Recharge From Precipitation in Three Small Glacial-Till-Mantled Catchments in the Puget Sound Lowland, Washington

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U.S. Geological Survey
Water-Resources Investigations Report 96-4219

Prepared in cooperation with
WASHINGTON STATE DEPARTMENT OF ECOLOGY

Tacoma, Washington
1997

U.S. DEPARTMENT OF THE INTERIOR

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ABSTRACT

Detailed water budgets for three small catchments in glacial-till-mantled terrains in the southern part of the Puget Sound Lowland, Washington, were computed for the purpose of estimating direct ground-water recharge from precipitation through glacial till. Water-budget calculations using time-series data of precipitation, streamflow, incoming solar radiation, and temperature for 2 and 3 year periods, together with soil and foliar-cover data, were calibrated against periodically observed soil moistures, perched soil-water levels in the 2-to-3-foot-thick topsoil layer above the till, and forest throughfall quantities. Recharge was also estimated independently at one location in each catchment by sampling and accounting for the distribution of thermonuclear-bomb-produced tritium in the unsaturated zone.

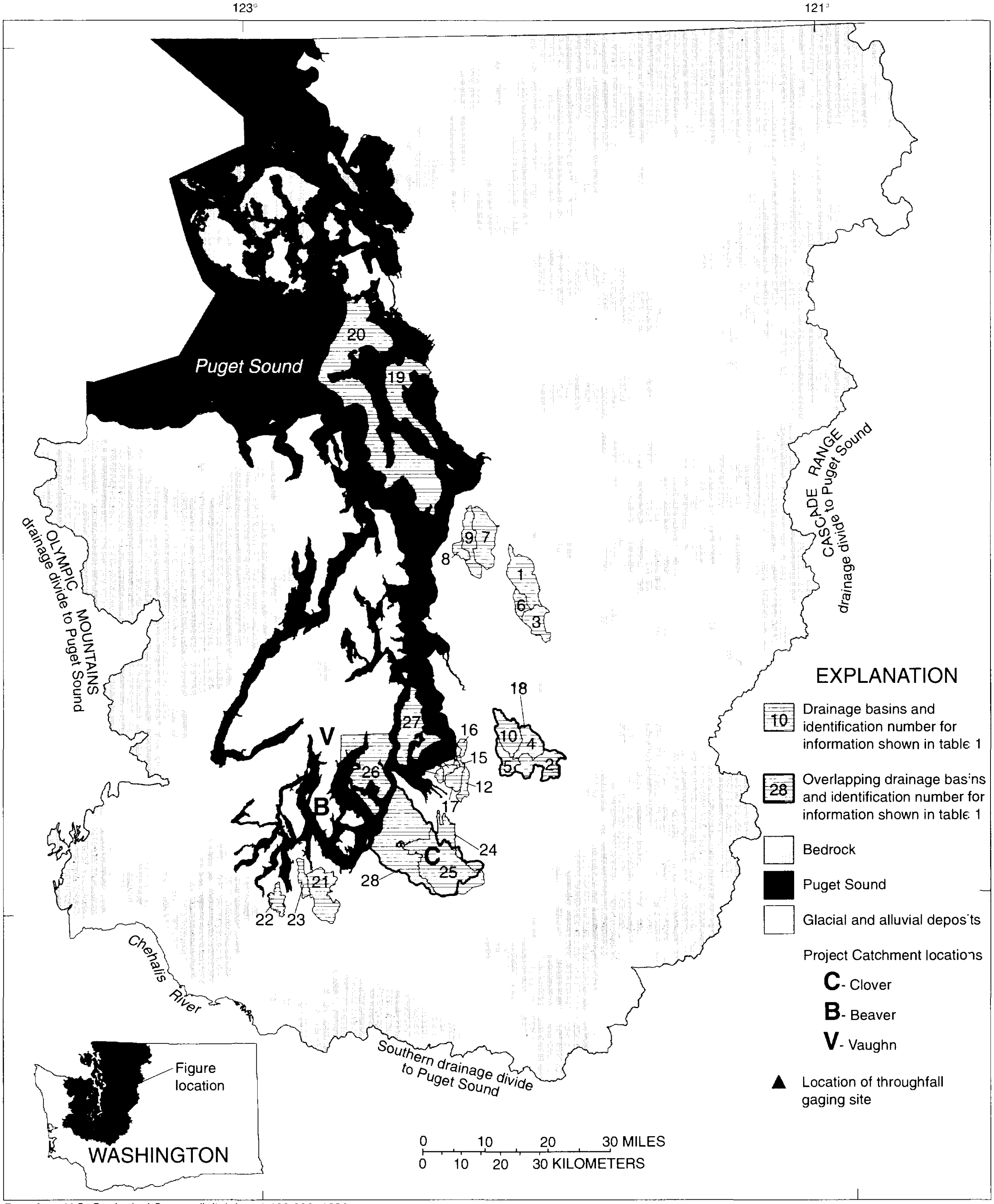
Water-budget-computed recharge to the water-table aquifer in the three catchments were 1.46, 5.44, and 6.79 inches per year or 4.0, 13.9, and 16.7 percent of precipitation, respectively. Average recharge rates estimated from the tritium in the unsaturated zone ranged from 1.67 to 2.10 inches per year, for the 1952-92 period, in one of the catchments and compared favorably with the water-budget of 1.46 inches per year for that same catchment. Only rough recharge estimates could be obtained using the tritium method for the other two catchments (4.09 to 5.28 and 6.66 to 7.87 inches per year). Differences in the recharge rates between the catchments appear to be largely due to variations in the amount of silt- and clay-sized particles in the till. Estimates of recharge made in this investigation are generally less than half those of most other investigations in the Puget Sound Lowland.

The components of direct runoff were examined by sampling and accounting for the concentrations of the oxygen-18 stable isotope in precipitation, soil water, and streamflow in one of the catchments during three storms. The observed isotopic compositions indicate that there is no significant overland-flow contribution to direct runoff in forested, till-mantled, moderately sloping areas of the Puget Sound Lowland. Instead, streamflows caused by storms consist mostly of antecedent soil water displaced by storm precipitation.

INTRODUCTION

The Puget Sound Lowland covers a region of about 8,000 square miles in the northwestern part of the state of Washington (fig. 1) and contains about 70 percent of the state's population, which was about 4.9 million in 1990. As the population of the region undergoes rapid growth, more water is being developed from ground-water sources than from surface-water sources. In 1965, 129 million gallons per day, or 15 percent, of the total water usage was derived from ground-water sources (Dion and Lum, 1977). By 1990, about 352 million gallons per day, or 44 percent of total water usage, was derived from ground-water sources (Ronald C. Lane, U.S. Geological Survey, written commun., 1995).

Most of the ground water used in the region is withdrawn from aquifers composed of coarse-grained glacial advance and glacial recessional outwash deposits of Pleistocene age. Typically these outwash deposits underlie glacial till, a compacted, generally fine-grained material that contains varying fractions of sand to boulder-size fragments. About 50 percent of the Lowland (excluding



Base from U.S. Geological Survey digital data 1:100,000, 1983
Universal Transverse Mercator projection, Zone 10

Figure 1.--Locations of the three catchments of this investigation, and locations of areas summarized on table 1 where recharge estimates were made by other investigators (Puget Sound Lowland approximately corresponds with areas of no bedrock).

areas covered by seawater) is mantled by as much as 80 feet of till, mainly the Vashon till, deposited during the Fraser glaciation. The annual rate of direct percolation from precipitation through the till is of major importance in estimating annual recharge to the aquifers of the region. Also, movement of soil-moisture that discharges to streams in till-covered areas is poorly understood and generally has not been quantified other than by rainfall-runoff modeling. A better understanding of this mechanism may aid in predicting the movement of contaminants, such as those which may originate from septic systems.

In order to better estimate ground-water recharge from direct precipitation through till-mantled areas and to better understand the soil-water movement processes in the Puget Lowland, a cooperative project was initiated between the U.S. Geological Survey and the State of Washington Department of Ecology in September 1991. The results and methodologies of this study, when applied to larger scale future ground- and surface-water investigations in the region, may improve the reliability of the results of those investigations.

Purpose and Scope

This report documents an investigation to estimate ground-water recharge through glacial till in three small catchments in the Puget Sound Lowland. It also describes interpretations of the likely pathways for the movement of water from precipitation to streams and ground water in these catchments.

Ground-water recharge cannot be directly measured and is difficult to accurately estimate. Indirect recharge estimates are subject to large errors, and, therefore, when possible, more than one method is needed to verify the estimates. Generally, the simplest, most reliable method is to equate ground-water recharge to ground-water discharge. However, because large quantities of ground-water discharge through the seabed and seep from the many shoreline bluffs, ground-water discharge cannot be measured in the Puget Sound Lowland. In this investigation, two other methods were used to estimate recharge through glacial till.

(1) A water-budget method was used in three till-mantled catchments in which estimates of evapotranspiration, direct runoff (surface runoff, and shallow-soil-water seepage to streams) are subtracted from precipitation to give an estimate of percolation into the subsoil, which is then assumed to equal recharge.

(2) A tritium-tracer method was used in the same three catchments. As a result of thermonuclear weapons testing, which began in the early 1950's, large quantities of tritium were produced and released into the atmosphere, combining with oxygen to form tritiated water. Maximum concentrations of tritiated water were reached in 1963. These high concentrations of tritiated water that fell with precipitation and infiltrated the soil are readily detected. The tritium-tracer method involved sampling and analyzing for tritiated water from the unsaturated zone above the permanent water table. Measurements of the vertical distribution of tritium and soil-moisture content were used to calculate recharge.

The source of streamflow during storms and the movement of soil water in till-mantled areas were also investigated. Different isotopic compositions of oxygen in soil water, streamflow, and precipitation were used to identify the contributions to streamflow. A dye tracer was also used to give visual information on the movement of soil water.

Acknowledgments

The authors express their appreciation to the private land owners within the study areas and to the State of Washington Department of Natural Resources which allowed access to its property for the purposes of constructing streamflow gaging stations, drilling test wells, installing hydrologic instrumentation, and collecting hydrologic data.

PREVIOUS INVESTIGATIONS

The most commonly used method for estimating recharge for ground-water investigations within the Puget Sound Lowland involved computing monthly soil-moisture excesses. In this method, moisture from precipitation during each month plus moisture remaining in the soil from the prior month is assumed to evaporate at a rate equal to a computed average monthly potential evapotranspiration rate. Potential evapotranspiration (PET) is defined as the evaporation and transpiration that occurs from a well-watered reference crop, usually alfalfa or grass, for the particular weather conditions, time of year, and latitude. If precipitation exceeds PET, the difference is added to the soil moisture for the next month's calculation. However, if this newly-computed soil moisture exceeds the available-water-holding capacity (AWC) of the soil in the root zone, this excess, referred to as potential recharge, is the recharge that would occur if there were no direct runoff. Available-water-holding capacity of a soil is defined as the difference between field capacity (the maximum water content held by a soil that is free to drain under the force of gravity, generally over a period of a few days) and the wilting point (the lowest moisture content at which plants can remove moisture from the soil).

In the previous investigations, monthly PET was computed with the methods of either Blaney-Criddle (U.S. Department of Agriculture, 1970) or Thornthwaite (Thornthwaite, 1948; Thornthwaite and others, 1957). Noble and Wallace (1966), Richardson and others (1968), Eddy (1975), and Grimstad and Carson (1981) computed the potential recharge, but because estimates of direct runoff were not made and subtracted from potential recharge, they did not estimate actual recharge. Drost (1982) presented a more complete natural-conditions water budget that included estimates of evapotranspiration by the above method, as well as estimates of the direct-runoff and baseflow components of streamflow. Assuming negligible storage changes, subtracting Drost's evapotranspiration and direct runoff values from his reported precipitation gives an average value of direct recharge from precipitation of 19.8 inches per year for a 59-square-mile area that is mostly mantled by glacial till. Carr and associates (1983), using the above monthly water-budget approach in conjunction with annual water-level fluctuations, estimated an average annual recharge rate of only 5 inches for a similarly till-mantled area. Brown and Caldwell (1985) equated total spring discharge to total ground-water inflow, which was the sum of direct recharge from precipitation, surface-water infiltration, and waste- and storm-water infiltration. Direct recharge from precipitation, computed as the residual, was 16 inches per year for a complex area overlain by large segments of both highly pervious materials and impervious urban structures, as well as glacial till.

Advances in computer technology allow intensive, daily soil-moisture budgeting methods, such as the Deep Percolation Model (DPM), which computes percolation beyond the root zone for any number of land segments (or cells) (Bauer and Vaccaro, 1987). DPM was used for an investigation in the Puget Sound Lowland to compute the recharge distributions for eight drainage basins in Southwest King County (Woodward and others, 1995). Also, an early unpublished version of DPM was used to compute recharge for Island County (Sapik and others, 1988).

Recharge in the Puget Sound Lowland has also been indirectly computed from application of the Hydrological Simulation Program-FORTRAN (HSPF) rainfall-runoff model (U.S. Environmental Protection Agency, 1984). Dinicola (1990) used HSPF to simulate streamflow for various locations in five drainage basins in King and Snohomish Counties. Berris (1995) used HSPF for three drainage basins in Thurston County, and Mastin (1996) used it for three drainage basins in Pierce County. HSPF calculates quantities of precipitation that become surface runoff, shallow-subsurface runoff, and percolation to, and delayed discharge from, various subsurface storages. When properly interpreted, some of the percolation values can be used as estimates of ground-water recharge.

The results of application of DPM and HSPF for drainage basins having large percentages of till-mantled areas, as well as the previously referenced recharge estimates, are summarized in table 1; figure 1 shows the locations of the study areas. These areas all consist of subareas overlain by three general types of subsoil or surficial materials: (1) highly-permeable glacial outwash, (2) impervious materials (parking lots, buildings, streets, etc., and also includes surface-water bodies), and (3) glacial till. Total recharge listed for a particular study area is a composite of the recharge in glacial outwash and till-mantled areas.

Values of recharge through only the till-mantled parts of these study areas were obtained from written communications from the principal authors or from information in published reports or unpublished project files. When recharge quantities through till-mantled areas were not specifically given, the following analysis was used to approximate these values.

Table 1.--*Summary of published estimates of ground-water recharge for pervious and till-mantled areas in the Puget Sound Lowland*

Reference number[1]	Name of study area	Total drainage area (square miles)	Till mantled area (square miles)	Highly pervious area (square miles)	Time period	Mean annual values, in inches					Source and technique used to compute recharge[2]
						Precipitation	Evapotranspiration	Estimated recharge for			
								Total drainage area	Pervious areas	Till mantled areas	
1	Upper Bear Creek[3]	26.81	21.5	2.52	10/84 - 09/86	40.45	20.25	11.88	20.2	12.5	RSD, HSPF
2	Covington Creek	20.6	9.93	8.47	10/84 - 09/86	42.19	20.60	15.37	21.6	13.5	RSD, HSPF
3	Evans Creek	14.6	9.24	3.17	10/84 - 09/86	40.61	19.58	13.17	21.0	13.6	RSD, HSPF
4	Jenkins Creek	16.01	5.70	8.40	10/84 - 09/86	38.64	19.15	14.63	19.5	12.3	RSD, HSPF
5	Lower Soos Creek[3]	10.61	6.30	3.09	10/84 - 09/86	36.32	18.88	11.25	17.4	10.4	RSD, HSPF
6	Lower Bear Creek[3]	8.02	4.64	2.34	10/84 - 09/86	40.18	19.13	12.75	21.0	11.4	RSD, HSPF
7	North Creek	27.61	19.40	2.43	10/84 - 09/86	38.22	17.89	8.70	20.3	9.8	RSD, HSPF
8	Scriber Creek	6.98	4.49	0.0	10/84 - 09/86	33.30	14.44	4.77	18.9	7.4	RSD, HSPF
9	Swamp Creek	23.6	15.55	1.77	10/84 - 09/86	33.36	16.25	6.55	17.1	8.0	RSD, HSPF
10	Upper Big Soos Creek	18.6	13.15	2.08	10/84 - 09/86	34.50	17.98	8.79	16.5	9.8	RSD, HSPF
11	Lakota Creek	3.03	1.64	1.16	01/87 - 12/87	33.01	14.77	15.83	18.5	16.11	SSS, DPM
12	Hylebos Creek	5.92	5.02	0.31	01/87 - 12/87	32.82	14.62	10.62	18.2	11.4	SSS, DPM
13	Joes Creek	2.58	1.46	1.04	01/87 - 12/87	33.31	13.26	14.26	19.8	11.1	SSS, DPM
14	Unnamed Creek #1	1.15	0.70	0.18	01/87 - 12/87	32.56	17.01	11.87	15.5	15.5	SSS, DPM
15	Unnamed Creek #2	0.80	0.43	0.25	01/87 - 12/87	32.68	15.56	14.49	17.1	17.0	SSS, DPM
16	Unnamed Creek #3	2.92	1.78	0.47	01/87 - 12/87	32.17	15.64	9.82	16.5	11.7	SSS, DPM
17	Hylebos Creek, Tributary	7.77	3.29	2.68	01/87 - 12/87	33.00	16.91	11.52	16.1	14.1	SSS, DPM
18	Big Soos Creek	872.12	41.03	21.64	01/67 - 12/87	47.80	19.21	20.61	28.6	21.2	SSS, DPM
19	Camano Island	40.1	[4]--	[4]--	01/51 - 12/77	29.12	16.44	12.68	12.7	12.7	DBS, PDPM
20	Whidbey Island	170.	[4]--	[4]--	01/51 - 12/77	25.17	13.32	11.85	11.8	11.8	DBS, PDPM
21	Woodland Creek	29.5	6.34	18.52	03/88 - 02/90	51.7	16.9	28.8	28.8	32.4	SNB, HSPF

Table 1.--*Summary of published estimates of ground-water recharge for pervious and till-mantled areas in the Puget Sound Lowland--Continued*

Reference number[1]	Name of study area	Total drainage area (square miles)	Till mantled area (square miles)	Highly pervious area (square miles)	Time period	Mean annual values, in inches: Precipitation	Evapotranspiration	Estimated recharge for: Total drainage area	Pervious areas	Till mantled areas	Source and technique used to compute recharge[2]
22	Percival Creek	8.3	2.40	2.07	03/88 - 02/90	60.7	17.0	21.7	21.7	37.4	SNB, HSPF
23	Woodard Creek	7.0	4.71	2.91	03/88 - 02/90	51.5	17.6	23.5	23.5	14.0	SNB, HSPF
24	Clear/Clark Basin	11.04	9.07	0.50	10/90 - 09/92	40.52	19.32	2.84	23.1	1.94	MCM, HSPF
25	Clover Creek	66.72	16.99	39.55	10/90 - 09/92	40.52	17.23	14.38	23.0	2.01	MCM, HSPF
26	Gig Harbor Peninsula	58.75	45.36	13.39	[5]--	51.11	19.34	19.8	31.8	16.3	Drost, 1982
27	Vashon Island	44.97	26.08	18.89	[6]--	40	20	[7]--	20	5	Carr and Associates, 1983
28	Clover/Clark Creek	144	[8]--	[8]--	[9]--	40.5	[9]--	16.0	[8]--	[8]--	Brown and Caldwell, 1985

[1]Keyed to area reference numbers on figure 1.

[2]RSD, Dinicola, 1990, and also R.S. Dinicola, U.S. Geological Survey, written communication, 1991; HSPF, U.S. Environmental Protection Agency, 1984; SSS, Sumioka, U.S.Geological Survey, written communication, 1991 and Woodward and others, in press; DPM, Bauer and Vaccaro, 1987; DBS, Sapik and others, 1988; PDPM, Unpublished fortran program, precursor to DPM, developed by author, 1985; SNB, Berris, 1995, and MCM, Mastin, 1996.

[3]Upper Bear Creek consists of combined drainage areas to U.S. Geological Survey gages 12122500 and 12123100. Lower Soos Creek consists of drainage area to U.S. Geological Survey gage 12112600 minus drainage areas to U.S. Geological Survey gages 12111000, 12110500, and 12112000. Lower Bear creek consists of drainage area to U.S. Geological Survey gage 12124500 minus drainage areas to U.S. Geological Survey gage 12122500, 12123100, 12123200, and 12124000.

[4]Recharge calculations made assuming runoff is negligible, and therefore, all areas have same computed recharge.

[5]Periods of record used for climatic data and streamflows.

[6]1968-1975 climatic and streamflow data used in part, 1981-82 water-level changes used in part, for recharge calculations.

[7]Recharge estimate of 5 inches per year made from annual water-table fluctuations under a till-mantled area, only.

[8]Could not be determined from information given in report.

[9]Not presented in referenced report; not applicable to methodology used to calculate recharge.

Ground-water recharge in outwash areas was assumed equal to the reported average precipitation minus the reported average evapotranspiration because outwash areas in the Puget Sound Lowland generally do not produce direct runoff from precipitation (Dinicola, 1990). Recharge over the till-covered areas, R_t, is then

$$R_t = \left(\bar{R}A - R_o A_o \right) / A_t \quad , \qquad (1)$$

where

$\bar{R}$ = the reported average recharge per unit area for the drainage basin;

A = area of drainage basin;

R_o = recharge per unit outwash area;

A_o = area of outwash; and

A_t = area of till.

The information in table 1 is intended only to give an approximate range of previous recharge estimates for till-mantled areas. The recharge quantities do not include any estimated effects of land cover, land slope, or textural differences of the till from one drainage basin to another.

METHODS AND HYDROLOGIC RATIONALE

An intensive water-budget was used as the primary method for estimating percolation of precipitation into the till for three small catchments, referred to in this report as the Clover, Beaver, and Vaughn catchments (fig. 1). The catchments were selected to meet the criteria of (1) being entirely mantled by glacial till and (2) containing no perennial streams. The first criterion assures that estimates of recharge are representative of till-mantled terrain and not a composite of a variety of subsurface materials. The second criterion allows the assumption that all of the measured streamflow is direct runoff. (For one of the catchments, this was found to not be strictly true and is discussed later in the report.) If the stream were perennial, direct runoff must be determined by subtracting estimates of ground-water discharge to streams (also referred to as "baseflow" in this report) from total streamflows. Determination of baseflows over the course of a year, or more, is a source of large uncertainty.

Daily water budgets were computed for the water years 1991-93 for the Clover catchment and for the water years 1992-93 for the Beaver and Vaughn catchments (water years run from October 1 through September 30). In each of the catchments, streamflow was continuously gaged with control structures that minimized measurement errors by providing stable and accurate stage-discharge relationships. Precipitation was continuously gaged with tipping-bucket rain gages. Evapotranspiration and other water-budget components were computed with a soil-moisture budgeting model (Bauer and Vaccaro, 1987), referred to as the deep percolation model (DPM). The DPM was modified to incorporate the results of recent experimental and theoretical evapotranspiration investigations for Douglas fir forest (see, for example, Giles and others, 1984) and to account for the effects of temporarily saturated soils overlying subsoils of limited infiltration capacity. The DPM and the conceptual basis for the modifications are described in the "Water Budget" section.

A second independent method that accounts for the vertical tritium-concentration distributions in the subsurface was also used to estimate recharge rates in each of the three catchments. Tritium produced by above-ground thermonuclear bomb testing after 1952 resulted in worldwide elevated levels of tritiated water in the atmosphere. Bomb testing and tritium concentrations reached a maximum in about 1963. Thus, peak tritiated-water concentrations in the environment can be analyzed to date relatively recent water. The method has successfully given site specific estimates of recharge for several other investigators (see, for example, Daniels and others, 1991, and Knott and Olimpio, 1986).

The average rate of vertical movement of water through unsaturated till was determined from the vertical distribution of tritiated water in the till and from the quantities of tritiated water in precipitation during the 1952-92 period. Test wells were drilled in each catchment, and the unsaturated till was sampled for tritium at regular intervals. Tritium concentrations in precipitation were interpolated monthly from data for a network of sites in the United States and Canada.

The test wells for the tritium sampling were drilled a few feet into the water table, and water-level data were collected periodically. Examination of the water-level fluctuations provided additional information on recharge. This information was generally less definitive in quantifying recharge, but it did provide some insight on the timing of deep percolation and the resulting recharge.

Two additional experiments were conducted in the Vaughn catchment to study the movement of soil water and the source of streamflow during storms. During rainy periods, it is commonly observed that the approximately 3-foot-thick soils overlying the till in most of the Puget Sound Lowland periodically become partially saturated because the till is poorly permeable. When the soils saturate, water moves both laterally through the soils toward streams and downward into the unweathered till. Results from a rainfall-runoff modeling study in several areas of the Lowland (fig. 1; table 1) indicate that percolation into the till is small in comparison with lateral, shallow-subsurface flow above the soil-till contact (Dinicola, 1990). Moreover, the results indicated that, in forested areas, there is little or no overland flow during storms and that most of the stormflow is routed through the soils. However, except for cursory personal observations, quantitative physical evidence of the runoff process within the soils above the till had not been studied.

In the first experiment, soil water, streamflow, and precipitation were sampled for the stable isotopes of oxygen and hydrogen during selected storms. The variability of the isotopes from storm to storm results in unique isotopic compositions of the soil and stream water. These different compositions were then used to identify the portions of streamflow that were derived directly from precipitation (that is, overland flow or surface runoff) and from soil water that was displaced to the stream. In the second experiment, a dye tracer was applied to the ground surface during the rainy winter season, and the soil was periodically excavated and inspected for dye-tracer evidence indicating soil-water movement. In addition, the soil-moisture and soil-saturation data collected in the three catchments for the water-budget method, when examined in relation to the streamflows, helped to clarify the runoff processes.

Description of Study Catchments

The three catchments investigated are located in Pierce County in the southern part of the Puget Sound Lowland in Washington (fig. 1). The surface of most of the Puget Sound Lowland is a drift plain covered mostly by deposits from the last glaciation, the Vashon stade (18,000 to 13,000 years before present, Crandell and others, 1965), and is characterized by rolling, hilly glacial-till mantled areas and generally level glacial-outwash bench lands. Numerous lakes, swamps, and peat bogs occupy depressions on the till plains, whereas the outwash plains generally are well drained. The till, locally referred to as "hardpan," is a dense basal (or lodgement) till that was compacted by the overriding glaciers. In most areas, about 3 feet of sandy-to-gravelly loam has developed on the till surface. The till commonly is exposed in road cuts in the headwater areas of drainage basins and along steep embankments along the Puget Sound shorelines. In the larger valley bottoms, the till is typically completely eroded away, exposing the underlying outwash deposits that consist of unconsolidated sand and gravel layers that are up to 100 feet thick (fig. 2).

Each of the three catchments studied in this investigation is overlain entirely by lodgement glacial till upon which there is about 3 feet of generally sandy, gravelly loam. The catchments are referred to by the name of the streams into which they drain: Clover, Beaver, and Vaughn Creeks. Detailed precipitation, streamflow, soil property, and ground-water conditions for each of the three catchments are presented in later sections of this report.

The climate of the region is typical of the mid-latitude, west-coast-marine type, characterized by warm, dry summers and cool, wet winters. The mean annual temperature in the Lowlands is about 51 degrees Fahrenheit (°F), and the mean monthly temperatures in January and July are 39°F and 65°F respectively (U.S. Department of Commerce, 1982). Mean annual precipitation ranges from about 15 to 65 inches, mostly as rain (U.S. Weather Bureau,1965). Seventy to 80 percent of the precipitation falls from October through May during long-duration, light-to-moderate-intensity storms. Rain during July through August is so little that soil-moisture is often depleted to near the wilting point for most plants. The relatively long wet season and growing season are conducive to evergreen forests and thick understory that blanket most of the Lowland.

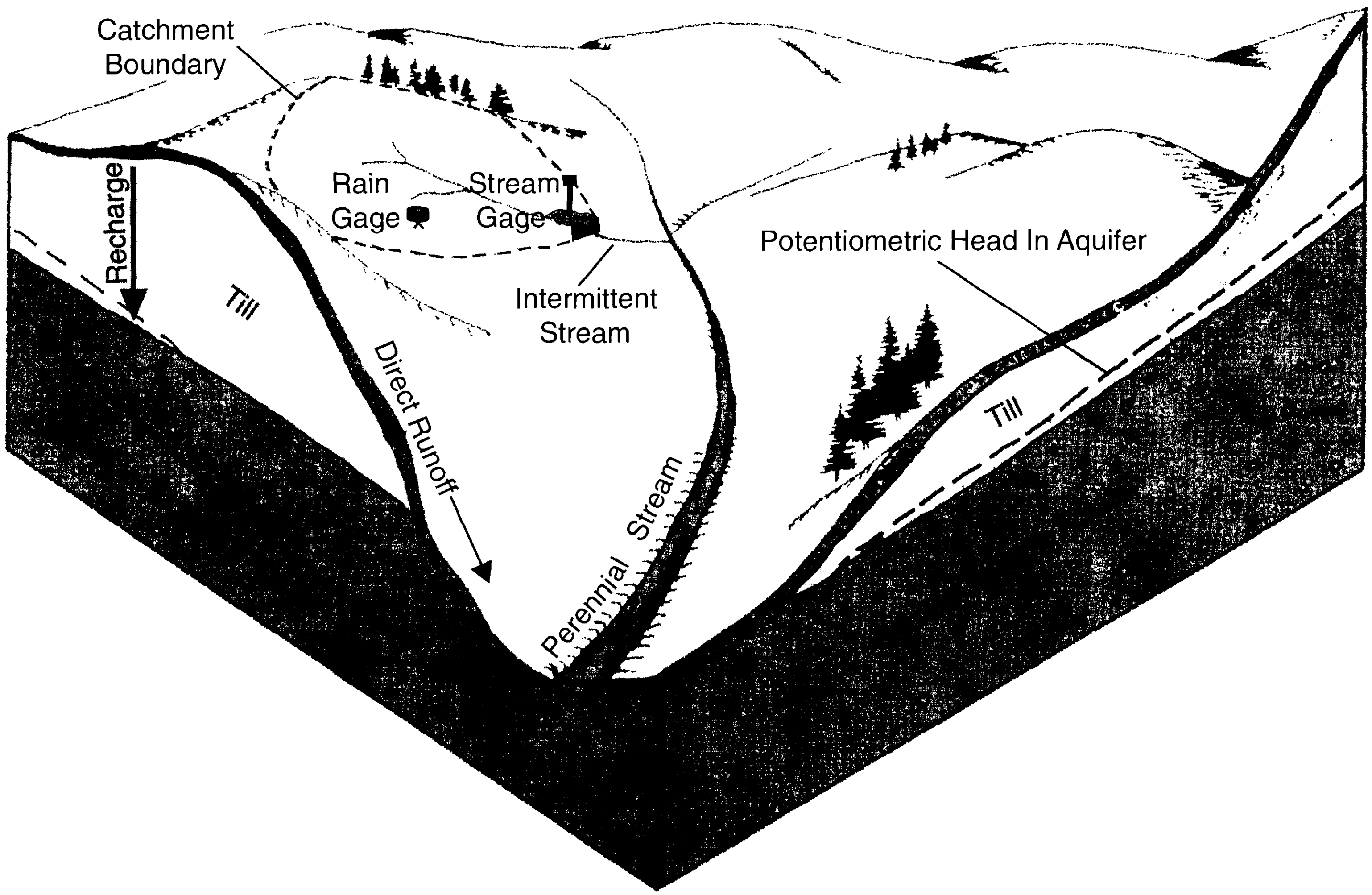


Figure 2.--The physical and subsurface setting of a typical till-mantled area in the Puget Sound Lowland.

