Estimating Ground-Water Recharge from Precipitation on Whidbey and Camano Islands, Island County, Washington, Water Years 1998 and 1999

Prepared in cooperation with the
ISLAND COUNTY HEALTH DEPARTMENT

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 03-4101
Version 1.20, August 2004

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By S. S. Sumioka and H. H. Bauer

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Tacoma, Washington
2003

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND DATUM

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch (in.)	25.4	millimeters
inch per day (in/d)	25.4	millimeter per day
inch per year	25.4	millimeter per year
inch per inch	25.4	millimeter per inch
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

Concentrations of chemical constituents in water are given in milligrams per liter. One milligram per liter is equivalent to one thousand micrograms per liter. One microgram per liter is equivalent to “parts per billion.”

The flux of chemical constituents in atmospheric deposition is expressed as milligrams per square meter (mg/m^2). For example, the flux, in milligrams per square meter per year [$(mg/m^2)/yr$], can be multiplied by the precipitation in millimeters per year (mm/yr) to obtain the concentrations in milligrams per liter of a constituent in wet or dry deposition.

DATUM

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

Estimating Ground-Water Recharge from Precipitation on Whidbey and Camano Islands, Island County, Washington, for Water Years 1998 and 1999

By S. S. Sumioka and H. H. Bauer

ABSTRACT

Ground-water recharge from precipitation to unconsolidated deposits on Whidbey and Camano Islands, Washington, was estimated for water years 1998-99 using a near-surface water-balance method and a chloride mass-balance method.

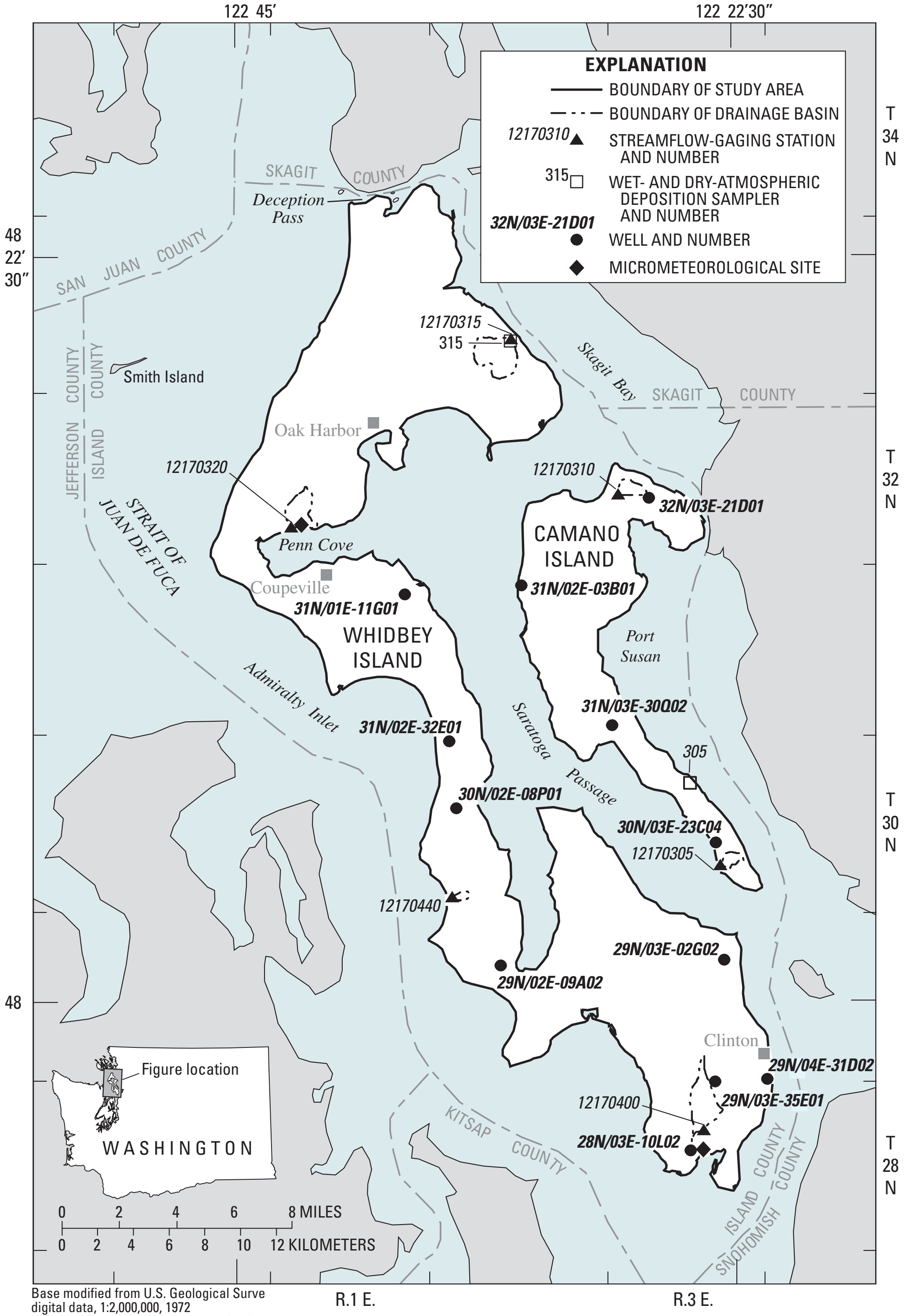
A daily near-surface water-balance method, the Deep Percolation Model (DPM), was used to simulate water budgets for October 1, 1997 through September 30, 1999 (water years 1998-99) for six small drainage basins—four on Whidbey Island and two on Camano Island. Adjusted parameters from the DPM for each small basin were then used in island-wide DPM simulations. A spatial distribution of annual recharge was simulated for each island, with island averages of 5.71 inches per year for Whidbey Island and 5.98 inches per year for Camano Island. The spatial distribution of simulated annual recharge for each island reflects variations in precipitation amounts and the distribution of surficial materials. DPM results indicate that recharge generally is higher in areas underlain by coarse-grained deposits (outwash) than in areas underlain by fine-grained deposits (till).

A chloride mass-balance method was used to estimate combined recharge to unconsolidated deposits on Whidbey and Camano Islands. The average combined recharge for Whidbey and Camano Islands estimated by this method was 2.00 inches per year. The range of chloride concentrations in ground-water samples from selected wells indicates that the average recharge to unconsolidated deposits ranges from 0.78 to 7.81 inches per year. Sources of chloride in ground water other than from the atmosphere would cause recharge estimated by the chloride mass-balance method to be less than the actual recharge, therefore, these estimates may represent lower limits.

INTRODUCTION

The principal source of drinking water on Whidbey and Camano Islands, located off the northwestern coast of Washington (fig. 1), is ground water derived from unconsolidated glacial- and interglacial-deposit aquifers. Some uncertainty exists regarding the quantity of recharge from precipitation reaching the aquifers used for water supply.

In 1997, the U.S. Geological Survey (USGS), in cooperation with the Island County Health Department, began a study to estimate recharge from precipitation to unconsolidated glacial- and interglacial-deposit aquifers on Whidbey and Camano Islands. Indirect recharge estimates can be subject to large errors, and therefore, when possible, more than one method should be used to verify the estimates. A commonly used indirect method equates ground-water recharge to measured ground-water discharge. However, much of the ground water in Island County probably discharges through the seabed, and this method cannot be used (Sapik and others, 1988). Therefore, two indirect methods were used: a near-surface water-balance method and a chloride mass-balance method.



Base modified from U.S. Geological Surve
digital data, 1:2,000,000, 1972
Universal Transverse Mercator projection,
Zone 10

Figure 1. Locations of six study basins on Whidbey and Camano Islands, Island County, Washington.

Purpose and Scope

The purpose of this report is to present the results of a study to (1) estimate ground-water recharge from precipitation to unconsolidated glacial- and interglacial-deposit aquifers in six study basins on Whidbey and Camano Islands for water years 1998-99 using a near-surface water-balance method and a chloride mass-balance method; (2) use the ground-water recharge estimates from the chloride mass-balance method to assess the reasonableness of estimates from the water-balance method; and (3) simulate ground-water recharge for the entire areas of Whidbey and Camano Islands for water years 1998-99 using recharge estimates from the near-surface water-balance method for the six study basins.

The near-surface water-balance was simulated on a daily basis using the Deep Percolation Model (DPM) (Bauer and Vaccaro, 1987; Bauer and Mastin, 1997) to estimate ground-water recharge. Annual ground-water recharge also was estimated using the chloride mass-balance method (Eriksson and Khunakasem, 1969). Data required to apply these methods were obtained from existing databases and collected as part of this study. Geographic information system programs (ARC/INFO and ARC/GRID) were used to enter study basin data into the DPM.

Data collected during water years 1998-99 included streamflow, precipitation, precipitation throughfall, shortwave solar radiation, air temperature, and atmospheric-chloride deposition (in precipitation and as dry deposition). Chloride concentrations in ground water were determined from samples collected at selected wells located throughout the study area in the autumn of 2000. Additional data (geology, soil properties, topography, and land cover) were obtained from existing databases.

Previous Studies

Anderson (1968) described the location and availability of ground water in Island County as well as the geographic and hydrologic setting of the county and the areal and vertical extent of ground water. In the descriptions of the hydrologic cycle in Island County, only a few general statements were made pertaining to ground-water recharge.

Cline and others (1982) summarized existing data regarding ground-water resources of Island County and identified areas where overpumping was evident or appeared imminent. In addition, water levels and chloride concentrations in wells were collected to identify existing and potential areas of seawater intrusion. Recharge for Island County was determined using a finite-difference model to simulate the position of the freshwater-seawater interface and was estimated to be 4.9 inches per year.

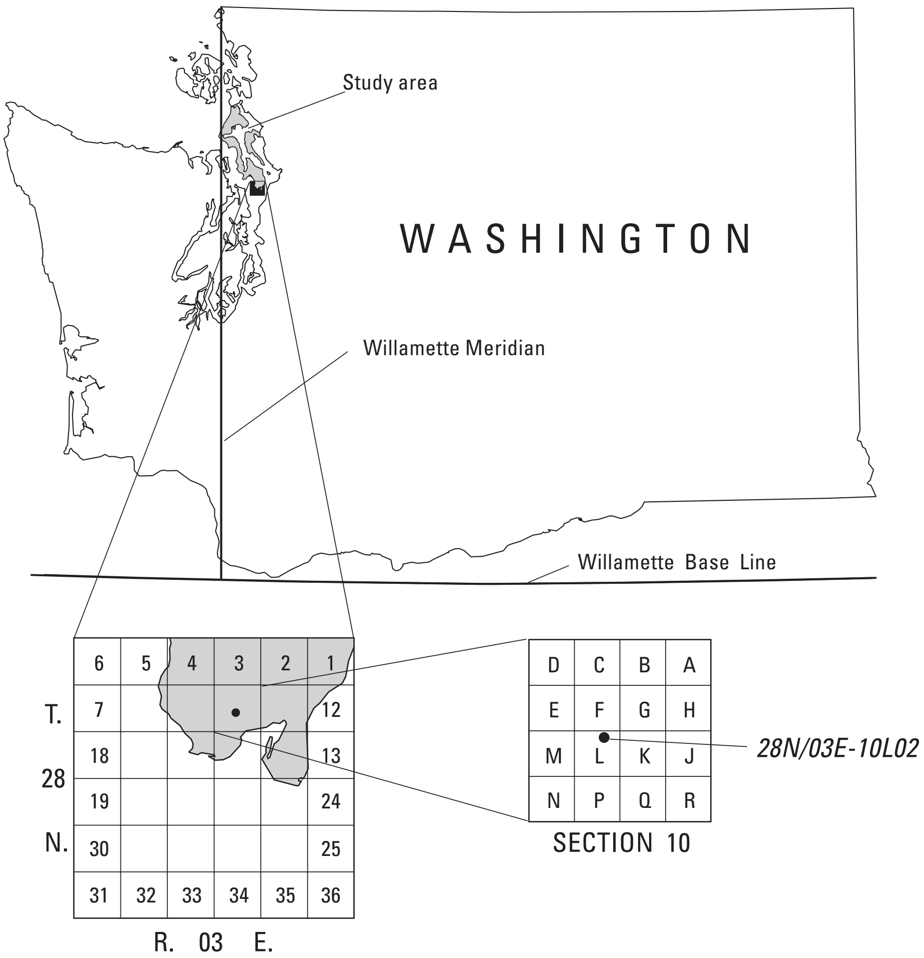
Sapik and others (1988) also summarized the geohydrology of Island County, and constructed a calibrated three-dimensional ground-water flow model to simulate the flow of fresh ground water in a multiple-layered aquifer system containing freshwater and seawater, separated by a sharp interface. Recharge for Island County was simulated using a daily soil-moisture accounting method and was estimated to be 12 inches per year.

Well-Numbering System

The well-numbering system used by the USGS in the State of Washington is based on the rectangular subdivision of public land, and indicates township, range, section, and 40-acre tract within the section (fig. 2). For example, in well number 28N/03E-10L02, the part preceding the hyphen indicates the township and range (Township 28 North, Range 3 East). The first number following the hyphen (10) indicates the section number, and the letter (L) gives the 40-acre tract within that section. The last number (02) is the sequence number of the well in that 40-acre tract.

Acknowledgments

Appreciation is expressed to all landowners who gave their permission to establish streamflow-gaging stations and meteorological sites on their property. Acknowledgment also is given to well owners who gave their permission to sample their wells to obtain data for the chloride mass-balance calculations.



Explanation Well-Numbering System

The USGS assigns numbers to wells and springs in Washington that identify their location in a township, range, and section. Well number 28N/03E-10L02 indicates successively, the township (T. 28 N) and range (R. 03 E) north and east of the Willamette Base Line and Meridian. The first number following the hyphen indicates the section (10) within the township, and the letter following the section number gives the 40-acre subdivision of the section, as shown above. The number (02) following the letter is the sequence number of the well within the 40-acre subdivision. This number indicates that the well was the second one inventoried by USGS personnel in that 40-acre tract. An "S" following the sequence number indicates that the site is a spring; a "D1" after the sequence number indicates that the original reported depth of the well has been changed once, and successive numbers indicate the number of changes in well depth.

Figure 2. Well-numbering system used in Washington.

DESCRIPTION OF STUDY AREA

The two major islands of Island County occupy an area of about 210 square miles off the coast of northwestern Washington State (fig. 1). The larger of the islands, Whidbey, has an area of about 168 square miles and Camano Island has an area of about 39 square miles. Land surface on both islands consists of rolling uplands, ranging in altitude from sea level to about 600 feet above sea level.

Description of Study Basins

Six small basins, four on Whidbey Island and two on Camano Island, were selected following field reconnaissance to represent common flow regimes, precipitation, surficial material characteristics, and land covers in Island County (fig. 1). The principal characteristics of each drainage basin and the USGS stream-gaging station numbers in the USGS database are shown in table 1.

Two of the basins are drained by perennial streams, the others are drained by intermittent streams. Streamflow-gaging stations were established in each of the six basins and equipped with data loggers. For this report, basins will be referred to by the USGS gaging station number.

Gaging station 12170305 is located on an intermittent stream draining into Saratoga Passage, on the west side of southern Camano Island. The contributing drainage area for this gaging station is 0.27 square mile. Land cover in the basin consists of coniferous forest with small areas of grassland. The basin is underlain by coarse to fine-grained unconsolidated deposits.

Table 1. Selected basin characteristics of the six study basins on Whidbey and Camano Islands, Island County, Washington, water years 1998-99

[DPM, Deep Percolation Model]

Basin	Contributing drainage area (square miles)	Gaging station No.	Predominant soil type	Geologic material underlying soil	Predominant DPM land cover	Precipitation (inches per year)		
						Long-term average annual	Water year 1998	Water year 1999
Southern Camano Island	0.27	12170305	Alderwood	Coarse to fine-grained unconsolidated deposits	Coniferous forest	27.7	28.9	33.9
Northern Camano Island	0.42	12170310	Bow	Coarse to fine-grained unconsolidated deposits	Coniferous forest	22.8	24.8	28.2
Northern Whidbey Island	1.6	12170315	Whidbey	Fine-grained unconsolidated deposits	Coniferous forest	24.5	25.3	31.1
Penn Cove, northern Whidbey Island	0.97	12170320	Swantown	Fine-grained unconsolidated deposits	Grassland	16.6	17.8	22.7
Cultus Creek, southern Whidbey Island	1.5	12170400	Whidbey	Fine-grained unconsolidated deposits	Coniferous forest	29.4	29.3	37.0
South Whidbey State Park, Whidbey Island	0.13	12170440	Whidbey	Fine-grained unconsolidated deposits	Coniferous forest	25.0	26.0	31.5

Station 12170310 is located on an intermittent stream on northern Camano Island. The natural drainage pattern for this basin is disrupted by a roadside ditch that channels runoff to Puget Sound. The contributing drainage area for the gaging station is 0.42 square mile. Land cover in the basin consists of coniferous forest. The basin is underlain by coarse to fine-grained unconsolidated deposits.

Station 12170315 is located on a perennial stream on the northern end of Whidbey Island near Skagit Bay. The contributing drainage area for the gaging station is 1.63 square miles. Land cover in the basin consists of coniferous forest and grass and cropland. This basin is underlain by fine-grained unconsolidated deposits.

Station 12170320 is located on an intermittent stream in north-central Whidbey Island on the northern side of Penn Cove. The contributing drainage area for the gage is 0.97 square mile. Land cover in this basin consists of grassland, coniferous forest, and some cropland. This basin is underlain by fine-grained unconsolidated deposits.

Station 12170400 is located on Cultus Creek, a perennial stream on southern Whidbey Island. The contributing drainage area for the gaging station is 1.5 square miles. Land cover in this basin consists primarily of coniferous forest. The basin is underlain by fine-grained unconsolidated material.

Station 12170440 is located on an unnamed stream on the west side of Whidbey Island, and drains into Admiralty Inlet. The contributing drainage area for the gaging station is 0.13 square mile. Land cover consists entirely of coniferous forest. The basin is underlain by fine-grained unconsolidated deposits.

Data also were collected at other sites on the two islands outside the study basins. Two temporary micrometeorological sites that measured solar radiation and air temperature were installed, one on northern Whidbey Island overlooking Penn Cove and one on southern Whidbey Island near the gaging station on Cultus Creek (station 12170400). Atmospheric deposition data were collected at one site on each island: on northern Whidbey Island near gaging station 12170315 and on the east side of southern Camano Island near gaging station 12170305 (the micrometeorological site was assigned the same number as the gaging station).

