin, 1979).

The Lookout Creek watershed has been sculpted over perhaps 3 million yr by glacial, mass movement, fluvial, geochemical, and other processes. Glacial landforms dominate the southeastern quadrant of the area with U-shaped valleys along upper Lookout Creek and Mack Creek. These and other north-flowing drainages bounded to the south by ridges over about 1200 m have well-developed cirque forms at their heads. The western part of the watershed is dominated by steep (approximately 30-35$^o$), straight slopes and narrow ridge crests and valley floors produced by stream erosion and shallow, rapid debris slides and flows. Several areas exhibit irregular terrain of moderate slope (5-10$^o$) resulting from deep-seated (> 5m thickness), slow-moving (generally <1 m/yr) landslides, locally referred to as earthflows (Swanson and Swanston, 1977; Pyles et al., 1987). Stream environments range from steep, narrow, bedrock chutes along small streams recently scoured by debris flows to wide alluvial reaches, which have accumulated behind constrictions of the valley floor. Much of the stream network is a boulder-dominated, stepped sequence of pools and steep channel units (Grant et al., 1990).

The area receives approximately 2300 mm of precipitation at low elevations, mainly as rain, and a greater amount in upper elevations, mainly as snow. Approximately 80% of precipitation falls between October and April during long-duration, low-intensity frontal storms. Snow packs are common at low elevations, but rarely persist longer than 2 weeks. A seasonal snow pack develops at elevations about 1000-1200 m. Major floods typically result from rain augmented by snowmelt (Harr, 1981). Evapotranspiration accounts for about 45% of precipitation. Based on analysis of long-term streamflow records from experimental watersheds (Table 1), 100% clearcutting and burning resulted in 40% increase in annual flows and 20-100% increase in moderate and small peak flows in the first 5 yr after treatment (Jones and Grant, 1996; Jones, 2000).

Studies of long-term trends of cation and nitrogen budgets for small watersheds indicate that nutrient cycling is tight within these forest ecosystems and increases in export following disturbance are suppressed within a few years (Martin and Harr, 1989; Vanderbilt, 2000). Net cation export derived from bedrock weathering accounts for about 3 t/yr of annual export or about 30% of long-term export from forested watershed conditions in lower elevation soil and rocktypes (Swanson et al., 1982). Contributions to cation export are $SiO2 >> Ca > Na > Mg > K$ (Martin and Harr, 1989).

Before forest removal, the vegetation of these basins consisted of mature to old-growth conifer forest with leaf area indices exceeding 8 (Marshall and Waring, 1986). Forests are dominated by Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) with some mountain hemlock (*Tsuga mertsiana*) and Pacific silver fir (*Abies amabilis*) at higher elevations. Post-treatment vegetation consists of shrub and deciduous tree species (for example, *Ceanothus spp.*, *Acer spp.*, *Alnus rubra*) and planted Douglas fir (Dyrness, 1973; Halpern, 1989; Halpern and Spies, 1995). Forestry treatments were imposed from 1962-1975 and ranged from 25% patch cutting to 100% clearcutting, with various amounts of road construction (Table 1). All treated basins had some roads, but densities varied.

Natural disturbances also have formed the forests at Andrews. Native forest at low and middle elevations of the area is dominantly old-growth (400-500 yr) Douglas fir with heights exceeding 70 m along with other conifer species. Middle and upper elevations experienced wildfire in the mid-1800s and parts of the ridge line burned in the 1880-1910s, in a period coincident with sheep grazing activities in meadows along these ridges. Wildfire was the dominant native disturbance agent in these forests, but windthrow, insects (such as, bark beetles), pathogens (such as, root rots), landslides, and other processes also kill forests.

The cold, clear, fast-flowing streams contain rich aquatic life, including nine species of fish, and complex ecological processes, which respond strongly to geomorphology and adjacent forest cover. Woody debris in streams is a dramatic example of interactions among forest and stream ecosystems with a strong mediating influence of landforms and geomorphic processes.

## INVITATION FOR USE OF ANDREWS FOREST DATA AND FIELD OPPORTUNITIES

The Andrews Forest is managed as a national and international research resource. You are cordially invited to make use of the landscape and long-term data sets for research and education. Please contact an Andrews Forest scientist or data manager to make arrangements. Our website is http://www.fsl.orst.edu/lter.

## Module 1. HYDRO-CLIMATOLOGY

[Julia Jones]

### Climate

The climate of the Andrews Forest is marine temperate, with a winter precipitation and high summer temperatures (Fig. 1.1). The highest precipitation occurs in late November, and minimum precipitation occurs in late July; very little precipitation occurs between June 1 and September 30. The annual hydrograph peaks in January, and minimum streamflow occurs in July and August (Fig. 1.2).

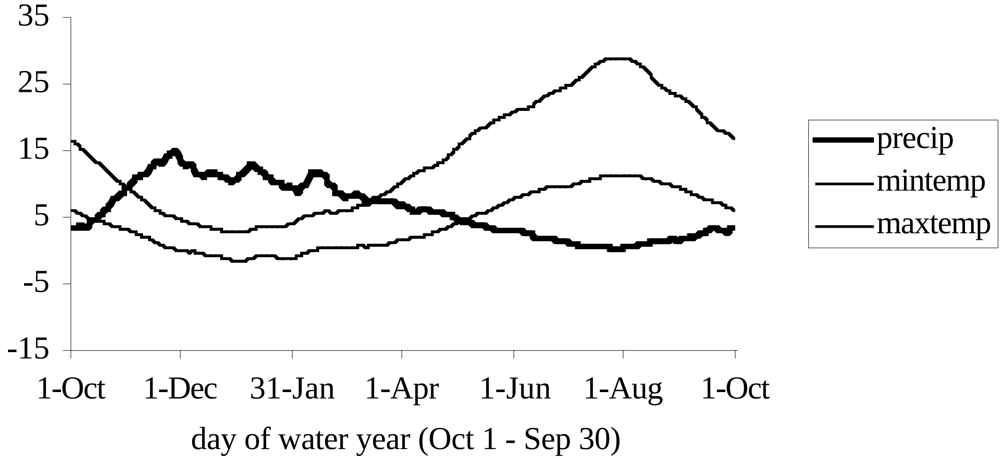

Figure 1.1. 15-day running mean of mean daily precipitation (mm) (1958-1996) and temperature (degrees C) (1952-1995) at Watershed 2.

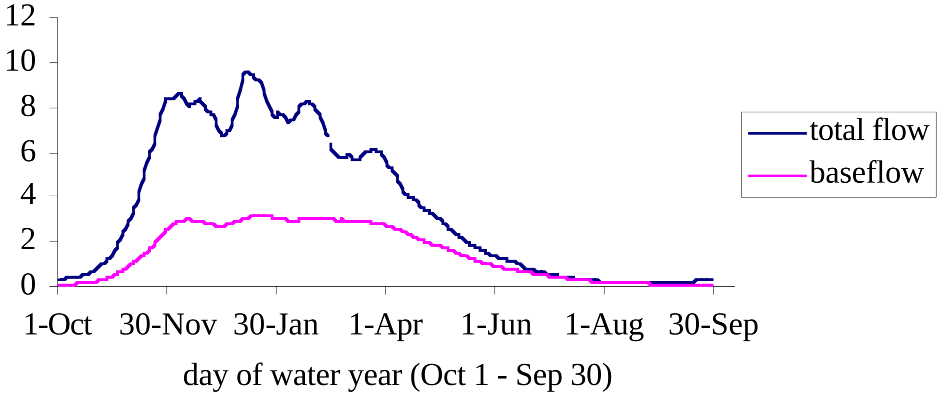

Figure 1.2. 15-day smoothing of unit area discharge (mm), Watershed 2, 1953-96.

## Long-Term Trends in Precipitation and Streamflow

Mean annual precipitation from 1958-1996 was 2259 mm, but ranged from 1309 mm in 1977 to 3074 mm in 1972 (Fig. 1.3). Mean annual streamflow at Watershed 2 from 1952-1996 was 1332 mm, but ranged from 370 mm in 1977 to 2187 mm in 1956. Streamflow is 56% of precipitation, but ranged from 40% in dry years to 70% in wet years. Thus, actual annual evapotranspiration is estimated to be 927 mm, or 44% of precipitation.

There has been a long-term decline in winter precipitation and winter streamflow (Figs. 1.3, 1.4). However, the trends do not obviously follow any simple model of climate shifts, such as the proposed 1976 "climate step" of Pacific Decadal Oscillation or of El Niño/Southern Oscillation (Greenland et al., 2001).

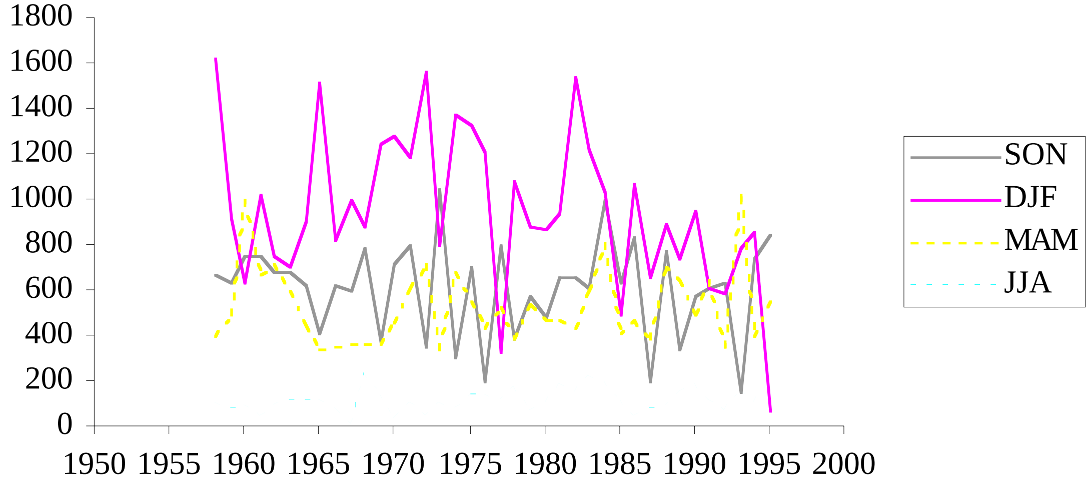

Figure 1.3. Annual precipitation (mm) at Watershed 2, 1958-96.

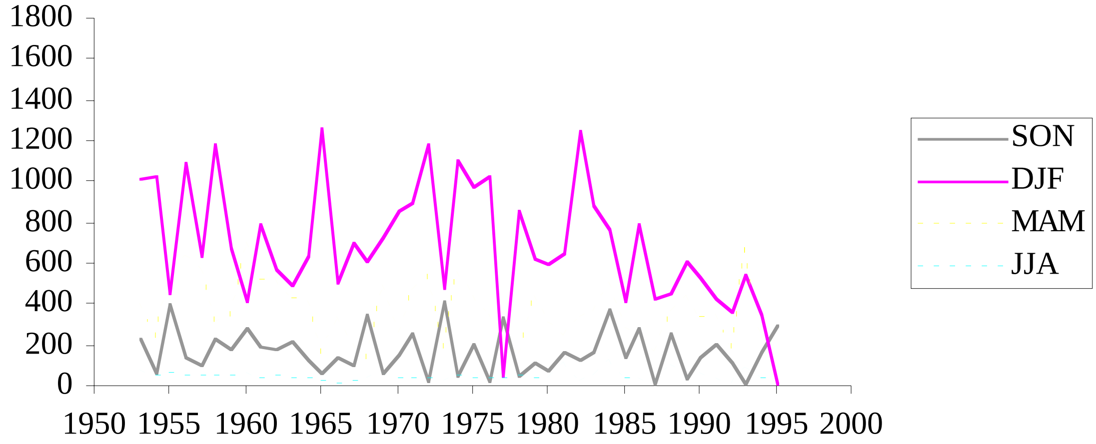

Figure 1.4. Annual discharge (mm) at Watershed 2, 1952-96.

## Estimates of Evapotranspiration and Water Use

Recent research has attempted to better characterize evapotranspiration by modeling, retrospective empirical analysis, and isolating its components by direct measurements. Model estimates at Andrews Forest indicate that evapotranspiration may be as high as 6 mm/day. Retrospective estimates from long-term records at Watershed 2 (that is, the difference between average precipitation and streamflow, or 927 mm) indicate that the average daily evapotranspiration may be 2.5 mm/day, but evapotranspiration may be much higher or lower than this during key periods of the year. The probable periods of maximum evapotranspiration are fall and spring, when temperatures and moisture are moderate. Sapflow measurements during the summer indicate that water use by old-growth trees may be only 0.5 mm/day, whereas water use by 30-yr-old alder and Douglas fir may be 1.5 mm/day (Barbara Bond, unpublished data).

## Module 2. SMALL WATERSHEDS - STREAMFLOW RESPONSE TO FOREST REMOVAL AND ROADS

[Julia Jones]

### Responses of Peak Flows to Forest Harvest and Roads

The magnitude, seasonality, and duration of peak discharge responses to forest removal and regrowth and roads in five pairs of experimental basins in the Andrews Forest are consistent with fundamental water balance and routing concepts in hydrology. Effects of forestry treatments on evapotranspiration, snowpack dynamics, and subsurface flow interception vary predictably by season, geographic setting, amount of forest canopy removal, stage of canopy regrowth, and arrangement of roads in the basin. Post-treatment responses of selected subpopulations of matched peak discharge events were examined over 21-34 yr post-treatment periods in treated and control basin pairs in a range of geographic settings. Changes in evapotranspiration associated with forest canopy removal and regrowth apparently accounted for significant increases in peak discharges during the first post-harvest decade (Fig. 2.1). Changes in snowpack dynamics apparently accounted for significant increases (25-31%) in winter rain-on-snow events, but other types of winter events did not change in four of five basins at the Andrews Experimental Forest (Fig. 2.2).

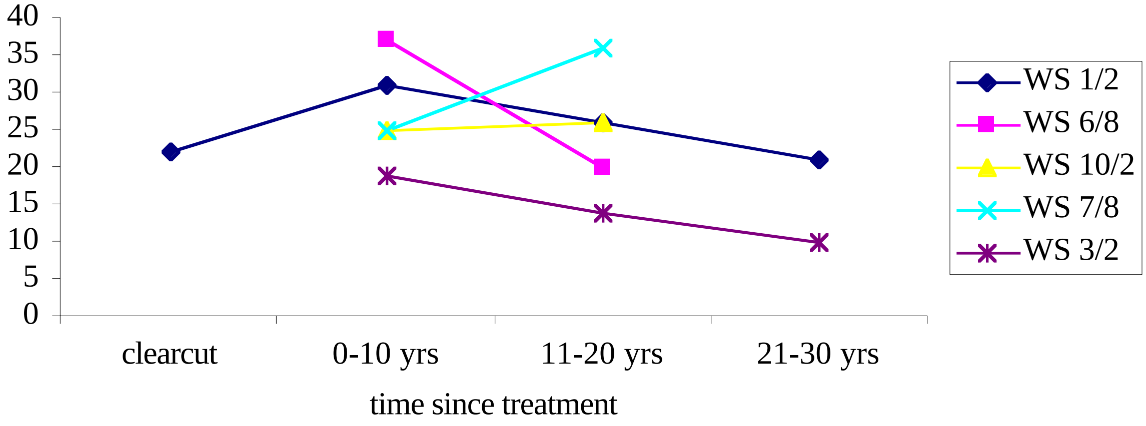

Figure 2.1. Statistically significant increases (%) in peak discharges of all event sizes by decade in different watersheds (WS) after forest harvest and road construction (from Jones, 2000).