Clover Catchment

The 0.140 square-mile (89.6 acres) Clover catchment (fig. 3) is a nearly square drainage area located in section 14, T19N, R3E, between Waller Road and Vickery Avenue and between 132nd and 138th Streets, approximately 3 miles southeast of the city limits of Tacoma. The topography slopes very gently and evenly from an altitude of about 430 feet to about 395 feet. Land cover is about 64 percent pasture and 36 percent forest and includes about 14 single-family residences and outbuildings. The forest is mostly a mixture of mature Douglas fir (about 30 percent), western cedar (about 10 percent) and broadleaf maple and red alder (about 60 percent). About 75 percent of the catchment area is covered by gravelly loam of the Kapowsin series and the remainder by gravelly, sandy loam of the Alderwood series (U.S. Department of Agriculture, 1979). Both of these soils are reported to have a permeability ranging from 0.6 to 2.0 inches per hour; the Kapowsin series is reported to have an AWC of 12 to 14 percent by volume, and the Alderwood from 7 to 11 percent by volume. Soil depths above the till (the till is described as a "cemented" soil layer) are 25 and 38 inches, for the Kapowsin and Alderwood, respectively.

Beaver Catchment

The 0.171 square-mile (109 acres) Beaver catchment (fig. 4) encompasses an area of rolling topography in sections 22 and 27, T21N, R1W, 1.5 miles northwest of the town of Home on the Key Peninsula. The catchment is about 1.1 miles long in the direction of the drainage channel and has a maximum width of 0.2 mile. The topography of the drainage area consists of a U-shaped valley about 20 feet deep, in the lower half, that grades upstream into a gently sloping area. Total relief is about 75 feet. The catchment parallels the Puget Sound shoreline, which lies 0.2 mile to the west. West of the catchment divide, the land surface drops precipitously 160 feet to the saltwater. Vegetation consists of a mixed forest of young (40 to 60 years old) Douglas fir and western hemlock (38 percent), mature broadleaf maple (56 percent), and brushy riparian plants (6 percent) in the small wetland area shown on fig. 4. There are only five widely spaced houses and outbuildings within the catchment. More than 90 percent of the catchment area is covered by gravelly, sandy loam of the Harstine series, and the remainder, in the vicinity of the riparian area, by silt loam of the Bow series (U.S. Department of Agriculture, 1979). The Harstine series is reported to have a permeability range of 0.6 to 2.0 inches per hour and an AWC of 7 to 9 percent by volume, above a cemented soil (till) reported to occur below a depth of 31 inches. The Bow series is reported to have a permeability of 0.06 to 0.20 inches per hour and an AWC of 5 to 21 percent by volume.

Vaughn Catchment

The 0.198 square-mile Vaughn catchment (fig. 5) also occupies an area of rolling topography and lies in sections 25 and 36, T22N, R1W, and in sections 30 and 31, T22N, R1E, 0.8 mile north of the town of Key Center on the Key Peninsula. It is mostly state-owned land (Department of Natural Resources) that is periodically planted and harvested for timber. Consequently, the vegetation is a monoculture of 60 to 70 year-old Douglas fir with a thick understory of salal. The topography is similar to the Beaver catchment except that the lower valley is deeper (about 30 feet) and more V-shaped in cross section, and the upper area is flatter. The length and maximum width are 0.9 and 0.3 mile respectively. Land-surface altitudes range from 165 to 245 feet. There are about 20 residences in a rural community development at the upstream end of the catchment. More than 95 percent of the catchment area is covered by gravelly, sandy loam of the Harstine series, previously described, and the remainder by a small pocket of Bellingham silty clay loam with a permeability of from 0.06-0.20 inches per hour and an AWC of from 20 to 24 percent by volume (U.S. Department of Agriculture, 1979).

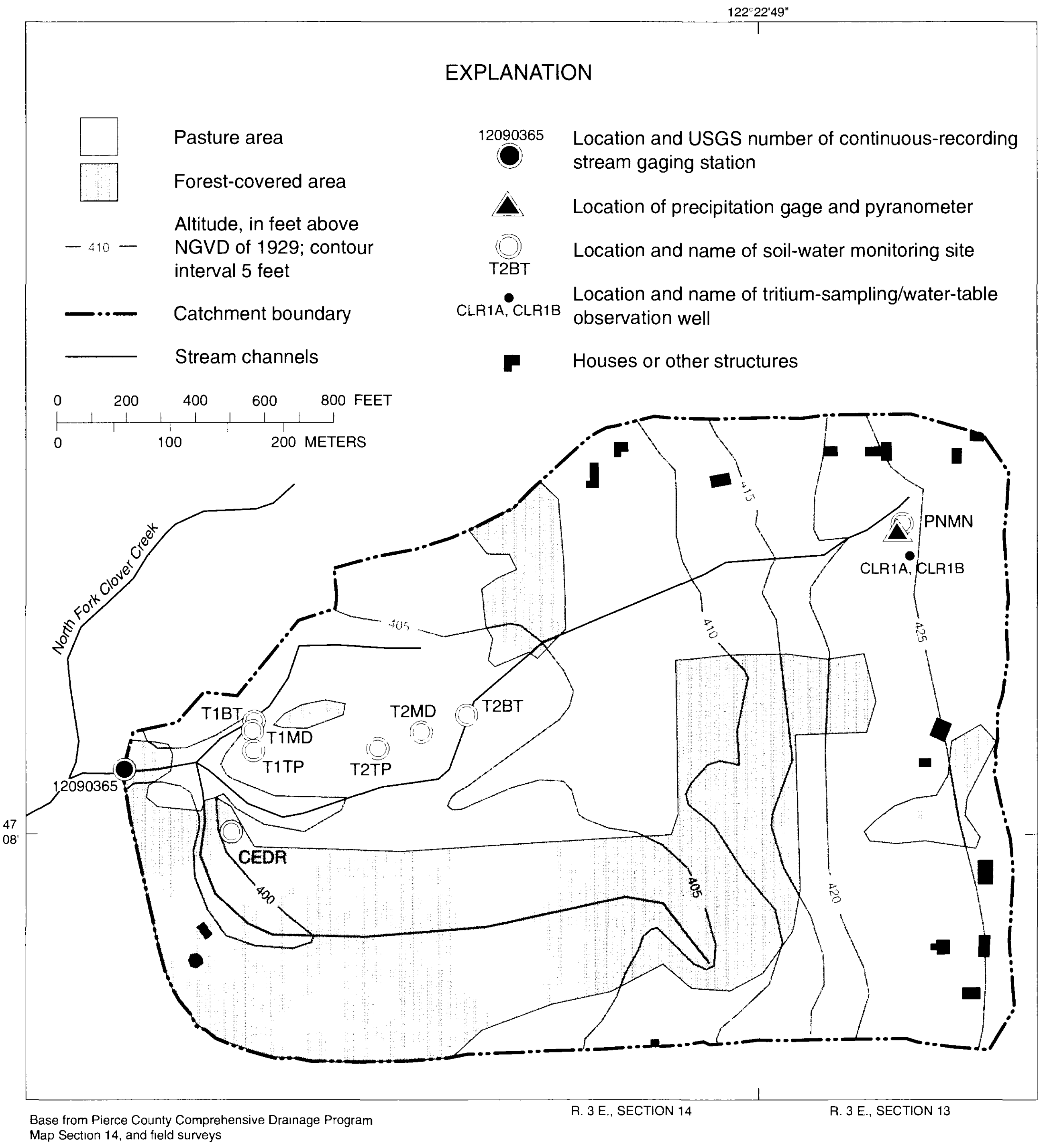
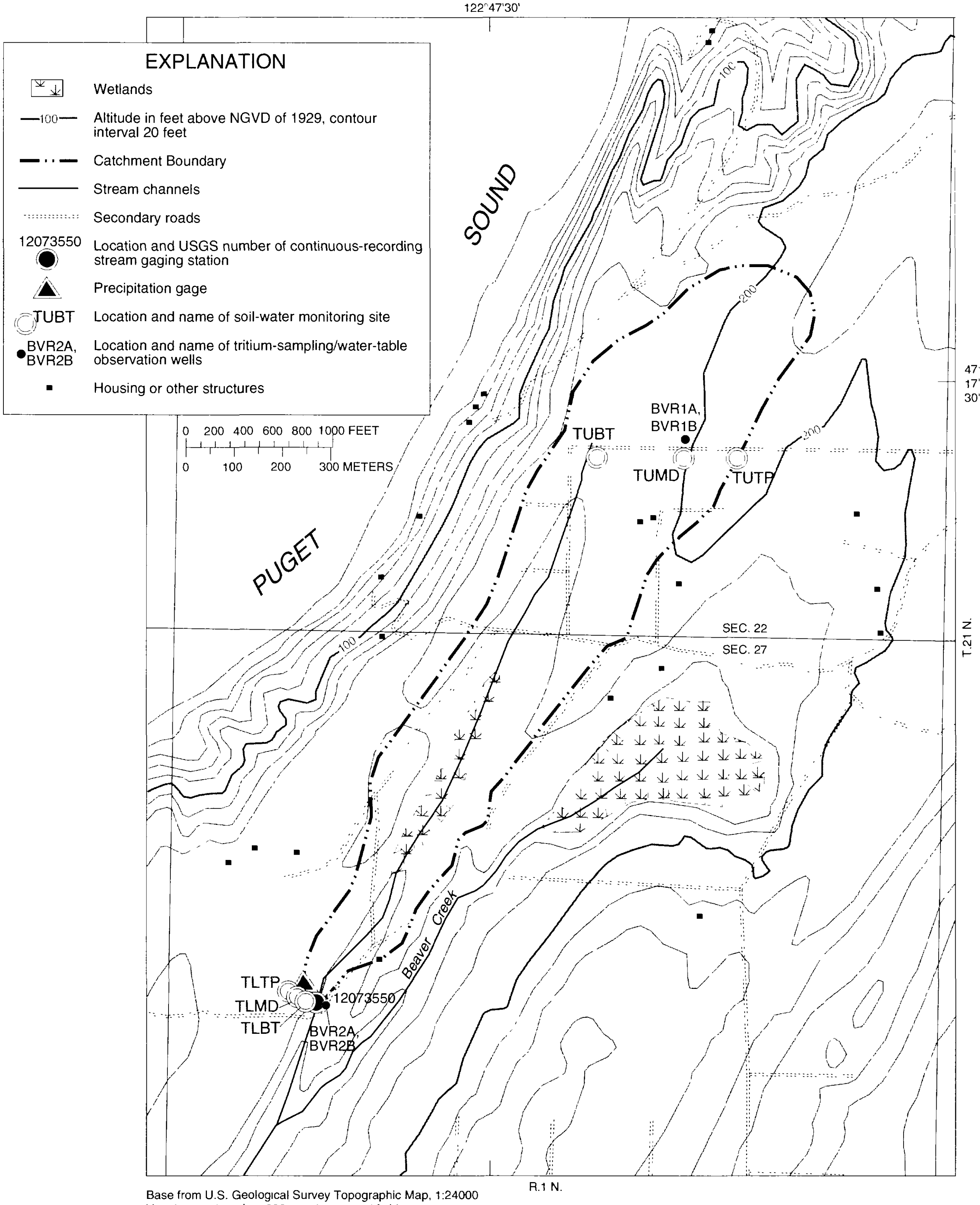


Figure 3.--The Clover catchment showing the locations of the precipitation gage, streamflow gage, tritium-sampling/ water-table observation wells, and soil-water monitoring sites.



Base from U.S. Geological Survey Topographic Map, 1:24000
Vaughn quadrangle, 1969, air photos, and field surveys

Figure 4.--The Beaver catchment and locations of the precipitation gage, streamflow gage, tritium sampling/water-table observation wells, and soil-water monitoring sites.

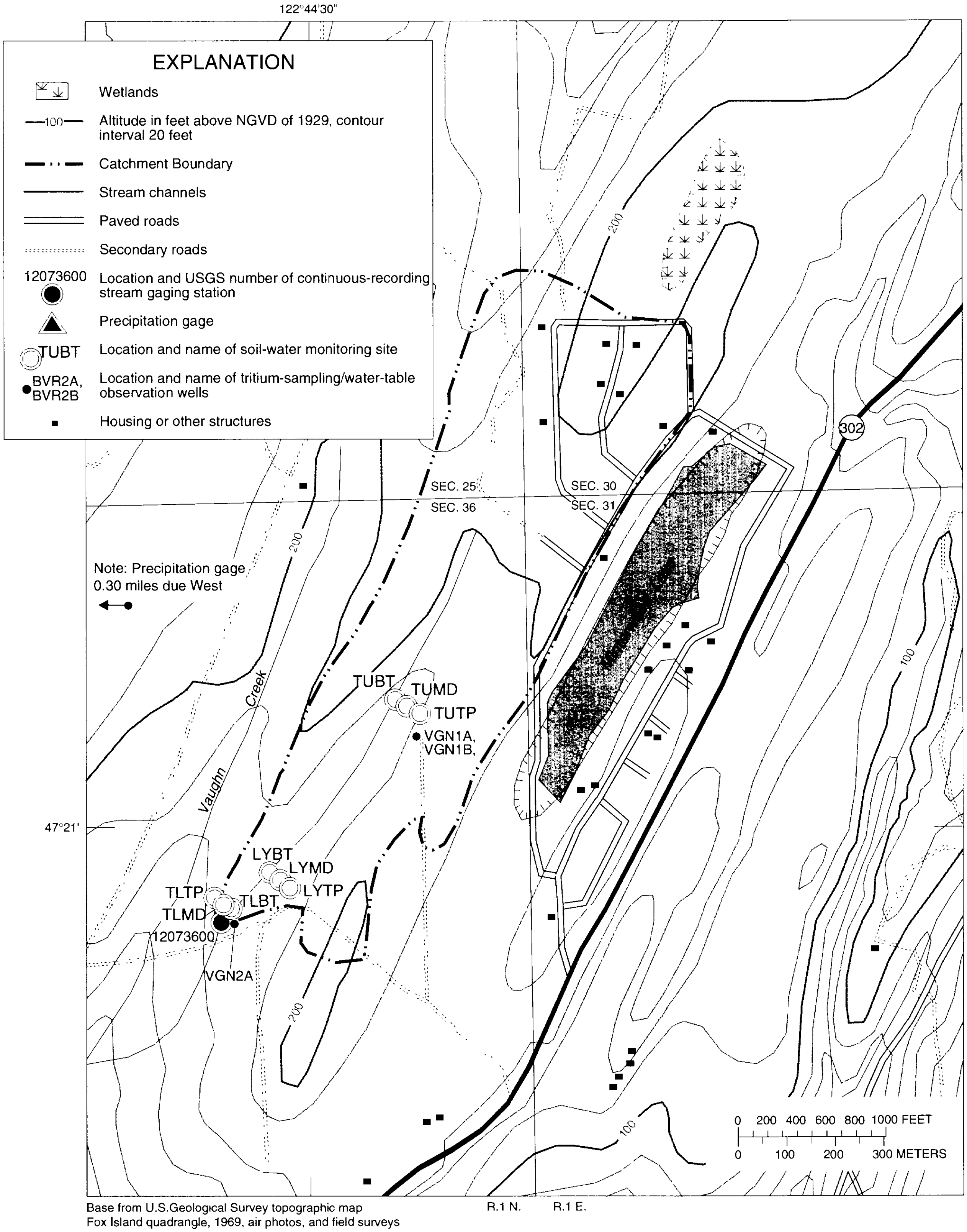


Figure 5.--The Vaughn catchment and locations of the precipitation gage, streamflow gage, tritium-sampling/ water-table observation wells, and soil-water monitoring sites.

WATER BUDGET

The primary method for estimating recharge through till in the three catchments was the water-budget method. In this method, all of the fluxes of water into and out of and changes within a volume extending from the top of the foliage to the bottom of the root zone are accounted for. If an unsaturated zone lies between the bottom of the root zone and the water table, the flux of water out of the bottom of the root zone (herein referred to as deep percolation) is assumed to move vertically downward, undiminished in amount, eventually recharging the saturated material beneath the water table. In general, deep percolation is computed as precipitation minus evapotranspiration minus direct runoff minus the change in soil moisture in the root zone.

Conceptually, the water-budget method is simple, but is usually difficult to implement accurately because the soils, subsoils, and vegetation vary spatially and the climate varies temporally. These variables strongly affect evapotranspiration. In this study, the spatial variables were minimized by selecting small homogeneous catchments. The temporal variables were accounted for by computing the water budget on a daily basis and summing the results over a multi-year period.

Evapotranspiration depends on soil-moisture availability as well as on meteorological and phenological conditions. Evapotranspiration, in turn, depletes soil moisture. Therefore, evapotranspiration and soil moisture must be calculated at sufficiently frequent intervals to assure good accuracy. The one-month computational time step used in many of the previously cited investigations was considered too long for this investigation because during one month in the growing season, soil moisture can change by as much as about 50 percent of the AWC (for example, see fig. 16, discussed later in report). This investigation used a 1-day time step, primarily because daily meteorological data are generally available. A 1-day time step is sufficiently short to assure that soil-moisture variations are small enough to avoid significant error in the evapotranspiration calculations.

The DPM was used to perform the thousands of daily water-budget computations over the multi-year period. The DPM was originally developed for use in eastern Washington, a drier region with different geologic conditions from the Puget Sound Lowland; therefore, it required certain modifications for use in western Washington. The next section briefly summarizes the operation of the DPM and it is followed by a section that describes the modifications in relation to the physical processes simulated. A user guide for operating the modified DPM is presented in appendix B.

Daily Deep Percolation Model

Daily water-budget calculations are made for any number of land segments (cells) that are used to divide up a drainage basin into unique combinations of soil, land-cover, precipitation regime, altitude, and slope. For each cell, the following equation is solved daily for a volume that extends from the vegetation covering the land surface down to the bottom of the effective root zone:

$$RCH = PRCP - EVINT - EVSOL - EVSNW - TR - RO - CHGINT - CHGSNW - CHGSM \quad , (2)$$

where

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

Daily values of precipitation and minimum and maximum temperatures measured at one or more locations and daily stream discharge from one gage are the basic time-series input data. DPM makes extensive use of weather-interpolation algorithms to provide the best estimates of the weather variables to each of the cells. Daily precipitation and maximum and minimum temperatures are estimated for each cell (interpolated by distance-weighted methods) from data from nearby weather stations. If altitudes of the cells are much different from the weather stations, further altitude corrections to temperature may be made using user-specified monthly lapse rates (temperature change due to unit increase in altitude) for both maximum and minimum temperatures. Similarly, precipitation may be adjusted using specified ratios of average annual precipitation between the cells and weather stations (this information is typically obtained from published isohyetal maps).

PET is estimated for each day for each cell. The alfalfa-based PET method of Jensen and Haise (Jensen, 1974) was originally selected for the DPM because it was well suited for the eastern Washington area for which the DPM was originally developed, and the required data for making daily PET calculations were readily available. These data are average daily temperature, daily solar radiation, altitude, latitude, and day-of-year. Depending on the options selected, the PET calculations are performed either for each cell, using the interpolated temperatures, or for each temperature weather station, whereupon the calculated results are interpolated to the cells.

Precipitation is assumed to be rain unless the average daily temperature for a cell is less than 32°F, in which case, all of the precipitation is assumed to be snow and is added to a snowpack term. When precipitation is rain, the foliage intercepts a quantity of rain that is equal to the lesser of the rain or the interception storage-capacity minus any carry-over intercepted storage from the previous day. Evaporation of the intercepted moisture, or interception loss, is assumed to proceed at a rate equal to PET. PET is then reduced by the interception loss and adjusted according to published growth-stage coefficients (see Bauer and Vaccaro, 1987, and U.S. Department of Agriculture, 1970).

If there is any snowpack, a user-specified amount of sublimation is subtracted from the snowpack, and if the temperature is above 32°F, snowmelt is computed. Snowmelt is computed from an empirical temperature relation or, if there is rain, from an empirical temperature-precipitation relation (Bauer and Vaccaro, 1987; Anderson, 1973). The quantity of precipitation that passes through the foliage (herein referred to as throughfall), plus any snowmelt, partly infiltrates the soil and partly runs off over the surface.

The direct runoff for the drainage area is determined by subtracting a user-supplied estimate of baseflow from the measured total streamflow. This difference is referred to as the observed direct runoff (even though it is, in part, estimated). A fraction of the observed direct runoff is assigned to each cell such that the total for all cells is equal to the observed direct runoff. The fraction for each cell is determined as follows. For each cell, direct runoff is first computed by the modified U.S. Soil Conservation Service (SCS) method of Wight and Neff (1983). (The Soil Conservation Service is now the Natural Resources Conservation Service, but SCS is used in this report.) It is unlikely that the sum of the cell values of the SCS-computed direct runoff equals the observed direct runoff, but it is assumed that the relative quantities from cell to cell are reasonably accurate. The fraction of the observed direct runoff assigned to each cell is, therefore, equated to the ratio of the SCS-computed direct runoff for the cell to the total for all cells. In this way, the sum of all the direct runoff quantities for the cells equals the observed direct runoff. The SCS-computed runoff for each cell may optionally be used directly, but produces unreliable results if the SCS method is not properly calibrated for the drainage basin.

The precipitation minus the interception loss minus the direct runoff plus any snowmelt is added to the soil-moisture storage. If the new soil moisture value exceeds the AWC of the soil in the effective root zone, the excess is assumed to displace an equal amount of water to the subsoil (deep percolation), which eventually becomes ground-water recharge.

Soil evaporation and transpiration (actual evapotranspiration, AET)) are calculated from empirical functions of soil texture and soil moisture. AET equals PET when the soil moisture is near field capacity and approaches zero as soil moisture approaches the wilting point. Soil moisture is reduced accordingly for the next day's calculations. For areas of bare soil, evaporation is limited to the upper foot of soil.

These steps are repeated on a daily basis for any number of years; and daily, monthly, annual, and average annual values of the water-budget components in equation 2 are computed and saved in output files. The above processes occur simultaneously in nature but must be treated sequentially for computations, as summarized on figure 6.

Recharge computed by equation 2 can sometimes be negative when the observed direct runoff is greater than precipitation. Each day this occurs, this negative value is added to a "water-budget deficit" term rather than to the recharge. This deficit can be considered an indicator of cumulative error which can result from errors in precipitation data, streamflow data, or baseflow estimates. Assuming the data are correct, the deficit indicates that baseflow was underestimated during certain periods, resulting in some daily values of direct runoff that are too large.

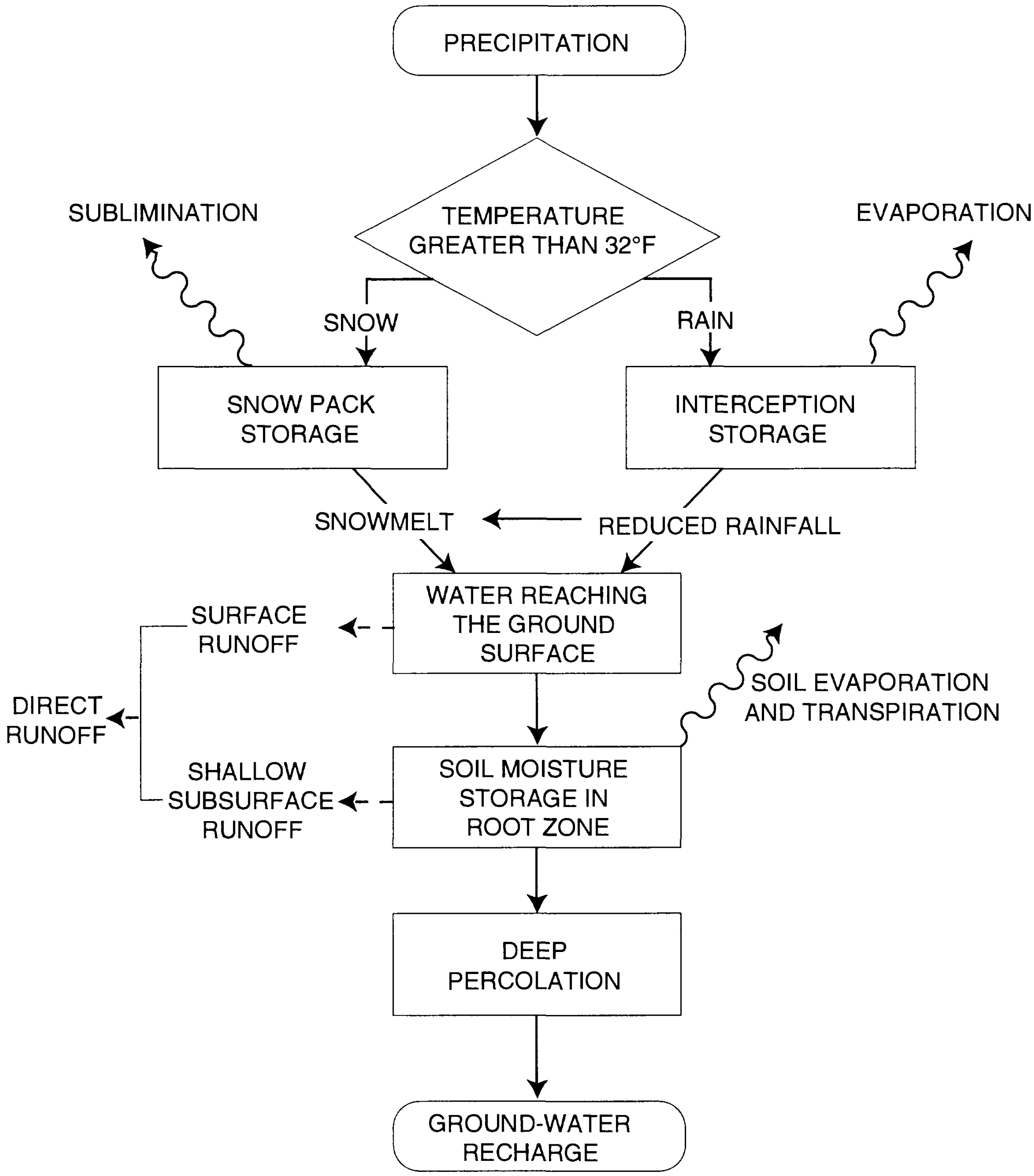


Figure 6.–Conceptual daily time-step routing of precipitation used in the DPM water-budget calculations (modified from Bauer and Vaccaro, 1987).

Modifications and Refinements to the Deep Percolation Model

The DPM was modified in order to better simulate recharge-related processes in the Puget Sound Lowland. Revisions, additions, and refinements were made regarding evaporation of intercepted moisture, soil saturation, simulated streamflow, PET, and incoming solar radiation. Additional flexibility is provided in the AET/PET—soil moisture relation; greater freedom is allowed in cell sizes, shapes, and locations; and input of data has been streamlined. Data input instructions for the modified program and archival of the modified source code are described in appendix B.

Interception Loss

During this investigation, throughfall was measured in a Douglas fir forested area, and precipitation was measured in an adjacent clear area (this work is fully described in a later section). This observed interception loss (precipitation minus throughfall) during winter months greatly exceeded that computed by the original DPM regardless of adjustments made to the interception storage parameter. This is because transpiration, which is driven by solar radiation, is probably negligible; but because of the large surface areas of the evergreen trees and the relatively warm winter temperatures, advective evaporation of intercepted precipitation far exceeded the radiation-based PET. The temporal distribution of precipitation during the day was also important in determining interception loss but could not be simulated by the original DPM because of the daily time step. For example, much more intercepted rain would evaporate during a day if the rain occurred as several light showers than if an equal amount occurred as one brief, heavy shower.

It was critical to estimate interception loss as accurately as possible because most deep percolation occurs during the winter. However, modification of the DPM to simulate the processes of short time-period interception loss and the concomitantly large data requirements would probably have resulted in a modified DPM that would have been difficult to apply in most practical applications (one of the principal goals in the development of the DPM). Therefore, a practical modification was used that provided for daily throughfall data as direct input to the DPM. Interception loss for each day was then calculated as the difference between the observed precipitation and the observed throughfall. For many of the land uses where interception storage and advective evaporation are minimal, such as for short grass, or where the winter climate is colder and less drizzly, the original interception formulation is probably adequate (Zinke, 1967). Thus, the DPM was modified so that it can be operated either way or in both modes simultaneously (some cells with, and some without, throughfall data).

Soil Saturation and Direct Runoff

In the Puget Sound Lowland, the soil saturation that commonly occurs over the low-permeability glacial till had to be accounted for in DPM. In the original DPM formulation, percolation into the subsoil was unrestricted, and root-zone soil-saturation was assumed not to occur. In the new formulation, the following conceptual model and DPM computational procedures are used to compute direct runoff for each cell.

After additions of water to the soil (from throughfall and snowmelt) bring the soil-moisture content up to the AWC, additional water begins to saturate the soil above the subsoil (till), whereupon water drains from the soil by two simultaneously occurring processes—downward percolation into the till (deep percolation) and down-slope saturated flow. In the DPM the thickness of soil that is saturated is computed from the amount of water in excess of the AWC and the specific yield of the soil. The quantity of water that moves downgradient (down-slope) and discharges to the nearest drainage is computed in the DPM by Darcy's law for saturated flow. The water percolates downward into the subsoil at a rate specified by the user, herein called the infiltration capacity. Surface runoff is also assumed to occur when throughfall plus snowmelt exceed the sum of the unsaturated pore space remaining from the previous day and the soil-water drainage computed for the current day. In the DPM all of this excess is assumed to be surface runoff; none is carried over to the next day to add to the soil. The computed down-slope saturated flow, plus any surface runoff, is the computed direct runoff. When the soil moisture drains back to the AWC, deep percolation and runoff are assumed to stop.

Thus, the SCS method for computing direct runoff for each cell has been replaced by a simple, physically-based formulation using Darcy's law for horizontal flow through partly saturated soil that is perched above a horizon of limited infiltration capacity. As before, the total computed runoff for all cells will usually be more or less than the observed direct runoff and is, therefore, used to apportion the observed total runoff among the cells. The moisture equivalent of the apportioned direct runoff for a cell is then first subtracted from throughfall plus snowmelt and then, if necessary, from the saturated pore space. Any remaining throughfall plus snowmelt is then added to the unsaturated pore space. The quantity of deep percolation for the day is then the lesser of the user-specified daily infiltration capacity or the remaining water in excess of the AWC. On days when the quantity of saturated pore space water is insufficient to account for all of the direct runoff, a negative deficit is tallied in the budget. If the soil completely saturates and the observed streamflow is insufficient to account for (or drain away) all of the water in excess of full saturation, a positive deficit is tallied.

In the context of a daily time step, the assumption of a constant infiltration rate is a good approximation. Experiments, in which infiltration rates of ponded water into soils were measured over time, demonstrate that nearly constant rates of infiltration are achieved in a matter of minutes to generally less than an hour after the onset of ponding (see, for example, Skaggs and Kahleel, 1982). Because the infiltration capacity of a subsoil is generally not known, trial-and-error adjustments to the infiltration capacities usually must be made until the deficit term is within acceptable limits and there is reasonable agreement between computed saturations and observations of soil-water levels, if available. Reasonable ranges of other uncertain values such as estimates of baseflow, field capacity, and specific yield of the soil column may also need to be tested and adjusted.

Potential and Actual Evapotranspiration

The DPM uses experimentally determined, time-of-year-dependent crop coefficients to adjust the Jensen-Haise PET for various types of agricultural crops. Crop coefficients are not available for non-agricultural foliage and, thus, were estimated. Extensive experimental and theoretical evapotranspiration investigations have been conducted in Douglas fir forest in southwestern British Columbia, Canada, using the Priestly-Taylor PET method (Giles and others, 1984; Black and Spittlehouse, 1981; Spittlehouse and Black, 1981; McNaughton and Black, 1973). Others successfully used this method for pasture areas in the drier interior of British Columbia, Canada (Wallis and others, 1983). Because the method has been "locally calibrated" for Douglas fir in a northwestern coastal environment, a setting identical to much of the Puget Sound Lowland, the Priestly-Taylor PET formula has been incorporated into the DPM for the non-agricultural land uses. The Jensen-Haise formula is retained in the DPM for the agricultural land uses. The data requirements are about the same for each method.