Climate and Precipitation

Island County has a temperate, marine climate with dry summers and wet winters. Average annual maximum temperature for 1984-2000 was 57.9 ^{o}F at Coupeville on Whidbey Island; average annual minimum temperature for the same period was 41.7 °F. July typically is the warmest month, with an average maximum temperature of 71.3 °F and January is the coldest month, with a long-term average minimum temperature of 50.3 ^{o}F (Western Region Climate Center, 2001).

Data from PRISM (Precipitation-Elevation Regression on Independent Slopes Model; Daly and others, 1994) indicate that average annual precipitation from 1961 to 1990 ranged from 35 inches on southern Whidbey Island to 29 inches on northern Whidbey Island, and from 25 inches on western Camano Island to about 31 inches on the northern part of Camano Island nearest the mainland (fig. 3). Some areas of Island County are influenced by the rainshadow effect of the Olympic Mountains, about 50 miles southwest of Island County. The central part of Whidbey Island receives fewer than 23 inches of average annual precipitation.

Hydrogeology

Unconsolidated Quaternary-age glacial and interglacial deposits overlie Tertiary- to Jurassic-age bedrock (fig. 4) throughout most of Whidbey and Camano Islands (Easterbrook, 1968; Cline and others, 1982). Bedrock exposures are limited to the Deception Pass area at the northern end of Whidbey Island (fig. 1), and the low tidal zone at Rocky Point, 5 miles to the south. Unconsolidated deposits consist of clay, silt, sand, and gravel, and range in thickness from a few hundred feet to about 3,000 feet in the central part of Whidbey Island (Cline and others, 1982; Pessel and others, 1989; Yount and others, 1993). Bedrock in the study area consists of sedimentary and metasedimentary units of marine origin, and volcanic rock (Cline and others, 1982; Whetten and others, 1988; Yount and Gower, 1991).

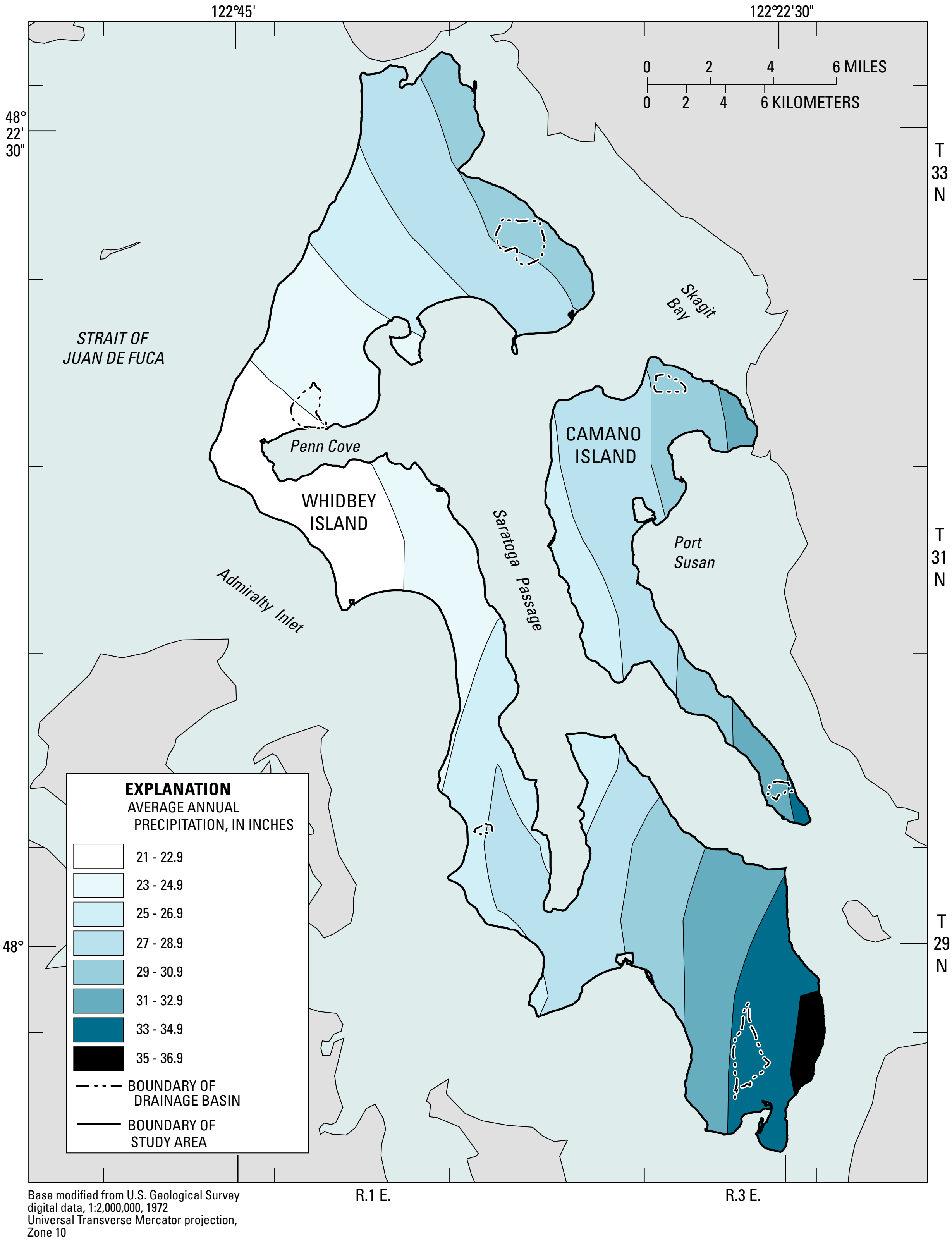
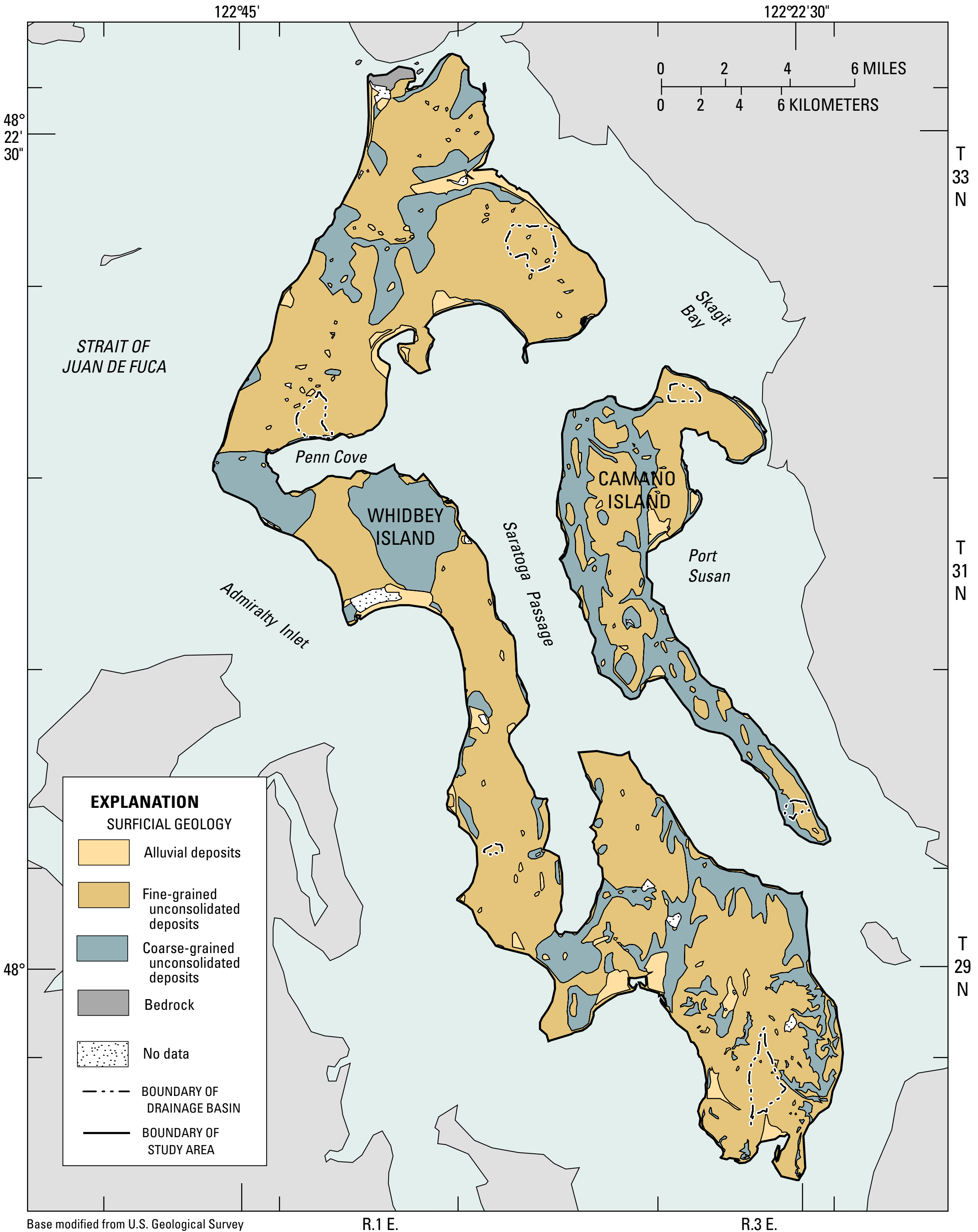


Figure 3. Average annual precipitation on Whidbey and Camano Islands, Island County, Washington. Precipitation values are from gridded values from PRISM (Oregon Climate Services, 1999) for 1961-90.



Base modified from U.S. Geological Survey
digital data, 1:2,000,000, 1972
Universal Transverse Mercator projection,
Zone 10

Figure 4. Generalized surficial geology of Whidbey and Camano Islands, Island County, Washington.

Most wells in the county (about 70 percent) are 200 feet or less in depth and obtain water from unconsolidated sand and gravel deposits at depths of a few tens of feet above sea level to about 200 feet below sea level (locally known as the sea-level aquifer). More than 90 percent are less than 300 feet deep. Most of the deeper wells (greater than 300 feet) are public-supply wells serving the cities and housing developments in the county. The sea-level aquifer is both confined and unconfined over its extent (Sapik and others, 1988). Deposits in the sea-level aquifer appear to be more continuous than similar deposits at shallower depths relative to land surface (Cline and others, 1982). Sand and gravel water-bearing deposits above the sea-level aquifer occur primarily in northeastern and southeastern Whidbey Island and likely are of limited vertical and areal extent. Sand and gravel water-bearing deposits below the sea-level aquifer are not widely used as a source of water and little is known about the extent or hydraulic properties of these deeper deposits. Bedrock in Island County generally yields little or no water to wells (Cline and others, 1982).

Recharge, Evapotranspiration, and Discharge

Direct recharge to ground water from precipitation (deep percolation) results from the infiltration of precipitation through the soil horizon and below the root zone to the water table. Factors controlling recharge from precipitation include storm duration and intensity, land cover, soil characteristics, and thickness of the unsaturated zone. Factors that control evapotranspiration (air temperature, shortwave solar radiation, wind speed, soil type, vegetation type, and land-surface slope) also affect rates of deep percolation. Deep percolation in many areas may be further limited by low-permeability materials underlying soils. For a period of time during and following a storm, rainwater infiltrating the soil that encounters low-permeability glacial till may move short distances horizontally, to local drainages that discharge directly to the ocean and thus, is not available for recharging the ground-water system (Anderson, 1968). The collection of detailed streamflow data was therefore an essential component of data-collection activities for this study to estimate these direct discharges to the ocean. Deep percolation in Island County probably is less than in most of western Washington because portions of the county are in the rainshadow of the Olympic Mountains and receive less precipitation.

If soil-moisture holding capacities and root-zone depths are sufficiently large, recharge (rainwater not evapotranspired) could, in places, be nearly zero. Additionally, results from recent USGS studies in coniferous forested areas in the Puget Sound Lowland of western Washington have shown that measured daily evaporation frequently exceeds daily PET (potential evapotranspiration) computed by traditional methods. Large amounts of advective evaporation by vegetation of intercepted precipitation (as much as 10 to 18 inches annually) are not accounted for in the traditional methods (Bauer and Mastin, 1997; Bidlake and Payne, 2001). The quantity of recharge in these areas could be less than would be expected.

Under natural conditions, ground-water recharge in Island County is in approximate balance with ground-water discharge to the ocean, to gaining reaches of streams, and to plant transpiration in areas of shallow water table. Withdrawals from wells and resultant ground-water level declines may decrease outflow to natural discharge areas and increase seawater intrusion of freshwater aquifers. Withdrawals also may decrease baseflow to streams leading to degradation of wildlife habitat. Most of the water pumped from wells in Island County is used for household purposes, with irrigation, commercial, and industrial uses accounting for the remainder.

ESTIMATES OF GROUND-WATER RECHARGE

Ground-water recharge cannot be measured directly and is difficult to accurately estimate. Indirect recharge estimates can be subject to large errors and therefore, when possible, more than one method should be used to verify the estimates. A common indirect method for hydrologic systems under equilibrium conditions is to equate ground-water recharge to ground-water discharge. However, much of the ground water in Island County probably discharges through the seabed, and this method cannot be used because the equilibrium equation, in this case, has two unknown quantities, ground-water discharge directly to the sea and recharge. Therefore, two other indirect methods were used: a near-surface water-balance method and a chloride mass-balance method.

Near-Surface Water-Balance Method

The primary method for estimating recharge from precipitation for this study was the near-surface water-balance model. The DPM, developed for eastern Washington (Bauer and Vaccaro, 1987) and modified for western Washington (Bauer and Mastin, 1997), was selected to estimate recharge from precipitation for this study. The DPM uses a daily water-budget approach to estimate recharge. For each cell, the following equation is solved, daily, for a column extending from the vegetation covering the land surface down to the bottom of the root zone.

$$RECHRG = PRECIP - EVINT - EVSOL - EVSNW - TR - RO - CHGINT - CHGSNW - CHGSM, \qquad (1)$$

where

RECHRG is	water percolating to below the root zone (recharge);
PRECIP is	precipitation;
EVINT is	evaporation of moisture intercepted by foliage (interception loss);
EVSOL is	evaporation from bare soil;
EVSNW is	sublimation;
TR is	transpiration;
RO is	direct runoff;
CHGINT is	change in moisture stored on foliage;
CHGSNW is	change in snowpack; and
CHGSM is	change in soil water in the root zone.

In this method, the model simulates daily fluxes of water into and out of a column extending from the top of foliage to the bottom of the root zone and accounts for changes in water content. Ground-water recharge is assumed to equal the water moving vertically downward from the bottom of the root zone (deep percolation).

Data required for the DPM include daily values of precipitation, precipitation throughfall (rain that reaches land surface beneath vegetation), air temperature, shortwave solar radiation, land-surface altitude, and properties of soils and land cover (vegetation type, surface water, or impervious surfaces), and "direct runoff." Direct runoff is herein defined as surface-water runoff plus water that drains from partially saturated soil to local drainage features. Areal variation in soils, vegetation, and land cover are accounted for in the DPM by dividing a drainage area into a number of cells of any size or shape such that each cell represents a single altitude, land cover, soil type, and climate regime. Areal variation in precipitation, temperature, and solar radiation were accounted for by using precipitation recorder stations spread within and (or) near the study basin and the two micrometeorological sites.

Soil moisture is accounted for, daily, by adding surplus water (precipitation plus snowmelt minus sublimation minus interception minus surface runoff) to the soil. Water is then removed by transpiration and soil evaporation. Surplus water is added to the soil-moisture reservoir layer by layer, using 6-inch layers for each soil. If the surplus is less than the difference between the available water capacity (field capacity minus the wilting point) and the current soil-moisture content, the current moisture content is increased by the surplus. If the surplus is greater than the difference, the water content of the soil is brought to available water capacity and the remaining surplus is passed down to the next layer. This process continues until there is no more surplus water or until all layers are filled. Any surplus after all layers are at field capacity is deep percolation.

The initial soil-moisture content was estimated to be a fraction of field capacity. This fraction was arrived at by evaluating precipitation prior to the simulation period and selecting an appropriate estimate based on the thickness of the soil and the available water capacity.

Evapotranspiration depends on soil-moisture availability as well as on meteorological conditions and their effects on vegetation. Evapotranspiration depletes soil moisture and shallow ground water; therefore, evapotranspiration and soil moisture must be calculated at sufficiently frequent intervals. The DPM uses a daily time step, primarily because daily meteorological data generally are available. A daily time step is sufficiently short to assure that soil-moisture variations are small enough to avoid significant error in the evapotranspiration calculations.

For each day of a DPM simulation, deep percolation for each cell is computed as precipitation minus evapotranspiration minus direct runoff minus the change in soil moisture in the root zone. Precipitation and the other weather variables from which evapotranspiration is computed are determined for each cell by simple distance extrapolation from the data-collection sites. Direct runoff for each cell is much more difficult to estimate. Although the total direct runoff for a drainage basin (total of all cells) can be readily estimated from the stream-discharge measurements, the contributions from individual cells can vary greatly depending on the soil and subsoil properties. For example, during a storm, a cell with a thick soil underlain by a permeable glacial-outwash deposit (sand and gravel) may not contribute to direct runoff, whereas a cell with thin soil overlying poorly permeable glacial till will produce a large quantity of direct runoff. The DPM disaggregates the total direct runoff to the cells in proportion to a calculated or theoretical direct runoff for each cell (for details, see Bauer and Mastin, 1997). A specified infiltration capacity for each cell, based on soils and subsoil properties, is incorporated into these calculations. By adjusting this parameter, a water balance is achieved for the modeled area. If the infiltration capacity is set too large, too little water will be available to support the measured total direct runoff. This is indicated as a "negative” soil-saturation deficit in the DPM output (DEFICIT); conversely, a positive soil-saturation deficit results when the infiltration capacities are set too small.

Three steps were used to estimate recharge using the near-surface water-balance method in this study: (1) all data needed for applying the DPM to the study area were assembled, checked for accuracy, and divided into uniform cells (a process known as "gridding"); (2) the DPM was adjusted for each of the six study basins; and (3) the DPM was applied to the entire island using results of the study basin simulations. Island-wide direct runoff data were not available, therefore, DPM simulations in step 3 used simulated direct runoff in place of disaggregated measured runoff.