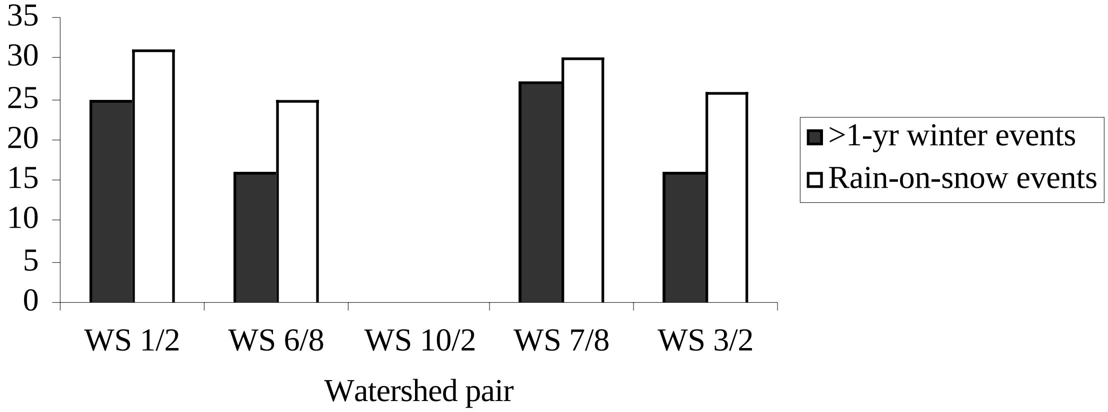

Figure 2.2. Statistically significant increases (%) in peak discharges of large and rain-on-snow events after forest harvest and road construction for all post-treatment years (from Jones, 2000).

Changes in subsurface flow interception by road cuts apparently accounted for significant increases (16-26%) in large (>1 yr return period) events in four of five basins, of which three had roads. Increases in small peak discharge events decreased rapidly after the first post-treatment decade, but increases in large events persisted into the second and third post-treatment decades (Jones, 2000).

Streamflow Yield Responses—Annual Yield, Summer Yield

Immediately after forest canopy removal, annual streamflow increased by 400-500 mm (40%) at all three 100% harvested basins at the Andrews Forest (Fig. 2.3). Twenty-five to thirty years after forest canopy removal, basins at the conifer forest site had persistent annual increases of 200-450 mm at upper elevations (Watersheds 6/8), 200-350 mm at middle elevations (Watersheds 1/2), and 100-250 mm at lower elevations (Watersheds 10/2) (Fig. 2.3 from Jones and Post, in review).

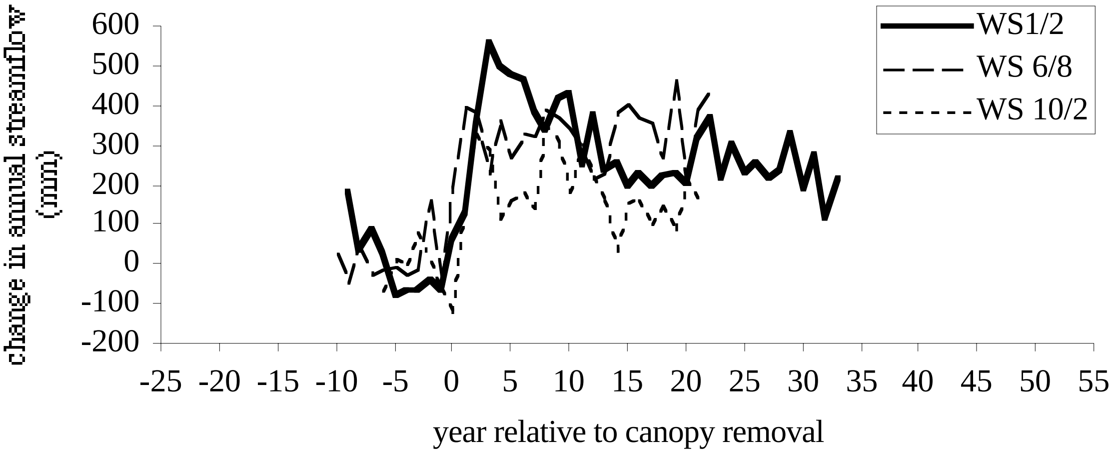

Figure 2.3. Absolute change in annual streamflow (mm at streamflow per unit area) over time after 100% canopy removal by watershed (WS) pairs.

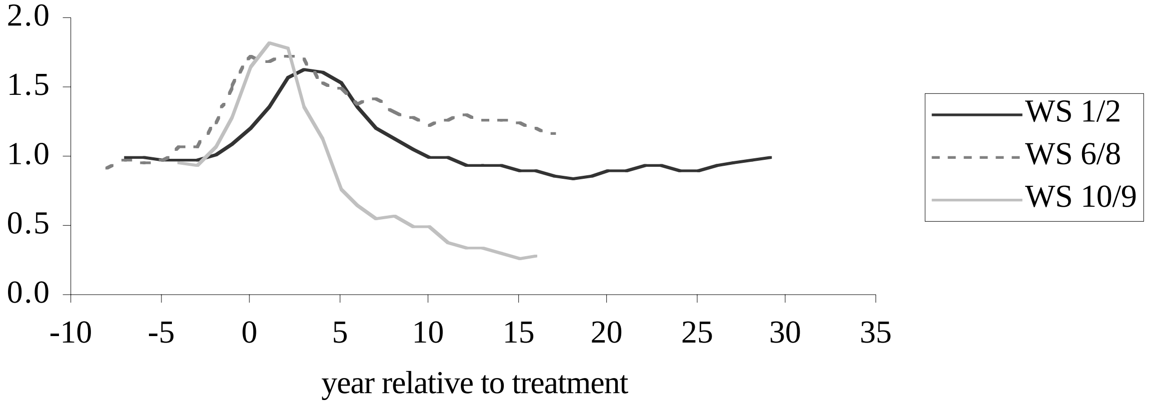

Figure 2.4. 5-yr smoothing of summer streamflow (June-September) responses to 100% forest harvest removal at the Andrews Forest, a fraction of pre-treatment flows by year relative to treatment Pre-treatment index = 1.

The apparent more rapid recovery of streamflow at the lowest elevation site (Watershed 10) is especially marked in the behavior of summer flows (Fig. 2.4; Jones, unpub. data). Summer streamflow recovered slightly at the high elevation basins (Watersheds 6, 8), recovered completely at the mid-elevation basins (Watersheds 1, 2), and declined to well below pre-treatment levels at the lowest elevation basins (Watersheds 10, 9).

## Hydrologic Responses to Forest Harvest and Regrowth by Day of Year

Forest harvest produced the biggest absolute increases in streamflow during the fall and spring at the Andrews Forest, based on the example of Watersheds 1/2 (Fig. 2.5). Streamflow increases were greatest in the fall, then the spring, and modest during the summer. Midwinter streamflow did not respond to 100% forest canopy removal in Watershed 1. Several alternative hypotheses have been proposed for the lack of response at this time of the year. First, interception, snow, and soil reservoirs may be full, hence transmitting all inputs, so removal of the canopy reservoir has no effect on streamflow. Second, losses of interception storage may be balanced by losses of cloudwater interception. Third, increased water delivered to the forest floor may be stored in a cooler more persistent snowpack, contributing to streamflow increases in the spring. Increases in summer streamflow disappeared within 5 yr after forest cutting, and increases of fall streamflow had mostly disappeared by 35 yr after it (Fig. 2.5). This recovery is probably due to increased summer and fall water use by regenerating vegetation. However, streamflow increases during the spring persisted with little decline for 35 yr after forest canopy removal.

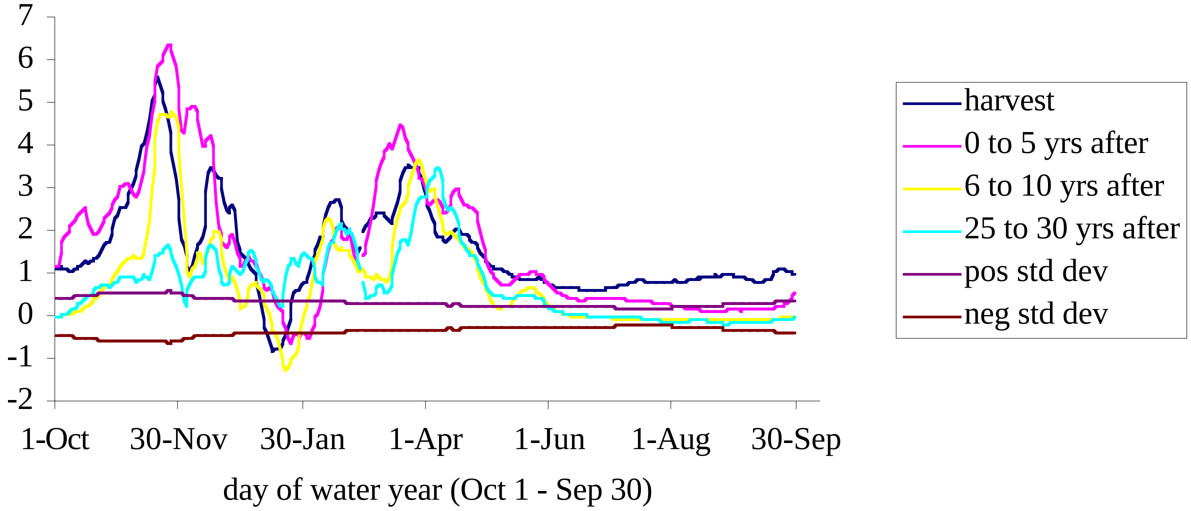

Figure 2.5. 15-day smoothing of absolute change (mm) in mean daily streamflow, Watershed 1 (100% harvest) v. Watershed 2 (control), for 5-yr periods after treatment. Standard deviation at control basin for period of record is shown for reference.

## Module 3. SMALL WATERSHEDS –NUTRIENT CYCLING

[Julia Jones]

Stream chemistry at the Andrews reveals many of the complex interconnections between the geophysical and ecological systems. Stream chemistry, and hence export of dissolved materials from small watersheds, has been studied in detail since the 1960s at the Andrews forest. Fluxes of materials in stream water have been measured since 1969 at the low elevation paired basins (Watersheds 9 and 10); since 1972 at the upper elevation paired basins (Watersheds 6, 7, and 8); and since 1981 at the mid-elevation control basin (Watershed 2) (see Introduction, Table 1, Fig. 1).

### Nutrient Budgets

Cations, N, P, conductivity, alkalinity, and pH have been measured, and N and P measurements have been made both for dissolved and particulate forms. In general, the fluxes of cations are very high and appear to be coupled to physical processes (precipitation, runoff, and mass movements). Streams export up to 10x more cations and Si than is input in precipitation. Moreover, fluxes of cations and Si are two to three orders of magnitude higher than fluxes of N and P (Figs. 3.1, 3.2, adapted from Martin and Harr, 1989).

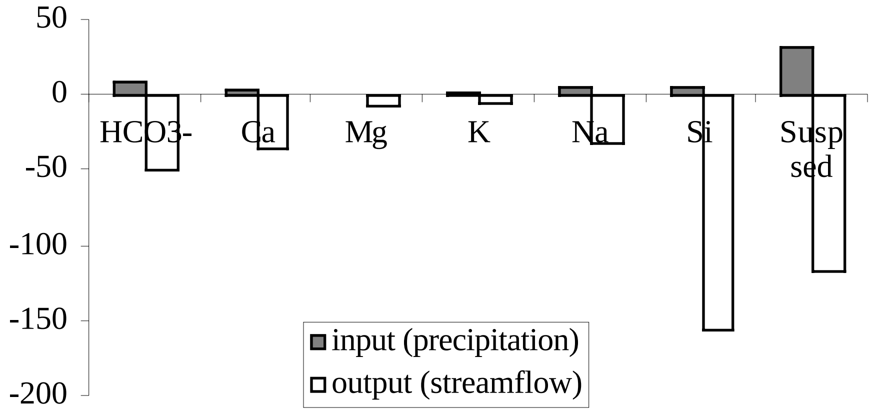

Figure 3.1. Budgets for inorganic constituents (kg/ha/hr) of Watershed 8 (high-elevation control) (from Martin and Harr, 1989).

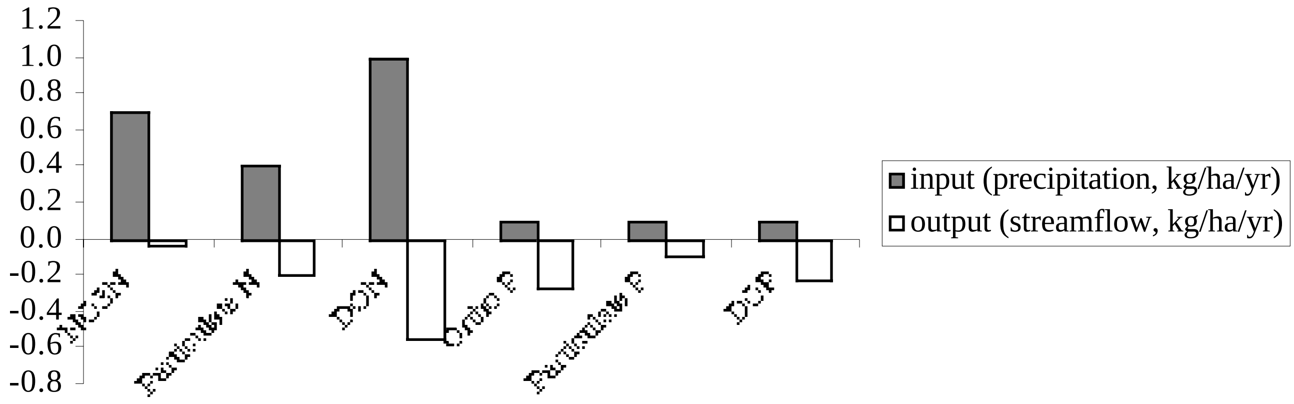

Figure 3.2. Budgets for organic constituents (kg/ha/hr) of Watershed 8 (high-elevation control) (from Martin and Harr, 1989).

The fluxes of biologically relevant nutrients, especially N and P, show more complex patterns. Both occur in very low concentrations and appear to be quite tightly held in the forest and stream ecosystem. Exports of N are lower than inputs from precipitation, but exports of P are about equal to inputs from precipitation (Fig. 3.2, adapted from Martin and Harr, 1989).

## N and P in Control Basins With Old-Growth Forest

Export of N and P in streamflow from old-growth forests is very low. Over the period 1981-87, total N in Watershed 2 ranged from 0-0.154 kg/ha, NH3N ranged from 0-0.13 kg/ha, and DON ranged from 0-0.1 kg/ha. Particulate N ranged from 0-0.26 kg/ha, except in the flood of record on 7 Feb 96, when it reached 4.1 kg/ha. Over the period 1969-97, total N in Watershed 9 ranged from 0-0.21 kg/ha, NO3N ranged from 0-0.07 kg/ha, and DON ranged from 0-0.2 kg/ha. Particulate N ranged from 0-0.26 kg/ha, except in the flood of record on 7 Feb 96, when it reached 2.3 kg/ha.

Over the course of the year, all N and P forms closely follow streamflow. DON fluxes follow streamflow in general, but they deviate from streamflow in some suggestive ways (Fig. 3.3) (also see Vanderbilt, 2000). In particular, DON rises rapidly during the early part of the wet season (October/November) and then remains somewhat constant during the period from December to February. Thus, there is both a dilution effect (nutrient output is proportional to streamflow) and a secondary effect (nutrient output reaches a maximum earlier in the water year than streamflow). A number of possible explanations for the secondary effect are being explored. These include atmospheric dry deposition of dust from the Willamette Valley, flushes of DON from soils, DON release from litterfall on soils or into streams, or DON release from early fall mortality of stream organisms.

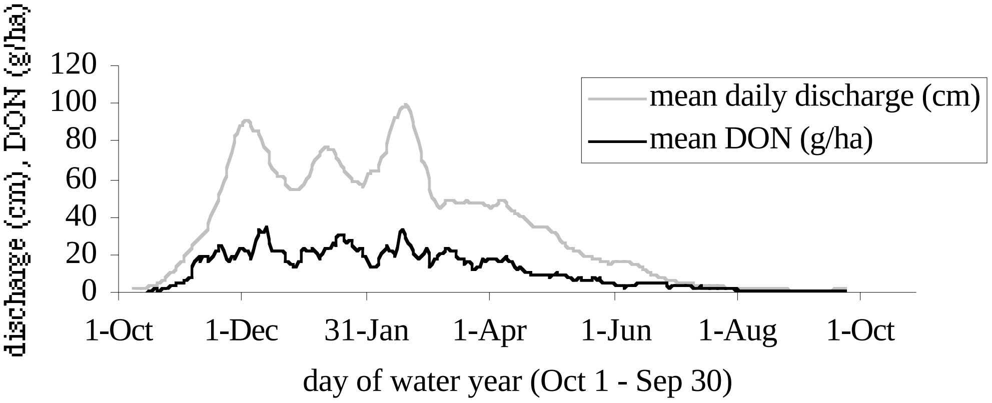

Figure 3.3. 15-day running means of daily streamflow and DON in streamflow from Watershed 2, 1981-1997.

