Vegetation Patterns, Hydrology, and Water Chemistry in Small Watersheds in the Hoh River Valley, Olympic National Park

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Foreword

The importance of watershed ecosystem research to the management of natural areas such as national parks cannot be overstated. Watershed conditions are affected by uncertain and complex interactive environmental trends, many of global occurrence. Questions about watershed science, although often site specific, thus require answers in a global context. Frequently, input to the highest levels of government decision making is needed if modern society is to mitigate, stop, or reverse the large scale alterations of watershed ecosystems worldwide. However, our ability to sensibly and effectively manage natural resources in today's global environment is often constrained by our lack of knowledge about the hydrologic cycle and its relation with the geosphere and biosphere. We know that the current condition of natural resources in parks and other preserved lands is subject to many widespread anthropogenic changes from acidification, eutrophication, toxic substances, boundary encroachments, overuse, species shifts or extirpation, desertification, loss of biodiversity, land use change, and sea level rise. Long-term watershed research and monitoring of natural and remote areas in the National Park System and in similar reserves provide important data on ecosystem processes and interactions for detecting spatial and temporal changes in environmental conditions. These data collections allow the partitioning of cause-and-effect relations of ecological change in watersheds. They also serve to meet reference and early warning objectives correlative with natural ecosystem change. Accordingly, the scientific and public policy communities can employ watershed ecosystem information as one means of obtaining early indications of the potential effects of anthropogenic stress and an improved assessment of its magnitude. Use of the concept to address several goals of research into *acid precipitation* or biogeochemical cycling demonstrated the utility of these integrated watershed data for inter-ecosystem comparison between preserved and other watersheds. The long-term management strategies of the National Park Service combined with the *protected* nature of park lands placed the service in a unique position among federal agencies and among international conservation organizations to document relations between ecosystem effects and anthropogenic influences.

Studies of watershed ecosystems collect long-term baseline data on the ecosystem health of park and equivalent reserves. Research and monitoring at the watershed level by the U.S. Geological Survey and the National Park Service since 1980 have contributed to the accumulation of important baseline information on deposition, meteorology, hydrology, ecosystem functioning, and biology in selected parks and biosphere reserves. Important information on biological diversity and biogeochemical processes have also been obtained. Activities have ranged from needs identification to reconnaissance or synoptic analyses to long-term monitoring and long-term ecosystem research. Quantification of the hydrologic cycle and chemical flux is a major objective of the watershed program. Such measurements, when combined with other

geographic resource data (e.g., geology, landuse, topography, and historic and pre-historic records), provide a better understanding of ecosystem-level processes and of how watershed ecosystems respond to various natural and anthropogenic stimuli. Currently, these data are available for developing, testing, and implementing state-of-the-art methods and procedures for improved management of water and land resources at the national and international levels.

By 1982, the National Park Service had implemented studies in three national parks: Sequoia-Kings Canyon (California), Rocky Mountain (Colorado), and Isle Royale (Michigan) national parks. Sites were selected to be biogeographically representative of mature ecosystems in relatively remote areas that receive varying levels of atmospheric contaminant inputs. Two years later, the largely pollution-free Olympic National Park (Washington) was added. The sites have several important common attributes including a long-term protected status, a core area (undisturbed watershed), research hypotheses and experimental design for detection of ecosystem change and understanding the mechanisms of change, basic inventory information, research or monitoring capabilities, monitoring techniques that will not change unless calibrated to new techniques, sampling protocols that fit within the time frame of known physical and biologic events, and standardized protocols for data collection, sample storage, sample archival, and data management.

Today, comprehensive watershed ecosystem inventory, monitoring, and research data, a series of publications on ecosystem function and structure, and to some extent management of park resources that span more than 15 years are available from the four original sites and from Shenandoah National Park (Virginia) where watershed studies began in 1979. Shorter or discontinuous records of watershed ecosystems are available from Big Bend (Texas), Denali (Alaska), Glacier (Montana), and Great Smoky Mountains (North Carolina and Tennessee) national parks and from Noatak National Preserve (Alaska). Six parks are now part of the National Park Service-U. S. Geological Survey Global Climate Change Program: Rocky Mountain, Isle Royale, Olympic, Sequoia, Glacier, and Crater Lake national parks. Three watershed sites are included in the cooperative Inventory and Monitoring Program of the service and the survey: Shenandoah, Great Smoky Mountains, and Denali national parks. Sites range from the hot Chihuahuan Desert in the Southwest to the moist boreal forests of Michigan, the eastern deciduous forests of Virginia, Tennessee, and North Carolina, the alpine environment of California and Colorado, and the Alaskan taiga-tundra.

The condition of natural resources within these natural watersheds has often been difficult to ascertain, but gaining this knowledge has provided the key to understanding the nature of ecosystem change. The existence of sites with a commitment to gathering "long-term" ecosystem level data permits research activities aimed at testing hypotheses relevant to ecosystem processes and structure. These data further make it possible to question existing paradigms and to obtain new understandings about fundamental relations within and

between naturally functioning ecosystems. This applies equally to other areas and is suggested as appropriate for a potential network of long-term global baseline research sites. Potentially significant conclusions, common to most long-term watershed ecosystem programs and studies, are thus emerging.

This monograph presents the results of the first 13 years of watershed research in Olympic National Park. It is an example of the value of staying the course to increased understanding of park natural resources and of mature boreal ecosystems.

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Abstract. Since the 1970s, there has been widespread concern about the effects of anthropogenic inputs of nitrogen and sulfur on forest ecosystems and their associated streams and lakes in North America and Europe. Few studies, however, have been conducted in areas that are still relatively pristine. Long-term monitoring in these ecosystems can be used to detect global change. This monograph summarizes our current understanding of the structure and functioning of two small, temperate old-growth watersheds in the Hoh River valley in Olympic National Park, Washington, in an environment with little apparent anthropogenic disturbance. Using the small watershed approach, we examined vegetation patterns, biomass distributions, hydrology, solution chemistry in precipitation, throughfall, stemflow, soil and stream, and long-term trends in precipitation and stream chemistry from 1984 to 1993. Some data from the 1994–97 period are also discussed, particularly NO_3-N in precipitation and the stream in the West Twin Creek watershed. The primary site for our studies was the valley-wall 58-ha West Twin Creek watershed (180–850 m elevation), located 32 km from the Pacific Ocean. The second site was the 125-ha Hoh Lake watershed (1250–1525 m elevation) located 50 km from the Pacific Ocean. The Hoh River valley contains a wide variety of species and community types. Five plant community types were identified in the West Twin Creek watershed, and three forest community types and a wet meadow community were identified in the Hoh Lake watershed. Elevation (mostly reflecting differences in temperature) and slope differences are the most important factors that control vegetation patterns. Western hemlock (*Tsuga heterophylla*) and Pacific silver fir (*Abies amabilis*) were the dominant tree species in the West Twin Creek watershed, although Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*) and Sitka spruce (*Picea sitchensis*) were present. Mountain hemlock (*Tsuga mertensiana*), Pacific silver fir, and Alaska yellow cedar (*Chamaecyparis nootkatensis*) were the dominant tree species in the Hoh Lake watershed. Large biomass accumulations were recorded in both the West Twin Creek (average live tree biomass 1044.7 Mg/ha) and Hoh Lake (average live tree biomass 1006.8 Mg/ha) watersheds. Coarse woody debris, both snags and logs, is a dominant structural component in these watersheds. Annual precipitation from 1984 to 1993 varied from 267 to 475 cm at the Hoh Ranger Station. Annual stream discharge in the West Twin Creek watershed ranged from 54% to 89% of precipitation. Precipitation chemistry was dominated by the sea salt ions, Na, and Cl, whereas stream chemistry was dominated by Ca and SO_4, products of weathering. There was little change in precipitation chemistry beyond 13 km from the coast. Nitrate-N concentrations were higher than NH_4-N concentrations in precipitation, and concentrations were low. Sulfate-S concentrations were also low. The chemistry of throughfall, stemflow, soil solution, and the stream in the West Twin Creek watershed was markedly different from that in precipitation. The pH averaged 5.3 in precipitation, 5.0 in throughfall, 4.3 in stemflow, 5.7 in the forest floor, 6.2 in soil solution (at 15 cm depth), and 7.3 in the stream. The concentration of most analytes in precipitation and in the West Twin Creek stream showed few trends from 1984 to 1993; NO_3-N concentrations in precipitation declined slightly, and SO_4-S in stream water increased. From fall 1993 through 1996, however, NO_3-N concentrations in precipitation and in the stream increased and pH decreased to as low as 4.6. There was also a slight increase in SO_4-S. This seems to have been due to across-Pacific transport of pollutants from Asia. The old-growth ecosystem in the West Twin Creek watershed is on the verge of N saturation, which has many implications

for the forest health. Long-term monitoring has provided the opportunity to examine the influence of increased NO_3-N inputs on forest streams in an area that is considered to be relatively pristine.

Key words: Vegetation, hydrology, precipitation chemistry, throughfall, stemflow, stream chemistry, old-growth forest.

Chapter 1. Introduction

Since the 1970s, there has been widespread concern about the effects of anthropogenic atmospheric inputs of sulfur and nitrogen into forest ecosystems and their associated streams and lakes in North America and Europe. To understand these effects, several major research programs were initiated in the 1980s: the National Acid Precipitation Assessment Program (NAPAP), funded mostly by the Environmental Protection Agency (NAPAP 1993); the Integrated Forest Study, funded by the Electric Power Research Institute (Johnson and Lindberg 1992); and the programs of Germany and other European countries. The National Acid Precipitation Assessment Program was established to (1) develop an understanding of the mechanisms and effects of atmospheric deposition (acid rain, air pollution) on forest ecosystems, (2) examine the influence of acidic precipitation and other air pollutants on the nation's vegetation and aquatic ecosystems, and (3) develop an objective and comprehensive information base for decision makers (Schroeder and Keister 1989).

Acidic deposition has been recognized as a potentially serious threat to biological systems in the northeastern United States and in parts of Europe (Overrein 1972; Braekke 1976; Wright and Gjessing 1976; Malmer 1976; Schofield 1976; Cronan et al. 1978). The southwestern United States have also experienced acid precipitation events (Lawson and Wendt 1982; Olson and Lefohn 1989; Olson et al. 1992). Acid precipitation can have several detrimental effects on forest ecosystems. They include (1) acidification of soils and the consequent release of aluminum ions, which are toxic to tree roots, (2) leaching of important nutrients from tree canopies and soils (particularly cations), (3) reduction of tree growth and increased mortality, (4) the adverse effects of heavy metals on soils and ecosystem processes, and (5) acidification of streams and effects on stream biology. In addition, excess N deposition in some areas is causing problems (Agren and Bosatta 1988; Aber et al. 1989) including NO_3 losses from ecosystems that suffer from N saturation.

To understand the effects of anthropogenic atmospheric deposition on natural forest ecosystems in the United States, several study sites were established in national parks in the early 1980s as part of NAPAP, and the small watersheds approach was used. The parks were Sequoia-Kings Canyon in California, Isle Royale in Michigan, Rocky Mountain in Colorado, Shenandoah in Virginia, and Olympic in Washington. Sequoia-Kings Canyon, Rocky Mountain, Isle Royale, and Shenandoah national parks were in areas affected by anthropogenic inputs. However, anthropogenic deposition in Olympic National Park was small and provided an opportunity to examine processes in a relatively pristine environment or sort of control site.

The small-watershed approach has been used successfully at Coweeta in North Carolina (Swank and Crossley 1988), Walker Branch in Tennessee (Johnson and Van Hook 1989), and Hubbard Brook in New Hampshire (Likens and Bormann 1995) to study biogeochemical cycling under the premise

that chemical fluxes and cycling are intimately linked to hydrological cycles. Understanding the biogeochemical cycles of nitrogen, sulfur, carbon, and other elements contributes to a basic understanding of ecological processes and responses of ecosystems to stress. Long-term data sets can point out changes in chemical cycling patterns and species composition and provide baselines against which to assess future conditions, including global change. We were particularly interested in determining whether nitrogen and sulfur air pollutants from Asia were reaching Olympic National Park, and if so, what effects they were having on stream chemistry.

Although there is considerable knowledge of coastal Pacific Northwest forest ecosystems (Edmonds 1982; Franklin and Dyrness 1988; Henderson et al. 1989), data on the function of small watersheds are limited, especially in the temperate rainforests on the western Olympic Peninsula.

Using the ecosystems approach, we studied terrestrial and aquatic ecosystems in two small watersheds in Olympic National Park: low elevation West Twin Creek and high elevation Hoh Lake. Both watersheds are in pristine, temperate, old-growth rainforests in the Hoh River valley.

From 1984 through 1993, we examined vegetation patterns, biomass distributions, hydrology, solution chemistry, and long-term trends in precipitation and stream chemistry. In the West Twin Creek watershed, we established baseline data for precipitation chemistry, canopy interception processes (throughfall and stemflow), soil solution, hydrology, and stream chemistry. Some data on precipitation and stream chemistry and hydrology have been assessed through 1997.

Chapter 2 of this monograph presents a description of the study sites. Subsequent chapters present methods, results, and discussions of our studies of the vegetation communities and distribution of biomass in the West Twin Creek and Hoh Lake watersheds, hydrologic cycle in the West Twin Creek watershed, solution chemistry in the West Twin Creek watershed, and long-term trends in precipitation and stream chemistry in the West Twin Creek watershed. Program publications are listed in Appendix E.

Chapter 2: Study Sites

Olympic National Park is located along a narrow coastal strip in the central portion of the Olympic Peninsula in the northwestern continental United States (Fig. 1). The west side of the Olympic Peninsula is an excellent location for examining forest ecosystems that are unaffected by air pollution because the inputs of atmospheric particles in rain and dryfall come directly off the Pacific Ocean. It has been hypothesized that coastal forest ecosystems, such as those in the Hoh River valley, should be as clean as or cleaner than any ecosystem in North America.

We conducted our research in two small, pristine watersheds (West Twin Creek—124° 00' 36" W, 47° 50' 00" N and Hoh Lake—123° 47' 12" W, 47° 53' 54" N) in the Hoh River valley in the western Olympic National Park (Table 1). The primary site for the study of hydrologic and forest ecosystem processes was the 58-ha West Twin Creek watershed, located 32 km from the

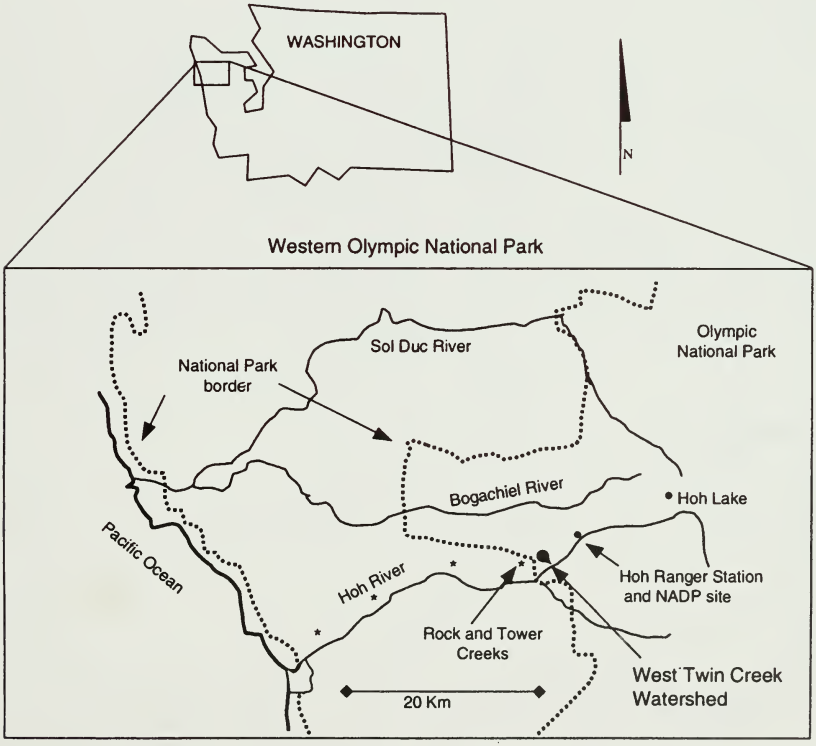

Figure 1. Washington state, western Olympic Peninsula, Hoh River, Hoh Ranger Station, National Atmospheric Deposition Program (NADP) site, and the precipitation collection sites and their proximity to the Pacific Ocean.

Table 1. Features of the West Twin Creek watershed and the Hoh Lake watershed.

Feature	West Twin Creek watershed	Hoh Lake watershed
Elevation range	180–850 m (500–2800 ft)	1250–1525 m (4100–5000 ft); lake at 1390 m
Area (ha)	58	125
Soils	marine deposits with minor conglomerates and breccias; green and black sandstones; coarse-loamy, mixed, mesic Typic Dystrochrepts	marine deposits of grayish-green and black sandstones; sandy-loam, Typic Cryorthods or Typic Cryumbrepts
Vegetation	low to middle elevation conifer forest; western hemlock, Pacific silver fir, western redcedar, Douglas-fir, Sitka spruce, swordfern, Oregon oxalis, oval-leaf huckleberry, red huckleberry	subalpine conifer forests with meadows; Pacific silver fir, mountain hemlock, Alaska yellow cedar, big huckleberry, avalanche fawnlily, common beargrass
Annual precipitation (cm)	350	380–500 (760–1300 snowpack)
Temperature (°C)		
January mean	4.5[a]	–2.5[b]
July mean	16[a]	15[b]

[a] Huff 1984.
[b] Tabor and Cady 1978.

Pacific Ocean (Fig. 1). Baseline data were collected on precipitation, throughfall, stemflow, and soil-solution and stream chemistry. Also, atmospheric input data (precipitation chemistry and rain depth) were collected for the National Atmospheric Deposition Program at the Hoh Ranger Station, approximately 10 km inland from the West Twin Creek watershed (Fig. 1). The 125-ha Hoh Lake watershed is located 50 km from the Pacific Ocean (Fig. 1).

West Twin Creek

Topography

West Twin Creek is a steep, dissected, first-order valley-wall watershed. Elevations of the watershed range from 180 m at the weir to greater than 850 m on the ridgetops (Fig. 2). The watershed has steep valley walls, and the first-

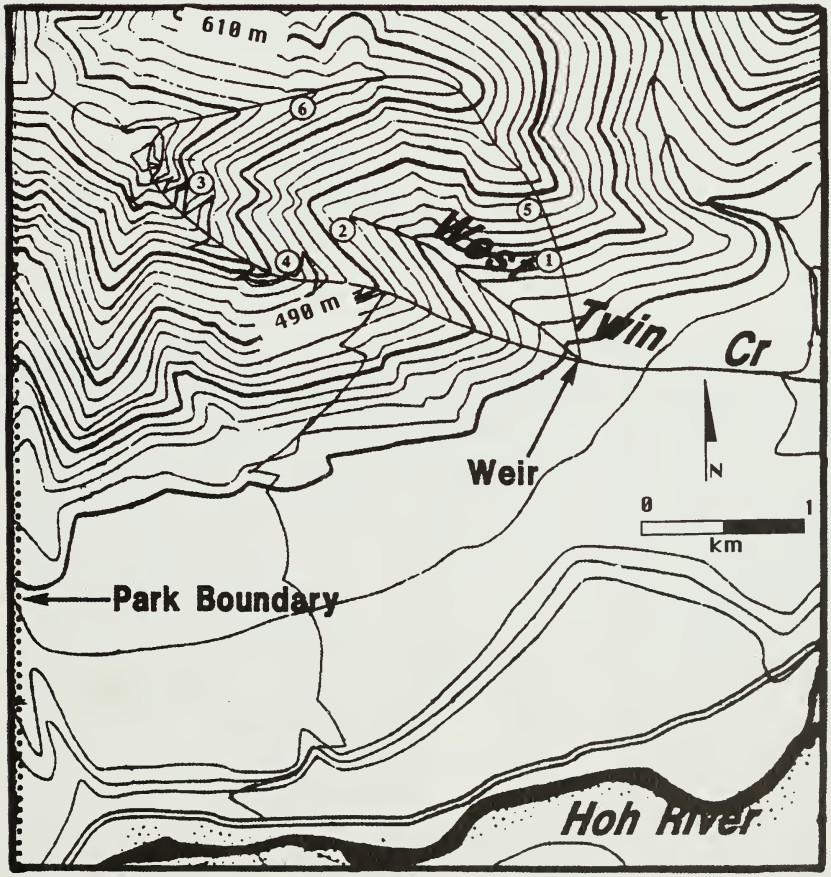

Figure 2. Topography and location of the six permanent sampling plots in the West Twin Creek watershed, Olympic National Park, Washington.

order stream runs southeast. Slopes range from 33%–80%. It generally faces southeast, but many aspects are represented.

Climate

The climate of the old-growth forest of the West Twin Creek watershed ranged from relatively cool and moist on the lower slopes to warm and dry on the ridgetops. At the Hoh Ranger Station (Fig. 1), located 10 km east of the watershed at an elevation of 183 m, mean January air temperatures were 4.5°C and mean July air temperatures were 16°C (Table 1). Average daily minimum soil temperatures in the lower watershed did not fall below 0°C, and average daily minimum air temperatures only occasionally fell below 0°C (Fig. 3). Between 1984 and 1993, average annual rainfall at the Hoh Ranger Station was about 350 cm (National Acid Deposition Program-National Trends Network 1994). Most of the rain fell between October and May, and there was a pronounced summer dry season. Snow rarely fell at the base of the watershed and generally lasted for only a few days. A winter snow pack may develop from December to March above 700 m elevation.

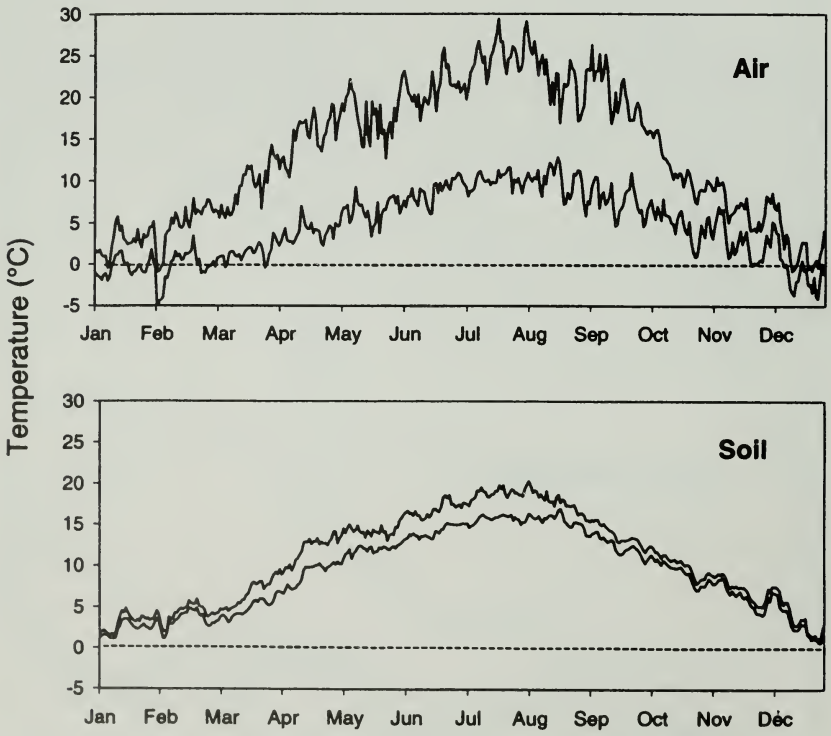

Figure 3. Average daily maximum and minimum air and soil temperatures in the lower West Twin Creek watershed throughout the year,1984–1993.

Soils

Soils are formed from marine deposits with minor conglomerates and breccias and contain some green and black sandstone (Tabor and Cady 1978). Soils vary with the complex topography. Dominant soils of the watershed are loamy to sandy-clay textured and were classified as coarse-loamy, mixed, mesic Typic Dystrochrepts. However, a moderate degree of volcanic ash or other (e.g., spodic) amorphous material present suggested that soils may alternatively be classified as medial mesic Andic Dystrochrepts. Because of windthrow that is common in the area, the mineral soil was mixed (Appendix A).

Vegetation

Western hemlock (*Tsuga heterophylla*) dominated the overstory vegetation in the lower watershed. In addition, Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*), and, at the lowest elevations in the watershed, Sitka spruce (*Picea sitchensis*) were present as massive old-growth trees (Fig. 4) and sporadic reproduction. The understory vegetation was dominated by swordfern (*Polystichum munitum*) and Oregon oxalis (*Oxalis oregana*).

Pacific silver fir (*Abies amabilis*) and western hemlock were the dominant overstory species in the upper watershed, but western redcedar was also present. The main understory species were oval-leaf huckleberry (*Vaccinium ovalifolium*), red huckleberry (*Vaccinium parvifolium*) and Oregon oxalis. Salal (*Gaultheria shallon*) occurred on south-facing slopes at mid to upper elevations (Appendix B).

Figure 4. Large, old-growth Douglas-fir tree in the West Twin Creek watershed.

Hardwoods were not common in the West Twin Creek watershed. However, riparian areas contained bigleaf maple (*Acer macrophyllum*), and disturbed areas, such as slope failures and creep slopes, contained red alder (*Alnus rubra*).

The tree population was composed of 82% western hemlock, 10% Pacific silver fir, 6% western redcedar, 1% Douglas-fir, and 1% Sitka spruce. However, only 26% of the tree basal area was composed of western hemlock. The remaining basal area was composed of 26% Pacific silver fir, 25% western redcedar, 15% Douglas-fir, and 6% Sitka spruce.

The forest was uneven–aged. The age of Douglas–firs ranged from 237 to 635 years, western redcedars from 123 to 600 years, western hemlocks from 71 to 262 years, and Pacific silver firs from 98 to 248 years. Maximum tree height was greater than 90 m, but the canopy was broken up and uneven. Diameter at breast height (DBH) of Douglas-firs ranged from 10 to 310 cm, western redcedars from 27 to 302 cm, western hemlocks from 5 to 260 cm, and Pacific silver firs from 9 to 190 cm.

Hoh Lake

Topography

The Hoh Lake watershed is a high-elevation subalpine site (Fig. 5). Slopes range from 55% to 78%, and the watershed generally faces south to southeast. Elevations range from 1250 to 1525 m; the lake is at 1390 m (Fig. 6).

Figure 5. View of Hoh Lake and the watershed from higher elevation.

Climate

Mean January air temperatures were –2.5°C and mean July air temperatures were 15°C (Table 1). Annual precipitation ranges from 380 to 500 cm; most fell between October and May, and there was a pronounced summer dry season. Most of the precipitation fell as snow, and typical snowpack depths ranged from 760 to 1300 cm.

Soils

Soils are formed from marine deposits of grayish-green and black sandstone (Tabor and Cady 1978) and were classified as Typic Cryorthods or Typic Cryumbrepts. Soils vary with the topography. Dominant soils of the watershed have sandy-loam texture (Appendix A).

Vegetation

The overstory vegetation of the Hoh Lake watershed contains three tree species: Pacific silver fir, mountain hemlock (*Tsuga mertensiana*), and Alaska yellow cedar (*Chamaecyparis nootkatensis*). The understory vegetation was dominated by Alaska huckleberry (*Vaccinium alaskaense*), big huckleberry

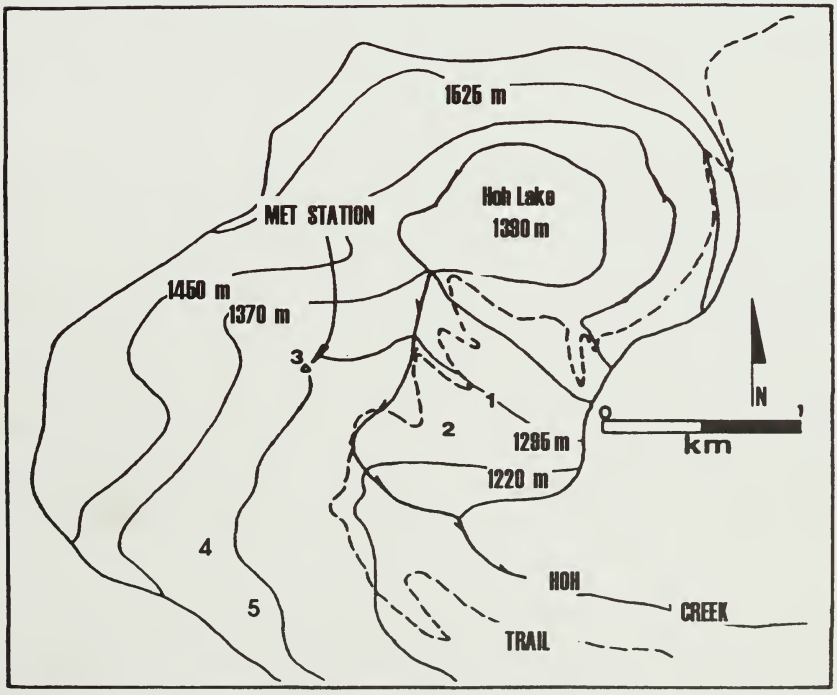

Figure 6. Topography of the Hoh Lake watershed and the locations of the permanent sampling plots.

(*Vaccinium membranaceum*), avalanche fawnlily (*Erythronium montanum*), and common beargrass (*Xerophyllum tenax*; Appendix B).

The forest was uneven-aged. The age of Pacific silver firs ranged from 155 to 452 years, mountain hemlocks from 198 to 482 years, and Alaska yellow cedars from 200 to 438 years. Maximum tree height was 51 m, and the canopy was uneven. Maximum DBH of Pacific silver fir was 123.9 cm, mountain hemlock 122.3 cm, and Alaska yellow cedar 65.7 cm.

Chapter 3: Vegetation Communities in the West Twin Creek and Hoh Lake Watersheds

Vegetation in old-growth forests in Oregon and Washington and the relations between the environment and vegetation have been described in some detail (Fonda and Bliss 1969; Fonda 1974; Zobel et al. 1976; del Moral and Long 1977; Grier and Logan 1977; Hemstrom et al. 1982; Agee and Kertis 1987; Franklin and Dyrness 1988; Henderson et al. 1989; Kirk and Franklin 1992). Grier and Logan (1977) presented a detailed vegetation description of an old-growth watershed in the Oregon Cascades, but detailed descriptions of old-growth forest vegetation on a watershed scale in the Olympic Mountains are not available. The present vegetation is only a remnant of the historic vegetation, and most of it is in Olympic National Park (Kirk and Franklin 1992). A better understanding of the spatial variability in vegetation patterns in watersheds will be helpful in developing ecologically sound management practices at the landscape level (Franklin 1993).

Our objectives were the description and classification of the vegetation in low (West Twin Creek) and high (Hoh Lake) elevation old-growth forested watersheds in the Hoh River Valley, Washington, and the examination of relations between the environment and plant species and communities.

Methods

One hundred and sixty-seven circular reconnaissance plots (500 m^2) were established in the West Twin Creek watershed in the summer of 1984. From approximately mid-slope baselines at West Twin Creek, transects were positioned upslope and downslope. Plots were spaced at 100-m intervals up to the ridge top and down to creek level. This spacing ensured sampling the full range of plant communities. Nested circular plots were used to sample the vegetation in each plot. Seedling presence by species was determined in four 20-m^2 subplots. In one 50-m^2 subplot, percent cover of herbs, shrubs, moss lichen, bare soil, litter and rocks (>8 cm) were recorded. Trees were measured and coded in 250 m^2 subplots, and large trees (>50 cm dbh) and all snags were measured in the whole reconnaissance plot. Using the reconnaissance data, five plant community types and a variant of one type were identified in the watershed. A permanent circular sample plot (1000 m^2) was randomly located in each of these six types (Fig. 7). Nested circular subplots were used to sample the understory vegetation in each plot: four 20-m^2 subplots for tree seedlings and one 50-m^2 subplot for percent cover of herbs, shrubs, mosses, lichens, bare soil, litter and rocks (>8 cm). Percent slope, aspect, elevation, topographic shape, and slope position were determined in each plot. At Hoh Lake, five circular permanent sample plots (1000 m^2) were established after delineation of the plant communities of the closed-canopy forest in the basin in an on-the-ground reconnaissance (Fig. 6).