Data Collection and Processing

In step 1 of the process, each of the six study basins was divided into a uniform grid of cells, each 30 meters (98.45 feet) on a side and with an area of 900 square meters (0.222 acre). The 30-meter cell size was selected to match the 30-meter resolution of the land-cover data, which was the highest resolution of all the coverages used. Each cell was assigned the predominant soil type and land use that occurred in the cell (tables 2 and 3). When the island-wide models were run, cell size was increased in order to accommodate file-size limitations in pre- and post-processing software. Increasing the cell size of a model may likely lead to a loss of resolution in model results, but a similar cell size was used for a recharge study of the Sequim-Dungeness area of Clallam County, Washington with good results (Thomas and others, 1999). The cell sizes for island-wide modeling was increased to a uniform grid of cells 210 meters (689 feet) on a side and an area of about 44,000 square meters (about 11 acres). General characteristics of the modeled basins and islands are shown in table 4.

Daily values of precipitation, precipitation throughfall, shortwave solar radiation, air temperature, and stream-discharge data collected by the USGS during water years 1998-99 were used in the model simulations. Most properties of soils, vegetation, and land cover were obtained from previous studies of Island County. DPM model parameters defining maximum clear-sky solar shortwave radiation, non-plant factors affecting transpiration, and snowmelt and sublimation were compiled from values used in two previous applications of the DPM to areas of western Washington. Bauer and Mastin (1997) estimated recharge in till-covered areas and Bidlake and Payne (2001) estimated recharge in areas covered by till and glacial outwash. These two studies used locally measured meteorological and hydrologic data, including direct stream runoff, soil-water content, and ground-water levels. Parameter values from these previous two studies were used in this study because all three study areas have similar climate, vegetation, geology, and topography.

Table 2. Predominant soil types used in the Deep Percolation Model to determine recharge from precipitation for the six study basins on Whidbey and Camano Islands, Island County, Washington

[**Area**: Percent, percentage of total basin area. Percentages do not always equal 100 percent because of rounding. –, no data]

Soil series	Whidbey Island								Camano Island			
	12170315		12170320		12170400		12170440		12170305		12170310	
	Area											
	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent
Alderwood	–	–	–	–	–	–	–	–	0.22	80.65	0.02	4.42
Bellingham	0.02	1.17	0.01	1.12	–	–	–	–	–	–	.02	3.94
Bow	–	–	–	–	–	–	–	–	–	–	.38	91.17
Casey	–	–	.20	21.08	–	–	–	–	–	–	–	–
Coveland	–	–	.10	10.25	–	–	–	–	–	–	–	–
Everett	–	–	–	–	–	–	–	–	–	–	.002	.47
Hoypus	.09	5.77	.03	2.71	0.01	0.69	–	–	–	–	–	–
Indianola	–	–	–	–	–	–	–	–	.04	13.00	–	–
Keystone	.03	1.72	–	–	.29	19.25	–	–	–	–	–	–
Norma	.07	4.50	.03	3.16	.06	4.11	–	–	.02	5.47	–	–
Rifle	–	–	–	–	.02	1.55	–	–	–	–	–	–
Rough, broken land	–	–	–	–	–	–	–	–	.000	.004	–	–
Semiahmoo	.01	.89	.003	.27	–	–	–	–	–	–	–	–
Swantown	.005	.29	.30	30.65	–	–	–	–	–	–	–	–
Tanwax	.003	.21	–	–	.01	.76	–	–	.002	.88	–	–
Townsend	–	–	.17	17.11	–	–	–	–	–	–	–	–
Whidbey	1.39	85.46	.13	13.66	1.11	73.64	0.13	100.00	–	–	–	–

Table 3. Land-cover categories used in the Deep Percolation Model for the six study basins on Whidbey and Camano Islands, Island County, Washington

[**Area**: Percent, percentage of total basin area. Percentages do not always equal 100 percent because of rounding. –, no data]

Land cover	Whidbey Island								Camano Island			
	12170315		12170320		12170400		12170440		12170305		12170310	
	Area											
	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent	Square miles	Percent
Coniferous forest	1.44	88.16	0.29	29.90	1.5	94.12	0.13	100.00	0.25	91.67	0.34	81.60
Grass	.08	4.93	.58	59.62	.09	5.88	–	–	.02	8.33	–	–
Alfalfa	.11	6.92	.10	10.21	–	–	–	–	–	–	.08	18.40
Open water	–	–	.003	0.27	–	–	–	–	–	–	–	–
Total	1.63	–	0.97	–	1.5	–	0.13	–	0.27	–	0.42	–

Table 4. Grid dimensions for modeled basins and Whidbey and Camano Islands, Island County, Washington

[DPM, Deep Percolation Model. Percentages do not always equal 100 percent because of rounding and may not agree exactly with similar percentages in other tables in this report]

Basin/Island	Cell size used for DPM (meters)	Number of cells	Modeled area (square miles)
12170305	30 × 30	792	0.27
12170310	30 × 30	1,206	.42
12170315	30 × 30	4,704	1.6
12170320	30 × 30	2,794	.95
12170400	30 × 30	4,351	1.45
12170440	30 × 30	366	.13
Whidbey Island	210 × 210	9,840	167.5
Camano Island	210 × 210	2,294	39.1

Precipitation

Six continuous recording tipping-bucket precipitation gages were installed at locations near gaging stations established for this study—four on Whidbey Island and two on Camano Island—and data were collected during water years 1998-99 (fig. 5). Precipitation gages were connected to data loggers. Each bucket tip, representing 0.01 inch of precipitation, was counted and the total amounts recorded in the data logger at 60-minute intervals. Data were retrieved from the data loggers at about 1-month intervals.

Two of the tipping bucket gages on the northern and southern ends of Whidbey Island were set up as part of two temporary micrometeorological sites that also collected temperature and shortwave solar radiation (see section "Shortwave Solar Radiation and Temperature").

Precipitation Throughfall

Evaporation of precipitation temporarily stored on the foliage in forested areas proceeds at considerably faster rates than transpiration, especially during the winter months, and annually can be as much as 50 percent of the total precipitation for the Puget Sound area (Bauer and Mastin, 1997). During this investigation, throughfall (that part of precipitation not evaporated from foliage) was measured at two sites: a coniferous forest near gaging station 12170315 on the northern end of Whidbey Island and beneath a large maple tree on the southern end of Camano Island. Seven storage type precipitation gages were installed at each site, placed randomly under the leaf cover. One precipitation gage was placed in an adjacent open area as a control. Rainfall was measured monthly. Throughfall, as a percentage of precipitation, was calculated for the periods between measurements as the average of the leaf-cover gage precipitation divided by the precipitation measured in the gage in the open area.

Because measurement times were variable, a consistent basis was required to produce 24-hour values of throughfall for each site. This was done by calculating the average throughfall as a fraction of precipitation for each rainy period, separated by non-precipitation periods of 1 or more days. For each site, the throughfall fraction for each rainy period was then assumed to be the same for each of the days during the wet period.

Streamflow

Gage height was measured during water years 1998-99 at gaging stations established at the upstream opening of pre-existing stream culverts in each of the six study basins. Instantaneous discharge was measured monthly on each stream to construct a gage-height/discharge relation for a range of flows. Gage height was recorded every 15 minutes and averaged and stored as daily mean gage height. The gage height/discharge relation was used to convert daily mean gage height to daily mean discharge (fig. 6).

During data collection, stage recorders or data loggers sometimes malfunctioned, leading to the loss of stage records. Daily mean discharge for periods of missing record were estimated using a regression equation developed using data from gaging stations in the other study basins and data from Huge and Big Beef Creeks in Kitsap and Pierce Counties about 50 miles southwest of Island County. The streamflow data are summarized in table 5. Streamflow derived from ground-water discharge into a stream (baseflow) was estimated from the total-flow hydrograph based on the assumption that total streamflow is equal to baseflow during summer months when precipitation is minimal and soils are below field capacity. A smooth baseflow curve was drawn for dry periods and then extended backward in time using wet-season flows from the total-flow hydrograph as a maximum allowable baseflow value.

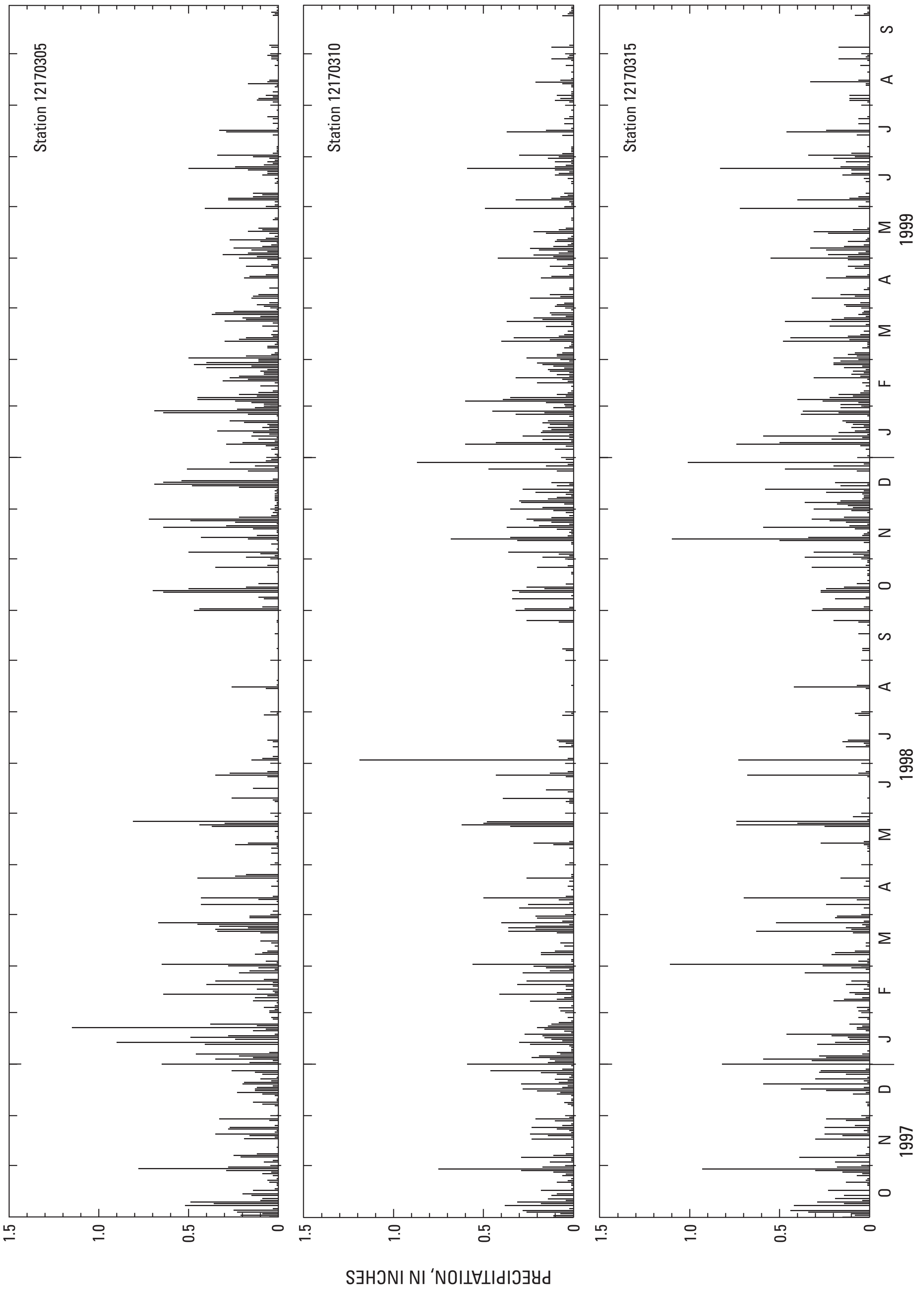


Figure 5. Precipitation for the six study basins on Whidbey and Camano Islands, Island County, Washington, water years 1998-99.

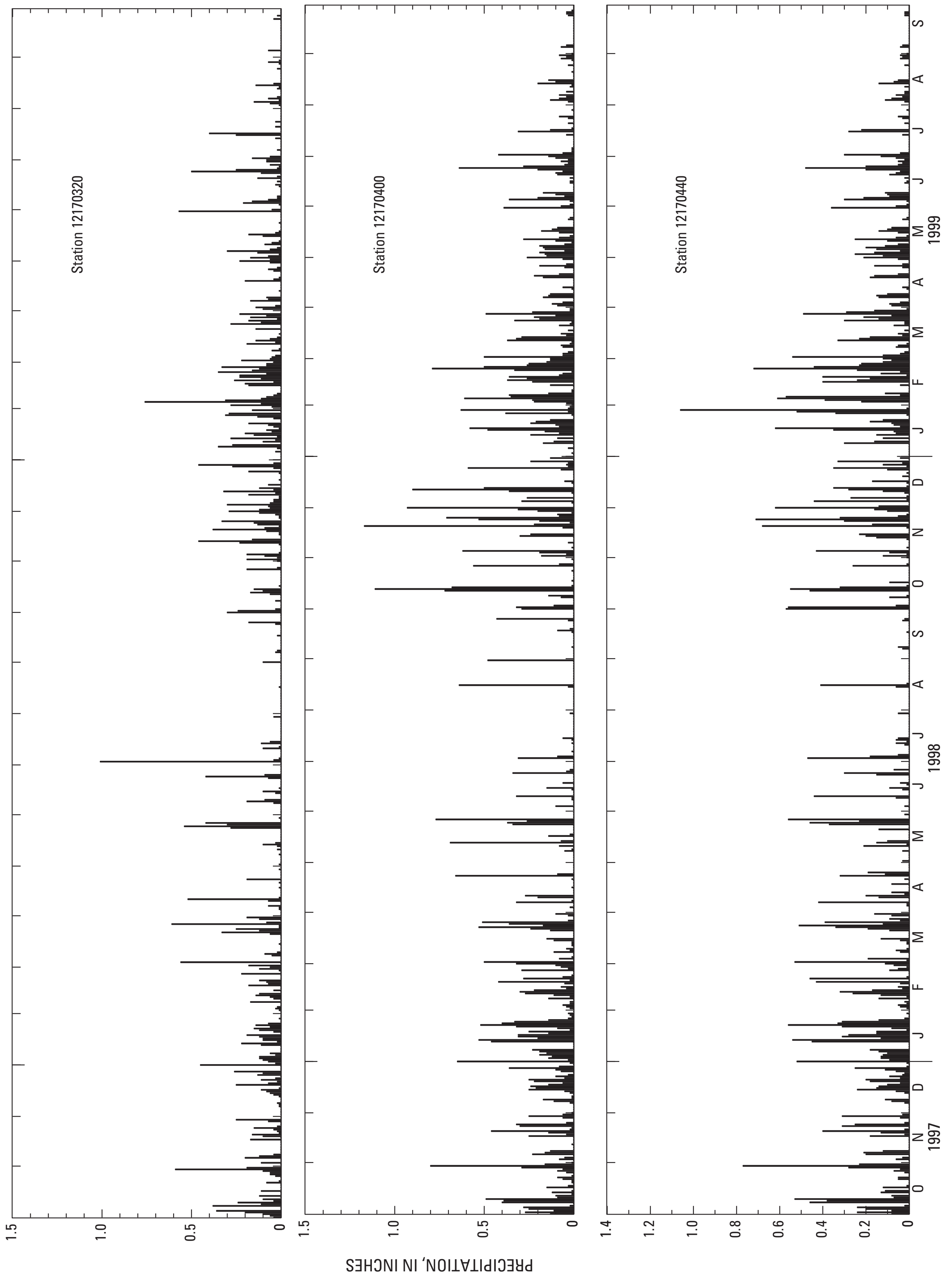


Figure 5.—*Continued*

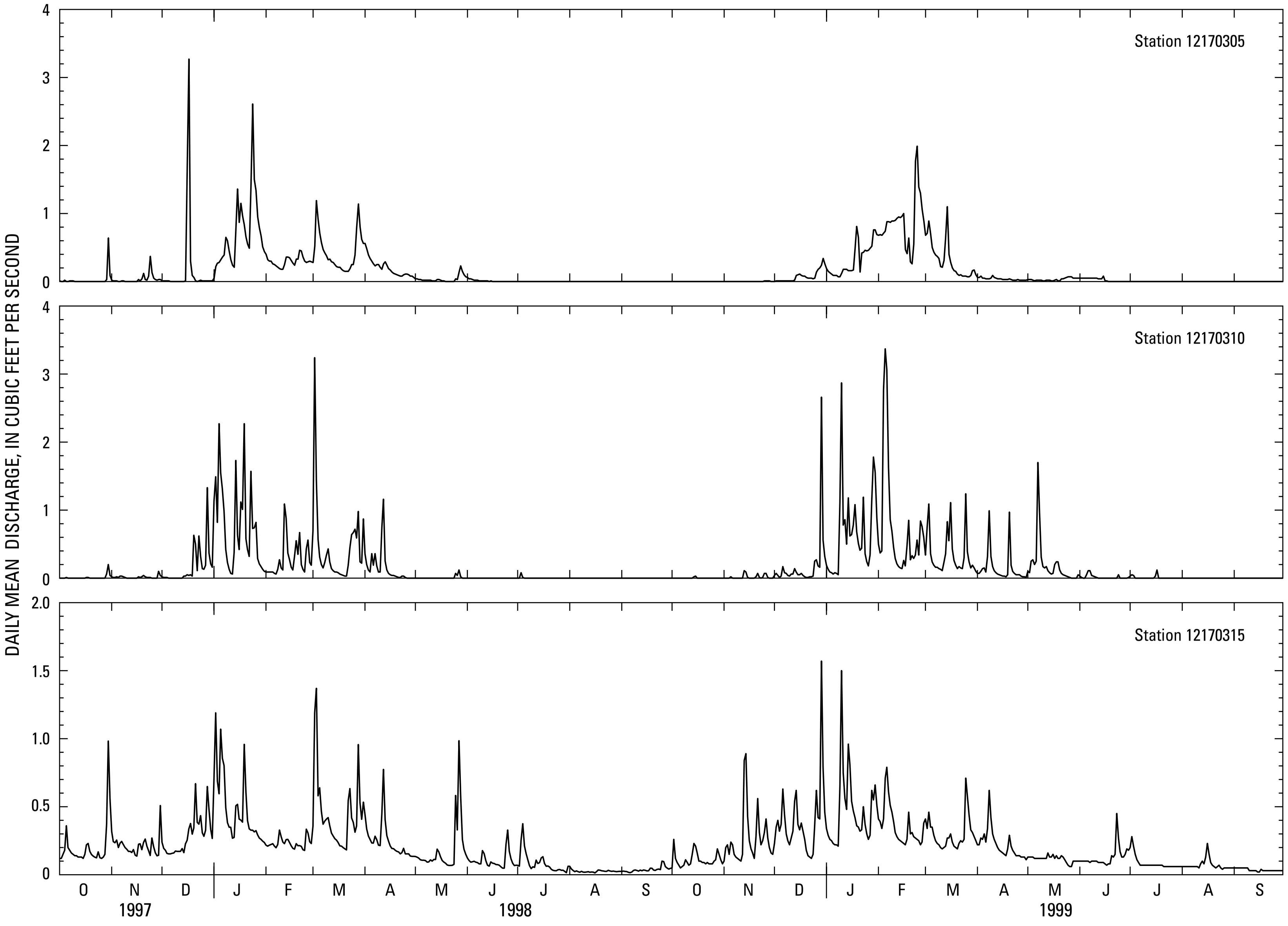


Figure 6. Daily mean stream discharges for the six study basins on Whidbey and Camano Islands, Island County, Washington, water years 1998-99.