## Stream N and P Over Time

Long term trends in N and P are dominated by seasonal variability. DON is the predominant or only N form in streamflow most of the time, but other N forms (NO3, NH4) are important during the fall (just after October in Fig. 3.4). In dry years (mid-1980s, early 1990s), DON remains the dominant component of N fluxes throughout the year (DON never falls below 50% of total N).

However, in other years (early 1980s, late 1980s, 1990-91), DON is overwhelmed by short-duration fluxes of NO3 and NH4 (Figure 3.4) (Jones, unpub. data).

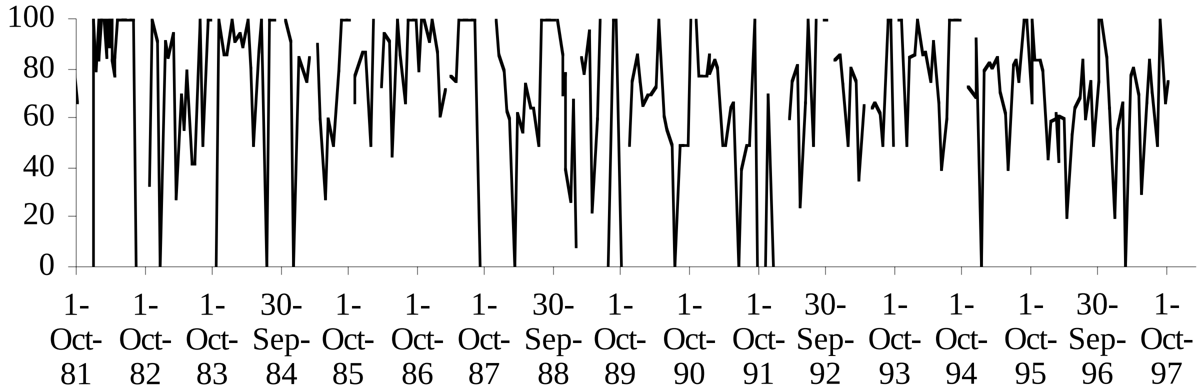

Figure 3.4. Dissolved organic N as percent of Total N, Watershed 2.

## Changes in Stream N and P Before/After Forest Removal

Stream N increased after 100% forest harvest in Watershed 6 in 1974 and Watershed 10 in 1975. Stream P did not appear to be affected by forest harvest. Stream N recovered to pre-treatment levels and in some cases declined to below pre-treatment levels by 15-20 yr after 100% forest canopy removal. This finding implies that early successional vegetation was using as much or more N and P than old-growth forest. Stream chemistry recovery at Watershed 10 and Watershed 6 does not match the recovery trajectory of annual streamflow or summer streamflow, which remained elevated above pre-treatment levels through the second post-harvest decade. Absolute changes in stream N after 100% forest removal were very small. Recovery of DON and NO3 in streamflow to pre-treatment levels was faster at the low-elevation basin with shallow soils (Watershed 10) than at the high elevation basin (Watershed 6).

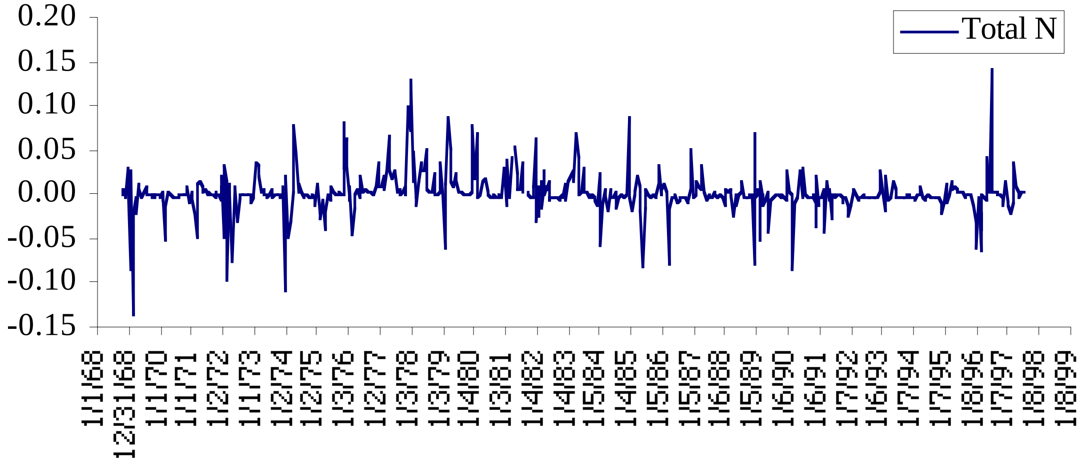

Figure 3.5. Absolute change in Total N (kg/ha), Watershed 10 v. 9.

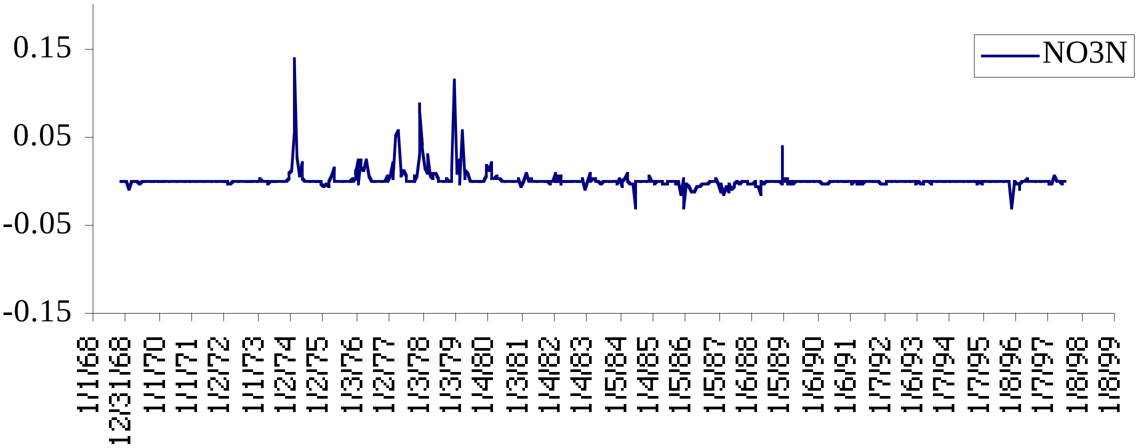

Figure 3.6. Absolute change in NO3N (kg/ha), Watershed 10 v. 9.

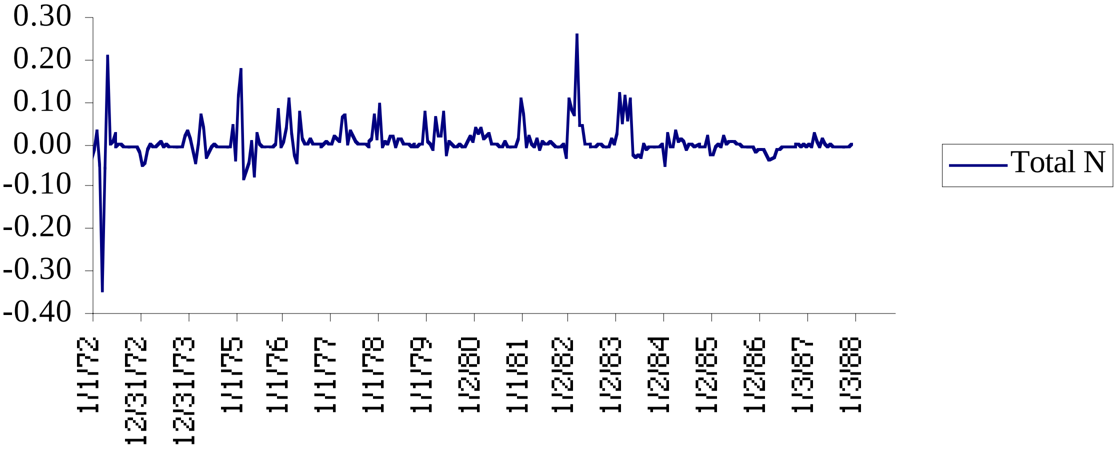

Figure 3.7. Absolute change in Total N (kg/ha), Watershed 6 v. 8.

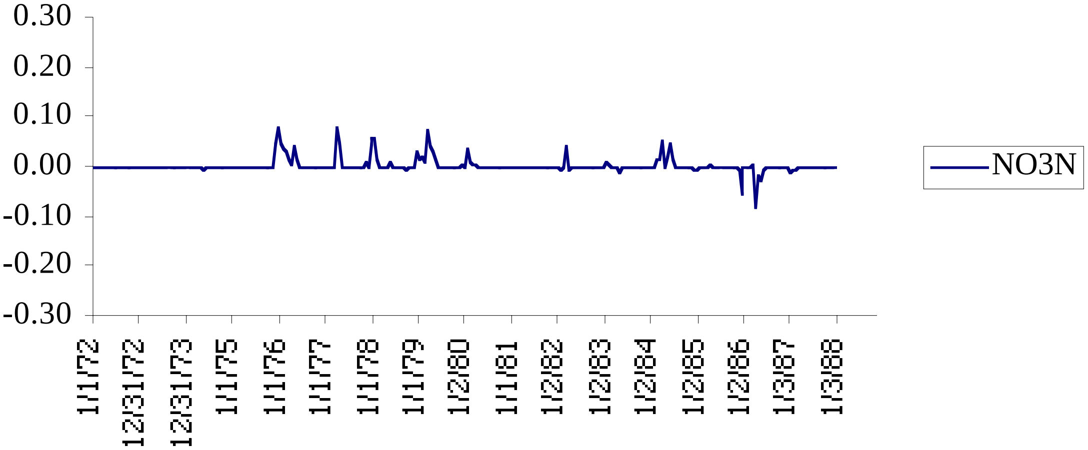

Figure 3.8. Absolute change in NO3N (kg/ha), Watershed 6 v. 8.

Relative to the pre-treatment period (1969-74), all N forms at Watershed 10 increased relative to Watershed 9 in the first 5-8 yr after 100% forest canopy removal (see, for example, total N, NO3N, DON Figs. 3.5, 3.6). By the early 1980s these increases had diminished, and by 1990, 15 yr after forest canopy removal, they had disappeared. Similar trends are apparent at Watersheds 6 and 8, although the pre- and post-treatment records are shorter (Figs. 3.7, 3.8).

## Module 4. SEDIMENT YIELD OF SMALL WATERSHEDS

[Gordon E. Grant, Shannon K. Hayes]

A persistent and often contentious debate surrounds evaluating effects of forest harvest activities on streamflow and sediment yield. Despite abundant discussion of peak flow changes following timber harvest in paired-watershed studies in the Andrews Forest and other basins in western Oregon (Jones and Grant, 1996, 2001a, 2001b; Thomas and Megahan, 1998, 2001; Beschta et al., 2000; Jones, 2000), no studies have evaluated the geomorphic response to observed peak flow changes—a question of great interest in interpreting potential downstream consequences of forest management on channels and ecosystems.

Decades of paired-watershed studies at the Andrews Forest have enhanced our understanding about the impacts of forest harvest on sediment transport through small mountain watersheds (Fig. 4.1). Early studies focused on the impacts of forest harvest on suspended sediment and bedload yields from experimental Watersheds 1, 2, and 3 (for example, Fredriksen, 1970; Grant and Wolff, 1991), and hillslope and channel sediment budgets from Watersheds 9 and 10 (Swanson et al., 1982a). Current research is aimed at disentangling the combined effects of hydrologic changes and increased sediment supply have on fluvial sediment transport following clear-cutting (Grant and Hayes, 2000).

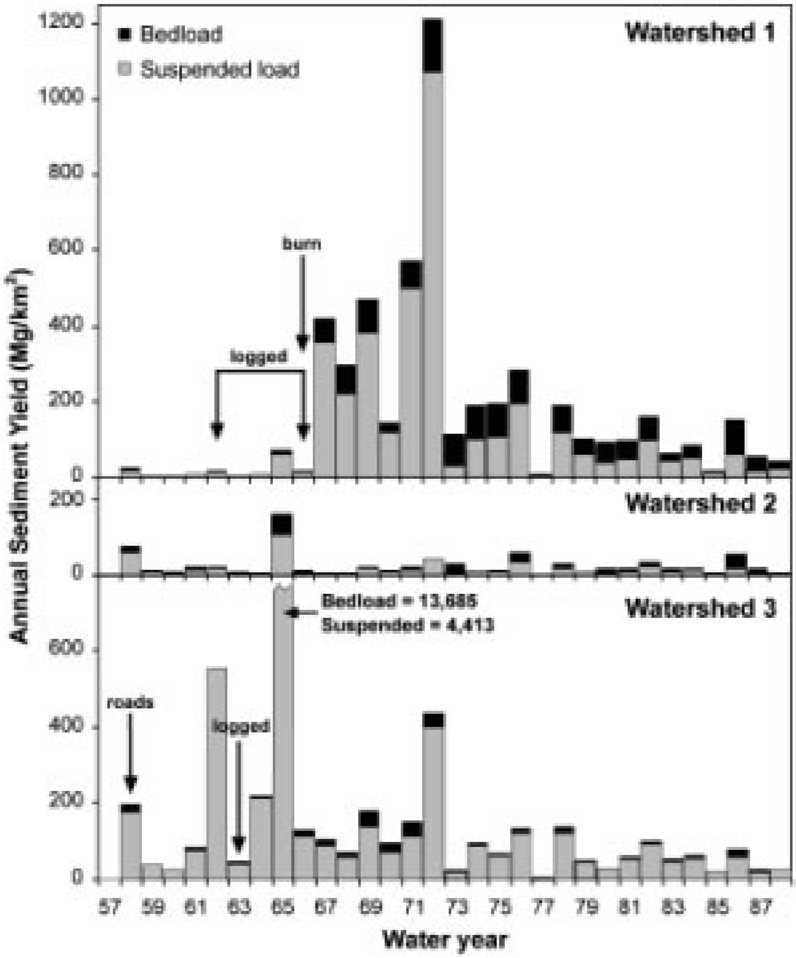

Figure 4.1. Annual sediment yields for Watersheds 1 (100% clear-cut), 2 (control), and 3 (25% clear-cut + roads) for water years 1958-1988 (from Grant and Wolff, 1991).

These studies document significant increases in sediment yields from harvested basins following treatment (Fig. 4.2). Although fluvial transport of sediment increased by at least an order of magnitude following treatment, episodic mass movements dominate long-term sediment output from some small watersheds. In Watershed 3, debris flows during the December 1964 storm transported 88% of the total post-treatment sediment yield through 1988; subsequent debris flows during the February 1996 storm moved comparable large volumes. Debris flows scoured the Watershed 3 channel of available sediment, so transport in intervening years was quite low. In the absence of large mass movements, sediment yields show a roughly exponential decline following treatment, although bedload and suspended sediment transport recover at different rates. Suspended sediment output from Watershed 1, which did not have debris flows, declined to pre-treatment levels within two decades following treatment, but bedload yields exceeded pre-treatment levels as recently as 1999.

The sediment yield histories from this paired-basin study suggest that the timing of land use changes with respect to large storms exerts significant control on magnitude and timing of sediment yield. Watershed 3 was prepared to exhibit a land-use-effects response to the December 1964 and January 1965 floods, but Watershed 1 was not because logging was only partially completed and fallen timber may have stabilized some hillslopes and channels.