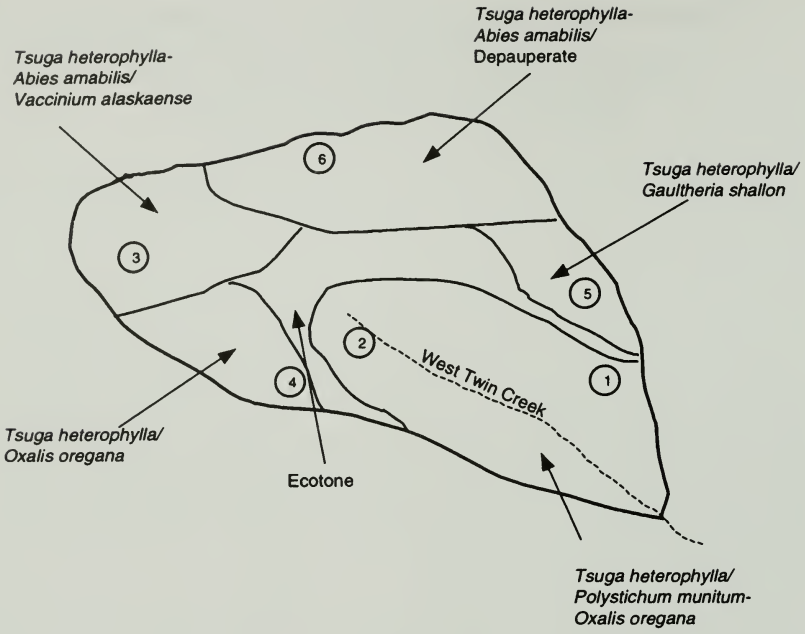

Figure 7. Major plant communities in the West Twin Creek watershed and the locations of the permanent sampling plots.

All measured trees were assessed for vigor and condition. These conditions included canopy class (dominant, codominant, intermediate, or suppressed), canopy condition, bole condition, any signs of mechanical or animal disturbance, cavities that would serve as courts for disease or insects, and signs of disease or insect damage or symptoms. In addition, crown damage and dieback were used as measures of the condition of individual trees.

Detrended correspondence analysis (DCA), an ordination technique, was used to analyze the data. Species and sample ordinations were calculated with DECORANA (Hill 1979a). The samples scores were weighted means of the species scores within each sample. Data were classified with the two-way indicator analysis program TWINSPAN (Hill 1979b).

Results and Discussion

Plant Communities in the West Twin Creek Watershed

Plots 1, 2, and 5 were in the lower watershed and plots 3, 4, and 6 were in the upper watershed (Fig. 7, Table 2). Average plot DBH ranged from 27.4 to 49.6 cm and total basal area ranged from 56.4 to 135.2 m^2/ha. Understory community composition and structure were also highly variable, ranging from 5 to 18 understory species/0.1-ha plot (Appendix C).

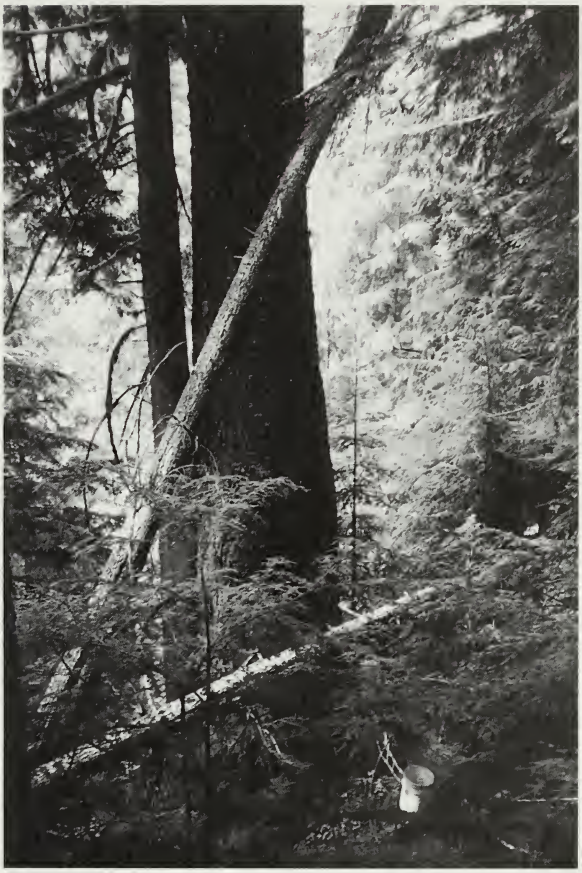

Figure 8. Permanent sampling plot 1 in the lower West Twin Creek watershed.

Lower Watershed

The most widespread community type in the entire watershed, *Tsuga heterophylla-Polystichum munitum-Oxalis oregana*, was located on the lower valley walls adjacent to the creek (Fig. 7). The two variants of this community type were represented in plot 1 (Fig. 8) and plot 2 (Fig. 9). Plot 1 was on a south slope (205° aspect) at an elevation of 342 m on a 67% slope and contained warm and dry indicator species salal and red huckleberry (Brockway et al. 1983; Lesher and Henderson 1989). Western hemlock was the most abundant tree species in the upper canopy (72% of the total; Table 2) and dominated the regeneration and intermediate size classes. Douglas fir represented 20% of the stocking, including some scattered large old trees, whereas western redcedar represented 8% of the stocking, including some large specimens (Table 2). Sword fern and Oregon oxalis were the most important understory species

Table 2. Features of permanent sampling plots in the West Twin Creek watershed, 1985.

	Lower watershed			Upper watershed		
Description	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
Elevation (m)	342	458	458	714	586	683
Aspect (degrees)	205	30	165	140	92	170
Slope (%)	67	75	74	80	43	33
Stem density (stems/ha)	421	375	983	448	239	948
western hemlock	301	312	809	295	195	779
Douglas-fir	84	37	12	0	0	0
Pacific silver fir	0	12	50	102	43	168
western redcedar	36	12	112	51	0	0
Stem density of dominant species						
DBH of dominant species						
western hemlock	30.6 (22.4)	26.3 (26.0)	18.3 (16.16)	20.5 (13.1)	49.5 (41.8)	17.7 (13.1)
Douglas-fir	55.0 (83.0)	86.7 (15.4)	159.6	0	0	0
Pacific silver fir	0	12.7	35.9 (6.0)	68.3 (404.4)	50.2 (13.5)	74.4 (36.8)
western redcedar	108.8 (70.4)	27.4	80.5 (35.0)	160.8 (24.6)	0	0
Average DBH (cm)	39.9 (46.1)	31.9 (30.4)	28.1 (31.2)	39.9 (37.6)	49.6 (38.0)	27.4 (29.2)
Basal area of dominant species						
western hemlock	24.2	32.9	38.5	14.1	63.1	29.4
Douglas-fir	59.2	22.6	24.9	0	0	0
Pacific silver fir	0	0.2	5.2	42.7	9.1	90.1
western redcedar	37.7	0.7	66.6	47.7	0	0
Total basal area (m^2/ha)	121.1	56.4	135.2	104.5	72.2	119.5

Table 2. *Continued.*

	Lower watershed			Upper watershed		
Description	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
Plant community type	*Tsuga heterophylla/ Polystichum munitum-Oxalis oregana* (south slope)	*Tsuga heterophylla/ Polystichum munitum-Oxalis oregana* (north slope)	*Tsuga heterophylla/ Gaultheria shallon*	*Tsuga heterophylla-Abies amabilis/Vaccinium alaskaense*	*Tsuga heterophylla/ Oxalis oregana*	*Tsuga heterophylla-Abies amabilis/ Depauperate*
Dominant understory species	red huckleberry salal swordfern Oregon oxalis Oregon beaked moss	swordfern Oregon oxalis Oregon beaked moss little shaggy moss mountain fern moss	Alaska huckleberry red huckleberry salal little shaggy moss	Alaska huckleberry red huckleberry	Oregon oxalis deerfoot vanillaleaf	Oregon beaked moss

DBH and basal area reported of trees > 5 cm DBH and corrected for slope.
Understory species included only if > 5% cover.

Figure 9. Permanent sampling plot 2 in the lower West Twin Creek watershed.

(Appendix C). Major associated species in this community type included red huckleberry and Oregon beaked moss (*Eurhynchium oreganum*; Appendix C). Western hemlock was the dominant regenerating species at 18 000 seedlings/ha (Table 3). Some Sitka spruce and western redcedar seedlings were also present, but no regeneration of Douglas fir or Pacific silver fir was found.

Plot 2 was on a north slope (30 degrees aspect) at an elevation 458 m on 75% slope (Table 2) and had a much richer herb layer with 75% cover by six moss species: *Eurhynchium oreganum*, *Rhytidiadelphus loreus*, *Hylocomium splendens*, *Polytrichum juniperinum*, *Dicranum scoparium* and *Mnium* (Appendix C). Western hemlock was the most abundant tree species (Tables 2 and 3). Tree stocking was less than in plot 1 (375 versus 421 trees/ha), and the basal area (56.4 m^2/ha) was less than half of that in plot 1 (121.1 m^2/ha; Table 2). The reason for this difference may have been the greater disturbance in plot 2

Table 3. Stem density (stems/ha) of tree species <5 cm diameter at breast height (DBH) in permanent sampling plots in the West Twin Creek watershed, 1985.

Species	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
western hemlock	18000	32300	9200	12400	32400	1500
Douglas-fir	0	200	0	700	400	0
Pacific silver fir	0	200	0	4400	500	7200
western redcedar	600	900	300	300	0	0
Sitka spruce	1100	500	0	0	0	0

as evidenced by the high percentage of bare soil (10%) and high rock content on the plot (Appendix C). Douglas fir was also regenerating on this plot at 200 seedlings/ha (Table 3). Five tree species were represented in the <5-cm diameter class, although western hemlock strongly dominated. As in plot 1, the understory vegetation was dominated by swordfern and Oregon oxalis; major associates were mosses and lichens.

Plot 5 (Fig. 10) was located at 458 m on a 74% slope on a southerly aspect in a *Tsuga heterophylla Gaultheria shallon* community type. The plot contained 983 trees/ha and 135.2 m^2/ha of basal area (Table 2). Western hemlock was represented in all size classes and made up 82% of the trees. Thus, it dominated the large size classes and made up 28% of the basal area; a few mid-size Pacific silver firs were present. Western hemlock also dominated the <5-cm-diameter class at 9,200 trees/ha (Table 3). Western redcedar at 300 trees/ha was the only other species. Salal covered 60% of the plot (Appendix C). *Vaccinium* species and vine maple (*Acer circinatum*) were shrub associates; only trace amounts of herbs were present (Appendix C).

Upper watershed

As elevation in the watershed increased, vegetation gradually changed from dominance by western hemlock to dominance by Pacific silver fir. Plot 3 (Fig. 11) was located in a transition community type (*Tsuga heterophylla-Abies amabilis Vaccinium alaskaense*). This plot was located on the steep southeast headwall near the top of the watershed, just below the Hoh Bogachiel Trail. The elevation of the plot was 714 m, and the slope was 80%. The overstory was dominated by large Pacific silver fir and western redcedar (Table 2). Western hemlock was present in the suppressed and intermediate size classes and had the highest stem density (295 trees/ha). Western hemlock and Pacific silver fir were regenerating in the plot; hemlock regeneration dominated over silver fir 3 to 1 (Table 3). Some Douglas fir and western redcedar were also regenerating. The understory was dominated by Alaska huckleberry (*Vaccinium alaskaense*), red huckleberry, and salmonberry (*Rubus spectabilis*). Except

Figure 10. Permanent sampling plot 5 in the lower West Twin Creek watershed.

deerfern (*Blechnum spicant*), herb species were present in only trace amounts (Appendix C).

Plot 4 was in the *Tsuga heterophylla-Oxalis oregana* community and was located on a gentle east-facing slope at 586 m (Fig. 12). This community at 239 trees/ha and a basal area of 72.2 m^2/ha had a lower stem density than the other types (Table 2). Western hemlock was the dominant tree in the overstory,

Figure 11. Permanent sampling plot 3 in the upper West Twin Creek watershed.

regeneration (Table 3), and intermediate size classes. Pacific silver fir was the only other mature tree species but was not abundant in any size class. Douglas fir regeneration was found in gaps created by canopy openings. Shrubs were conspicuously absent; the understory was covered by a rich herb layer. Oregon oxalis and deerfoot vanillaleaf (*Achlys triphylla*) covered 80% of the plot, and white trillium (*Trillium ovatum*), Smith's fairybells (*Disporum smithii*), and western springbeauty (*Montia sibirica*) were associates (Appendix C).

Plot 6 (Fig. 13) was classified as *Tsuga heterophylla-Abies amabilis* Depauperate type. This community type was located on a warm, dry, upper-slope position. The slope was gentle (33%) and faced south. This type had little or no understory development of regenerating conifers or understory vegetation. Traces of Alaska huckleberry and northwestern twayblade (*Listera caurina*) were present. The lack of understory vegetation was probably due to the dense

Figure 12. Permanent sampling plot 4 in the upper West Twin Creek watershed.

Figure 13. Permanent sampling plot 6 in the upper West Twin Creek watershed.

stocking of mature trees (948/ha). The south-facing ridgetop position of this community type was particularly susceptible to wind disturbance that prevails from the south and west. The accumulation of litter in this stand was high;

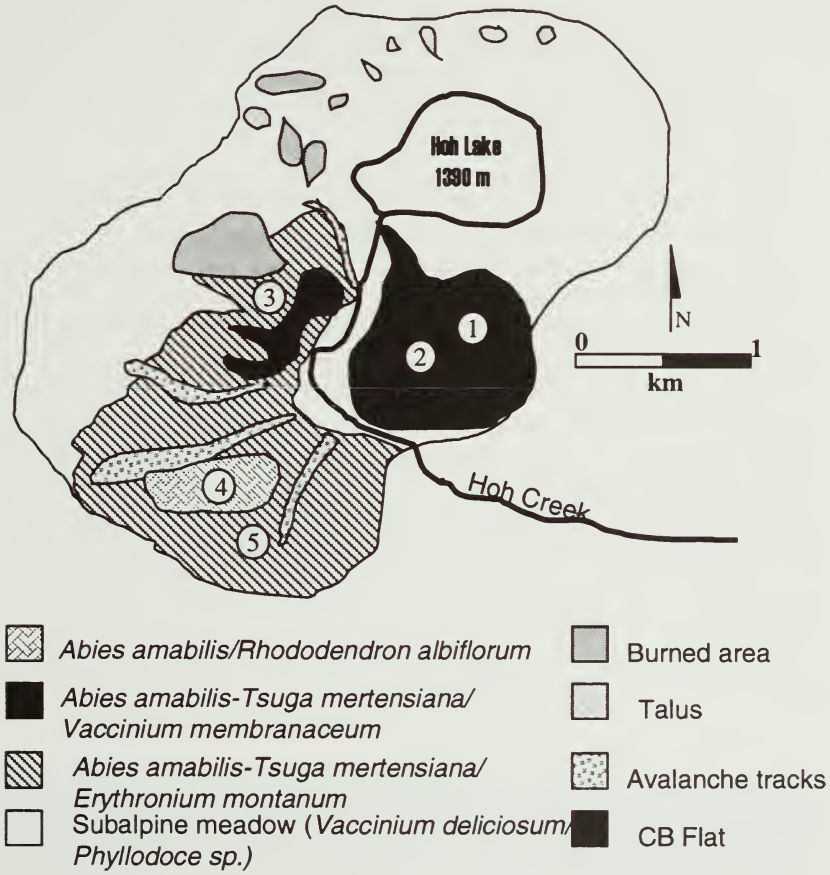

Figure 14. Major plant communities and disturbed areas in the Hoh Lake watershed and the locations of the permanent sampling plots.

large logs of varying decay classes and recent fresh branch and twig litter covered most of the plot.

Plant Communities in the Hoh Lake Watershed

The environment at Hoh Lake is predominantly cold and wet. Gale force winds buffet the ridgetops above Hoh Lake, and forests are entirely absent. Just below the elevation of Hoh Lake (1390 m), forests were continuous except where avalanche tracks occurred. Three plant community types occurred in the closed-can*opy forest (Abies amabilis-Tsuga mertensiana Vaccinium membranaceum, Abies amabilis-Tsuga mertensiana Erythronium montanum, and Abies amabilis Rhododendron albiflorum*) along with a subalpine community (Figs 6 and 14). Above the lake and at CB Flat, a subalpine wet meadow

Vaccinium deliciosum-Phyllodoce spp. community occurred. The meadow at CB Flat covered approximately 6 ha of gentle ground (<20% slope). Community composition and structure were slightly simpler at Hoh Lake (8–13 understory species/0.1-ha plot; Appendix C) than at West Twin Creek (5–18 understory species/0.1-ha plot).

Five plots were established in the closed-canopy forest. Plot 1 at 1295-m elevation and plot 2 at 1257-m elevation were located in the *Abies amabilis-Tsuga mertensiana Vaccinium membranaceum* community on the south-facing slopes east of CB Flat (Fig. 14). Plot 1 had a slope of 55%; plot 2 had a slope of 78%. Both plots had abundant exposed bedrock. More than 50% of the plot areas were covered by large litter (>10 cm) and coarse woody debris (Appendix C). The overstory in plot 1 was dominated by Alaska yellow cedar, but Pacific silver fir and Alaska yellow cedar were codominant in plot 2 (Table 4). Basal area was 121.3 m^2/ha in plot 1 and 125.5 m^2/ha in plot 2 (Table 4). Tree density ranged from 799 stems/ha in plot 1 to 989 stems/ha in plot 2. Regeneration of Alaska yellow cedar and mountain hemlock was also present, but regeneration was clearly dominated by Pacific silver fir at over 15 000 stems/ha (Table 5). Big huckleberry was the dominant understory shrub, and there was a smaller cover of Alaska huckleberry. Except for small amounts of avalanche fawnlily and beargrass, only trace amounts of herbs were present.

Plot 3 (Fig. 15) at 1290-m elevation and plot 5 at 1300-m elevation faced east and were in *Abies amabilis-Tsuga mertensiana Erythronium montanum* associations. Slopes in both plots were similar (65%–70%), and the plots were

Figure 15. Permanent sampling plot 3 in the Hoh Lake watershed.

Table 4. Features of permanent sampling plots in the Hoh Lake watershed, 1985.

Description	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Elevation (m)	1295	1257	1290	1310	1300
Aspect (degrees)	192	166	94	42	70
Slope (%)	55	78	65	56	70
Stem density (stems/ha)	799	989	358	527	354
Pacific silver fir	262	533	191	183	159
Alaska yellow cedar	514	419	0	126	0
mountain hemlock	23	38	167	218	195
Stem density of dominant species					
DBH of dominant species					
Pacific silver fir	37.9 (27.8)	32.1 (27.0)	69.3 (28.6)	15.2 (16.5)	46.1 (48.1)
Alaska yellow cedar	41.6 (10.5)	35.4 (14.3)	0	19.8 (19.1)	0
mountain hemlock	28.5 (26.1)	28.8 (22.1)	66.3 (10.4)	47.7 (18.4)	49.0 (41.1)
Average DBH (cm)	40.0 (18.3)	33.4 (22.1)	67.9 (21.8)	29.7 (23.3)	48.0 (44.1)
Basal area of dominant species					
Pacific silver fir	45.2	72.9	83.3	7.0	53.0
Alaska yellow cedar	74.1	49.1	0	7.2	0
mountain hemlock	2.0	3.5	58.8	44.6	63.2
Total basal area (m2/ha)	121.3	125.5	142.1	58.8	116.2

Table 4. *Continued.*

Description	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Plant community type	*Abies amabilis - Tsuga mertensiana/ Vaccinium membranaceum*	*Abies amabilis -Tsuga mertensiana/ Vaccinium membranaceum*	*Abies amabilis-Tsuga mertensiana/ Erythronium montanum*	*Abies amabilis/ Rhododendron albiflorum*	*Abies amabilis-Tsuga mertensiana/ Erythronium montanum*
Dominant understory species	big huckleberry	Alaska huckleberry big huckleberry	Alaska huckleberry avalanche fawnlily common witch's hair	Alaska huckleberry avalanche fawnlily Cascades azalea rustyleaf pink mountain heather strawberry-leaf blackberry white rhododendron common witch's hair	No species have 5% cover

DBH and basal area reported of trees > 5 cm DBH and corrected for slope.
Understory species included only if > 5% cover.

Table 5. Stem density (stems/ha) of tree species <5 cm diameter at DBH in permanent sampling plots in the Hoh Lake watershed, 1985.

Species	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Pacific silver fir	15600	25200	25900	12700	22200
Alaska yellow cedar	0	4800	100	3700	0
Mountain hemlock	0	0	0	200	300

open with few trees, averaging only 358 stems/ha in plot 3 and 354 stems/ha in plot 5. The overstory was codominated by Pacific silver fir in plot 3, but by mountain hemlock in plot 5 (Table 4). Four huckleberry species dominated the shrub layer with 6% cover, and avalanche fawnlily averaged greater than 5% of the cover. Other forbs were only in trace amounts (Appendix C).

Plot 4 at 1310-m elevation faced northeast and was located in the *Abies amabilis Rhododendron albiflorum* association. Tree density was 527 trees/ha; Pacific silver fir, western hemlock, and Alaska yellow cedar had similar proportions in the overstory (Table 4). Basal area (58.8 m^2/ha) was the lowest of the five plots at Hoh Lake. However, the shrub cover was high, averaging more than 55%; 35% was white rhododendron (*Rhododendron albiflorum*). Avalanche fawnlily cover was as high as 20%, and this was the only plot where pink mountain heather (*Phyllodoce empetriformis*) was present (15%; Appendix C). The arboreal lichen, common witch's hair (*Alectoria sarmentosa*), was visibly present throughout the closed-canopy forest of the Hoh Lake Basin, particularly in plots 3 and 4.

Plant Community Classification and Ordination

Elevation is extremely important in explaining the vegetation distribution in the West Twin Creek and Hoh Lake watersheds in the Hoh River valley, and elevation corresponds to DCA Axis I in Figure 16. Temperature and other environmental factors are integrated by elevation. Fonda and Bliss (1969) also suggested that elevation was extremely important in explaining the vegetation distribution in the Olympic mountains. Furthermore, Agee and Kertis (1987) found that DCA Axis 1 corresponded to elevation in an analysis of forest types in North Cascades National Park, and del Moral and Long (1977) found that elevation was responsible for much of the variation among community types in the Cedar River watershed in the central Washington Cascade mountains.

Axis 2 in Figure 16 seems to correspond to slope. In the Cascade Mountains, del Moral and Long (1977) and Agee and Kertis (1987) found the second factor to be a moisture gradient, not slope. However, on the west slopes of the Olympics, there is less of a moisture gradient, so that the influence of slope increases in importance.

The Hoh River valley contains a wide array of species and community types (Fig. 17). Considerable variability is related to changes in elevation, reflecting

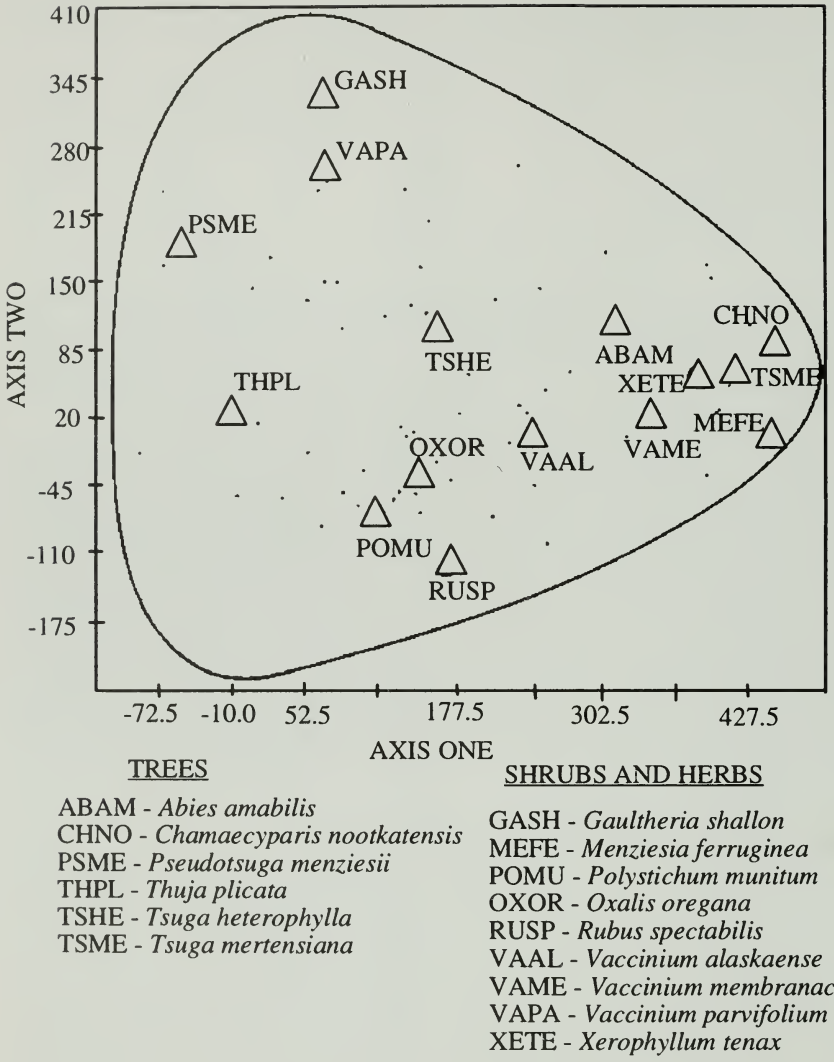

Figure 16. Species ordination of the Hoh River valley and specific ordination of 15 diagnostic species. Axis 1 corresponds to elevation, and Axis 2 corresponds to slope.

a strong temperature gradient. Henderson et al. (1989) also found that in the Olympic Mountains vegetation type strongly correlated with elevation. In the two small watersheds, variability in vegetation was considerable and mostly related to slope differences.

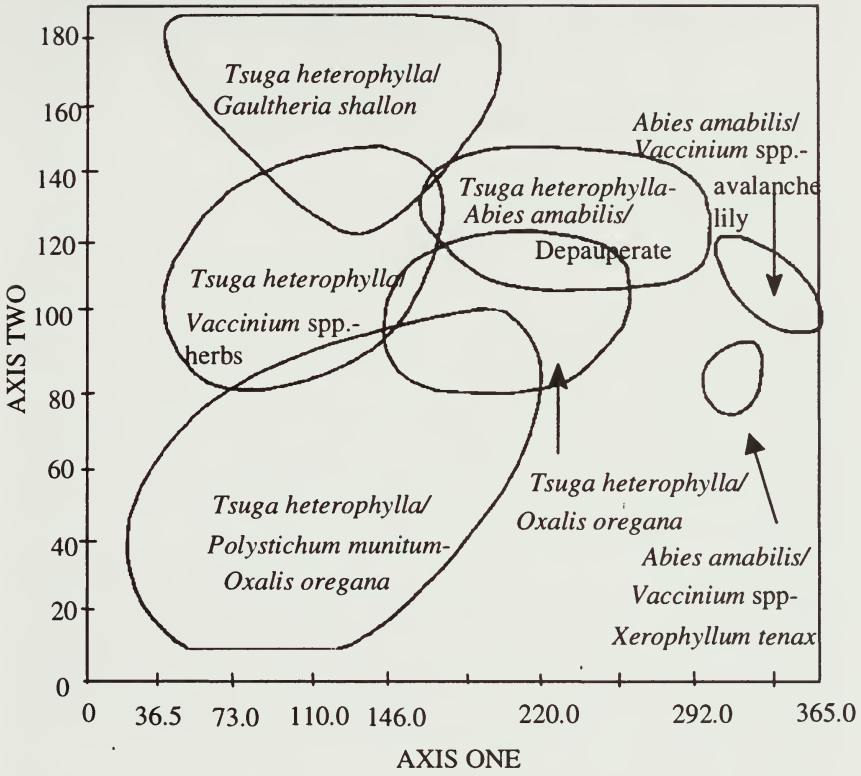

Figure 17. Ordinations of major plant communities in the Hoh River valley based on 108 sample plots. Axis 1 corresponds to elevation, and axis 2 corresponds to slope.

Chapter 4: Biomass Distributions in the West Twin Creek and Hoh Lake Watersheds

In recent years, interest has been great in organic matter accumulations in the world's forests related to global warming. Organic matter accumulations in forests could directly affect global climate change by sequestering C through plant growth and releasing C through decomposition (Dixon et al. 1994). Compilation of organic matter budgets for ecosystems is important if we are to determine the effects of global change and forest management on C pools and fluxes (Harmon et al. 1990; Dixon et al. 1994; Turner et al. 1995).

Interest in organic matter accumulations in Pacific Northwest United States forests extends beyond C pools and fluxes. Dead and downed coarse woody debris (CWD) as a structural and functional element of forests seems valuable in promoting ecosystem stability, habitat diversity, and long-term productivity (Franklin 1992; Swanson and Franklin 1992; Caza 1993). Forest managers are being urged to leave CWD on harvested lands to provide important habitat for vertebrates, invertebrates, and plants, to provide soil organic matter and nutrients in the long-term, and to reduce erosion (Harmon et al. 1986; Franklin et al. 1989, Franklin 1992). However, how much CWD must be left in various plant communities to fulfill certain ecological functions remains unclear. Natural levels of CWD can vary greatly among different ecosystem types, depending on climatic influences on plant growth and decomposition.

Old-growth forests of the Pacific Northwest are among the largest forests in the world and can accumulate impressive amounts of living and dead organic matter (Grier and Logan 1977; Franklin and Waring 1979). Forest communities near the coast may be expected to have very high biomass accumulations because high moisture levels could increase productivity and lengthen fire frequencies. Agee and Huff (1987) found accumulations of CWD that exceeded 500 Mg/ha in old-growth forests of the western Olympic Mountains; Keenan et al. (1993) found a similar maximum accumulation of 400 Mg/ha in old-growth sites on northern Vancouver Island, Canada. Although vegetation and CWD biomass in coastal old-growth forests have been estimated by several authors (Graham and Cromack 1982; Agee and Huff 1987; Harcombe et al. 1990), few total organic matter budgets have been compiled.

Similarly, ecosystem biomass budgets have been compiled of only few high elevation forests in the Pacific Northwest. An organic matter budget was compiled of a high-elevation, old-growth Pacific silver fir forest in the Washington Cascades (Grier et al. 1981) where total ecosystem organic matter was 1247 Mg/ha. A recent study by Prichard (1996), which provided the first estimate of ecosystem biomass in the Olympic Mountains, reported that total ecosystem biomass ranged from 569 to 957 Mg/ha in Pacific silver fir-mountain hemlock forests.

Our objective in this research was the compilation of organic matter budgets of living and detrital material in two old-growth watersheds: the low-elevation West Twin Creek watershed and the high-elevation Hoh Lake watershed. In the West Twin Creek watershed, biomass of overstory and understory, CWD, forest floor, soil organic matter, and fine roots were determined; in the Hoh Lake watershed only overstory vegetation and CWD were determined.