Development of the Priestly-Taylor equation follows from the general combination Penman equation (Jensen and others, 1990). Evaporation from wet surfaces, E_{max} (expressed as depth of water per unit time), is computed by the general combination Penman formula as

$$E_{max} = \frac{s}{(s+\gamma)}\frac{\left(R_n - G\right)}{L\rho_w} + \frac{\rho_a c_p h}{(s+\gamma)}\frac{\left(e_0 - e\right)}{L\rho_w} \quad , \qquad (3)$$

where

s = slope of the saturation vapor pressure - temperature curve (pressure/temperature),
γ = psychometric constant (pressure/temperature),
R_n = net solar radiation (energy/area/time),
G = heat flux density to the ground (energy/area/time),
L = latent heat of vaporization of water (energy/mass), and
ρ_w = density of water (mass/volume)
ρ_a = density of air (mass/volume),
c_p = specific heat of moist air at constant pressure (energy/mass/temperature),
h = heat transfer coefficient (length/time),
e_0 = saturation vapor pressure (pressure), and
e = actual vapor pressure (pressure).

The first term on the right side of the equation 3 is primarily a function of the net radiation, whereas the second term, an advective term, is primarily a function of the vapor-pressure deficit and the heat-transfer coefficient. The heat-transfer coefficient, in turn, is a complicated function of surface roughness and wind speed.

The first term alone on the right side of equation 3, when multiplied by an appropriate coefficient, α, often gives a good approximation to the general combination Penman formula (Priestly and Taylor, 1972). Over a 24-hour period, the net heat-flux density to the ground is usually small in comparison with the net solar radiation and can be ignored for calculations involving one day or longer time periods. Thus, the general combination Penman equation, can be approximated by

$$E_{max} = \alpha\left(\frac{s}{s+\gamma}\right)\frac{R_n}{L\rho w} \quad , \qquad (4)$$

which is referred to as the Priestly-Taylor equation or method. The slope of the saturation vapor pressure curve, s, is evaluated at the average daytime temperature according to equations cited by Jensen (1990, p. 174-175).

The psychometric constant, γ, is defined as

$$\gamma = \frac{c_p P}{0.622L} \quad , \qquad (5)$$

where

c_p = specific heat of moist air (energy/mass/temperature),

P = atmospheric pressure (pressure), and

0.622= ratio of the molecular weight of water to that of dry air (dimensionless).

The specific heat of air varies only slightly with humidity and is assumed to be constant at a value of 1.013 kilojoules per kilogram for moist air. Atmospheric pressure is evaluated as a function of altitude only, and the latent heat of vaporization is evaluated at the average daytime temperature according to formulas cited by Jensen and others (1990, p. 169).

Without local calibration, $\alpha = 1.26$ is generally used for wet surfaces in non-arid areas of low surface roughness (Jensen and others, 1990, p. 145). When the foliage is dry and there is only transpiration, which proceeds at a slower rate than wet surface evaporation, α must be determined for the specific foliar cover. Giles and others (1984) found that $\alpha = 0.73$ gave good results in computing growing season transpiration at seven sites in a 70-year-old Douglas fir forested area on Vancouver Island, British Columbia, Canada. A previous investigation by Shuttleworth and Calder (1979) used $\alpha = 0.72$ for two conifer stands in the United Kingdom, and Spittlehouse and Black (1981) used $\alpha = 0.80$. A value of 1.05 was used for a Douglas fir forest that did not experience soil-moisture deficits (McNaughton and Black, 1973). In the modified DPM, $\alpha = 0.73$ is used for conifer-forest transpiration. For hay, Wallis and others (1983) found no significant difference in α for wet ($\alpha = 1.17$) or dry ($\alpha = 1.27$) conditions. Accordingly, $\alpha = 1.27$ is used for the grass transpiration in the modified DPM.

Transpiration is assumed to occur only during daylight hours. Therefore, the net radiation, R_n, is evaluated only for daytime hours and is the sum of the net daytime shortwave and longwave radiation. R_n can be measured directly or can be estimated as follows from incoming short-wave radiation and air temperature.

$$R_n = (1-a) R_s + R_{ln} \quad , \qquad (6)$$

where

a = albedo of the canopy (integrated reflectivity for shortwave, 0.15-4.0 micrometers radiation),

R_s = daytime incoming shortwave radiation (energy/area/time), and

R_{ln} = net daytime net longwave radiation (energy/area/time).

The canopy albedo is assumed constant at 0.12 (after Jarvis and others, 1976). Incoming shortwave radiation was measured during this investigation. Evaluation of the other terms is according to Giles and others (1984) and is summarized below.

$$R_{ln} = \left(c + d\frac{R_s}{R_{s_{max}}} \right) \varepsilon_v \left(\varepsilon_a - 1 \right) \sigma K^4 \quad , \qquad (7)$$

where

c = empirical constant (dimensionless),

d = empirical coefficient (dimensionless),

$R_{s_{max}}$ = maximum observed daily clear sky solar radiation (energy/area),

ε_v = longwave emissivity of the vegetation (dimensionless),

ε_a = effective longwave emissivity of the sky (dimensionless),

σ = Stephan-Boltzmann constant (energy/area/time/absolute temperature^4), and

K = average temperature of the daylight hours (absolute temperature).

The variables c and d, the sum of which equals unity, are used to improve the estimates for small values of net longwave radiation. The value of $R_{s_{max}}$ used by Giles and others (1984) is 0.73 times the daily extraterrestrial solar radiation. (Extraterrestrial solar radiation is the solar radiation incident on the land surface if the atmosphere were removed and is a function of the time of year, latitude, and land surface slope and aspect.) Examination of solar-radiation data for Seattle (U.S. Department of Commerce, 1978 and 1979), however, indicated that $R_{s_{max}}$ varied between 0.61 and 0.77 times the extraterrestrial solar radiation depending upon the month of the year. Therefore, instead of 0.73, a month-dependent variable multiplier of the extraterrestrial solar radiation was used to evaluate $R_{s_{max}}$. The value of ε_v is considered constant at 0.96, and ε_a is calculated as a function of average daytime temperature, T, in degrees Celsius (°C), using the formula of Idso and Jackson (1969)

$$\varepsilon_a = 1 - 0.261 e^{-0.00077 T^2} \quad . \tag{8}$$

A two-to-one weighting of the maximum daily temperature to the minimum daily temperature approximates the average daylight temperature, T, that is

$$T = \frac{\left(2T_{max} - T_{min}\right)}{3} \quad , \tag{9}$$

where T_{max} and T_{min} are the maximum and minimum daily temperature. This weighting also applies to the absolute temperature in equation 7 and all other equations presented or cited in this section that require average daytime temperature.

During the growing season, the soil-moisture content is often depleted to the extent that transpiration is limited by the amount of water that can move through the soil toward the roots. Furthermore, the matric potential and hydraulic conductivity of the soil decrease with decreasing soil moisture, resulting in a decrease in the flow of moisture towards the roots. Thus, the ratio of AET to PET is a function of soil matric potential, which in turn, is related to soil type and moisture content. An AET/PET relationship was coded as part of the original DPM as an empirical function of soil texture and soil moisture, but now a soil-limiting coefficient can optionally be specified such that the daily transpiration is limited according to Spittlehouse and Black (1981) and Giles and others (1984).

$$E_s = b\theta \quad , \tag{10}$$

where

E_s = soil-limited transpiration rate (length/time),

b = experimentally determined soil-limiting coefficient (length/time), and

θ = available soil-water content, expressed as the fraction of pore space in excess of the wilting point (volume/volume).

The actual transpiration, then, is the lesser of E_{max} (equation 4) or E_s. For this investigation, values of b were determined by making adjustments to b for each catchment until the best agreement between periodically observed soil moisture values and the DPM-computed values was achieved during the growing seasons. Values determined for b and soil-moisture comparisons are presented in the "Estimates of Recharge" section.

Drainage-Basin Subareas or Cells

The original DPM required a geographically ordered grid system consisting of quadrilateral cells. These requirements were primarily for bookkeeping purposes and for efficient interpolation of weather data. To allow greater flexibility, the cells are now identified in an input table of attributes that includes a sequence number, x-y location of the geometric center, area, and several other attributes. Cells may be of any size and shape, and no geographic order is required.

Meteorological Data

Daily time-series data of precipitation, throughfall, streamflow, temperature, and incoming short-wave solar radiation are necessary input to compute the daily water budgets with the DPM. Water budgets were calculated for multi-water-year periods for each of the three catchments: October 1, 1990, through September 30, 1993, for the Clover catchment and October 1, 1991, through September 30, 1993, for the Beaver and Vaughn catchments. The meteorological data collected for these periods are described in this section; the streamflow data are discussed in a following section in relation to the soil- and ground-water data.

Incoming shortwave radiation, temperature, and humidity were measured in a pasture (grass) area in the Clover catchment from July 17, 1991, through September 30, 1993. A LI-COR LI-200S pyranometer positioned about 10 feet above ground measured incoming radiation. The pyranometer and a Campbell Scientific 207 temperature and relative humidity probe were connected to a Campbell Scientific 21X micrologger, which sampled output from the sensors every 15 seconds and recorded the averages every 60 minutes. The solar radiation data collected at the Clover catchment was used directly for each catchment. Daily incoming shortwave radiation for the period October 1, 1990, through July 16, 1991, prior to the installation of the solar temperature instrumentation in the Clover catchment, was estimated using monthly regressions that relate the ratio of incoming shortwave solar radiation to the extraterrestrial solar radiation to the difference between the maximum and minimum daily temperature (Bauer and Vaccaro, 1987). Solar radiation data (U.S. Department of Commerce, 1978 and 1979) for Seattle and solar-radiation data collected for this study were used for developing the regressions. For the Clover catchment, maximum and minimum temperature data were used from the Puyallup NOAA weather station from October 1, 1990, to July 17, 1991. For the Beaver and Vaughn catchments, maximum and minimum daily temperatures from three NOAA weather stations—Seattle, Olympia, and Shelton—were interpolated by linear distance weighting in the DPM.

Precipitation gages were installed and data collected during water years 1991-93 for the Clover catchment and for most of the water years 1992-93 for the Vaughn and Beaver catchments. Texas Electronics tipping-bucket precipitation gages were installed in clear areas in, or within a mile of, each catchment. They were mounted on masts approximately six feet above ground and connected to Campbell Scientific CR10 microloggers. Each bucket tip, representing 0.01 inch of precipitation, was counted and the total amounts recorded at 15-minute intervals.

In order to construct water budgets on a complete water-year basis, precipitation data from nearby NOAA weather stations were used for October, November, and part of December 1991, before installation of precipitation gages for the Beaver and Vaughn catchments. The weather station's daily precipitation values were multiplied by the ratio of total precipitation at the project gages to the total precipitation at the weather station gages for the data collection period. Daily precipitation values for each of the catchments are shown on figure 7. Table 2 shows monthly values of precipitation recorded at the three USGS catchment gages for water years 1991-93 and for the nearest NOAA weather stations. Departures from normal are also shown for the NOAA stations. Monthly precipitation values at the USGS project gages are very similar to those at the NOAA stations (table 2). For example, on an annual basis, the average of the absolute differences and maximum difference between the measurements is only 0.94 and 1.83 inches respectively, or 2 and 5 percent, respectively, of the average annual precipitation values recorded for the catchments.

On the basis of long-term data for these three NOAA weather stations, the water-year 1991 was 7.9 inches wetter than normal, whereas the water-years 1992 and 1993 were 8.46 and 9.32 inches drier than normal. (Note that the average departure from normal for water-year 1993 is a weighted average of only two of the NOAA stations because one of the three NOAA stations was discontinued in May 1993.)

Interception Loss Experiment

In forested areas, interception loss proceeds at considerably faster rates than transpiration, particularly during winter months. Although interception loss during winter months has not received much attention, it had been observed more than 30 years ago (Rutter, 1964, 1967). In an analysis of evapotranspiration from a Scotts pine forest in southeast England during a 6-year period (1957-62), Rutter (1967) found that interception losses increased with precipitation and the energy required to evaporate these amounts of water often exceeded the energy in the observed solar radiation energy by four to five times. More often than not, when the foliage is wet, the latent heat flux exceeds the amount of net radiation; Stewart (1977) concluded that, for reliable estimates of forest evapotranspiration, separate calculations need to be made of interception loss and of transpiration. Because most of the precipitation in the Puget Sound Lowland occurs during the winter months and because most of the Puget Sound Lowland and the catchments studied are covered by Douglas fir forest, throughfall data were collected under a Douglas fir forest so that improved estimates of the large interception-loss component of the water budget could be made. The data were used to verify equations used to compute daily values of throughfall necessary for DPM calculations for the three catchments.

In order to measure interception loss, following Hewlett (1982), 8 Data Lynx model 260-500 storage-type precipitation gages were installed at one conveniently accessible forested site that could be visited frequently, located at NW1/4, NE1/4, section 25, T21N, R1E-- about 6 miles east of the center of a line connecting the Beaver and Vaughn catchments. Seven of the gages were installed at ground level at randomly selected locations within a Douglas fir stand containing mostly salal understory. A single gage was placed in a clear area about 300 feet from the stand. These gages were visited at frequent, but varying, intervals that were primarily determined by the amount of precipitation. The amount of interception loss was calculated as the difference between the water collected in the clearing gage and the average of the water collected in the throughfall gages. These data are presented in table A1 in appendix A. During the period of collection, November 6, 1992, to December 16, 1993, 21.06 inches (49.9 percent) of the 42.22 inches of precipitation became interception loss.

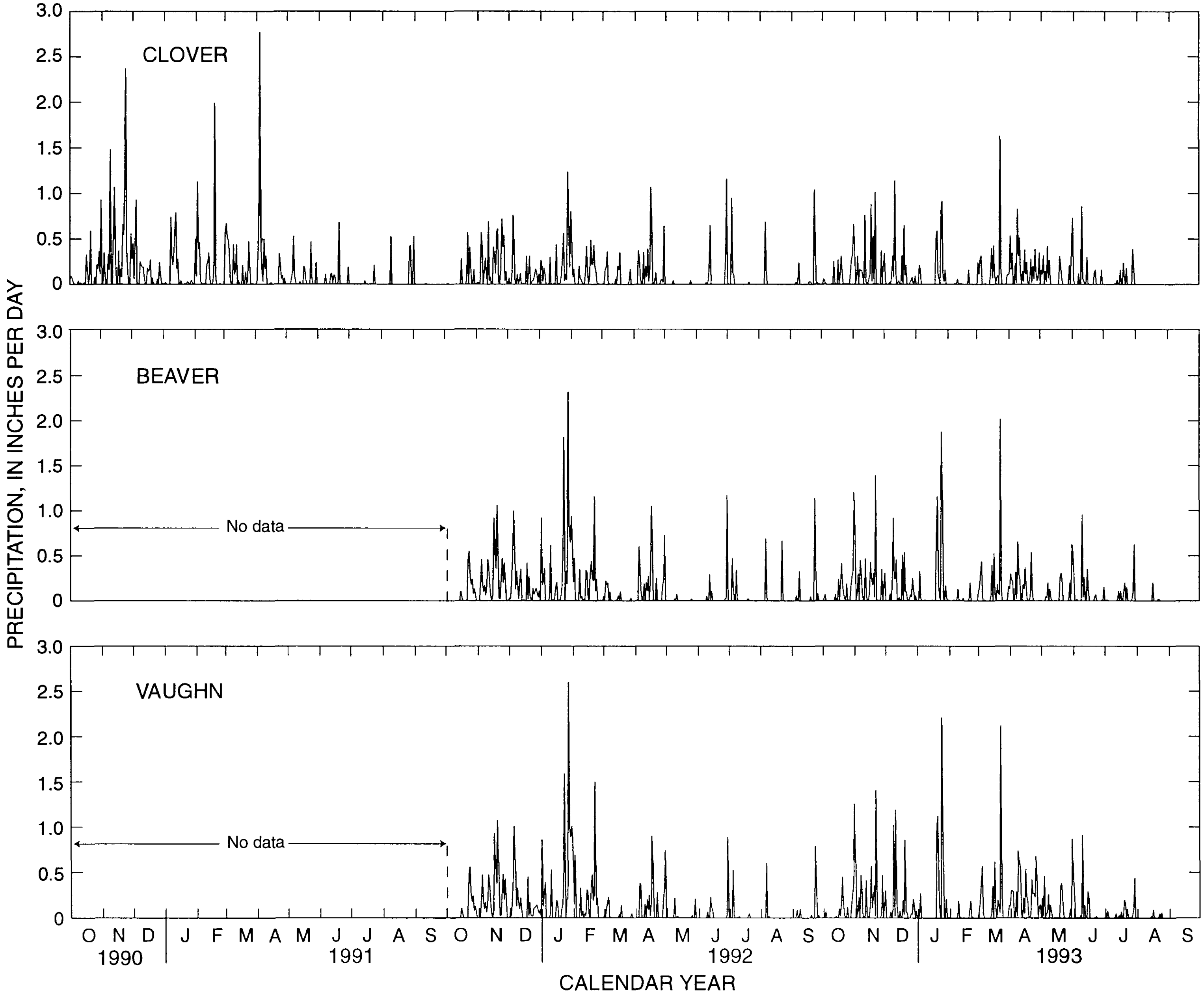


Figure 7.--Daily precipitation in the three catchments during the study period.

Table 2.--*Summary of precipitation measured at U.S. Geological Survey project gages and at nearest National Oceanic and Atmospheric Administration weather stations*

[--, indicates no data; USGS, U.S. Geological Survey; NOAA, National Oceanic and Atmospheric Administration]

Month and year		Clover Catchment[1]			Beaver Catchment[2]			Vaughn Catchment[3]		
		Precipitation		NOAA departure[4]	Precipitation		NOAA departure[4]	Precipitation		NOAA departure[4]
		USGS	NOAA		USGS	NOAA		USGS	NOAA	
					1991 Water year (all values in inches)					
October	1990	3.40	4.75	1.31	--	5.85	1.11	--	6.65	1.95
November	1990	11.15	8.41	2.75	--	12.32	4.82	--	14.45	6.65
December	1990	4.12	4.12	-2.42	--	5.76	-2.98	--	5.97	-2.39
January	1991	4.21	4.46	-1.77	--	6.51	-2.12	--	6.17	-1.88
February	1991	5.24	5.49	0.98	--	7.48	1.18	--	6.74	0.40
March	1991	4.96	4.87	1.06	--	6.51	1.31	--	6.11	0.52
April	1991	6.40	6.88	4.06	--	8.62	5.36	--	9.10	5.81
May	1991	2.08	2.03	0.21	--	2.92	1.04	--	2.35	0.28
June	1991	1.46	1.26	-0.37	--	1.49	0.06	--	1.53	-0.02
July	1991	0.26	0.28	-0.53	--	0.45	-0.47	--	0.93	0.04
August	1991	1.91	1.95	0.52	--	3.04	1.73	--	2.95	1.71
September	1991	0.02	0.16	-1.90	--	0.00	-2.36	--	0.23	-1.87
Totals:		45.21	44.66	3.90	--	60.95	8.68	--	63.18	11.20
					1992 Water year (all values in inches)					
October	1991	1.66	1.36	-2.08	2.14	2.41	-2.33	2.16	2.16	-2.49
November	1991	6.51	6.65	0.99	7.50	8.06	0.56	7.58	7.58	-0.22
December	1991	3.08	3.54	-3.00	5.08	4.86	-3.88	4.86	4.98	-3.31
January	1992	6.13	6.03	-0.20	11.25	11.86	3.23	11.75	11.24	3.12
February	1992	3.09	3.52	-0.99	4.62	6.10	-0.20	5.12	5.09	-1.22
March	1992	1.73	1.46	-2.35	0.98	1.03	[5]-4.17	0.81	0.91	-4.58
April	1992	4.64	3.92	1.45	5.25	5.77	2.51	4.66	4.74	1.42
May	1992	0.08	0.19	-1.63	0.13	0.09	-1.79	0.50	0.34	-1.69
June	1992	2.38	2.38	0.75	1.69	1.59	[5]0.16	1.43	1.39	-0.16
July	1992	1.21	0.86	0.05	1.02	1.02	0.10	0.67	0.72	-0.17
August	1992	0.84	0.95	-0.48	1.41	0.67	-0.64	0.66	0.71	-0.52
September	1992	1.82	1.73	-0.33	2.05	1.49	-0.87	1.36	1.66	-0.43
Totals:		33.17	32.59	-7.82	43.12	44.95	-7.32	41.56	41.52	-10.25

Table 2.--*Summary of precipitation measured at U.S. Geological Survey project gages and at nearest National Oceanic and Atmospheric Administration weather stations--Continued*

Month and year		Clover Catchment[1] Precipitation USGS	Clover Precipitation NOAA	Clover NOAA departure[4]	Beaver Catchment[2] Precipitation USGS	Beaver Precipitation NOAA	Beaver NOAA departure[4]	Vaughn Catchment[3] Precipitation USGS	Vaughn Precipitation NOAA	Vaughn NOAA departure[4]
1993 Water year (all values in inches)										
October	1992	2.60	2.41	-1.03	3.46	4.10	-0.64	3.24	2.27	-2.32
November	1992	5.71	6.16	0.50	6.05	6.45	-1.05	5.96	7.70	-0.27
December	1992	3.45	3.58	-2.96	4.03	4.54	-4.20	4.42	4.47	-3.73
January	1993	3.67	4.43	-1.36	6.01	6.43	-1.46	6.16	6.05	-2.02
February	1993	0.26	0.23	-4.23	0.44	0.15	-6.26	0.54	0.55	-5.64
March	1993	4.38	4.37	0.47	4.88	5.86	0.21	5.45	5.37	-0.12
April	1993	5.61	5.64	2.84	3.91	7.15	3.99	6.99	7.22	3.81
May	1993	3.53	3.24	1.26	2.60	[6]--	[6]--	3.67	3.39	1.33
June	1993	1.91	2.30	0.53	2.30	[6]--	[6]--	1.89	1.93	0.37
July	1993	1.31	1.39	0.51	1.47	[6]--	[6]--	1.28	1.78	0.87
August	1993	0.00	0.12	-1.18	0.24	[6]--	[6]--	0.24	0.27	-0.94
September	1993	0.00	0.03	-1.90	0.00	[6]--	[6]--	0.00	0.00	-2.04
Totals:		32.43	33.90	-6.55	35.39	--	--	39.84	41.00	-10.70

[1]Nearest NOAA weather station: PUYALLUP 2 W EXP STN, index number 6803, period of record 1914 to present (U.S. Department of Commerce, 1990-93).

[2]Nearest NOAA weather station: GRAPEVIEW 3 SW, index number 3284, period of record 1908-1992 (U.S. Department of Commerce, 1991-93).

[3]Nearest NOAA weather station: WAUNA 3 W, index number 9021, period of record 1908-1992 (U.S. Department of Commerce, 1991-93).

[4]Departure is the difference between the monthly precipitation value presented and the average monthly precipitation for the period of record.

[5]Departures from normal not reported by NOAA because of incomplete record, value estimated from existing data.

[6]NOAA station discontinued 5/93.

The throughfall values obtained from the data were mostly cumulative, multi-day quantities, which for use in the DPM had to be converted to daily values. Interception loss on any given day depends, in large part, upon the amount of moisture that can be held by the foliage (storage capacity) and on the temporal distribution of precipitation during the day, as well as on the climatic variables that control the rate of evaporation (temperature, humidity, solar radiation, and wind speed). For example, other factors being equal, more interception loss will occur from several light showers spread widely over a day than from one brief heavy shower; and more interception loss will occur in a tall, dense forest than in a short, sparse forest. Because interception loss for a day can exceed the storage capacity of the foliage, a time step shorter than one day was used for interception loss calculations, which then were accumulated to give daily quantities. Interception loss calculations were made on the 15-minute time step used for the precipitation data loggers, for convenience, and because interception loss during a 15-minute period, even during the warmest months, never exceeds the moisture storage capacity of the foliage. For any 15-minute period interception loss is assumed to proceed at the potential rate, E_{max}. Additionally, if precipitation was recorded during the 15-minute period, it was assumed to have occurred at a constant rate during that period. Under these assumptions, interception loss during each 15-minute period is simply the lesser of (1) E_{max} for the period or (2) the moisture remaining from the previous 15 minutes plus the precipitation during the 15 minutes.

Giles and others (1984) successfully used the Priestly-Taylor equation (equation 4), with an α of 3.65, to compute interception loss from Douglas fir forest in southwest British Columbia, Canada, an area with about the same climatological conditions as the Puget Sound Lowland. The Priestly-Taylor equation with $\alpha = 3.65$ was initially used during this investigation to compute 15-minute values of interception loss. Only 15-minute intervals during daylight hours were used because the Priestly-Taylor method is a radiation-based method. However, these calculations did not agree with observed interception losses during winter months. In fact, during the winter months, the cumulative observed interception loss exceeded the cumulative total Priestly-Taylor PET computed with $\alpha = 3.65$ (fig. 8). Upward adjustments of α and the storage capacity of the foliage to improve winter predictions of interception loss could not be made without overpredicting interception loss for the rest of the year. Giles and others (1984) presented results only for the growing-season water budget and, therefore, did not encounter this difficulty. For this investigation, however, the winter water budget is of greater importance than that of the growing season.

Pearce and others (1980) concluded that interception loss during nighttime was 50 to 60 percent of the total interception loss from an evergreen mixed forest, where about 50 percent of the rain falls during the night, a pattern similar to that of the Puget Sound Lowland winters. This pattern further indicates that evaporation from a wet canopy is driven mainly by advected energy rather than by solar radiation, at least during the winter months, and that the advective term of the general combination Penman formula could not be ignored. Measurement of wind speed and humidity at various heights within and above the forest canopy necessary to compute, on a daily basis, the heat-transfer coefficient in equation 3 was beyond the scope of this project. Therefore, an attempt was made to find the best constant value of the heat-transfer coefficient that would give interception losses that, on average, matched the observed interception losses over multi-day periods throughout the year. This attempt was unsuccessful because when good agreement was obtained for winter months, the computed summer interception losses were too high.

Overestimation of summer interception losses resulted from the increased solar radiation term, suggesting that reduction or elimination of the solar-radiation term might improve results. Elimination of the first term in equation 3 and use of a best-fit heat-transfer coefficient in the second term produced a much better match with the observed interception loss. For the coldest, wettest periods, interception loss was slightly underestimated in comparison with all other periods. When an appropriate specified lower daily limit was imposed on E_{max} (for all days of the year), an excellent overall match to the data was obtained (fig. 9). The throughfall was computed using a heat transfer coefficient of 0.38 meters per second, a minimum E_{max} of 0.15 inches per day, and a foliar storage capacity of 0.13 inches.

It is not known if the above relations and the values of the parameters used are applicable to other areas or even for other time periods in the study area. The relations were developed primarily to produce daily values of throughfall for DPM input for the three catchments from the measured variable-time-period throughfall data. However, the technique described rather than the values of the parameters obtained may be useful for other investigations.

Observation of Streamflow, Soil Water and Shallow Ground Water

Runoff was continuously measured at the mouth of each catchment with flow control structures that provided accurate and constant stage-discharge relationships. For the Beaver and Vaughn tributaries, 6-inch Parshall flumes were installed in clay-soil-filled wooden impoundment structures. In the Clover tributary, a pre-existing 18-inch-diameter concrete road-culvert pipe was used. Streamflow stage at each site was monitored continuously by a float attached to a potentiometer. The float was installed in a vertical stilling pipe that was open to the bottom center of each Parshall flume or open to the streambed where no Parshall flume was used. Output from the potentiometer was sampled and recorded every 15 minutes by a Campbell Scientific CR10 micrologger. The theoretical ratings for the Parshall flumes were checked against flow measurements made by USGS personnel at several stages, and the theoretical rating was slightly modified as necessary. Standard USGS rating techniques were used for the Clover Creek tributary site. Data were entered into the USGS National Water Inventory System (NWIS) data base. Daily streamflow values are also published in the USGS annual water-resources data books for Washington State (U.S. Geological Survey, 1994; 1995).

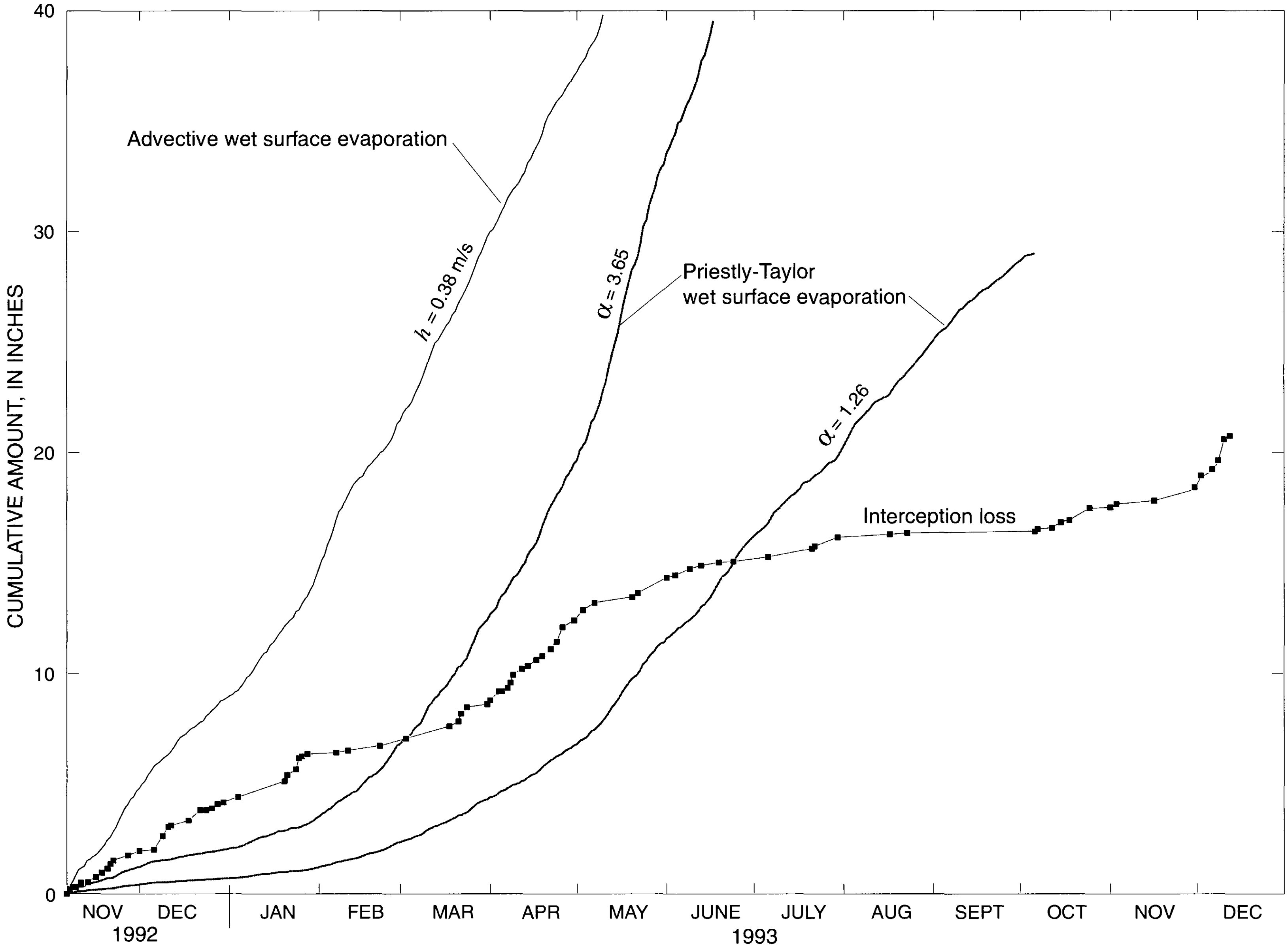


Figure 8.--Observed cumulative interception loss in a Douglas fir stand near the Beaver and Vaughn catchments and computed cumulative maximum wet surface evaporation using the Priestly-Taylor method (equation 4) and using the advective term of the Penman method (last term in equation 3).