Since the relation between sediment transport and discharge typically follows a power law, small increases in discharge can translate into large increases in sediment transport. But timber harvest typically influences both the hydrologic regime and sediment supply of a watershed, making it difficult to isolate the peak flow effect alone. We addressed this problem by using paired-watershed data from Watersheds 1 and 2 to predict streamflow response in the absence of cutting. We combined the predicted hydrology with observed relations between discharge and sediment transport to disentangle the relative effects of changes in hydrology and sediment supply. While peak flow increases alone can account for modest increases in both suspended and bedload transport in Watershed 1, the peak flow effect is dwarfed by the increased supply of sediment following treatment.

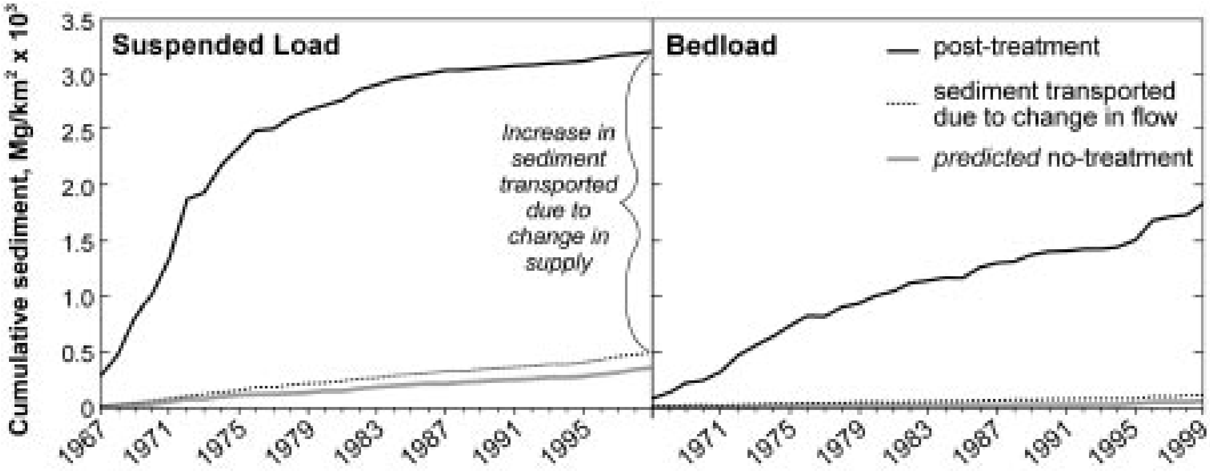

Figure 4.2. Watershed 1 sediment yield after clearcut and prescribed fire for water years 1967-1999.

## Module 5. SEDIMENT BUDGETS OF SMALL WATERSHEDS

[Fred Swanson]

Sediment budgets have been used to characterize the fluxes and storages of soil and sediment within and through watersheds or sub-systems within watersheds. A sediment budget was compiled for the forested condition of 10-ha Watershed 10 which was covered with old-growth and some mature forest before clearcut logging (with only a ridge road and prescribed burning in a small area near the ridge) in 1975 as part of experimental watershed studies during the International Biological Program (Table 5.1). This sediment budget study revealed that the most episodic transport process, debris flow, accounted for about half of the long-term export, although only one debris flow is estimated to occur in about 600 years under forest cover, based on the extensive debris-flow inventory data for the Andrews Forest (Swanson et al., 1982a). The pervasive and persistent process of dissolved export accounted for about 30% of annual average export.

Table 5.1. Process characteristics and transfer rates of organic and inorganic material to the channel by hillslope processes (T/yr) and export from the channel by channel processes (T/yr) for Watershed 10

| | | | Material transfer | |
|---|---|---|---|---|
| Process | Frequency | Area influenced (% of watershed) | Inorganic | Organic |
| Hillslope processes | | | | |
| Solution transfer | Continuous | 99 | 3 | 0.3 |
| Litterfall | Continuous, seasonal | 100 | 0 | 0.3 |
| Surface erosion | Continuous | 99 | 0.5 | 0.3 |
| Creep | Seasonal | 99 | 1.1 | 0.04 |
| Root throw | 1/yr | 0.1** | 0.1 | 0.1 |
| Debris avalanche | 1/370 yr | 1-2** | 6 | 0.4 |
| Slump/earthflow | Seasonal* | 5-8% | 0 | 0 |
| TOTAL | | | 10.7 | 1.4 |
| Channel processes | | | | |
| Solution transfer | Continuous | 1 | 3.0 | 0.3 |
| Suspended sediment | Continuous, storm | 1 | 0.7 | 0.1 |
| Bedload | Storm | 1 | 4.6 | 0.3 |
| Debris torrent | 1/580 yr | 1 | 4.6 | 0.3 |
| TOTAL | | | 8.9 | 1.0 |

*Inactive in past century in Watershed 10.

**Area influenced by one event.

In the first 12 years after logging (1975-1986) surface erosion increased from 80-200 kg ha$^{-1}$ yr$^{-1}$, dissolve load from 332-354 kg ha$^{-1}$ yr$^{-1}$, suspended load from 70-320 kg ha$^{-1}$ yr$^{-1}$, and bedload from 90-305 kg ha$^{-1}$ yr$^{-1}$. In general the rates of surface erosion and these export processes experienced increases for several years and then declined. On February 22, 1986, rainfall on melting snow triggered a 300 m$^3$ slide from a bedrock hollow at the head of the south fork. This mass moved down the channel as a debris flow, ultimately destroying the gauging station and depositing 700 m$^3$ of inorganic and organic debris (approximately 50:50) in the sediment basin and on the head of the alluvial fan at the mouth of the watershed. This single event accounted for about 85% of post-logging export, and the export for the period was about 7 times estimated background, based on sediment yield from multiple experimental basins and slide inventories for a more extensive area. In the flood of February 6, 1996, another debris flow (about 200 m$^3$) began as a streamside slide on the north fork, hit the gauging station, inflicting only minor damage, and accumulated in the sediment basin and on the adjacent road. Channel scouring by the 1996 event was less severe than the 1986 event because of smaller size and amount of large wood, and bank protection by wet snow.

Less complete sediment budgets have been compiled for other watersheds, but comparisons reveal some interesting similarities and differences (Fredriksen, 1970; Swanson and Fredriksen, 1982). Watersheds 3 and 10, for example, have been quite susceptible to debris flows, which can flush sediment from channel storage, including material that had entered channels before logging. Thus the sediment export histories of these two basins have been dominated by debris flows. Poor roads in bad locations, such as through toes of large landslide deposits, have been a major source of sediment and debris flows in Watershed 3. Watershed 1 (clearcut and burned) has not been susceptible to debris flows, possibly because of relatively wide valley floor, moderate channel gradient, and more limited number of initiation sites in its headwaters. The hot prescribed burning of the steep slopes in Watershed 1, on the other hand, appears to have contributed a large amount of surface erosion to the channel (Swanson and Fredriksen, 1982). Thus, both intrinsic watershed properties and specific aspects of management practices affect sediment routing through watersheds and its representation in sediment budgets, such as expressed in the relative significance of episodic and more continuous processes.

Sediment budgets for small watersheds do not necessarily represent larger watersheds in which they are embedded. We have not developed sediment budgets for the Lookout Creek watershed, for example, but the larger basin includes geomorphic processes and depositional features not represented in small watersheds, such as earthflow terrain and alluvial valley floor areas upstream of passive (bedrock notches) or active (landslide) constrictions.

## Module 6. FLOOD HISTORY AND 1996 FLOOD CHANNEL CHANGE

[Julia Jones, John Faustini, Fred Swanson]

Major storms and floods in Dec 1964 and Jan 1965 strongly influenced the Andrews Forest landscape and had a strong imprint on scientists' and land managers' perceptions of landscape change. Many stream reaches and riparian zones experienced disturbance by debris flows, floodwaters, and floated wood. Debris slides from recent cutting units and roads contributed to the extent of disturbance, although about a quarter of inventoried mass movement events initiated in forested areas (Dyrness, 1967). The flood of February 1996 gave contemporary researchers the chance to observe such events first hand and to assess flood effects with abundant data and knowledge of preflood conditions. Gordon Grant shot video during the flood in the lower Lookout Creek and Blue River Reservoir area (see Torrents of Change video produced by Association of Forest Service Employees for Environmental Ethics, Eugene, Oregon).

### Flood History and Meteorology

Many large floods have occurred over the 50-yr record at the Andrews (Table 6.1). The largest of these floods occurred in Dec 64/Jan 65, Feb 96, Nov 77, Jan 72, and Feb 86.

Table 6.1. Date and unit area peak discharge ($m^3/s/km^2$) of the largest 15 floods at Lookout Creek and three unharvested control basins over periods of record (see column headings) at the Andrews.

| | Lookout | | WS9 | | WS2 | | WS8 | |
|---|---|---|---|---|---|---|---|---|
| | 62 km2, all elevations | | 9 ha, low elevation | | 60 ha, mid elevation | | 21 ha, high elevation | |
| Rank | (1949-96) | | (1968-96) | | (1952-96) | | (1963-96) | |
| | Date | $m^3/s/km^2$ | date | $m^3/s/km^2$ | date | $m^3/s/km^2$ | date | $m^3/s/km^2$ |
| 1 | 7-Feb-96 | 4.93 | 7-Feb-96 | 1.47 | 7-Feb-96 | 2.17 | 22-Dec-64 | 1.93 |
| 2 | 22-Dec-64 | 3.03 | 1-Jan-76 | 1.35 | 22-Dec-64 | 1.65 | 13-Dec-77 | 1.50 |
| 3 | 21-Jan-72 | 1.90 | 9-Dec-71 | 1.26 | 27-Jan-65 | 1.35 | 21-Jan-72 | 1.45 |
| 4 | 18-Jan-53 | 1.65 | 2-Mar-72 | 1.14 | 20-Dec-57 | 1.29 | 7-Feb-96 | 1.31 |
| 5 | 25-Nov-77 | 1.39 | 11-Jan-72 | 1.12 | 18-Jan-53 | 1.27 | 25-Nov-77 | 1.30 |
| 6 | 13-Dec-77 | 1.36 | 23-Feb-86 | 1.11 | 21-Jan-72 | 1.27 | 23-Feb-86 | 1.12 |
| 7 | 20-Dec-57 | 1.31 | 9-Jan-89 | 1.07 | 8-Jan-76 | 1.19 | 4-Dec-75 | 1.08 |
| 8 | 23-Feb-86 | 1.23 | 21-Jan-72 | 1.06 | 23-Feb-86 | 1.19 | 25-Dec-80 | 1.07 |
| 9 | 11-Dec-56 | 1.16 | 16-Jan-71 | 0.97 | 28-Jan-65 | 1.16 | 14-Dec-77 | 0.90 |
| 10 | 22-Nov-53 | 1.13 | 30-Nov-75 | 0.95 | 11-Dec-56 | 1.15 | 24-Dec-64 | 0.88 |
| 11 | 21-Dec-55 | 1.10 | 13-Jan-95 | 0.94 | 22-Feb-86 | 1.11 | 27-Dec-73 | 0.87 |
| 12 | 10-Feb-61 | 1.07 | 13-Feb-84 | 0.93 | 9-Jan-89 | 1.03 | 6-Dec-81 | 0.81 |
| 13 | 18-Jan-71 | 1.07 | 5-Dec-71 | 0.93 | 10-Feb-61 | 1.03 | 13-Feb-84 | 0.80 |
| 14 | 25-Dec-80 | 1.01 | 23-Jan-82 | 0.92 | 13-Feb-84 | 1.01 | 28-Jan-65 | 0.78 |
| 15 | 4-Dec-68 | 0.98 | 6-Dec-81 | 0.92 | 19-Dec-61 | 0.99 | 18-Jan-71 | 0.78 |

All major floods have occurred between late November and the end of February, the periods of highest precipitation, but large floods differ in their character. Some large floods were forest-wide and occurred on the same day; the three largest floods at Lookout Creek (7 Feb 96, 22 Dec 64, and 21 Jan 72) ranked within the top 6 floods at all basins that had gages. Other floods were forest-wide, but peaked at different times over a 2-3 day period; the floods of 22-23 Feb 86 and 27-28 Jan 65 produced multiple peaks within 2 days, ranking in the top 15 at one or two basins. Still other floods affected only part of the forest; the fifth-largest event at Lookout Creek (25 Nov 77) produced a peak ranking in the top 15 only at the highest elevation basin.

Large floods at the Andrews Forest typically occur during "rain-on-snow" conditions, when a warm, subtropical front delivers precipitation and warm winds to a landscape blanketed with a snowpack (Harr, 1981, 1986). Rain-on-snow floods may be exacerbated by the creation of gaps in the forest, including by clearcutting, because snowpacks accumulate to greater depths during snow precipitation, and melt more rapidly during rain events, than under forest cover (Harr, 1986; Marks et al., 1998). The geomorphic work performed by large floods has profound ecological implications, including changes in riparian structure and function (Swanson et al., 1998; Johnson et al., 2000) and associated changes in aquatic ecology (Hunter, 1998).

Rain-on-snow conditions are a key ingredient of the recipe for the largest floods at the Andrews (Fig. 6.1). Three factors contribute to this behavior. First, the highest amounts of precipitation occur when snow is on the ground. Second, some subbasins during the period of record had been harvested, and changes in snowpacks augmented their flood peaks by up to 10 or 20% (Jones, 2000). Third, controlling for precipitation amount, some aspect of flood production in subbasins and routing to the Lookout Creek gage augments rain-on-snow peaks beyond those recorded in the control basins (Jones and Perkins, in prep.)

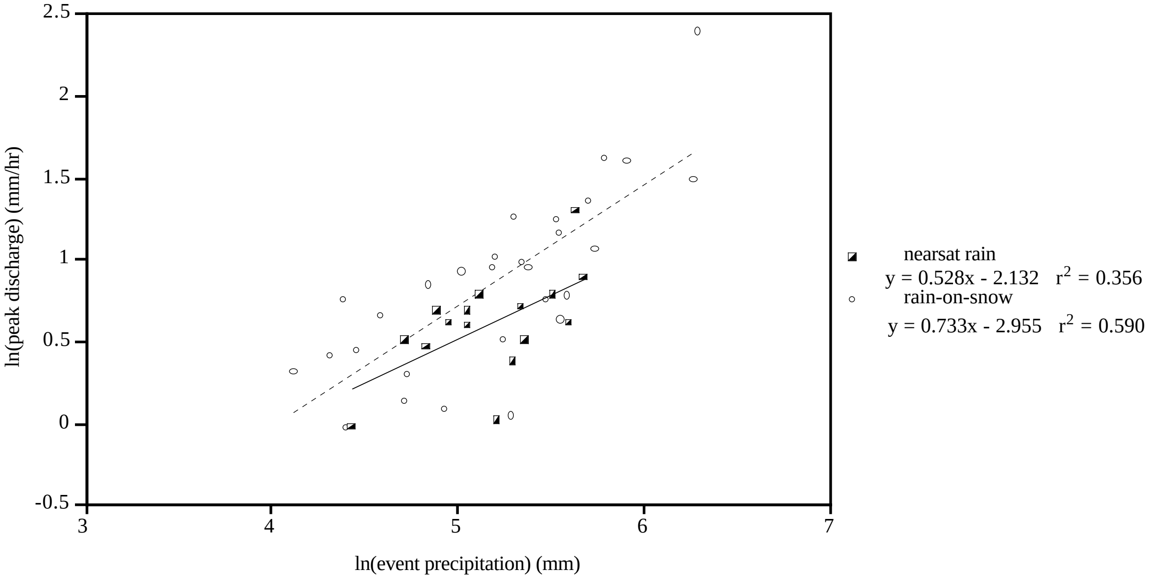

Figure 6.1. Lookout Creek >0.4 yr peak discharges coded by event type at Watersheds 2, 8; dotted line indicates 1-yr peak discharge; solid line = near saturated rain events; dashed line = near-saturated rain-on-snow events (from Jones and Perkins, in review).

In addition, not all subbasins in the Andrews Forest have an equal capacity to produce large floods. The (log-transformed) distributions of peak discharges from these basins (Fig. 6.2) shows that Lookout Creek has a much greater capacity to produce large flood peaks than any of the instrumented first and second-order subbasins. This suggests that channel routing and synchrony of flood peaks are critical ingredients in producing the largest floods at Andrews Forest (Perkins and Jones, in prep.; Jones and Perkins, in prep.)