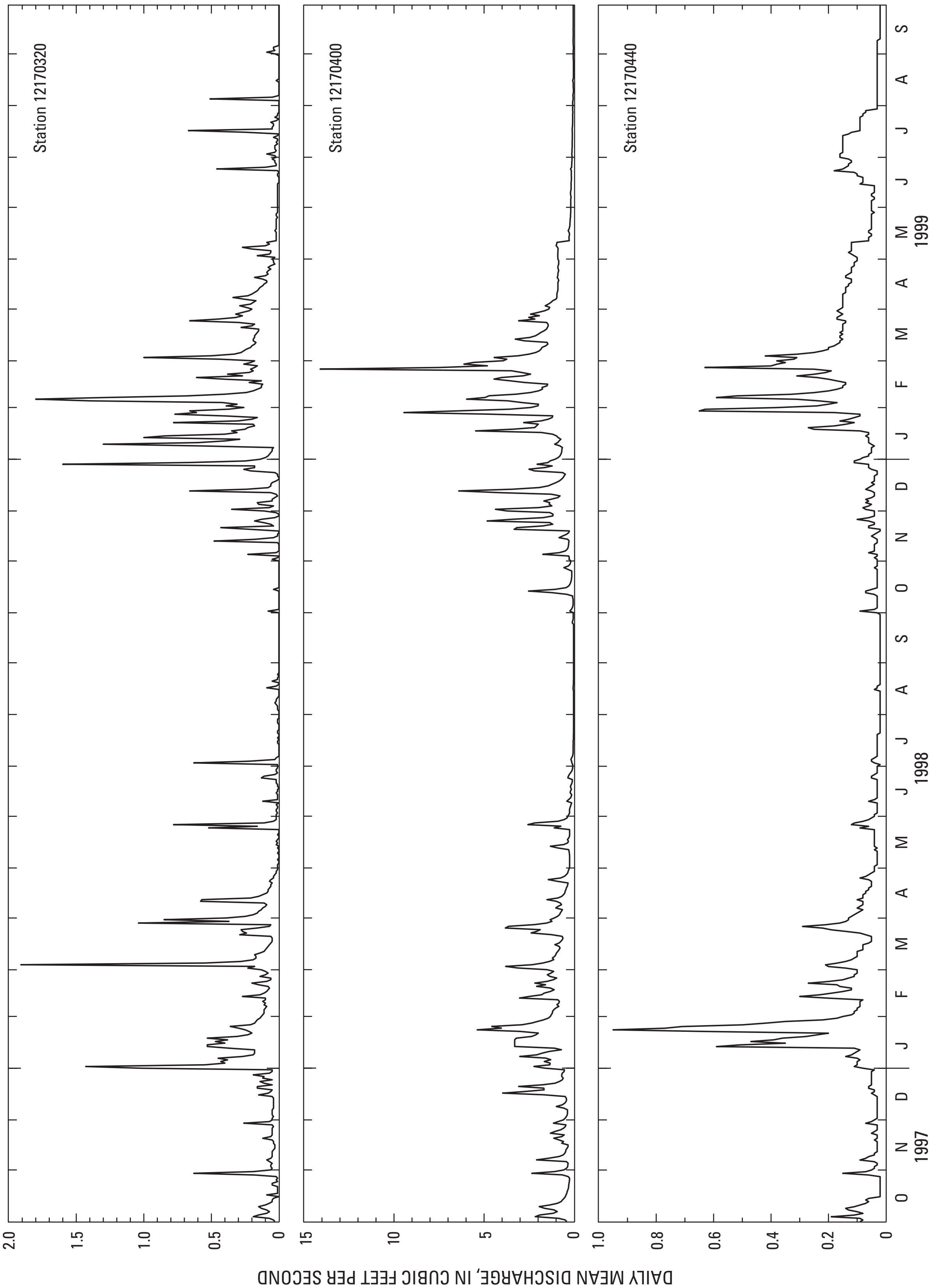


Figure 6.—*Continued*

Table 5. Summary of streamflow data for the six study basins on Whidbey and Camano Islands, Island County, Washington, water years 1998-99

Basin	Gaging station No.	Area (square miles)	Water year	Total annual discharge (inches)	Daily mean discharge	Maximum daily discharge
					Cubic feet per second	
Southern Camano Island	12170305	0.27	1998	4.8	0.14	2.6
			1999	5.0	.19	1.5
Northern Camano Island	12170310	.42	1998	3.5	.16	3.2
			1999	3.6	.19	3.4
Northern Whidbey Island	12170315	1.6	1998	.47	.22	1.4
			1999	.47	.22	1.6
Penn Cove, northern Whidbey Island	12170320	.97	1998	.47	.10	1.7
			1999	.48	.13	1.8
Cultus Creek, southern Whidbey Island	12170400	1.5	1998	3.8	.85	8.8
			1999	4.1	1.1	14
South Whidbey State Park, Whidbey Island	12170440	.13	1998	2.2	.08	1.1
			1999	2.9	.11	.65

Shortwave Solar Radiation and Temperature

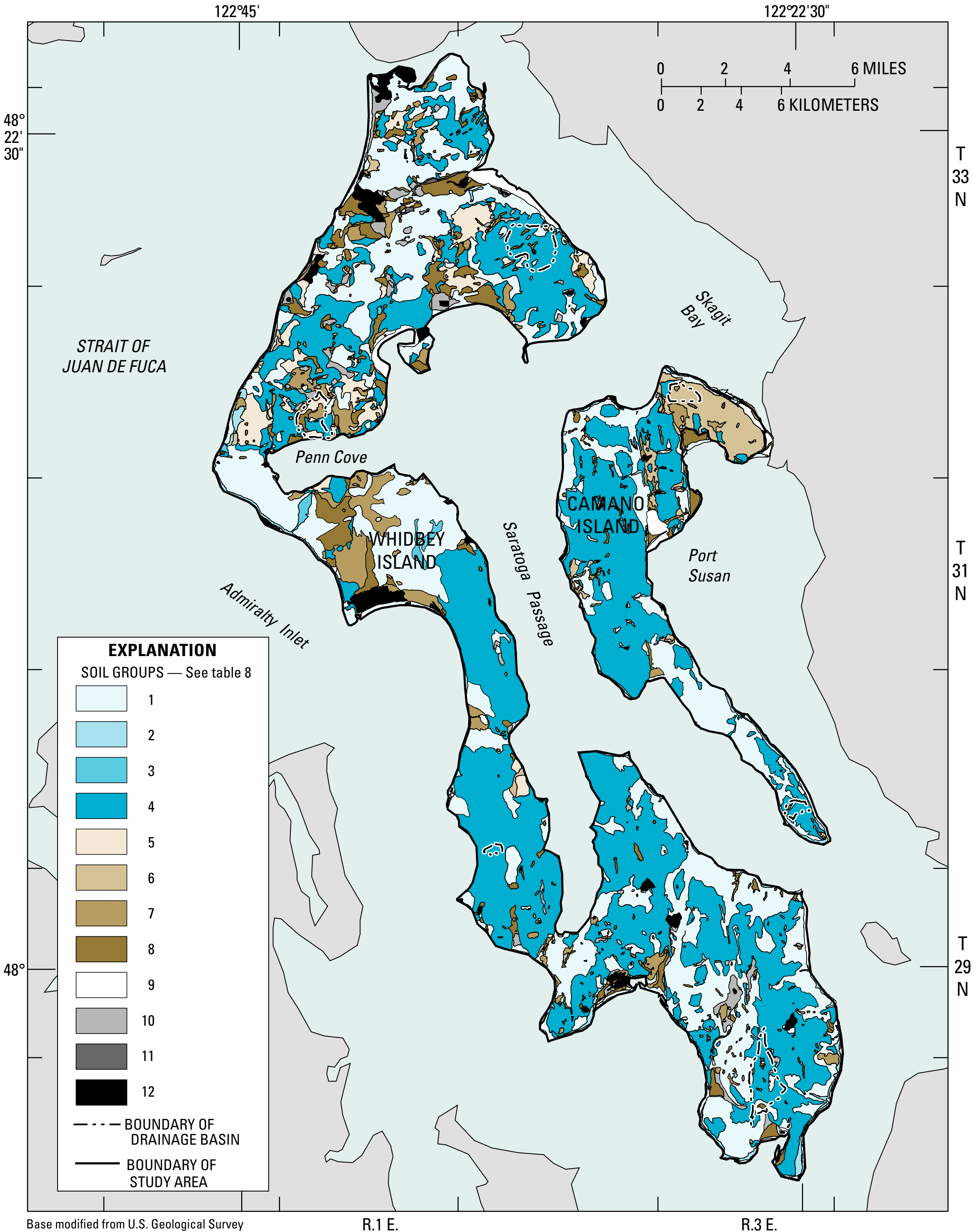
Daily incoming shortwave radiation and temperature were measured during water years 1998-99 at the two temporary micrometeorological sites. Pyranometer and temperature probes were installed at a site (on southern Whidbey Island near gaging station 12170400) in a pasture 200 feet from the nearest trees. Probes were installed at a second site on Whidbey Island on a bluff overlooking Penn Cove near gaging station 12170320. The pyranometer, positioned about 5 feet above ground, measured incoming radiation. The pyranometer and temperature probes were connected along with the precipitation gage to a data logger, which sampled output from the sensors every 15 minutes and recorded the average every 60 minutes.

Soil and Subsoil Properties

The soil properties used in the DPM are depth, available water-holding capacity, horizontal hydraulic conductivity, specific yield, and texture. With the exception of values for hydraulic conductivities and specific yields, soil properties were obtained from soil surveys conducted by the Natural Resources Conservation Service (U.S. Department of Agriculture, 1958). Soil information and the areal distribution of soil properties for Island County and six study basins were obtained from the State of Washington Department of Natural Resources Geographic Information System (GIS) and the Natural Resources Conservation Service (Alan Walters, written commun., 1997). This GIS coverage was completed in 1990, and data from the coverage were checked against the soil survey of the area.

Island County soils are classified into 35 series (Alan Walters, Natural Resources Conservation Service, written commun., 1997). The 35 soil series were combined into 12 composite soil groups (fig. 7) for the model. The soil groupings were based on similarities in depth, texture, vertical permeability, and available water-holding capacity. Consideration also was given, to the extent possible, to underlying geologic material and soil texture when grouping the soils (U.S. Department of Agriculture, 1958).

Properties of a soil group were computed as area-weighted averages of the properties of the soil series in the group. Ranges of the properties for each of the 12 composite soil groups were 0.04 to 0.45 inch per inch for available water-holding capacity, 0.34 to 20.0 feet per day for vertical hydraulic conductivity, 60 to 70 inches for soil depth. Soil texture ranged from peat to gravelly sandy loam.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Universal Transverse Mercator projection, Zone 10

Figure 7. Generalized soil groupings of Island County soil series for Whidbey and Camano Islands, Island County, Washington.

Saturated vertical hydraulic conductivity of the subsoil is usually an unknown property used in the DPM but it is important because this parameter affects the downward movement of water. The values used in DPM simulations in Bauer and Mastin (1997) for till-covered drainage basins ranged from 4.0 to 40.0 inches per year, and the values used in DPM simulations by Bidlake and Payne (2001) were 26.28 inches per year for till and 876 inches per year for glacial outwash and other coarse-grained deposits. Vertical hydraulic conductivity values used for the DPM in this study ranged from 2 to 200 inches per year (see section "Model Adjustment").

Land Cover and Vegetation

Land-cover information for the study area was obtained from GIS coverages prepared by the USGS National Mapping Division for the Puget Sound National Water-Quality Assessment program. Coverages were developed from Landsat Thematic Mapper satellite data collected at a 30-meter resolution during the early 1990s (Vogelmann and others, 1998). The DPM does not accommodate all 19 categories of land cover from the GIS data. Therefore, the GIS land-cover categories were grouped into DPM land-cover categories according to similarities in foliar coverage, root depth, and seasonal crop growth characteristics (fig. 8 and table 6; Bauer and Vaccaro, 1987).

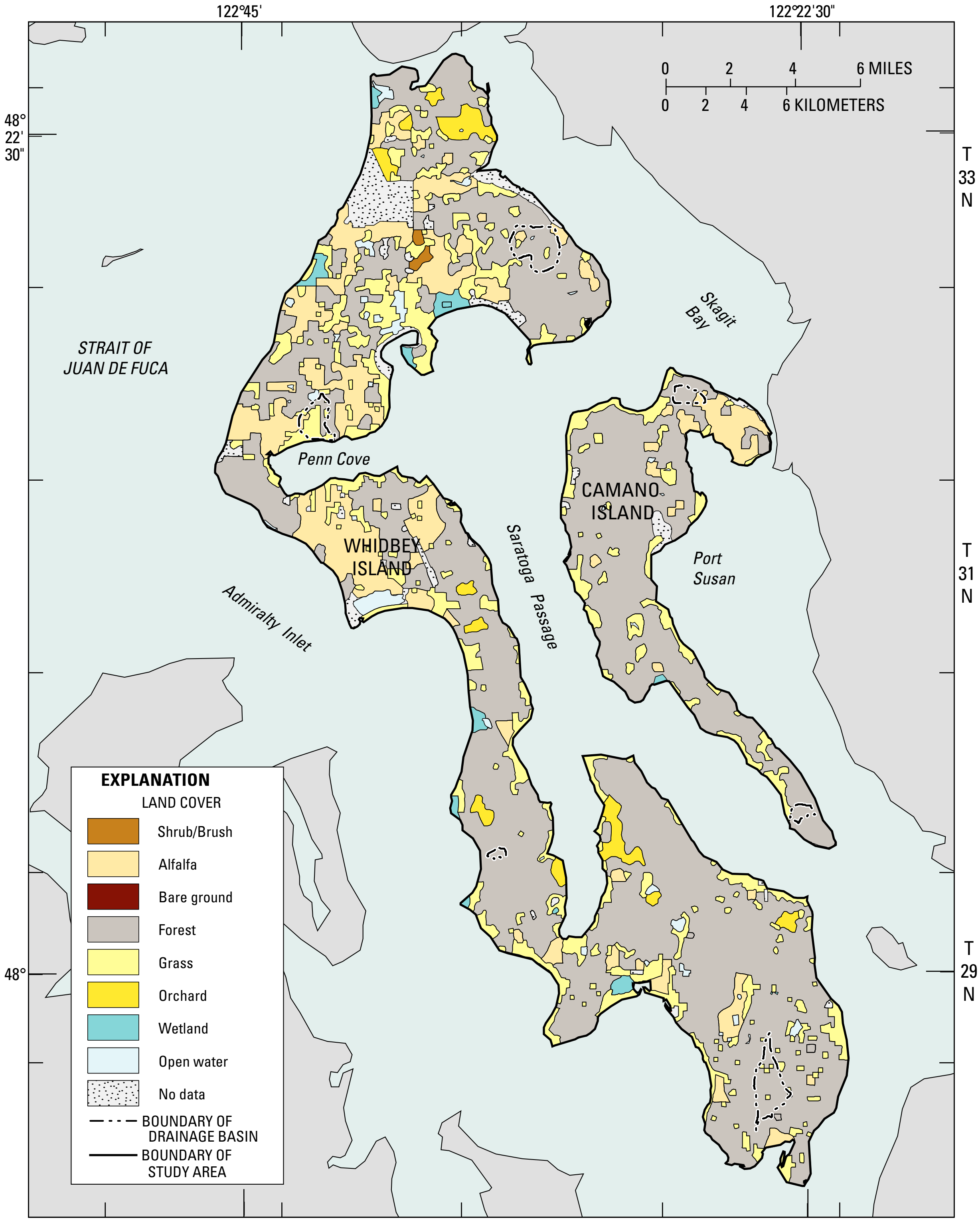
A foliar cover value was used for all DPM land-cover categories (except surface water). Maximum root depths were set at 5 feet for all non-agricultural (pasture/hay) and native vegetation (forest, shrubland) land covers, and 3 feet for grassland and annual crops (row crops and wheat). The 5-foot depth for non-agricultural and native vegetation generally corresponds with the deepest reported soil depths of the predominant soils, the 3-foot depth for grasses is from Bauer and Mastin (1997), and the 3-foot depth for annual crops is from James and others (1988).

Table 6. Reclassification of land-cover data to categories used by the Deep Percolation Model for Whidbey and Camano Islands, Island County, Washington

Original classification categories for land cover	Grouped land-cover categories used in DPM
Commercial	Open water
Cropland and pasture	Alfalfa
Deciduous forest	Orchard
Evergreen forest	Coniferous forest
Forested wetland	Grass
Non-forested wetland	Open water
Herbaceous rangeland	Grass
Mixed forest	Coniferous forest
Mixed rangeland	Grass
Mixed urban	Grass
Other agricultural land	Grass
Other urban	Grass
Residential	Grass
Shrub/brush rangeland	Shrub/brush
Strip mine, quarry, or gravel pit	Bare ground
Transitional area	Bare ground
Transportation, communications, and services	Bare ground
Water—lake	Open water
Water—reservoir	Open water

Land Surface

Land-surface altitude data for the study area were in the form of 10-meter-resolution digital elevation models (DEMs) obtained from the University of Washington (2000, accessed September 2000, http://wagda.lib.washington.edu/data). The DEMs were then converted at 30-meter resolution into topographic maps using GIS. The topographic maps were checked for data reliability against USGS 7.5-minute quadrangle maps of the area.



Base modified from U.S. Geological Survey
digital data, 1:2,000,000, 1972
Universal Transverse Mercator projection,
Zone 10

Figure 8. Distribution of land cover reclassified for the Deep Percolation Model for Whidbey and Camano Islands, Island County, Washington.