Methods

Field Measurements and Calculations

In each permanent plot in the West Twin Creek and Hoh Lake watersheds, overstory and understory vegetation and coarse woody debris were measured to estimate biomass. All live stems, logs, and snags were mapped. In the West Twin Creek watershed, the depth of the forest floor was measured, and forest floor and mineral soil samples were taken to determine the C content. Fine root biomass was estimated in only one plot of the West Twin Creek watershed. All values were adjusted for slope.

Live Vegetation Biomass

In each permanent plot in both watersheds, diameter at breast height (DBH) of trees greater than 5 cm was measured and species were recorded in 1985. Biomass of the overstory component of each species in the plots was calculated with equations developed by Gholz et al. (1979). No calculations were performed if the DBH was less than 7 cm because biomass was negative below that point. Tree biomass was separated into components of foliage, branches, roots, and bole-and-bark. Biomass of coarse roots was calculated from two sources: Pacific silver fir root biomass was calculated from equations in Keyes (1982), and all other species were calculated with the equations for Douglas fir in Gholz et al. (1979). Allometric equations for root biomass have not been developed for the other tree species in the West Twin Creek and Hoh Lake watersheds.

In the West Twin Creek plots, understory vegetation was sampled for biomass with ten 1-m^2 nested circular plots. In these subplots, all understory plants were clipped to ground level at the height of the growing season (late July 1985). Biomass samples were taken to the laboratory and stems and foliage were separated by *live* and *dead* categories.

In May 1992, three soil cores measuring 5.08 cm × 20 cm were collected in Plot 1 of the West Twin Creek watershed. Fine roots of less than 2 mm in diameter were sorted from the cores and were dried at 75°C for 48 hours. Fine root biomass was estimated in Mg/ha.

Coarse Woody Debris

Decay class, physical dimensions, and species of snags and fallen logs were recorded in each permanent plot. The DBH and height of snags were recorded.

The length and diameter of both ends of logs were recorded. When a log extended beyond the permanent plot, only the portion in the plot was measured. These physical dimensions were converted to biomass in the following manner.

Calculating biomass of snags and logs involved correcting for wood density of each decay class and then calculating volume and biomass. Density values were used from Means et al. (1992). These values were derived for Douglas fir, but were used here for all measured species. Smalian's formula was used to calculate the volume of logs (Hartman et al. 1981):

$$\text{Volume} = 0.00007854 * (D1 + D2)/2 * L/10$$

where D1 and D2 equal the end diameters and L equals the length of the log. These volumes were converted to biomass (Mg/ha) with the following formula:

$$\text{Biomass} = \text{volume } (m^3) * \text{density } (g/cm^3) * (kg/10^3 g) * (10^6\ cm^3/m^3) * (10^4\ m^2/ha) * (Mg/10^3\ kg)$$

The same density values were used for both logs and snags. Snag volume was calculated as the frustum of a cone (Husch et al. 1972) with an assumed taper of 1:96:

$$\text{Volume} = \text{Height}/30 * (A1 + (\text{square root}(A1 * A2)) + A2)/1000$$

where A1 and A2 equal the area at the upper and lower ends of the snag. In order to use this formula, the top diameter was calculated with the following formula (Jim Agee, University of Washington, personal communication):

$$\text{Upper Diameter (D2)} = \text{Diameter 1} - (1/96 * \text{Height})$$

where diameter 1 equals DBH. Snag volumes were converted to biomass (Mg/ha) with the same formula applied to logs.

Forest Floor Depth, Soil Carbon, and Biomass

In July and August 1993, sampling was conducted to estimate mass of C in the forest floor and mineral soil in the West Twin Creek watershed. In 5 of the 6 permanent plots, sampling was conducted at three 10-m transects along randomly placed radials from the plot center. Forest floor depth was measured with a 1-cm diameter steel probe at 0.25-m intervals along the transect. The rod was inserted into the forest floor until an increase in resistance was felt, at which point it was assumed the transition between the organic horizon and mineral soil was reached. Soil cores of 2-cm diameter were taken to a depth of 40 cm at 6 points along each transect. Each core was separated into 3 components: O horizon, 0–4 cm mineral soil, and 4–40 cm mineral soil. The forest

floor samples were oven dried at 75°C and weighed for biomass. Mineral soil samples were air dried, ground, and analyzed on a Leco furnace for total C concentration. Percent organic matter was calculated as 1.724 times percent total C.

Bulk density samples were taken with a soil corer (diameter = 5.4 cm, volume = 137.4 cm^3) in all permanent plots in the West Twin Creek watershed. Three small soil pits were dug in each plot, and soil cores were taken from the 0–10 cm depth and 10–40 cm depth. These samples were oven dried at 104°C for 48 hours. Bulk density values were used to convert percent organic matter in mineral soil to Mg/ha.

Results and Discussion

Biomass in the West Twin Creek and Hoh Lake Watersheds

The average biomass of live trees was similar in the West Twin Creek watershed (1044.7 Mg/ha, Table 6) and the Hoh Lake watershed (1006.8 Mg/ha, Table 7) despite the higher elevation at Hoh Lake. Standard deviations were similar in both watersheds. Hoh Lake, however, had lower total CWD biomass (182.1 Mg/ha) than West Twin Creek (263.3 Mg/ha). The average biomass of snags (standing dead trees) in the West Twin Creek watershed was 171.0 Mg/ha (Table 6) compared to 144.5 Mg/ha in the Hoh Lake Watershed (Table 7). Log biomass averaged 92.3 Mg/ha in the West Twin Creek watershed and 37.6 Mg/ha in the Hoh Lake watershed. Shrub and herb components were not determined at Hoh Lake, but they accounted for < 1 Mg/ha in the West Twin Creek watershed (Table 6). Forest floor and soil organic matter were also not determined at Hoh Lake, but they contributed considerably (450.1 Mg/ha) to the total ecosystem biomass of 1758.6 Mg/ha in the West Twin Creek watershed (Table 6).

Live tree, snag, forest floor and ecosystem total biomass was higher in the lower West Twin Creek watershed than in the upper watershed (Table 6). Soil biomass was greater in the upper watershed, while log biomass was similar in the upper and lower watershed. These differences reflect the cooler environment in the upper watershed.

Living biomass in the West Twin Creek watershed (616.0–1732.8 Mg/ha) was similar or slightly higher than that reported from other studies in the Pacific Northwest (Table 8). For example, Agee and Huff (1987) reported living biomass values exceeding 1000 Mg/ha in an old-growth stand in the Hoh River, and Grier (1976, 1978) found similar vegetation biomass in a Sitka spruce stand on the Oregon coast. High living biomass also occur in old-growth Douglas fir stands in the Washington and Oregon Cascades (Grier and Logan 1977; Franklin and Waring 1979; Cole and Rapp 1980), and Franklin and Waring (1979) reported a value as high as 1318 Mg/ha (Table 8).

The range of snag biomass (24.0–570.6 Mg/ha) found in the West Twin Creek watershed was generally higher than previously reported in the Pacific

Table 6. Average biomass distribution and standard deviations (Mg/ha)[a] by ecosystem component in the upper; lower, and entire West Twin Creek watershed, 1985.

	Lower watershed		Upper watershed		Total watershed	
Biomass Component	Average	SD	Average	SD	Average	SD
Tree						
Foliage	29.1	12.4	32.5	5.9	30.8	8.9
Branches	111.2	26.8	132.3	44.6	121.8	34.9
Roots	306.2	152.3	216.1	41.3	261.1	111.4
Bole + Bark	781.9	387.3	478.8	89.6	630.4	301.3
Total Live Tree	1228.4	566.3	859.7	75.9	1044.1	414
Shrub						
Leaves	0.2	0.2	0.1	0	0.1	0.2
Stems	0.4	0.4	0.1	0	0.3	0.3
Herb						
Leaves	0.2	0.2	0.1	0	0.1	0.1
Stems	0.2	0.2	0.1	0	0.1	0.1
Total Live Biomass	1229.4	566.5	860.1	76	1044.7	414.3
Detritus						
Standing Dead (snags)	241.9	289.6	100.0	47.6	171.0	201.2
Fallen Logs	92.3	10.5	92.4	6.7	92.3	7.9
Total CWD	334.2	279.1	192.4	44.8	263.3	194.9
Dead shrubs	0.1	0	0	0	0.1	0
Dead herbs	0.4	0.4	0.1	0	0.4	0.3
Forest floor	97.1	34.4	84.9	21.3	89.8	23.8
Soil	329.1	67.4	391.5	83.8	360.3	76.3
Ecosystem Total	1990.3		1529.0		1758.6	

[a] Tree biomass was estimated with equations by Gholz et al. (1979). Coarse woody debris dimensions were measured empirically. The biomass of logs was calculated with formulas from Hartman et al. (1981), and the biomass of snags with formulas from Husch et al. (1972) and Means et al. (1992). Density values of coarse woody debris were taken from Means et al. (1992). Values were corrected for slope.

Northwest (Table 8). Log biomass (80.2–99.7 Mg/ha) was below the maximum values reported from other studies (Table 8). Previous estimates of CWD biomass in the Hoh River watershed range from 26.4 to 84.5 Mg/ha in snags and 93.6 to 452.9 Mg/ha in logs (Graham and Cromack 1982; Agee and Huff 1987). In old-growth forests on Vancouver Island, Keenan et al. (1993) reported snag biomass ranging from 19.6 to 164.3 Mg/ha and log biomass ranging from 175.1 to 397.5 Mg/ha. Grier (1976, 1978) reported log biomass values equaling 212 Mg/ha in an old-growth stand at Cascade Head, Oregon. The

Table 7. Average biomass distribution and standard deviations (Mg/ha)[a] by ecosystem component in the Hoh Lake watershed, 1985.

Biomass Component	Average	SD
Tree		
Foliage	45.0	15.2
Branches	102.5	37.7
Roots	224.3	78.5
Bole + Bark	635.0	264.7
Total Live Tree	1006.8	383.7
Detritus		
Standing Dead (snags)	144.5	178.8
Fallen Logs	37.6	29.4
Total CWD	182.1	188.6

[a] Tree biomass was estimated with equations by Gholz et al. (1979). Coarse woody debris dimensions were measured empirically. The biomass of logs was calculated with formulas from Hartman et al. (1981), and the biomass of snags with formulas from Husch et al. (1972) and Means et al. (1992). Density values of coarse woody debris were taken from Means et al. (1992). Values were corrected for slope.

great variability in snag and log biomass in these coastal stands reflects differences in fire history, presence of diseases and insects, and extent of windthrow.

Biomass estimates of forest floor (65.7–121.4 Mg/ha) in the West Twin Creek watershed (Table 8) are in the range of previously reported in old-growth forests of the Pacific Northwest (Grier 1976, 1978; Cole and Rapp 1980; Agee and Huff 1987; Boone et al. 1988; Means et. al 1992), but soil organic matter was slightly higher (281.4–471.0 Mg/ha). Keenan et al. (1993) reported much higher forest floor biomass on Vancouver Island because of the large amounts of decaying wood included in the estimates. Young stands of Douglas fir and western hemlock in coastal Washington had much lower forest floor biomass values (9.7–13.7 Mg/ha) than those found in this study, while soil organic matter was similar (213–532 Mg/ha; Edmonds and Chappell 1994). Differences in soil organic matter among sites could reflect either varied sampling depths or different climatic conditions and decomposition processes. Forest floor biomass in a high elevation forest in Colorado was similar to the estimates found in the West Twin Creek watershed (Arthur and Fahey 1992). However, biomass estimates of organic horizons in high elevation forests in the western Olympic mountains were lower (29.8 Mg/ha; Prichard 1996). Organic matter in mineral soils in the high elevation Olympics was slightly lower (177 Mg/ha) than that found in the West Twin Creek watershed (Prichard 1996).

The living biomass estimates in the Hoh Lake watershed (479–1392.8 Mg/ha) are greater than values reported from other high elevation sites (Turner and Singer 1976; Grier et al. 1981; Arthur and Fahey 1990; Prichard 1996;

Table 8. Biomass of vegetation, snags, logs, forest floors, and soil organic matter from other studies.

Reference	Location	Stand Type[a]	Biomass (Mg/ha)				
			Vegetation	Snags	Logs	Forest Floor	Soil OM
this study	West Twin Creek	old-growth PSME/TSHE	616.0–1,732.8	24.0–570.6	80.2–99.7	65.7–121.4	281.4–471.0
	Hoh Lake	old-growth TSME/ABAM	479.0–1,392.8	7.2–369.3	10.9–84.0	ND[b]	ND
Agee and Huff 1987	Hoh River, WA	181-yr-old TSHE/PSME	581.0	33.4	126.6	32.0	ND
		515-yr-old TSHE/PSME	1,114.0	84.5	452.9	98.3	ND
Alban and Perala 1992	Michigan	40–80 yr-old aspen	118.2–153.6	6.0–10.3	2.8–5.1	ND	ND
Arthur and Fahey 1990	Colorado	200–500-yr-old PIEN/ABLA	90.2 (live boles)	18.5	52.0	68.0	ND
Bingham and Sawyer 1988	California	Old-growth Redwood	ND	ND	200.0	ND	ND
Boone et al. 1988	Oregon	225 yr-old TSHE	315.0	10.0–100.0	ND	43.0	62.9
Cole and Rapp 1980	Oregon/Washington	old-growth PSME	126.5–915.5	ND	ND	20.5–301.1	ND
Franklin and Waring 1979	Oregon/Washington	old-growth PSME	564–1,318	37–122	70–156	ND	ND
Graham and Cromack 1982	S.F. Hoh River, WA	old-growth PISI/TSHE	ND	26.4–40.2	93.6–120.8	ND	ND
Grier 1976, 1978	Cascade Head, OR	121-yr-old /PISI	1,106.6	ND	212.0	34.0	ND
Grier and Logan 1977	H.J. Andrews, OR	450-yr-old PSME	605.3–1,186.6	3.8–70.0	55.2–580.6	27.5–57.2	ND
Grier et al. 1981	Findley Lake, WA	130-yr-old ABAM	445.0	157.0	75.0	ND	ND

Table 8. *Continued.*

Reference	Location	Stand Type[a]	Biomass (Mg/ha)				
			Vegetation	Snags	Logs	Forest Floor	Mineral Soil
Harmon et al. 1987	California	SEGI/mixed conifer	ND	7.0–51.9	28–383	ND	ND
Keenan et al. 1993	Vancouver Island	old-growth THPL/TSHE	ND	19.6–164.3	175.1–397.5	233.6–319.7	ND
Long and Turner 1975	Thompson site, WA	73-yr-old PSME	210.6	55.2	ND	ND	ND
Means et al. 1992	H.J. Andrews, OR	450-yr-old PSME	ND	137.0	222.0	55.0	380 (0–100 cm)
Muller and Liu 1991	Kentucky	old-growth oak forest	ND	5.2	14.5	ND	ND
Prichard 1996	Olympic Mountains	old-growth TSME/ABAM	501.0	23.9	ND	29.8	102.6
Sollins 1982	Wind River, WA	350–550-yr-old PSME	ND	54.0	81.0	ND	ND
Spies et al. 1988	Oregon/Washington	400–500-yr-old PSME	ND	41–63	54–73	ND	ND
Turner and Singer 1976	Findley Lake, WA	old-growth ABAM	466.6	ND	ND	53.5	244 (0–60 cm)

[a] Stand types are abbreviations of scientific names: PSME = *Pseudotsuga menziesii,* TSHE = *Tsuga heterophylla*, TSME = *Tsuga mertensiana*, PISI = *Picea sitchensis*, ABAM = *Abies amabilis*, PIEN = *Picea engelmannii*, ABLA = *Abies lasiocarpa*, THPL = *Thuja plicata*, SEGI = *Sequoiadendron giganteum.*
[b] ND = Not determined.

Table 8). In other mountain hemlock-Pacific silver fir stands in the Olympic Mountains, ecosystem living biomass averaged 501 Mg/ha (Prichard 1996). Total ecosystem biomass was lower in high elevation forests in Colorado (420 Mg/ha; Arthur and Fahey 1992). In Pacific silver fir stands in the Washington Cascades, vegetation biomass was 450 Mg/ha (Turner and Singer 1976; Grier et al. 1981), which is the low end of the vegetation biomass reported in this study. The high living vegetation biomass observed in the Hoh Lake watershed and by Prichard (1996) could reflect the moister conditions of forests in the western Olympic Mountains. These forests receive abundant moisture from storms off the Pacific Ocean and may be more productive than high elevation sites in the Cascade and Rocky Mountains. In contrast, the log biomass estimates in Hoh Lake (10.9–84.0 Mg/ha) are in the same range as other studies (Grier et al. 1981; Arthur and Fahey 1990; Prichard 1996). Log and snag biomass combined ranged from 2.5 to 51.4 Mg/ha in the Olympic Mountains (Prichard 1996). In Pacific silver stands in the Cascades, log biomass was 75 Mg/ha (Grier et al. 1981); it was 52 Mg/ha in Colorado (Arthur and Fahey 1990).

Clearly, Pacific Northwest forest ecosystems are dominated by large trees, which creates very high ecosystem biomass values composed mostly of living trees and CWD. Understory plants do not contribute greatly to ecosystem biomass. However, below-ground stores, including the forest floor, mineral soil, and roots, contribute substantially to total ecosystem biomass. In contrast to temperate deciduous forest ecosystems, conifer forests in the Pacific Northwest have very high biomass (Franklin and Waring 1979). For example, in a mature aspen stand in Michigan, vegetation biomass ranged from 118 to 154 Mg/ha, snag biomass ranged from 6 to 10 Mg/ha, and log biomass ranged from 3 to 5 Mg/ha (Alban and Perala 1992). Similarly, an old-growth oak forest in Kentucky showed much smaller snag (5 Mg/ha) and log biomass values (14 Mg/ha; Muller and Liu 1991) than those found in this study. Moisture and temperature regimes combined with litter quality directly affect accumulations of detrital material by influencing decomposition processes. Thus, CWD and forest floor material decomposes more rapidly in the warm deciduous forests of the southeast United States than in the Pacific Northwest (Muller and Liu 1991). Long-lived coniferous species combined with climatic conditions that slow decomposition lead to large total ecosystem biomass accumulations.

Variability within West Twin Creek and Hoh Lake Watersheds

There was considerable variability in biomass within the West Creek watershed. For example, the average total live tree biomass in the lower West Twin Creek watershed (1228.4 Mg/ha) was much greater than that in the upper West Twin Creek watershed (859.7 Mg/ha; Table 6). Total ecosystem biomass was also higher in the lower watershed. There was considerable variability in live tree biomass among the various plots in both the upper and lower watershed in

the West Twin Creek watershed (Appendix D). In the West Twin Creek watershed, the highest total biomass (2393.2 Mg/ha) was in plot 5 in the lower watershed in the western hemlock/salal community type. The highest total live tree biomass, however, was in plot 1 in the western hemlock/swordfern-Oregon oxalis community (Appendix D). Log biomass, however, was not very variable and only ranged from 80.2 to 99.7 Mg/ha (Appendix D). In contrast, snag biomass was highly variable and ranged from 24.0 to 570.6 Mg/ha (Appendix D). Forest floor biomass ranged from 65.7 to 121.4 Mg/ha. Soil organic matter ranged from 281.4 to 471.0 Mg/ha (Appendix D).

There was also a lot of variability in biomass in the various plant communities in the Hoh Lake watershed (Appendix D). The highest ecosystem biomass was found in plot 5 in the Pacific silver fir-mountain hemlock/lily community (1785.2 Mg/ha). This community also had the greatest biomass in trees and logs of all the plots. The lowest biomass value in the Hoh Lake watershed was found in plot 4 (501.4 Mg/ha) in the Pacific silver fir/rhododendron community (Appendix D), attributable to small tree, snag, and log biomass values. There was great variability in biomass of both logs and snags among the Hoh Lake watershed plots. Log biomass ranged from 10.9 to 84.0 Mg/ha, while snags ranged from 7.2 to 369.3 Mg/ha (Appendix D).

Distribution of Biomass Among Ecosystem Components

Live biomass was 59.4% of the total ecosystem biomass in the West Twin Creek watershed. CWD made up 15.0% of the ecosystem total and forest floor and soil was 25.6% (Table 6). The live understory made up only 0.03% of the total ecosystem biomass; live and dead understory totaled only 1.1 Mg/ha.

Snags had greater biomass than logs in both the upper and lower watershed, but the difference was greater in the lower watershed (Table 6). Mineral soil contributed higher amounts of organic matter than the forest floor because of the larger soil volume measured.

No fine root biomass data are presented in Table 6 because fine root biomass was determined only in plot 1 of the West Twin Creek watershed, where it averaged 3.5 Mg/ha. This falls within the range of values from the Washington Cascades (2.8–6.0 Mg/ha) reported by Vogt et al. (1980) and Vogt et al. (1987). Fine root biomass is typically greater in high elevation forests, due to nutrient poor soils (Grier et al. 1981). In an old-growth Pacific silver stand in the Washington Cascades, fine root biomass was 12.8 Mg/ha (Grier et al. 1981). This estimate could be high due to definition of fine roots as <5 mm, rather than <2 mm. However, Arthur and Fahey (1992) also observed high fine root biomass (9.0 Mg/ha) in high elevation forests in Colorado. Estimates of fine root biomass in a mature hardwood forest in the Hubbard Brook Experimental Forest in New Hampshire were comparable to values in this study and ranged from 4.3 to 4.7 Mg/ha depending on the season (Fahey and Hughes 1994).

As previously mentioned, understory vegetation represented a very small component of the total ecosystem biomass in the West twin Creek watershed.

The biomass of understory vegetation was similar to a mature forest in the Cedar River Watershed (Turner 1975). In that study, vascular understory plants made up 0.2 Mg/ha, while moss contributed an additional 1.0 Mg/ha (Turner 1975). However, the understory biomass values in this study were lower than previous estimates in old-growth stands in Oregon and Washington (3.7–9.7 Mg/ha; Johnson et al. 1982).

We found the average forest floor mass to be 89.8 kg/ha and soil values averaged 360.3 Mg/ha (Table 6) representing 25.6% of the total ecosystem biomass. The biomass estimates of forest floor and soil in the West Twin Creek watershed were similar to values found in other coniferous ecosystems (Cole and Rapp 1980; Agee and Huff 1987; Arthur and Fahey 1992). Soil organic matter can represent a substantial component of the ecosystem total, ranging from 9% to 45% of the total ecosystem biomass and averaging 33% in the Pacific Northwest (Cole and Rapp 1980). Forest floor and soil organic matter (to 60 cm depth in mineral soil) accounted for 34% of the total ecosystem biomass in an old-growth stand in the Washington Cascades (Grier et al. 1981). Similarly, Arthur and Fahey (1992) found that soil organic matter made up 30% of the ecosystem total. Prichard (1996) found that mineral and organic soils contributed 18% of total ecosystem C, while roots contributed an additional 11% in forests of the Olympic Mountains.

The large biomass values reported from the West Twin Creek and Hoh Lake watersheds have direct implications with respect to global change. Productive forests composed of large, long-lived trees, such as those found on the west side of the Olympic Peninsula, provide a sink in the global C cycle (Harmon et al. 1990; Dixon et al. 1994). On the other hand, large accumulations of CWD could also act as a C source through decomposition. Downed logs respired from 2.7 to 8.3 g CO_2 m^2/day in old-growth stands in the Hoh River watershed; the rate depended on log species, decay class, and season (Marra and Edmonds 1994). Although decomposition of CWD may reflect a substantial release of C to the atmosphere, old-growth stands with large biomass accumulations in living vegetation and detritus can store greater amounts of global C than the conversion of these stands to fast-growing, second-growth stands (Harmon et al. 1990; Dixon et al. 1994).

Chapter 5: The Hydrological Cycle in the West Twin Creek Watershed

Because water has a vital role as a transporting agent, chemical solvent, and catalyst in ecosystems, gathering quantitative data on hydrology is extremely important in understanding the biogeochemistry of watersheds (Likens et al. 1977; Likens and Bormann 1995). A better understanding of hydrologic processes in coastal forests on the Olympic Peninsula will also be helpful in developing management schemes for Pacific salmon, a topic of great interest in the Pacific Northwest.

There is a considerable amount of hydrologic data available on the Olympic Peninsula. The USGS operates many continuous stream gauging stations, but most are on larger rivers and streams. There are few on smaller streams and only a handful in Olympic National Park (Amerman and Orsborn 1987a and 1987b). Our study helps to fill this data gap. Examination of annual hydrologic budgets and hydrograph patterns in small watersheds in natural systems can provide much insight into the functioning of forests (Waring et al. 1981).

One of the problems in determining annual hydrologic budgets, however, is determination of the water year. An ideal water year is that successive period that most consistently, year after year, gives the highest correlation between precipitation and stream discharge. In the Pacific Northwest, the water year is considered to start on 1 October after the dry summer, and end on 30 September.

Small watershed studies enable one to calculate annual evapotranspiration from annual precipitation and runoff over a weir at the base of the watershed, assuming that the geologic base of the watershed is watertight. Evapotranspiration refers to the total water loss from the soil as a result of evaporation from soil and plant surfaces and transpiration from the trees. The living components of ecosystems, particularly forest canopies, strongly influence hydrologic cycles in ecosystems (Likens et al. 1977; Larson 1979; Sollins et al. 1980), and interception of fog by an old-growth canopy may contribute 30% of the annual input to the forest floor (Harr 1982). Watersheds at Hubbard Brook in New Hampshire have relatively impermeable bedrock and little deep seepage. At Hubbard Brook from 1956 to 1974, an average of 129.5 cm of water fell on each unit area of watershed annually (Likens et al. 1977). Of this, 62% became stream discharge and the remaining 38% was lost as evapotranspiration.

In the Pacific Northwest, runoff is generally a higher proportion of precipitation than it is in the eastern United States because of the higher precipitation, cooler temperatures, and lower evapotranspiration. For example, Larson (1979) found annual runoff to be 91% of precipitation in small watersheds in the Hoh River valley in 1975–76. In a drier year (1976–77), runoff was only 86% of precipitation. In the drier Oregon Cascades, Sollins et al. (1980) found that annual runoff from a small, old-growth watershed was 65% of precipitation.

The objectives of this study were to determine the hydrologic budget for the pristine old-growth West Twin Creek watershed and to examine the hydrograph patterns. Precipitation, evapotranspiration, and stream discharge, and how they change seasonally and annually were characterized. Typically, precipitation and runoff vary greatly from year to year, so to understand an ecosystem's hydrologic flux, a long-term record is needed (Likens et al. 1977). Therefore, we conducted our study from 1984 to 1994.

Methods

Precipitation

Precipitation was collected at the Hoh Ranger Station to the east of the study site (Fig. 1). Using a standard rain gauge, precipitation was collected daily from January 1984 to December 1994.

Stream Discharge

Initially, stream discharge was measured with a trapezoidal weir constructed in September 1984. In May 1988, the weir was changed to a 3:1 V-notch (Fig. 18). This change was made to measure stream stage more accurately during summer low flows. Stream width at the weir ranged from about 1 to 2 m depending on the season. From October 1984 through October 1994, the stage and discharge at the weir were measured every two weeks. Stage was continu-

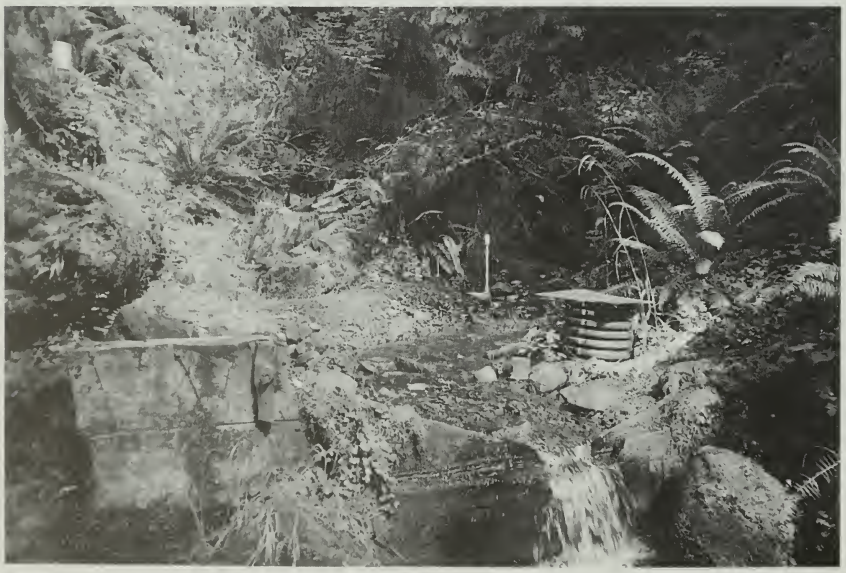

Figure 18. The 3:1 V-notch weir at West Twin Creek, showing the stilling well in the foreground and the proportional flow sampler in the background

ously recorded at the weir by a Fluid Data Systems float-driven potentiometer and data were collected with a Campbell Scientific CR21 data logger. Stage-discharge measurements were used to construct a rating curve for the weir. From 1984 to April 1988, the discharge equation used was $y = 1.12 + 1.83\ x$, and from May 1988 to 1994, the equation used was $y = 1.18 + 2.22\ x$, where y = log discharge (in cubic feet per second) and $\times$ = log stage height (in feet). Annual discharge was determined in centimeters by converting discharge to metric units and assuming the area of the watershed was 58 ha. During 1990–91, stage data were unreliable and not used in this analysis.

The following hydrologic budget equation (Swift et al. 1988) was used on a water-year basis: Annual stream discharge or runoff = annual precipitation—annual evapotranspiration + soil storage (assumed to be zero on an annual basis). Fog input was not included in annual precipitation.

Throughfall

Throughfall is precipitation that reaches the forest floor after contacting the tree canopy. Throughfall was collected in seven throughfall samplers placed randomly in a circular 0.01-ha plot located approximately 100 m below the weir. The collectors consisted of 20-cm diameter polyethylene funnels placed on inverted 2-L polyethylene containers with the bottom removed. The funnel and containers were placed on 12-L polyethylene buckets. A 2-cm outside diameter tube was attached to the bottom of the funnel, and throughfall drained into a polyethylene bag in the bucket. Two layers of nylon window screen were placed over the top of the funnel. Samples were collected every four weeks from January 1992 to December 1994.

Results and Discussion

Precipitation

Monthly precipitation from 1984 to 1993 at the Hoh Ranger Station is shown in Figure 19. Precipitation was extremely variable from month to month and year to year. Rain fell in every month of the year, but there was a distinctly seasonal pattern of highest precipitation in the fall and winter and lowest precipitation in the summer. Annual precipitation ranged from a low of 267 cm during 1992–93 to 475 cm during 1990–91 (Table 9). Larson (1979) recorded an even higher annual precipitation of 537 cm during 1975–76 in a nearby watershed. The high precipitation during 1990–91 was due to intense storms in the fall (Fig. 19). Fog does occur in the watershed, but no estimates of fog drip as a contribution to precipitation reaching the forest floor were made. Harr (1982) estimated that fog drip contributed as much as 30% of the annual precipitation in the Bull Run watershed near Portland in the Oregon Cascades.