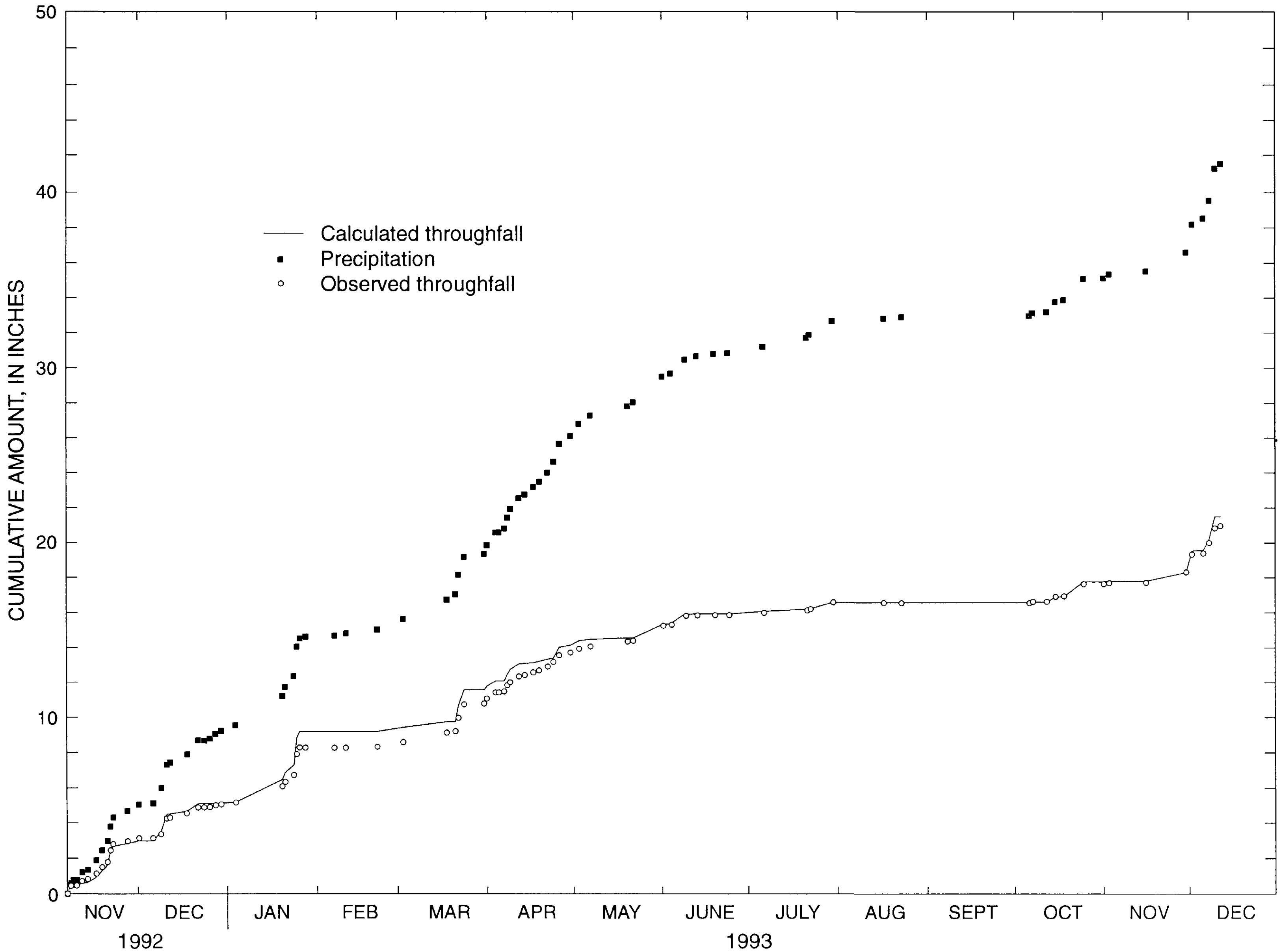


Figure 9.--Cumulative precipitation, observed cumulative throughfall, and computed cumulative throughfall in a Douglas fir stand near the Beaver and Vaughn catchments.

Mean, maximum, and total discharges for each catchment for each water year are presented in table 3, and the daily streamflow hydrographs for the three catchments are shown on figure 10. The daily discharges on the hydrographs are shown as inches per day so that the runoff response per unit area can be directly compared between the catchments.

The hydrographs (fig. 10) show both distinct seasonal and storm responses for each catchment. The tributaries draining the Clover and Beaver catchments flowed continuously from mid-autumn to late spring-early summer. Streamflow in the Beaver tributary began almost one month earlier and lasted two to four weeks longer than in the Clover catchment. The storm responses of these two tributaries are similar but streamflow in the Beaver catchment was slightly greater because of more precipitation. The streamflow pattern for the Vaughn Creek tributary is considerably different; streamflow was generally intermittent throughout the winter and only occurred during and after the heaviest winter storms. The peak stormflows, however, were comparable to those of the nearby Beaver Creek tributary, which has nearly the same precipitation pattern and quantities.

Soil saturation was monitored with piezometers consisting of 2-foot long, 0.006-inch slotted, stainless steel drive-points connected to 1 1/4-inch galvanized steel pipe and manually driven into the soil to refusal at the till surface. These soil-water piezometers were placed along lines, or transects, extending from near ridge tops downslope to the streambed. In the Beaver and Vaughn catchments, one transect was located in the upper part of the catchment and one near the stream gage. One additional transect was placed in the Vaughn catchment, where soil-moisture samplers were also installed. In the Clover catchment, placement of soil-water piezometers was constrained by property ownership, and these two transects had to be situated in the lower to middle part of the catchment. Moreover, at the request of the owner of the land in the lower area, the soil piezometers in the Clover catchment were removed before the end of the data-collection period. One soil-water piezometer was placed on another parcel of land in the upper part of the catchment for the duration of the data-collection period. The locations of the soil-water piezometers are shown on figures 3, 4, and 5. Soil-saturation was monitored by measuring water levels in the piezometers at approximately two-week intervals. Maximum water levels between visits were also recorded using simple floating cork-particle crest-stage indicators. These soil-water-level data are presented in tables A2, A3, and A4 in the appendix.

Table 3.--*Summary of streamflow measured for the three catchments*

[USGS, U.S. Geological Survey]

Catchment name	USGS station number	Area (square miles)	Water year	Mean daily discharge: Inches per day	Mean daily discharge: Cubic feet per second	Maximum daily discharge: Inches per day	Maximum daily discharge: Cubic feet per second	Total discharge: Inches	Total discharge: Cubic feet per second-days[1]
Clover	12090365	0.140	1991	0.061	0.23	1.81	6.8	22.69	85.45
			1992	0.025	0.093	0.69	2.6	9.09	34.21
			1993	0.022	0.082	0.50	1.9	7.94	29.90
Vaughn	12073600	0.198	1992	0.019	0.10	1.18	6.3	7.08	37.68
			1993	0.0064	0.034	0.86	4.6	2.30	12.26
Beaver	12073550	0.171	1992	0.035	0.162	0.89	4.1	12.86	59.11
			1993	0.028	0.13	0.89	4.1	10.52	48.38

[1]Cubic feet per second-days is the sum of the mean daily discharges for the year.

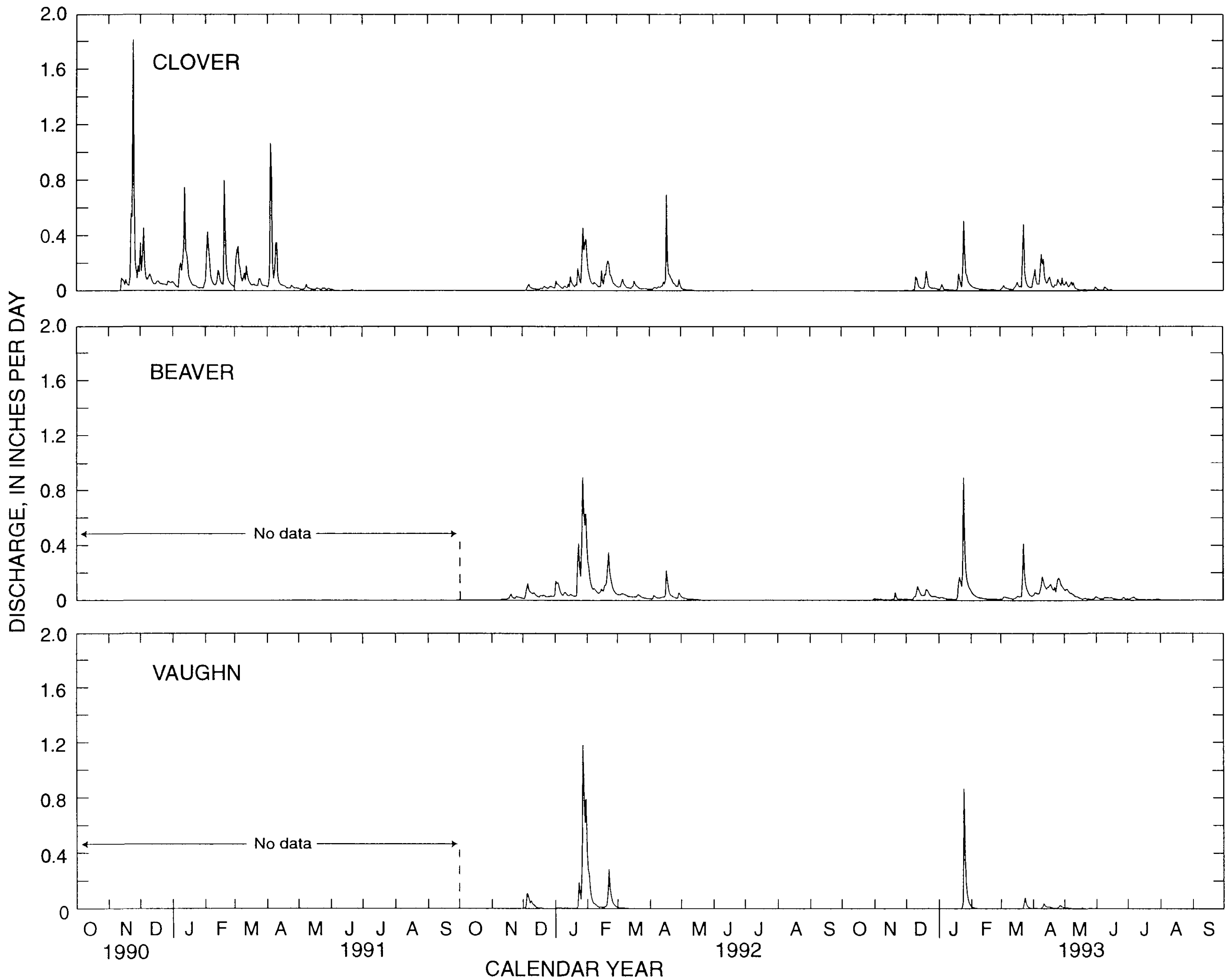


Figure 10.--Daily stream discharge from the three catchments during the study period.

Water-table observation wells were also drilled within each catchment (some of these wells were also used to sample for tritium in the unsaturated zone during drilling and are discussed later). They were drilled with a truck-mounted drilling rig using 3 1-4 inch inside-diameter (ID) hollow-stem augers. Each well was screened at the bottom using the same type of drive point as for the soil piezometers. They were connected to the surface with lengths of 1 1/4-inch galvanized steel pipe. The subsurface materials encountered and ground-water levels observed (as well as other information, discussed later) are shown on figures 11, 12, and 13 for the Clover, Beaver, and Vaughn catchments, respectively.

In the Clover catchment, one well (CLR1A) was drilled to refusal at 77 feet below land surface and screened in a saturated sandy gravel unit. The sand unit extends from the bottom of the till (at 73 feet) to an unknown depth below the bottom of the well. A second observation well (CLR1B) was drilled about 5 feet west of CLR1A to a depth of 21 feet and screened in unsaturated (at the time of drilling) till.

In the Beaver catchment, a pair of wells were drilled 5 feet apart in the upper part of the catchment to depths of 31 and 17 feet and screened in saturated fine sand and in saturated till, respectively. The bottom of the till is at 22 feet, and the fine sand extends down to an unknown depth. A pair of wells were also drilled near the stream gage, about 50 feet apart, to depths of 33 and 21 feet, and screened in saturated fine sand and in saturated till, respectively. The bottom of the till is at 28 feet below land surface and the sand extends down to 36 feet, where a clay unit, extending to unknown depth below the bottom of the well, was encountered.

In the upper part of the Vaughn catchment, a pair of wells was drilled 5 feet apart to depths of 72 and 32 feet and screened at 61 feet in saturated fine sand and at 32 feet in unsaturated till, respectively. The bottom of the till is at about 36 feet below land surface and the sand extends down to unknown depth. Near the catchment stream gage, a single well was drilled to a depth of 29 feet and screened in a saturated, silty, gravelly sand. The bottom of the till is at 17 feet below land surface and the sand extends to an unknown depth below the bottom of the well.

Figures 11, 12, and 13 show hydrographs of streamflow, soil saturation (shown as a water level in feet above the soil-till contact), and water table elevations for each catchment. Most of the soil piezometers for a catchment are shown on a single plot. Data from one or two soil-water piezometers located in the stream channels in each of the catchments are not shown because they are not considered representative of the catchment-wide soil-saturation conditions. Water levels are plotted along the soil-till contact (zero water-level value) when the soil-water piezometers were observed to be dry so that it can be seen when the soil was actually observed to be unsaturated. The maximum water levels between field visits (crest-stage water levels) are not plotted because they are less reliable and the time of each maximum is known only to have occurred during a certain time period. However, the crest-stage water levels (tables A5, A6, and A7 of appendix A) provided some important insight regarding soil saturation during storms. For example, piezometer LYMD in the Vaughn catchment was never saturated during field visits, but the crest-stage indicator showed saturation during two storms.

Water-table hydrographs of adjacent pairs of observation wells are plotted together on figures 11, 12, and 13 (except for at the Vaughn catchment gage, where only one water-table observation well was drilled). Lithology for each location and well depths for each well are also shown. Dry-hole observations, as for the soil-water piezometers, are plotted along the well-bottom line.

It is evident from figures 11, 12, and 13 that, for all three catchments, the magnitude of stream discharge correlates with the overall amount of observed soil saturation, whereas the altitude of the water table does not appear to be related to the stream flows.

In the Clover catchment, the water table at observation well CLR1A (near the topographic divide) declined below the well bottom and never recovered during the data collection period (fig. 11). However, because the water table was always more than about 45 feet below the lowest land-surface altitude in the catchment, there was no ground-water contribution to the streamflow from the saturated sand below the till. The shallow well, CLR1B, screened in the till showed seasonal saturation, beginning in late winter and lasting through most of the summer. This indicated that moisture was moving slowly downward through the till as a saturated wetting front and that later, at a greater depth, the wetting front redistributed to unsaturated conditions. Such redistribution from saturated to unsaturated conditions in a vertical section is commonly observed in experiments and is also analytically predicted (see, for example, Marshall and Holmes, 1979, p. 121-126). Quantitative analysis of the redistribution of moisture in the till section was beyond the scope of this investigation.

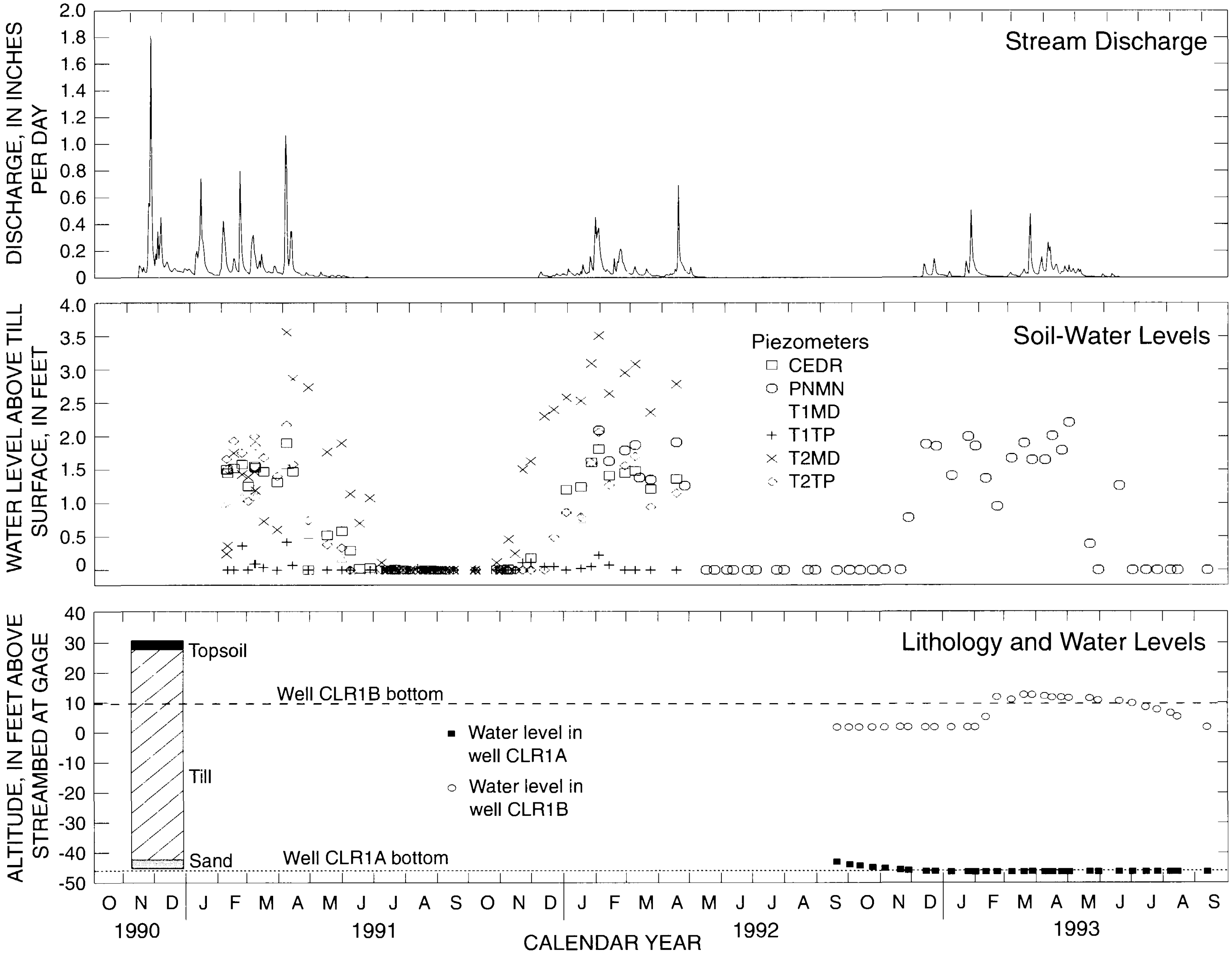


Figure 11.--Stream discharge, soil-water levels, and lithology and water levels in the test-observation wells in the Clover catchment. Piezometer and well locations shown on figure 3. Soil-water levels for T1BT and T2BT were not plotted because they are located in the stream channel and are not representative of catchment-wide soil-water conditions.

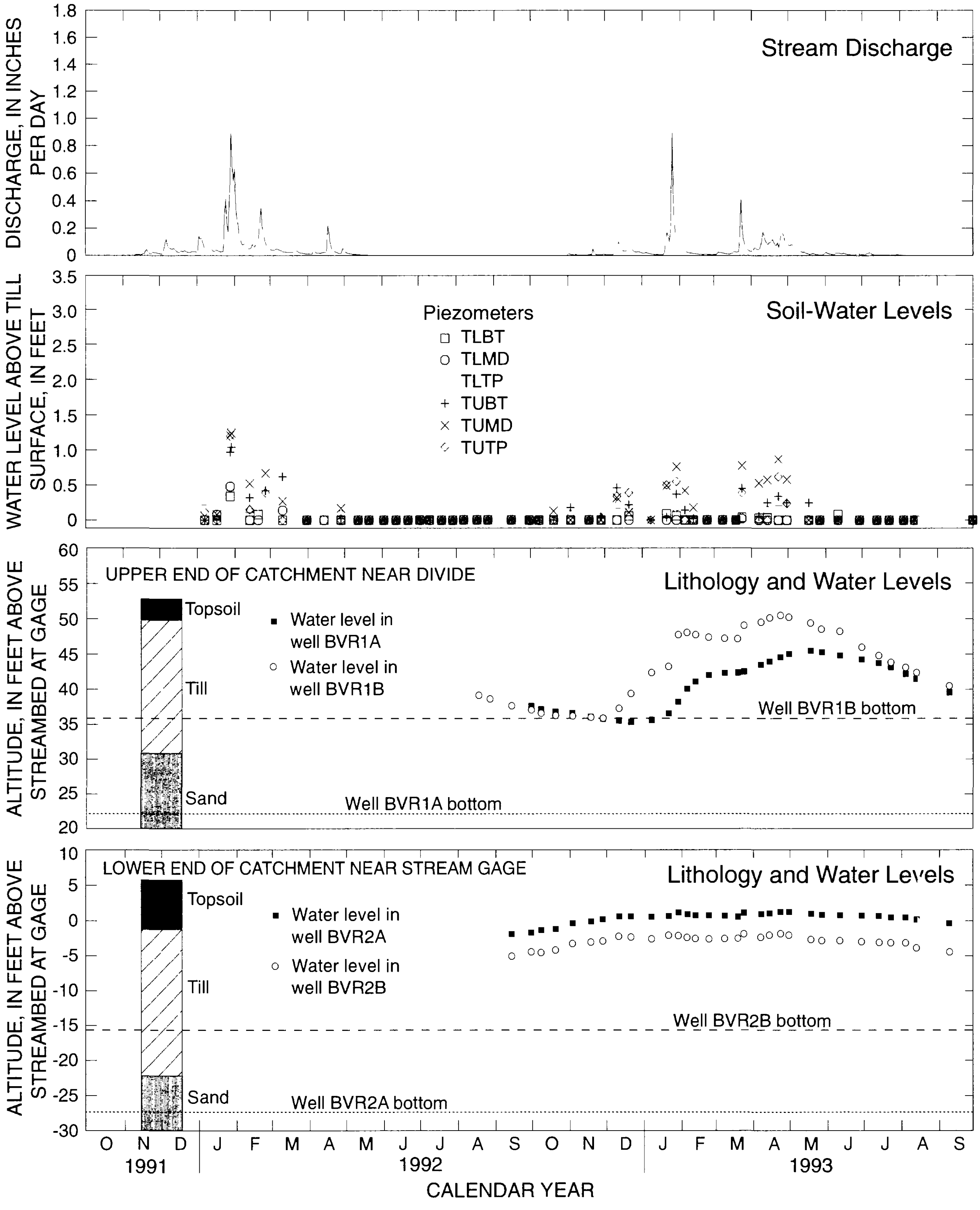


Figure 12.--Stream discharge, soil-water levels, and lithology and water levels in the test-observation wells in the Beaver catchment. Piezometer and well locations shown on figure 4.

NOTE: The top graph corrects an error on the third graph, figure 11, p. 31; the bottom two graphs correct errors on the third and fourth graphs, figure 13, p. 33.

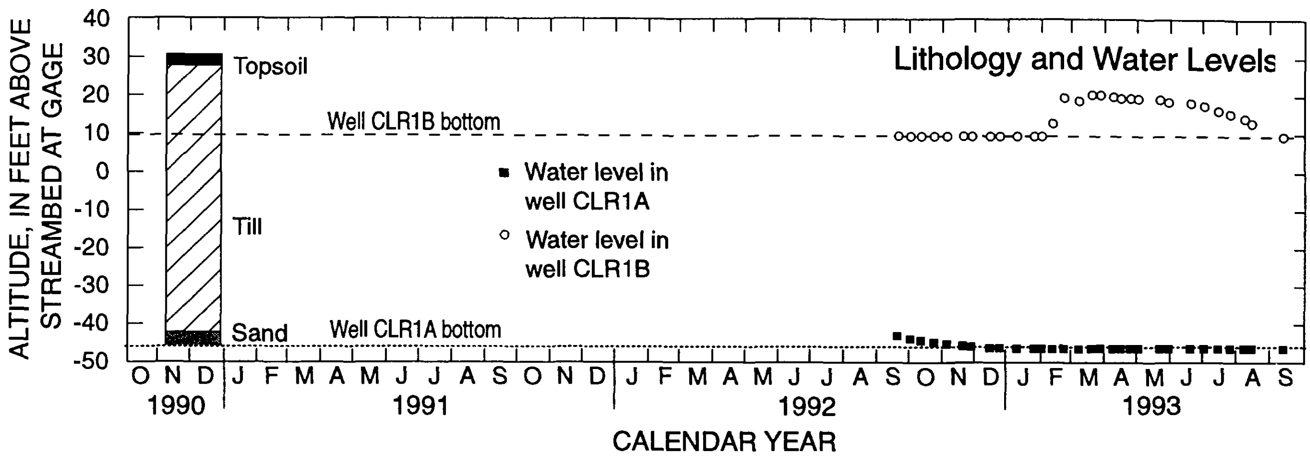


Figure 11.--Stream discharge, soil-water levels, and lithology and water levels in the test-observation wells in the Clover catchment. Piezometer and well locations shown on figure 3. Soil-water levels for T1BT and T2BT were not plotted because they are located in the stream channel and are not representative of catchment-wide soil-water conditions.

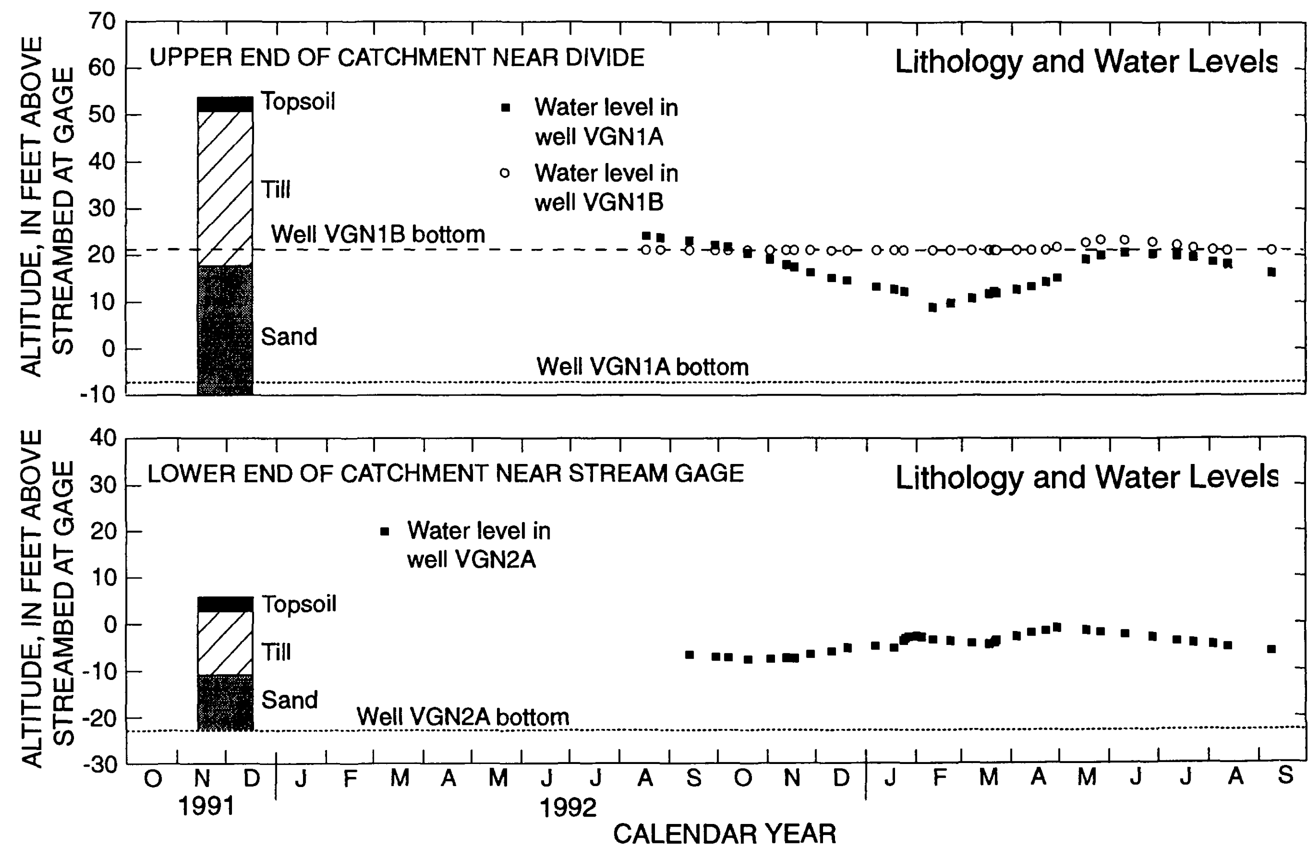


Figure 13.--Stream discharge, soil-water levels, and lithology and water levels in the test-observation wells in the Vaughn catchment. Piezometer and well locations shown on figure 5. Soil-water levels for TLBT, LYBT, and TUBT were not plotted because they are located in the stream channel and are not representative of catchment-wide soil-water conditions. Soil-water levels for TUTP not plotted because it was found that openings were plugged with clay.

In the Beaver catchment, the permanent water table, observed in well BVR1A near the topographical divide, showed a delayed response of about two months, to the first observed soil saturation (fig. 12). The highest permanent water-table levels occur in the late spring and the lowest in mid-winter, the wettest time of the year. Water levels in the lower part of the till unit, observed in well BVR1B were nearly identical to those in the underlying sand, observed in BVR1A, from mid-summer to early winter, after which there was an abrupt divergence in water levels (fig. 12). Water levels in the till (BVR1B) began to rise while those in the sand (BVR1A) continued to decline for another month. At this location, the saturated wetting front in the till appears to have propagated downward, as was also observed in well CLR1B in the Clover catchment, but due to the very shallow water table, redistribution of the wetting front to unsaturated conditions did not occur before the wetting front reached the water table. An approximate unit head gradient between the saturated lower till (BVR1B) and the screened part of the sand (at about 7 feet below the bottom of the till in BVR1A) persisted until about late spring, when the ground-water levels began to decline again. By mid-summer, the vertical gradient was negligible, indicating that vertical flow had ceased.

Water-table levels in the observation wells near the gage (BVR2A and BVR2B) in the Beaver catchment are only a few feet below ground and remain nearly constant throughout the year, most likely because of topographical control a few hundred feet downstream of the gage where ground water seeps into the streambed creating a perennial flow downstream of this location. A slight rise of the water table began in October, but data are insufficient to determine if it was due to streambed leakage to the water table or direct recharge from precipitation. By December, ground-water levels were about a foot above the streambed; therefore, ground-water was probably discharging to the stream. The nearly constant difference of about 4 feet between water levels in these two wells was probably due to a horizontal gradient of the water table toward the downstream discharge area. The well with the lower water levels, BVR2B, is about 50 feet downstream of BVR2A.

In the Vaughn catchment, there is an almost inverse relationship between water-table altitude and streamflow (fig. 13). The water table near the topographic divide, observed in well VGN1A, showed a delayed response to the first observed soil saturation of about two to three months. The highest water-table levels occurred during the dry summer months, while the lowest levels occurred during the wettest winter months. The adjacent, shallow well (VGN1B), screened near the bottom of the till, showed saturation beginning late spring which lasted through most of the summer before becoming unsaturated. During this period, a downward gradient existed between the bottom of the till and the underlying sand (fig. 12), a situation similar to that in the Beaver catchment.

Soil Moisture, Field Capacity, and Specific Yield

Total volumetric soil-moisture content was measured in situ at the same locations and times as was the soil saturation (see previous section). The moisture in the same volume of soil at each location was measured each time using the time domain reflectometry (TDR) method described by Topp and others (1980). The TDR method is based on the fact that the dielectric constant of a soil varies strongly with the water content and is almost independent of soil texture, mineralogy, density, temperature, and electrical conductivity. A regression equation developed by Topp and others (1980) relates the dielectric constant to the volumetric water content of a soil to within a standard error of 1.3 percent when compared against gravimetric determinations of water content.