Two other land-surface parameters used in the model for calculating direct runoff are (1) a measure of the distance between the smallest drainage channels in the basin, and (2) the slope between such channels and the drainage divides separating them (Bauer and Mastin, 1997). Values for these parameters were obtained from a previous study in western Washington (Bauer and Mastin, 1997) with similar glacial topography.

Other Data

Additional variables used by the DPM to simulate atmospheric and land-cover processes include sublimation rates for snowpack, snowmelt coefficient, monthly maximum possible solar radiation, and maximum interception storage capacity for land covers where throughfall data were not available. These variables were assigned values from Bauer and Mastin (1997), or default values from the DPM.

Model Adjustment

The DPM recharge analysis was done for each of the six study basins. For each study basin, various DPM parameters were adjusted in order to minimize the value of DEFCIT and also to achieve the smallest difference between measured and simulated runoff values (RUNOFF) and fluxes of water (see section "Near-Surface Water-Balance Method"). Such a balance was achieved primarily by adjusting values assigned to the vertical hydraulic conductivity of the subsoil and to the soil depths and water-holding capacities. Three distinct subsoils composed of glacial deposits were identified in the study area: clay, till, and outwash. Soils underlain by clay generally have lower vertical hydraulic conductivity and allow less recharge than soils underlain by till and outwash deposits. Subsoil materials in the study basins and islands were determined using data from a soil survey of Island County (U.S. Department of Agriculture, 1958; and Jones, 1999). None of the study basins contain bedrock in the subsoil.

The model adjustments were: (1) Vertical hydraulic conductivities of subsoils were adjusted to 2 inches per year for clay; 5 to 20 inches per year for till; and 20 to 200 inches per year for outwash. Different values of hydraulic conductivities were assigned to till and outwash soils when information from the Soil Conservation Service (U.S. Department of Agriculture, 1958) or the National Resources Conservation Service (Alan Walters, Natural Resources Conservation Service, written commun., 1997) indicated that till and outwash soils had different characteristics; (2) Horizontal hydraulic conductivities of soils generally were set to as much as two orders of magnitude greater than the vertical hydraulic conductivities; (3) Specify initial water content of the soil. The amount of soil water is expressed as a fraction of the available water-holding capacity (unsaturated soil) and as a fraction of specific yield (saturated soil). The start of the simulation for the six basins was October 1997. Based on examination of prior precipitation quantities, the initial soil moisture as a fraction of available water-holding capacity for all the basins was estimated to be 30 percent.

Measured runoff (RUNOFF, Appendix A, tables A1 through A6, at back of report) for the study basins was compared to simulated runoff for the island-wide models (SYM-RO, Appendix B, tables B1 and B2, at back of report). By continued adjustment of horizontal and vertical hydraulic conductivity values of soils and subsoils in the DPM, monthly and annual SYM-RO values were simulated to match as closely as possible to measured runoff. In addition, soil-saturation deficit values (DEFCIT, Appendix A, tables A1 through A6) were minimized by adjusting vertical hydraulic conductivities and initial soil permeabilities (DEFCIT is the amount of streamflow not accounted for). Differences between values of measured and simulated runoff generated by DPM when measured runoff was not used for the study basins range from about 1 to 7 inches.

Basin	Gaging station	Measured runoff (inches)	Average monthly simulated runoff (inches)
Southern Camano Island	12170305	7.15	6.90
Northern Camano Island	12170310	5.77	1.38
Northern Whidbey Island	12170315	0.90	3.53
Penn Cove	12170320	1.70	1.73
Cultus Creek	12170400	4.32	5.32
South Whidbey State Park	12170440	8.94	3.15

Reducing these differences further for all basins was not possible to achieve because changing a parameter to improve the DEFCIT for one basin increased DEFCIT in other basins.

After model adjustment, the average simulated annual deep percolation (recharge) values, in inches per year, for the six study basins from October 1997 to September 1999 were:

Basin	Gaging station	Simulated recharge (inches per year)		
		WY1998	WY1999	Average
Southern Camano Island	12170305	5.45	7.27	6.36
Northern Camano Island	12170310	3.17	3.85	3.51
Northern Whidbey Island	12170315	5.50	6.38	5.94
Penn Cove	12170320	2.21	3.68	2.94
Cultus Creek	12170400	5.96	6.62	6.29
South Whidbey State Park	12170440	2.14	2.54	2.34

Average annual precipitation in the study basins (PRECP, Appendix A, tables A1 through A6) for water years 1998-99 ranged from 15 to 26 percent above the long-term (1961-90) average annual precipitation computed from gridded precipitation data using the PRISM model (Oregon Climate Service, 1999). Because precipitation is the primary source of recharge in the study basins, a 15- to 26-percent increase in precipitation would lead to a corresponding but not necessarily equal increase in DPM simulated recharge.

Other conditions, such as antecedent soil moisture in the study basins, may affect the amount of recharge that occurs in response to a precipitation event. Precipitation during 1997, the year prior to data collection, as recorded at Coupeville, Washington (fig. 1) by the National Oceanic and Atmospheric Administration (1997) indicates that this period was about 25 percent wetter than the long-term average (30-year) at the Coupeville station. Because less precipitation is needed to replenish soil moisture following a wet year, more water is available for recharge and thus actual recharge may be higher than recharge simulated by the DPM for the study period.

Island-Wide Recharge Estimates for Whidbey and Camano Islands Using the Deep Percolation Model

Adjusted model input values and parameters from the six study basins were used in the DPM simulations of the entire areas of Whidbey and Camano Islands. Input data for the island-wide DPM simulations were compiled in a similar manner as for the study-basin simulations. Land-use and soil data coverages used in the DPM for each island are shown in tables 7 and 8, and in figures 7 and 8. Average annual precipitation assigned to island-wide model cells were interpolated from spatially gridded data produced by the PRISM model using annual precipitation data averaged for 1961-90 (Oregon Climate Service, 1999, fig. 3). Adjusted vertical hydraulic conductivities of the subsoil, soil depth, and lateral permeability of the soil were from the study basins for the corresponding subsoil materials and soil types.

Simulated average annual recharge, in inches per year, during water years 1998-99 was 5.71 for Whidbey Island and 5.98 for Camano Island (Appendix B, tables B1 and B2). The areal distribution of simulated average annual recharge for each island (fig. 9) reflects variations in precipitation amounts (fig. 3) and the distribution of surficial materials (fig. 4). Recharge generally is higher in areas underlain by coarse-grained deposits (outwash) than in areas underlain by fine-grained deposits (till). DPM-simulated recharge in areas underlain by fine-grained deposits generally were less than 10 inches per year. DPM-simulated recharge in areas underlain by coarse-grained deposits commonly ranged from 10 to 20 inches per year, and as high as 25 inches per year in some areas (fig. 9).

Table 7. Land-cover categories used in the Deep Percolation Model (DPM) for Whidbey and Camano Islands, Island County, Washington

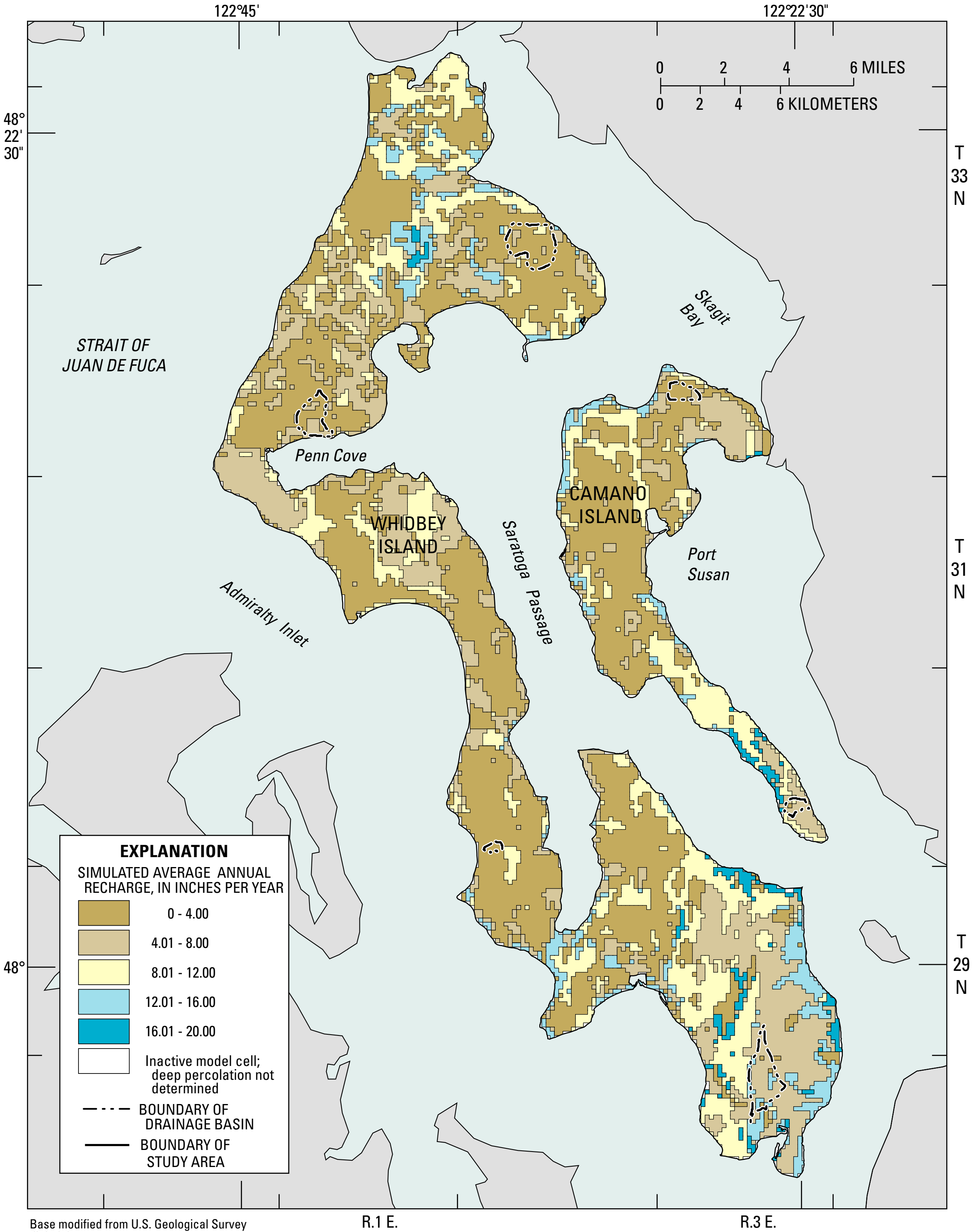
[–, no data]

DPM land cover	Whidbey Island		Camano Island	
	Area (square miles)	Area (percent)	Area (square miles)	Area (percent)
Coniferous forest	103	61	29.2	75
Grass	24.5	15	5.4	14
Alfalfa	24.9	15	4.04	10
Open water	8.55	5	0.34	1
Orchard	4.53	3	–	–
Bare ground	1.65	1	.12	<1
Shrub/brush	.37	<1	–	–
Total	167.5		39.1	

Table 8. Soil groups composited for the Deep Percolation Model using Island County soil series for Whidbey and Camano Islands, Island County, Washington

[**Area**: Sum of cell areas used in DPM. Percentages do not always equal 100 percent because of rounding and may not agree exactly with similar percentages in other tables in this report. –, no data]

DPM soil group (see fig. 7)	Soil series	Whidbey Island		Camano Island	
		Area (square miles)	Area (percent)	Area (square miles)	Area (percent)
1	Coastal beach	–	–	0.65	1.6
	Ebeys	1.2	0.72	.02	.06
	Hovde	.51	.30	.09	.23
	Hoypus	29.0	17.0		
	Indianola	–	–	6.3	16.0
	Keystone	25.1	15.0	–	–
	Pondilla	.19	.11	–	–
	San Juan	1.5	.92	–	–
2	Rough broken land	2.6	1.6	1.2	3.1
3	Snakelum	.79	.47	–	–
4	Alderwood	–	–	20.0	50.0
	Townsend	3.04	1.8	.16	.40
	Whidbey	70.0	42.0	–	–
5	Swantown	6.8	4.0	–	–
6	Bow	–	–	4.6	11.0
	Bozarth	.28	.17	–	–
7	Bellingham	.99	.59	.97	2.46
	Casey	8.5	5.0	–	–
	Tidal marsh	1.0	0.62	.26	.66
8	Coupeville	2.2	1.3	.01	.03
	Coveland	3.2	1.9	.04	.10
	Lummi	1.8	1.1	.47	1.2
	Norma	3.1	1.8	.40	1.0
9	Puget	–	–	.33	.84
10	Carbondale	.28	.16	–	–
	Semiahmoo	.93	.56	.06	.14
	Tacoma	.51	.31	.01	.02
	Tanwax	.70	.42	.12	.29
	Fresh water marsh	.11	.06	.01	.03
	Greenwood	.11	.06	–	–
	Mulkilteo	1.3	.75	.06	.15
	Rifle	1.0	.61	.10	.24
11	Everett	–	–	3.8	9.64
12	Rough stony land	.36	.22	–	–
	Made land	.95	.57	.02	.05
	Total	168.05		39.68	



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Universal Transverse Mercator projection, Zone 10

Figure 9. Distribution of average annual recharge simulated by the Deep Percolation Model, Island County, Washington.

In order to assess the validity of the island-wide simulations, average annual recharge estimates from study-basin simulations were compared to average annual recharge from the island-wide simulations for the same study basin areas for the same period of time (water years 1998-99).

Basin	Gaging station	Average annual recharge (inches)	
		Study-basin simulations	Island-wide simulations for the study basin
Southern Camano Island	12170305	6.4	5.1
Northern Camano Island	12170310	3.5	4.4
Northern Whidbey Island	12170315	5.9	4.3
Penn Cove	12170320	2.9	3.1
Cultus Creek	12170400	6.3	5.9
South Whidbey State Park	12170440	2.3	3.2

Differences between average annual recharge for study-basin and island-wide simulations ranged from 0.2 to 1.6 inches, and averaged 0.88 inch. The magnitude of these differences is small, but because of the small amount of recharge, the percentage of differences range from about 7 to 39 percent. The output summary tables of the island-wide DPM simulations, which present monthly water-budget components, are shown in Appendix B.

Sources of Uncertainty in DPM Recharge Estimates

In the construction of numerical models, sensitivity or uncertainty analyses are often done to assess which input parameters have the most "control" of model output. In the case of the DPM, because recharge generally is unknown and there is no "calibration" of the model (with the exception of streamflow), such analyses were not done. Values for the soil parameters were the least known and most often were adjusted during the DPM simulations.

Although the uncertainties in recharge estimates using the DPM could not be quantified, their major sources, nonetheless, warrant discussion. Sources of uncertainty fall into three main groups: (1) factors and conditions that affect the reliability of estimates of downward drainage below the root zone, as simulated with the DPM; (2) assumptions concerning equivalency of downward drainage from the root zone and recharge to ground water; and (3) assumptions involved with scaling up results from study basins to estimate annual recharge for entire island areas.

There are several sources of error associated with water-balance components that were derived for the study basins, including the sources listed below.

- Errors are associated with the collection of field data. Precipitation can greatly vary from one location to another for any particular storm. Therefore, errors in the water balance can develop when precipitation and precipitation throughfall at one or two measuring points are used to represent the precipitation and precipitation throughfall for a drainage basin. Moreover, the forest throughfall data are subject to additional error because of the wide variety of age, density, and species within the forested areas. Data-collection sites selected may or may not be fully representative of the larger forested areas.
- Malfunctions in data-collection instruments require that streamflow and precipitation be estimated from regression analyses.
- The best streamflow data are considered accurate to only about 5 percent, and due to the small size of the streams in this study, probably only a 10-percent accuracy was achieved.
- A reliable means for computing direct runoff from total streamflow is not available, and subjective estimates of baseflow were used. This source of error would only be significant for the northern Whidbey Island (12170315) and Cultus Creek (12170400) study basins. The other study basins did not have baseflow during the period of study.
- Errors in assignments to DPM parameters used to characterize soil and plant properties could have caused errors in the modeled simulations of the water balances and ultimately recharge.
- Little published information exists concerning transpiration in western Washington with which to verify that transpiration estimates were accurate. Simulated transpiration in this study accounted for a substantial percentage (from 24 to 38 percent) of precipitation on an average annual basis. However,

during the dormant winter periods, transpiration error relative to precipitation is small because transpiration is small. Transpiration error also probably is small during summer and autumn when all available soil moisture is transpired during this time. Errors in transpiration values during times when soil moisture is at field capacity during the growing season would result in greater errors in calculated recharge. The greatest potential for error in calculated recharge during this study is during the months of March through May.

- Errors associated with PRISM precipitation data.

Equating recharge to the downward flow below the root zone also could lead to errors. In most environments, water that percolates below a few feet from the soil surface is destined to recharge a saturated system (extremely arid environments can be an exception, where bare soil evaporation may be a large component of ground-water discharge). A hydrogeologic system can contain multiple unsaturated zones that are separated by saturated zones. The arrangement and vertical and horizontal extents of saturated and unsaturated zones in areas underlain by glacial deposits may be complex. As a result, not all water that percolates downward below a root zone necessarily becomes recharge to the saturated zone that has been identified as an aquifer in the hydrogeologic framework. For example, water percolating through predominantly unsaturated materials below a root zone, upon meeting a layer of fine-grained sediments with low hydraulic conductivity, could recharge a thin, saturated zone not tapped by wells, flow laterally, and discharge to a stream or spring. The water in this example might not reach the saturated ground-water-flow system that is used as a source of water to wells.

Additional errors may result from extending the recharge results of the 2-year water balance from the study basins to estimates of island-wide recharge. The assumption was made that the parameters that control recharge and direct runoff are identical for similar geologic, soil, land-cover, and precipitation conditions. Without actual measurement of streamflow for all drainage basins, this assumption could lead to errors at locations where extrapolated parameter conditions do not reflect actual parameter heterogeneity. For example, an area mapped as coarse-grained outwash may, in part, be underlain by fine-grained till. This would result in local recharge estimate error comparable to the range in recharge depicted in figure 9.

Chloride Mass-Balance Method

The chloride mass-balance method was used as a second, independent means of estimating recharge in the study area. This method was used to estimate combined recharge to both Whidbey and Camano Islands. The chloride mass-balance method for estimating recharge is based on the principle that a known fraction of chloride in precipitation and dry-atmospheric deposition is transported to the water table by the downward flow of water. As water percolates downward, some evaporates directly or is taken up and transpired by plants. Where this occurs, the concentration of chloride in soil water increases with depth because little or no chloride is lost by these processes. At greater depths, where no evapotranspiration occurs, the chloride concentration should be uniform if climate, soil, and other conditions near the surface have been steady for a sufficiently long time.