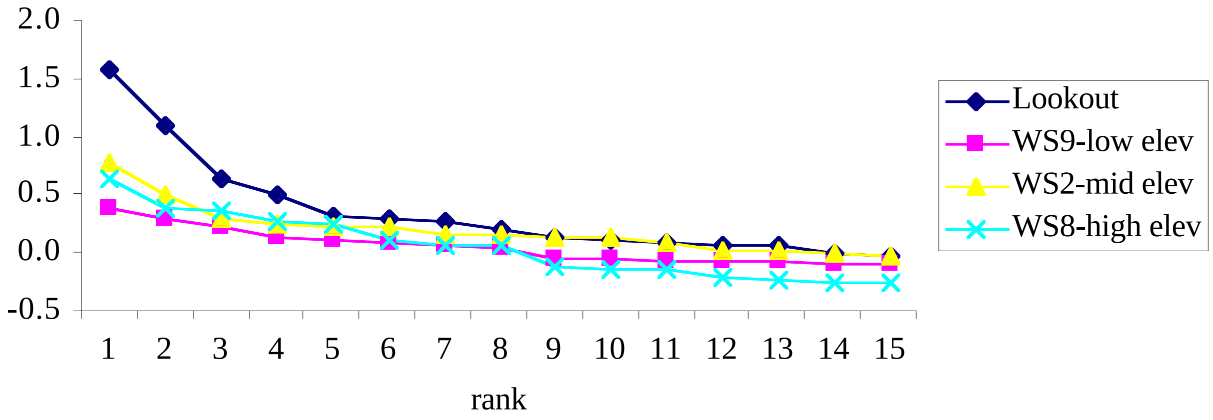

Figure 6.2. Frequency distribution of 15 largest peak discharges in small subbasins (Watersheds [WS] 2, 8, 9, each ~1% of Lookout) of Lookout Creek. Units are 1n(peak discharge, $m^3/s^{-1}/km^2$).

## The Flood of 1996

The flood of 1996, as does any flood, triggered a great variety of physical processes operating in isolation and in combination. We attempted to capture some of this notion by adopting a disturbance propagation perspective to describe how a suite of processes transforms from one to another down through the stream network (Nakamura et al., 2000). One aspect of this perspective is to place some focus on transitions from one process to the next and the roles of landforms, including roads, in those transformations.

Land use effects are revealed in part by comparisons of effects of floods of 1964-1965 with 1996 (Johnson et al., 1997; Swanson et al., 1998). In the Lookout Creek watershed in 1964, clearcuts less than 15 yr old covered nearly 20% of the landscape accompanied by a road system that included practices of the 1950s. Numerous debris slides and flows occurred in both forest areas and associated with roads and clearcuts. These events delivered batches of large wood to the mainstem channel, where the moving wood appears to have aggravated disturbance of valley floor and riparian forests (Johnson et al., 2000). Paucity of cutting and road construction in the Andrews Forest after 1970 resulted in the 1996 storm sensing a landscape with clearcuts with forest stands mainly over 20 yr in age, a network of older roads where the most unstable sites had failed in earlier storms, and many of the channels most prone to debris flows had been previously flushed of large wood and not had a chance to restock. Therefore, the watershed seems to have had a more muted response to the 1996 flood.

Ecological responses to the 1996 flood ranged greatly by physical capability and life history traits of individual species and by location within the watershed (Swanson et al., 1998). The more mobile stream and riparian species generally showed little population response to the flood, and some species exhibited positive responses over the next few years, such as cutthroat trout that may have benefited by more extensive, cleaner spawning gravel. Where wood moved though mainstem channels in congested masses, such as below the confluence of a channel that debouched a debris flow, stands of young red alder (*Alnus rubra*) riparian vegetation were commonly removed (Johnson et al., 2000). Where wood moved in uncongested fashion (individual pieces) toppling of riparian alder was more common. Simple inundation of streamside alder trees by water and sediment caused little mortality. Much of this riparian disturbance occurred in sites previously disturbed by the 1964-1965 floods. Some sites have geomorphic conditions favoring disturbance, such as proximity to sources of mobile wood and locations in flow paths.

## Floods and Stream Channel Changes

Stream channels experienced varied amounts of change in response to floods (Faustini, 2000). Stream cross sections have been instrumented at five locations in Andrews Forest since 1978, with approximately annual repeat surveys (Fig. 6.3).

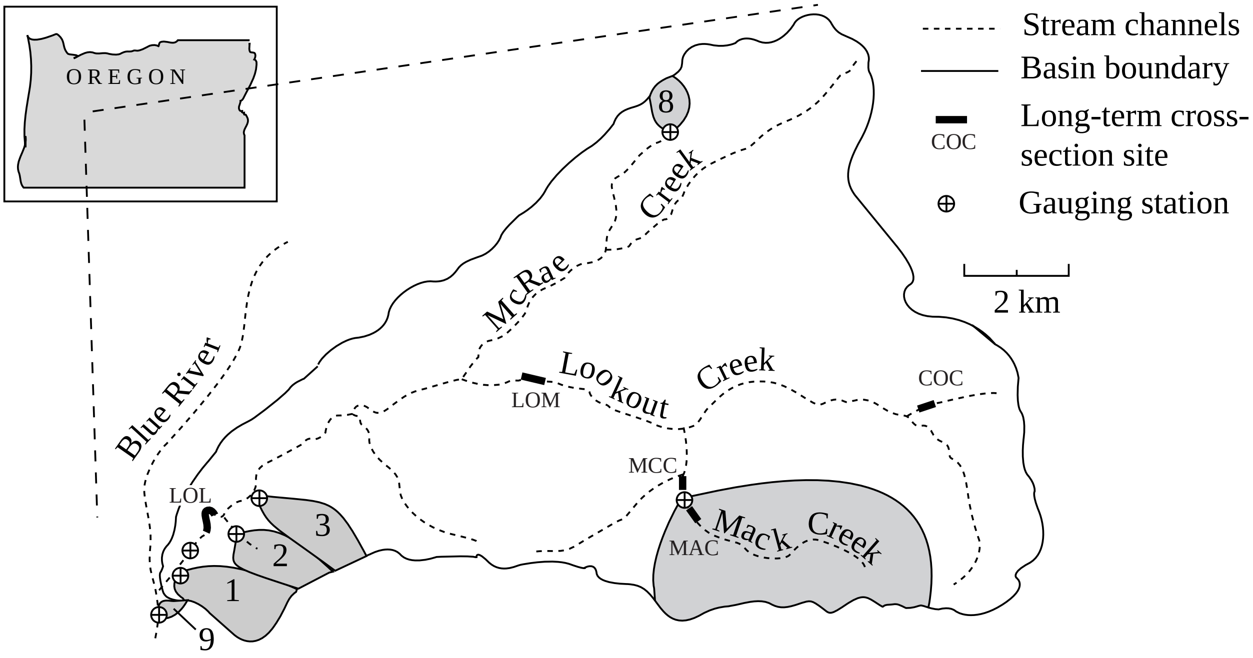

Figure 6.3. Location of long term cross-section monitoring sites, small experimental watersheds, and gauging stations in the Lookout Creek watershed.

The presence of large wood in stream channels increases channel resistance to change during small (5-7 yr return period) floods in the Mack Creek cross-section sites (see Fig. 6.3) (Faustini and Jones, in review). The longitudinal profile of a site without large wood at the Mack Creek clearcut reach (MCC) is more variable than the reach with large wood (MAC in old-growth forest) at the finest scale (~1 m) due a greater frequency of boulder steps, but the reach with large wood is more variable at the channel unit scale. The reach with abundant large wood was less responsive to moderate streamflow events (return period < 5-7 yr), but it responded similarly to peak flows with a return period of about 10-25 yr. Although the average magnitude of cross-section changes was the same during the largest flood in the record (25 yr return period), the reach without large wood experienced scour and coarsening of the bed surface, whereas the reach with large wood experienced aggradation upstream of large wood structures. Mack Creek may be representative of many steep mountain streams in which channel structure is controlled by nonfluvial processes: a legacy of large boulders from glacial or mass-movement processes and a legacy of dead wood from ecological processes (Faustini and Jones, in review).

At the Lower Lookout site (LOL), the stream channel experienced a cycle of changing roles of wood interacting with the stream channel (Fig. 6.4). After the major floods of 1964, 1965, and 1972, the stream channel lacked large wood (Fig. 6.4a). By 1984, several large wood pieces had fallen into the channel and some pieces had floated in from upstream (Fig. 6.4b). By 1990, small floods had brought in small wood pieces that accumulated to create wood jams (Fig. 6.4c). In the 1996 flood, all of this wood was removed (Fig. 6.4d). Today this section has accumulated more pieces of large wood, beginning to resemble the 1984 diagram.

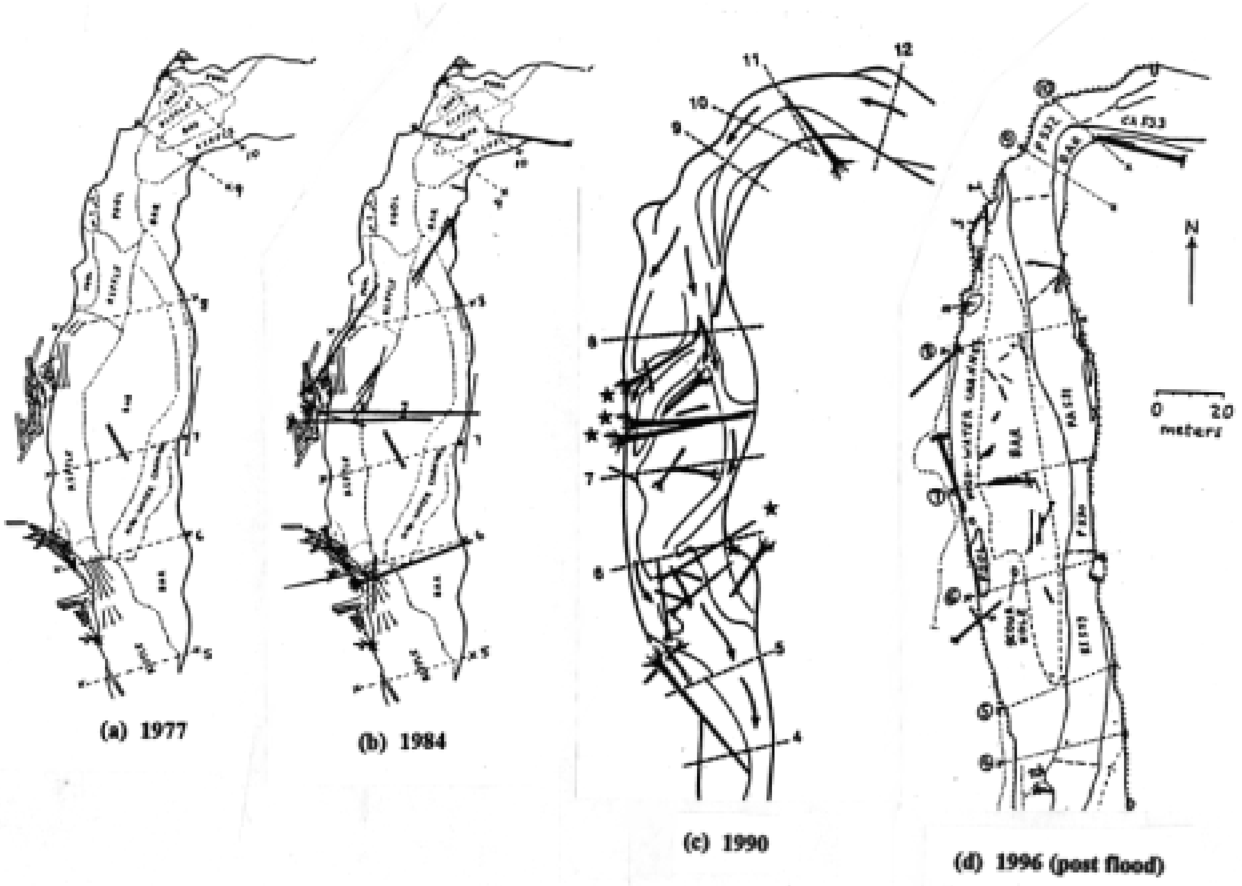

Figure 6.4. Schematic diagrams of the lower Lookout cross-section site in (a) 1977, (b) 1984, (c) 1990, and (d) 1996, after the flood (from Nakamura and Swanson, 1993; Faustini, 2000).

Both minor and major changes in stream channel cross-sectional geometry were documented over the period 1978-1997. Cross sections 5-8 at the lower Lookout Creek site, for example, experienced major changes in the stream channel during the 1996 flood, but only minor changes from 1996-1998 (Fig. 6.5).

At the watershed scale, results of long-term cross-section monitoring support the idea that the spatial scale and frequency of channel adjustment should increase in the downstream direction. The magnitude of channel response was log-linearly related to flood-return period, but channel responsiveness (the slope of this relationship) varied among sites (Faustini, 2000). The high-gradient first-order stream, Cold Creek, which has large boulders and large wood, had only minor change in response to any flow during the monitored period. Some intriguing differences were apparent in the responses of the third-order streams with and without large wood, and the fourth- and fifth-order streams. This pattern is the expected result of a downstream increase in sediment

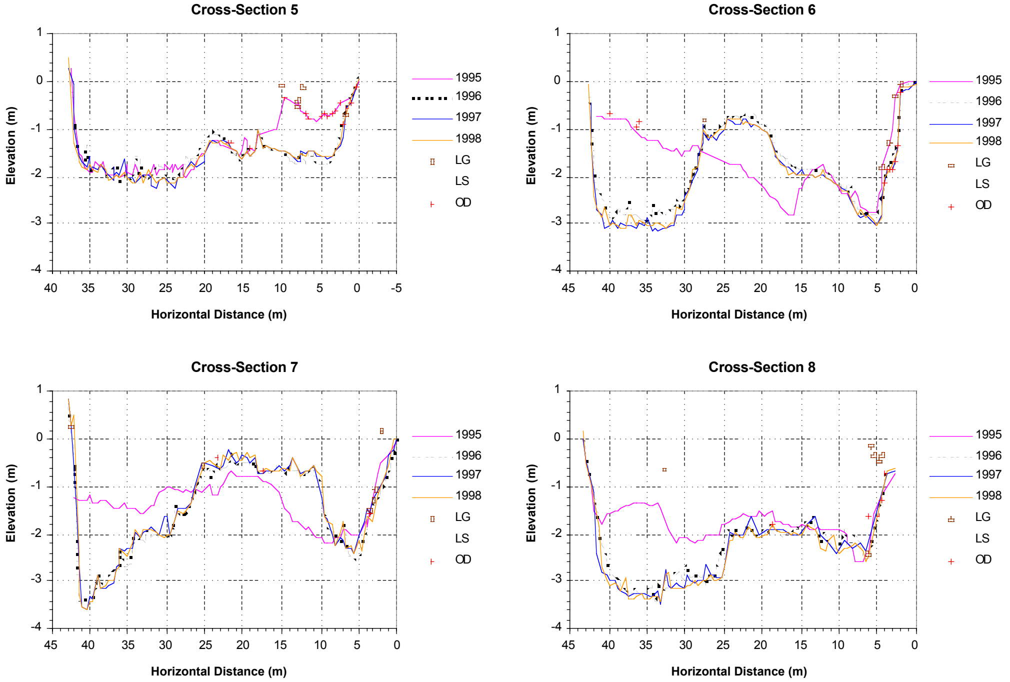

Figure 6.5. Selected cross-section profile plots for the Lower Lookout Creek (LOL) site, 1995-98. Cross-section locations are shown in Figure 6.3 (from Faustini, 2000).

supply relative to transport capacity, which results in more transportable sediment in the channel and hence increased bed mobility. Consistent with this hypothesis, cross sections from the fourth- and fifth-order sites exhibit larger, more frequent and, in years with large flood events, more spatially continuous, changes than cross sections at second- and third-order sites (Fig. 6.6). At finer scales, this pattern is modified by variations in the degree of channel confinement by bedrock and landforms, the abundance of large roughness elements, such as individual large logs and log jams, and local stochastic processes, such as debris-flow inputs from tributaries (Faustini, 2000).