Stream Discharge

Annual stream discharge ranged from 175 cm during 1986–87 to 347 cm during 1989–90 (Table 9). Stream hydrographs can be separated into two main

components: direct runoff (or quickflow) and baseflow, which represents the groundwater contribution (Gordon et al. 1992). The stream discharge hydrograph for January 1992 to December 1993 is shown in Figure 20. Large peaks are related to storms in February 1992, January 1993, May 1993, and December 1993. The stream at West Twin Creek flows throughout the year, but it almost

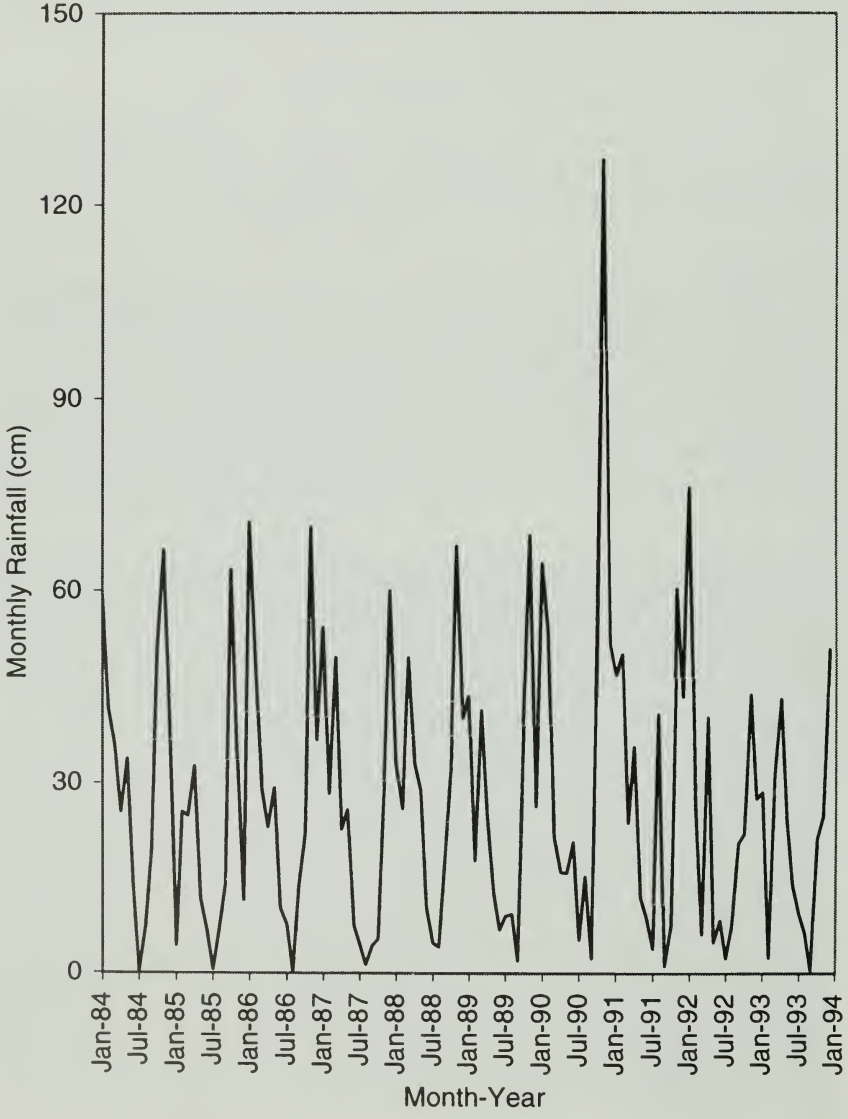

Figure 19. Monthly rainfall at the Hoh Ranger Station (National Acid Deposition Program/National Trends Network 1994), 1984–1993.

Table 9. Estimated yearly water budgets in the West Twin Creek watershed, from water year 1985–1986 to water year 1993–1994.

Water year	Percent missing stage data	Stream discharge (cm)	Precipitation (cm)	Evapotranspiration (cm)	Percent discharge	Percent evapotranspiration
1985–86	39	319	368	49	87	13
1986–87	19	175	325	150	54	46
1987–88	44	191	302	111	63	37
1988–89	14	315	354	39	89	11
1989–90	18	347	427	80	81	19
1990–91	100	ND[a]	475	ND	ND	ND
1991–92	31	251	304	53	83	17
1992–93	2	204	267	63	76	24
1993–94	10	283	319	36	89	11
Average[b]		260.7	333.3	72.6	77.8	22.2

[a] ND = Not determined.

[b] Average calculated only of years with corresponding discharge.

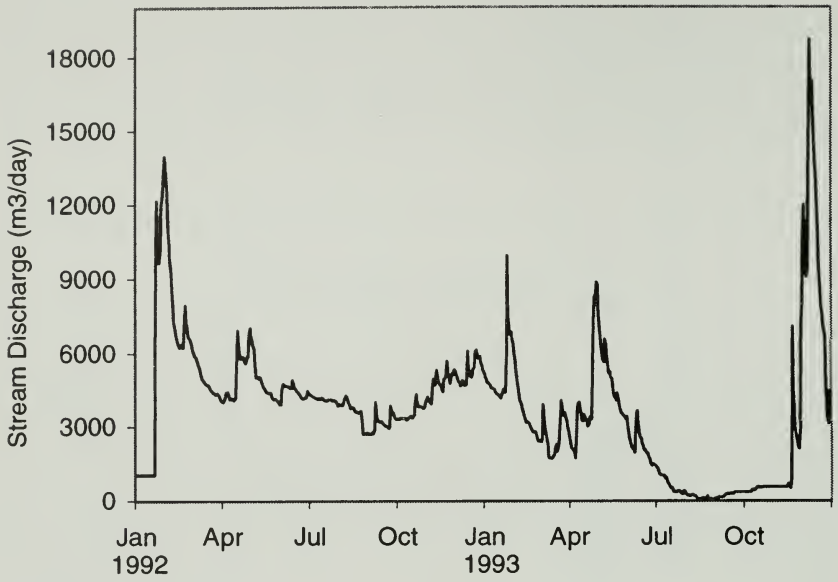

Figure 20. Stream discharge hydrograph at the weir on the West Twin Creek, 1992–1993.

stopped flowing in August and September 1993. Summer flow in 1992 was much greater than in 1993. Figure 21 shows the detailed hydrograph for the storm on 25 January 1993. Baseflow was about 4500 m^3/day. During the storm, stream discharge rose quickly to about 10 000 m^3/day and fell quickly to about half the peak discharge, or 7000 m^3/day. It then took several days to return to the previous discharge rate.

Figure 22 shows the hydrograph for a storm on 8 September 1992, during the dry season. Baseflow was about 2700 m^3/day. During the storm, discharge increased quickly to about 4000 m^3/day, and like the winter storm, it fell rapidly to about half the peak discharge. However, recovery to initial levels was slower, and elevated flows were still recorded two weeks after the storm.

Hydrograph shape is influenced by many factors including the slope and length of the upland surface, catchment shape, microtopography, permeability and moisture content of the soil, subsurface geology, vegetation cover, drainage density, channel characteristics, and storm patterns (Gordon et al. 1992). The West Twin Creek hydrograph has a rapid response and rises quickly. Such hydrographs are typical of steeply sloping watersheds (Swift et al. 1988). Short, wide catchments cause streams to rise faster than longer narrow ones because of short travel times. Catchment factors, however, may not always correlate well with hydrograph shape because they do not reflect orientation of the catchment to storm tracks that may move up, down, or across a stream. In West Twin Creek the storms typically move from west to east across the stream.

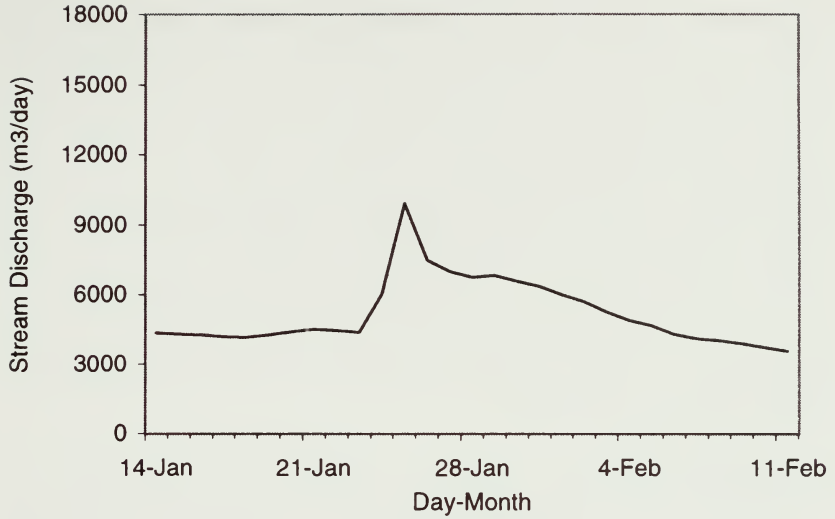

Figure 21. Hydrograph of one storm (25 January 1993) during the wet season, demonstrating a typical, high-volume stream discharge at the weir on West Twin Creek.

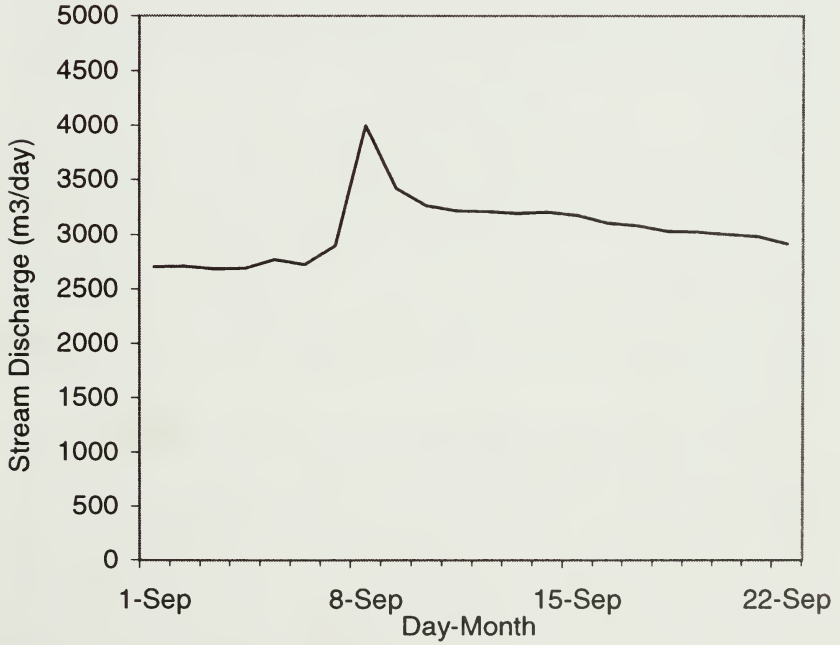

Figure 22. Hydrograph of one storm (8 September 1992) during the dry season, demonstrating a typical, low-volume stream discharge at the weir on West Twin Creek.

Vegetation cover and land use also strongly influence hydrograph shape (Gordon et al. 1992; Jones and Grant 1996; Wemple et al. 1996). Old-growth forests moderate peak discharge and reduce the effect of storms. Jones and Grant (1996) illustrated this in a study in the western Oregon Cascade Mountains, where forest removal and road construction changed the shape of the hydrograph. Complete clearcutting of the old-growth forest not only increased peak discharge, but also increased total storm volumes compared to the uncut forest. The suppression of evapotranspiration after removal of deep-rooted conifers led to increased subsurface moisture storage for many years after cutting, even though shallow soil moisture returned to pretreatment levels one year after harvesting. Watersheds with just 6% of their surface in roads had much higher peak storm discharges, but the hydrograph fell rapidly in contrast to that in clearcut watersheds.

Hydrologic Budget

A large amount of the precipitation falling on the West Twin Creek watershed leaves the watershed via the stream. From 1985 to 1993, discharge ranged from 54% to 89% (Table 9). This is typical for Northwest forests. Larson (1979) found discharge to range from 86% to 91% in nearby old-growth watersheds in the Hoh River Valley. In the Cascades near Seattle, he found discharge to range from 73% to 79% of precipitation in a watershed consisting of 10–20 and 40–50-year-old Douglas fir stands with some residual old growth (Larson 1973). In the eastern United States, Swift et al. (1988) also found that watersheds at Coweeta with steep slopes and shallow soils yielded 75% of rainfall as runoff.

Discharge was positively related to precipitation in the six years for which we had reliable data (Fig. 23, $r^2 = 0.72$, $p = 0.06$). Fog inputs, however, are not taken into account in Figure 23, and as mentioned previously, fog can contribute as much as 30% of the annual precipitation (Harr 1982). A data point showing discharge and precipitation from a small watershed in the Oregon Cascades (Sollins et al. 1980) is also included in Figure 23, and it falls very close to the regression line. At Hubbard Brook in New Hampshire, annual stream discharge was also highly correlated with annual precipitation (Likens et al. 1977).

Evapotranspiration also varied from year to year and ranged from 36 to 150 cm (Table 9) or 11% to 46% of precipitation. Figure 24 shows average monthly precipitation, potential evapotranspiration, and actual evapotranspiration from 1913 to 1965 for Forks, Washington, located 50 km to the northwest of our study site. There was a water surplus except for July and August, and there was very little water deficit. At Forks, actual evapotranspiration averaged 20% of precipitation from 1913 to 1965 (Phillips and Donaldson 1972) and was similar to evapotranspiration at the Quinault Ranger Station, which is located in an old-growth forest to the south of our site (Phillips and Donaldson 1972). At West Twin Creek, evapotranspiration calculated from precipitation and

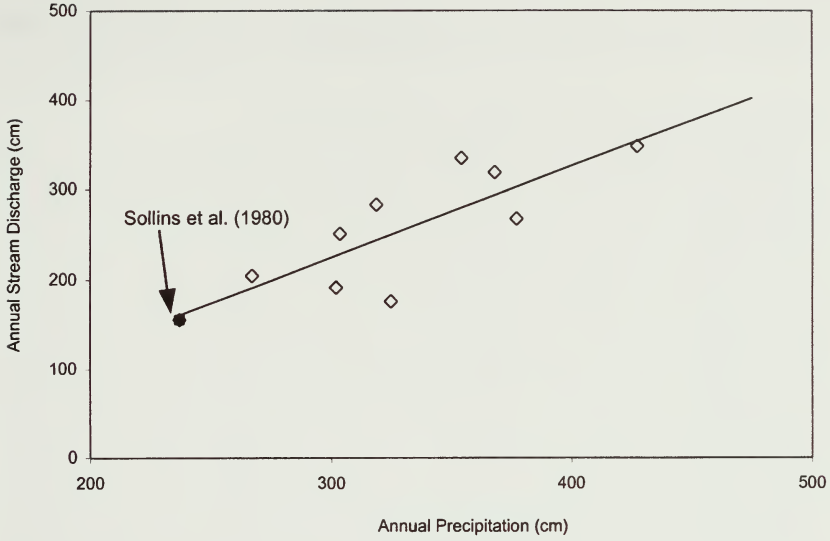

Figure 23. Annual stream discharge at the West Twin Creek weir and precipitation at the West Twin Creek from Water Year 85–86 to 93–94.

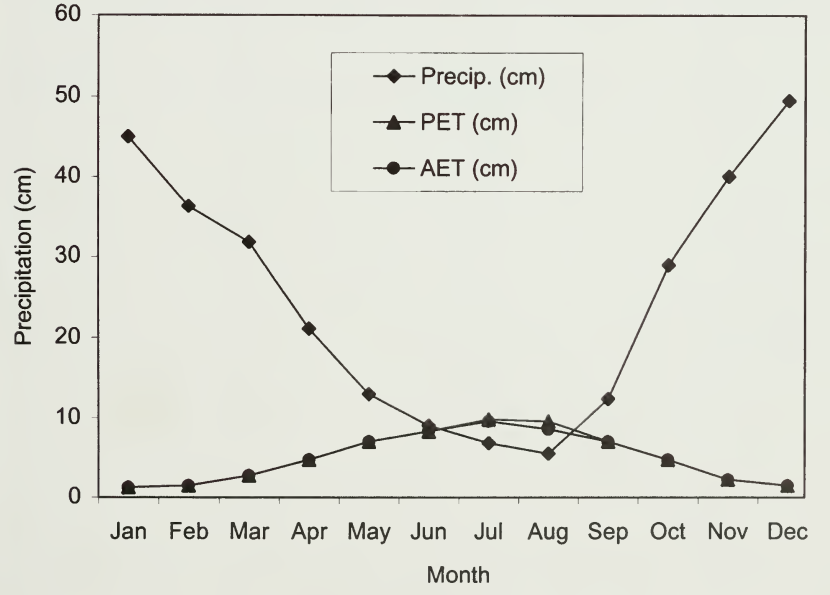

Figure 24. The relations among average monthly precipitation, potential evapotranspiration, and actual evapotranspiration (in cm) measured in Forks, Washington, 1913–1965.

stream discharge averaged 22.2% of precipitation (Table 9), which is similar to actual evapotranspiration calculated for Forks from 1913 to 1965.

Relations between Throughfall and Precipitation

Although precipitation varied from year to year, the percentage of annual precipitation reaching the forest floor in throughfall was remarkably constant, ranging from 56.4% to 63.1% from 1992 to 1994 and averaging 60.4% (Table 10). Similar percentages were observed by Fahey et al. (1988) and Blew et al. (1993) in drier Rocky Mountain forests. On a monthly basis, however, the percentage of throughfall to precipitation ranged widely from 0 to nearly 89%. Monthly throughfall is plotted against precipitation in Figure 25, revealing that as precipitation increased, throughfall also increased, but only to a monthly precipitation of about 50 cm. If monthly precipitation totals exceeded 50 cm, throughfall remained constant at about 30 cm. It is presumed that a large proportion of the water reaching the forest floor is via stemflow when precipitation is high, and during large storm events, stemflow was commonly observed.

Fahey et al. (1988) proposed that throughfall could be predicted using the following equation: throughfall = $0.634 \times \text{rainfall}^{1.181}$. Similarly, Blew et al. (1993) suggested that throughfall could be predicted using this equation: throughfall = $0.558 \times \text{precipitation}^{1.175}$. The range of their data, however, was for precipitation events <10 cm. These equations would vastly overpredict throughfall for monthly precipitation >10 cm in the West Twin Creek watershed.

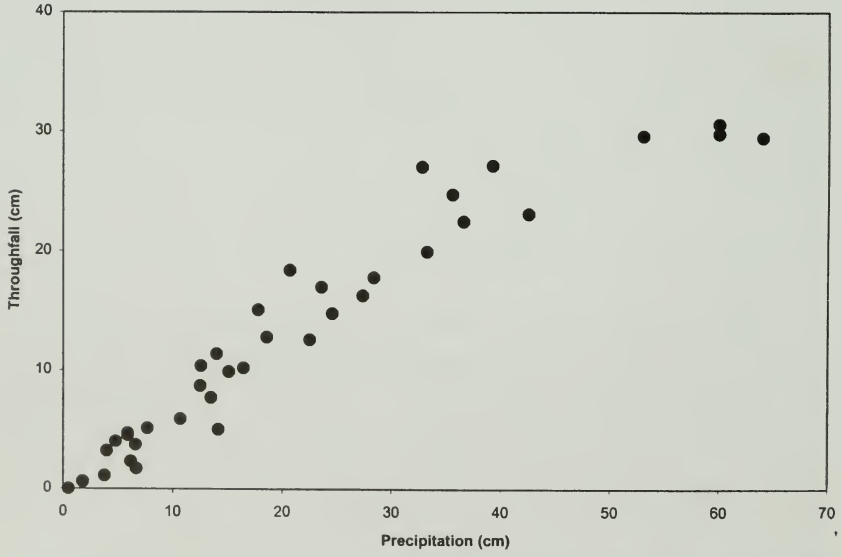

Figure 25. Relation between monthly throughfall and precipitation (in cm) in the West Twin Creek watershed.

Table 10. Estimated monthly precipitation and throughfall (in cm) and the percentage of precipitation recovered as throughfall in the West Twin Creek watershed, 1992–1994.

Date	Precipitation	Throughfall	Percent Throughfall
01-13-92	28.4	17.8	62.7
02-10-92	64.0	29.5	46.1
03-11-92	27.4	16.3	59.5
04-08-92	7.7	5.1	66.2
05-06-92	33.3	20.0	60.1
06-03-92	4.8	4.0	83.3
07-01-92	10.7	5.9	55.1
07-29-92	1.8	0.6	33.3
08-26-92	5.9	4.5	76.3
09-23-92	14.0	11.4	81.4
10-21-92	20.7	18.4	88.9
11-18-92	35.6	24.7	69.4
12-16-92	39.3	27.1	69.0
Total 1992	293.6	185.3	63.1
01-02-93	ND[a]	ND	ND
02-09-93	ND	22.7	ND
03-09-93	15.1	9.9	65.8
04-07-93	23.6	17.0	72.0
05-02-93	42.6	23.1	54.2
06-02-93	22.5	12.6	56.0
06-30-93	14.2	5.0	35.2
07-30-93	6.7	1.7	25.3
08-26-93	5.9	4.7	79.7
09-22-93	0.5	0.0	0.0
10-21-93	6.2	2.3	37.1
11-17-93	17.8	15.1	84.8
12-15-93	60.0	29.8	49.7
Total 1993	215.0	121.2	56.4
01-12-94	32.8	27.0	82.3
02-07-94	12.6	10.4	82.5
03-07-94	60.0	30.6	51.0
04-03-94	18.6	12.8	68.8
05-03-94	24.6	14.8	60.2
05-31-94	13.5	7.7	57.0
06-28-94	16.5	10.2	61.8
07-26-94	4.0	3.2	79.4
08-24-94	3.8	1.1	28.9
09-21-94	12.5	8.7	69.5
10-21-94	6.6	3.7	56.1
11-22-94	53.1	29.6	55.7
12-16-94	36.6	22.5	61.5
Total 1994	295.2	182.3	61.7

[a] ND = Not determined.

Chapter 6: Precipitation Chemistry along a Gradient Inland from the Pacific Ocean

The oceans serve as a source of aerosols necessary for cloud formation (Charlson et al. 1987) and precipitation. These aerosols contain several ions (Na, Cl, SO_4 and Mg) that are the main constituents of precipitation in areas that have a marine influence (Bormann et al. 1989; McDowell et al. 1990). In such areas, the relative amounts in precipitation of these and other solutes of sea salt origin remain quite constant and similar to amounts in seawater. For example, several studies have suggested that the ratio of Cl to Na in rainwater collected within several hundred kilometers of the ocean is the same as in seawater (Junge and Werby 1958; Vong 1989). Likewise, the marine contribution to SO_4 and Ca deposition can be estimated from their ratios with Na or Cl in sea salt (Junge 1963; Schwartz 1988).

Marine influences on precipitation chemistry are especially important in the northwest United States due to the dominant westerly flows that bring air masses inland from the Pacific Ocean. Several studies have investigated marine influences on the chemistry of atmosphere and precipitation along the Pacific coast of Washington state (Ludwick et al. 1977; Vong et al. 1985; Andreae et al. 1988; Quinn et al. 1988; Vong et al. 1988a and 1988b; Vong 1989; Edmonds et al. 1991). Studies of precipitation and atmospheric chemistry on the Olympic Peninsula generally have had one of three designs: investigations of on-shore precipitation that included analysis of back-trajectories of marine air masses (Ludwick et al. 1977; Vong et al. 1988a and 1988b; Quinn et al. 1988), estimation of chemical inputs to ecosystems using multiple sampling sites that were considered equivalent enough to be used as replicates (Vong 1989; Edmonds et al. 1991), and investigations of precipitation chemistry at several coastal sites to assess natural or background concentrations of pollutant constituents (Vong 1989).

Several studies have demonstrated the influence of oceans on the chemistry of precipitation falling on land masses and changes in precipitation chemistry across land masses. Junge (1958) and Junge and Werby (1958) reported on the distribution and sources of NH_4, Cl, Na, K, Ca, and SO_4 concentrations in precipitation over the continental United States. McColl (1982) and McColl et al. (1982) examined the relations between distance from the Pacific Ocean and chemical composition of wet and dry deposition. However, such studies involving spatial distribution of precipitation chemistry had resolutions of only tens to hundreds of kilometers. Also, they were concerned with sources and long range transport of atmospheric constituents across land masses and oceans rather than examination of changes in precipitation chemistry associated with ocean/continent interfaces. Little is known about the changes in precipitation chemistry across relatively short distances inland from the coast.

Our study assessed changes in precipitation chemistry at the Pacific Ocean/Olympic Peninsula interface on a finer spatial scale than has previously been reported. Objectives were to determine the effect of distance inland from the Pacific Ocean on concentrations of major cations and anions in bulk precipitation, to determine spatial and seasonal variation in deposition rates of major cations and anions to coastal temperate rain forests, and to examine oceanic influences on precipitation chemistry on the Pacific coast.

Methods

The precipitation transect was located in the Hoh River valley immediately west of the Olympic National Park boundary (32 km from the Pacific coast) and extended nearly to the coast (Fig. 1). Four sampling sites were located in clearcuts that were large enough to have no sampling interference from the forest canopy. Sampling sites were located 4, 13, 24, and 31 km from the ocean at elevations of 120, 100, 170, and 200 m, respectively. At each sampling location there were two bulk precipitation collectors and a Belfort standard raingauge. Each bulk collector consisted of a 20-cm diameter polyethylene funnel with a netted top to exclude debris. The precipitation drained from the funnel into a polyethylene bag. Samples were poured into triple-rinsed 1-L polyethylene bottles and transported to the Analytical Laboratory at the College of Forest Resources, University of Washington, within 48 h of collection and stored at 4°C. Samples used in this analysis were collected between February 1989 and September 1992. Samples were collected at two-week intervals through June of 1990 and then at four-week intervals thereafter. Sampling at the intermediate sites (13 and 24 km from ocean) was discontinued in October 1991.

Electrical conductivity, pH, and alkalinity (reported as HCO_3) were determined on non-filtered samples within a few days after arrival at the laboratory. Electrical conductivity was determined with a YSI Model 31 Conductivity Bridge (Yellow Springs Instrument Co., Yellow Springs, OH) and corrected to 25°C. pH was measured with a Radiometer PHM85 pH meter (Radiometer, Copenhagen, Denmark). Alkalinity was determined by titration (Rhoades 1982) to an end point of pH 5.

Remaining samples were filtered through Whatman GF/A filters (1.6 μm pore size), stored at 4°C, and analyzed within a month after arrival at the laboratory. Solutions were analyzed for Ca, Mg, K, and Na, using a IL 951 Atomic Absorption Analyzer (Instrumentation Laboratory, Wilmington, MA). Ammonium was measured by the automated phenate method (EPA Method 350.1) with a Technicon Autoanalyzer II (Technicon, Tarrytown, NY). Sulfate, Cl, NO_3, and PO_4 were determined with a Dionex 2010 Ion Chromatograph (AS4A and AG4A columns; Dionex, Sunnyvale, CA). Macro-Kjeldahl digests were done on all samples having sufficient volume and those digests were analyzed for N and P.

Data screening was a three step process based on the procedures of Vong (1989). First, samples were eliminated if field notes made at the time of sample collection indicated any obvious problems with sample quality. The next screening step excluded those samples with a charge balance error greater than 40%. Charge balance error was calculated as the difference between anions and cations divided by the sum of anions and cations multiplied by 100. Finally, samples were screened on the basis of the Cl:Na ratio. To determine amounts of SO_4 and Ca in precipitation that were in excess of that derived from sea salt (excess SO_4 and excess Ca) based on Na ratios in sea salt, we compared the Cl:Na ratio in precipitation to that found in sea salt. Precipitation collected within several hundred kilometers of the ocean generally has the same Cl:Na ratio as seawater (Junge 1963). Samples with Cl:Na molar ratios that deviated from the sea salt ratio of 1.17 (1.8 mass ratio) by of factor greater than 2 were excluded from the data set.

Concentrations of excess SO_4 and excess Ca were calculated based on the ratios of Na with SO_4 and Ca in sea salt such that:

$$\text{Excess } SO_4 = SO_4 - (\text{Na} \bullet 0.117) \text{ and}$$
$$\text{Excess Ca} = \text{Ca} - (\text{Na} \bullet 0.0434)$$

where Excess SO_4, SO_4, Excess Ca, Ca, and Na are ion concentrations in μeq/L. Correlation coefficients (Wilkinson 1990) were calculated to investigate relations between concentrations of measured chemical parameters and precipitation amount.

The effect of distance from the ocean on ion concentrations in precipitation was investigated using volume-weighted mean concentrations from each of the two collectors at each site. Volumes were based on precipitation depth in Belfort rain gauges at each site. Statistical analysis for the effect of distance from the ocean used one-way analysis of variance (ANOVA; Wilkinson 1990).

Mean deposition rates were calculated by totaling deposition for each of 13 four-week periods each year and then averaging equivalent periods from each year. Annual deposition rates at each site were determined by the 13 four-week means. This method of calculation was necessary due to missing data for several four-week periods that did not allow for calculation of annual totals for each individual year. Unfortunately, this calculation allowed only for an estimate of the average annual deposition and did not allow for any estimation of the variability associated with annual deposition. Wet deposition data from the Hoh Ranger Station (National Atmospheric Deposition Program/National Trends Network 1992) was used for comparison to the data collected in this study and as an extension of the transect to 41 km inland (Fig. 1).

Screening of data based on field notes and charge balance resulted in the removal of 36 of a total of 327 samples. An additional 41 samples were removed based on Cl:Na ratio screening. The remaining 250 samples were included in the analysis.

Results

Correlations Between Constituents

There were no significant positive correlations between precipitation depth and any chemical parameter, but there was a negative correlation with excess SO_4 (Table 11). Strong correlations were found between Cl, SO_4, Mg, and Na (Table 11). Electrical conductivity was most closely correlated with concentrations of those same ions (Table 11).

Correlations between TKN and TKP, PO_4, and NH_4 were significant (Table 11). These correlations appeared to be due to influential outliers. Outliers were also reflected in the high standard deviations associated with these variables (Table 12), especially at the sites 13 and 24 km from the ocean. These outliers may represent the input of organic contaminants to the precipitation collector during a few sampling periods. This suggests that the source of PO_4 and NH_4 on some occasions may have been from mineralization of organic material in the collector. As a result, the data presented here may be overestimates of the atmospheric deposition of these constituents.

Distance Effects

Significant effects ($p < 0.05$) of proximity to the Pacific Ocean were found for electrical conductivity and for concentrations of H, Cl, SO_4, Mg, Na, and excess Ca (non-sea-salt Ca; Table 12). (ANOVA indicated a significant distance effect for H ($p = 0.050$), but the conservative nature of Tukey's HSD to control experiment-wise error rate rather than comparison-wise error rate, failed to demonstrate significant differences between any of the group means.) Concentrations of Cl, SO_4, Mg, and Na were highest nearest to the coast. These higher ion concentrations were reflected in significantly higher electrical conductivity in precipitation falling closest to the coast. Concentrations of other ions did not differ significantly at different distances from the coast. However, NO_3, H, and K tended to be highest at the coastal site.

Annual deposition of Na, K, Mg, Ca, excess Ca, NO_3, and Cl tended to be lower at the collection site farthest from the ocean (Table 13). Sea salt Ca (total minus excess) deposition decreased from 0.64 at 4 km to 0.29 kg/ha/year at 31 km from the ocean. Even though total SO_4 deposition remained relatively unchanged as distance from the ocean increased (12.6 kg/ha/year at 4 km and 12.2 kg/ha/year at 31 km), the amounts attributable to sea salt and non-sea-salt sources tended to change. Excess SO_4 (non-sea-salt SO_4) deposition increased from 3.81 at 4 km to 4.59 kg/ha/year at 31 km from the ocean. Deposition of SO_4 of sea salt origin (total minus excess) decreased from 8.79 kg/ha/year at 4 km to 7.61 kg/ha/year at 31 km from the ocean.