The dielectric constant of a moist soil is directly related to the propagation velocity, v, of an electromagnetic wave through the soil according to

$$v = \frac{c}{\sqrt{k}} \quad , \qquad (11)$$

where c is the speed of light and k is the dielectric constant (dimensionless) of the soil. Topp and Davis (1985) developed a practical technique for measuring v using a TDR cable tester. Briefly, in this method the cable tester sends out electromagnetic pulses to a pair of parallel metal rods embedded in the soil. The metal rods serve as a wave guide between which the pulses continue to propagate through the soil. Part of each signal is reflected back to the cable tester from the soil surface, and part of the signal is also reflected when it reaches the ends of the metal rods. These reflections show up as characteristic extreme points on a trace of the reflected signal voltage versus time. The time difference between these points is converted to a velocity, which is used to evaluate the dielectric constant in equation 11.

At each soil-moisture measurement location, three pairs of steel rods were driven vertically into the soil to depths of about 1 foot, 2 feet, and down to the soil-till contact (generally about 3 feet), where they remained for the entire data collection period. The 1-foot rods generally consisted of 1/8-inch-diameter stainless steel welding rods, but the longer rods were 1/4-inch diameter needed to penetrate the stony soil deeper than one foot without serious bending or deflection.

A Tektronix 1502 TDR cable tester, which displays the signal voltage versus time, was connected to a Campbell Scientific CR10 micrologger that was programmed to sample the reflected signal voltages and numerically output the time difference between the soil surface and end-of-rod reflections. The software in the micrologger and the procedures for interfacing the TDR cable tester with the micrologger were developed and provided by W. C. Herkelrath and C. W. O'Neil (U.S. Geological Survey, written commun., 1989).

Topp and others (1982) demonstrated that the TDR measured soil moisture over the length of the rods is independent of the moisture distribution along this length to within one percent by volume. Thus, for each column of soil penetrated by a pair of rods, a very accurate average moisture content was determined. A rough measure of the soil-moisture distribution within the soil column could be determined by taking depth-weighted differences between successive pairs of rods. For example, the moisture in the 2-to-3 foot depth interval is determined by subtracting 2 feet times the average moisture content determined from the 2 foot long rods from the product of 3 feet times the moisture content determined from the 3 foot long rods. Similarly, the moisture in the 1 to 2 foot interval can be obtained. Because the soils in all of the catchments wetted and dried fairly uniformly over the full soil depth, moisture distribution in the soil above the till was unimportant for soil-moisture budgeting purposes, and the soil-moisture data for all rod lengths are presented only in tables A8 through A15 in appendix A.

Soil-moisture measurements, in conjunction with measurements of soil saturation over the course of a year, were used to determine AWC values and specific yields of the soils for each of the three catchments. As described previously, these parameters were necessary for the soil-moisture-budgeting calculations performed by the DPM. Due to the wet winters and the dry summers of the Puget Sound Lowland, the two moisture extremes, wilting point and field capacity that define AWC are usually experienced by non-irrigated soils during most years. Figure 14 illustrates how these parameters were determined from the soil-moisture and soil-water-level data at soil-water monitoring location TUMD in the Vaughn catchment. During protracted dry periods in late summer, soil moisture declined asymptotically toward a minimum. This minimum value was taken to be the wilting point. The field capacity was equated to the moisture content generally a few days after free water was no longer observed in the soil-water piezometer, usually during late winter or early spring months. The specific yield of a soil is defined as the change in water content, or storage, per unit area divided by the change in water level. If it is assumed that the moisture content in the soil above the saturated part of the soil remains constant (presumably at field capacity) for periods of time when declines in water level and total moisture content are observed, then specific yield is the ratio of the change in total soil moisture (expressed as volume per area) to the change in water level for these time periods. Generally, for each soil-water monitoring location, two or more determinations of specific yield for different time periods on the hydrographs were made and averaged.

In this manner, wilting point, field capacity, AWC, and specific yield for the undisturbed soil were calculated for each catchment and used in DPM instead of those values reported by the SCS, which were determined by tests on extracted (and probably disturbed) samples and reported as a wide range of values for occurrences of the soil for the county as a whole. Tables 4 through 6 present values of wilting point (shown as minimum observed moisture content), field capacity, AWC, and specific yield determined for each of the soil-water monitoring locations in each of the three catchments.

The amount of water that can be stored in the soil and be available for transpiration plays an important role in the annual amounts of evapotranspiration (and therefore recharge). If more water can be stored in the soil, then more water will be available for transpiration during periods of little or no precipitation. The total available water is determined by multiplying the AWC by the soil depth from which roots can extract water (effective root depth). Commonly, tree roots in till-mantled areas extend down to, but do not penetrate into, the till.

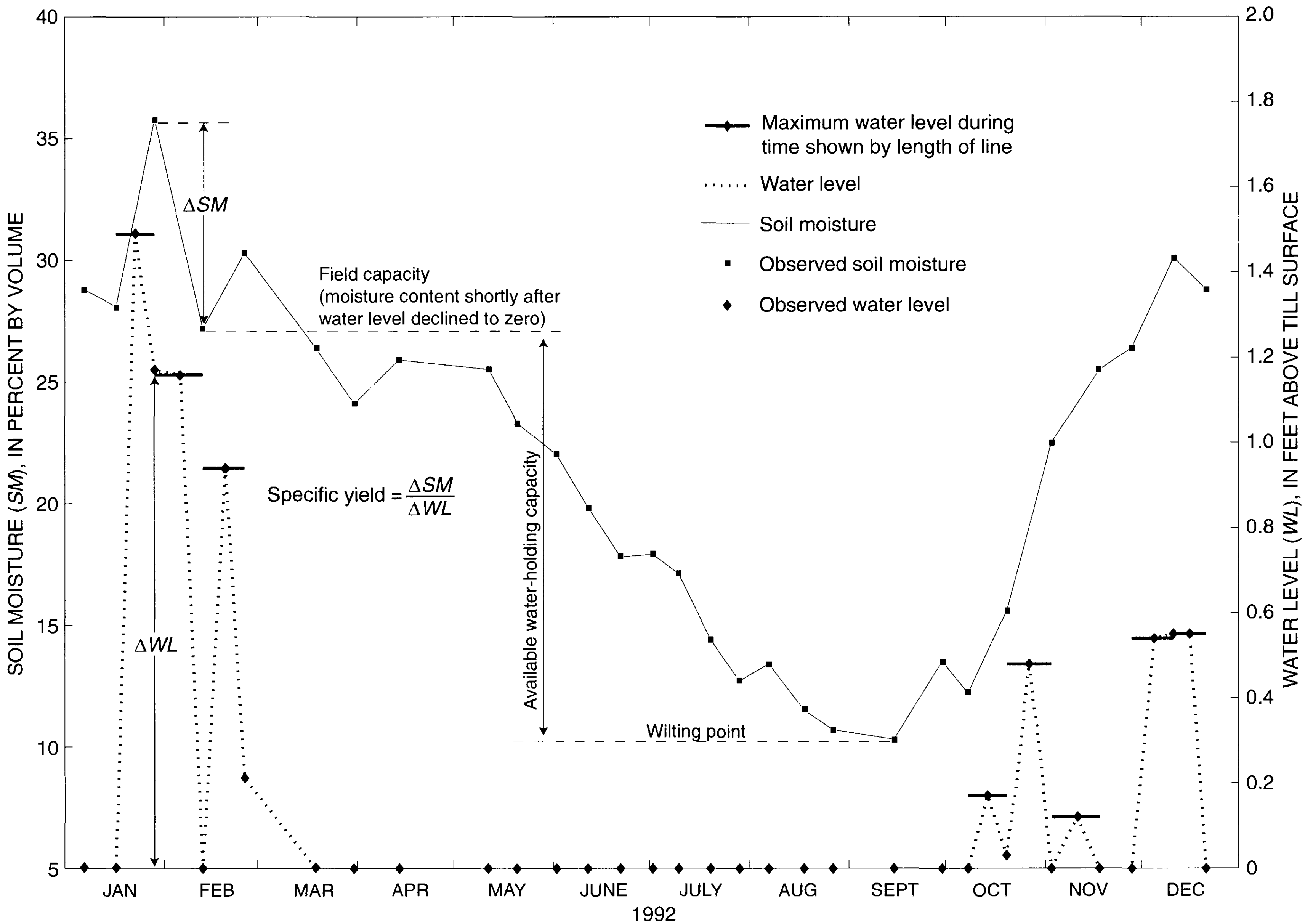


Figure 14.--Soil-moisture content and water-level hydrographs at soil-water monitoring site TUMD in the Vaughn catchment, illustrating the determination of available water-holding capacities and specific yields at soli-monitoring sites for the water-budget calculations.

Table 4.--*Soil-moisture characteristics determined from the time-domain reflectometry (TDR) method and soil-water piezometer measurements in the Clover catchment*

Location identifier[1]	Maximum TDR rod depth (feet)	Soil-piezometer depth (feet)	Measurements of moisture, in percent by volume			
			Field capacity	Minimum observed moisture	Available water capacity	Specific yield
T1BT	4.8	[2]5.2	28.0	[3]21.0	[3] --	9.1
T1MD	2.9	3.4	28.0	10.3	17.7	9.8
T1TP	3.9	3.4	25.5	8.7	16.8	11.0
T2BT	1.9	[2]3.0	36.0	[3]15.7	[3] --	4.2
T2MD	3.9	3.6	31.5	17.9	13.6	7.1
T2TP	2.9	3.4	26.0	10.4	15.6	10.8
CEDR	3.9	3.6	27.0	13.3	13.7	6.1
PNMN	2.8	2.6	38.5	16.2	22.3	8.2
Averages:		[2]3.3	30.1	12.8	16.6	8.3

[1]Locations shown on figure 3.

[2]Piezometers at T1BT and T2BT were driven deeper than top of till and are not included in the average, which was used as the measure of representative soil depth.

[3]Minimum soil moisture at T1BT and T2BT were not at wilting point and were not used in the average or in determining available water capacities.

Table 5.--*Soil-moisture characteristics determined from the time-domain reflectometry (TDR) method and soil-water piezometer measurements in the Beaver catchment*

Location identifier[1]	Maximum TDR rod depth (feet)	Soil-piezometer depth (feet)	Measurements of moisture, in percent by volume			
			Field capacity	Minimum observed moisture	Available water capacity	Specific yield
TLBT	2.9	2.9	28.5	12.3	16.2	49.7
TLMD	2.9	2.9	18.0	8.6	9.4	20.6
TLTP	2.9	2.7	29.5	12.6	16.9	48.0
TUBT	2.9	2.3	30.5	12.9	17.6	26.7
TUMD	2.9	2.8	24.5	9.6	14.9	22.4
TUTP	2.9	2.8	20.5	7.7	12.8	30.7
Averages:		2.7	25.2	10.6	14.6	33.0

[1]Locations shown on figure 4.

Table 6.--*Soil-moisture characteristics determined from the time domain reflectometry (TDR) method and soil-water piezometer measurements in the Vaughn catchment*

Location identifier[1]	Maximum TDR rod depth (feet)	Soil-piezometer depth (feet)	Measurements, in percent by volume			
			Field capacity	Minimum observed moisture	Available water capacity	Specific yield
TLBT	2.8	[2]3.1	23.3	9.1	14.2	17.9
TLMD	2.9	2.4	24.3	10.7	13.6	25.6
TLTP	2.7	2.6	30.3	14.1	16.2	[3] --
LYBT	2.9	[2]2.6	26.6	12.7	13.9	19.2
LYMD	2.9	2.9	19.8	7.2	12.6	[3] --
LYTP	2.9	2.9	22.6	8.6	14.0	[3] --
TUBT	1.9	[2]2.1	32.0	[4]17.9	[4] --	26.2
TUMD	2.9	2.9	25.9	10.3	15.6	18.7
TUTP	2.9	3.0	39.5	21.8	17.7	18.3
Averages:		[2]2.8	27.1	[4]11.8	14.7	21.0

[1] Locations shown on figure 5.

[2]Piezometers TLBT, LYBT, and TUBT were located in stream channels. The soil depths at these locations are not representative for most of the catchment and are not included in the average, which was used as the measure of representative soil depth.

[3]Piezometers TLTP, LYMD, and LYTP did not show sufficient soil saturation from which specific yield could be determined.

[4]Minimum soil moisture at TUBT was not at wilting point and was not used in the average or in determining the available water capacity.

The assumption that flow is only downward below the root zone may not be strictly true all of the time because root uptake of soil moisture from near the bottom of the root zone may, at times, dry the soil, lowering the matric potential below that of the subsoil and causing some upward movement of moisture back into the root zone. Infiltration experiments have shown, however, that the quantity of water moving from moist to dry soil during a period of several months is small if no additional water is added to the wet soil and the soil is not in contact with a free-water surface (Chow, 1964, Section II). Additionally, the quantity of such upward movement is small in comparison with the water-holding capacity of the root-zone soils in the catchments. This effect was compensated for in this investigation by assuming a root-zone depth slightly greater than that observed according to the following observations.

The soil-water piezometers were all driven into the soil until there was an abrupt and very large increase in driving resistance (that is, "refusal"). The top of the till was assumed to lie at this depth, and the penetration depths of the soil piezometers were used as measurements of soil depth. In addition, one soil piezometer and a pair of TDR probes were driven about 2 feet into the till to a total depth of 4.8 feet at location T1BT in the Clover catchment (fig. 3). Soil-moisture measurements showed typical annual moisture variations of about 24 percent, by volume, in the upper three feet of soil at this location but only about 10 percent, by volume, in the 3-to-5-foot depth interval. Moreover, after the saturated water drained from this depth interval, further moisture decrease was no more than about 5 percent. If it is assumed that this 5 percent moisture from this interval moved upward and was transpired, then this amount is about equal to the AWC in 6 inches of the upper soil. Therefore, the catchment averages of the depths to refusal, plus 6 inches, were used as effective root depths.

Estimates of Recharge

Daily water budgets were computed with the DPM for multi-water-year periods for each of the three catchments: October 1, 1990, through September 30, 1993, for the Clover catchment and October 1, 1991, through September 30, 1993, for the Beaver and Vaughn catchments. The daily time-series input data of precipitation, throughfall, streamflow, temperature, and incoming short-wave solar radiation were previously discussed.

Division of the catchments into subareas, or cells, for the DPM was based only on land cover. Because all variables except land cover were approximately uniform, only two cells were used in the DPM to represent the Clover catchment, which was 0.0892 square mile of pasture and 0.0506 square mile of mixed deciduous and Douglas fir forest. Similarly, only two cells were also used for the Beaver catchment to represent 0.1607 square mile of a mixed deciduous and Douglas fir forest and 0.0103 square mile of low brushy riparian plants. Only one cell was required for the Vaughn catchment, representing a forest consisting of Douglas fir with a salal and huckleberry understory.

Interception loss was calculated for each forest-cover cell of each catchment using the method and parameters described in the "Interception Loss" section. The same heat transfer coefficient and minimum PET rate were used, irrespective of the particular mixture of Douglas fir and deciduous trees. However, the foliar-moisture storage capacity for the deciduous trees was varied over the year. From about May 1 to September 15, when the leaves are fully developed, a storage capacity of 0.08 inch was used (Zinke, 1967). From November 15 to March 31, when the trees are bare, a storage capacity of 0.02 inch was used. The storage capacity was assumed to vary linearly between these time periods (dates used were from local observation). The storage capacities for the deciduous trees were area-weight averaged with that of the constant Douglas fir storage capacity to yield composite, time-varying storage capacities for each forest cell. For the grass and riparian areas, which have small advective evaporation compared with forest, the Priestly-Taylor method with $\alpha = 1.26$ was used to compute interception loss and, thus throughfall (Jensen and others, 1990, p. 145). A storage capacity of 0.06 inch was used (Zinke, 1967).

The DPM was operated repeatedly for each catchment, using trial-and-error values for the subsoil (glacial till) infiltration capacity and the soil-limiting-transpiration parameter, until the water-budget deficit term was minimized and a good match was obtained between computed and observed hydrographs of soil saturation and soil-moisture content. A soil-limiting evapotranspiration coefficient (b in equation 10 of 0.60 inch per day worked well for all three catchments but is larger than values of 0.16 to 0.4 inch per day determined by Giles and others (1984) and Spittlehouse and Black (1981), respectively. The optimized subsoil-infiltration capacities were 4, 30, and 40 inches per year for the Clover, Beaver, and Vaughn catchments, respectively. For comparison, estimated area-averaged hydraulic conductivity values for till, for various locations throughout the Puget Sound Lowland, compiled from other sources and determined from permeameter tests, range from 4.4 to 44 inches per year (J. J. Vaccaro, written commun., U.S. Geological Survey, 1994). Table 7 summarizes the annual and average values of precipitation, computed deep-percolation, computed water-budget deficits, and the optimized subsoil-infiltration capacities. As previously discussed, the water-budget deficits are approximate measures of error on the computed deep-percolation values. Figures 15 and 16 show the observed and computed soil-saturation and soil-moisture hydrographs for each of the catchments. Data points for locations T1BT and T2BT (fig. 3) in the Clover catchment and for locations TLBT and TUBT in the Vaughn catchment (fig. 5) are not shown on the hydrographs because these locations are situated in the streambeds and are not representative of conditions computed by the DPM.

Figure 17 shows the monthly water-budget components of precipitation, deep percolation, runoff, and evapotranspiration for each catchment as a whole; table 7 summarizes the annual water-budget components for each land use for each catchment. Tables A16 through A18, which are results of DPM runs, present a more detailed accounting of the water-budget components, including monthly values of transpiration, interception loss, and changes in soil moisture; also included are temperature, PET, simulated direct runoff, the deficit term, and certain other terms such as snowpack and bare soil evaporation, which were all zero.

Table 7.--*Annual summaries of the water-budget results for the three till-mantled catchments*

Clover Catchment

Mixed forest area = 0.0506 square mile
Pasture area = 0.0892 square mile
Till infiltration capacity = 4.0 inches per year

Water year quantities[1]:

Water year	Vegetation	Precipitation	Interception loss	Direct runoff	Transpiration[2]	Recharge	Change in soil moisture	Soil-saturation deficit
		Values, in inches						
1991	Mixed forest	45.21	17.25	16.62	12.27	1.37	-0.69	-1.60
	Pasture	45.21	6.19	26.20	13.83	1.44	-0.58	-1.86
Area-weighted averages:		45.21	10.19	22.73	13.26	1.41	-0.62	-1.77
1992	Mixed forest	33.17	13.96	4.41	13.93	0.69	0.72	-0.55
	Pasture	33.17	4.35	11.76	15.25	1.45	0.90	-0.55
Area-weighted averages:		33.17	7.83	9.10	14.77	1.18	0.83	-0.55
1993	Mixed forest	32.43	15.14	3.77	13.00	1.18	-0.64	-0.01
	Pasture	32.43	5.97	10.33	14.56	2.15	-0.57	0.01
Area-weighted averages:		32.43	9.29	7.95	13.99	1.80	-0.59	-0.01

1991-93 water year averages[1]:

Vegetation	Precipitation	Interception loss	Direct runoff	Transpiration[2]	Recharge	Change in soil moisture	Soil-saturation deficit
	Values, in inches						
Mixed forest	36.94	15.45	8.27	13.07	1.08	-0.20	-0.72
Pasture	36.94	5.50	16.10	14.55	1.68	-0.08	-0.81
Area-weighted averages:	36.94	9.10	13.26	13.98	1.46	-0.13	-0.78

Table 7.--*Annual summaries of the water-budget results for the three till-mantled catchments--Continued*

Beaver Catchment

Mixed forest area = 0.1607 square mile
Riparian area = 0.0103 square mile
Till infiltration capacity = 0.0-30.0 inches per year[3]

Water year quantities[1]:

Water-year	Vegetation	Precip-itation	Inter-ception loss	Direct runoff	Trans-pira-tion[2]	Re-charge	Change in soil moisture	Soil-satur-atior deficit
		Values, in inches						
1992	Mixed forest	43.12	15.21	8.77	12.02	6.77	0.37	-0.02
	Riparian	43.12	4.90	27.71	9.50	0.00	0.79	0.22
Area-weighted averages:		43.12	14.59	9.91	11.63	6.36	0.39	-0.01
1993	Mixed forest	35.39	13.88	6.75	11.56	4.81	-1.18	-0.44
	Riparian	35.39	5.15	21.00	9.69	0.00	-1.17	0.72
Area-weighted averages:		35.39	13.35	7.61	11.44	4.52	-1.17	-0.37

1991-92 water year averages[1]:

	Vegetation	Precip-itation	Inter-ception loss	Direct runoff	Trans-pira-tion[2]	Re-charge	Change in soil moisture	Soil-satur-ation deficit
		Values, in inches						
	Mixed forest	39.25	14.55	7.76	11.79	5.79	-0.40	-0.23
	Riparian	39.25	5.03	24.36	9.59	0.00	-0.19	0.47
Area-weighted averages:		39.25	13.97	8.76	11.53	5.44	-0.39	-0.19

Table 7.--*Annual summaries of the water-budget results for the three till-mantled catchments--Continued*

Vaughn Catchment

Douglas fir forest area = 0.198 square miles
Till infiltration capacity = 40.0 inches per year

Water year quantities[1]:

Water-year	Vegetation	Precip-itation	Inter-ception loss	Direct runoff	Trans-pira-tion[2]	Re-charge	Change in soil moisture	Soil-satur-ation deficit
		Values, in inches						
1992	Douglas fir	41.56	19.69	7.08	10.96	4.92	-0.49	-0.59
1993	Douglas fir	39.84	18.62	2.30	10.86	8.66	-0.54	-0.07

1991-92 water year averages[1]:

Vegetation	Precip-itation	Inter-ception loss	Direct runoff	Trans-pira-tion[2]	Re-charge	Change in soil moisture	Soil-satur-ation deficit
	Values, in inches						
Douglas fir	40.70	19.16	4.69	10.91	6.79	-0.52	-0.33

[1]Sum of budget components may not exactly equal precipitation because of round-off errors.

[2]May include small quantities of snow evaporation.

[3]30.0 from 10-01-91 through 02-09-92, 0.0 from 02-10-92 through 04-09-92, 30.0 from 04-10-92 through 09-30-92, 30.0 from 10-01-91 through 02-28-93, 0.0 from 03-01-93 through 05-31-93, 30.0 from 06-01-93 through 09-30-93.

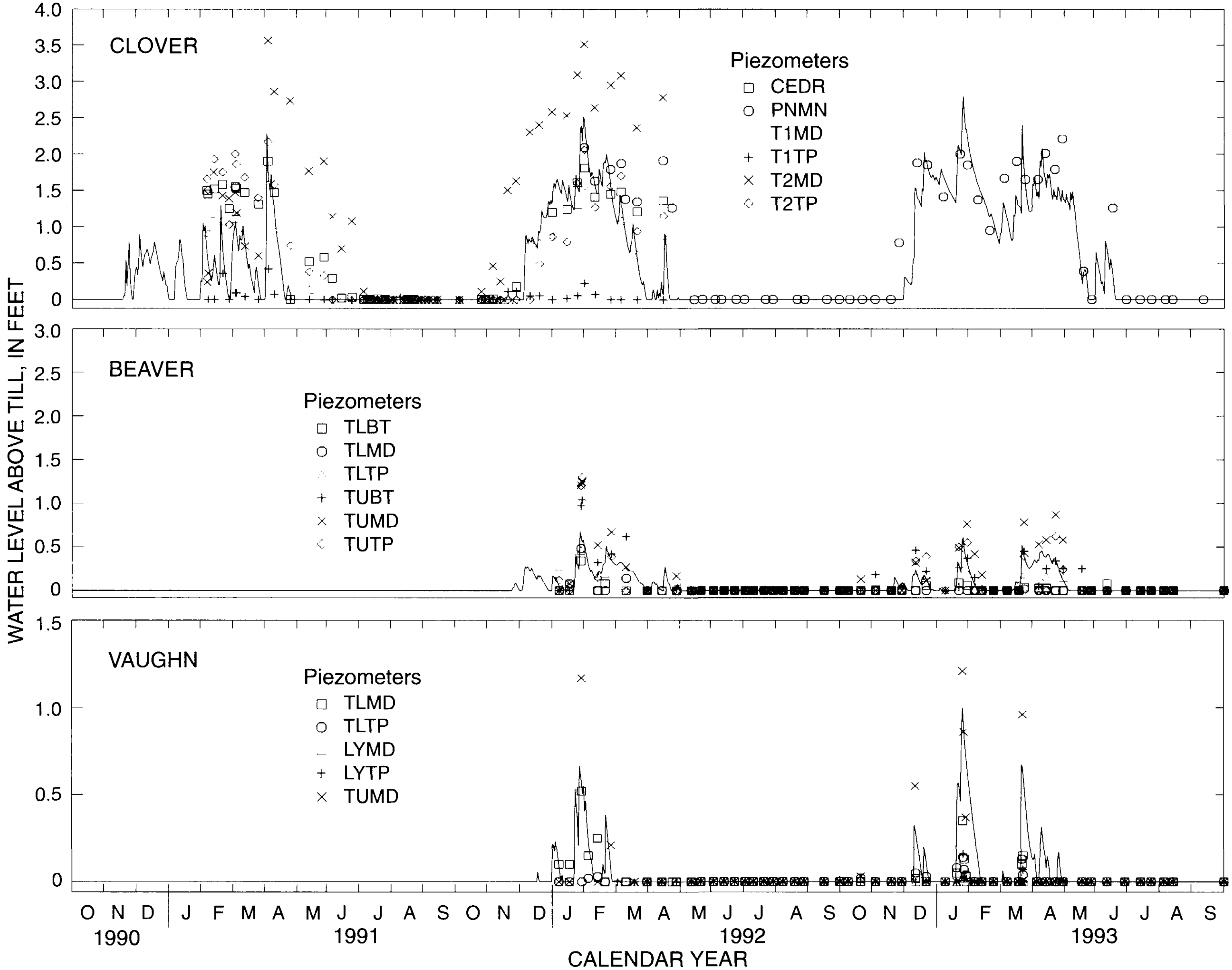


Figure 15.--Observed (symbols) and Deep Percolation Model water-budget-calculated (lines) soil-water levels during the study period for the three catchments. Piezometer locations shown on figures 3-5. Water levels not plotted for certain piezometers as noted on figures 11 and 13.

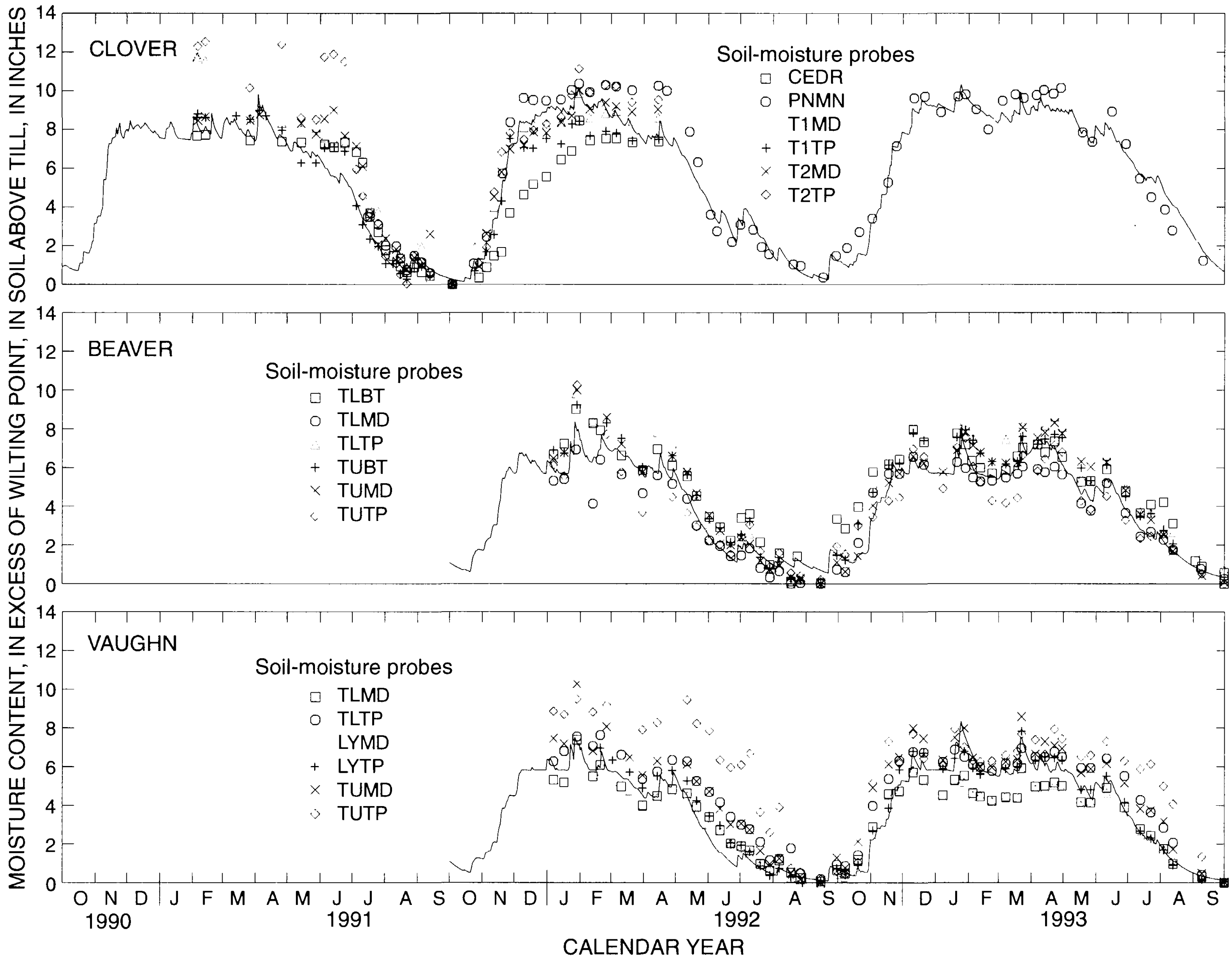


Figure 16.--Observed (symbols) and Deep Percolation Model water-budget-calculated (lines) soil-moisture contents during the study period for the three catchments. Soil-moisture-monitoring locations shown on figures 3-5. Moisture contents for T1BT and T2BT in the Clover catchment and TLBT and LYBT in the Vaughn catchment were not plotted because they are located in the stream channel and are not representative of catchment-wide soil-moisture conditions.