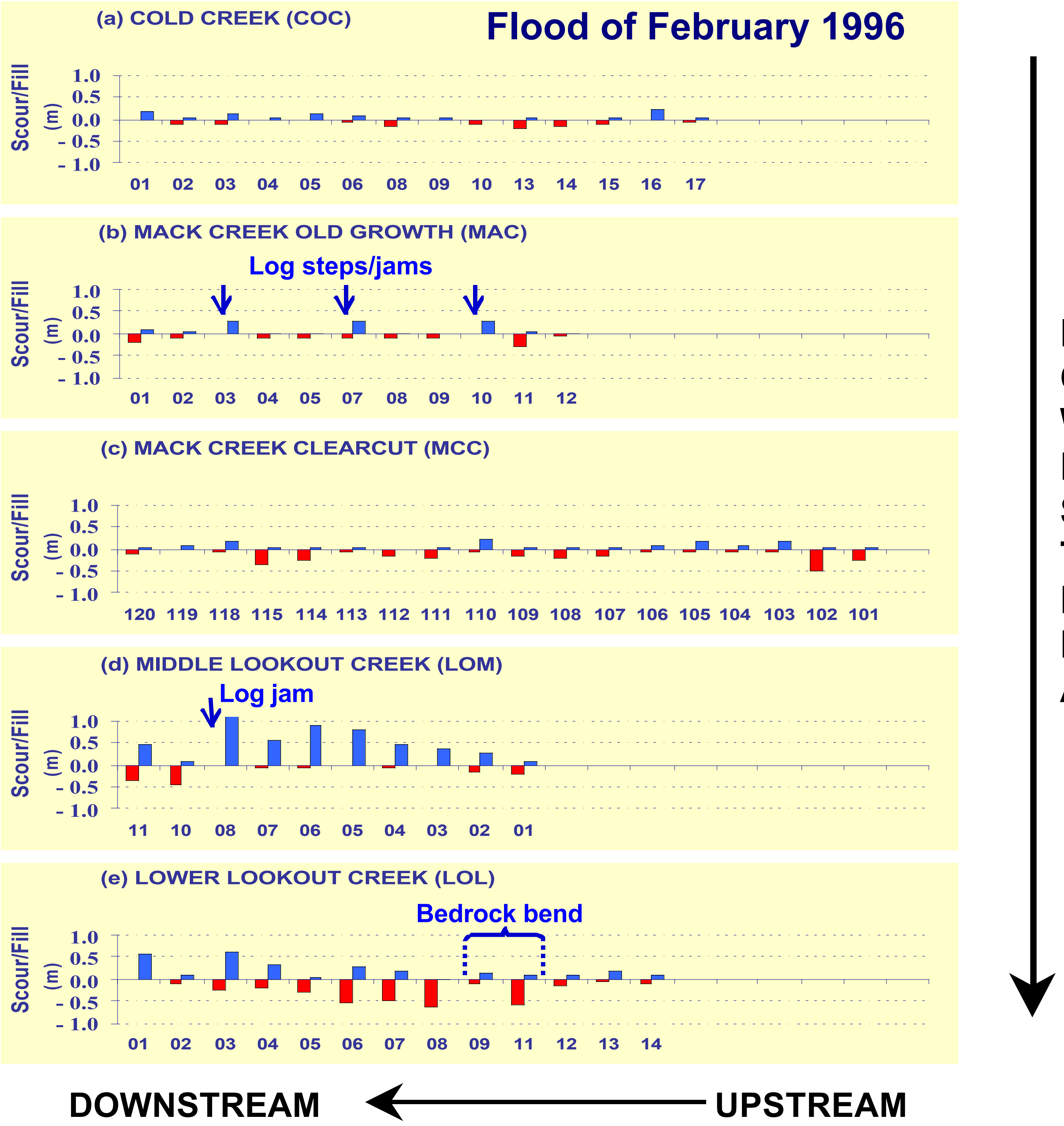

Figure 6.6. Changes (scour and fill) at individual cross sections at all five cross-section sites (see Fig. 6.3 for locations) during the February 1996 flood at the Andrews Forest (Faustini, 2000).

## Module 7. WOOD IN STREAMS

[Fred Swanson]

Wood in streams has been an important theme of Andrews Forest research since the early 1970s, beginning with inventory of wood as part of stream-ecology studies (Froehlich, 1973) and then mapping of wood to assess structure and dynamics (Swanson et al., 1976; Lienkaemper and Swanson, 1987). Initial emphasis was on ecologic and geomorphic functions of static wood pieces and accumulations in streams. Studies in part of the River Continuum project (Vannote et al., 1980), which occurred in the Andrews Forest and four other sites across the country, placed emphasis on variation in wood conditions and processes down through a stream network (Keller and Swanson, 1979). Later modeling studies (Braudrick et al., 1997; Braudrick and Grant, 2000) and the experience of the 1996 flood (Swanson et al., 1998; Johnson et al., 2000) led to interest in the ecologic functions of mobile wood. Static wood can protect patches of riparian vegetation from flood disturbance, but once the wood begins to move can it serve as tools for riparian disturbance.

Amount, arrangement, dynamics, and functions of wood vary with stream size. Small (first- and second-order) streams flowing through old-growth Douglas fir forest contain large amounts of wood (500 to >1000 $m^3$/ha, Harmon et al., 1986) generally randomly located where it fell from the adjacent stand. In channels subject to periodic debris flows this material and associated sediment deposits may undergo cycles of gradual filling and abrupt evacuation. The third-order Mack Creek flowing through old growth contains about 600 $m^3$/ha of wood that is somewhat clumped around large “key” pieces which anchor jams. Long-term observations indicate that wood pieces longer than channel width tend to remain in place, but smaller pieces can be moved during high flows (Lienkameper and Swanson, 1987). Lower Lookout Creek (fifth order) contained about 200 $m^3$/ha in the late 1970s, but the amount and arrangement varied rather dramatically with gradual accumulation over the 1964-1996 interflood period and then substantial flushing in the 1996 flood (Fig. 4.4). In progressively larger channels the relative importance of wood-delivery processes shifts, and a higher proportion of pieces is mobile. This results in attendant shifts in patterns of structures (more aggregation) and functions (reduced sediment-storage function) (Keller and Swanson, 1979).

Forest-stand conditions, such as size distribution of trees, species, stocking levels, and disturbance history affect past, present, and future conditions of wood in streams. More massive and productive forests with wood of slow decay rates and tendency to topple as fresh wood (vs. dying and decaying while standing) are conditions that favor accumulation of high levels of wood in streams (Harmon et al., 1986).

Wood pieces have been placed in streams throughout the Pacific Northwest with the intent of improving fish habitat. However, few experiments have been conducted to assess effects of these practices. Two studies are underway in the Andrews Forest and vicinity: the Quartz Creek (South) Study with wood structures placed in a single reach and the Pool Complexity Study with installations of three levels of wood complexity in pools with treatments replicated at three study reaches. Three of four sets of structures survived the 1996 flood well. In the fourth case, sediment deposition in pools and lateral channel change rendered many structures ineffective. Fish response to the structures has been nil to slightly positive—more wood equals more fish. The Quartz Creek Study demonstrated that placement of the largest part of the size distribution of wood found in an old-growth reach (Mack Creek used as reference) resulted in recruitment of the full old-growth size distribution of wood pieces in about 5 yr, as a result of input from upstream and the adjacent riparian stand (Figs. 7.1, 7.2).

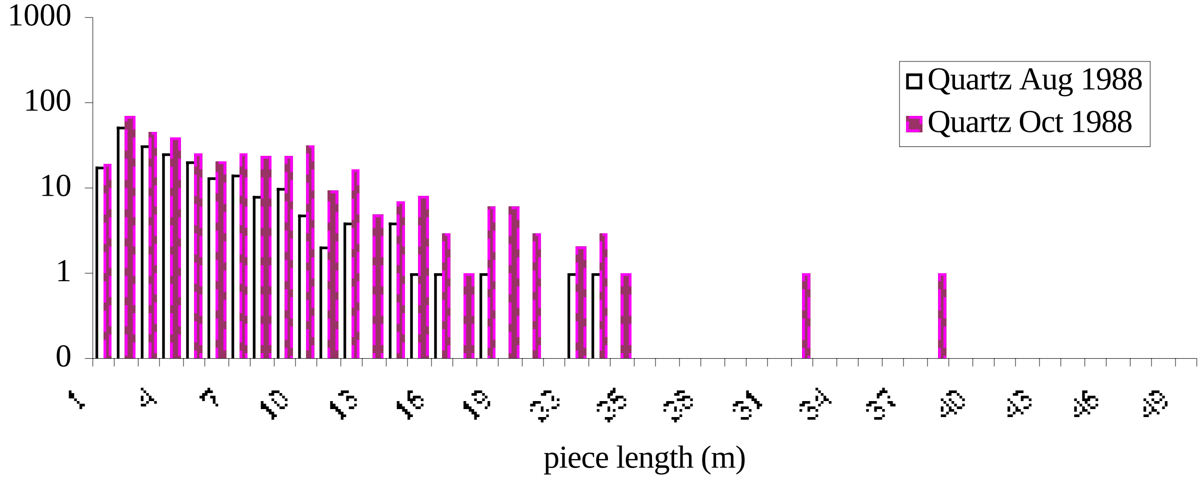

Figure 7.1. Quartz Creek (South) wood piece size distributions in stream before and after placement of 30-40+ m pieces in 1988 (from Randy Wildman, Oregon State University).

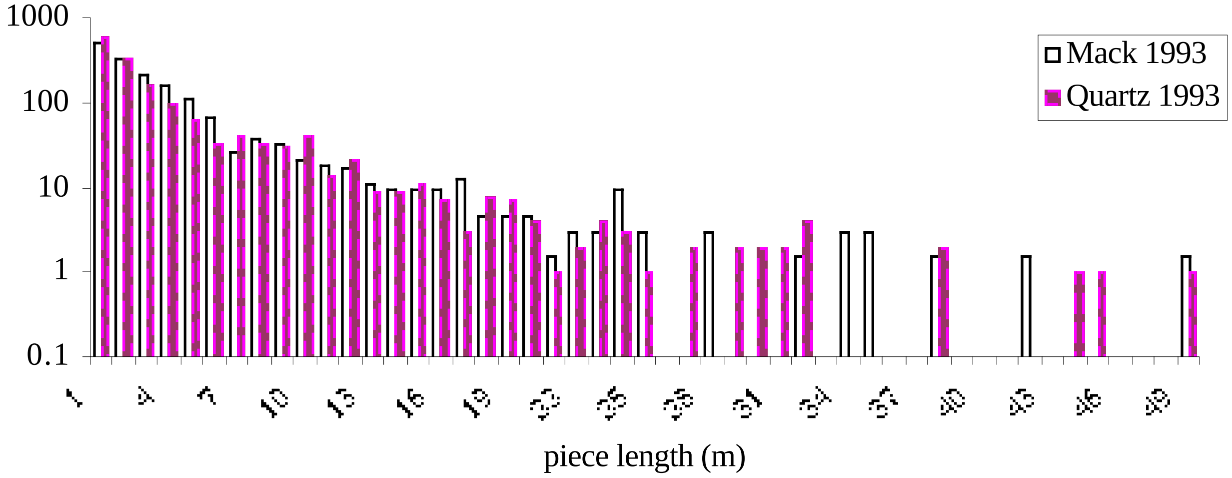

Figure 7.2. Quartz Creek (South) wood piece size distribution at year 5 after wood input (1993), relative to wood distribution in old-growth stream at Mack Creek in 1993 (from Randy Wildman, Oregon State University).

## Module 8. ROAD HYDROLOGY AND GEOMORPHOLOGY

[Fred Swanson, Julia Jones, Beverley Wemple]

Effects of roads on routing of water, sediment, wood, and other materials, such as propagules of exotic plants, through landscapes have been the subjects of many studies in the Andrews Forest. These studies have taken a variety of perspectives, such as focus on processes of peak-flow generation and routing of sediment and disturbances through stream networks. From a landscape-ecology perspective we are interested in how road networks interact with stream networks in part because concepts of network properties are not well developed in this field, which has been dominated by terrestrial ecology studies in landscapes composed of vegetation patchworks. On a fundamental level, roads can be viewed as corridors facilitating movement along them, barriers to movement, sources of materials, such as landslides, or sinks for organisms or materials, such as roadkill reducing a population of organisms (Fig. 8.1). We therefore examine how road segments function in relation to their location in the landscape, such as proximity to ridges and patterns of intersection with stream networks. Beverley Wemple's work gives examples of many of these issues (Wemple et al., 1996, 2001; Wemple, 1998).

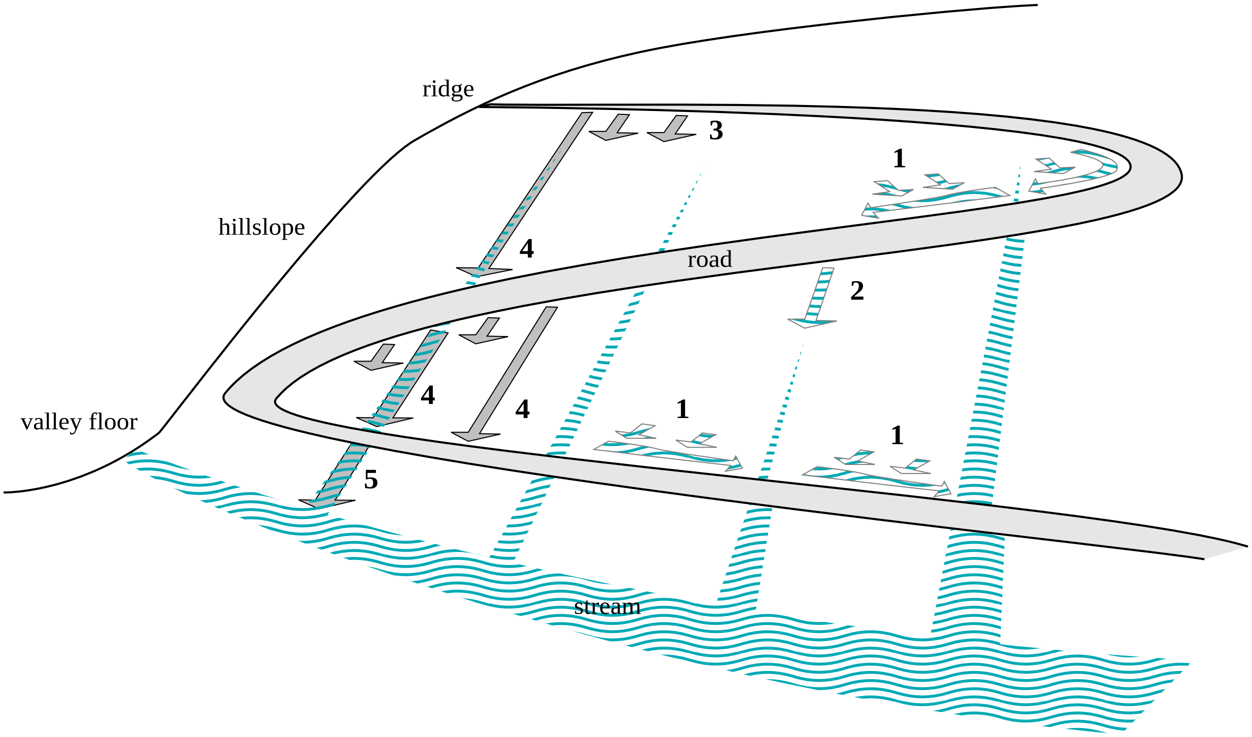

Figure 8.1. Interactions between road and stream networks. The road network consists of a valley floor road segment parallel to a large stream, hillslope road segments perpendicular to streams, and near-ridge roads without streams. Roads (1) intercept water in surface and subsurface flowpaths, (2) alter water flowpaths and extend the channel network, (3) initiate mass movements of sediment in unstable roadfills, (4) deposit sediment moved by mass movements on roads and (5) on valley floors. Overall, roads function to divert water and sediment from paths followed in roadless landscapes, and they initiate multiple new cascading flowpaths.