Deposition of total P (0.21 kg/ha/year) and PO_4 (0.05 kg/ha/year) remained unchanged as distance from the ocean increased (Table 13). Nitrate (NO_3) in bulk deposition tended to decrease from 1.86 kg/ha/year at 4 km to 1.58 kg/ha/year at 31 km from the coast. Total Kjeldahl N deposition (TKN) also ap-

Table 11. Correlation coefficients of relations among electrical conductivity (EC), precipitation depth (PPT), and concentrations of chemical constituents of bulk deposition. Only correlation coefficients with significant probabilities ($p < 0.05$) are tabulated.

Analyte	EC	HCO_3	Cl	NO_3	PO_4	SO_4	Excess SO_4	H	NH_4	Ca	Excess Ca	K	Mg	Na	TKN[a]	TKP[b]	PPT
EC																	
HCO_3																	
Cl	0.95																
NO_3																	
PO_4		0.30															
SO_4	0.82		0.71	0.35													
Excess SO_4	0.34			0.32		0.79											
H		–0.66				0.26	0.27										
NH_4		0.43			0.82	0.27	0.32	–0.25									
Ca		0.53						–0.39									
Excess Ca		0.58						–0.41		0.99							
K							0.26										
Mg	0.87		0.87			0.65											
Na	0.92		0.94			0.67				0.25			0.85				
TKN		0.39			0.85	0.26	0.34		0.86			0.27					
TKP		0.34			0.89	0.26	0.29		0.85						0.86		
PPT							–0.30										

[a] TKN = Total Kjeldhal nitrogen.
[b] TKP = Total Kjeldhal phosphorus.

Table 12. Volume-weighted mean concentrations of ions and electrical conductivity (EC) in bulk precipitation along a transect inland from the Pacific Ocean, 1989–1992. Numbers in parentheses are standard deviations.

	Distance (km)				
Analyte	4	13	24	31	41[a]
EC (mS/m)	1.02a (0.03)	0.66ab (0.06)	0.47b (0.21)	0.51b (0.02)	0.60
			μeq/L[b]		
HCO_3	5.28a (0.77)	6.68a (0.51)	3.93a (1.47)	3.99a (0.18)	ND[c]
Cl	55.9a (1.7)	35.0b (0.6)	25.4b (9.9)	28.9b (0.3)	27.3
NO_3	0.95a (0.08)	0.56a (0.17)	0.42a (0.20)	0.49a (0.11)	1.21
PO_4	0.06a (0.08)	1.08a (1.46)	0.02a (0.02)	0.02a (0.12)	ND
SO_4	9.11a (0.34)	6.23ab (0.94)	4.40b (1.73)	4.92b (0.47)	5.81
Excess SO_4	2.81a (0.28)	1.88a (0.65)	1.37a (0.38)	1.58a (0.43)	ND
H	5.07a (0.32)	3.01a (0.35)	2.75a (1.07)	3.15a (0.12)	4.02
NH_4	0.08a (0.02)	1.85a (2.32)	0.43a (0.10)	0.03a (0.02)	0.98
Ca	5.51ab (0.01)	5.89a (0.78)	3.93ab (1.05)	3.32b (0.15)	1.84
Excess Ca	4.16a (0.08)	4.54a (0.61)	3.19ab (0.77)	1.55b (0.11)	ND
K	2.95a (1.93)	1.25a (0.28)	1.70a (0.36)	1.12a (0.17)	0.5
Mg	7.38a (0.10)	3.51b (0.79)	2.22b (0.70)	2.55b (0.17)	5.25
Na	53.9a (0.53)	38.5ab (1.00)	26.3b (11.6)	28.8b (0.26)	22.9

[a] Data from Hoh Ranger Station (National Atmospheric Deposition Program/National Trends Network 1992).

[b] Numbers followed by the same letter within a row are not significantly different ($p < 0.05$).

[c] ND = Not determined.

Table 13. Average of annual deposition rates (kg/ha/yr) at two distances from the Pacific Ocean, 1989–1992.

	Distance (km)	
Analyte	4.00	31.00
Cl	57.20	49.30
NO_3	1.86	1.58
PO_4	0.05	0.05
SO_4	12.60	12.20
Non-sea-salt SO_4	3.81	4.59
Sea salt SO_4	8.79	7.61
H	0.16	0.19
NH_4	0.04	0.04
Ca	2.86	2.14
Non-sea-salt Ca	2.22	1.85
Sea salt Ca	0.64	0.29
K	3.03	2.23
Mg	2.41	0.88
Na	36.10	31.20
TKN	3.39	3.08
TKP	0.21	0.21
Total N	3.42	3.11
Precipitation (cm)	278.00	351.00

peared to decrease as distance from the ocean increased (3.39 kg/ha/year at 4 km and 3.08 kg/ha/year at 31 km).

Annual precipitation increased from 278 cm at 4 km to 351 cm at 13 km from the coast and remained constant to 41 km inland (Fig. 26).

Annual and Seasonal Patterns of Deposition

Precipitation was highest in the late autumn and winter months and lowest during the summer (Fig. 27). The rain season in the Hoh River valley begins in early November and continues through April. Deposition rates of many chemical constituents, particularly NO_3 and H, had seasonal patterns similar to that of precipitation (Fig. 27). Seasonal patterns of deposition rates for K and excess Ca were not as apparent.

Discussion

Volume-weighted mean pH of bulk precipitation was 5.3 at 4 km, 5.5 at 13 km, 5.6 at 24 km, and 5.5 at 31 km from the ocean. Precipitation pH reported

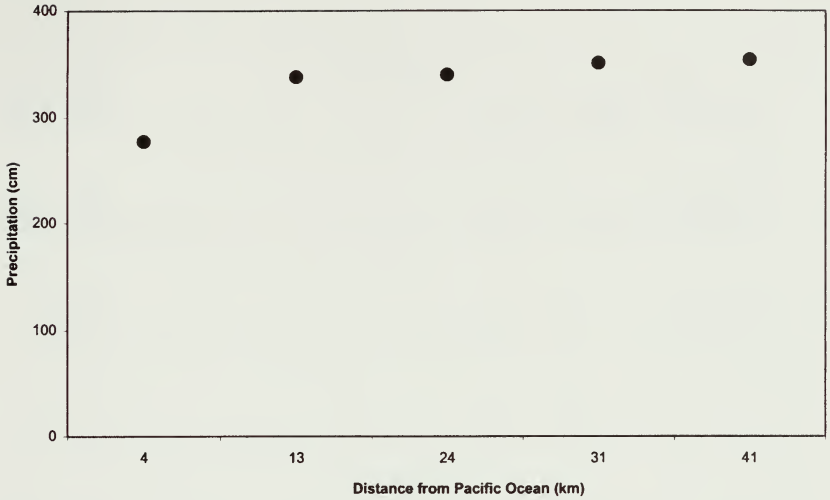

Figure 26. Mean annual precipitation at each of the collection sites and at the Hoh Ranger Station (National Atmospheric Deposition Program/National Trends Network 1992), 1989–1992.

in this study (5.3 to 5.6) was within the range reported for other sites along the Pacific Northwest coast and at remote sites elsewhere in the world (Vong 1989). Farther inland, at sites experiencing anthropogenic influences on atmospheric chemistry, lower precipitation pH has been reported. Vong et al. (1985) reported volume-weighted pH of 4.41 in the metropolitan Seattle area (approximately 140 km east of the Hoh River valley).

We found that precipitation chemistry in the Hoh River valley was dominated by sea salt ions, Na and Cl, and was consistent with that previously reported for the Hoh River valley by Edmonds et al. (1991). Mean electrical conductivity of precipitation collected at each site ranged from 0.47 to 1.02 mS/m (Table 12). The correlations among the major sea salt ions (Cl, SO_4, Mg, and Na), and between these ions and electrical conductivity, are indicative of the important role of oceans on the composition and ionic strength of bulk precipitation in coastal areas. With the exception of Mg and Ca, the relative contribution of sea salt ions to precipitation chemistry (Fig. 28) remained constant along the length of the transect even though concentrations of most constituents decreased as distance from the ocean increased (Table 12). Much of the change in precipitation chemistry occurred between the sampling sites at 4 km and at 13 km. These changes in precipitation chemistry may have been dilution effects resulting from increased precipitation rates farther inland along the transect. The greatest increase in rainfall also occurred between the sites at 4 km and 13 km from the ocean (Fig. 26).

McColl et al. (1982) demonstrated a decrease in the concentration of Cl with increasing distance inland from the Pacific coast in northern California.

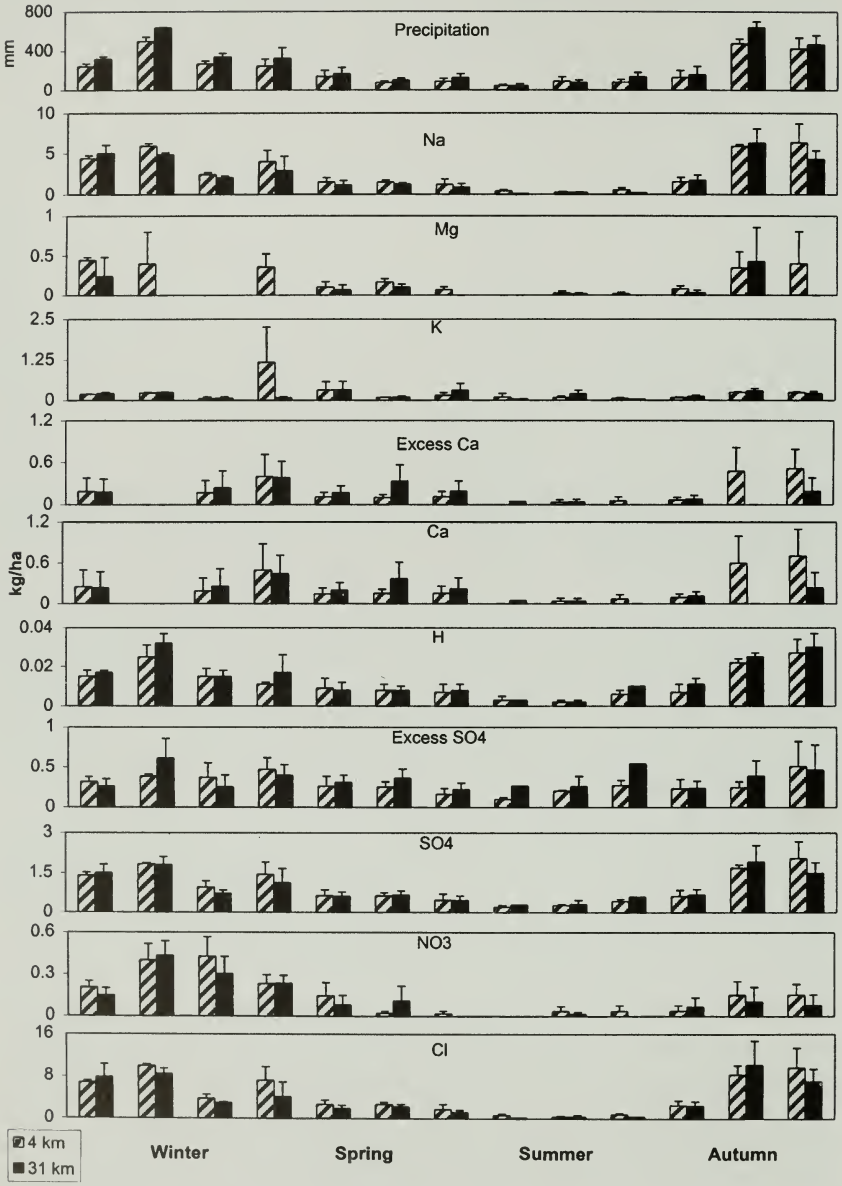

Figure 27. Seasonal deposition rates of chemical constituents of rainfall (kg/ha) and precipitation depth (mm) at each end of transect, 1989–1992. Bars represent deposition during each 4-week collection period averaged across similar time periods during 1989–1992. Error bars are standard errors. Excess Ca and Excess SO_4 are Ca and SO_4 in excess of those expected from sea salt.

In that study, Cl concentration decreased rapidly between 0 and 80 km inland and decreased more slowly farther inland. The results of our study also indicate that most ion concentrations, including Cl, decreased as distance from the coast increased. However, the ion concentrations tended to stabilize closer to the coast (13 to 24 km inland) than was reported for Cl (80 km inland) by McColl et al. (1982). Also, McColl (1982) predicted, using Cl ratios, that K and Ca would stabilize 20 to 30 km inland and Na and Mg at 80 to 100 km inland at the northern California site.

After sea salt ions (Cl, SO_4, Mg, Na), the main chemical constituents of precipitation were excess Ca and excess SO_4. Excess Ca concentrations found in bulk precipitation in our study were similar to those reported at other Pacific Northwest sites (Vong 1989). The presence of excess Ca is indicative of terrestrial influences on precipitation chemistry. The source of excess Ca in precipitation was most likely wind-blown dust formed from crustal material. More of this material would be collected in bulk deposition collectors used in our study than in the wet deposition collectors used in other studies, because of the inclusion of dryfall in bulk deposition collectors. The high concentration and deposition rates of excess Ca at some of the sites in this study was most likely due to their proximity to gravel roads. This effect may have been greatest at the 4 km site because this site was within 300 m of a gravel road. The presence of Mg in local bedrock (Larson 1979) suggests that some of the Mg deposited, like Ca, may have been from terrestrial sources. This may ac-

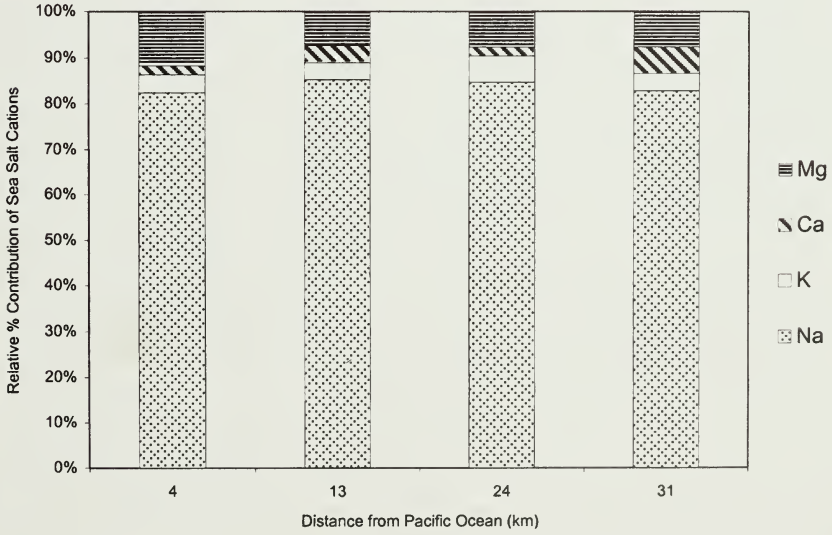

Figure 28. Relative contribution of ions to total sea salt cations in precipitation at four distances along a transect from the Pacific Ocean to Olympic National Park, February 1989–September 1992.

count for the much greater concentration and annual deposition of Mg at 4 km than at 31 km and, as previously noted, the higher relative abundance of Mg compared to other sea salt ions in precipitation collected at the 4 km site (Fig. 28).

Using the Junge equation (Junge 1963) and known, fine SO_4 aerosol concentrations (Schwartz 1988), Vong (1989) determined that background SO_4 concentrations in precipitation should be in the range of 3 to 16 μeq/L. Mean SO_4 concentrations in our study were within this range (Fig. 29). However, excess SO_4 concentrations were lower than those reported for other sites in the Pacific Northwest (Vong 1989). In remote coastal areas, the source of this excess SO_4 is the marine emission of $(CH_3)_2S$ (dimethylsulfide or DMS) which is excreted by certain marine phytoplankton (Andreae and Raemdonck 1983). DMS reacts in the atmosphere to form SO_4 and methane sulfonate.

It is important to note that excess SO_4 concentration was the only measured parameter that correlated with precipitation depth. There are several possible explanations for this negative correlation. It is possible that increased concentrations of SO_4 in the atmosphere coincided with the dry season. This may reflect the seasonal production and emission of DMS from the ocean. Bates et al. (1987) reported higher concentrations of DMS in temperate oceans during the summer. Also, Bates et al. (1987) calculated greater flux rates of DMS from ocean to atmosphere during the summer than in the winter in temperate oceans. This seasonal change corresponds to lower rainfall amounts during the summer months in our study (Fig. 27).

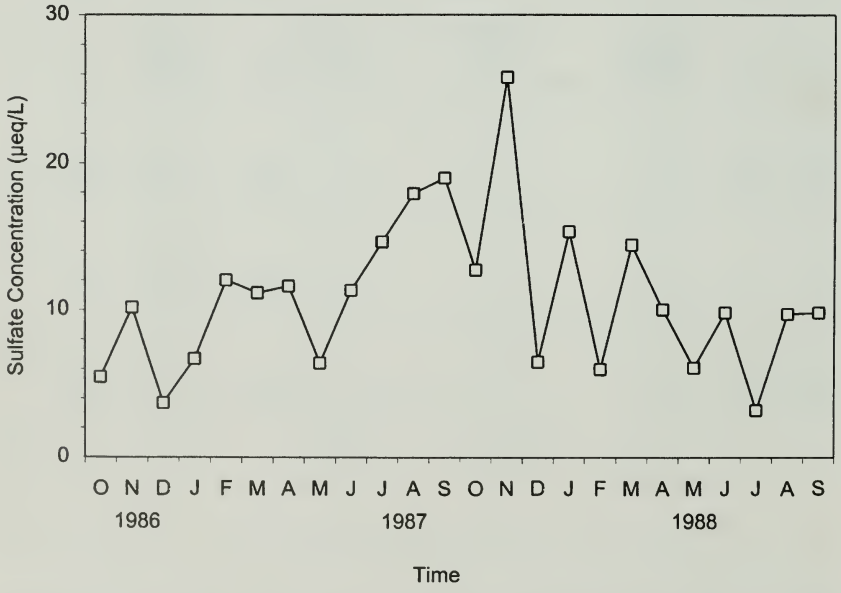

Figure 29. Average monthly SO_4 concentrations in precipitation near West Twin Creek from October 1986–September 1988.

The correlation between excess SO_4 and rainfall depth may be related to the role of non-sea-salt SO_4 as cloud condensation nuclei (CCN). This non-sea-salt SO_4 aerosol has been reported to be the principal nuclei for cloud condensation in the marine atmosphere (Charlson et al. 1987). Warneck (1988) suggested that in clouds, essentially all nuclei having a radius greater than 0.2 μm would become condensation nuclei. If all available nuclei have been engaged and assuming CCN density to be constant, then the rate of condensation of water vapor to the nuclei would control the amount of H_2O condensed and subsequently deposited. The correlation between excess SO_4 and rainfall depth may simply reflect greater rates of water vapor condensation on nuclei, resulting in greater rainfall. This would result in decreased excess SO_4 concentrations associated with increased rainfall depth. During the summer this effect would be amplified by the greater CCN density in the atmosphere, as suggested by the calculated flux rates of DMS from ocean to atmosphere reported by Bates et al. (1987). If the suggestion that, in clouds, all CCN have undergone nucleation (Warneck 1988) is correct, then there would be a potential for greater SO_4 concentration in precipitation during the summer, even with the reduced potential for high rates of water vapor condensation.

Another explanation for the negative correlation is the possibility that a large part of that SO_4 was deposited independently of precipitation in the form of dryfall. Dry deposition of SO_4 was reported to be most important at drier sites (Lindberg 1992), and it may be inferred to have greater impact during the dry season in this forest.

Sulfate deposition (12.2 and 12.6 kg/ha/year) was similar to that reported by Larson (1979) in the Hoh River valley for the water year 1976–77 (11 kg/ha/year). The deposition rates reported by Larson (1979) and in our study are greater than those measured in wet deposition between 1988 and 1991 at the Hoh Ranger Station (8.7 kg/ha/year; National Atmospheric Deposition Program/National Trends Network 1992). This difference may represent the addition of SO_4 as dry deposition in the bulk deposition collectors used in this study and by Larson (1979), but excluded by the wet deposition collectors used at the Hoh Ranger Station.

The SO_4 deposition rates determined in this study were also similar to those reported for Washington forests in the Integrated Forest Study (IFS), but were lower than SO_4 deposition in IFS forests in the eastern United States (Lindberg 1992). Vong et al. (1988a) suggested that on the Olympic Peninsula, precipitation chemistry showed little influence from anthropogenic sources, especially during periods of on-shore air flow.

Total N deposition in bulk precipitation found in our study (3.11 to 3.42 kg/ha/year) was less than that reported for Washington forests in IFS. Lovett (1992) reported total N deposition of 4.76 kg/ha/year to a forest approximately 180 km east of the Hoh River valley. That IFS study used wet and dry deposition estimates to estimate total N deposition. The dry deposition estimate in that study included deposition of coarse and fine particulates and deposition of

HNO_3 vapor. Because total N deposition in our study was based on bulk deposition alone, some dry deposition components would have been included by sedimentation. However, no effort was made in our study to actively determine total particulate impact or vapor input.

Chapter 7: Solution Chemistry in the West Twin Creek Watershed

There has been a great deal of interest in nutrient retention mechanisms in forest ecosystems (Likens et al. 1970; Vitousek and Reiners 1975; Likens et al. 1977; Vitousek et al. 1979; Sollins et al. 1980; Johnson and Lindberg 1992; Van Miegroet et al. 1992). The study of element inputs and losses and internal transformations in solutions as they flow through small watersheds is important in understanding nutrient retention mechanisms. Forest canopies strongly modify precipitation chemistry (Tarrant et al. 1968; Feller 1977; Larson 1979; Sollins et al. 1980; Binkley et al. 1982; Cronan and Reiners 1983; Parker 1983; Lindberg et al. 1986; Edmonds et al. 1991; Lindberg 1992; Lovett 1992). After leaving the canopy, water flowing through the forest floor and mineral soil is further chemically modified so that by the time it reaches a stream, its ionic composition may be vastly different from that of precipitation (Feller 1977; Likens et al. 1977; Binkley et al. 1982; Martin and Harr 1988; Sollins et al. 1980).

Vitousek and Reiners (1975) related nutrient losses, especially for N, to ecosystem succession. In undisturbed ecosystems, they hypothesized that nutrient inputs equal outputs. Immediately after a disturbance, losses of limiting elements, such as N, exceed inputs. During later succession, N losses are low because biomass is accumulating. As the system approaches steady state, biomass accumulation ceases and inputs equal outputs again. Vitousek and Reiners (1975) noted that mature undisturbed watersheds in New Hampshire had relatively high, constant stream NO_3 outputs, but that successional ecosystems had lower stream NO_3 concentrations with pronounced seasonal cycles involving growing season minima. From this evidence, they concluded that plant uptake regulated N losses from these ecosystems. They also suggested that K, Mg, and Ca, which are essential but not limiting plant nutrients, were more effectively retained in successional than in mature ecosystems. Mobile elements such as Na and Cl were not retained.

Unlike undisturbed, mature ecosystems in New Hampshire (Likens et al. 1970; Vitousek and Reiners 1975), pristine, old-growth Douglas fir ecosystems in Oregon, had low stream NO_3 concentrations (Sollins et al. 1980; Martin and Harr 1988). Total biomass was still accumulating despite the advanced age of these ecosystems (Sollins et al. 1980). Old-growth forests in watersheds in the Pacific Northwest may not be in steady state because disturbances caused by fire, wind, insects, and diseases are common. Disturbance patch size may also influence nutrient retention in these ecosystems (Vitousek and Reiners 1975).

Van Miegroet et al. (1992) recently further examined NO_3 retention mechanisms in forest ecosystems and determined that the degree of retention depended on relative N source and sink strengths. Sink strengths are determined both by

natural ecosystem characteristics (e.g., age and type of vegetation, soil age and organic matter accumulation), and anthropogenic influences (e.g., management practices and pollution). Ecosystems residing on more recently developed soils (e.g., after volcanic ash deposition or glaciation) are still in an active stage of C and N accumulation. Nitrogen retention should be at or near maximum in these ecosystems. On the other hand, ecosystems that have accumulated large amounts of C and N, because of age, site disturbance, or N fixation, usually have large NO_3 leaching losses. Cole et al. (1992) suggested that sites with a narrow soil C:N ratio (<20:1) and with a total soil N content >5000 kg/ha appear to be susceptible to nitrification and NO_3 leaching.

The chemistry of solutions flowing through the West Twin Creek watershed is strongly related to ecosystem function. Thus, the objectives of this study were to determine concentrations of major cations and anions and dissolved organic C in bulk precipitation, throughfall, stemflow, and soil solutions, and nutrient retention mechanisms in this pristine watershed.

Methods

Sample Collection

Precipitation. Precipitation in the Hoh River valley was collected bi-weekly from October 1984 through September 1993 in bulk precipitation collectors. Precipitation was collected in an autoclavable polyethylene bag. From 1984 to 1987, four collectors, two at each of two sites, were located at elevations from 229 to 640 m in clearcuts among a 16 km^2 area on Washington State Department of Natural Resources land adjacent to Olympic National Park and as close as 2 km west of the watershed boundary (Fig. 1). Since there was little variability with elevation among samplers, two collectors at only one site were used from 1988 to 1993. Each collector was a 20-cm diameter polyethylene funnel with a netted top to exclude debris. If precipitation fell as snow, it was collected in 10-L snow buckets lined with acid-rinsed linear polyethylene (LPE) bags. Samples were transported in triple-rinsed 1-L polyethylene bottles in a cooler to the Analytical Laboratory at the College of Forest Resources, University of Washington, within 48 hours of collection and stored at 4°C.

Throughfall, Stemflow, and Soil Solution. Plots for studying throughfall, stemflow, and soil solution analyses were established in the West Twin Creek watershed in areas representing the two major vegetation zones of the basin: at the base (180 m elevation) and top (800 m elevation) of the watershed. Sampling began October 1986 and was conducted through December 1993 in the plot at the base of the watershed, but only through September 1988 in the plot at the top of the watershed. Samples were collected biweekly.

Throughfall and stemflow were collected around four tree species. The trees were of different diameters and ages; at lower elevation, two western redcedar (40 and 112 cm dbh), two Douglas fir (145 and 247 cm dbh), and two western hemlock (49 and 77 cm dbh) trees, and at higher elevation, two western hem-

lock (73 and 81 cm dbh) and two Pacific silver fir (59 and 141 cm dbh) trees were monitored. The trees were in a 2.2-ha area in the upper watershed and a 3.3-ha area in the lower watershed.

Throughfall collectors were constructed of 10-cm PVC rain gutters extending from the bole of a sampling tree to the edge of the crown. One collector per tree was used; they were placed such that throughfall would be collected from that tree only. Collectors were lined with acid-washed and triple-rinsed linear polyethylene and covered with 2-mm nylon chiffon mesh to keep out litterfall. Stemflow collars were made from 2.5-cm diameter Tygon tubing that was halved lengthwise and fastened to the lower boles of the trees, encircling the stem. Throughfall and stemflow were collected in 120-L polyethylene containers lined with polyethylene bags. Volumes were determined in the field and a 1-L sample from each collector was returned to the laboratory for chemical analysis.

Soil solutions were collected using tension lysimetry (Cole 1968). Sixty-millimeter diameter, fritted glass Buchner funnels were modified by cutting off the funnel 1 cm above the fritted-glass surface and bending the stem at right angles. The modified funnels were placed beneath the forest floor at 5 cm and 40 cm below the top of mineral soil. Tension of 0.01 MPa was applied using a 1-m hanging water column. In the lower watershed, at the same locations as the throughfall and stemflow collectors, three replicate samples for each soil horizon were taken. No lysimeter samples were collected at the upper watershed plot. Soil solutions were collected in 10-L polyethylene bottles, and volumes were recorded in the field. If individual sample volumes were insufficient for analysis, samples were composited by horizon. Soil solutions were sampled monthly, except during dry periods, and they were handled in the same manner as other solutions. Also, in the same locations as the throughfall and stemflow collectors in upper and lower watershed plots, soil samples of the O horizon, 0 to 5 cm depth (BA horizon) and 6 to 40 cm depth (Bw horizon) of the mineral soil were obtained. Samples were placed in a cooler and transported to the Analytical Laboratory at the College of Forest Resources, University of Washington, where they were air dried.

Solution Chemical Analysis

Specific conductance, pH and alkalinity were determined on non-filtered samples within a few days after arrival at the laboratory. Specific conductance was determined with a YSI Model 31 Conductivity Bridge (Yellow Springs Instrument Co., Yellow Springs, OH) and pH with a Radiometer PHM 85 pH meter (Radiometer, Copenhagen, Denmark). Alkalinity was determined by titration (Rhoades 1982) to an end point of pH 5.

After these measurements, the water samples were filtered through a Whatman GF/A filter, stored at 4°C and analyzed within a month after arrival at the laboratory. Solutions were analyzed for Ca, Mg, K, and Na using an IL 951 Atomic Absorption Analyzer (Instrumentation Laboratory, Wilmington,

MA). Ammonium and NO_3 were determined with a Technicon Autoanalyzer II (Technicon, Tarrytown, NY). Sulfate, Cl, and PO_4 were determined with a Dionex 2100 Ion Chromatograph (Dionex, Sunnyvale, CA). Dissolved organic carbon (DOC) was determined using persulfate oxidation at 100 °C and an OI Model 700 Organic Carbon Analyzer (OI Corporation, College Station, TX). Precipitation, stemflow, throughfall, and soil solution quantities were used to determine volume-weighted average concentrations.

Soil Chemistry Analysis

Available N (NH_4 and NO_3) was determined on moist field samples immediately upon arrival at the laboratory using 1 M KCl extraction (Keeney and Nelson 1982) and a Technicon Autoanalyzer II (Technicon, Tarrytown, NY). Samples were then air-dried for other analyses; moisture correction was applied by drying a subsample at 105 °C. Total C was determined using a Leco C analyzer (Leco Corp., St. Joseph, MI). Total N was determined using an H_2SO_4/$LiSO_4$/H_2O_2/Se digestion (Parkinson and Allen 1975) and a Technicon Atomic Absorption Analyzer II (Technicon, Tarrytown, NY). Phosphorus (Bray No. 1) was determined using the method of (Jackson 1958) and a Technicon Autoanalyzer II (Technicon, Tarrytown, NY). Sodium, K, Ca, Mg, and Al were determined with 1 M NH_4Cl extraction and an IL 951 Atomic Absorption Analyzer (Instrumentation Laboratory, Wilmington, MA). Cation exchange capacity was determined by extraction with 1 M NH_4Cl and a saturation wash with 1 M KCl (Oak Ridge National Laboratory, Oak Ridge, TN, EPRI Forest Response Program Protocol). A 1:1 soil:H_20 paste was used for determination of pH with a Radiometer PHM 85 pH meter.

Quality Control (QC)

Sampling and analysis of water samples from precipitation, throughfall, stemflow, and the stream followed QA/QC procedures outlined by Environmental Protection Agency (EPA). Field samples were collected in acid-washed and triple-rinsed containers, labeled, placed in coolers as soon as possible, and transported to the Analytical Laboratory at the University of Washington within 48 hours of collection and stored at 4 °C. Samples were generally analyzed for all constituents within 4 weeks of collection. Standard laboratory protocol included replications and 10% National Bureau of Standards rain-water standards and blanks during chemical analysis.