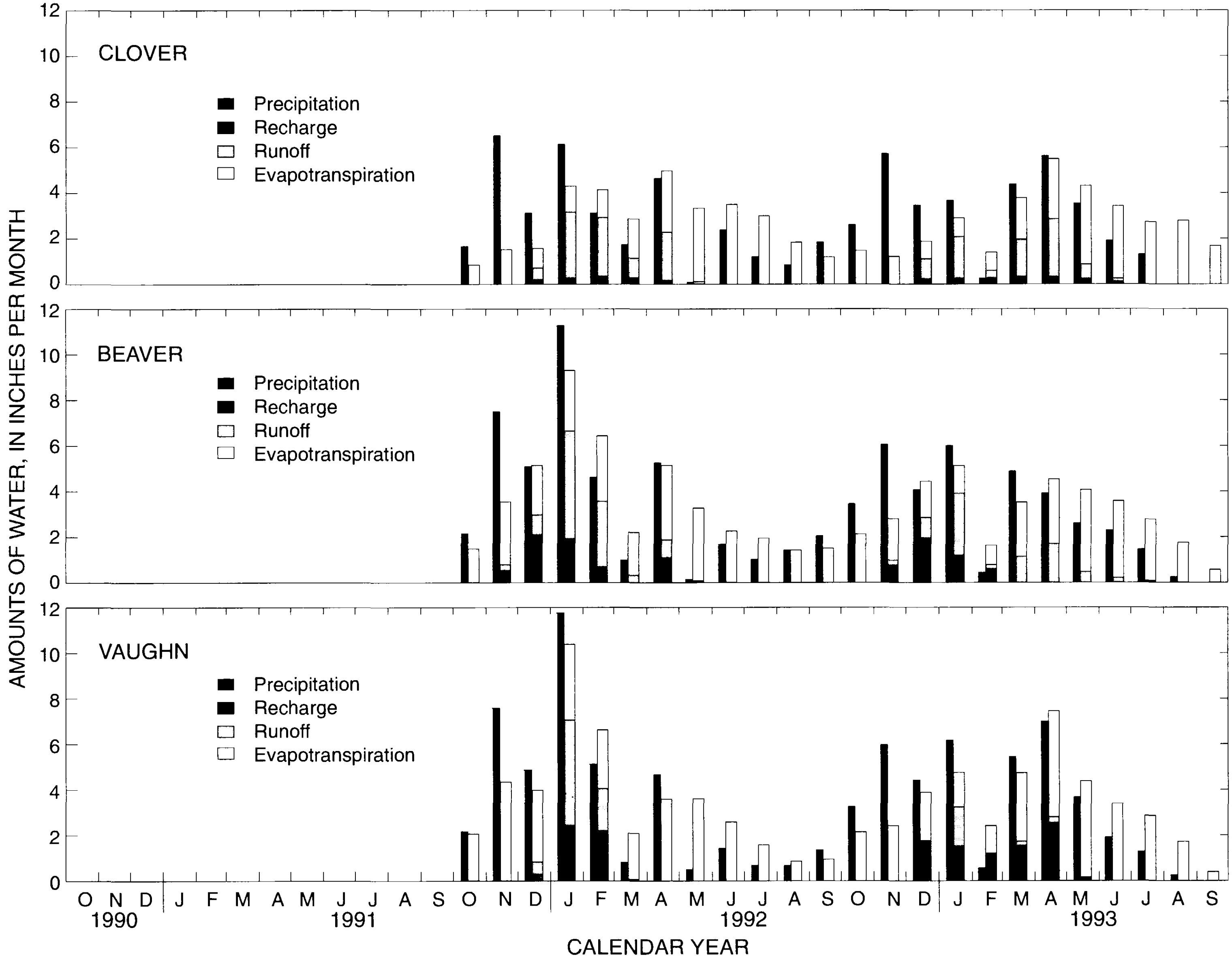


Figure 17.--Monthly water-budget components during the study period for the three catchments.

In the Clover catchment, the average annual recharge for the water-years 1991-93 was calculated at 1.46 inches, or 4.0 percent of precipitation, with 1.08 inches for the forested area and 1.68 inches for the pasture area (table 7). On a monthly basis, when deep percolation occurs, it is always relatively uniform and a very small part of the total water budget (fig. 17). Calculated recharge is limited by the infiltration capacity of the till, which is estimated to be 4.0 inches per year for this area. Differences in annual recharge amounts result mainly from differences in the quantities of precipitation in late spring and summer rather than from total annual precipitation. For example, during water-year 1991, there was 45.21 inches of precipitation and an average of 1.44 inches of recharge, but for water-year 1993, there was only 32.43 inches of precipitation, but recharge increased to 1.84 inches. This increase in recharge is due in large part to more May and June precipitation in 1993 than in 1991.

Analysis of the water budget for the Beaver catchment proved more complicated because of unanticipated geologic and ground-water conditions. At the outset of the investigation, a main criterion for catchment selection was that the streamflow generated in each catchment would consist only of direct runoff to the stream channel and its tributaries. The main indicators of this criterion during the reconnaissance and selection period was that the streambeds were dry during the summer and early autumn months and that water levels, as reported on drillers logs of nearby domestic wells, indicated a water table that was lower than streambed elevations. These indicators were observed during early autumn of 1991, but it was later discovered during the test-well-drilling phase of the project that there was a shallow perched water table caused by a clay layer at an approximate depth of 35 feet. During the winter months, the water table rose above the streambed and, for some periods, up into the topsoil (fig. 12).

Thus, in the Beaver catchment, a part of streamflow, during certain periods, was ground-water discharge from the perched aquifer. Daily values of this baseflow had to be quantified and input for the DPM computations. During periods of no soil saturation, baseflow was assumed equal to total streamflow, thus establishing some control points on the baseflow hydrograph. The relation between water-table levels observed in well BVR1B (fig. 4 and 12) and baseflows at these times was used as a guide in estimating baseflows from water-table levels during periods when the soils were saturated. Also, during periods of soil saturation following periods of precipitation, upper limits of baseflow were defined by minimum values on the falling limbs of the streamflow hydrograph. In this manner, a baseflow hydrograph for the Beaver catchment was constructed. It is interesting to note that, initially, when DPM calculations were made assuming that all streamflow came from soil drainage and surface runoff, the water-budget deficit term could not be made reasonably small while maintaining reasonable agreement between observed and computed soil saturation and soil moisture hydrographs. After the baseflow was subtracted from the streamflow, the water-budget deficit term was acceptable (3 percent of computed deep percolation).

The effect on deep percolation rates caused by the water table rising into the topsoil during certain periods also had to be addressed. Downward movement of water through (and into) the till is equal to the product of the vertical hydraulic conductivity and the vertical head gradient. When the till is unsaturated, the vertical head gradient is unity, and infiltration is approximately equal to the unsaturated hydraulic conductivity (for steady flow conditions it is exactly equal to the hydraulic conductivity), and for very wet unsaturated conditions it approaches the saturated hydraulic conductivity (or infiltration capacity). After about the end of January through the end of April, water levels measured at well BVR1B (completed in the till) and in the nearest soil piezometer, TUMD (fig. 4 and 12) were both only 2 feet below land surface, indicating that the vertical head gradient from the top of the water table down to screened depth of the well was nearly zero. Therefore, the vertical saturated flow into the till must have been much less than the infiltration capacity. To approximate these conditions for the DPM computations, the infiltration capacity was set to zero during those periods when the water table was observed to rise into the topsoil.

In the Beaver catchment, the average annual recharge through the till for the water years 1992-93 was calculated at 5.44 inches, or 13.9 percent of precipitation, and is 3.6 times that in the Clover catchment for this period (1.51 inches, table 7). Recharge to aquifers below the clay layer, however, cannot exceed about 2.5 inches per year, which is the difference between the deep percolation to the water table and the estimated stream baseflow (2.9 inches per year).

In the Vaughn catchment, the average annual recharge for the water-years 1992-93 was calculated at 6.79 inches, or 16.7 percent of precipitation, and is comparable to that in the Beaver catchment but 4.5 times that in the Clover catchment (1.51 inches) for the same period. During the wettest months, the computed monthly deep percolation is about 2.4 to 2.5 inches (about one third of precipitation), but during some relatively dry winter months no deep percolation was computed. This difference indicates potential for greater annual quantities of deep percolation under more favorable precipitation patterns during the wet season. Differences in annual recharge due to differences in the timing of precipitation can also be seen in a comparison of the deep percolation for the 1992 and 1993 water years (table 7). In water-year 1992, the total precipitation for the Vaughn catchment was 42 inches, and the computed deep percolation was 5.0 inches. In water-year 1993, the precipitation was slightly less at 40 inches, but the deep percolation was 76 percent more at 8.8 inches. The precipitation was temporally more uniform during the winter months, resulting in more deep percolation and much less total runoff (fig. 17; table 7).

For the time periods investigated, the average of the calculated recharge for the three catchments was 4.56 inches per year, about 12 percent of the average precipitation quantities measured during this investigation (39.0 inches per year). The average recharge estimated for till-mantled areas from previous investigations, cited on table 1, is 13.3 inches per year, about 34 percent of the average of the annual precipitation quantities cited in these studies (38.7 inches per year).

ESTIMATES OF RECHARGE USING TRITIUM TRACING

Very small quantities of tritium, the radioactive hydrogen isotope (^3H) are produced by cosmic ray interactions with the atmosphere and occur naturally in water molecules in the atmosphere. Prior to thermonuclear bomb testing, few reliable measurements of natural tritium in the atmosphere had been made, but they were sufficient to establish that natural atmospheric tritium concentrations ranged from 4 to 25 tritium units (TU) (Fritz and Fontes, 1980), with an average annual world-wide concentration of about 5 TU (Mazor, 1991). The average annual pre-bomb tritium concentration for Washington State was also about 5 TU (Thatcher, 1962). One TU is defined as one atom of tritium per 10^{18} atoms of normal hydrogen.

With the onset of H-bomb tests in about 1952, world-wide tritium concentrations increased dramatically, reaching a maximum in June 1963 of more than 3,000 TU in the Pacific Northwest. Thereafter, atmospheric tritium concentrations declined because of the ban on above-ground H-bomb testing, gradually returning to near-natural concentrations by about 1985. The return to near-natural concentrations resulted from tritium's relatively short half-life of 12.43 years and because of uptake of atmospheric water by oceans and other bodies of water, including ground water.

The average annual concentrations of tritium in precipitation at the project area (fig. 18) were determined using an unpublished computer program that interpolates monthly tritium deposition data collected at a network of sites in the United States and Canada (Robert Michel and Brian Cross, U.S. Geological Survey, written communication, 1990). Figure 18 also shows the effects of radioactive decay on the tritium concentrations: the curve labeled "radioactive-decay corrected" shows what the tritium concentrations in precipitation that fell at the indicated time (year axis) would have decayed to by 1992, the year of soil-water tritium sampling and analysis for this investigation.

This history of tritium deposition and the fact that tritium is a part of the water make tritium an excellent environmental tracer and age indicator for ground water in both the saturated and unsaturated zones. Several investigators have made estimates of ground-water recharge using tritium as a tracer. Daniels and others (1991) estimated a recharge rate of 1.4 inches per year. through glacial till in Indiana by detecting a tritium concentration peak in a column of unsaturated till. The water at the tritium peak was assumed to be the same water that fell as precipitation in 1963. Assuming downward piston-type flow (the displacement of an equal volume of pre-existing water ahead of the percolating water) in the unsaturated zone, all of the water above the peak entered the soil between 1963 and the time of sampling. Summing the volumetric soil-water contents in the soil above the peak and dividing by the number of years elapsed since 1963 gives the average annual recharge rate during that time period. This method, herein referred to as the transit-time method, is useful mainly where there is a thick unsaturated zone or where recharge rates are small because of either low permeability subsoils or arid to semi-arid environments. Phillips and others (1988) and Dincer and others (1974) describe the use of this method in arid environments.

In humid, high-permeability environments, vertical soil-water velocities are greater than in semi-arid environments, and water tables are likely to be shallower, making it much more probable that the tritium peak has moved entirely through the unsaturated zone and into the saturated zone, where lateral flow would transport the peak away from the vertical column. In such areas, tritium tracing can be used to bracket ground-water ages within the aquifers, which can then be used to compare against flow-path travel times predicted by ground-water models (see for example Bradbury, 1991; Robertson and Cherry, 1989; and Campana and Mahin, 1985). Where ground water flows mainly downward from the water-table surface, such as beneath a ground-water divide, the transit-

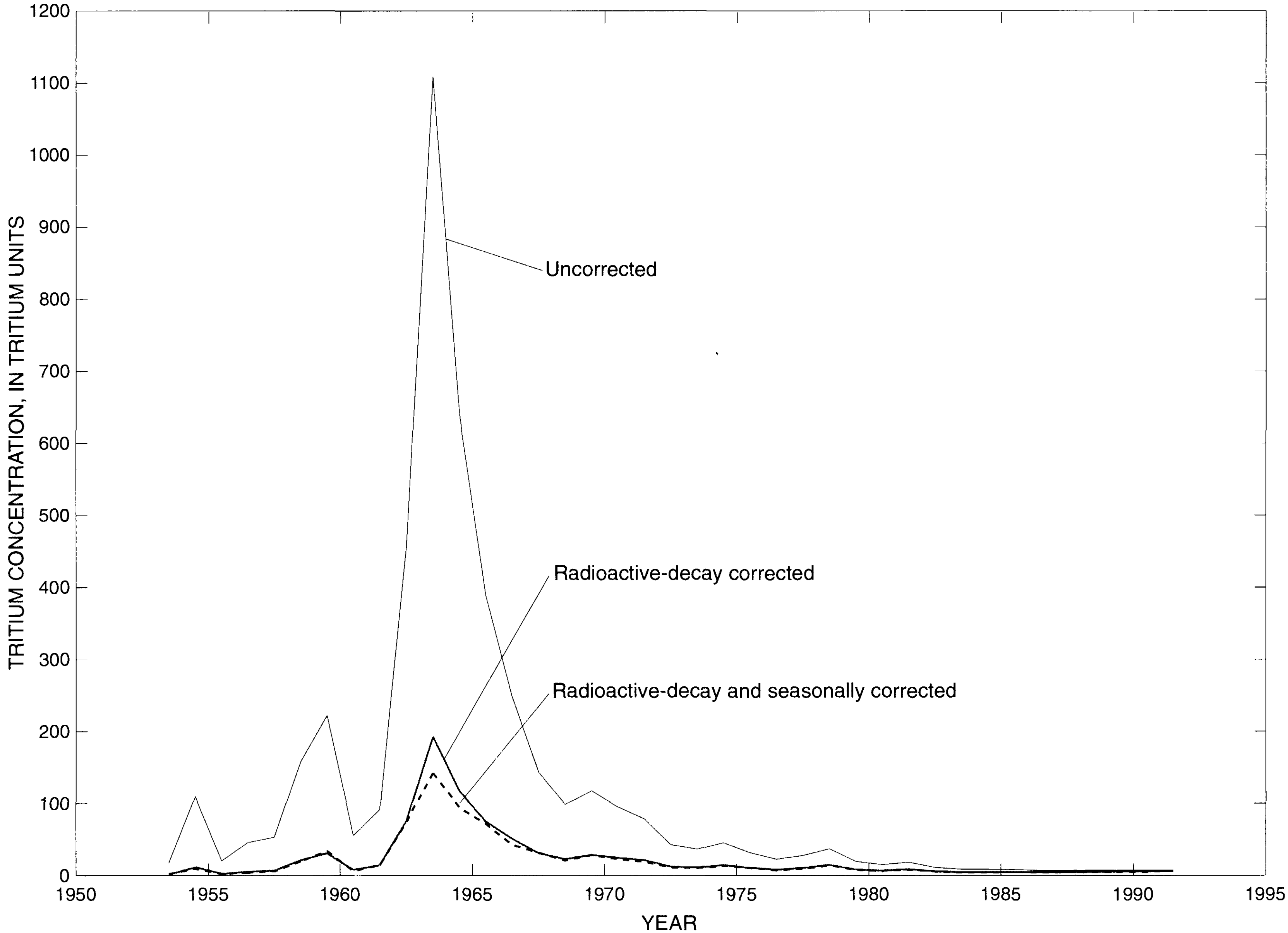


Figure 18.--Tritium concentrations in precipitation: (1) at time of precipitation (uncorrected), (2) corrected for radioactive decay to time of sampling, 1992 (radioactive-decay corrected), and (3) only during periods of soil saturation and corrected for radioactive decay (radioactive-decay and seasonally corrected).

time method has been used. For example, Knott and Olimpio (1986) estimated a recharge rate of as much as 26 inches per year to a shallow water table, only 20 feet below land surface, by locating a tritium peak in a vertical column of the saturated material below the water table near the ground-water divide.

Sampling

For this investigation, test holes were drilled and sampled for tritium at one location in each of the three catchments during the summer of 1992. These holes were located in the upper parts of the catchments near the topographic divides (fig. 3,4,and 5). Holes were drilled using 3 1/4-inch-ID hollow-stem augers, and samples of the till were taken at 5-foot depth intervals using an 18-inch-long, 3-inch outside-diameter (OD) split-spoon sampler. The sampler was driven into the till with a 400-pound, cathead-driven, sliding hammer dropped repeatedly from a height of 4 to 5 feet. Sample recovery of the till was generally good, but progress was extremely slow. Split-spoon samples typically required in excess of 300 blows per foot of penetration (table 8). Occasionally, the sample was poor or lost and for this reason a second, shallower hole was drilled a few feet away and sampled at those depths where recovery was unsatisfactory in the first hole. These test holes were finished and used as water-level observation holes as described in the section "Observation of Streamflow, Soil Water, and Shallow Ground Water."

Each sample was immediately transferred from the split spoon into a sealed glass canning jar and was sent to the U.S. Geological Survey Tritium Laboratory in Reston, Va., for analysis. The soil moisture was extracted from each sample by a vacuum-distillation process and then analyzed for tritium by direct gas counting without enrichment. Moisture content by weight of total sample was also determined. The dried samples were later sent to the U.S. Geological Survey's Cascades Volcano Observatory in Vancouver, Wash., for particle-size analysis. A summary of the laboratories' test results appear in tables 8 and 9.

Transit-Time Analysis

Test hole CLR1A (fig. 3) yielded a well-defined tritium peak of about 28 TU at a depth of about 14 feet (fig. 19). Test holes BVR1A (fig. 4) and VGN1A (fig. 5) yielded no tritium peaks, and tritium concentrations at all depths sampled (fig. 19) approximately equaled current meteoric water concentrations, indicating water ages considerably younger than 1963.

In order to calculate recharge at CLR1A using the transit-time method, the moisture contents had to be converted from a percent-by-weight basis (table 9) to volumetric moisture contents. Because of the disruptive nature of drive sampling, undisturbed sample volumes could not be determined. Instead, the following formula was used to determine the volumetric moisture content, θ_v, for each sample:

$$\theta_v = \theta_m \frac{\beta}{\rho_w} \quad , \tag{12}$$

where θ_m is percent moisture by dry weight, β is the bulk dry density of the till, and ρ_w is the density of water. Olmsted (1969) reported that β for till in the Puget Sound Lowland ranges from 120 to 150 pounds per cubic foot. Because the particle density of most mineral soils ranges between 162 and 168 pounds per cubic foot, the porosity of the till based on these reported bulk densities would then be from 9 to 27 percent. However, when the volumetric moisture contents are computed for bulk dry densities of more than about 135 pounds per cubic foot, θ_v generally exceeds the porosity, an impossible situation. Therefore, for the Clover catchment the bulk dry density of the till probably ranges between 120 and 130 pounds per cubic foot. Using these values, the total water content above the tritium peak is probably between 23.5 and 25.3 inches, and therefore, the average deep percolation between 1963 and 1992 computed by the transit time method is between 0.78 and 0.84 inches per year.

Tritium concentrations at BVR1A and VGN1A showed no peak, and the concentrations were comparable to post-bomb-peak meteoric water. Therefore, assuming piston flow, all of the water in the till above the water table at both of these locations is probably younger than 30 years. Assuming β of 125 pounds per cubic foot, the total water content above the water table at BVR1A and VGN1A probably is about 31 and 40 inches, respectively, and therefore, the recharge must be greater than about 1.0 and 1.3 inches per year, respectively.

If piston flow predominates in the unsaturated till, then the tritium concentration distribution with depth should closely resemble the decay-corrected tritium concentration distribution in precipitation with time. Figure 20 shows both of these distributions for the Clover catchment with the time and depth-axis scales adjusted so that (1) the precipitation-tritium peak aligns with the soil-moisture tritium peak and (2) the year of soil-moisture sample collection aligns with the soil surface (tritium from rain falling during that year should be near the surface).

Table 8.--*Lithology and particle-size distribution of soil samples from the tritium test holes in the three catchments*

Catchment name and test hole[1]	Depth interval, below land surface (feet)		Lithology	In percent by weight			Median particle size (millimetes)	Blow counts, per foot of penetration
				Gravel	Sand	Silt		
Clover CLR1A	3.0	4.5	till	10.6	54.6	34.8	0.140	160
	8.0	9.0	till	30.6	41.5	27.9	0.318	400
	13.0	14.0	till	25.0	44.0	31.0	0.213	400
	18.0	19.5	till	25.5	41.6	32.9	0.184	343
	23.0	24.0	till	20.0	58.7	21.3	0.246	320
	28.0	29.5	till	16.0	46.1	37.9	0.121	300
	38.0	38.5	till	33.1	44.8	22.1	0.468	600
	44.0	45.5	till	18.1	37.2	44.7	0.095	133
	48.0	49.5	till	25.1	43.2	31.7	0.200	167
	53.0	54.0	till	22.7	32.3	45.0	0.105	600
	58.0	58.9	till	26.4	43.4	30.2	0.220	480
	63.0	63.6	gravel	51.2	42.5	6.3	4.347	600
	68.0	69.0	gravel	64.9	32.6	2.5	6.949	300
	73.0	73.7	gravel	50.9	46.2	2.9	4.329	533
	Till averages:			23.0	44.3	32.7	0.210	355
Beaver BVR1A	4.0	5.0	till	36.2	45.7	18.1	0.854	[2]--
	8.5	10.0	till	27.3	59.8	12.9	0.454	200
	13.5	14.5	till	17.6	58.8	23.6	0.211	480
	18.5	20.0	till	31.2	54.4	14.4	0.441	200
	23.5	24.7	till	34.1	49.1	16.8	0.520	171
	28.5	29.5	sand	23.6	70.6	5.8	0.488	200
	30.0	35.0	sand	1.0	69.5	29.5	0.158	[2]--
	Till averages:			29.3	53.5	17.2	0.496	263
Vaughn VGN1A	3.0	3.5	till	38.2	49.0	12.8	0.863	[2]--
	8.0	9.2	till	54.5	39.5	6.0	5.657	214
	13.0	13.7	till	34.0	49.9	16.1	0.766	400
	18.0	19.0	till	33.2	52.5	14.3	0.820	410
	23.0	24.0	till	30.6	52.6	16.8	0.620	327
	28.0	29.2	till	39.9	46.8	13.3	1.870	200
	33.0	33.5	till	30.7	48.4	20.9	0.511	800
	48.0	52.0	sand	5.3	69.5	25.2	0.264	171
	58.0	62.0	sand	9.1	74.6	16.3	0.403	[2]--
	68.0	72.0	sand	13.7	74.4	11.9	0.540	[2]--
	Till averages:			37.3	48.4	14.3	1.587	391

[1]Locations shown on figures 3, 4, and 5.
[2]Augur flight samples.

Table 9.--*Tritium concentrations and moisture contents in soil water from the tritium test holes in the three catchments*

Catchment name and test hole identifer[1]	Depth interval, below land surface (feet)		In tritium units		Moisture content, in percent dry weight
			Tritium concentration	Accuracy	
Clover CLR1A	3.0	4.5	5.65	1.18	10.1
	8.0	9.0	12.24	2.58	6.5
	13.0	14.0	28.23	2.80	7.2
	18.0	19.0	18.29	1.80	6.3
	23.0	24.0	10.84	2.58	9.6
	28.0	29.5	17.30	2.98	9.8
	38.0	38.5	12.92	8.04	6.0
	44.0	45.5	11.61	1.99	12.0
	48.0	49.5	13.23	1.58	9.2
	53.0	54.0	8.26	2.58	11.0
	58.0	58.9	6.65	2.39	9.9
	63.0	63.6	6.77	2.80	8.8
	68.0	69.0	3.29	2.17	10.4
	73.0	73.7	4.78	2.17	11.1
Beaver BVR1A	4.0	5.0	6.15	2.39	14.5
	8.5	10.0	5.16	2.39	6.2
	13.5	14.5	5.65	2.58	8.2
	18.5	20.0	5.87	1.18	9.3
	23.5	24.7	5.16	1.40	7.1
	28.5	29.5	4.97	1.18	6.4
	30.0	35.0	5.56	1.40	10.6
Vaughn VGN1A	3.0	3.5	5.78	2.39	7.2
	8.0	9.2	0.00	5.96	2.9
	13.0	13.7	5.65	2.17	7.2
	18.0	19.0	2.98	2.39	6.3
	23.0	24.0	7.05	2.39	5.9
	33.0	33.5	4.78	2.17	6.4
	50.0	[2]--	4.97	1.40	16.1
	60.0	[2]--	6.86	1.40	15.9
	70.0	[2]--	7.14	1.40	14.2

[1]Locations shown on figures 3, 4, and 5.

[2]Augur flight samples taken at approximate depth indicated; sampled interval uncertain, but probably less than 1 foot.

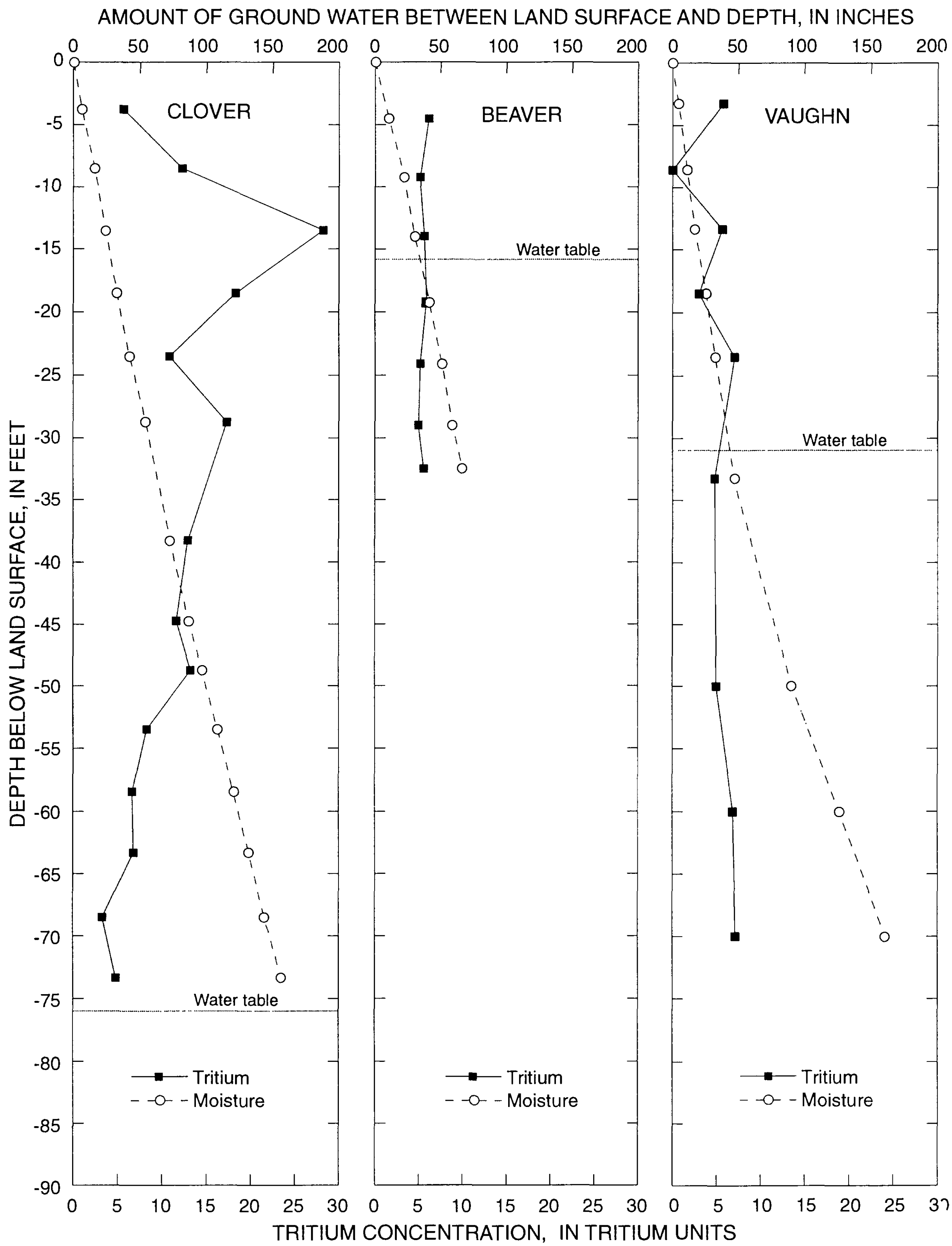


Figure 19.--Tritium concentrations in soil water and cumulative water contents with depth, in test observation wells drilled in the three catchments, summer of 1992.

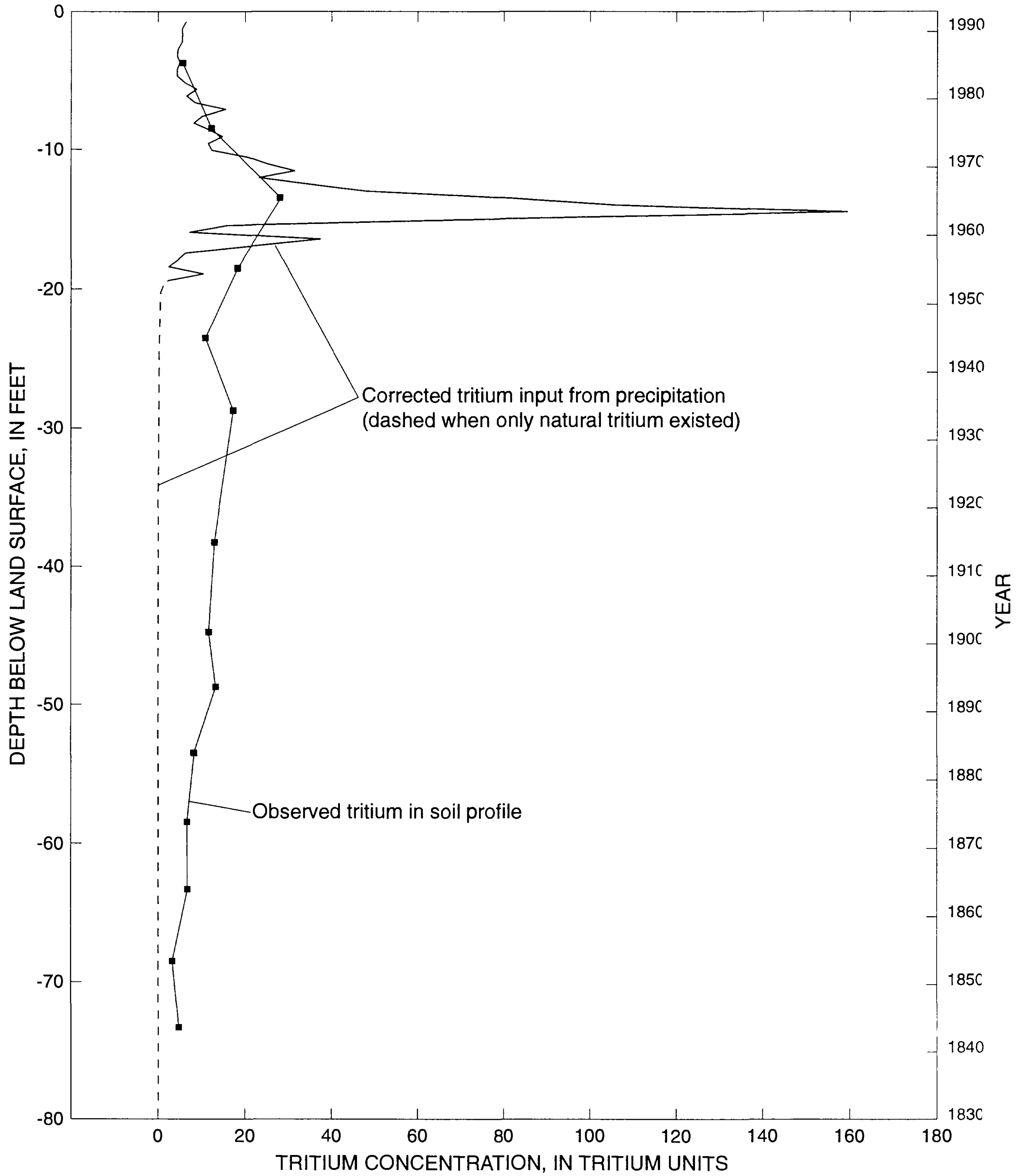


Figure 20.--Observed tritium concentrations in the till in the Clover catchment and radioactive-decay-corrected tritium in precipitation; time scale adjusted to align tritium peaks and to align time of sampling with land surface.