To test the hypothesis that roads may increase peak flows in Watershed 3 in the Andrews Forest (Jones and Grant, 1996), Wemple surveyed apparent extent of road ditches that carry channelized flow, similar to the stream network. Upper Blue River and Lookout Creek have drainage densities of about 3.0 km km$^{-2}$ and road densities of 1.9. Wemple et al. (1996) found that about 60% of the road network seemed to route surface runoff and subsurface water caught in cutslopes down ditches and into the natural drainage network. Work to measure water routing associated with roads in upper Watershed 3 seems to confirm that such processes can contribute to increased peak flows from this 100 ha watershed (Wemple, 1998; Wemple and Jones, in review).

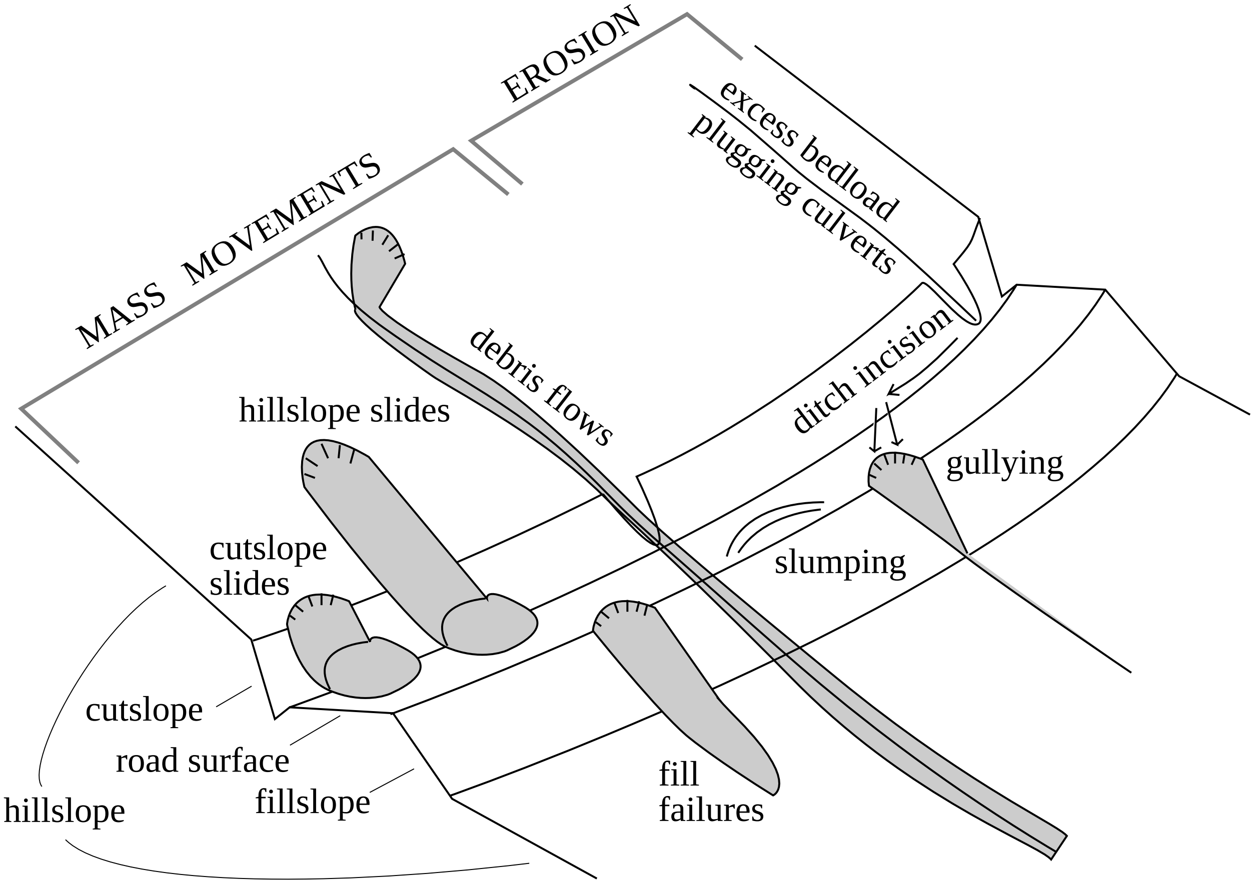

Figure 8.2. Eight types of road failures inventoried in the Lookout Creek and Blue River watershed (from Wemple et al., 2001).

The February 1996 flood triggered varied types of erosion and deposition events (Fig. 8.2) associated with roads in the upper Blue River and Lookout Creek area.

Wemple et al. (2001) inventoried these events and stratified their occurrence on the upper slope (within 100 m of ridge), mid-slope (below the upper slope zone), and valley floor (floodplain, terrace, alluvial fan landforms). Frequency of these features increased downslope (Table 8.1). Roads caused cascades of events involving transformations from one type of sediment-transport process to another. For example, excess bedload plugged culverts, diverting flow down a ditch, which was gullied, until water flowed over the road, saturating a fill, leading to a fillslope slide (Fig. 8.3). Upper-slope roads were net sources of sediment (0 $m^3$ reached the road from upslope and 5450 $m^3$ moved downslope from roads). Mid-slope roads were net sources of sediment to downslope areas (12,500 $m^3$ reached roads, 27,100 $m^3$ moved downslope). Valley floor roads were net sinks for sediment (13,200 $m^3$ reached roads, 6,100 $m^3$ moved downslope).

Table 8.1. Distribution and frequency (numbers per kilometer of road length) of mass movement and fluvial features associated with roads, according to hillslope position and function of the road in intercepting or producing sediment (from Wemple et al., 2001).

| | | Number | | Frequency (no./km) | |
|---|---|---|---|---|---|
| Slope position / function | Road length (km) | Mass Movement | Fluvial Feature | Mass Movement | Fluvial Feature |
| *Upper slope* | | | | | |
| Intercepted by roads | | 0 | 0 | 0 | 0 |
| Produced on roads | | 5 | 0 | 0.05 | 0 |
| Total | 102 | 5 | 0 | 0.05 | 0 |
| *Midslope* | | | | | |
| Intercepted by roads | | 11 | 9 | 0.05 | 0.04 |
| Produced on roads | | 41 | 5 | 0.20 | 0.02 |
| Total | 205 | 52 | 14 | 0.25 | 0.07 |
| *Valley floor* | | | | | |
| Intercepted by roads | | 10 | 4 | 0.24 | 0.10 |
| Produced on roads | | 10 | 8 | 0.24 | 0.20 |
| Total | 41 | 20 | 12 | 0.49 | 0.29 |

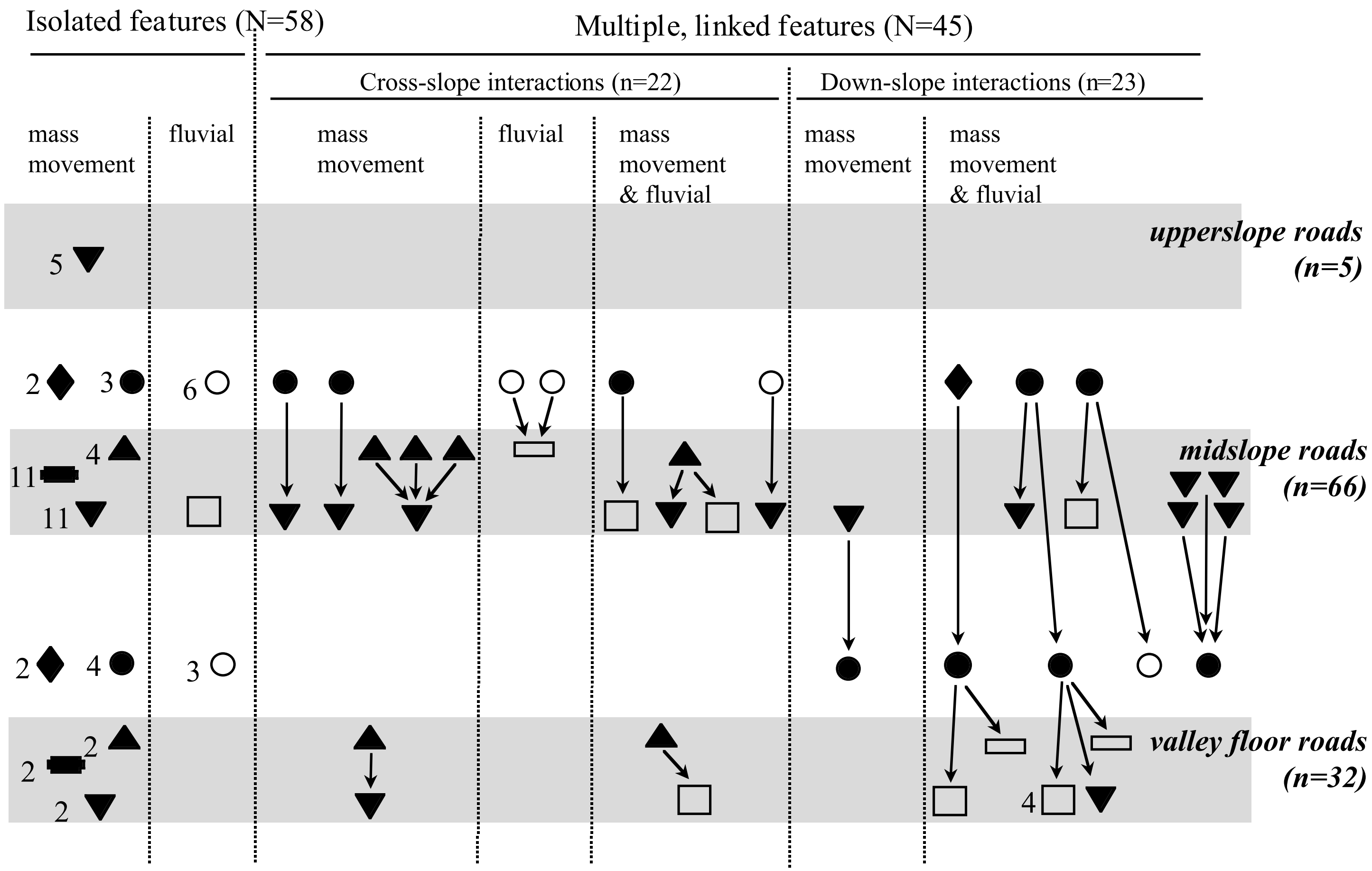

Figure 8.3. Schematic representation of the distribution and spatial complexity of features inventoried in this study. Closed symbols represent mass movements (● debris flows, ◆ hillslope slides, ▲ cutslope slides, ▼ fillslope slides, and ▬ slumps). Open symbols represent fluvial features (○ plugged 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 an associated feature, and show impacts to multiple tiers of roads where applicable. Numbers beside symbols indicate number of inventoried features of that type.

## Module 9. DEBRIS SLIDES AND DEBRIS FLOWS

[Fred Swanson, Kai Snyder]

Shallow (failure planes 1-3 m deep), rapid (up to approximately 10 m $s^{-1}$) mass movements of soil, sediment, and organic matter are common in the Andrews Forest, as they are elsewhere in western Oregon and similar steep wet landscapes. Terminology for these processes has changed somewhat over the years; we use *debris slide* to refer to processes operating on hillslopes and *debris flow* to refer to processes in stream channels. Commonly debris slides continue their movement down channels. We make the slope-channel distinction because of the different implications for the ecosystem, sediment routing, and land management.

Effects of land management on these processes and the role of mass movements of different types in natural systems on sediment production, routing, and ecosystem disturbance have been important research themes at Andrews Forest since early efforts to document these processes mainly in the context of small-watershed studies (Fredriksen, 1970). Inventory of debris slides and flows for the 1950-1975 period revealed that (1) these are natural processes under forest cover, (2) the landscape can be broadly zoned into areas with different susceptibility to sliding, (3) recently (<20 yr) clearcut areas had soil erosion rates by slides that exceeded uncut forest rates by several fold, and (4) road rights-of-way had soil erosion rates about 30 times forest rates (Dyrness, 1967; Swanson and Dyrness, 1975). These findings parallel results of similar inventories elsewhere in slide-prone landscapes.

The occurrence of numerous debris slides and debris flows in the February 1996 flood prompted updating of these inventory records. The extent of slides and flows in forested parts of the watershed were similar in 1996 and 1964-1965, which, along with similarities of discharge from the low-elevation experimental watersheds, suggests that these events had similar effects on soil moisture conditions. The near absence of logging and road construction in the watershed since 1970 made it possible to examine effects of about 25 yr of passive watershed restoration from past forestry land use and glimpse into future effects of establishment of Late Successional Reserves as part of the Northwest Forest Plan. The rate of sliding from clearcut areas was much lower in the 1996 storm, possibly because the greater age of cutting units permitted recovery of root strength and site hydrologic processes and perhaps because unstable sites had failed in earlier storms. The 91 inventoried debris flows occurring in the 1946-1996 period took place in only 12 yr and 75% occurred in 1964-1965 and 1996 (Snyder, 2000). Inventoried debris slides occurred mainly in the lower elevation parts of the landscape (Fig. 9.1) where slopes are steep, soils contain expansive clays, early land-use practices were most extensive, and snowmelt during warm rain events has the greatest potential to create extreme soil-water conditions.

From an ecologic perspective we have been interested in how debris flows create disturbance patches and leave refuges in stream networks (Fig. 9.1). Note that the stream networks of some tributary watersheds have been thoroughly scoured by debris flows. However, most tributary watersheds contain first-order and in some cases larger channels that were not scoured, thus providing relatively intact stream and riparian ecosystems to serve as refuges through the 1996 flood and sources of organisms for recolonization of severely disturbed stream reaches.

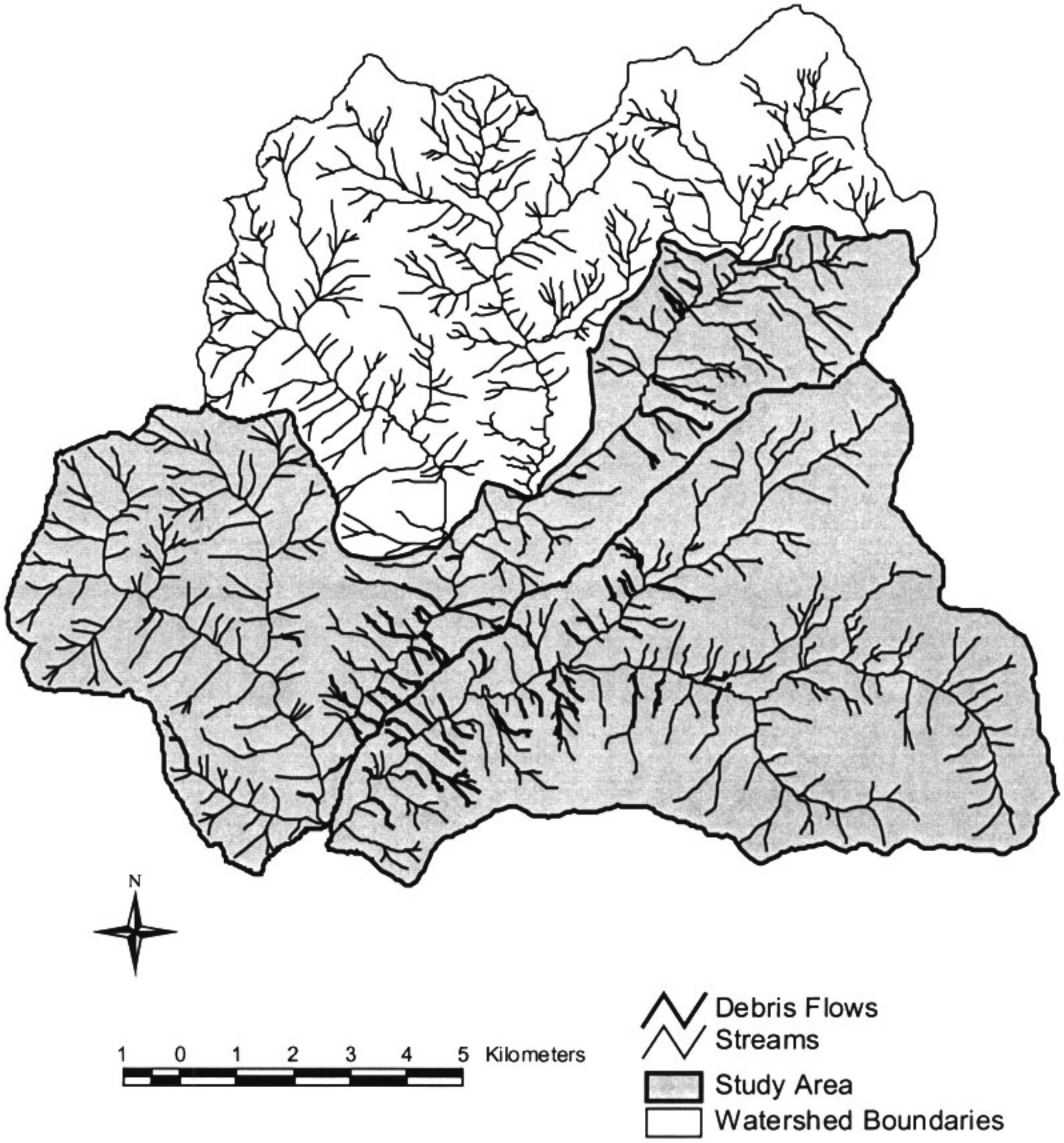

Figure 9.1. Debris flowpaths of Lookout Creek and part of the upper Blue River for 1946-1996 (Snyder, 2000).