Results and Discussion

Precipitation Chemistry

Precipitation pH averaged 5.3 (Table 14), which is typical for relatively pristine sites in the western United States (Larson 1979; Martin and Harr 1988; Bormann et al. 1989). Slightly lower pH (4.5–4.8) have been reported in sites near Vancouver, British Columbia (Feller 1977; Binkley et al. 1982) and Se-

Table 14. Average pH, electrical conductivity, and dissolved organic carbon (DOC) of precipitation, stemflow and throughfall of Douglas fir, western hemlock, western redcedar, and Pacific silver fir, and soil solutions in the West Twin Creek watershed October 1986-September 1988. Numbers in parentheses are standard deviations.

	pH	Electrical conductivity[a]	DOC[b]
		mS/m	mg/L
Precipitation	5.3a	1.15a	1.5a
	(0.3)	(0.63)	(1.1)
Throughfall			
Lower watershed			
Douglas-fir	5.1a	2.24ab	10.5a
	(0.2)	(0.13)	(17.9)
western hemlock	5.1a	1.82ab	7.5ab
	(0.2)	(0.06)	(5.9)
western redcedar	5.1a	2.11ab	7.1ab
	(0.2)	(1.97)	(5.1)
Upper watershed			
Pacific silver fir	4.9ab	2.76ab	15.6b
	(0.2)	(1.28)	(6.6)
western hemlock	5.1a	1.67a	8.5b
	(0.2)	(0.79)	(4.7)
Stemflow			
Lower watershed			
Douglas-fir	4.1cd	7.02c	25.5c
	(0.4)	(2.68)	(9.3)
western hemlock	4.5bc	4.03bc	26.5c
	(0.4)	(1.71)	(20.4)
western redcedar	4.0d	5.25bc	26.0c
	(0.2)	(1.78)	(12.2)
Upper watershed			
Pacific silver fir	4.5bc	9.80c	33.8c
	(0.4)	(5.20)	(25.9)
western hemlock	4.4cd	4.56bc	26.1c
	(0.3)	(2.42)	(9.9)
Soil solution (lower watershed)			
Forest floor	5.7ae	1.78a	10.8b
	(0.1)	(0.82)	(1.1)
A	5.8e	1.53a	9.0b
	(0.1)	(0.67)	(4.6)
B	6.2f	2.6ab	2.9a
	(0.1)	(0.65)	(1.1)

[a] Numbers followed by a different letter are significantly different ($p = 0.5$).
[b] DOC determined only in 1987-1988.

attle, Washington (Van Miegroet 1986), probably because of anthropogenic inputs. Electrical conductivity (EC) of precipitation was low (1.15 mS/m; Table 14), which suggests low concentrations of ions in the precipitation.

Concentrations of total cations and total inorganic anions in precipitation were relatively even, with only a small anion deficit (Table 15). Cations minus anions yielded a deficit of 8.4 $\mu mol_c/L$ (Table 15), and the cation:anion ratio was 1.10, both indicating that organic anions were fewer. This is supported by the low concentration of dissolved organic carbon (DOC) in precipitation (1.5 mg/L; Table 14).

Sodium, at an average concentration of 54.3 μeq/L (Table 15), was the major cation in precipitation followed by Ca, Mg, and K. Reflecting the proximity of the site to the ocean, the high Na concentration is 2 to 5 times higher than those reported from inland sites (Feller 1977; Sollins et al. 1980; Wolfe 1988). High Na concentrations in precipitation have been found in other studies near salt water bodies (Attiwill 1966; Carlisle et al. 1966; Larson 1979; Bormann et al. 1989). At sites in the Appalachian and Cascade Ranges, located more than 50 km from an ocean, cation concentrations rank Ca > Na > K > Mg (Henderson et al. 1978). Likewise, chloride was the dominant anion in precipitation (57.6 μeq/L) because of proximity to the ocean. Chloride concentrations were 1.5 to 4 times higher than those reported from sites farther inland (Feller 1977; Sollins et al. 1980; Wolfe 1988) but were similar to those at other coastal sites (Larson 1979; Bormann et al. 1989). Anion concentrations ranked $Cl > HCO_3 > SO_4 > NO_3 > PO_4$ (Table 15).

Sulfate concentration averaged 11.2 μeq/L, of which 47% of the SO_4 was non-sea-salt SO_4 (NSS; Edmonds et al. 1991). NSS SO_4 is derived from oxidation of dimethyl sulfide produced by marine algae (Charlson et al. 1987), dust, and wood smoke from slash burning. The SO_4 concentration in precipitation was lower than that in precipitation in Puget Sound (Wolfe 1988) and in southwestern British Columbia (Feller 1977) where anthropogenic inputs could be expected, and much lower than those observed in the eastern United States (Vitousek and Reiners 1975; Likens et al. 1977; Johnson and Lindberg 1992). However, SO_4 concentration in precipitation was similar to that observed in the Oregon Cascades, (Sollins et al. 1980) and at coastal sites (Larson 1979; Vong and Larson 1983; Bormann et al. 1989). From 1986 to 1988, highest concentrations of SO_4 were observed in spring, late summer, and fall (Fig. 29).

In the Hoh River valley, concentrations of NH_4 in precipitation were low (0.4 μeq/L; Table 15). Higher NH_4 concentrations in precipitation have been found at study sites in and near regions of human development and anthropogenic sources in Puget Sound (Wolfe 1988) and southwestern British Columbia (Feller 1977). Nitrate concentration in precipitation (1.4 μeq/L; Table 15) was higher than that of NH_4. Similar to the pattern of NH_4 found in precipitation, these NO_3 concentrations are comparable to those observed in precipitation in the Oregon Cascades (Sollins et al. 1980), coastal sites (Bormann et al. 1989), lower than NO_3 concentrations in precipitation in Puget Sound (Wolfe 1988),

Table 15. Average concentrations (μeq/L) of chemical elements in precipitation, throughfall, stemflow, and soil solution in the West Twin Creek watershed from October 1986 through September 1988. Standard deviations are shown in parentheses.

		Cations[a]						Anions[a]					Anions
	n[b]	H	NH_4	Ca	K	Mg	Na	HCO_3	NO_3	Cl	SO4	PO_4	(umol$_c$/L)
Precipitation	39[c]	5.5a (6.6)	0.4a (0.7)	6.6a (5.8)	2.8a (0.9)	10.6a (1.5)	54.3a (28.9)	8.0a (5.1)	1.4a (0.9)	57.6a (37.8)	11.2a (8.4)	0.2a (0.4)	8.4
Throughfall	401	8.1ab (9.3)	0.6a (1.1)	11.0a (17.6)	25.1ab (30.1)	19.6a (9.8)	76.5b (41.0)	5.4a (8.8)	0.1b (0.3)	74.7a (65.2)	11.6a (7.8)	4.0a (5.4)	56.1
Stemflow	264	54.4ab (43.8)	2.7ab (6.4)	20.4ab (84.2)	119.6b (110.7)	46.2a (49.6)	118.0a (68.9)	1.5ab (15.6)	0.1a (0.3)	160.2a (121.4)	14.6ab (13.4)	20.8 (31.2)	225.5
Soil solution													
Forest floor	9	2.1a (0.7)	3.1a (5.6)	65.6b (25.8)	33.7b (12.0)	45.0a (41.6)	73.6a (22.1)	22.1c (2.8)	0.1b (0.02)	113.6a (99.6)	11.0a (13.2)	2.0a (1.2)	75.3
BA horizon	9	1.5a (0.5)	0.6a (0.9)	36.0b (19.8)	26.5b (13.0)	19.6a (8.4)	71.8a (20.5)	20.6a (4.6)	0.3ab (0.7)	98.1a (49.7)	15.8a (8.43)	0.2a (0.4)	21.1
B horizon	8	0.6a (0.2)	1.5a (0.9)	43.8b (19.4)	21.6b (7.4)	24.4b (9.6)	83.4a (26.2)	39.7c (16.9)	0.2ab 0.4)	108.9a (44.6)	19.8a (7.4)	0.4a (0.6)	8.4

[a] Numbers in a column followed by a different letter are significantly different ($p = 0.05$).
[b] Numbers of analyzed samples.
[c] Composite of all precipitation samples.

and much lower than those observed in the eastern United States (Vitousek and Reiners 1975; Likens et al. 1977; Johnson and Lindberg 1992). There were no obvious seasonal patterns in NH_4 and NO_3 concentrations.

Throughfall Chemistry

Most coniferous canopies show a tendency toward net acidification of bulk precipitation inputs (Cronan and Reiners 1983). Acidification processes may involve uptake of NH_4, nitrification, washing off of dry deposition, and leaching of plant-derived acids. In conifers, the acidification processes tend to dominate over neutralization processes. Neutralization processes may involve plant surface-ion exchange, and release of organic or bicarbonate salts (Cronan and Reiners 1983).

Throughfall pH in West Twin Creek averaged near 5.0 (Table 14), only slightly lower than the incoming precipitation pH of 5.3. While a similar trend was found in southwestern British Columbia (Feller 1977) and coastal Washington (Larson 1979), the opposite trend was found in Cedar River watershed in the Puget Sound region, Washington (Cole and Johnson 1977; Van Miegroet 1986), and Cascade Head, Oregon (Tarrant et al. 1968). The increase in pH at Cedar River and Cascade Head from precipitation to throughfall may be due to appreciable quantities of HCO_3 in throughfall (Parker 1983). Concentrations of HCO_3 in throughfall in the Cedar River watershed were considerably higher (>40 μeq/L; Cole and Johnson 1977) than that in the throughfall (5.4 μeq/L) and precipitation (8.0 μeq/L) in West Twin Creek watershed (Table 15).

Although there was no significant difference between precipitation and throughfall pH, there was a trend towards acidification in throughfall. The dominant acidification mechanism in the watershed appeared to be leaching of plant-derived acids. Overall, dissolved organic carbon (DOC) in throughfall increased (Table 14), indicating organic-acid leaching. Throughfall DOC concentrations were significantly different from precipitation DOC only under Pacific silver fir and western hemlock in the upper watershed (Table 14). Pacific silver fir throughfall pH was consistently lower than that of western hemlock (Fig. 30). The high DOC in Pacific silver fir throughfall (Table 14) may contribute to low pH values, in particular, because Pacific silver fir retain needles longer than other species (Kimmins 1987), and the needles may decompose on the branch, contributing organic acids to throughfall. There were no significant differences in throughfall pH or DOC among species (Table 14). McDowell and Likens (1988), Ugolini et al. (1988), and Koprivnjak and Moore (1992) also reported increases in DOC concentration in throughfall relative to that in the precipitation.

Throughfall pH displayed slight seasonal patterns. Generally, higher pH values were observed in spring and summer and the lower pH values were observed in fall and winter (Fig. 30). The seasonal pattern may be related to decomposition activities in the canopy and the lower rainfall volume in spring and summer.

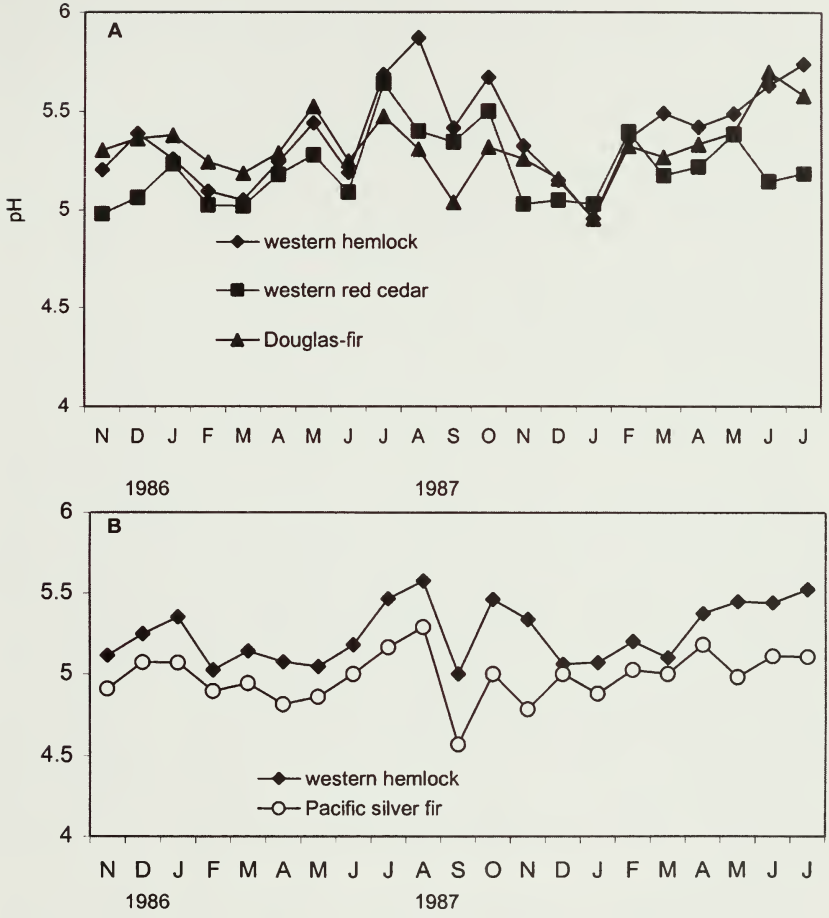

Figure 30. Average monthly pH of throughfall beneath (A) western hemlock, western red cedar, and Douglas-fir in the lower West Twin Creek watershed, and (B) western hemlock and Pacific silver fir in the upper West Twin Creek watershed,October 1986–July 1988.

There was a trend for both electrical conductivity (EC, Table 14) and cation concentrations (Table 15) to be higher in throughfall than in precipitation, but not significantly. As for precipitation, the major cation in throughfall was Na (76.5 μeq/L; Table 15). Throughfall cation concentrations ranked Na > K > Mg > Ca. Throughfall was enriched relative to precipitation in the order K > Na > Mg > Ca, indicating that K was most readily leached from the canopy. Cronan and Reiners (1983) noted that most forest canopies show a marked enrichment in ions as rainfall leaches through the canopy.

Leaching, washing-off of deposited particles, and evaporation from tree crowns all contribute to cation enrichment in throughfall. Leaching is probably the dominant mechanism at West Twin Creek watershed for both throughfall and stemflow, which is more enriched in cations than throughfall (Table 15). Washing off of dry deposition or marine aerosols containing sea salt appears important, based on the increased concentrations of Na and Cl in throughfall and stemflow relative to precipitation (Table 15). Evaporation is probably less important since SO_4 concentration changed little with passage through the canopy (Table 15). Sulfate commonly shows little interaction with foliage (Lindberg et al. 1986).

Often through foliar uptake, NH_4 concentrations in precipitation decrease after interaction with the canopy (Feller 1977; Parker 1983). However, NH_4 concentrations in throughfall were not lower than that in precipitation at West Twin Creek (Table 15). In fact, there was a slight, but not significant, increase.

Dominant anions in throughfall were Cl (74.7 μeq/L) and SO_4 (11.6 μeq/L; Table 15). The mean concentrations of all anions were not significantly different from those in precipitation. Sulfate concentration in throughfall was lower than that in throughfall in southwestern British Columbia (Feller 1977) and Cedar River watershed, Washington (Johnson 1975), but it was similar to that in throughfall in the Oregon Cascades (Sollins et al. 1980). Again, higher SO_4 concentrations in the Puget Sound area near Seattle are due to anthropogenic inputs.

There were no significant differences in the concentrations of any of the cations or anions in throughfall among species (Table 16). The highest Ca concentration in throughfall occurred under western redcedar, a known Ca accumulator (Bledsoe and Zasoski 1981). Pacific silver fir tended to influence throughfall chemistry to a greater extent than the other species, producing throughfall with the highest mean concentrations of K, Mg, Na, Cl, SO_4, and PO_4 (Table 16).

In summary, the chemistry of throughfall at West Twin Creek watershed was similar to that of precipitation and was dominated by oceanic influences. There were trends toward increases in acidity and enrichment of DOC and cations, probably due mostly to leaching, but in no case were concentrations of cations in throughfall significantly greater than those in precipitation.

Stemflow Chemistry

Stemflow solutions typically had higher ionic concentrations than precipitation and throughfall. This is usual for most forest ecosystems (Parker 1983). There was also a much larger anion deficit in stemflow (225.5 $\mu mol_c/L$) than in throughfall (56.1 $\mu mol_c/L$; Table 15). The stemflow cation/anion ratio ranged from 1.91 to 2.60, and the throughfall cation/anion ratio ranged from 1.30 to 1.42. This was largely due to the presence of organic anions in stemflow, as indicated by the high DOC concentrations (Table 14). Koprivnjak and Moore (1992) noted a similar trend in throughfall and stemflow DOC in a lichen woodland in Quebec.

Table 16. Average volume weighted concentrations (ueq/L) of chemical elements in throughfall and stemflow solutions from different tree species in West Twin Creek watershed from October 1986 through September 1988. Numbers in parentheses are standard deviations.

		Cations[a]						Anions[a]				
	n[b]	H	NH_4	Ca	K	Mg	Na	HCO_3	NO_3	Cl	SO_4	PO_4
Lower watershed												
Throughfall												
Douglas-fir	85	7.3a	0.4a	22.6a	22.9a	20.2a	83.9ab	5.0a	0.1a	92.5a	12.8a	5.8ab
		(3.4)	(0.7)	(13.8)	(50.5)	(12.9)	(48.0)	(4.5)	(0.1)	(67.8)	(9.4)	(9.4)
western hemlock	86	7.5a	0.7a	17.4a	21.5ab	19.4a	72.2ab	4.9a	0.1a	88.1a	11.3a	2.0a
		(4.1)	(1.0)	(12.0)	(25.3)	(13.4)	(34.0)	(4.0)	(0.3)	(60.1)	(9.0)	(3.1)
western redcedar	84	7.1a	0.8a	30.9ab	15.0a	17.6a	63.4a	10.3a	0.1a	73.3a	9.8a	1.8a
		(18.0)	(1.6)	(26.8)	(16.9)	(13.4)	(33.2)	(16.1)	(0.3)	(51.1)	(6.2)	(3.2)
Upper watershed												
Pacific silver fir	70	12.7a	0.5a	26.8ab	57.8a	25.7a	99.1ab	1.3a	0.1a	107.0a	26.8a	19.8ab
		(5.6)	(0.9)	(19.0)	(62.0)	(21.4)	(62.3)	(2.9)	(0.6)	(79.9)	(21.4)	(12.2)
western hemlock	80	7.9a	0.6a	11.9a	19.0a	16.4a	70.1ab	4.1a	0.1a	76.1a	22.4a	5.0a
		(3.4)	(1.0)	(5.4)	(12.7)	(9.4)	(35.2)	(4.6)	(0.6)	(89.6)	(11.9)	(6.0)

Table 16. *Continued.*

		Cations[a]						Anions[a]				
	n[b]	H	NH_4	Ca	K	Mg	Na	HCO_3	NO_3	Cl	SO_4	PO_4
Stemflow												
Lower watershed												
Douglas-fir	49	78.1bc	2.1a	78.9a	127.9c	56.2a	154.5c	T[c]	0.1a	208.2bc	19.6bc	32.1ab
		(44.5)	(2.0)	(37.0)	(40.0)	(29.5)	(62.4)		(0.1)	(88.1)	(13.8)	(21.5)
western hemlock	57	29.4a	1.8a	45.1ab	114.7b	28.3a	85.2ab	0.8a	0.1a	103.4a	7.2a	5.7a
		(13.2)	(8.8)	(34.9)	(80.7)	(24.3)	(36.9)	(7.6)	(0.5)	(58.9)	(4.9)	(10.1)
western redcedar	58	95.1c	4.5a	50.1a	23.0ab	34.8a	73.9ab	0.1a	0.1a	98.4a	9.7ab	3.8a
		(28.4)	(6.8)	(26.8)	(15.4)	(68.7)	(33.0)	(0.2)	(0.01)	(69.5)	(6.3)	(5.5)
Upper watershed												
Pacific silver fir	46	41.3ab	2.6a	201.6b	270.5b	81.0a	184.3b	7.2b	0.1a	270.1a	25.2a	56.1b
		(26.8)	(2.8)	(135.0)	(152.6)	(56.8)	(82.1)	(36.8)	(0.1)	(184.2)	(19.9)	(49.8)
western hemlock	55	38.2ab	2.1a	50.8ab	98.4b	32.4a	97.4ab	0.7a	0.1a	129.5a	11.4a	8.5ab
		(23.6)	(8.6)	(42.2)	(62.4)	(27.6)	(45.7)	(2.5)	(0.5)	(84.4)	(8.2)	(15.0)

[a] Numbers followed by a different letter within a column are significantly different ($p = 0.05$).
[b] n = total number of samples analyzed.
[c] T = Trace.

The concentrations of cations and anions, except HCO_3 and NO_3, tended to be higher in stemflow solution than in throughfall and precipitation solution, but only in the case of K was stemflow concentration significantly higher (Table 15). Potassium (119.6 μeq/L) and Na (118.0 μeq/L) were the dominant cations in stemflow, and the dominant anion was Cl (160.2 μeq/L; Table 15). The ranking of cation concentrations was K>Na>Mg>Ca. Similar to throughfall, stemflow was enriched relative to precipitation in the order of K>Ca>Mg>Na, indicating that K was easily leached from the canopy. The dominant mechanism for cation enrichment for both throughfall and stemflow is probably leaching.

Commonly, NH_4 and NO_3 in precipitation are taken up by the canopy, resulting in negative net throughfall and stemflow (Parker 1983). This was observed of NH_4 in throughfall in southwestern British Columbia (Feller 1977) and of NO_3 in Oregon (Sollins et al. 1980) and Washington (Johnson 1975). In the West Twin Creek watershed, NH_4 concentrations did not differ among stemflow (2.7 μeq/L), precipitation (0.4 μeq/L), and throughfall (0.6 μeq/L; Table 15). However, the trend toward a higher NH_4 concentration in both throughfall and stemflow suggests that N was fixated in the old-growth canopy. Denison (1973) noted that the epiphytic lichen *Lobaria oregana* fixes N in the canopy of old-growth trees in the Oregon Cascades, and this species occurs in the West Twin Creek watershed. Nadkarni (1984) also found that in the Olympic rainforest the amounts of N were higher in throughfall beneath branches with epiphytes than beneath stripped branches.

The pH was lower and DOC and EC were higher in stemflow than in throughfall (Table 14). Stemflow pH ranged from 4.0 to 4.5 (average of 4.3) and was significantly lower than precipitation and throughfall pH. Plant-derived acids strongly controlled stemflow acidity. Stemflow pH also depended on species (Table 14). Stemflow pH was lowest in western redcedar (4.0) and Douglas fir (4.1) and highest in western hemlock (4.5). Stemflow pH was similar in western hemlock in both the upper and lower watershed (Table 14). The bark is rougher of western redcedar and Douglas fir than of western hemlock, providing a greater surface area for contact and chemical reaction. Western redcedar bark also contains high concentrations of phenolics (Barton 1963). The pH of stemflow solution from Pacific silver fir was relatively higher (4.5) despite the comparably high DOC concentration (Table 14). Seemingly, the high cation concentrations, especially Ca, in Pacific silver fir stemflow (Table 16) had a neutralizing influence on the solution.

Tree species also influenced cation and anion concentrations in stemflow. The concentrations of cations and anions were generally highest in stemflow solution of Pacific silver fir and relatively low in that of western redcedar (Table 16). Phosphate concentrations were generally high in stemflow of Pacific silver fir and Douglas fir (Table 16), suggesting that P is being leached from the canopies of these species.

Cronan and Reiners (1983) suggested that cation enrichment in solutions flowing through forest canopies is mostly from plant recycling, whereas most

of the inorganic anions are from atmospheric sources. In the West Twin Creek watershed, the same mechanisms are operating, although wash-off of sea-salt-derived aerosols is probably responsible for much of the Na enrichment. The anions Cl, SO_4, and NO_3 were dominantly from atmospheric sources, whereas PO_4 enrichment was more likely from plant sources.

In summary, cations tended to be more concentrated in stemflow than in throughfall and precipitation. The pH of stemflow also was much lower, which was caused by organic acids from plant sources. Organic anions from plant sources dominated inorganic anions in stemflow and were associated with cation leaching in the canopy. Although only 5%–20% of the volume of precipitation reaches the forest floor in stemflow (Parker 1983), it is a major source of plant nutrients to fine roots near the base of trees and could be an important source of nutrients to plant roots in the West Twin Creek watershed.

Soil Solution Chemistry

Whereas the pH of solutions moving through the West Twin Creek forest canopy decreased from 5.3 in precipitation, 5.0 in throughfall, and 4.3 in stemflow, it increased in the forest floor solution to 5.7 (Table 14). Soil solution pH increased further at 15-cm depth to 5.8, and at 40-cm depth to 6.2 (Table 14). Soil pH also increased with depth from 4.2 in the forest floor to 4.9 in the lower mineral soil (Table 17). The pH is commonly lower in soil than in soil solution. Adsorption of organic anions onto soil particles or weathering of silicate minerals and increase in HCO_3 may be responsible for the increasing pH in solution with soil depth. Concentrations of DOC and anion deficit decreased with soil depth (Tables 14 and 15). The cation:anion ratio decreased from 1.50 in the forest floor solution to 1.05 at the 40-cm soil depth, indicating that adsorption of organic anions is an important mechanism for neutralizing the natural acidity in stemflow and throughfall in this ecosystem.

The chemical composition of a soil solution depends on a complex series of equilibrium, adsorption, immobilization, plant uptake, displacement, weathering, and decomposition reactions (Feller 1977). The leaching of cations depends on the amount of anions in the solution. Organic anions and HCO_3 are the dominant anions associated with leaching in undisturbed Pacific Northwest forests, and organic anions dominate at low pH (McColl 1972; Johnson et al. 1977; Ugolini et al. 1977). Organic anions dominated the canopy leaching, but as the solution moved through the forest floor, organic anions became less important and HCO_3 dominated at the 40-cm depth (Table 15).

Concentrations of cations were generally lower in forest floor leachates than in stemflow yet slightly higher than in throughfall (Table 15). Binkley et al. (1982) also found that cations were higher in forest floor solutions than in throughfall in coastal forests in British Columbia. Cation concentrations tended to be lower in the mineral soil than in the forest floor (Table 15), perhaps reflecting plant uptake. The dominant cation in the forest floor and mineral soil solutions was again Na (Table 15). Cation concentrations generally de-

Table 17. Average soil chemistry for West Twin Creek watershed. Standard deviations are shown in parentheses (n = 3).

Horizon	pH	$N0_3$-N	NH_4-N	PO_4-P	N	C	Na	K	Ca	Mg	Al	CEC
	---------- mg kg^{-1} ----------				--------- % ---------		---------- cmol kg^{-1} ----------					
O	4.2	0.4	10.2	43.0	1.0	35.3	0.1	0.8	6.0	2.6	3.5	28.3
	(0.3)	(0.01)	(1.2)	(27.2)	(0.05)	(12.9)	(0.05)	(0.1)	(1.6)	(0.7	(2.4)	(4.0)
BA (0–4 cm)	4.6	0.2	2.0	5.0	0.3	8.8	0.05	0.3	1.2	0.7	8.5	24.8
	(0.5)	(0.1)	(0.8)	(7.7)	(0.1)	(0.9)	(0.03)	(0.04)	(1.6)	(0.5)	(5.8)	(2.6)
B (5–40 cm)	4.9	0.2	1.2	2.2	0.2	3.1	0.1	0.1	0.14	0.2	8.1	20.5
	(0.5)	(0.1)	(0.8)	(0.7)	(0.01)	(1.3)	(0.03)	(0.05)	(0.1)	(0.03)	(6.0)	(8.4)

creased in the order of Na > Ca > Mg > K in the forest floor and in mineral soil. Anion concentrations decreased in the order of Cl > HCO_3 > SO_4 > PO_4 > NO_3. Because chloride moves with Na in solution, it had little influence on the leaching of nutrient cations.

The dominant anion in the soil solution away from coastal influence is HCO_3, particularly in low-elevation forests (Feller 1977; Johnson et al. 1977; Sollins et al. 1980). HCO_3 concentration was relatively higher in soil solution than in throughfall and stemflow solutions, probably because of decomposition and root respiration. The difference of SO_4 concentrations was little among precipitation, throughfall, stemflow, and soil solutions (Table 15), but concentrations tended to increase slightly with depth in the mineral soil, perhaps as a result of weathering. Phosphate tended to be lower in the soil solution than in stemflow and throughfall (Table 15) because of plant uptake and soil retention mechanisms.

Nitrate concentrations in the soil solution and bulk soil NO_3 were low and changed little with depth (Tables 15 and 17). In the forest floor and soil solutions, NO_3 concentrations were generally lower (0.1–0.3 μeq/L) than NH_4 (0.6–3.1 μeq/L; Table 15). A trend in the bulk soil was similar (Table 17). Sollins et al. (1980) and Feller (1977) found similar ranges of NO_3 in the soil solution. Feller (1977) also found similar soil NH_4 concentrations (2.77 μeq/L) in forest floor and soil solutions in southwestern British Columbia. Thus, N was retained in the ecosystem despite the very high rainfall. However, increased atmospheric NO_3 inputs in the 1993–96 period were not retained as discussed in Chapter 8, and it seems that the ecosystem is on the verge of N saturation.

Chapter 8: Long-Term Trends in Precipitation and Stream Chemistry in the West Twin Creek Watershed

The influence of anthropogenic sources of H, SO_4, NH_4, and NO_3 on forested watersheds has been the subject of much research (Swank and Waide 1988; Driscoll et al. 1988; Federer et al. 1989; Johnson and Van Hook 1989; Aber et al. 1991; Johnson and Lindberg 1992; Hedin et al. 1994; Likens and Bormann 1995). Human induced long-term changes in precipitation chemistry have occurred at many sites in eastern North America and Europe (Driscoll et al. 1989; Likens et al. 1990; Hedin et al. 1994), and similar changes in stream chemistry have also been noted at Hubbard Brook in New Hampshire (Driscoll et al. 1989), in the Catskill Mountains of New York (Stoddard 1991), and in eastern Canada (Clair and Ehrman 1995).

Strong seasonal patterns in precipitation and stream chemistry have also been noted in eastern North America (Swank and Waide 1988; Likens and Bormann 1995), but few long-term monitoring studies of precipitation and stream chemistry have been conducted in coastal or near-coastal sites in western North America, which are considered to be relatively pollution free. Most studies have been short term (Larson 1979; Sollins et al. 1980; Martin and Harr 1988; Bormann et al. 1989; Edmonds et al. 1995), although precipitation and stream chemistry were monitored from 1971 to 1986 in a small forested basin in southwestern British Columbia (Feller 1987). This site, however, was influenced by mildly acid precipitation. Galloway et al. (1995) predicted that atmospheric N on a global scale will continue to rise because of increased fossil-fuel combustion and fertilizer use; about two-thirds of the increase are in Asia. Nitrogen deposition to forests in western North America could increase if there is long-range transport across the Pacific Ocean. Thus, examination of long-term trends in atmospheric inputs and outputs of N and other elements in relatively pristine areas to detect long-range transport and global change is particularly important.

Our objectives were the determination of trends in precipitation and stream chemistry over a 9-year period in a pristine, old-growth forest watershed and the determination of seasonal patterns in precipitation and stream chemistry. This chapter is focused on data collected from 1984 to 1993, but trends in NO_3 in precipitation and the stream between 1993 and 1997 are also presented.

Methods

Sample Collection and Analytical Procedures

Samples were collected biweekly from November 1984 through June 1990 and at 4-week intervals thereafter through December 1997. Bulk precipitation

was collected in a clear-cut immediately adjacent to the Olympic National Park boundary and 1–2 km from the West Twin Creek watershed (Fig. 1). Two bulk precipitation collectors were located in the sampling site. Each bulk precipitation collector consisted of a 20-cm diameter polyethylene funnel with a netted top to exclude debris. The precipitation drained from the funnel into a polyethylene bag. Samples were collected in triple-rinsed 1-L polyethylene bottles and within 48 hours of collection transported in a cooler to the Analytical Laboratory at the College of Forest Resources, University of Washington, where they were stored at 4°C. Collection volumes were determined. A National Acid Deposition Program (NADP) station is also located at the Hoh Ranger Station (Fig. 1; National Acid Deposition Program-National Trends Network 1994).