Tritium concentrations down to about 12 feet closely match those in precipitation back to about 1968. At greater depths, the soil-moisture tritium concentration curve becomes attenuated and broadened (that is, "spread out") relative to the decay-corrected tritium in precipitation. Under piston-flow conditions soil-water tritium concentrations below a depth of about 20 feet, which would correspond with the atmospheric tritium just prior to the onset of H-bomb testing, should be less than about 2 TU, diminishing to nearly zero at the bottom of the hole at 75 feet below land surface. However, soil-moisture tritium concentrations were considerably higher than decay-corrected precipitation tritium concentrations at all depths sampled below 20 feet, declining roughly linearly with depth to the bottom of the hole, where tritium concentrations were less than about 3 TU (fig. 20). Thus, the assumption of piston flow in unsaturated till at this location appears valid only at shallow depth.

Molecular diffusion alone cannot account for the elevated tritium levels found at such great depths below the peak (about 60 feet). For example, after some time, the characteristic diffusion length, which can be thought of as the spreading of an initial spike of tracer, is approximately equal to the square root of the product of the elapsed time since the spike and of the diffusion coefficient. The diffusion coefficient of water in a porous medium is less than that of just water, which is about one centimeter-squared per day. Using a time of 30 years (the time elapsed since the peak tritium concentration in precipitation) and the diffusion coefficient of water, calculation of the characteristic diffusion length yields only 3.4 feet, the maximum distance a tracer could move in a porous material as a result of molecular diffusion. The large spread in the tritium profile is probably the result of hydrodynamic dispersion, the nature of which in the till is not known. Flow along fractures seems unlikely because fractures have not been observed in road cuts or erosional exposures of the till in or near the project area. Also, root casts, wormholes, or animal burrows are not possible at these great depths.

In a chloride-tracer study to determine deep percolation in an unsaturated zone in eastern Washington, Prych (1995) noted that if there is diffusion of a tracer in unsaturated soil, there is no theoretical justification for using the peak concentration on the tracer profile in the soil to match against the peak in the depositional history of the tracer. In this case it is preferable to match the depth centroid of the mass of the tracer in the soil column with the time centroid of the deposited tracer. The depth centroid of a tracer in the soil column is the summation of the products of the tracer concentration and depth, from the surface down to the depth limit of the tracer, divided by the sum of these concentrations. The time centroid of the deposited tracer is similarly calculated, but using time instead of depth over the depositional history of the tracer. If the percolation velocity and diffusion coefficient are uniform with depth, then the depth centroid of the mass of the tritium moves at the same rate as the percolation velocity.

The computed tritium depth centroid for CLR1A occurred at a depth of 37 feet (considerably deeper than the tritium peak at 14 feet), and the time centroid of the tritium in precipitation occurred during mid-1966, 3 years after the peak. Assuming all of the water above the 37-foot depth equals all of the water that entered the subsurface since mid-1966, then the recharge rate is probably between 2.53 and 2.77 inches per year, assuming bulk till densities of 120 and 130 pounds per cubic foot, respectively.

This centroid transit-time method could not be used at BVR1A or at VGN1A because no information regarding the positions of the centroids of bomb-produced tritium in the subsurface could be determined from the tritium profiles.

Mass-Balance Analysis

In the tritium-tracer methods discussed above, the requirement of piston flow is not met, nor is it known if the percolation velocity and diffusion coefficient are constant with depth. However, the use of a tritium mass-balance method does not require that any of these conditions be met. In this method, the total amount of tritium down to some depth, all of which is known to have entered the subsurface after a known time, is compared against the total amount of tritium in precipitation since that time. The ratio of total soil-moisture tritium to the total tritium in precipitation is assumed to equal the ratio of recharge to precipitation (Marshall and Holmes, 1979, p. 172-173).

The tritium profile of CLR1A is very well suited to this type of analysis because it appears that nearly all of the anthropogenic tritium that entered the subsurface is contained within the depth explored. Linear extrapolation of the tritium concentration-depth curve beyond the 75-foot exploration depth indicates that there would be no anthropogenic tritium below a depth of about 85 feet. Summing all of the soil-moisture tritium down to this depth and dividing by the sum of all the monthly decay-corrected tritium in precipitation since 1952 gives a ratio of 0.0459. When this is multiplied by the total precipitation since 1952, the resulting average annual recharge rate is 1.83 inches per year, about twice the amount estimated by the peak transit-time method but less than that estimated by the centroid transit-time method.

The tritium sampled above the water table from BVR1A and VGN1A did not exceed 6 and 7 TU, respectively. Examination of the post-1963 annual average decay-corrected tritium concentrations in precipitation shows that the corrected tritium concentrations did not decline to 6 TU and 7 TU until 1983 and 1982, respectively (fig. 18). Assuming all of the water above the water table is younger than 1983 and 1982, the recharge rates for the Beaver and Vaughn catchments can thus be calculated by summing all of the soil-moisture tritium down to the water table and dividing by the sum of all the monthly decay-corrected tritium in precipitation since 1983 and 1982. The results are 4.09 and 6.66 inches per year, respectively. These two recharge rates are only rough estimates because all of the anthropogenic tritium was not accounted for. It was assumed that only water from precipitation after 1982-83 occurs in the till down to the water table and that no water younger than 1982-83 percolated below the water table (piston-type flow), when, in fact, there probably has been vertical mixing of older and younger water, as is indicated in the tritium profile for CLR1A. (See discussion in the "Transit-Time Analysis" section.)

Seasonal Corrections for the Mass-Balance Analysis

The above mass-balance analysis is rigorous only if (1) the tritium concentrations in precipitation are fairly constant throughout each year (year to year concentrations may vary, however) or (2) the fraction of precipitation that becomes recharge remains constant from month to month throughout the year. Neither of these conditions, however, can be assumed true in the Puget Sound Lowland. Between 1952 and 1987, monthly-average tritium concentrations in precipitation in the Pacific Northwest have varied seasonally, with higher concentrations occurring during mid-summer and lower concentrations occurring early- to mid-winter. For example, the ratio of the January to the June tritium concentration averages 0.46 for this period. Also, recharge is not constant throughout the year. Almost all of the precipitation that falls during the summer months evapotranspires, and, therefore, the higher tritium concentrations in summer precipitation do not contribute to the tritium below the root zone, resulting in the above tritium mass-balance analysis underestimating recharge.

In order to compensate for the seasonal variabilities of recharge and tritium concentrations in precipitation, the mass-balance analysis was performed for only those time periods when there were indications that recharge occurs. From the soil-saturation data (fig. 15) it is evident that, typically, the topsoil is subject to saturation during the months of about December through April, and, therefore, percolation of water into the till occurs mainly during these months. Additionally, during the month of November, soil moisture from precipitation accumulates, which subsequently percolates into the till during the winter months (fig. 16). During May through October, the soil-moisture contents are almost always below field capacity, precluding significant percolation of moisture into the till. The third curve on figure 18 shows average November-through-April, decay-corrected tritium concentrations in precipitation.

In the Clover catchment, the ratio of the total tritium in the till (projected down to 85 feet below land surface) to the November-through-April monthly decay-corrected tritium in precipitation since 1952 is 0.0727. Multiplying by the total precipitation during November through April since 1952 results in an average annual recharge of 2.10 inches per year at CLR1A. In the Beaver and Vaughn catchments (test holes BVR1A and VGN1A), the ratios of total tritium in the till above the water table to the November-through-April monthly decay-corrected tritium in precipitation since 1983 and 1982, respectively, are 0.0132 and 0.0207, resulting in average annual recharge rates of 4.49 and 7.21 inches per year, respectively. Again, these two estimates are approximate because piston-type flow was assumed.

Because of variations in seasonal precipitation, the months during which recharge occurs may vary from those assumed, resulting in some error. To test the magnitude of such error, recharge was also calculated using two equivalent length (six months) time periods that were shifted earlier and later by one month relative to the "normal" period. Longer and shorter recharge seasons were also tested by adding one month to and subtracting one month from the beginning and end of the normal period. The results, in inches per year, for the following recharge periods are these:

	Clover	Beaver	Vaughn
November through April	2.10	4.49	7.21
October through March	2.32	4.64	7.45
December through May	1.91	4.43	7.10
October through May	2.05	4.38	7.08
December through March	2.25	4.87	7.68

Thus, the maximum estimated error in this method due to precipitation variations is about 0.22, 0.38, and 0.47 inches per year for the Clover, Beaver, and Vaughn catchments, respectively.

In order to compensate for seasonal variations of tritium in precipitation in using the mass-balance analysis, Knott and Olimpio (1986) devised a "tritium input function" to weight the annual tritium concentrations to approximate more closely the average tritium concentration for the part of the annual precipitation that percolates beyond the root zone. The weighted annual tritium concentration for each year was evaluated by weighting the observed monthly tritium concentrations during the year by the fractions of the annual recharge (computed by a water-budget method) that occur during the respective months and then summing these weighted monthly tritium concentrations over each year. The weighted annual tritium concentrations then are used instead of the observed average annual tritium concentrations in summing the total tritium in precipitation in the above mass-balance analysis. A problem with this method is that the computed recharge is partly a function of monthly estimates of recharge derived from the water-budget method.

A method similar to the mass-balance analysis of Knott and Olimpio (1986) was tested in order to compare the results with the other mass-balance analyses. It relies, in part, on the independently determined monthly values of recharge from the water-budget method, described earlier, and, therefore, is herein referred to as the "hybrid" mass-balance method.

The total amount of tritium that percolates beyond the root zone into the till, T_p, between times t_1 and t_2, can be expressed as

$$T_p = \int_{t_1}^{t_2} R C_T \, dt \quad , \tag{13}$$

where R is the instantaneous rate of recharge (or percolation beyond the root zone) and C_T is the tritium concentration of the water at the bottom of the root zone. Because the only measures of C_T are the observed average monthly tritium concentrations in precipitation, C_{T_m}, equation 13 is approximated by

$$T_p = \sum_{m=1}^{M} R_m C_{T_m} \quad , \tag{14}$$

where R_m is the recharge for each month and M is the total number of months in the time period. T_p in the Clover catchment for the 1953 through 1992 period is known from the tritium profile in the till; but the many values of R_m cannot be evaluated directly with equation 14. However, assuming that each R_m can be approximated with a constant, average, calender-month-dependent recharge, equation 14 for the Clover catchment can be expressed as

$$T_p = \overline{R_a} \sum_{y=1953}^{1993} \left(\sum_{m=1}^{12} f_m C_{T_{y_m}} \right) \quad , \tag{15}$$

where $\overline{R_a}$ is the average annual recharge, f_m is the monthly fraction of the average annual recharge, and y is the year index from 1953 to 1992. Using values for f_m from the DPM results for the 1991-93 water years ("Water Budget" section, fig. 17, and table A16) and solving for $\overline{R_a}$ yields an average annual recharge of 1.67 inches per year for the Clover catchment.

In the Beaver and Vaughn catchments, average annual recharge rates of 5.28 and 7.87 inches per year, respectively, are computed by this method. As in the other mass-balance methods, piston-type flow was assumed, and, consequently, these two estimates are approximate.

The largest source of error in this hybrid method probably is due to the assumption that, for any given month, the tritium concentration in water at the bottom of the root zone is the same as the average tritium concentration in precipitation for that month. This is not strictly correct for at least two reasons. First, water entering the top of the root zone during a month will displace or mix with the antecedent soil moisture, producing soil water at the bottom of the root zone that is of a different tritium concentration from that of the average in precipitation for the month. This effect is discussed by Foster and Smith-Carrington (1980), who proposed a simple soil-water tritium mixing model. Second, during periods of high soil saturation, much of the precipitation may run off directly to a stream. The recharge for such a month, however, would be large and the tritium concentration in precipitation for that month would be heavily weighted by equation 15, when, in fact, relatively little of this tritium percolates to the bottom of the soil.

Both of the above sources of error are, in effect, related to the fact that antecedent soil moisture contents and tritium concentrations are ignored. To roughly test the magnitude of such errors, the monthly fractions of recharge were shifted backwards in time by one month and by two months relative to the monthly tritium concentrations in precipitation in order to account for some delay of tritium in precipitation reaching the bottom of the root zone. These calculated time-shifted recharge estimates, in inches per year, compare as follows:

	Clover	Beaver	Vaughn
No time shift	1.67	5.28	7.87
One month shift	2.00	5.03	8.40
Two month shift	2.27	4.56	8.17

On the basis of the various tritium analyses discussed above, the average annual recharge in the Clover catchment is between 0.80 and 2.65 inches and is similar to the water-balance estimate of 1.68 inches for the pasture area. (The test hole for the tritium sampling was located in the pasture area.) For the tritium mass-balance methods only, the recharge estimates fall in a narrower range, between 1.67 and 2.10 inches per year. For the Beaver and Vaughn catchments, rough tritium mass-balance estimates of recharge of from 4.09 to 5.28 and from 6.66 to 7.87 inches per year, respectively, also are similar to the water-balance estimates of 5.79 and 6.79 inches per year, respectively. Table 10 summarizes the recharge estimates for both the water-balance and tritium-tracer methods.

Relation Between Recharge and the Textural Composition of the Till

It appears that the textural composition of the till (table 8) and the amount of recharge into the till are related. The average percentages of silt and finer particles (fines) in the Beaver and Vaughn catchments are roughly comparable at 17 and 14 percent, respectively; but in the Clover catchment, the fines averaged 33 percent (table 8). Both the tritium-mass-balance and the water-budget estimates of recharge show that recharge in the Beaver and Vaughn catchments is about two to five times as great as in the Clover catchment.

The relation of the amounts of fines between catchments is also consistent through the full depth of the till. The till sample with the lowest percentage of fines from the Clover catchment has a greater percentage of fines than any of the till samples from either the Beaver or Vaughn catchments. The medians of the sample median grain sizes for the Beaver and the Vaughn catchments are 0.45 and 0.82 millimeters respectively, but for the Clover catchment it is only 0.20 millimeters. This suggests that, if a sufficient number of till-mantled catchments could be analyzed, as above, a quantitative relation may be found between recharge, till particle-size distribution, and precipitation (or throughfall).

TRACING STREAMFLOW GENERATION USING THE STABLE ISOTOPE OF OXYGEN

The field sites and types of data collected during this investigation provided an opportunity to examine more closely streamflow-generation processes in forested till-mantled areas in the Puget Sound Lowland. Although the soil-saturation, soil-moisture, and streamflow data provided good insight, the flow paths and timing of water from precipitation as it moves toward streams and ground water are still uncertain. More specifically, how much of the precipitation from a storm flows directly or quickly to a stream, and how much mixes with or displaces antecedent soil water before finally reaching a stream? These processes are important for understanding (1)streamflow responses to rainfall, (2)magnitudes of peak discharge, (3) fates of contaminants on land surfaces (pesticides, fertilizers, chemical spills, etc.), and (4) fates of contaminants originating within the soil (for example, septic effluent).

Many theories of the streamflow generation from hillslopes exist, and despite many intense field investigations, the question of how and when water arrives at the stream channel after it hits the land surface is still controversial (Pearce and others, 1986). In the past, soil water generally has not been considered a major contributor to stormwater runoff. However, recent studies show that soil water can contribute significant quantities of water during a storm (Swistock and others, 1989; Kennedy and others, 1986). Turner and MacPherson (1990) discuss the importance of a perched, ephemeral aquifer at depths of 2 to 3 meters in the generation of streamflow in many catchments in Western Australia.

Table 10.--*Summary of the deep percolation estimates for the three till-mantled catchments*

[--, indicates not applicable for particular combination of method, time period, or vegetation]

			Deep percolation estimated from indicated method					
				Tritium tracer method[1]				
Catchment	Vegetation	Water years	Water-budget method	Peak transit time	Centroid transit time	Simple mass balance	Seasonal mass balance	Hybrid mass balance
			Values in inches per year					
Clover	Pasture	1991-93	1.68	--	--	--	--	--
		1952-92	--	0.80	2.65	1.83	2.10	1.67
	Mixed forest	1991-93	1.08	--	--	--	--	--
Beaver	Mixed forest	1992-93	5.79	--	--	--	--	--
		1983-92	--	>1.0	--	4.09	4.49	5.28
Vaughn	Douglas fir	1992-93	6.79	--	--	--	--	--
		1982-92	--	>1.3	--	6.66	7.21	7.87

[1]Evaluated using bulk density of till of 125 pounds per cubic foot.

The perceived role of soil water in storm runoff varies. Dunne and Black (1970) reported that most of the storm runoff from a steep till-covered hill-slope in Vermont is produced by overland flow in small saturated areas near stream channels (saturated overland flow). Moseley (1979) reports that rapid transmission of soil water by way of macropore flow dominated the storm hydrograph in steep-forested catchments in New Zealand. Sklash and others (1986), however, working on the same catchments in New Zealand, determined that less than 25 percent of storm discharge was from the precipitation that generated the discharge. Kennedy and others (1986) concluded that displacement of pre-storm soil water is the predominant runoff mechanism during storms in the Mattole River Basin, California. Different processes probably predominate for different combinations of topography, soils, subsoils, ground-water levels, and climate.

Naturally occurring stable isotopes of oxygen and hydrogen, namely oxygen-18 (^{18}O) and deuterium (^{2}H), provide a means of tracing the short-term movement of precipitation water. The concentrations of these two isotopes often vary sufficiently from one storm to another such that "isotopic signatures" identify "new water" (water brought in by storms) and "old water" (water present in the watershed prior to the storm). Swistock and others (1989), Kennedy and others (1986), and Sklash and others (1986) used variations of these isotopes in precipitation, streamflow, soil water, and shallow ground water in mixing models to separate the streamflow hydrograph quantitatively into its different flow components.

As part of this investigation, a limited experiment was conducted in the Vaughn catchment to better identify the streamflow generation process using ^{18}O for tracing precipitation water as it travels toward the stream. Isotopic responses of streamflow and soil water to three stream-flow-producing storms were sampled and analyzed. All sample collection was performed manually and had to be coordinated with other data collection tasks, and as a result, sampling times and sample accumulation periods were seldom ideal. Thus, only qualitative interpretations were attempted from the limited data.

Sampling

A network of sites was selected in the Vaughn catchment to sample the isotopic composition of water from precipitation, streamflow, and the soil before, during, and after the storms. Four soil-water samplers were installed at roughly equal distances from about 20 feet upslope of the stream to a point approximately 200 feet upslope along the transect of the LYBT, LYMD, and LYTP soil-water monitoring sites (fig. 5). The sampling locations are designated L1, the lowest location, through L4, the highest location. The entire area was covered by a dense fir forest containing thick salal underbrush. Each soil-water lysimeter consisted of a 4-foot-long, 1 3/4-inch inside diameter polyvinyl-chloride plastic pipe with a 2-inch-long porous ceramic tip at the lower end. They were buried vertically such that the ceramic cup was just above the soil-till contact, at about 3 feet below ground. A suction of approximately 0.5 to 0.8 atmosphere was applied with a vacuum pump and maintained for a period of from about 1 to 24 hours, during which time soil moisture was slowly drawn by the vacuum through the porous ceramic cup into the sampler.

Two precipitation samplers were installed at the precipitation gage set up for this catchment. Each sampler consisted of a simple metal stand that funneled rain water from an 8-inch-diameter opening into a 4-liter plastic jug. One sampler was used to collect samples at intervals during the storm, and the other was used to collect a composite sample for the entire storm. Two supplemental precipitation samples were taken during January 20-24, 1993, from a storage-type precipitation gage at the throughfall data collection site previously described.

Grab samples of stream water were collected at irregular intervals during and after the selected storms at the streamflow gage location (USGS station number 12073600) located at the mouth of the catchment (fig. 5).

All samples were stored in 2-ounce glass bottles with polyseal caps. Selected samples were analyzed for ^{18}O (and a few for ^{2}H) at the USGS Central Laboratory. Isotopic concentrations of ^{18}O and ^{2}H are reported relative to those in standard mean ocean water (SMOW), specifically, if R_z is the ratio of the heavy (or rare) isotope to the light (abundant) isotope in the sample and R_s is the ratio in SMOW, then the concentration, in permil (tenths of a percent), is

$$1,000\ \frac{(R_z - R_s)}{R_s} \qquad (16)$$

Precision is reported by the lab to be ±0.15 permil.

Water samples were collected for three winter storms, each producing a different maximum discharge and total amount of runoff. Soil moisture before each storm was near field capacity. Each of the three storms consisted of about two days of rain preceded by at least 3 days of only very minor amounts of rain and at least 10 days of no streamflow. Stream discharge reached a maximum about 1 day after the middle of each storm and receded to zero, or near zero, 4 to 10 days after the peak flow (table 11). Initially, a few samples from storm 1 were also analyzed for ^{2}H, but, subsequently, only ^{18}O was used in the analysis. The ^{2}H and ^{18}O concentrations, when plotted together with the global meteoric line (Mazor, 1991), indicate no unusual sources of water or unusual isotopic fractionation processes in the catchment (fig. 21).

Table 11.--*Precipitation, peak discharge, and total runoff for the three storms sampled for stable isotopes in the Vaughn catchment*

Storm number	Total storm rainfall: Quantity (inches)	Total storm rainfall: Period	Peak discharge: Quantity (cubic feet per second)	Peak discharge: Date	Total storm runoff quantity[1] (inches)	Total storm runoff quantity[1] (in percent of rainfall)
1	1.48	April 16-17, 1992	0.008	April 17	0.0059	0.4
2	3.26	January 24-25, 1993	6.2	January 25	1.74	53.4
3	2.39	March 22-23, 1992	0.57	March 23-24	0.20	8.4

[1]Measured as the total runoff for 10 days beginning the first day of peak rainfall.

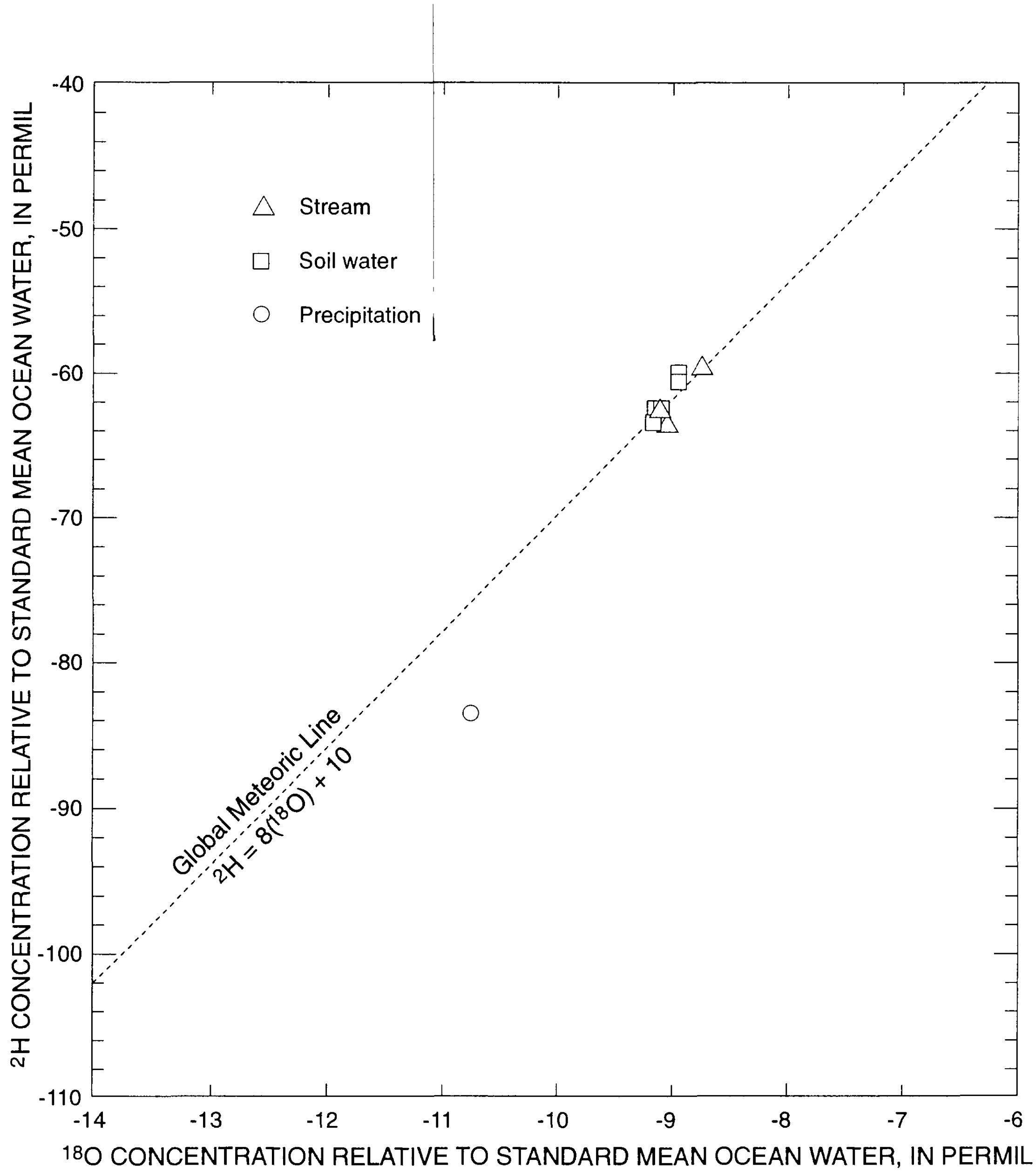


Figure 21.--Concentration relations of deuterium and oxygen-18 in streamflow, soil water and precipitation during storm 1 in the Vaughn catchment, compared with the global meteoric relation.

Interpretations of Observed Isotopic Compositions

The locations, times, and isotope concentrations in the samples collected and also the times that sample accumulation began and ended for the precipitation and soil-moisture samples are shown in table 12. Figures 22-24 show, for storms 1-3, respectively (in chronological order), the quantities of precipitation, streamflow, and soil saturation and the ^{18}O concentrations in precipitation, streamflow, and soil water for periods of time extending from about 20 to 29 days prior to the storms to the ends of the runoff periods produced by the storms. Table 11 also shows total quantities of precipitation and streamflow for each storm. Storm 1 produced only minor streamflow of short duration. Storm 2, the largest of the three sampled storms and the largest storm of the water-year, was sampled the most intensively. Two precipitation samples from storm 3 showed that it had the greatest isotopic variability of the three storms, making storm 3 the most complicated and uncertain to analyze; therefore, additional samples from storm 3 were not isotopically analyzed.

The ^{18}O concentrations (figs. 22-24) show some consistent patterns in the runoff process. The ^{18}O concentration in precipitation (new water) sampled during storms 2 and 3 was more variable than and generally different from the ^{18}O concentration in the streamflow, which varied little during the storms (only one precipitation sample was available from storm 1). The streamflow ^{18}O variations between storms were much greater than during storms. The maximum observed streamflow ^{18}O differences during storms were 0.35, 0.28, and 0.07 permil for storms 1, 2, and 3, respectively, whereas the maximum difference between the average ^{18}O concentrations for each storm was 2.02 permil. The observed ^{18}O concentration in precipitation varied by 2.34 permil during storm 2 and by 2.64 permil during storm 3. Because of the brevity of storm 1, only one precipitation sample, which was a composite of the entire storm, was collected. The ^{18}O variation of the soil water (old water) during storms was intermediate between that of the precipitation and the streamflow, with values approaching the value of the stream as the storm progressed. The maximum observed soil-water ^{18}O differences were 0.20, 3.83, and 0.75 during storms 1, 2, and 3, respectively.

The ^{18}O concentrations indicate no direct or quick isotopic response between precipitation and resulting streamflow; therefore, precipitation water must reside in the soil for periods of time exceeding the period of streamflow resulting from a storm. Significant quantities of overland flow or macropore flow probably did not occur during the sampled storms.

The ^{18}O concentration of streamflow is more closely related to the soil moisture than to precipitation. During the runoff period produced by storm 1, soil water and streamflow ^{18}O concentrations were nearly identical (fig. 22). During the runoff period of storm 2, the ^{18}O concentration of the early streamflow was about one permil less than in the average for the soil moisture samples, and the difference gradually decreased to a negligible amount during the streamflow-recession period (fig. 23). The reason for the early differences is not clear. A surface runoff component to the streamflow cannot account for it because all precipitation samples from storm 2 when runoff was occurring (January 24 to February 4) had higher ^{18}O concentrations than the soil moisture and streamflow (fig. 23). A possibility is that because the soil water sampled was from the bottom of the soil zone near the soil-till interface, it was not representative of the section of the soil column from which water was draining to the stream. During January 19-21, 5 days prior to the peak flows of storm 2, the 2.34 inches of rain that fell was considerably depleted in ^{18}O relative to the rain that fell during storm 2 (fig. 23). A composite sample of the January 19-21 rain, plus 0.89 inches from one month earlier, had a ^{18}O value of -15.45 permil, compared with values of from -10.67 to -8.28 permil for the soil water sampled shortly before, during, and shortly after storm 2. A mixture of the January 19-21 (and earlier) precipitation (the bulk of which may have been at shallower soil depths just prior to storm 2) and the pre-storm soil water near the bottom of the soil column could account for the isotopic composition of the stream. During periods of high soil-water saturation during and shortly after the storm, some shallower soil water would also flow laterally to the stream, thereby mixing with the deeper soil water discharging to the stream, and thus producing the observed ^{18}O concentration in the stream. As the shallower, more isotopically-depleted soil moisture moved downward through the soil during the streamflow recession period, the ^{18}O concentration of the samples taken from the deep soil more closely approached that of the streamflow.

Table 12.--*Isotope concentrations in stream, soil-water, precipitation, and ground water for the three sampled storms in the Vaughn catchment*

[^{18}O, oxygen-18; ^{2}H, deuterium]

Location[1]	Type of sample	Sample accumulation[2] Date	Sample accumulation[2] (Time)	Sample collection Date	Sample collection (Time)	Isotope concentration, in permil ^{18}O	Isotope concentration, in permil ^{2}H
			Storm 1				
Streamgage	Stream			04-17-92	(0830)	-9.05	-63.5
				04-17-92	(1842)	-9.10	-62.5
				04-20-92	(1705)	-8.75	-59.5
L1	Soil water	04-17-92	(0900)	04-17-92	(1826)	-8.95	-60.5
		04-17-92	(1830)	04-20-92	(1650)	-8.95	-60.0
L2		03-19-92	(1100)	03-20-92	(0845)	-9.10	-62.5
		04-17-92	(0900)	04-17-92	(1810)	-9.15	-62.5
		04-17-92	(1815)	04-20-92	(1636)	-9.15	-63.0
Precipitation gage	Storm precipitation	03-19-92	(0930)	04-17-92	(1910)	-10.75	-83.5
			Storm 2				
Streamgage	Stream			01-25-93	(0954)	-10.96	
				01-25-93	(1605)	-10.96	
				01-26-93	(1128)	-11.01	
				01-27-93	(1050)	-11.05	
				01-28-93	(1054)	-11.05	
				01-29-93	(1450)	-11.12	
				02-02-93	(1100)	-10.88	
				02-05-93	(1050)	-10.84	
L1	Soil water	01-07-93	(1100)	01-19-93	(1505)	-8.18	
		01-19-93	(1510)	01-25-93	(1132)	-8.28	
		01-25-93	(1135)	01-26-93	(1040)	-9.97	
		01-27-93	(1100)	01-28-93	(1129)	-10.15	
		01-28-93	(1135)	02-02-93	(1150)	-10.42	
L2		01-19-93	(1510)	01-25-93	(1123)	-9.43	
		01-27-93	(1105)	01-28-93	(1120)	-10.67	
		01-28-93	(1125)	02-02-93	(1142)	-11.91	
L3		01-07-93	(1110)	01-19-93	(1515)	-8.63	
L4		01-07-93	(1115)	01-19-93	(1520)	-8.08	
		01-19-93	(1520)	01-25-93	(1110)	-8.82	
		01-25-93	(1115)	01-26-93	(1017)	-9.86	
		01-27-93	(1110)	01-28-93	(1105)	-10.31	
		01-28-93	(1110)	02-02-93	(1125)	-10.37	

Table 12.--*Isotope concentrations in stream, soil-water, precipitation, and ground water for the three sampled storms in the Vaughn catchment--Continued*

Location[1]	Type of sample	Sample accumulation[2] Date	(Time)	Sample collection Date	(Time)	Isotope concentration, in permil ^{18}O	^{2}H
			Storm 2--Continued				
Precipitation gage	Pre-storm precipitation	12-21-92	(0903)	01-21-93	(1605)	-15.45	
		01-20-93	(1300)	01-21-93	(1000)	-12.07	
	Storm precipitation	01-21-93	(1000)	01-24-93	(1130)	-9.75	
		01-21-93	(1605)	01-25-93	(1015)	-7.41	
		01-25-93	(1015)	01-26-93	(0918)	-9.51	
		01-21-93	(1600)	02-02-93	(0945)	-7.79	
VGN1A	Ground water			01-25-93	(1400)	-9.50	
				01-28-93	(1448)	-9.62	
				02-05-93	(1259)	-9.52	
VGN2A				01-28-93	(1342)	-9.82	
			Storm 3				
Streamgage	Stream			03-23-93	(1400)	-10.60	
				03-25-93	(0722)	-10.64	
				03-28-93	(1313)	-10.67	
L2	Soil water	02-02-93	(1145)	03-19-93	(1129)	-12.74	
		03-19-93	(1130)	03-24-93	(1246)	-11.99	
Precipitation gage	Storm precipitation	03-19-93	(0900)	03-22-93	(1137)	-9.49	
		03-19-93	(0900)	03-24-93	(0950)	-12.13	

[1]Locations of L1 through L9 are as follows on figure 5: L1 = between LYBT and LYMD; L2 = at LYMD; L3 = between LYMD and LYTP; L4 = at LYTP. Locations of VGN1A and VGN2A are shown on figure 4; gage locations shown on figure 5 are the following: stream = U.S. Geological Survey 12073600; precipitation = U.S. Geological Survey 472128122451200.