The chloride mass-balance method is based on the assumption that precipitation and dry-atmospheric deposition are the only sources of chloride in ground water and in surface-water runoff. Human sources such as septic systems and animal sources such as cow manure contribute minimal amounts of chloride to the water in the study area, and natural sources such as evaporite rocks or connate seawater are not present in the hydrogeologic units above sea level. Another possible source of chloride is residual chloride from early post-ice-age seawater that may have intruded the glacial materials while the island was below sea level from the time after the glaciers retreated and before the island isostatically rebounded to above sea level (Culhane, 1993). A mass balance of chloride in precipitation, surface runoff, and ground water is expressed in the following equation (Prych, 1995; Maurer and others, 1996):

$$P \times C_p = (GWR \times C_g) + (SWR \times C_p), \tag{2}$$

where

P is annual precipitation, in inches;

C_p is concentration of chloride in precipitation, in milligrams per liter;

GWR is annual ground-water recharge, in inches;

C_g is concentration of chloride in ground water, in milligrams per liter; and

SWR is annual surface-water runoff, in inches.

Rearranging the terms in equation 2 and solving for GWR gives:

$$GWR = \frac{(P \times C_p) - (SWR \times C_p)}{C_g} \tag{3}$$

Implicit in the derivation and uses of equation 3 is the assumption of "plug flow," or piston flow, which assumes that (1) the direction of water flow and chloride transport is vertical and downward, (2) areal distributions of the rate of percolation of water and of chloride on the local scale (a few tenths of a meter) are uniform (no preferred pathways), (3) all chloride is dissolved in soil water, and the distribution of the dissolved chloride in the soil water is relatively uniform within a pore (no solid chloride phase, sorption by soil, or anion exclusion), and (4) advection is the dominant mode of chloride transport, and diffusion is relatively unimportant. Additional assumptions are that (5) minerals in the soil are not a source of chloride, and the only sources are precipitation and dry-atmospheric deposition, (6) measured chloride concentrations are at depths great enough that seasonal variations in concentration are small, and (7) the concentration of chloride in surface-water runoff is the same as that in precipitation. The method is still valid if chloride is taken up by growing vegetation as long as it is also released by decaying vegetation at the same rate.

Data Collection

The chloride mass-balance method involves sampling chloride from the atmosphere (precipitation and dry deposition), the water-table aquifer, and/or the unsaturated-zone soil moisture. Chloride concentrations were determined from samples of precipitation and dry-atmospheric deposition from May 20, 1998 through April 9, 1999 and from ground-water samples collected in the autumn of 2000. Two atmospheric-chloride deposition-collection sites were established — one on northern Whidbey Island and the other on southern Camano Island (fig. 1). A wet and dry atmospheric-deposition sampler was installed at the sites. The sampler consists of two buckets mounted on an electromechanical device that senses precipitation and automatically places a cover on one or the other of the buckets. During periods of precipitation, the "dry" bucket is covered while the "wet" bucket collects precipitation. When it is not raining, the "wet" bucket is covered to prevent any influx from the dry atmosphere (including insects, bird droppings, and wind-blown ground debris) and to minimize evaporation. At the same time, the dry bucket is open to collect microscopic crystals of chloride salts that fall from the atmosphere.

The sampling buckets were collected and replaced with clean buckets on a monthly basis. All bucket samples were weighed, and filtered aliquots were sent to the USGS National Water-Quality Laboratory (NWQL) for low-level chloride determinations. Aliquots from the dry buckets were taken by first adding a known quantity of distilled water to the bucket, which was thoroughly swirled and then sampled. Chloride concentrations in ground-water samples from wells in the study area (fig. 1) also were determined at the NWQL.

Recharge Estimates and Sources of Uncertainty Using Chloride Mass-Balance Method

Implicit in the derivation of equation 2 is the assumption that all atmospheric chloride in soil water is deposited by precipitation (wet deposition). However, about 18 percent of the total chloride deposition in the study area occurs as dry deposition (table 9). Orr and others (2002) determined that about 37 percent of the total chloride deposition in the San Juan Islands of Washington occurred as dry deposition during water years 1997-98. In that study, equation 3 was modified to:

$$GWR = 0.0394FWD(1-SWR/P)/C_g \qquad (4)$$

where

FWD *is* the total of the wet and dry chloride deposition expressed in mg/m^2;

Cg *is* in mg/L; and

GWR, SWR, P *are* in inches.

In order to obtain a long-term average recharge value from equation 4, the terms in this equation should ideally also be long-term averages. Because of mixing and generally multi-year residence times of water in most aquifers, C_g probably represents a long-term average. However, *SWR* and *P* are two-year averages and *FWD* is a one-year estimate.

Owing to mechanical difficulties with the wet-and-dry atmospheric-deposition samplers, a full year's chloride deposition data were not obtained at either of the two sites. Continuous data were collected from July 21, 1998 through April 9, 1999 at site 12170305 and from May 20, 1998 through December 8, 1998 at site 12170315. Consequently, the two data sites were combined to produce a single, longer period data set (May 20, 1998 through April 9, 1999). For those periods when data were available from both collectors, the total chloride flux values were computed for each site and averaged to provide single values (see table 9).

Table 9. Summary of chloride in precipitation and dry-atmospheric deposition measured at two locations on Whidbey Island, Island County, Washington, May 1998 through April 1999

[**Location**: See figure 1 for locations 315 and 305; “avg” means that values are averages from locations 315 and 305; “est” means no data for this period and values are estimated from data for other periods. **Chloride concentrations**: Wet+dry buckets: Concentration resulting if chloride from dry bucket were added to wet bucket]

Measurement period Year-month-day From	To	Location	Chloride concentrations (in milligrams per liter) Wet bucket	Wet+dry buckets	Atmospheric chloride fluxes (milligrams per square meter) In precipitation (wet)	As dry deposition (dry)	Total of wet+dry
05-20-98	06-19-98	315	0.28	1.5	3.6	15.0	19.0
06-19-98	07-21-98	315	.52	(1)	26.0	[2]11.0	37.0
07-21-98	08-28-98	avg	.44	12.0	3.4	[3]5.6	[3]9.00
08-28-98	10-06-98	avg	.38	.60	9.9	5.7	16.0
10-06-98	11-03-98	avg	.86	1.1	44.0	10.0	54.0
11-03-98	12-08-98	avg	1.30	1.4	170.0	17.0	180.0
12-08-98	01-20-99	est	(4)	(4)	(4)	(4)	[2]280.0
01-20-99	02-26-99	305	1.40	1.6	250.0	39.0	280.0
02-26-99	04-09-99	305	3.20	4.0	200.0	51.0	250.0
04-09-99	05-20-99	est	(4)	(4)	(4)	(4)	[2]130.0

[1] Sample lost or destroyed.

[2] Value estimated from preceding and following data periods.

[3] Average values adjusted to account for different time periods for the two stations.

[4] Data not collected during this period.

For the period when both collectors were operating, the total chloride fluxes were similar, 85.73 mg/m^2 at site 12170315 and 70.06 mg/m^2 at site 12170305. In order to extend the data set to represent a full year of deposition, it was first assumed that the seasonal pattern of chloride deposition is similar from year to year and therefore, chloride flux values could be interpolated between months regardless of the year associated with the month. Accordingly, average daily deposition rates were calculated for the first and last periods in the measured data set and an average of their rates was applied to the part of the year (April 10 to May 20) when data were missing. The annual chloride deposition estimated in this manner was 1,268 mg/m^2.

Ground-water samples used for determining C_g (eq. 4) were collected from wells where the only source of chloride in the aquifer was from the atmosphere (fig. 1 and table 10). Samples from any wells that may be intruded by seawater could not be used. One requirement that assures that there would be no seawater intrusion is that the bottoms of the wells be above sea level. For such wells, the water levels cannot be drawn down by pumping to below sea level, and therefore, no potential gradient from seawater to the well could develop. The only potential migration of chloride from seawater would be by diffusion, which would only occur over distances that are small compared with distances from seawater to such wells. Chloride concentrations for the 12 wells sampled ranged from 6.4 to 44.4 mg/L and averaged 21.8 mg/L (table 10).

Surface-water runoff, *SWR* (also referred to as "direct runoff") and precipitation, *P*, in equation 4 were estimated from the same six gaging stations in the study basins that were used to estimate recharge using the DPM (tables 1 and 5). When averaged over the six study basins for the 2-year period, *SWR* and *P* are 5.07 and 28.04 inches per year. Using the annual average values for the variables discussed above in equation 4, the combined average annual recharge for Whidbey and Camano Islands is 2.00 inches for water years 1998-99, about 17 percent of the average annual recharge estimated for Whidbey and Camano Islands using the DPM. Orr and others (2002) reported an annual recharge estimate for Lopez Island using the chloride mass-balance method that was about 23 percent of the annual recharge estimated for Lopez Island using the DPM.

Table 10. Summary of selected physical characteristics and chloride concentrations for wells used in the chloride-mass balance, Whidbey Island, Island County, Washington, water years 1998-99

Well No.	Island	Altitude of land surface (feet)	Altitude of bottom of well (feet)	Well depth (feet below land surface)	Chloride, dissolved (milligrams per liter)
28N/03E-10L02	Whidbey	255	206	49	16.4
29N/02E-09A02	Whidbey	165	76	89	14.9
29N/03E-35E01	Whidbey	310	274	36	9.8
29N/04E-31D02	Whidbey	180	156	24	6.4
29N/03E-02G02	Whidbey	150	73	77	8.93
30N/02E-08P01	Whidbey	265	68	197	16.6
30N/03E-23C04	Camano	150	82	68	8.41
31N/01E-11G01	Whidbey	188	63	125	44.4
31N/02E-32E01	Whidbey	265	209	56	33.6
31N/03E-30Q02	Camano	84	10	74	15.9
32N/03E-21D01	Camano	135	8	127	35.9
32N/01E-03B03	Camano	130	36	94	36.0

Attempts were not made to estimate the distribution of recharge from the data used for this method. For any particular sampling point within the aquifer, ground water generally has a predominantly horizontal flow component. Therefore, any ground-water sample consists of an unknown mixture of water, consisting of water percolating vertically downward from recharge at the surface and from other upgradient areas. Recharge computed from chloride concentrations in single samples of ground water would therefore represent upgradient composite recharge.

Equation 4 and the data collected can be used to estimate certain limiting values of recharge. For example, areas with highly permeable subsoils would produce no direct runoff and therefore would have the largest amount of recharge and the lowest chloride concentrations. Selecting the lowest chloride concentration of 6.4 mg/L in ground water from table 10, and setting $SWR = 0$ in equation 4, and maintaining the annual value of atmospheric chloride deposition, yields an annual recharge estimate of 7.81 inches. Selecting the highest chloride concentration of 44.4 mg/L (table 10) and using direct runoff and precipitation values from the study basin with the highest direct runoff to precipitation ratio results in an estimated minimum annual recharge of 0.78 inch.

Sources of chloride in ground water other than from the atmosphere would cause recharge estimated by the chloride mass-balance method to be less than the actual recharge. This is evident from equation 3, in which the computed recharge is inversely proportional to the chloride concentration in ground water, if the other variables remain unchanged. Therefore, the recharge values of from 0.78 to 7.81 inches per year computed by the chloride-mass balance method may represent lower limits, which is consistent with the generally higher simulated recharge using the DPM for the study basins (4.36 to 8.44 inches per year).

SUMMARY

The principal source of drinking water on Whidbey and Camano Islands, located off the northwestern coast of Washington, is ground water derived from unconsolidated glacial and interglacial deposit aquifers. Some uncertainty exists regarding the quantity of recharge from deep percolation of precipitation reaching the aquifers used for water supply. In 1998, the U.S. Geological Survey, in cooperation with the Island County Health Department began a study to estimate the quantity of recharge from precipitation to unconsolidated-deposit aquifers on Whidbey and Camano Islands. Two methods were used to estimate recharge from precipitation to unconsolidated deposits on the islands — a daily near-surface water-balance method (DPM), and a chloride mass-balance method.

The DPM uses a daily water and energy budget approach to simulate recharge. In this method, the model simulated daily moisture fluxes of precipitation, evapotranspiration, direct runoff, and deep percolation for October 1, 1997 through September 30, 1999 (water years 1998-99) for six small drainage basins — four on Whidbey Island and two on Camano Island. The DPM requires precipitation, precipitation throughfall, streamflow, shortwave solar radiation, air temperature, surficial material properties, land-cover, and land-surface altitude data. Surficial material (soil and subsoil) parameters were estimated for the different geologic and soil conditions in each of the six small basins during DPM adjustment. Model parameters were adjusted until the difference between measured and simulated daily flows and fluxes of water were minimized. Adjusted parameters from the DPM for each small basin were then used in island-wide DPM simulations. A spatial distribution of annual recharge was simulated for each island, with island averages of 5.71 inches per year for Whidbey Island and 5.98 inches per year for Camano Island. The spatial distribution of simulated annual recharge for each island reflects variations in precipitation amounts and the distribution of surficial materials. DPM results indicate recharge generally is higher in areas underlain by coarse-grained deposits (outwash) than in areas underlain by fine-grained deposits (till). DPM-simulated recharge in areas underlain by fine-grained deposits generally were less than 10 inches per year. DPM-simulated recharge in areas underlain by coarse-grained deposits commonly ranged from 10 to 20 inches per year, and as high as 25 inches per year in some areas.

A chloride mass-balance method was used to compute combined recharge to unconsolidated deposits on Whidbey and Camano Islands. This method is based on the principle that a known fraction of chloride in precipitation and dry-atmospheric deposition is transported to the water table by the downward flow of water. The chloride mass-balance method requires measurements of atmospheric chloride deposition, precipitation, streamflow, and chloride concentrations in ground water. The average combined recharge for Whidbey and Camano Islands estimated by this method was 2.00 inches per year. The range of chloride concentrations in ground-water samples from selected wells indicates that the average recharge to unconsolidated deposits is between 0.78 and 7.81 inches per year. Sources of chloride in ground water other than from the atmosphere would cause recharge estimated by the chloride mass-balance method to be less than the actual recharge, therefore, these estimates may represent lower limits.

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APPENDIX A. MONTHLY COMPUTER WATER-BUDGET SUMMARIES FOR THE SIX STUDY BASINS

Table A1. Monthly and annual computed water-budget summaries for the southern Camano Island study basin, Camano Island, Gaging Station 12170305

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity - evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield – starting soil moisture) – measured direct runoff – recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**					**Water Year 1998**						
October	1997	4.6	1.2	0.11	0.06	0.08	0.08	3.19	1.05	0.00	49.7	-0.01
November	1997	2.4	.56	.15	.38	.07	.07	1.34	.45	.00	44.6	-.01
December	1997	2.0	.33	.77	.89	.00	.00	0.23	.33	.00	39.9	-.16
January	1998	6.3	.39	3.07	1.36	.00	.00	1.51	.39	.00	40.1	.00
February	1998	2.8	.69	1.15	.91	.02	.02	-.02	.66	.00	43.9	.00
March	1998	4.2	1.6	1.84	1.05	.40	.40	-.16	1.07	.00	44.5	.00
April	1998	2.0	3.0	.82	.73	1.66	1.66	-1.91	.74	.00	46.5	.00
May	1998	2.5	3.3	.16	.07	1.97	1.92	-.23	.63	.00	52.4	-.05
June	1998	1.2	4.1	.04	.00	2.55	2.42	-1.81	.58	.00	56.0	-.04
July	1998	.48	4.6	.00	.00	3.07	2.26	-2.17	.38	.00	61.5	.00
August	1998	.36	4.7	.00	.00	3.26	1.16	-1.02	.22	.00	59.2	.00
September	1998	.05	3.1	.00	.00	2.25	.39	-.39	.05	.00	55.4	.00
Totals		29	28	8.12	5.45	15.35	10.38	-1.42	6.56	0.00	49.5	-0.26
Month	**Year**					**Water Year 1999**						
October	1998	3.74	1.13	0.00	0.01	0.31	0.29	2.69	0.71	0.00	48.3	0.00
November	1998	4.46	.40	.15	.58	.00	.00	3.25	.40	.00	45.3	-.01
December	1998	4.03	.31	.32	1.09	.00	.00	2.24	.31	.00	38.4	.04
January	1999	4.07	.34	1.36	1.19	.00	.00	1.17	.34	.00	40.7	.02
February	1999	4.87	.53	3.29	1.17	.00	.00	-.11	.53	.00	41.2	.00
March	1999	3.68	1.47	1.37	1.03	.26	.26	-.03	1.10	.00	42.2	.02
April	1999	1.43	2.66	.16	.71	1.27	1.26	-1.63	0.93	.00	44.0	.00
May	1999	2.76	3.06	.13	.72	1.27	1.25	-.72	1.33	.00	49.1	.00
June	1999	2.45	3.46	.11	.59	1.49	1.45	-1.08	1.42	.00	55.5	.00
July	1999	1.34	4.49	.00	.17	2.84	2.68	-2.12	.61	.00	57.8	.00
August	1999	.87	3.74	.00	.01	2.14	1.88	-1.83	.81	.00	59.7	.00
September	1999	.21	2.97	.00	.00	2.01	1.31	-1.31	.21	.00	53.9	.00
Totals		33.88	24.56	6.89	7.27	11.59	10.39	0.54	8.69	0.00	48.0	0.07

Table A1. Monthly and annual computed water-budget summaries for the southern Camano Island study basin, Camano Island, Gaging Station 12170305—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	Average monthly values										
October	4.16	1.14	0.06	0.04	0.19	0.18	2.94	0.88	0.00	49.0	0.00
November	3.43	.48	.15	.48	.04	.04	2.30	.43	.00	44.9	-.01
December	3.04	.32	.55	.99	.00	.00	1.24	.32	.00	39.1	-.06
January	5.20	.37	2.21	1.28	.00	.00	1.34	.37	.00	40.4	.01
February	3.82	.61	2.22	1.04	.01	.01	-.06	.60	.00	42.5	.00
March	3.93	1.54	1.61	1.04	.33	.33	-.10	1.09	.00	43.3	.01
April	1.69	2.84	.49	.72	1.46	1.46	-1.77	.83	.00	45.2	.00
May	2.63	3.20	.15	.39	1.62	1.59	-.47	.98	.00	50.8	-.02
June	1.82	3.77	.07	.29	2.02	1.94	-1.44	1.00	.00	55.8	-.02
July	.91	4.54	.00	.08	2.95	2.47	-2.14	.50	.00	59.6	.00
August	.61	4.21	.00	.01	2.70	1.52	-1.43	.52	.00	59.4	.00
September	.13	3.05	.00	000	2.13	.85	-.85	.13	.00	54.7	.00
Totals	31.35	26.07	7.51	6.36	13.47	10.38	-0.44	7.62	.00	48.8	-0.09