Stream water samples were collected with a Qualimetric stage proportional sampler just upstream from a V-notch weir at the base of the West Twin Creek watershed. Samples were returned to the laboratory for chemical analysis in the same manner as precipitation samples.

Electrical conductivity (EC), pH, and alkalinity (reported as HCO_3) were determined on nonfiltered samples. EC was determined with a YSI Model 31 Conductivity Bridge (Yellow Springs Instrument Co., Yellow Springs, Ohio) and corrected to 25°C. The pH was determined with a Radiometer PHM85 pH meter (Radiometer, Copenhagen, Denmark). Alkalinity was determined by titration to an end point of pH 5 (Homann et al. 1992). Remaining sample material was filtered through Whatman GF/A filters and stored at 4°C and analyzed within 1 month after arrival at the College of Forest Resources laboratory at the University of Washington.

Solutions were analyzed for Ca, Mg, K, and Na with a IL 951 Atomic Absorption Analyzer (Instrumentation Laboratory, Wilmington, Massachusetts) prior to July 1993 and by Inductively Coupled Plasma atomic emission spectrometry thereafter. Samples were analyzed by both methods for 6 months to ensure that a change in technique did not influence the data. Ammonium was determined with a Technicon Autoanalyzer II (Technicon, Tarrytown, New York). Sulfate, Cl, NO_3 and PO_4 were determined with a Dionex 2100 Ion Chromatograph (AS4A and AG4A columns; Dionex, Sunnyvale, California). Macro- Kjeldahl digests were done on all samples of sufficient volume, and those digests were analyzed for N and P (reported here as Total Kjeldahl N and P (TKN and TKP)).

QA-QC Procedures

Standard chemical analysis QA-QC laboratory procedures were followed including use of replications, National Bureau of Standards rain water standards and blanks. Data were transferred from laboratory notebooks to computer spreadsheets and edited. Outliers were checked and data were eliminated if field notes at the time of sampling indicated obvious problems with the sample's quality. Precipitation samples were also screened on the basis of Cl:Na ratio.

Samples with Cl:Na ratios that deviated from the sea salt ratio of 1.17 by a factor of 2 were excluded. Only a few samples were excluded, however.

Statistical Analyses

Time trends and seasonal differences were examined with Autoregressive Integrated Moving Average Analysis (ARIMA; SPSS 1994). Data were log transformed. Because of the irregular sampling schedule, missing values were filled with the mean of two nearby points.

Results and Discussion

Precipitation Chemistry

There was no significant change in EC, pH, or concentrations of TKN and TKP in precipitation from 1984 to 1993 (Fig. 31). EC was low, reflecting the low concentrations of ions in precipitation in this site, and averaged 0.77 mS/m (Table 18). The pH averaged 5.3 and ranged from 4.3 to 7.1 (Fig. 31), which is typical for relatively pristine sites in the western United States (Larson 1979; Martin and Harr 1988; Bormann et al. 1989), and it was similar to that determined at the nearby NADP site at the Hoh Ranger Station (5.4; National Acid

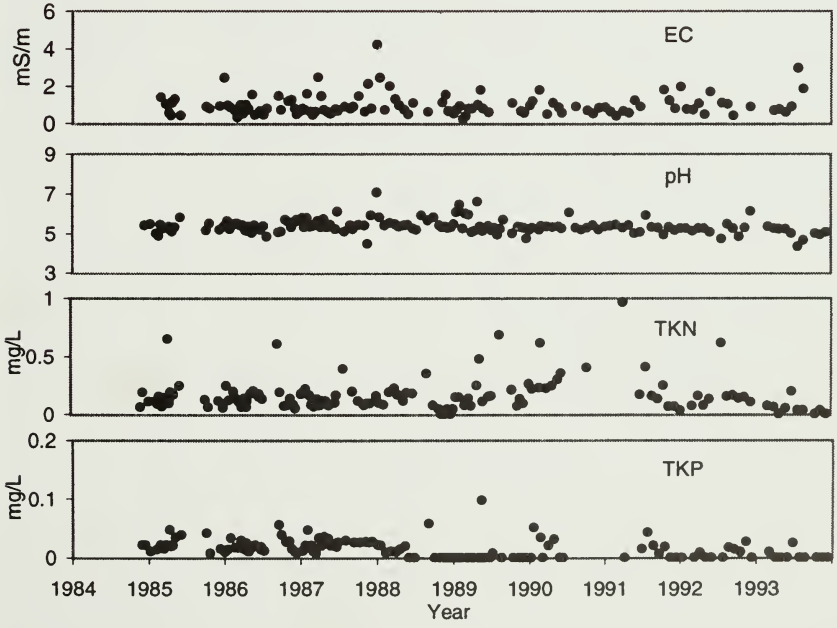

Figure 31. Trends in EC, pH, and concentrations of TKN and TKP in precipitation falling near West Twin Creek, 1984–1993.

Table 18. Annual volume-weighted means of analytes from precipitation samples collected near West Twin Creek, 1987–1993.

Year	pH	EC	HCO_3	Cl	SO_4	NO_3	PO_4	Ca	Na	Mg	K	NH_4	H	TKN[a]	TKP[b]
		mS/m	µeq/L											mg/L	
1987	5.21	0.99	7.83	47.5	11.65	1.12	0.19	11.19	47.3	9.39	2.81	0.14	6.151	0.12	0.024
1988	5.48	1.14	11.23	64.1	9.76	1.03	0.05	13.91	64.1	10.61	1.51	0.30	3.297	0.10	0.008
1989	5.53	0.46	6.39	29.7	4.33	0.55	0.03	7.98	31.3	0.11	0.50	0.05	2.948	0.11	0.001
1990	5.29	0.90	6.06	51.0	8.18	0.59	0.03	6.73	54.5	5.11	1.61	0.03	5.182	0.17	0.011
1991	5.32	0.70	6.40	39.8	6.33	0.30	0.00	1.81	33.7	8.34	3.13	0.02	4.737	0.15	0.002
1992	5.39	0.70	5.15	37.8	7.48	1.02	0.10	1.45	32.7	3.87	1.29	0.06	4.104	0.08	0.005
1993	5.27	0.49	1.88	45.5	12.57	0.29	0.11	2.97	33.0	0.66	ND[c]	0.23	5.405	0.04	0.003
Mean	5.34	0.77	6.42	45.1	8.61	0.70	0.07	6.58	42.4	5.44	1.81	0.12	4.546	0.16	0.015
S.D.	0.12	0.26	2.82	11.0	2.92	0.35	0.07	4.82	13.1	4.17	0.99	0.11	1.159	0.07	0.008

[a] TKN = Total kjeldahl nitrogen.
[b] TKP = Total kjeldahl phosphorus.
[c] ND = Not determined.

Deposition Program-National Trends Network 1994). In general, the chemistry of precipitation in the NADP site and in our collection site was similar (Edmonds et al. 1995). Slightly lower pH (4.5–4.8) has been reported in sites near Vancouver, British Columbia (Feller 1977; Binkley et al. 1982; Feller 1987) and Seattle, Washington (Van Miegroet 1986), probably because of anthropogenic inputs. Volume-weighted annual average concentrations of TKN and TKP were relatively low, averaging 0.16 mg/L of TKN and 0.015 mg/L of TKP (Table 18). Total N ranged from 0.33 mg/L to 0.56 near Vancouver, British Columbia (Feller 1987).

Time trends in concentrations of anions in precipitation were absent (Fig. 32), except in NO_3 concentrations, which showed a slight declining trend ($p < 0.001$). Between 1984 and 1993, there was little evidence yet of transport of NO_3 or NH_4 across the Pacific Ocean from Asia, and concentrations varied little from year to year (Table 18; Edmonds and Blew 1997). Continued data collection, however, revealed that NO_3 concentrations have increased since 1993, suggesting that the trans-Pacific transport of NO_3 predicted by Galloway et al. (1995) may now be occurring. This increased NO_3 was also reflected in NADP sites in coastal Oregon and California. Chloride was the dominant anion in precipitation because of the proximity to the ocean, (volume-weighted annual average 45.1 μeq/L; Table 18). Sulfate concentrations averaged 8.61 μeq/L, HCO_3 6.42 μeq/L, NO_3 0.70 μeq/L, and PO_4 0.07 μeq/L (Table 18). Non-sea-salt SO_4 can account for as much as 47% of the SO_4 (Edmonds et al. 1995) and is derived from the oxidation of dimethyl sulfide produced by marine algae, dust, and wood smoke from slash burning. Martin and Harr (1988) reported HCO_3 as the dominant anion in precipitation in the Cascade Mountains of Oregon, 160 km from the Pacific Ocean. In sites with urban influences on precipitation chemistry in the Northwest, SO_4 is the dominant anion (Binkley et al. 1982; Vong et al. 1985; Feller 1987). Increases in SO_4 and NO_3 were observed from 1971 to 1986 near Vancouver, British Columbia, reflecting the urban influence (Feller 1987).

Average annual SO_4 concentrations in precipitation are higher in the eastern United States than we observed (i.e., typically >40 μeq/L). However, at Hubbard Brook in New Hampshire, annual volume-weighted concentrations of SO_4 in precipitation decreased from more than 60 μeq/L in 1964 to near 40 μeq/L in 1987 with a slight increase in pH from about 4.1 to 4.3 (Driscoll et al. 1989). This was associated with a decline in SO_2 emissions in the eastern United States. Average annual NO_3 concentrations in precipitation are also much higher in the eastern United States (15–35 μeq/L) than we reported. Emissions of NOx in the eastern United States influence NO_3 concentrations in precipitation and, unlike SO_2, NOx emissions have not declined (Likens et al. 1990).

Concentrations of anions in precipitation were without strong seasonal patterns (Fig. 32), but concentrations of SO_4 were typically highest in late spring and summer. This may have been due to the influence of non-sea-salt SO_4 as described above. Bates et al. (1987) calculated greater flux rates of DMS from

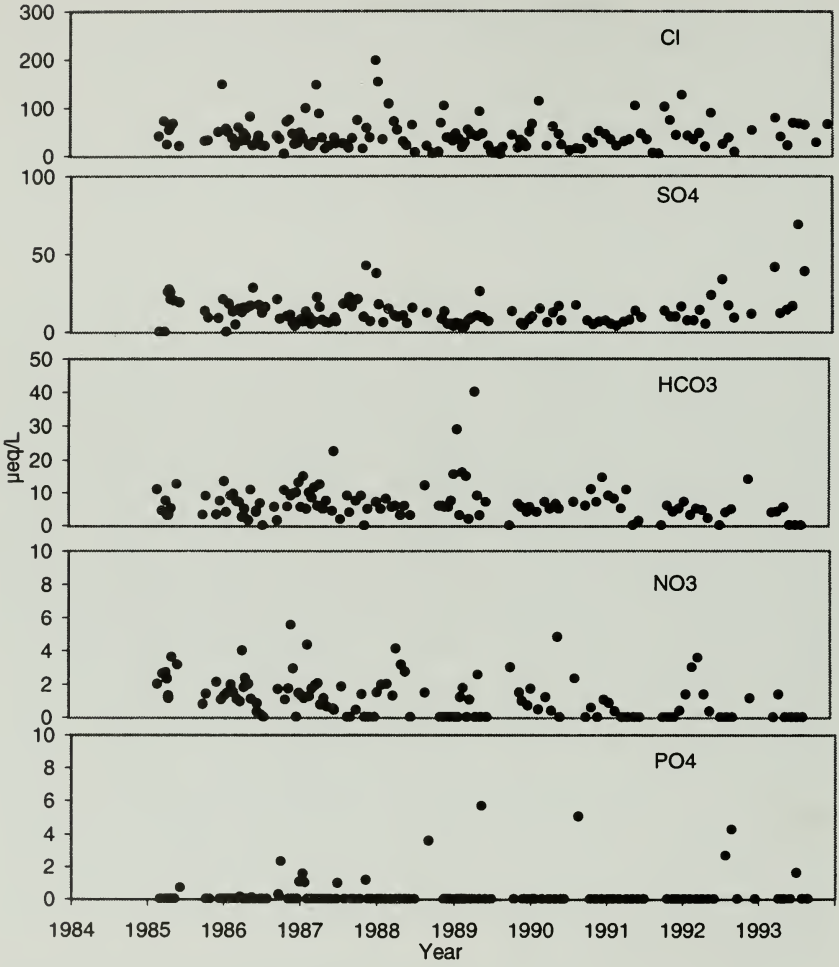

Figure 32. Trends in concentrations of anions in precipitation falling near the West Twin Creek, 1984–1993.

the ocean to the atmosphere during summer than winter, which may result in greater concentrations of SO_4 in the atmosphere at that time. Blew and Edmonds (1995) reported SO_4 concentration to be negatively correlated with precipitation amount. In addition to the seasonality of DMS emission from the ocean, Blew and Edmonds (1995) suggested that this may be the result of increased dry deposition of SO_4 during the summer dry season. This is an important consideration because these samples were collected as bulk precipitation rather than only as wet precipitation.

The dominant cation in precipitation was Na followed by Ca > Mg > K > NH_4 (Fig. 33; Table 18). The high Na concentration (2–5 times higher than more inland sites (Feller 1977; Sollins et al. 1980)) reflects the proximity to the ocean. Average annual volume-weighted concentrations of Na, Ca, Mg, K, and NH_4 were 42.4, 6.58, 5.44, 1.81 and 0.12 μeq/L (Table 18). Hydrogen averaged 4.546 μeq/L. Other studies near salt water also report high Na con-

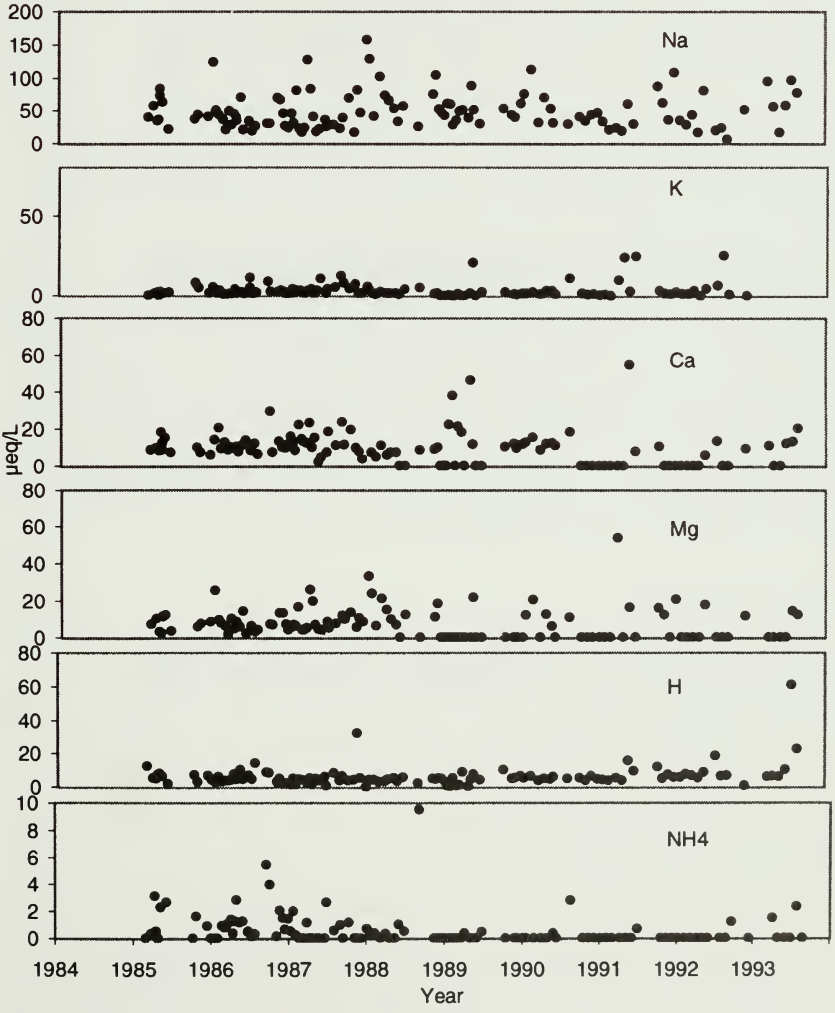

Figure 33. Trends in concentrations of cations in precipitation falling near the West Twin Creek, 1984–1993.

centrations (Bormann et al. 1989). In sites located more than 50 km from the ocean, the Ca concentration is greater than Na concentration (Sollins et al. 1980). Concentrations of NH_4 in precipitation were less in the Hoh River Valley than in the Puget Sound (Wolfe 1988) and British Columbia (Feller 1987), reflecting anthropogenic influence. In precipitation in our site, nitrate concentrations were higher than NH_4 concentrations, which is typical in sites near the ocean (Likens and Bormann 1995).

We found no seasonal trends in concentrations of cations in precipitation (Fig. 33), but the sum of cations (Ca, K, Mg, Na; $p<0.001$), especially of Ca, significant declined. In fact, the volume-weighted annual averages of Ca steadily declined from 13.91 μeq/L in 1988 to 1.45 μeq/L in 1992 (Table 18). Declines of Mg and Na were similar. This was probably associated with a decrease in timber harvest in the area after 1990. The bulk precipitation collectors were located in a clear-cut in a managed forest immediately adjacent to Olympic National Park and were within a few hundred meters of gravel logging roads. Dust from these roads had probably influenced the chemistry of bulk precipitation during periods of heavy use of the nearby roads.

Concentrations of base cations in precipitation (sum of non-sea-salt Ca, Mg, K, and Na), especially Ca, also declined from 1963 to 1991 over large areas in western Europe and eastern North America (Hedin et al. 1994). This decline is attributed to reductions in point source emissions from fuel combustion, industrial processes, road paving, and changes in agricultural tilling practices. Natural emissions from forest fires and wind erosion of arid soils are also important sources of base cations. This reduction in base cations could offset the reductions of SO_4 deposition in many areas and could contribute to increased sensitivity of poorly buffered ecosystems.

Stream Chemistry

There were no changes in pH, TKN, and TKP in stream water of West Twin Creek through time or season, but seasonal differences in EC were significant ($p<0.001$; Fig. 34). EC was highest in late summer before the rainy season began. Electrical conductivity was 1 order of magnitude higher in the stream than in precipitation, reflecting the high concentration of ions from weathering in the stream. The average stream pH was 7.3, and the range was 5.5–9.0. Larson (1979) recorded similar pH values in nearby streams, and Martin and Harr (1988) noted stream pH values above 7.0 in Alaska, British Columbia, and Oregon. Stottlemyer (1992) observed stream pHs as high as 8.5 in Denali National Park, Alaska. In southwestern British Columbia, stream water pH was lower, averaging 6.6 from 1971 to 1985. However, pH values of less than 6.1 were not recorded, even though mean annual precipitation pH values ranged from 4.5 to 4.9. This indicates that the moderate acidic precipitation in this site had not yet significantly affected stream water chemistry (Feller 1987). The EC was 1 order of magnitude lower in this British Columbia stream than in the West Twin Creek watershed. Annual average volume-weighted concentrations

of TKN and TKP in West Twin Creek were relatively low: 0.15 mg/L of TKN and 0.017 mg/L of TKP (Table 19) and similar to those in precipitation. Edmonds et al. (1995) had previously reported that N and P losses from West Twin Creek were similar to inputs.

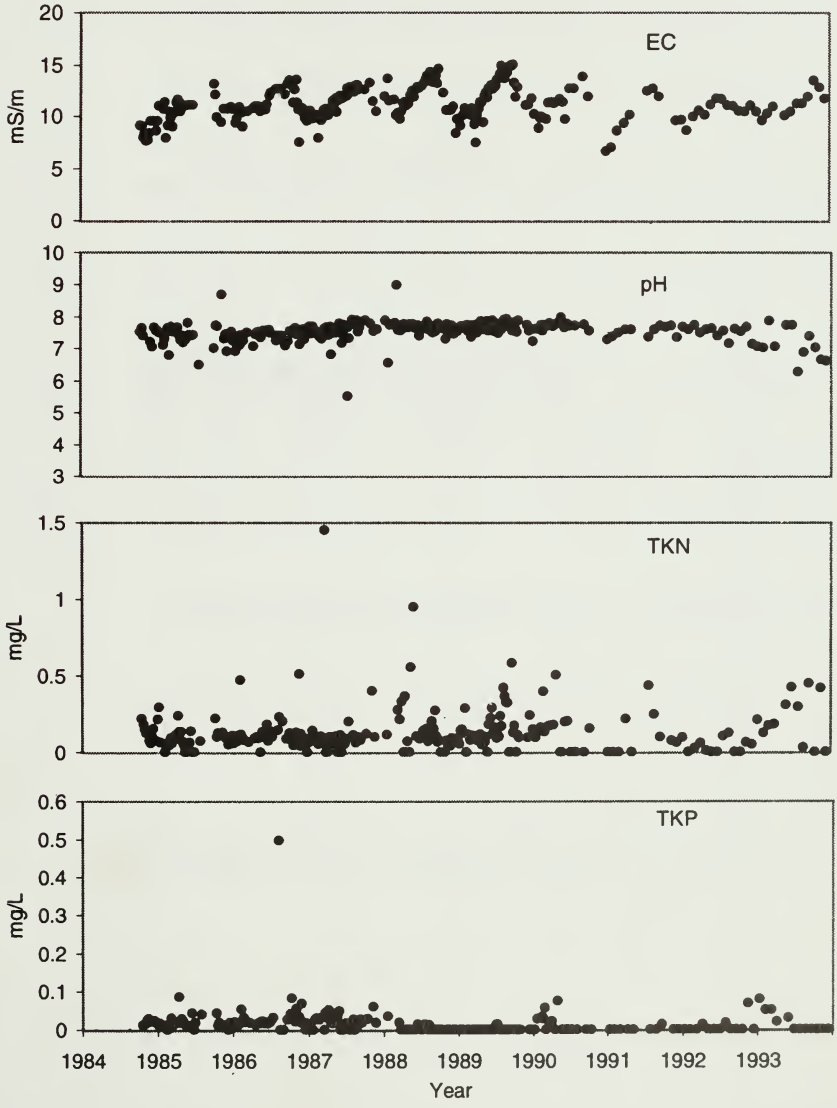

Figure 34. Trends in EC, pH, and concentrations of TKN and TKP in stream water of the West Twin Creek, 1984–1993.

Table 19. Annual means of analytes from stage proportional samples from West Twin Creek, 1984–1993.

Year	pH	EC	HCO_3	Cl	SO_4	NO_3	PO_4	Ca	Na	Mg	K	NH_4	H	TKN[a]	TKP[b]
		mS/m	μeq/L											mg/L	
1984	7.36	8.6	623.7	83.7	268.3	6.42	0.00	653.5	211.3	142.2	14.80	0.36	0.044	0.13	0.020
1985	7.28	10.5	596.6	98.7	299.8	6.11	0.07	692.7	169.1	150.7	6.33	0.61	0.053	0.10	0.020
1986	7.34	11.1	580.0	88.6	319.8	6.17	1.63	730.0	167.9	150.8	15.27	1.57	0.046	0.12	0.038
1987	6.95	11.2	591.3	75.6	323.8	4.43	0.21	746.5	167.5	152.7	8.63	0.53	0.111	0.13	0.022
1988	7.54	12.1	601.7	85.0	329.7	4.44	0.00	773.2	187.1	160.1	7.72	0.28	0.029	0.17	0.003
1989	7.68	11.9	585.1	84.3	343.3	5.07	0.03	748.2	184.8	158.1	6.51	0.21	0.021	0.16	0.001
1990	7.66	11.1	481.2	72.4	309.5	4.38	0.00	710.5	179.5	148.4	7.22	0.00	0.022	0.21	0.020
1991	7.51	8.8	526.2	66.3	298.0	3.61	0.00	649.9	155.6	143.4	15.19	0.00	0.031	0.19	0.002
1992	7.49	10.6	678.0	65.9	360.8	10.70	0.51	796.2	173.2	156.4	15.70	0.00	0.032	0.04	0.008
1993	6.88	11.2	629.5	78.4	383.3	9.24	0.82	837.1	206.4	177.5	ND[c]	6.63	0.132	0.26	0.038
Mean	7.28	10.7	589.3	79.9	323.6	6.06	0.33	733.8	180.2	154.0	10.82	1.02	0.052	0.15	0.017
S.D.		0.9	50.4	9.7	25.5	2.16	0.49	50.1	13.2	8.7	3.76	1.91	0.036	0.06	0.013

[a] TKN = Total kjeldahl nitrogen.
[b] TKP = Total kjeldahl phosphorus.
[c] ND = Not determined.

Concentrations of anions in the stream (Fig. 35) except SO_4, which increased significantly ($p < 0.001$), were without time trends. Bicarbonate was the dominant anion in stream water (volume-weighted annual average 589.3 µeq/L), followed by SO_4 (323.6 µeq/L), Cl (79.9 µeq/L), NO_3 (6.06 µeq/L), and PO_4 (0.33 µeq/L; Table 19). Hydrogen averaged only 0.052 µeq/L. Larson (1979) in nearby streams and Stottlemyer (1992) in coastal Alaska found similar patterns of stream water chemistry. Concentrations of SO_4 were higher than observed in many streams in the eastern United States (Stoddard 1991) and

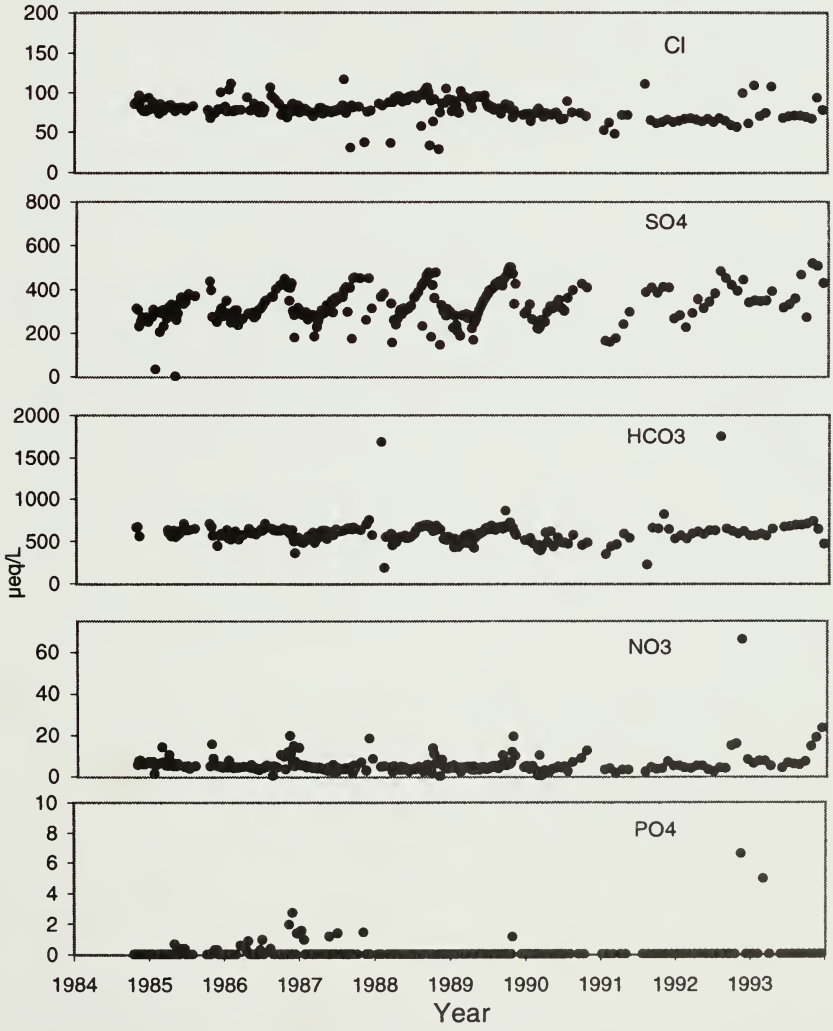

Figure 35. Trends in concentrations of anions in stream water of the West Twin Creek, 1984–1993.

Canada (Clair and Ehrman 1995). This strongly reflects the parent material in our site, which consists of uplifted marine sediments. Stream water SO_4 concentrations are now decreasing in many streams in the eastern United States as a result of reduced atmospheric SO_4 inputs (Likens and Bormann 1995; Stoddard 1991). At Hubbard Brook, New Hampshire, however, stream pH did not increase despite the decrease in SO_4, perhaps because of a decrease in basic cations. Because all major elements act together to regulate the acidity of soils and drainage waters, deposition of all elements, including cations and NO_3, needs to be considered. A combination of increasing NO_3 in precipitation and decreasing Ca and Mg seems to be outweighing the influence of declining trends in SO_4 inputs and outputs in the eastern United States.

Concentrations of NO_3 in West Twin Creek did not increase with time (Fig. 35) and were 1 order of magnitude lower in eastern streams where NO_3 seems to be increasing (Johnson and Lindberg 1992; Stoddard 1991 and 1994) because of increased atmospheric N deposition and possible N saturation (Aber et al. 1991). However, continued monitoring since 1993 revealed an increase in stream NO_3 concentrations, mirroring the increase in NO_3 concentrations in precipitation. Stream pH has also been depressed since 1993.

Seasonal patterns were strong in NO_3 , EC (Fig. 34), HCO_3, and SO_4 (Fig. 35; $p < 0.001$). The pattern associated with EC, HCO_3, and SO_4 in stream water seems to be related to seasonal patterns of stream discharge. As stream discharge decreased during summer and fall, concentrations of the dominant ions increased. Concentrations of the dominant ions reached their maximum prior to the onset of the wet season and fell drastically after the beginning of the rainy season. Presumably, as surface flow in the watershed decreased, a greater proportion of the water in the stream was from subsurface or groundwater discharge into the stream. This water has had greater interaction with the parent material and consequently carried greater concentrations of the products of weathering reactions. We did not determine weathering rates in the West Twin Creek watershed. However, stream SiO_2 concentration averaged 39.9 μeq/L from 1991 to 1993 (R. L. Edmonds, unpublished data), indicating active weathering. Concentrations of weathering products in the stream water are related to stream discharge rates. These results were consistent with those reported by Feller (1977) in a forested watershed in southwestern British Columbia. In addition to the weathering of carbonate minerals, an alternate source for HCO_3 is the dissolution of CO_2 released from respiration in the soil. Sollins et al. (1980) presumed that increases in HCO_3 as solutions passed through the mineral soil were solely because of respiration. However, in the streams studied by Sollins et al. (1980), the amount of HCO_3 was 1 order of magnitude less than we report here of West Twin Creek.

Seasonal patterns of NO_3 in stream water were a little different from those of the dominant ions. Nitrate concentrations increased slightly with decreasing stream flow. But the more prominent pattern was a large increase in NO_3 concentrations after the onset of the rainy season and a subsequent decline to

background levels soon after (Fig. 35). Plant uptake of N is far less during this period in late fall and early winter than in spring and summer. The loss of this N sink may have resulted in an accumulation of NO_3 in the soil that would then be leached from the surface soil by the first significant rain events of the wet season and be subsequently carried to the stream. Other investigators have reported high NO_3 concentrations in stream water peaking in early spring (Vitousek and Reiners 1975; Stoddard 1994; Likens and Bormann 1995) after the onset of snowmelt or spring rainstorms.