## Module 10. WATER USE BY MAJOR TREE SPECIES

[Barbara Bond, Julia Jones, Georgianne Moore, Jeff McDonnell, David Post, Nathan Phillips]

Vegetation water use by evapotranspiration accounts for an estimated 500 mm annually in old-growth forests at the Andrews, based both on water budgets and on measured increases in annual water yield after forest canopy removal (see stream response module). Recovering forest, aged 30 to 35 yrs, may use up to 150 or 200 mm of water per year. Vegetation may influence water budgets through a variety of processes, including interception (both of precipitation and of cloudwater), evaporation, and transpiration.

Since 1999, new research at the Andrews has focused on measuring vegetation water use, particularly in Watersheds 1 (clearcut in 1962-66) and 2 (control) (see Table 1 of introduction). In the summers of 1999 and 2000, sapflow was measured at 20-minute intervals in trees of varying ages and species. In 1999, sap flow was measured from July 1-September 8 in seven Douglas-fir and seven red alder selected to represent the typical range in size for this site, along a ~60-m transect running upslope perpendicular to the stream in Watershed 1. In 2000, sapflow was measured in seven 30-yr-old Douglas-fir in Watershed 1 and five 450-yr-old Douglas-fir and western hemlock on the alluvial fan donwstream of the gage at Watershed 2 (Bond et al., submitted; Moore et al., in preparation). Tree-level measurements were converted to a ground-area basis using estimates of sapwood basal area of all woody vegetation from vegetation surveys. In 1999, species and sapwood basal area of trees > 1 cm diameter at breast height were measured in 100 $m^2$ plots arranged systematically along seven, 50 m transects perpendicular to the stream – each transect included five contiguous plots. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) accounts for about 66% of the total sapwood basal area and nearly 100% of coniferous basal area in within the riparian corridor (arbitrarily defined as a 100m-wide swath centered on the stream bed). Most of the remaining 34% of the sapwood basal area is hardwoods, with bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra* Bong.) dominating (Bond et al., submitted).

### Diel patterns of streamflow and sapflow

A strong diel variation was apparent in stream flow of Watershed 1 during some of the summers from 1952 to the mid-1990s, stimulating the installation of a V-notch weir starting in 1999 to more accurately capture small variations in stream flow. The diel signal in 1999 to 2001 appeared in late June and disappeared by mid-September. Thus, the diel cycle must be due to vegetation water use, rather than to snowmelt or temperature effects on water viscosity. In the early to mid summer, the combination of high evaporative demand, relatively high soil moisture content and very heavy vegetation cover result in very high rates of transpiration. In the spring and early summer, the diel signal was often obscured by precipitation-induced fluctuations in stream flow and cloud cover-induced reductions in transpiration. Both measured transpiration rates and “missing stream flow” (the area between successive daily maximum streamflows on days without precipitation) were greatest in late June and early July. By mid-July, missing stream flow accounted for between 5 and 6 percent of total daily stream flow (Bond et al., submitted).

In early summer (June 24-30), maximum sap flow explained 80% of the variation in minimum stream flow 4 hours later ($r^2 = 0.76$). By August 5-11, maximum sap flow accounted for only 50% of the variation in minimum stream flow, and the lag had increased to 8 hours.

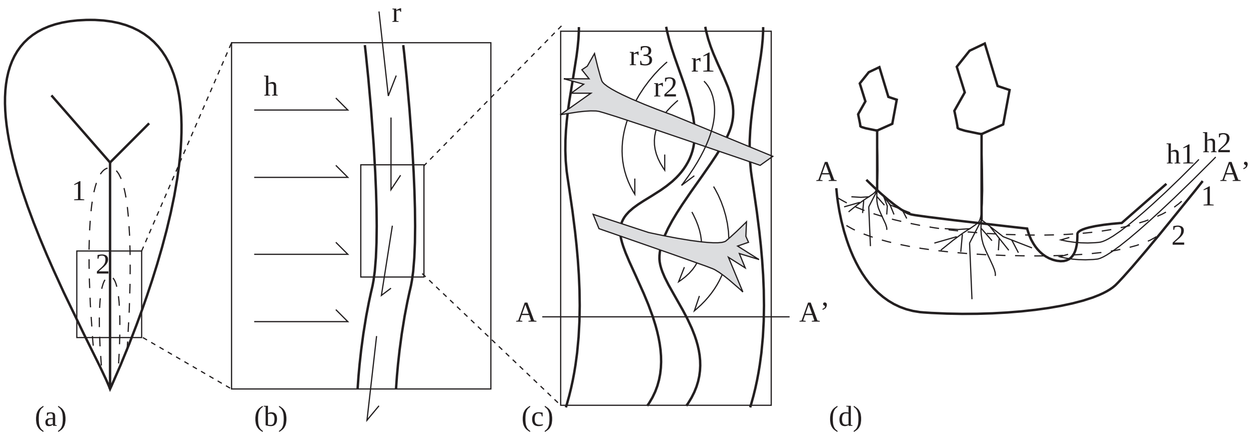

Figure 10.1. Conceptual model of vegetation-hydrology coupling at diel time scales over the summer baseflow recession period in a headwater basin (Watershed 1) in the Andrews Forest. (a) The basin consists of hillslopes and the valley floor, including the stream channel and floodplain/terraces, the groundwater system and the riparain zone. (b) Hyrologic flowpaths operate on hillslopes (h) and in the riparian zone (r). (c) Riparian zone flowpaths include in-stream flow (r1), near-stream, fast,hypotheic exchange flowpaths (r2), and far-from-stream, slow, hyporheic exchange flowpaths (r3),created by sediment and large wood stored in the valley floor. (d) A cross-section of the valley floor shows shallow flowpaths (h1) and deep flowpaths on hillslopes contributing lateral flow to the valley floor and stream, and the changing positions of a water table or near-saturated zone in early summer (time 1) and late summer (time 2). The vegetation zone of influence on diel cycles in streamflow can be envisioned as an area of lower hillslopes and the riparian zone (a) with a water table at a given height (1 or 2 in part d of figure).

According to our conceptual model (Fig. 10.1) the strongest coupling and the shortest lag between maximum water use by vegetation and minimum stream flow each day should occur during the early summer, when vegetation is using water in short hyporheic exchange flowpaths. As the summer progresses, diel stream flow fluctuations become less sensitive to transpiration rates, as vegetation increasingly taps water in long hyporheic exchange flowpaths.. During the early part of the summer (from about June 24 to July 14), transpiration increased, and so did missing stream flow as a percent of total stream flow. The estimated effective zone of influence of vegetation on daily stream flow was only about 0.3 ha (i.e., 0.3% of the total basin) in the early summer. However, during the latter part of the summer (from about July 15 to August 11), transpiration decreased only slightly, but missing stream flow as a percent of total stream flow declined significantly. The estimated zone of influence contracted in the late summer compared with early summer. We infer that from July 15 onward, vegetation water use was increasingly decoupled from the short hyporheic exchange flowpaths and increasingly coupled to long hyporheic exchange flowpaths (Bond et al., submitted).

### Seasonal trends in water use by species and age of trees

Vegetation water use declines from early spring to late fall for all species (Douglas-fir, western hemlock, and red alder). However, the amounts of water use and the rate of decline of water use differ between species and according to tree age. In the spring and early summer, old-growth Douglas-fir uses more water than old-growth western hemlock (Fig. 10.2). However, by the end of August, old-growth western hemlock trees are using more water than old-growth Douglas-fir trees (Fig. 10.2). Thus, in early summer hemlock accounts for only about 1/3 of water use by old-growth dominant trees, but by November, hemlock accounts for as much as 80% of water use by old-growth trees (Fig. 10.3).

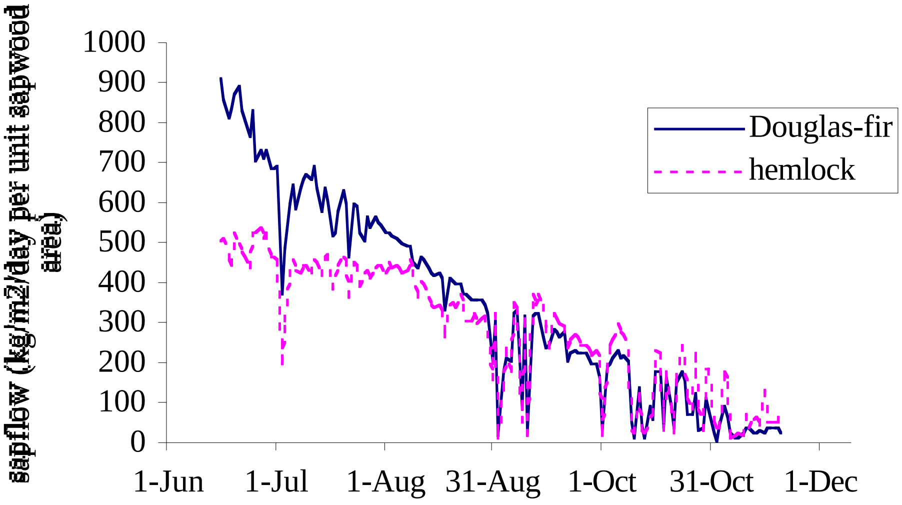

Figure 10.2. Water use by 450-yr-old Douglas-fir (n=5) and western hemlock (n=3) near Watershed 2 during the summer and fall of 2000, estimated from sapflow measurements (G. Moore, unpublished data).

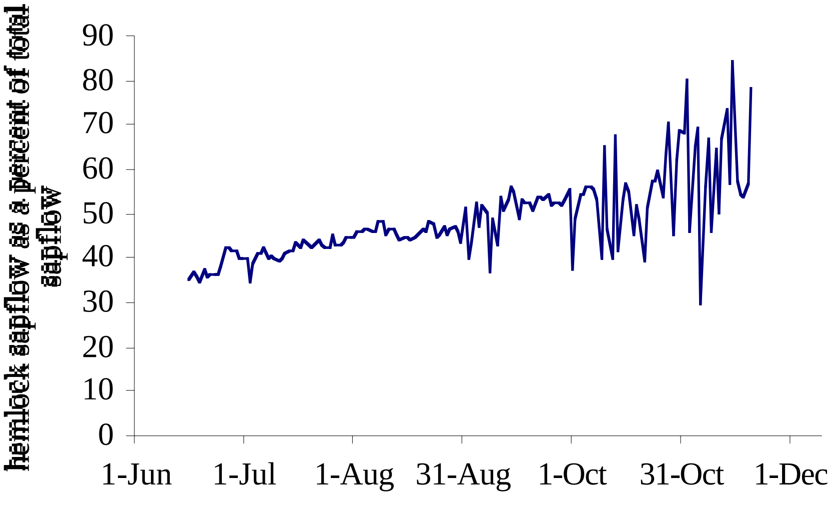

Figure 10.3. Water use by old-growth hemlock (n=3) as a percent of total water use by old-growth Douglas-fir and hemlock (n=8) near Watershed 2, during the summer and fall of 2000, estimated from sapflow measurements (G. Moore, unpublished data).

Water use by young Douglas-fir is much higher than that by old Douglas-fir or western hemlock (Fig. 10.4). Young Douglas-fir use five times more water than old Douglas-fir, and this differential was preserved throughout the summer and into the fall.

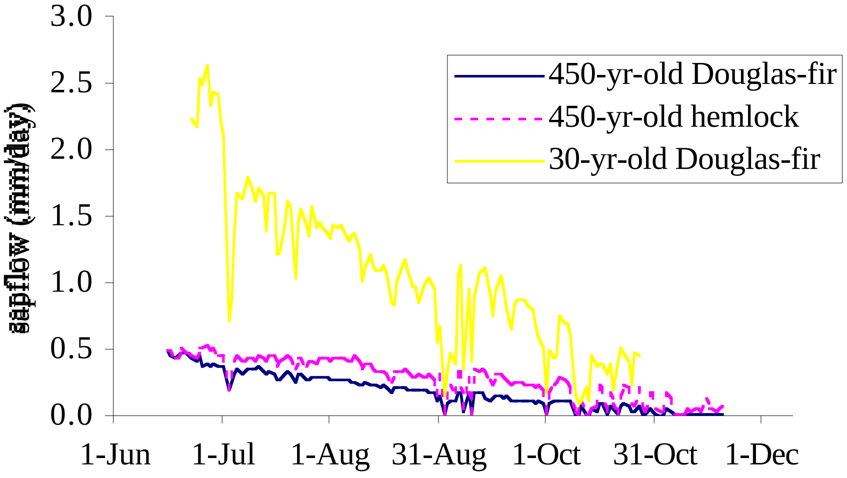

Figure 10.4. Water use by 30-yr-old Douglas-fir in Watershed 1, and 450-yr-old Douglas-fir and western hemlock near Watershed 2, during the summer and fall of 2000, estimated from sapflow measurements adjusted by relative basal areas of the species (G. Moore and B. Bond, unpublished data).

Water use by young Douglas-fir did not vary from 1999 to 2000 (Fig. 10.5). However, young Douglas-fir used more water than red alder during the early summer, but declined over the summer. By August, young Douglas-fir and red alder were using about the same amounts of water (Fig. 10.5).

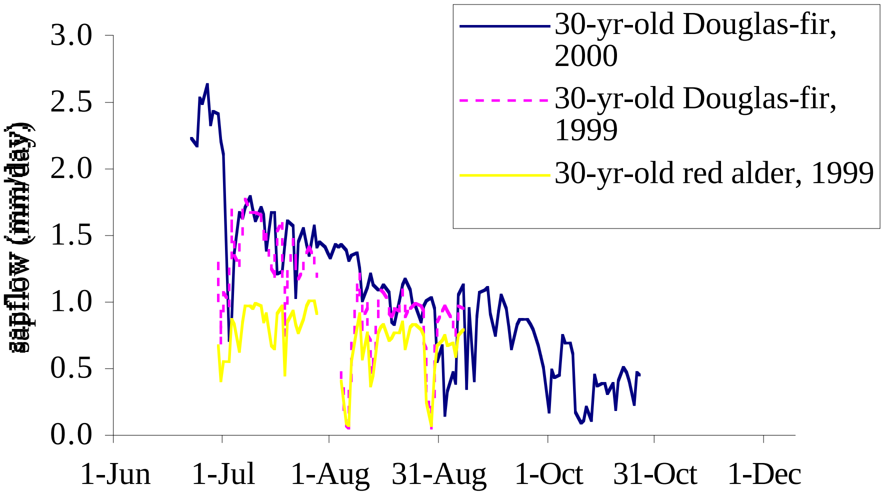

Figure 10.5. Water use by 30-yr-old Douglas-fir in Watershed 1 during the summers of 1999 and 2000, compared to read alder in Watershed 1 during the summer of 1999, estimated from sapflow measurements adjusted by relative basal areas of the species (G. Moore and B. Bond, unpublished data).