Table A2. Monthly and annual computed water-budget summaries for the northern Camano Island study basin, Camano Island, Gaging Station 12170310

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **CHGINT**, change in moisture stored on foliage (zero for cells with land cover for which throughfall data are used); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity – evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield - starting soil moisture) – measured direct runoff – recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**	**Water Year 1998**										
October	1997	3.87	0.93	0.03	0.00	0.36	0.36	2.58	0.91	0.00	48.0	-0.02
November	1997	1.98	.47	.04	.02	.20	.20	1.21	.52	.00	42.5	-.01
December	1997	2.19	.32	.45	.10	.08	.08	1.08	.64	.00	38.2	-.15
January	1998	3.71	.37	2.19	.67	.04	.04	.23	1.07	.00	38.8	-.52
February	1998	2.30	.56	.71	.75	.22	.22	.07	.63	.00	42.3	-.09
March	1998	3.50	1.29	1.28	.78	.58	.58	.04	1.01	.00	42.5	-.18
April	1998	1.54	2.40	.42	.09	1.49	1.49	-1.14	.89	.00	43.9	-.20
May	1998	2.34	2.66	.02	.11	1.77	1.76	.05	.39	.00	50.5	.00
June	1998	1.28	3.24	.00	.30	2.14	2.11	-1.59	.45	.00	53.4	.00
July	1998	1.59	3.50	.01	.31	2.40	2.28	-1.33	.32	.00	57.8	.00
August	1998	0.01	3.70	.00	.03	2.70	1.51	-1.54	.01	.00	55.5	.00
September	1998	0.44	2.48	.00	.00	1.73	0.44	-.21	.20	.00	51.6	.00
Totals		24.75	21.91	5.16	3.17	13.73	11.09	-0.55	7.04	0.00	47.1	-1.18
Month	**Year**	**Water Year 1999**										
October	1998	2.31	0.97	0.00	0.30	0.54	0.50	0.80	0.70	0.00	45.7	0.00
November	1998	3.65	.38	.04	.32	.13	.13	2.51	.64	.00	44.0	.00
December	1998	3.83	.33	.51	.36	.05	.05	1.72	1.19	.00	37.2	-.01
January	1999	3.82	.33	1.89	.64	.04	.04	.67	.92	.00	39.3	-.38
February	1999	3.28	.50	1.92	.71	.15	.15	-.03	.88	.00	39.6	-.35
March	1999	2.91	1.19	1.00	.65	.46	.46	-.07	1.09	.00	40.1	-.21
April	1999	1.35	2.12	.40	.09	1.35	1.35	-.61	.39	.00	41.1	-.27
May	1999	2.67	2.45	.55	.19	1.53	1.53	.22	.43	.00	46.7	-.26
June	1999	2.02	2.80	.04	.23	1.77	1.76	-.48	.47	.00	54.0	.00
July	1999	1.20	3.58	.02	.25	2.41	2.38	-1.77	.33	.00	55.6	.00
August	1999	0.91	2.92	.00	.10	1.98	1.90	-1.38	.29	.00	57.2	.00
September	1999	0.29	2.35	.00	.02	1.64	1.33	-1.19	.13	.00	50.7	.00
Totals		28.24	19.91	6.39	3.85	12.03	11.58	0.39	7.46	0.00	46.0	-1.48

Table A2. Monthly and annual computed water-budget summaries for the northern Camano Island subbasin, Whidbey Island, Gaging Station 12170310—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Average monthly values**										
October	3.09	0.95	0.02	0.15	0.45	0.43	1.69	0.80	0.00	46.9	-0.01
November	2.81	.42	.04	.17	.16	.16	1.86	.58	.00	43.2	.00
December	3.01	.32	.48	.23	.07	.07	1.40	.92	.00	37.7	-.08
January	3.76	.35	2.04	.66	.04	.04	.45	1.00	.00	39.0	-.45
February	2.79	.53	1.32	.73	.19	.19	.02	.76	.00	40.9	-.22
March	3.20	1.24	1.14	.71	.52	.52	-.01	1.05	.00	41.3	-.20
April	1.44	2.26	.41	.09	1.42	1.42	-.88	.64	.00	42.5	-.24
May	2.50	2.56	.28	.15	1.65	1.64	.14	.41	.00	48.6	-.13
June	1.65	3.02	.02	.27	1.96	1.94	-1.04	.46	.00	53.7	.00
July	1.39	3.54	.02	.28	2.41	2.33	-1.55	.33	.00	56.7	.00
August	.46	3.31	.00	.07	2.34	1.71	-1.46	.15	.00	56.3	.00
September	.36	2.42	.00	.01	1.68	.89	-.70	.17	.00	51.1	000
Totals	26.49	20.91	5.77	3.51	12.88	11.33	-0.08	7.25	0.00	46.5	-1.33

Table A3. Monthly and annual computed water-budget summaries for the northern Whidbey Island study basin, Gaging Station 12170315

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **CHGINT**, change in moisture stored on foliage (zero for cells with land cover for which throughfall data are used); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity – evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield - starting soil moisture) ° measured direct runoff – recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**	**Water Year 1998**										
October	1997	4.41	1.13	0.06	0.03	0.47	0.47	2.71	1.17	0.00	47.5	-0.03
November	1997	2.16	.53	.06	.66	.26	.26	.59	.58	.00	41.9	.00
December	1997	2.44	.32	.09	.87	.13	.13	.66	.69	.00	37.7	.00
January	1998	4.07	.38	.21	.97	.09	.09	1.57	1.10	.00	38.4	.10
February	1998	1.47	.64	.03	.73	.29	.29	-.11	.52	.00	41.8	.00
March	1998	3.90	1.53	.19	.91	.75	.75	.64	1.20	.00	41.9	.23
April	1998	1.25	2.93	.06	.74	2.01	2.00	-2.22	.67	.00	43.2	.00
May	1998	2.59	3.38	.08	.50	2.38	2.19	-.62	.44	.00	49.9	.00
June	1998	.78	4.19	.03	.10	3.15	2.66	-2.18	.19	.00	52.6	-.02
July	1998	1.32	4.54	.04	.00	3.28	2.16	-1.28	.44	.00	56.8	-.03
August	1998	.51	4.82	.01	.00	3.59	.92	-.62	.21	.00	54.4	-.01
September	1998	.41	3.17	.01	.00	2.32	.30	-.09	.21	.00	50.5	-.01
Totals		25.31	27.56	0.87	5.50	18.72	12.20	-0.96	7.43	0.00	46.4	0.22
Month	**Year**	**Water Year 1999**										
October	1998	2.21	1.19	0.05	0.00	0.68	0.61	0.88	0.72	0.00	45.0	-0.05
November	1998	4.57	.42	.14	.28	.17	.17	3.20	.85	.00	43.6	-.06
December	1998	4.35	.32	.21	.96	.06	.06	1.76	1.35	.00	36.8	.00
January	1999	4.03	.33	.19	.97	.06	.06	1.30	.99	.00	38.9	.47
February	1999	2.88	.56	.09	.83	.15	.15	.03	.86	.00	39.1	.93
March	1999	3.04	1.40	.09	.85	.59	.59	-.21	1.26	.00	39.5	.46
April	1999	1.65	2.53	.05	.75	1.63	1.63	-1.32	.53	.00	40.2	.00
May	1999	3.23	3.05	.02	.80	1.95	1.92	-.08	.58	.00	46.0	.00
June	1999	2.40	3.63	.04	.69	2.44	2.23	-1.13	.57	.00	53.5	.00
July	1999	1.43	4.67	.02	.25	3.34	2.79	-2.02	.39	.00	54.9	.00
August	1999	1.04	3.80	.02	.00	2.76	2.13	-1.43	.32	.00	56.5	.00
September	1999	.31	2.99	.01	.00	2.21	1.02	-.82	.11	.00	49.7	.00
Totals		31.14	24.90	0.94	6.38	16.06	13.37	0.14	8.51	0.00	45.3	1.75

Table A3. Monthly and annual computed water-budget summaries for the northern Whidbey Island study basin, Gaging Station 12170315—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Average monthly values**										
October	3.31	1.16	0.05	0.02	0.57	0.54	1.79	0.95	0.00	46.2	-0.04
November	3.37	.47	.10	.47	.22	.22	1.90	.71	.00	42.8	-.03
December	3.40	.32	.15	.92	.09	.09	1.21	1.02	.00	37.3	.00
January	4.05	.36	.20	.97	.08	.08	1.43	1.05	.00	38.6	.29
February	2.18	.60	.06	.78	.22	.22	-.04	.69	.00	40.5	.46
March	3.47	1.46	.14	.88	.67	.67	.21	1.23	.00	40.7	.35
April	1.45	2.73	.06	.74	1.82	1.82	-1.77	.60	.00	41.7	.00
May	2.91	3.22	.05	.65	2.16	2.05	-.35	.51	.00	47.9	.00
June	1.59	3.91	.04	.39	2.80	2.45	-1.66	.38	.00	53.1	-.01
July	1.38	4.60	.03	.12	3.31	2.48	-1.65	.42	.00	55.9	-.02
August	.78	4.31	.02	.00	3.18	1.53	-1.03	.26	.00	55.4	-.01
September	.36	3.08	.01	.00	2.27	.66	-.46	.16	.00	50.1	-.01
Totals	28.23	26.23	0.90	5.94	17.39	12.79	-0.41	7.97	0.00	45.9	0.99

Table A4. Monthly and annual computed water-budget summaries for the Penn Cove study basin, Whidbey Island Gaging Station 12170320

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **CHGINT**, change in moisture stored on foliage (zero for cells with land cover for which throughfall data are used); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity – evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield - starting soil moisture) – measured direct runoff – recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**						**Water Year 1998**					
October	1997	2.98	1.00	0.10	0.00	0.30	0.30	1.94	0.72	0.00	46.4	-0.10
November	1997	1.46	.47	.07	.04	.11	.11	.93	.34	.00	40.5	-.04
December	1997	1.32	.31	.09	.20	.03	.03	.71	.31	.00	36.6	-.02
January	1998	2.43	.35	.45	.46	.03	.03	.99	.46	.00	37.5	.00
February	1998	1.43	.57	.12	.50	.16	.16	.20	.41	.00	40.8	.00
March	1998	2.75	1.35	.33	.64	.56	.56	.54	.69	.00	40.5	.00
April	1998	.91	2.63	.16	.37	1.77	1.76	-1.74	.37	.00	41.4	.00
May	1998	1.74	3.09	.07	.00	2.09	2.06	-.67	.35	.00	48.5	-.07
June	1998	1.04	3.82	.03	.00	2.63	2.29	-1.66	.40	.00	50.8	-.03
July	1998	1.38	4.01	.04	.00	2.87	1.97	-.89	.30	.00	54.3	-.04
August	1998	.01	4.37	.01	.00	3.33	.88	-.88	.01	.00	51.8	-.01
September	1998	.38	2.85	.00	.00	2.01	.27	-.11	.22	.00	47.9	.00
Totals		17.83	24.83	1.48	2.21	15.90	10.43	-0.63	4.59	0.00	44.8	-0.31
Month	**Year**						**Water Year 1999**					
October	1998	1.30	1.10	0.00	0.00	0.58	0.50	0.42	0.37	0.00	43.2	0.00
November	1998	2.74	.39	.09	.01	.08	.08	2.20	.40	.00	42.7	-.06
December	1998	2.77	.31	.22	.16	.02	.02	1.91	.49	.00	36.0	-.02
January	1999	2.81	.33	.46	.59	.03	.03	1.23	.46	.00	37.9	.00
February	1999	4.21	.54	.45	.64	.05	.05	2.17	.77	.00	38.0	.15
March	1999	2.12	1.26	.35	.69	.38	.38	-.10	.75	.00	38.0	.06
April	1999	1.04	2.27	.17	.60	1.35	1.35	-1.56	.47	.00	38.2	.01
May	1999	2.10	2.77	.06	.51	1.62	1.61	-.70	.63	.00	44.4	.00
June	1999	1.78	3.36	.03	.27	2.07	2.05	-1.24	.67	.00	52.5	.00
July	1999	1.06	4.28	.06	.20	3.00	2.71	-2.28	.37	.00	53.4	.00
August	1999	.64	3.43	.02	.01	2.36	1.48	-1.24	.37	.00	54.8	.00
September	1999	.13	2.69	.01	.00	1.97	.64	-.61	.10	.00	47.5	-.01
Totals		22.70	22.72	1.93	3.68	13.51	10.90	0.19	5.83	0.00	43.9	0.12

Table A4. Monthly and annual computed water-budget summaries for the Penn Cove study basin, Whidbey Island Gaging Station 12170320—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Average monthly values**										
October	2.14	1.05	0.05	0.00	0.44	0.40	1.18	0.54	0.00	44.8	-0.05
November	2.10	.43	.08	.02	.10	.10	1.56	.37	.00	41.6	-.05
December	2.05	.31	.16	.18	.03	.03	1.31	.40	.00	36.3	-.02
January	2.62	.34	.46	.53	.03	.03	1.11	.46	.00	37.7	.00
February	2.82	.55	.28	.57	.10	.10	1.19	.59	.00	39.4	.08
March	2.44	1.31	.34	.66	.47	.47	.22	.72	.00	39.3	.03
April	.98	2.45	.17	.49	1.56	1.56	-1.65	.42	.00	39.8	.00
May	1.92	2.93	.06	.26	1.85	1.83	-.69	.49	.00	46.4	-.03
June	1.41	3.59	.03	.14	2.35	2.17	-1.45	.54	.00	51.7	-.01
July	1.22	4.15	.05	.10	2.94	2.34	-1.59	.33	.00	53.9	-.02
August	.33	3.90	.02	.01	2.84	1.18	-1.06	.19	.00	53.3	-.01
September	.26	2.77	.00	.00	1.99	.46	-.36	.16	.00	47.7	0.00
Totals	20.27	23.77	1.70	2.94	14.70	10.66	-0.22	5.21	0.00	44.3	-0.09

Table A5. Monthly and annual computed water-budget summaries for the Cultus Creek study basin, Whidbey Island, Gaging Station 12170400

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity – evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield - starting soil moisture) – measured direct runoff – recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**	**Water Year 1998**										
October	1997	4.47	1.23	0.37	0.23	0.47	0.47	2.39	1.19	0.00	51.2	-0.19
November	1997	2.62	.61	.29	.90	.29	.29	.41	.73	.00	46.4	.00
December	1997	2.58	.35	.45	.96	.10	.10	.26	.81	.00	41.4	.00
January	1998	5.81	.42	1.25	1.37	.04	.04	1.22	1.89	.00	41.2	.04
February	1998	2.66	.75	.49	.90	.29	.29	.20	.77	.00	45.3	.02
March	1998	3.47	1.72	.82	.98	.81	.81	-.36	1.04	.00	46.3	.18
April	1998	1.59	3.14	.29	.60	2.06	1.96	-2.19	.93	.00	48.8	.00
May	1998	2.80	3.44	.26	.02	2.26	2.02	-.18	.79	.00	54.2	-.11
June	1998	1.06	4.22	.08	.00	2.85	2.23	-1.69	.51	.00	58.4	-.08
July	1998	.51	4.93	.02	.00	3.53	1.12	-.71	.11	.00	64.7	-.02
August	1998	1.15	4.88	.00	.00	3.39	.43	-.01	.73	.00	62.5	.00
September	1998	.59	3.28	.01	.00	2.29	.27	.02	.30	.00	58.8	-.01
Totals		29.31	28.97	4.32	5.96	18.37	10.01	-0.63	9.81	0.00	51.6	-0.17
Month	**Year**	**Water Year 1999**										
October	1998	4.12	1.14	0.21	0.03	0.67	0.67	1.84	1.47	0.00	50.6	-0.11
November	1998	5.20	.41	.73	.83	.15	.15	2.61	.91	.00	46.5	-.04
December	1998	4.45	.31	1.18	1.14	.09	.09	.21	1.65	.00	39.5	.19
January	1999	3.81	.34	1.21	1.08	.11	.11	.10	1.31	.00	41.9	.01
February	1999	5.89	0.53	1.93	1.29	.12	.12	.37	1.94	.00	42.7	.23
March	1999	3.77	1.53	.90	.95	.70	.70	-.36	1.59	.00	44.0	.00
April	1999	1.59	2.78	.36	.65	1.77	1.74	-1.64	.48	.00	46.7	.00
May	1999	2.78	3.17	.19	.59	1.99	1.94	-.48	.54	.00	51.2	.00
June	1999	2.70	3.53	.05	.02	2.12	2.02	-.17	.78	.00	56.9	.00
July	1999	1.29	4.64	.03	.04	3.17	2.66	-1.81	.37	.00	59.8	-.01
August	1999	1.11	3.93	0.01	.00	2.64	1.18	-.46	.39	.00	61.9	-.01
September	1999	.24	3.10	.01	.00	2.19	.42	-.30	.12	.00	56.9	-.01
Totals		36.95	25.42	6.82	6.62	15.74	11.80	-0.09	11.56	0.00	49.9	0.25

Table A5. Monthly and annual computed water-budget summaries for the Cultus Creek study basin, Whidbey Island, Gaging Station 12170400—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Average monthly values**										
October	4.30	1.19	0.29	0.13	0.57	0.57	2.12	1.33	0.00	50.9	-0.15
November	3.91	.51	.51	.87	.22	.22	1.51	.82	.00	46.5	-.02
December	3.52	.33	.81	1.05	.10	.10	0.23	1.23	.00	40.4	.09
January	4.81	.38	1.23	1.23	.07	.07	.66	1.60	.00	41.6	.02
February	4.28	.64	1.21	1.09	.21	.21	.29	1.36	.00	44.0	.12
March	3.62	1.62	.86	.96	.75	.75	-.36	1.32	.00	45.2	.09
April	1.59	2.96	.33	.62	1.92	1.85	-1.91	.70	.00	47.7	.00
May	2.79	3.30	.22	.31	2.13	1.98	-.33	.67	.00	52.7	-.06
June	1.88	3.88	.06	.01	2.48	2.13	-.93	.65	.00	57.6	-.04
July	.90	4.78	.03	.02	3.35	1.89	-1.26	.24	.00	62.3	-.01
August	1.13	4.41	.01	.00	3.01	.81	-.23	.56	.00	62.2	-.01
September	.42	3.19	.01	.00	2.24	.34	-.14	.21	.00	57.8	-.01
Totals	33.13	27.19	5.57	6.29	17.05	10.91	-0.36	10.68	0.00	50.8	0.04