The seasonality of NO_3 concentrations we observed in West Twin Creek also appears in the Hoh, Queets, Quinault, and Quilayute rivers of Washington (U.S. Geological Survey 1972, 1973, 1986), suggesting that this pulse of NO_3 in streams is common over a wide area on the western Olympic Peninsula. Regardless of its source, this pulse of NO_3, represented a considerable portion of the annual total N loss from the West Twin Creek watershed. Edmonds et al. (1995) estimated annual NO_3 discharge from this stream to be 2.25 kg/ha/year and total N loss to 7.13 kg/ha/year. We estimated the loss of N from the watershed as NO_3 during this pulse to be approximately 1.8 kg/ha/year, which represented approximately 25% of the total annual discharge of N from this watershed. This contrasts to reports of watershed NO_3 loss in other sites in the Pacific Northwest. For example, Martin and Harr (1988) reported NO_3-N losses from watersheds in the Cascade Mountains of Oregon of only 0.1 kg/ha/year.

The dominant cation in stream water was Ca (Fig. 36). Volume-weighted annual concentrations averaged 733.8 μeq/L of Ca followed by Na (180.2 μeq/L) >Mg (154.0 μeq/L) >K (10.82 μeq/L) >NH4 (1.02 μeq/L; Table 19). The high Ca concentration and the high HCO_3 and SO_4 concentrations in the stream reflect active weathering. High Na concentrations reflect the proximity to the ocean as well as weathering. Annual deposition of Na in bulk precipitation to this watershed during 1986–88 (41 kg/ha/year) was equal to approximately one-third of that discharged from the watershed by the stream (124 kg/ha/year; Edmonds et al. 1995).

Seasonal patterns of Ca, Mg, and Na (Fig. 36) resembled those of HCO_3 and SO_4 and were statistically significant ($p < 0.001$). Potassium, NH_4, and H were without seasonal patterns. In the stream NH_4 concentrations were lower than NO_3 concentrations. Plant uptake and microbial and soil processes are important processes for NH_4 retention in the ecosystem. Similar general patterns of stream water chemistry have been reported of other watersheds in the Northwest. Binkley et al. (1982) in coastal British Columbia and Martin and Harr (1988) in the Oregon Cascade Mountains, reported Ca and HCO_3 as the dominant ions in stream water.

Long-term Trends

The concentration of most analytes in precipitation and stream water showed few statistically significant trends from 1984 to 1993. However, NO_3 in precipitation declined slightly, whereas SO_4 in stream water increased. There also

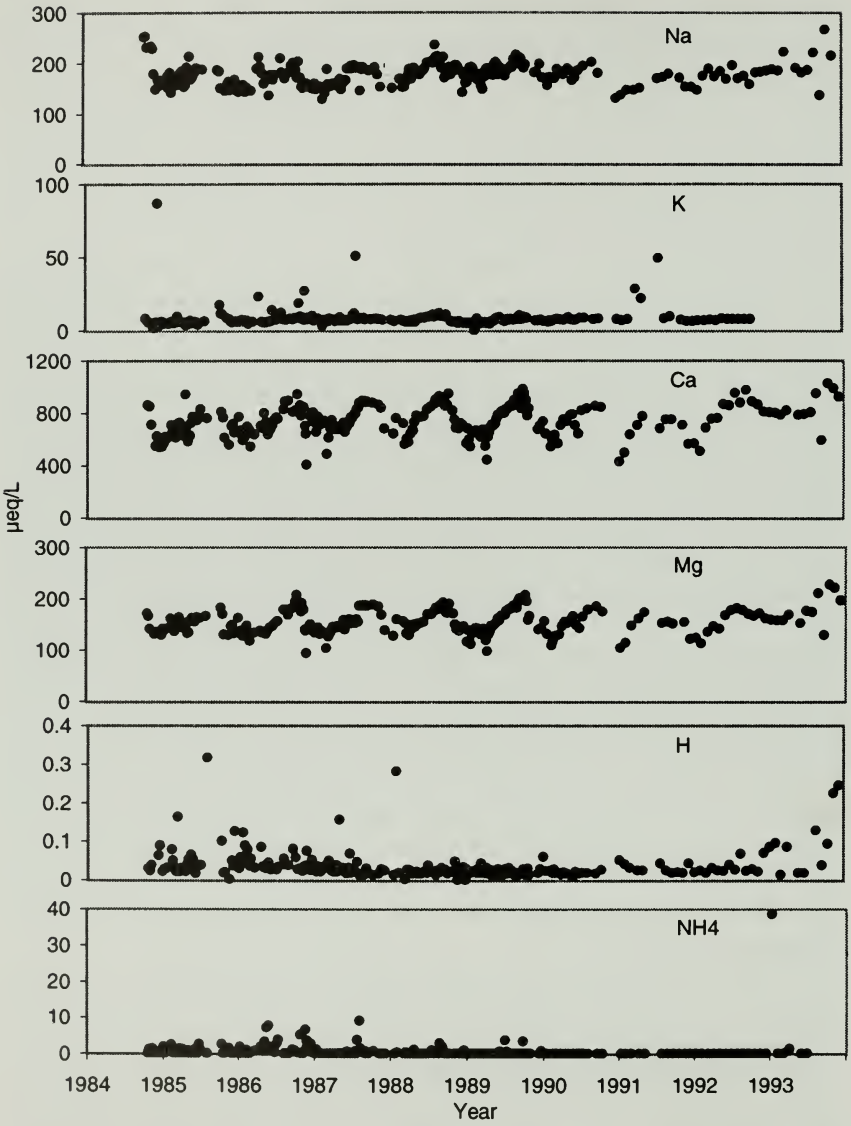

Figure 36. Trends in concentrations of cations in stream water of the West Twin Creek, 1984–1993.

appeared to be a trend toward decreasing concentrations of cations in precipitation. Since 1993, however, NO_3 concentrations in precipitation and in the stream have increased and pH has decreased (Fig. 37). This seems to be across-Pacific transport of NO_3 from Asia. The sharp increase in NO_3 in the stream during the 1993–1996 period suggests that the ecosystem is on the verge of N saturation.

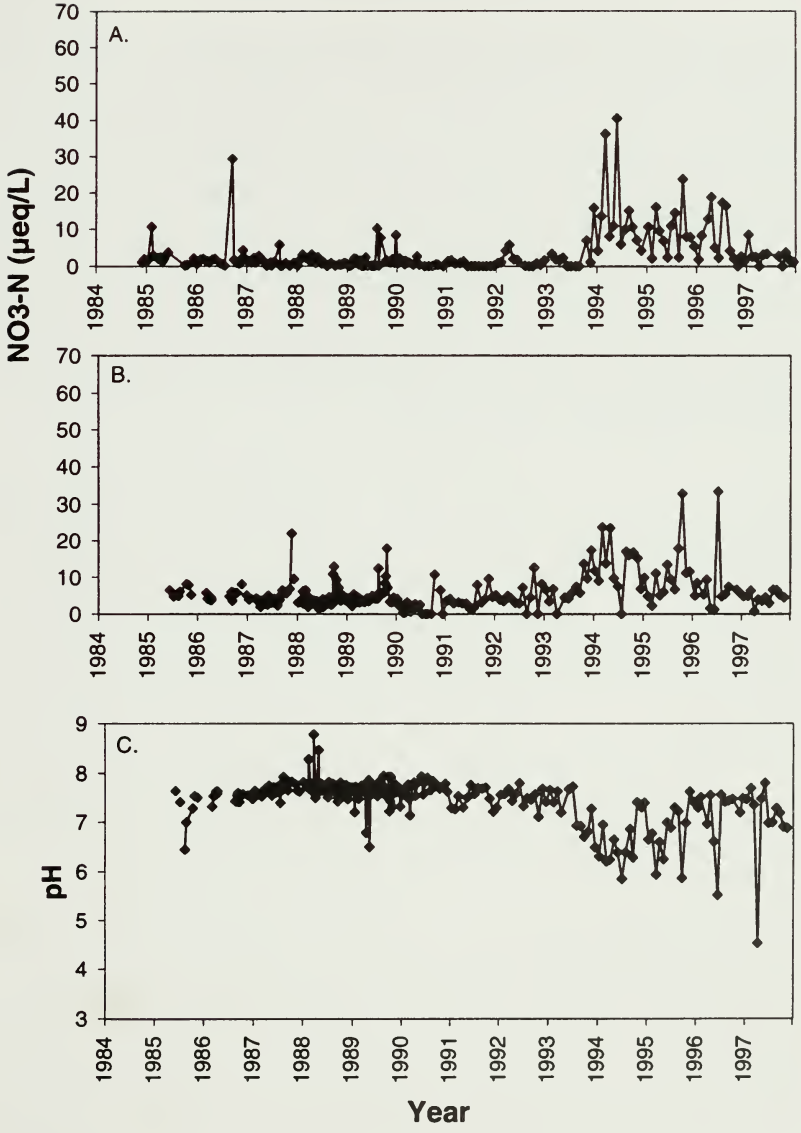

Figure 37. Concentrations of NO_3-N in (A) precipitation falling near the West Twin Creek watershed and (B) in the stream in the watershed, 1984–1997. Stream pH is also shown (C).

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Appendix A: Soil Profile Descriptions.

Soil Profile Description of the Lower Portion of the West Twin Creek Watershed

General description of soil pit site

Classification: Typic Dystrochrept

Deep, well-drained soil derived from colluvial material on a bench between streams. Slope is 20%, aspect is 160°, and elevation is 244 m (800 ft). Potential natural vegetation is *Picea sitchensis, Tsuga heterophylla,* and *Vaccinium parvifolium* with a ground cover dominated by mosses. Area is disturbed by windthrow.

Horizons

Oi 10.2 to 6.4 cm

Oe 6.4 to 1.3 cm

Oa 1.3 to 0 cm; abrupt wavy boundary; pH 3.86

Bw1 0 to 33 cm, with a thickness of 12.7 to 40.6 cm; moist color (10YR 4/4), clay loam texture; moderate, medium subangular blocky structure; firm moist consistence, slightly sticky, slightly plastic; 30% gravel, 5% cobble, and 5% stone; many fine, medium, and coarse roots; very fine and fine interstitial and vesicular pores; clear broken boundary; pH 4.55

Bw2 33 to 61 cm, with a thickness of 20 to 30 cm; moist color (10YR 5/4); clay loam texture; moderate, medium subangular blocky structure; firm moist consistence, slightly sticky, slightly plastic; some cutans present; 25% gravel, 5% cobble, and 10% stone; few fine, medium, and coarse roots; very fine and fine interstitial and vesicular pores; clear broken boundary; pH 5.06; irregular patches of Bh present (color 10YR 2/1)

Bw3 61 to 102 cm, with a thickness of 38 to 46 cm; moist color (7.5YR 4/6); loam texture; moderate, coarse subangular blocky structure; firm moist consistence, slightly sticky, slightly plastic; 25% gravel, 5% cobble, and 10% stone; very few fine and medium roots; very fine and fine interstitial and vesicular pores; clear smooth boundary; pH 5.49; irregular patches of Bh present (color 10YR 2/1)

Bw4 102 cm and down; moist color (10YR 5/6); silty clay loam texture; moderate, medium subangular blocky structure; friable moist consistence, slightly sticky, slightly plastic; 20% gravel, 5% cobble, and 50% stone; very few medium roots; pH 5.75

Soil Profile Description of the Upper Portion of the West Twin Creek Watershed

General description of soil pit site

Classification: Typic Dystrochrept

Moderately deep, fairly well-drained soil derived from marine sediments of sandstone and siltstone. Slope is 20%, aspect is 180°, and elevation is 671 m (2200 ft). Profile is located on a slight convexity in a midslope position. Natural vegetation is *Tsuga heterophylla* and *Abies amabilis,* with a depauperate understory.

Horizons

Oi 4 to 2 cm

Oa 2 to 0 cm, pH 3.80

EB 0 to 5 cm, with a thickness of 2.5 to 10.2 cm; moist color (7.5YR 3/3); silty clay loam texture; moderate, medium subangular blocky structure parting to crumb; firm moist consistence, slightly sticky, slightly plastic; 5% gravel with no cobble or stones; many micro, common very fine, fine, and medium, and few coarse roots; many tubular and common vesicular pores; clear wavy boundary; pH 3.49

Bs1 5 to 28 cm, with a thickness of 15 to 28 cm; moist color (7.5YR 4/5), clay loam texture; moderate to strong, coarse subangular blocky structure; very firm moist consistence, slightly sticky, slightly plastic; 5% gravel; few micro, very few fine, medium, and coarse roots; common tubular pores; clear wavy boundary; pH 3.73

Bs2 28 to 41 cm, with a thickness of 7.6 to 17.8 cm; moist color (7.5YR 4/6); clay loam texture; moderate, coarse subangular blocky; firm to friable moist consistence, slightly sticky, slightly plastic; 5% gravel; common micro and fine, few very fine and medium roots; common tubular pores; clear wavy boundary; pH 4.40

Bs3 41 to 69 cm, with a thickness of 10 to 30 cm; moist color (7.5YR 4/6); sandy clay loam texture; moderate, medium subangular blocky structure parting to crumb; firm moist consistence, slightly sticky, slightly plastic; 20% gravel; few fine, medium and coarse roots; few tubular pores; gradual wavy boundary; pH 4.38

BC 69 cm and down; too rocky to sample for color, structure, and texture; 40% gravel, 20% cobble; few fine and coarse roots, few tubular and vesicular pores; pH 4.58

Soil Profile Description of Soil near the Hoh Lake Watershed

General description of soil pit site

Classification: Typic Cryumbrept

Vegetation type: Abies amabilis/Rhododendron albiflorum association

Physiographic position: mountain upland, 1249 m (4100 ft) elevation

Topography: moderately steep (40%), northeast exposure, concave upper slope

Drainage: excessive

Disturbance: fire, wind throw

Horizons

13–11 cm Organic horizon; no roots

11-0 cm Organic horizon; medium and fine roots common

0-9 cm Gray brown (10YR 5/2) silt loam, 5% gravel; moderate, medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; extremely acid (pH 4.0); few medium and coarse roots; diffuse boundary; charcoal throughout

9–19 cm Brown to dark brown (7.5YR 4/2) sandy silt loam, 5% gravel; moderate, medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; extremely acid (pH 4.0); few fine and medium roots; clear smooth boundary; charcoal throughout

19-35 cm Brown to dark brown (7.5YR 4/4) sandy loam, 12% clay, 20% gravel, 5% cobbles, reddish yellow (7.5YR 6/8) mottles; weak, fine subangular blocky structure; slightly hard, friable, nonsticky, nonplastic; very strongly acid (pH 4.4); few fine and medium roots; diffuse boundary

35-40 cm Dark reddish brown (5YR 3/2) sandy loam, 10% clay; weak, fine granular structure; slightly hard, friable, nonsticky, nonplastic; very strongly acid (pH 4.5); few fine roots; abrupt boundary

40-58 cm Brown to dark brown (7.5YR 4/4) sandy loam, 20% gravel, 10% cobble, 30% stone; weak, fine granular structure; slightly hard, friable, nonsticky, nonplastic; pH unknown; no roots; clear, smooth boundary

58+ cm Unconsolidated bedrock

Appendix B: Vegetation in Permanent Sampling Plots in the West Twin Creek and Hoh Lake Watersheds.

West Twin Creek Watershed

Scientific name and authority	Common name	Alpha
Trees		
Abies amabilis (Dougl.) Forbes	Pacific silver fir	ABAM
Acer macrophyllum Pursh	bigleaf maple	ACMA
Alnus rubra Bong.	red alder	ALRU
Picea sitchensis (Bong.) Carr	Sitka spruce	PISI
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir	PSME
Thuja plicata Donn	western redcedar	THPL
Tsuga heterophylla (Raf.) Sarg.	western hemlock	TSHE
Shrubs		
Acer circinatum Pursh	vine maple	ACCI
Berberis nervosa Pursh	Oregon grape	BENE
Gaultheria shallon Pursh	salal	GASH
Rubus spectabilis Pursh	salmonberry	RUSP
Sambucus racemosa (T. & G.) Gray	red elderberry	SARA
Vaccinium alaskaense How.	Alaska huckleberry	VAAL
V. ovalifolium Smith	oval-leaf huckleberry	VAOV
V.parvifolium Smith	red huckleberry	VAPA
Herbs and Forbs		
Achlys triphylla (Smith) DC.	deerfoot vanillaleaf	ACTR
Adenocaulon bicolor Hook.	pathfinder	ADBI
Athyrium filix-femina (L.) Roth	ladyfern	ATFI
Blechnum spicant (L.) With.	deerfern	BLSP
Boykinia elata (Nutt.) Greene	coast boykinia	BOEL
Disporum smithii (Hook.) Piper	Smith's fairybells	DISM
Epilobium angustifolium L.	fireweed	EPAN
Galium triflorum Michx.	sweetscented bedstraw	GATR
Goodyera oblongifolia Raf.	rattlesnake plantain	GOOB
Hieracium albiflorum Hook.	white hawkweed	HIAL
Lactuca muralis (L.) Fresen.	wall lettuce	LAMU
Listera spp.	twayblade	LISSP
Luzula parviflora (Ehrh.) Desv.	small-flowered wood-rush	LUPA
Montia sibirica (L.) How.	western springbeauty	MOSI

Scientific name and authority	Common name	Alpha
Oxalis oregana Nutt. ex T. & G.	Oregon oxalis	OXOR
Polystichum munitum (Kaulf.) Presl.	swordfern	POMU
Smilacina racemosa Wats.	false solomonplume	SMRA
Tiarella trifoliata L.	three-leaved coolwort	TITR
Trillium ovatum Pursh	white trillium	TROV
Epiphytes		
Alectoria sarmentosa	common witch's hair	ALSA
Dicranum scoparium Hedw.	broom moss	DISC
Eurhynchium oreganum (Sull.) J. & S.	Oregon beaked moss	EUOR
Hylocomium splendens (Hedw.) B.S.G.	mountain fern moss	HYSP
Lobaria oregana	lungwort	LOOR
Mnium spp.		MNSPP
Polytrichum juniperinum Hedw.	juniper haircap moss	POJU
Rhytidiadelphus loreus (Hedw.) Warnst.	little shaggy moss	RHLO

Hoh Lake Watershed

Scientific name and authority	Common name	Alpha
Trees		
Abies amabilis (Dougl.) Forbes	Pacific silver fir	ABAM
Chamaecyparis nootkatensis (D. Don) Spach	Alaska yellow cedar	CHNO
Tsuga mertensiana (Bong.) Carr	mountain hemlock	TSME
Shrubs		
Gaultheria ovatifolia Gray	slender gaultheria	GAOV
Menziesia ferruginea Smith	rustyleaf	MEFE
Phyllodoce empetriformis (S.W.) D. Don	pink mountain heather	PHEM
Rhododendron albiflorum Hook.	white rhododendron	RHAL
Rubus pedatus J.E. Smith	strawberry-leaf blackberry	RUPE
Sorbus sitchensis (Wenzig) C.L. Hitchcock	Sitka mountain ash	SOSI
Vaccinium alaskaense How.	Alaska huckleberry	VAAL
V. deliciosum Piper	blueleaf huckleberry	VADE
V. membranaceum Dougl. ex Hook.	big huckleberry	VAME
V. ovalifolium Smith	oval-leaf huckleberry	VAOV

Scientific name and authority	Common name	Alpha
Herbs and Forbs		
Erythronium montanum Wats.	avalanche fawnlily	ERMO
Goodyera oblongifolia Raf.	rattlesnake plantain	GOOB
Listera spp.	twayblade	LISSP
Luzula parviflora (Ehrh.) Desv.	small-flowered wood-rush	LUPA
Montia sibirica (L.) How.	western springbeauty	MOSI
Nothochelone nemorosa (Dougl.)	woodland bear-tongue	NONE
Polystichum munitum (Kaulf.) Presl.	swordfern	POMU
Pyrola secunda L.	one-sided wintergreen	PYSE
Pyrola uniflora L.	wax-flower	PYUN
Tiarella trifoliata L.	three-leaved coolwort	TITR
Trillium ovatum Pursh	white trillium	TROV
Valeriana sitchensis Bong.	Sitka valerian	VASI
Xerophyllum tenax (Pursh) Nutt.	bear-grass	XETE
Epiphytes		
Alectoria sarmentosa	common witch's hair	ALSA
Dicranum scoparium Hedw.	broom moss	DISC
Peltigera aphthosa (L.) Willd.		PEAP
Rhytidiopsis robusta (Hook.) Broth.	robust moss	RHRO

Appendix C. Estimated percent cover of major vegetation, rock, bare soil, and litter in the permanent sampling plots in the West Twin Creek and Hoh Lake watersheds, Olympic National Park, Washington.

West Twin Creek Watershed

Lower watershed		
Plot 1	Plot 2	Plot 5
Tsuga heterophylla/ Polystichum munitum-Oxalis oregana (south slope)	*Tsuga heterophylla/ Polystichum munitum-Oxalis oregana* (north slope)	*Tsuga heterophylla/ Gaultheria shallon*
Upper watershed		
Plot 3	Plot 4	Plot 6
Tsuga heterophylla-Abies amabilis/ Vaccinium alaskaense	*Tsuga heterophylla/ Oxalis oregana*	*Tsuga heterophylla-Abies amabilis/ Depauperate*

	Lower watershed			Upper watershed		
Lifeform	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
Rock (> 8 cm)	3	35	0	1	0	0
Bare soil	3	10	0		8	0
Litter	30	45	30	60	80	90
Tall shrubs						
Alaska huckleberry (*Vaccinium alaskaense*)	3	2	7	15		Tr
red huckleberry (*Vaccinium parvifolium*)	6		7	8	Tr	
salmonberry (*Rubus spectabilis*)	1	Tr		1	Tr	
vine maple (*Acer circinatum*)			Tr			

Lifeform	Lower watershed			Upper watershed		
	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
red elderberry (*Sambucus racemosa*)				Tr		
Low shrubs						
salal (*Gaultheria shallon*)	5		60	Tr		
Oregon grape (*Berberis nervosa*)	Tr			Tr		
Herbs						
swordfern (*Polystichum munitum*)	15	30			1	
deerfern (*Blechnum spicant*)	1	Tr	Tr	4		
ladyfern (*Athyrium filix-femina*)	2	1				
western springbeauty (*Montia sibirica*)					Tr	
Oregon oxalis (*Oxalis oregana*)	40	65			70	
three-leaved coolwort (*Tiarella trifoliata*)				Tr		
twayblade (*Listera* spp.)				Tr		Tr
Smith's fairybells (*Disporum smithii*)	Tr	Tr		Tr	Tr	
fireweed (*Epilobium angustifolium*)					Tr	
white hawkweed (*Hieracium albiflorum*)	Tr				Tr	
white trillium (*Trillum ovatum*)	Tr	1		Tr		
starry solomonplume (*Smilacina racemosa*)				Tr		
trail plant (*Adenocaulon bicolor*)	Tr					

Lifeform	Lower watershed			Upper watershed		
	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
wall lettuce (*Latuca muralis*)	1					
sweetscented bedstraw (*Galium triflorum*)		Tr				
rattlesnake plantain (*Goodyera oblongifolia*)	Tr		Tr			
small-flowered wood-rush (*Luzula parviflora*)	Tr	Tr		Tr		
coast boykinia (*Boykinia elata*)		Tr				
deerfoot vanillaleaf (*Achlys triphylla*)		Tr			11	
Moss or lichen						
Oregon beaked moss (*Eurhynchium oreganum*)	8	5	3	—	Tr	5
little shaggy moss (*Rhytidiadelphus loreus*)		25	5	—	Tr	
Mnium spp.		2				1
mountain fern moss (*Hylocomium splendens*)		8				
juniper haircap moss (*Polytrichum juniperinum*)		Tr				
broom moss (*Dicranum scoparium*)		4	3			
lungwort (*Lobaria oregana*)	Tr		—	Tr		
common witch's hair (*Alectoria sarmentosa*)						Tr

Plots 1 and 2 represent the same community type but have subtle differences because of aspect.
Cover values: Tr <1%; 1%–10% by 1 percent increments; 15%–100% by 5 percent increments.

Hoh Lake Watershed

Plot 1	Plot 2	Plot 3
Abies amabilis - Tsuga mertensiana/ Vaccinium membranaceum	*Abies amabilis - Tsuga mertensiana/ Vaccinium membranaceum*	*Abies amabilis- Tsuga mertensiana/ Erythronium montanum*
Plot 4	Plot 5	
Abies amabilis/ Rhododendron albiflorum	*Abies amabilis- Tsuga mertensiana/ Erythronium montanum*	

Lifeform	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Rock (> 8 cm)	9	50	8	4	20
Bare soil	5	0	0	Tr	0
Litter	60	45	65	45	50
Tall shrubs					
Alaska huckleberry (*Vaccinium alaskaense*)	3	9	6	8	Tr
big huckleberry (*Vaccinium membranaceum*)	5	12	2	2	2
blueleaf huckleberry (*Vaccinium deliciosum*)			Tr		
oval-leaf huckleberry (*Vaccinium ovalifolium*)				4	Tr
white rhododendron (*Rhododendron albiflorum*)				35	
rustyleaf (*Menziesia ferruginea*)			Tr	7	Tr
Sitka mountain ash (*Sorbus sitchensis*)					
Low shrubs					
slender gaultheria (*Gaultheria ovatifolia*)			Tr		
pink mountain heather (*Phyllodoce empetriformis*)				15	
strawberry-leaf blackberry (*Rubus pedatus*)			Tr	6	
Herbs					
swordfern (*Polystichum munitum*)	Tr			1	

Lifeform	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Beargrass (*Xerophyllum tenax*)	Tr	1			
avalanche fawnlily (*Erythronium montanum*)	2	2	7	20	3
western springbeauty (*Montia sibirica*)	Tr				
twayblade (*Listera* spp.)	Tr	1			
rattlesnake plantain (*Goodyera oblongifolia*)	Tr				
three-leaved coolwort (*Tiarella trifoliata*)					Tr
one-sided wintergreen (*Pyrola secunda*)		Tr			
wax-flower (*Pyrola uniflora*)		Tr			
Sitka valerian (*Valeriana sitchensis*)		Tr			
wood-rush (*Luzula* spp.)		Tr			
white trillium (*Trillium ovatum*)		Tr			
woodland bear-tongue (*Nothochelone nemorosa*)		Tr			
Moss or lichen					
common witch's hair (*Alectoria sarmentosa*)	3		25	8	3
broom moss (*Dicranum scoparium*)	1		4	3	2
freckle pelt (*Peltigera aphtosa*)				Tr	
robust moss (*Rhytidiopsus robusta*)				Tr	

Plots 1 and 2 represent the same community type but have subtle differences because of aspect.
Plots 3 and 5 represent the same community type but have subtle differences because of aspect.
Cover values: Tr <1%; 1%–10% by 1 percent increments; 15%-100% by 5 percent increments.

Appendix D. Biomass distribution (Mg/ha) [a] by plot in the West Twin Creek and Hoh Lake watersheds, Olympic National Park, Washington.

Biomass distribution (Mg/ha)[a] by plot in the West Twin Creek watershed

	Lower Watershed			Upper watershed		
	Plant Community Type					
	Tsuga heterophylla/ Polystichum munitum/ Oxalis oregana	*Tsuga heterophylla/ Polystichum munitum Oxalis oregana*	*Tsuga heterophylla/ Gaultheria shallon*	*Tsuga heterophylla-Abies amabilis Vaccinium alakaense*	*Tsuga heterophylla/ Oxalis oregana*	*Tsuga heterophylla-Abies amabilis/ Depauperate*
	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
Biomass Component						
Tree						
Foliage	30.1	16.2	40.9	34.2	25.9	37.3
Branches	123.0	80.6	130.1	102.6	183.6	110.6
Roots	419.5	133.0	366.1	263.0	199.7	185.5
Bole + Bark	1159.3	385.5	801.0	536.8	375.6	524.0
Total Live Tree	1731.9	615.3	1338.2	936.6	784.8	857.5
Shrub						
Leaves	0.0	0.0	0.4	0.1	no shrubs	0.1
Stems	0.1	0.2	0.9	0.1	no shrubs	0.1
Herb						
Leaves	0.4	0.2	0.0	0.1	0.1	0.1
Stems	0.4	0.3	0.0	0.1	0.0	0.1

Biomass distribution (Mg/ha)[a] by plot in the West Twin Creek watershed (continued)

	Lower Watershed			Upper watershed		
	Plant Community Type					
	Tsuga heterophylla/ Polystichum munitum/ Oxalis oregana	*Tsuga heterophylla/ Polystichum munitum Oxalis oregana*	*Tsuga heterophylla/ Gaultheria shallon*	*Tsuga heterophylla-Abies amabilis Vaccinium alakaense*	*Tsuga heterophylla/ Oxalis oregana*	*Tsuga heterophylla-Abies amabilis/ Depauperate*
	Plot 1	Plot 2	Plot 5	Plot 3	Plot 4	Plot 6
Total Live Biomass	1732.8	616.0	1339.5	937.0	784.9	857.7
Detritus						
Standing Dead (snags)	24.0	131.2	570.6	143.2	48.9	107.8
Fallen Logs	99.7	96.9	80.2	85.2	93.3	98.6
Total CWD	123.7	228.1	650.8	228.4	142.3	206.4
Dead Shrubs	0.1	0.0	0.1	0.0	no dead shrubs	no dead shrubs
Dead Herbs	0.7	0.6	no dead herbs	0.1	0.1	no dead herbs
Forest floor	72.7	—	121.4	107.9	65.7	81.1
Soil	376.7	—	281.4	471.0	399.6	303.9
Ecosystem Total	2306.7	—	2393.2	1744.4	1392.7	1449.2

[a] Understory vegetation was empirically derived. Tree biomass was estimated using equations by Gholz et al. 1979. Coarse woody debris dimensions were measured empirically and biomass was calculated using formulas from Hartman et al. (1981) for logs, and using formulas from Husch et al. (1972) and Means et al. (1992) for snags. Density values for coarse woody debris were taken from Means et al. (1992). Forest floor biomass was determined by sample weight and diameter of corer. Soil values were derived from % organic matter and bulk density values from 0-40 cm. All values are corrected for slope.

Biomass distribution (Mg/ha)[a] by plot in the Hoh Lake watershed

	Plant Community Type				
	Abies amabilis-Tsuga mertensiana Vaccinium membranaceum	*Abies amabilis-Tsuga mertensiana Vaccinium membranaceum*	*Abies amabilis-Tsuga mertensiana/ Erythronium monatum*	*Abies amabilis/ Rhododendron albiflorum*	*Abies amabilis-Tsuga mertensiana/ Erythronium monatum*
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Biomass Component					
Tree					
Foliage	61.3	54.5	47.0	21.6	40.5
Branches	92.4	103.6	140.3	44.8	131.2
Roots	203.9	214.6	298.6	108.3	296.3
Bole + Bark	495.1	565.6	885.3	304.3	924.8
Total Live Tree	852.7	938.3	1371.2	479.0	1392.8
Detritus					
Standing Dead (snags)	369.3	26.2	7.2	11.5	308.4
Fallen Logs	14.1	43.3	35.7	10.9	84.0
Total CWD	383.4	69.5	42.9	22.4	392.4
Total	1236.1	1007.9	1414.1	501.4	1785.2

[a] Tree biomass was estimated using equations by Gholz et al. (1979). Coarse woody debris dimensions were measured empirically and biomass was calculated using formulas from Hartman et al. (1981) for logs, and using formulas from Husch et al. (1972) and Means et al. (1992) for snags. Density values for coarse woody debris were taken from Means et al. (1992). Values are corrected for slope.

Appendix E. Program Publications and Abstracts.

Blew, R. D. and R. L. Edmonds. 1994a. Precipitation chemistry along a transect inland from the Pacific coast and stream chemistry on the Olympic Peninsula, Washington. 79th Annual Meeting of the Ecological Society of America, 7-11 August, 1994. Bulletin of the Ecological Society of America 75(2):17 (Supplement).

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