Table A6. Monthly and annual computed water-budget summaries for the South Whidbey State Park study basin, Whidbey Island Gaging Station 12170440

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **RUNOFF**; measured or estimated direct runoff; **RECHRG**; soil water that percolates below the root zone (recharge); **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature; **DEFCIT**, if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity –evaporation and transpiration components – measured direct runoff; if the following is positive: rain + snowmelt – (available water-holding capacity + specific yield – starting soil moisture) – measured direct runoff –recharge. All values in inches of water except AVTMP, which is in degrees Fahrenheit. All values rounded to two significant figures. Because of rounding totals may not exactly equal the sum of the shown monthly values]

DATE		PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Year**	**Water Year 1998**										
October	1997	4.26	1.04	0.52	0.00	0.42	0.42	2.69	1.15	0.00	47.2	-0.52
November	1997	2.33	.49	.36	.00	.23	.23	1.45	.65	.00	41.5	-.36
December	1997	1.96	.32	.37	.40	.08	.08	.63	.62	.00	37.4	-.15
January	1998	5.19	.37	2.83	.79	.04	.04	-0.17	1.73	.00	38.1	-.07
February	1998	2.40	.61	1.18	.47	.29	.29	.01	.69	.00	41.5	-.25
March	1998	3.15	1.47	1.14	.44	.64	.64	.20	1.04	.00	41.5	-.31
April	1998	1.60	2.82	.68	.03	1.70	1.70	-1.20	.99	.00	42.7	-.60
May	1998	2.31	3.15	.43	.00	2.05	2.05	-.31	.57	.00	49.5	-.43
June	1998	1.21	3.86	.30	.00	2.58	2.58	-1.83	.47	.00	52.1	-.30
July	1998	.95	4.08	.19	.00	2.85	2.42	-1.70	.23	.00	56.1	-.19
August	1998	.48	4.39	.03	.00	3.11	1.36	-1.08	.20	.00	53.7	-.03
September	1998	.14	2.92	.00	.00	2.09	.50	-.44	.08	.00	49.8	.00
Totals		25.98	25.51	8.03	2.14	16.07	12.29	-1.73	8.41	0.00	46.0	-3.21
Month	**Year**	**Water Year 1999**										
October	1998	2.99	1.13	0.33	0.00	0.68	0.67	1.48	0.84	0.00	44.5	-0.33
November	1998	3.77	.40	.37	.00	.19	.19	2.99	.60	.00	43.4	-.37
December	1998	3.47	.31	.51	.08	.08	.08	1.96	1.22	.00	36.6	-.39
January	1999	4.26	.33	1.22	.66	.09	.09	1.01	1.36	.00	38.6	-.10
February	1999	5.43	.56	2.32	.77	.15	.15	.41	1.79	.00	38.8	.00
March	1999	3.59	1.37	1.81	.85	.53	.53	-1.16	1.56	.00	39.1	.00
April	1999	1.30	2.49	1.20	.14	1.61	1.61	-1.13	.38	.00	39.6	-.90
May	1999	2.48	2.90	.69	.05	1.86	1.86	.06	.44	.00	45.5	-.62
June	1999	2.22	3.35	.62	.00	2.08	2.08	-.49	.63	.00	53.2	-.62
July	1999	1.11	4.26	.68	.00	2.95	2.95	-2.12	.29	.00	54.5	-.68
August	1999	.75	3.43	.04	.00	2.35	2.17	-1.68	.27	.00	56.0	-.04
September	1999	.14	2.77	.04	.00	1.98	1.11	-1.04	.07	.00	49.1	-.04
Totals		31.51	23.28	9.85	2.54	14.53	13.46	0.29	9.44	0.00	44.9	-4.12

Table A6. Monthly and annual computed water-budget summaries for the South Whidbey State Park study basin, Whidbey Island Gaging Station 12170440—*Continued*

DATE	PRECP	POTET	RUNOFF	RECHRG	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	DEFCIT
Month	**Average monthly values**										
October	3.63	1.08	0.43	0.00	0.55	0.54	2.09	0.99	0.00	45.8	-0.43
November	3.05	.45	.37	.00	.21	.21	2.22	.62	.00	42.4	-.37
December	2.72	.31	.44	.24	.08	.08	1.29	.92	.00	37.0	-.27
January	4.73	.35	2.02	.73	.06	.06	.42	1.54	.00	38.4	-.09
February	3.92	.58	1.75	.62	.22	.22	.21	1.24	.00	40.2	-.12
March	3.37	1.42	1.48	.64	.58	.58	-.48	1.30	.00	40.3	-.15
April	1.45	2.66	.94	.08	1.65	1.65	-1.16	.69	.00	41.1	-.75
May	2.40	3.02	.56	.02	1.96	1.96	-.12	.50	.00	47.5	-.53
June	1.72	3.60	.46	.00	2.33	2.33	-1.16	.55	.00	52.7	-.46
July	1.03	4.17	.44	.00	2.90	2.68	-1.91	.26	.00	55.3	-.44
August	.62	3.91	.04	.00	2.73	1.76	-1.38	.23	.00	54.8	-.04
September	.14	2.84	.02	.00	2.03	.81	-.74	.07	.00	49.4	-.02
Totals	28.75	24.40	8.94	2.34	15.30	12.88	-0.72	8.93	0.00	45.4	-3.66

APPENDIX B. MONTHLY COMPUTER WATER-BUDGET SUMMARIES FOR WHIDBEY AND CAMANO ISLANDS

Table B1. Monthly and annual computed water-budget summaries for Whidbey Island, Island County, Washington

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **CHGINT**, change in moisture stored on foliage (zero for cells with land cover for which throughfall data are used); **RUNOFF**, measured or estimated direct runoff; **RECHRG**, soil water that percolates below the root zone (recharge); **ACTSEV**, actual bare-soil evaporation; **SNWEVP**, direct evaporation of snow; **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperature]

DATE		PRECP	POTET	CHGINT	RUNOFF	RECHRG	ACTSEV	SNWEVP	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	SYM-RO
Month	Year	Water Year 1998													
October	1997	4.03	1.21	0.01	0.00	0.16	0.09	0.00	0.41	0.41	2.24	0.98	0.00	53.4	0.13
November	1997	2.10	.60	.01	.00	.44	.04	.00	.26	.26	.77	.50	.00	48.8	.08
December	1997	1.87	.35	-.01	.00	.57	.02	.00	.09	.09	.62	.47	.00	43.7	.10
January	1998	4.63	.40	-.01	.00	1.59	.03	.00	.06	.06	1.31	1.07	.00	43.6	.56
February	1998	2.26	.71	.02	.00	.85	.05	.00	.24	.24	.04	.60	.00	47.6	.46
March	1998	3.52	1.69	-.01	.00	1.03	.12	.00	.73	.73	.13	1.00	.00	48.7	.51
April	1998	1.53	3.24	-.01	.00	.38	.22	.00	2.02	1.92	-1.85	.77	.00	51.2	.10
May	1998	2.27	3.57	.00	.00	.12	.23	.00	2.36	1.90	-.36	.45	.00	56.7	-.08
June	1998	1.20	4.41	.00	.00	.04	.28	.00	3.00	2.11	-1.44	.41	.00	60.2	-.21
July	1998	1.06	4.86	.00	.00	.01	.30	.00	3.44	1.78	-1.06	.27	.00	64.9	-.24
August	1998	.24	5.16	.00	.00	.00	.33	.00	3.76	.83	-.71	.10	.00	64.4	-.31
September	1998	.24	3.48	.00	.00	.00	.22	.00	2.46	.30	-.21	.14	.00	60.6	-.21
Totals		24.93	29.68	0.00	0.00	5.18	1.94	0.00	18.84	10.63	-0.54	6.77	0.00	53.7	0.88
Month	Year	Water Year 1999													
October	1998	2.68	1.28	0.00	0.00	0.02	0.09	0.00	0.70	0.60	1.19	0.72	0.00	52.4	0.04
November	1998	3.77	.44	.02	.00	.60	.03	.00	.14	.14	2.21	.59	.00	48.7	.19
December	1998	3.59	.32	.00	.00	.94	.02	.00	.03	.03	1.19	1.14	.00	41.8	.26
January	1999	3.80	.34	.00	.00	1.31	.03	.00	.06	.06	1.07	.88	.00	43.4	.44
February	1999	4.76	.58	-.01	.00	1.56	.04	.00	.10	.10	.96	1.20	.00	43.6	.90
March	1999	3.16	1.56	-.01	.00	.92	.12	.00	.63	.63	-.45	1.15	.00	46.5	.78
April	1999	1.31	2.94	.00	.00	.41	.21	.00	1.83	1.76	-1.77	.46	.00	49.7	.24
May	1999	2.56	3.36	.00	.00	.33	.23	.00	2.03	1.84	-.49	.61	.00	54.6	.04
June	1999	2.20	3.87	.00	.00	.09	.25	.00	2.39	1.99	-.72	.69	.00	62.1	-.11
July	1999	1.22	4.97	.00	.00	.03	.32	.00	3.45	2.27	-1.52	.36	.00	63.7	-.25
August	1999	.80	4.01	.00	.00	.01	.25	.00	2.71	1.31	-.92	.35	.00	64.0	-.21
September	1999	.18	3.32	.00	.00	.00	.21	.00	2.36	.61	-.55	.11	.00	59.8	-.20
Totals		30.03	26.98	0.00	0.00	6.24	1.80	0.00	16.42	11.32	0.20	8.27	0.00	52.6	2.13

Table B1. Monthly and annual computed water-budget summaries for Whidbey Island, Island County, Washington—*Continued*

DATE	PRECP	POTET	CHGINT	RUNOFF	RECHRG	ACTSEV	SNWEVP	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	SYM-RO
Month	**Average monthly values**													
October	3.36	1.25	0.00	0.00	0.09	0.09	0.00	0.55	0.50	1.72	0.85	0.00	52.9	0.09
November	2.93	.52	.01	.00	.52	.04	.00	.20	.20	1.49	.54	.00	48.8	.13
December	2.73	.33	.00	.00	.75	.02	.00	.06	.06	.90	.81	.00	42.8	.18
January	4.21	.37	.00	.00	1.45	.03	.00	.06	.06	1.19	.98	.00	43.5	.50
February	3.51	.65	.01	.00	1.21	.05	.00	.17	.17	.50	.90	.00	45.6	.68
March	3.34	1.62	-.01	.00	.97	.12	.00	.68	.68	-.16	1.08	.00	47.6	.64
April	1.42	3.09	-.01	.00	.40	.22	.00	1.93	1.84	-1.81	.61	.00	50.5	.17
May	2.41	3.46	.00	.00	.22	.23	.00	2.19	1.87	-.42	.53	.00	55.6	-.02
June	1.70	4.14	.00	.00	.07	.27	.00	2.70	2.05	-1.08	.55	.00	61.2	-.16
July	1.14	4.91	.00	.00	.02	.31	.00	3.45	2.02	-1.29	.31	.00	64.3	-.24
August	.52	4.59	.00	.00	.01	.29	.00	3.23	1.07	-.82	.23	.00	64.2	-.26
September	.21	3.40	.00	000	.00	.22	.00	2.41	.45	-038	.12	.00	60.2	-.20
Totals	27.48	28.33	0.00	0.00	5.71	1.87	0.00	17.63	10.97	-0.17	7.52	0.00	53.1	1.50

Table B2. Monthly and annual computed water-budget summaries for Camano Island, Island County, Washington

[**PRECP**, measured precipitation; **POTET**, potential evapotranspiration (may be less than sum of evaporation and transpiration components, as discussed in report); **CHGINT**, change in moisture stored on foliage (zero for cells with land cover for which throughfall data are used); **RUNOFF**, measured or estimated direct runoff; **RECHRG**, soil water that percolates below the root zone (recharge); **ACTSEV**, actual bare-soil evaporation; **SNWEVP**, direct evaporation of snow; **PPLTR**, foliage-type-dependent potential transpiration; **APLTR**, actual plant transpiration; **CHGSM**, change in soil moisture; **EVINT**, interception loss computed from input precipitation throughfall, and DPM-simulated throughfall where land use is not evergreen forest; **CHGSNW**, change in snowpack; **AVTMP**, average temperatureSYM-RO = DPM-simulated direct runoff]

DATE		PRECP	POTET	CHGINT	RUNOFF	RECHRG	SOLPEV	ACTSEV	SNWEVP	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	SYM-RO
Month	**Year**	**Water Year 1998**														
October	1997	4.18	1.19	0.01	0.00	0.16	0.02	0.02	0.00	0.43	0.42	2.47	1.06	0.00	53.5	0.04
November	1997	2.16	.58	.01	.00	.40	.01	.01	.00	.26	.26	.91	.55	.00	48.9	.02
December	1997	2.18	.34	.00	.00	.55	.00	.00	.00	.09	.09	.90	.59	.00	43.8	.05
January	1998	4.49	.40	-.01	.00	1.63	.01	.01	.00	.05	.05	1.20	1.15	.00	43.7	.46
February	1998	2.46	.70	.01	.00	1.03	.01	.01	.00	.24	.24	.03	.68	.00	47.7	.45
March	1998	3.76	1.69	-.01	.00	1.21	.02	.02	.00	.75	.75	.14	1.12	.00	48.8	.53
April	1998	1.66	3.25	-.01	.00	.51	.05	.04	.00	2.08	2.02	-2.05	.91	.00	51.3	.24
May	1998	2.45	3.57	.00	.00	.10	.04	.04	.00	2.44	2.13	-.30	.45	.00	56.8	.03
June	1998	1.30	4.39	.00	.00	.03	.05	.05	.00	3.04	2.47	-1.69	.46	.00	60.3	-.02
July	1998	1.35	4.81	.00	.00	.01	.05	.05	.00	3.44	2.18	-1.17	.32	.00	64.9	-.03
August	1998	.12	5.13	.00	.00	.00	.06	.06	.00	3.83	1.10	-1.04	.06	.00	64.4	-.05
September	1998	.35	3.46	.00	.00	.00	.05	.04	.00	2.51	.38	-.20	.17	.00	60.6	-.03
Totals		26.47	29.51	0.00	0.00	5.63	0.37	0.34	0.00	19.16	12.09	-0.80	7.52	0.00	53.8	1.67
Month	**Year**	**Water Year 1999**														
October	1998	2.72	1.27	0.00	0.00	0.02	0.02	0.02	0.00	0.71	0.64	1.23	0.80	0.00	52.4	0.01
November	1998	3.97	.43	.01	.00	.58	.01	.01	.00	.14	.14	2.50	.66	.00	48.8	.07
December	1998	3.97	.32	.00	.00	.90	.00	.00	.00	.04	.04	1.58	1.30	.00	41.9	.15
January	1999	4.00	.34	.00	.00	1.35	.00	.00	.00	.06	.06	1.24	.97	.00	43.4	.39
February	1999	4.04	.58	-.01	.00	1.43	.01	.01	.00	.13	.13	.62	1.13	.00	43.7	.72
March	1999	3.21	1.56	.00	.00	1.07	.02	.02	.00	.67	.67	-.52	1.25	.00	46.6	.72
April	1999	1.41	2.95	.00	.00	.53	.04	.04	.00	1.90	1.86	-1.80	.48	.00	49.8	.30
May	1999	2.77	3.36	.00	.00	.38	.04	.04	.00	2.10	2.00	-.35	.61	.00	54.7	.08
June	1999	2.22	3.86	.00	.00	.04	.04	.04	.00	2.43	2.22	-.78	.69	.00	62.4	.00
July	1999	1.28	4.94	.00	.00	.01	.05	.05	.00	3.45	2.65	-1.80	.40	.00	63.9	-.03
August	1999	.92	3.97	.00	.00	.01	.05	.04	.00	2.73	1.58	-1.06	.38	.00	64.1	-.03
September	1999	.26	3.30	.00	.00	.00	.05	.04	.00	2.38	.79	-.68	.14	.00	59.9	-.03
Totals		30.78	26.88	0.00	0.00	6.33	0.34	0.31	0.00	16.75	12.78	0.19	8.82	0.00	52.7	2.34

Table B2. Monthly and annual computed water-budget summaries for Camano Island, Island County, Washington—*Continued*

DATE	PRECP	POTET	CHGINT	RUNOFF	RECHRG	SOLPEV	ACTSEV	SNWEVP	PPLTR	APLTR	CHGSM	EVINT	CHGSNW	AVTMP	SYM-RO
Month	**Average monthly values**														
October	3.45	1.23	0.00	0.00	0.09	0.02	0.02	0.00	0.57	0.53	1.85	0.93	0.00	53.0	0.02
November	3.06	.51	.01	.00	.49	.01	.01	.00	.20	.20	1.71	.60	.00	48.9	.05
December	3.07	.33	.00	.00	.72	.00	.00	.00	.06	.06	1.24	.94	.00	42.9	.10
January	4.25	.37	-.01	.00	1.49	.01	.01	.00	.06	.06	1.22	1.06	.00	43.6	.42
February	3.25	.64	.00	.00	1.23	.01	.01	.00	.19	.19	.33	.91	.00	45.7	.58
March	3.49	1.63	.00	.00	1.14	.02	.02	.00	.71	.71	-.19	1.18	.00	47.7	.62
April	1.54	3.10	.00	.00	.52	.04	.04	.00	1.99	1.94	-1.92	.70	.00	50.6	.27
May	2.61	3.46	.00	.00	.24	.04	.04	.00	2.27	2.07	-.33	.53	.00	55.8	.06
June	1.76	4.13	.00	.00	.04	.05	.05	.00	2.74	2.35	-1.23	.58	.00	61.3	-.01
July	1.32	4.88	.00	.00	.01	.05	.05	.00	3.45	2.41	-1.49	.36	.00	64.4	-.03
August	.52	4.55	.00	.00	.00	.06	.05	.00	3.28	1.34	-1.05	.22	.00	64.2	-.04
September	.31	3.38	.00	.00	.00	.05	.04	.00	2.44	.58	-044	.16	.00	60.3	-.03
Totals	28.62	28.20	0.00	0.00	5.98	0.35	0.33	0.00	17.96	12.43	-0.31	8.17	0.00	53.2	2.00

USGS

Sumioka and Bauer

Estimating Ground-Water Recharge from Precipitation on Whidbey and Camano Islands, Island County, Washington, Water Years 1998 and 1999

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