[2]Sample accumulation for the soil-water samples is the time when suction is first applied to the suction lysimeters; for the precipitation samples, it is the time when the collection jug was emptied to begin collection of any subsequent precipitation.

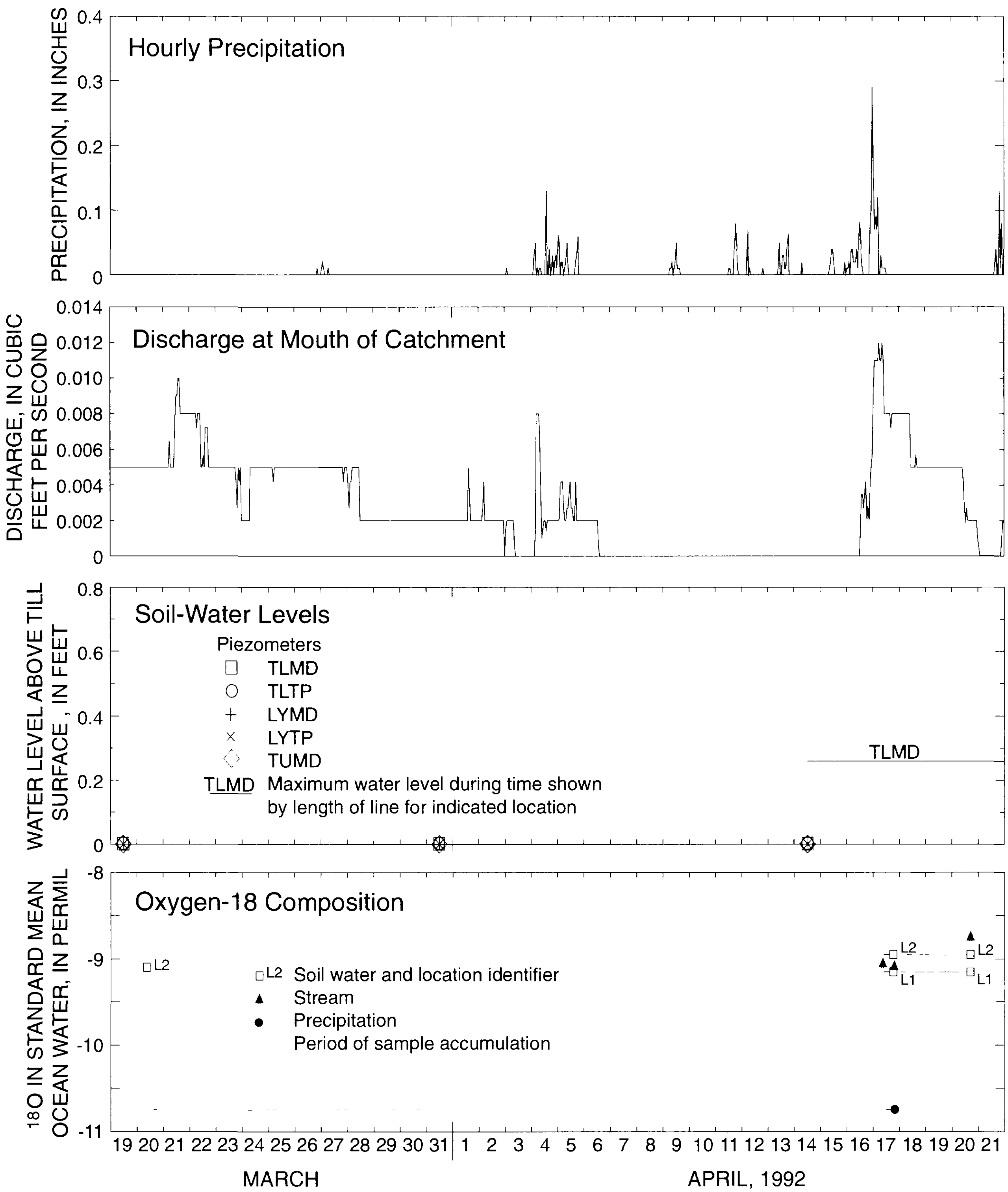


Figure 22.--Precipitation, stream discharge, soil-water levels and oxygen-18 compositions of precipitation, streamflow, and soil water in the Vaughn catchment resulting from storm 1. Sampling locations shown on figure 4. Maximum water level data for TLMD (shown to April 21) collected on April 24.

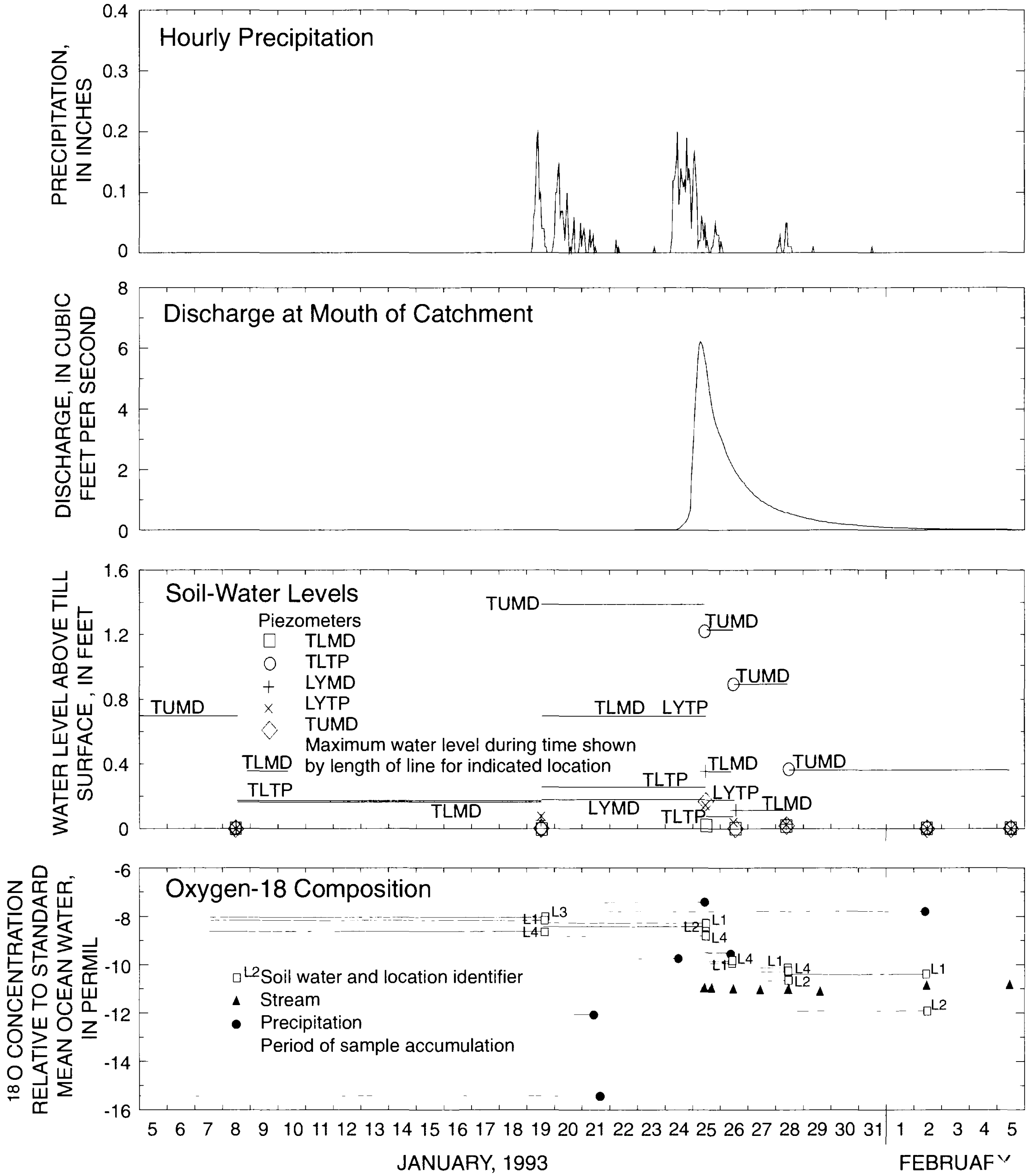


Figure 23.--Precipitation, stream discharge, soil-water levels and oxygen-18 compositions of precipitation, streamflow, and soil water in the Vaughn catchment resulting from storm 2. Sampling locations shown on figure 4.

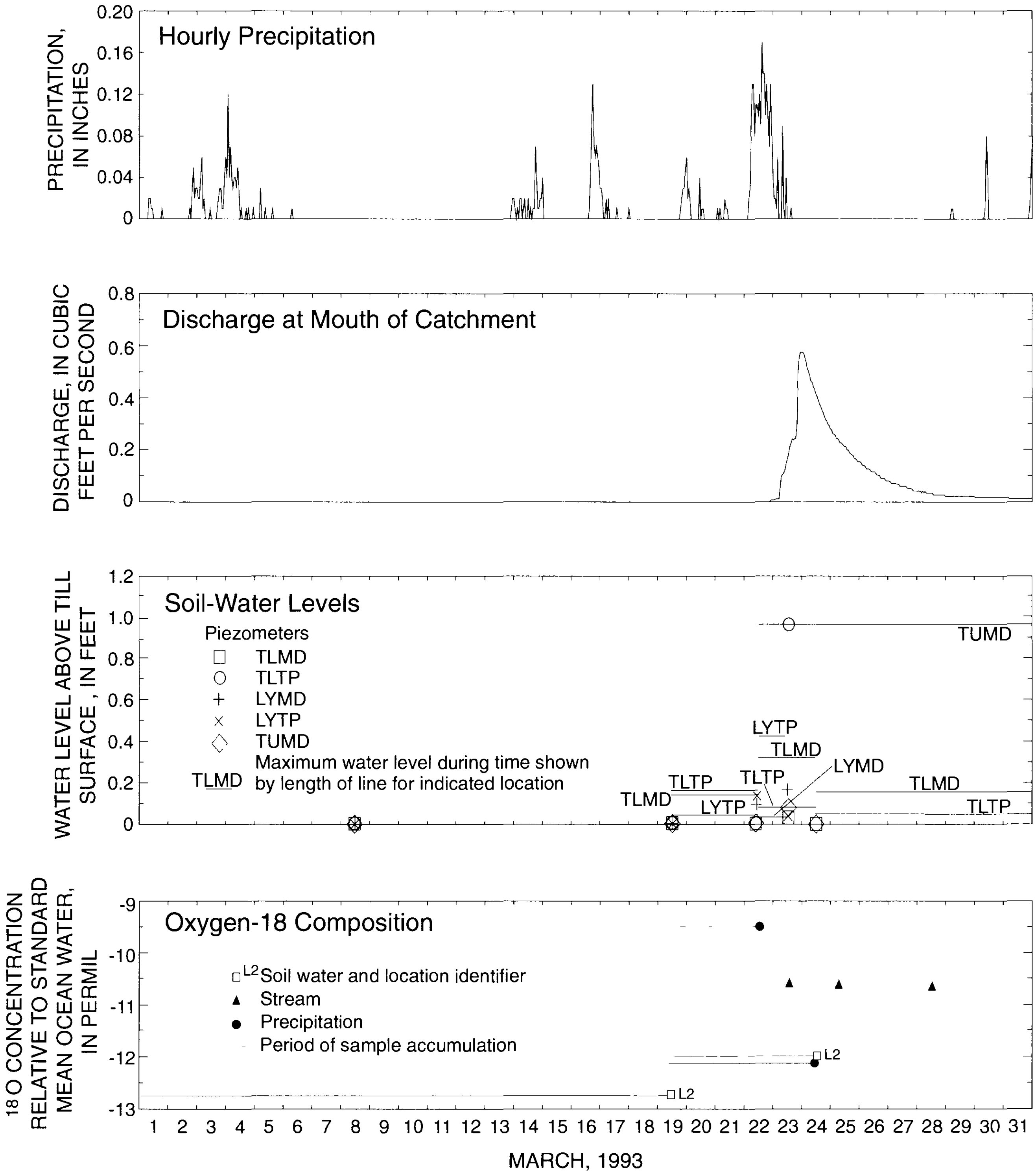


Figure 24.--Precipitation, stream discharge, soil-water levels and oxygen-18 compositions of precipitation, streamflow, and soil water in the Vaughn catchment resulting from storm 3. Sampling locations shown on figure 4. Maximum water level data for TUMD, TLMD, and TLTP (shown to March 31) collected on April 5.

The ^{18}O concentration of the streamflow produced by storm 3 is less closely associated with that of the soil moisture than that produced by either storm 1 or storm 2. The data are insufficient to identify a probable cause, but the mechanism presented above for the early streamflow/soil-moisture ^{18}O differences for storm 2 is also plausible for storm 3, inasmuch as the stream ^{18}O concentration resulting from storm 3 is also intermediate between that of the sampled soil water and that of precipitation occurring prior to storm 3 (fig. 24).

Runoff generally would not begin until one or more soil piezometers indicated that soil saturation had occurred (figs. 22-24). Of the three storms sampled, storm 2 had the highest soil-water levels, indicating the largest expanse of saturated soil conditions and the largest ratio of runoff to precipitation, 53.4 percent. Soil saturation was the least during storm 1, which also had the smallest ratio of runoff to precipitation (0.4 percent). The runoff during storm 3 was 8.4 percent of precipitation.

From an analysis of the isotopic compositions of precipitation, soil water, and streamflow for two storms, several conclusions can be made about direct-runoff generation in forested, till-mantled areas of Puget Sound:

(1) Overland flow was negligible even during the heaviest storm of the data collection period.

(2) Almost all of storm runoff is derived from pre-storm soil water displaced by storm precipitation. This indicates that flow paths of water from precipitation start with the vertical migration of water into the soil, which is later displaced by subsequent storm precipitation to temporarily saturated soil layers where it moves laterally and relatively rapidly toward streams.

(3) For periods at least as long as the storm-runoff duration, the vertical and lateral movement of soil moisture and varying lateral flow-path lengths to streams combine to produce runoff of a relatively constant composition that is equivalent to well-mixed pre-storm soil water.

DYE TRACER EXPERIMENT

A dye tracer experiment was attempted during the winter-spring period of 1992 in order to visually observe the movement of precipitation into and within the soil and the directions and relative quantities of flow at the soil-till interface. A food coloring dye, FD&C blue No. 1, was applied to the surface of the ground on January 28, 1992, along a strip parallel to the strike of the hill slope at soil-water monitoring site LYTP in the Vaughn catchment (fig. 5). One and one-half pounds of dye, supplied as a powder, was mixed with 12 gallons of water and applied, using a sprinkler watering can, to a strip 2 feet wide and 40 feet long.

Observation trenches were periodically excavated by hand, down to the till, across the dye strip so that the dye distribution in the soil could be observed and photographed. Excavations were made January 30, February 4, February 20, and March 19 of 1992. On February 4, a clearly visible dye plume extended from 0.5 to 2.3 feet below land surface, but had not yet reached the till surface at 3.3 feet. By February 20, the top of the plume dropped slightly to 0.8 feet below the surface, but the bottom of the plume was unchanged. By March 19, the dye distribution in the soil profile did not perceptibly change, and it was thought that this was due to onset of warmer, drier weather resulting in the evaporation of most precipitation and thus limiting significant additions of water to the soil. Therefore, no further excavations were made until after the onset of wet weather in the fall of 1993.

Additional excavations were made November 13 and February 26 of 1993. No appreciable dye movement had occurred by either of these dates, indicating that the soil particles had effectively sorbed all of the dye. Timing of the investigation did not allow for a second experiment using a different dye that would penetrate further into the soil. The distribution of the dye in all excavations showed only vertical, relatively uniform movement of soil moisture with no significant preferential flow. The only conclusion that could, therefore, be made is that when the soil was near field capacity, there was no significant horizontal or preferential flow in the upper 2 feet of the forest soil. This at least supports the hypothesis presented for explaining some of the observed ^{18}O concentrations in streamflow resulting from the storms discussed in the previous section.

SUMMARY AND CONCLUSIONS

Water budgets using a daily soil-moisture budgeting model were calculated for three small catchments (Clover, Beaver, and Vaughn catchments) in glacial till mantled terrains in the southern part of Puget Sound Lowland in the State of Washington for the purpose of quantifying direct recharge from precipitation through glacial till. Precipitation, throughfall under a forest canopy, streamflow, soil moisture, soil-water levels, shallow water-table levels, and incoming solar radiation were monitored for a period of 3 water years for the Clover catchment and 2 water years for the Beaver and Vaughn catchments. Model calculations of evapotranspiration were calibrated using the soil-moisture and throughfall data. Recharge was calculated by the model after till infiltration capacities and soil-moisture- limited transpiration rates were adjusted such that the differences were minimized between (1) observed and calculated free soil-water levels, (2) observed and calculated soil moisture below field capacity, and (3) observed daily stream discharges and daily soil water available for direct runoff.

Recharge was also independently estimated at one location in each catchment by determining and accounting for the distribution of H-bomb-produced tritium in the unsaturated zone. Results from a tritium concentration transit-time analysis and a mass-balance analysis were compared.

By use of the water-budget-method, average recharge to the water-table aquifer for the Clover, Beaver, and Vaughn catchments was estimated at 1.46, 5.44, and 6.79 inches per year (4.0, 13.9, and 16.7 percent of precipitation) for the water years 1991-93, 1992-93, and 1992-93, respectively (table 10). By use of the tritium mass-balance method, the average annual recharge estimated for a pasture area in the Clover catchment was between 1.67 and 2.10 inches for the 1952-92 period, which is similar to the water-budget estimate of 1.68 inches for the pasture area. (The water-budget estimate for the forested portion of the Clover catchment was 1.08 inches per year.) For the Beaver and Vaughn catchments, most of the H-bomb-produced tritium had completely traversed the unsaturated zone, and thus only rough recharge estimates of 4.09 to 5.28 and 6.66 to 7.87 inches per year, respectively, could be made.

For till-mantled areas in the Puget Sound Lowland that are hydrologically similar to the Clover catchment, the small amounts of recharge are relatively independent of annual precipitation and vegetation. This is because the soils above the till are saturated most of the time during the rainy winter season and the recharge rate is, therefore, limited by the infiltration capacity of the till. For till-mantled areas similar to the Vaughn and Beaver catchments, recharge will be dependent on annual precipitation and vegetation as well as on the infiltration capacity of the till. An interception loss experiment demonstrated that in evergreen forested areas, such as the Beaver and Vaughn catchments, interception loss can be the largest single water-budget component (excluding precipitation) and was measured to be almost one half of the annual precipitation during this investigation. Therefore, in these areas, land use changes will affect recharge quantities.

Particle-size distributions of the till indicate that the differences in the recharge rates between the catchments are largely related to regional variations in the amount of silt- and clay-sized particles in the till. Also the differences in percentages of coarse and fine materials over the thickness of the till within each catchment were small in comparison to differences between the catchments. This suggests that if a sufficient number of till-mantled catchments could be analyzed, a quantitative relation may be found to predict recharge from average annual precipitation, land use, and particle-size distributions of samples obtained only from shallow depths in the till.

The recharge amounts computed in this investigation are representative only of recharge to the water-table aquifer. Recharge to deeper aquifers cannot usually be equated to recharge to shallow or perched water-table aquifers because of ground-water discharge to streams and springs from these shallow or perched water-table aquifers. This effect was observed in the Beaver catchment, where it was estimated that of 5.44 inches per year recharge to a shallow water table, no more than about 2.5 inches per year percolated down to the aquifer commonly tapped by wells.

Examination of concentrations of the stable oxygen-18 isotope in precipitation, soil water, and streamflow in the Vaughn catchment during three storms indicates that there is no overland flow contribution to runoff in forested, till-mantled areas of the Puget Sound Lowland. Streamflow caused by a storm consists mostly of antecedent soil water displaced by storm precipitation. Neither the isotopic composition of streamflow or observations of dye movement into soils during the wettest months of the investigation indicated that there was any macropore flow.

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APPENDIX A--Basic data tables for precipitation-throughfall, soil-water levels, and soil-moisture contents, and computed monthly water-budget summaries, for the catchments

Table A1.--*Precipitation and throughfall in a Douglas fir forest located near the Beaver and Vaughn catchments*

[--, indicates no data]

Date[1]	Time	Precip-itation (inches)[2] (#1)	Throughfall under forest canopy at indicated gage number, in inches[2] (#2)	(#3)	(#4)	(#5)	(#6)	(#7)	(#8)
921106	1530	--	--	--	--	--	--	--	--
921107	0900	0.58	0.35	0.18	0.51	0.28	0.55	0.43	0.35
921108	0900	0.12	0.04	0.01	0.06	0.04	0.04	0.07	0.03
921109	1530	0.02	0	0	0	0	0	0.01	0.01
921111	1630	0.44	0.29	0.07	0.27	0.18	0.35	0.28	0.31
921113	1000	0.12	0.13	0.07	0.10	0.04	0.15	0.10	0.10
921116	1600	0.57	0.33	0.11	0.48	0.26	0.44	0.35	0.31
921118	0700	0.56	0.47	0.11	0.53	0.25	0.44	0.37	0.41
921120	0900	0.50	0.36	0.13	0.35	0.20	0.40	0.38	0.32
921121	1000	0.86	0.73	0.31	0.78	0.85	0.64	0.59	0.67
921122	1100	0.50	0.38	0.18	0.48	0.20	0.46	0.35	0.33
921127	1630	0.39	0.19	0.03	0.21	0.14	0.21	0.20	0.18
921201	1100	0.35	0.15	0.09	0.20	0.13	0.19	0.18	0.15
921206	1100	0.08	0.04	0.01	0.01	0.01	0.01	0.03	0.04
921209	1100	0.89	0.21	0.10	0.32	0.24	0.32	0.38	0.29
921211	1430	1.31	0.96	0.84	1.25	0.59	1.09	0.69	0.85
921212	1400	0.09	0.08	0.02	0.01	0.01	0.03	0.04	0.06
921218	1400	0.47	0.35	0.16	0.36	0.17	0.21	0.20	0.31
921222	0800	0.81	0.42	0.14	0.35	0.26	0.38	0.37	0.41
921224	1200	0.02	0	0	0	0	0	0	0
921226	1400	0.10	0.03	0.01	0.02	0.02	0.01	0.01	0.01
921228	1400	0.30	0.18	0.05	0.07	0.10	0.09	0.11	0.17
921230	1330	0.15	0.10	0.06	0.04	0.01	0.06	0.03	0.08
930104	1600	0.33	0.13	0.01	0.07	0.08	0.08	0.12	0.13
930120	1300	1.65	1.15	0.53	1.15	0.76	1.08	0.75	1.07
930121	1000	0.54	0.20	0.13	0.41	0.19	0.38	0.24	0.23
930124	1130	0.65	0.51	0.18	0.50	0.31	0.43	0.37	0.50
930125	0930	1.68	1.27	0.67	1.52	1.02	1.75	1.02	1.03
930126	1500	0.45	0.39	0.11	0.59	0.27	0.54	0.26	0.38
930128	1600	0.11	0	0	0	0	0	0.01	0.02
930207	0930	0.06	0	0	0	0	0	0	0
930211	1600	0.11	0.01	0	0	0.01	0.01	0.03	0.02
930222	1400	0.24	0.03	0	0.03	0.01	0.02	0.03	0.07
930303	1600	0.60	0.18	0.05	0.28	0.27	0.42	0.28	0.40
930318	0700	1.11	0.50	0.39	0.71	0.47	0.75	0.41	0.63
930321	1744	0.28	0.10	0.01	0.05	0.08	0.09	0.09	0.12
930322	1600	1.11	0.75	0.42	0.94	0.60	1.13	0.61	0.78
930324	1708	1.07	0.77	0.40	1.16	0.62	1.13	0.61	0.72

Table A1.--*Precipitation and throughfall in a Douglas fir forest located near the Beaver and Vaughn catchments--Continued*

Date[1]	Time	Precipitation (inches)[2] (#1)	Throughfall under forest canopy at indicated gage number, in inches[2] (#2)	(#3)	(#4)	(#5)	(#6)	(#7)	(#8)
930331	1045	0.18	0.07	0	0.03	0.06	0.04	0.06	0.10
930401	1150	0.47	0.25	0.13	0.35	0.26	0.47	0.27	0.27
930404	1430	0.72	0.40	0.07	0.39	0.32	0.46	0.34	0.37
930405	1230	0.02	0	0	0	0	0	0	0
930407	1115	0.22	0.08	0.01	0.06	0.06	0.06	0.09	0.09
930408	1300	0.60	0.39	0.12	0.53	0.31	0.42	0.28	0.40
930409	1600	0.53	0.14	0.08	0.25	0.15	0.24	0.21	0.16
930412	1700	0.61	0.32	0.17	0.50	0.26	0.46	0.33	0.34
930414	1500	0.22	0.11	0.01	0.08	0.10	0.09	0.09	0.13
930417	0900	0.42	0.20	0.07	0.09	0.10	0.18	0.17	0.24
930419	1930	0.30	0.12	0.07	0.07	0.08	0.17	0.17	0.15
930422	1630	0.53	0.24	0.05	0.26	0.19	0.31	0.26	0.28
930424	1830	0.60	0.30	0.04	0.25	0.21	0.30	0.29	0.43
930426	1830	1.03	0.35	0.10	0.40	0.30	0.42	0.47	0.52
930430	1800	0.48	0.17	0.03	0.22	0.15	0.22	0.20	0.20
930503	1930	0.66	0.21	0.05	0.23	0.17	0.22	0.25	0.31
930507	1930	0.48	0.13	0.02	0.14	0.15	0.15	0.17	0.19
930520	1000	0.53	0.30	0.09	0.31	0.29	0.31	0.26	0.35
930522	0730	0.23	0.07	0	0.05	0.08	0.04	0.06	0.10
930601	1000	1.47	0.82	0.23	0.84	0.74	1.16	0.86	0.82
930604	0930	0.17	0.05	0.01	0.05	0.06	0.11	0.08	0.07
930609	1630	0.82	0.59	0.16	0.60	0.57	0.68	0.46	0.59
930613	1150	0.17	0.02	0	0.01	0.01	0	0.02	0.02
930619	1000	0.15	0.02	0	0.01	0.01	0.03	0.04	
930624	0700	0.04	0	0	0	0	0	0	0
930706	1630	0.35	0.16	0.05	0.17	0.18	0.11	0.15	0.18
930721	1000	0.52	0.11	0	0.15	0.16	0.22	0.21	0.16
930722	1042	0.16	0.06	0.01	0.06	0.07	0.02	0.05	0.08
930730	0900	0.82	0.45	0.16	0.34	0.36	0.66	0.43	0.51
930817	1700	0.15	0.01	0.01	0.02	0.02	0.03	0.02	0.02
930823	1900	0.06	0	0	0	0	0	0	0
931006	1000	0.08	0	0	0	0	0	0	0
931007	0900	0.17	0.11	0.01	0.04	0.06	0.08	0.11	0.10
931012	0930	0.06	0.01	0	0	0	0.01	0.01	0.02
931015	1700	0.54	0.30	0.18	0.28	0.30	0.32	0.27	0.30
931018	1700	0.13	0.01	0	0.03	0.04	0.05	0.04	0.03
931025	1200	1.22	0.66	0.25	0.94	0.73	0.95	0.62	0.69

Table A1.--*Precipitation and throughfall in a Douglas fir forest located near the Beaver and Vaughn catchments--Continued*

Date[1]	Time	Precip-itation (inches)[2] (#1)	Throughfall under forest canopy at indicated gage number, in inches[2] (#2)	(#3)	(#4)	(#5)	(#6)	(#7)	(#8)
931101	0930	0.04	0	0	0	0	0	0	0
931103	0940	0.20	0.04	0.02	0.07	0.05	0.07	0.08	0.03
931116	1600	0.18	0.02	0.01	0.03	0.04	0.05	0.05	--
931130	0830	1.10	0.68	0.30	0.65	0.54	0.83	0.58	0.57
931202	0940	1.57	1.06	0.52	1.28	1.05	1.34	1.03	0.86
931206	0940	0.35	0.05	0.03	0.07	0.06	0.10	0.09	0.05
931208	0930	1.00	0.59	0.30	0.73	0.60	0.72	0.67	0.62
931210	1700	1.82	0.83	0.36	1.12	0.86	0.96	0.89	0.86
931212	1100	0.28	0.13	0.04	0.13	0.12	0.14	0.12	0.15
931216	1220	0.55	0.20	0.03	0.24	0.19	0.23	0.18	0.31

[1]Dates are listed as year, month, day.

[2]Values represent cumulative amounts from the date and time of the prior record to those of current record.

Table A2.--*Water levels in soils in the Clover catchment*

[--, indicates no data]

Date[1]	PNMN	T1BT	T1MD	T1TP	T2BT	T2MD	T2TP	CEDR
	Water levels above bottom of piezometer at indicated locations, in feet[2]							
910206	--	4.78	1.00	--	0.80	0.24	1.66	1.50
910207	--	4.85	0.92	0.00	1.42	0.36	1.51	1.45
910213	--	4.95	1.18	0.00	2.88	1.75	1.93	1.52
910221	--	4.89	1.09	0.36	2.74	1.43	1.75	1.58
910227	--	4.78	--	0.00	2.79	1.39	1.03	1.25
910305	--	4.85	1.21	0.09	2.68	1.47	2.00	1.55
910306	--	4.92	1.11	0.09	2.87	1.19	1.86	1.53
910314	--	4.88	0.98	0.04	2.85	0.73	1.68	1.47
910327	--	4.78	0.78	0.00	2.82	0.60	1.40	1.31
910405	--	5.03	1.58	0.42	2.95	3.56	2.17	1.90
910411	--	4.85	0.94	0.07	2.85	2.86	1.58	1.47
910426	--	4.59	0.54	0.00	--	2.73	0.74	0.00
910514	--	4.43	0.14	0.00	2.53	1.77	0.38	0.52
910528	--	4.56	0.18	0.00	2.61	1.90	0.33	0.58
910605	--	3.55	0.00	0.00	1.86	1.14	0.00	0.29
910614	--	3.52	0.00	--	1.55	0.70	0.00	0.02
910624	--	3.30	0.00	0.00	1.92	1.08	0.00	0.03
910705	--	2.09	0.00	0.00	0.88	0.11	0.00	0.00
910711	--	1.26	0.00	0.00	0.08	0.00	0.00	0.00
910718	--	0.80	0.00	0.00	0.01	0.00	0.00	0.01
910726	--	0.38	0.00	0.00	0.06	0.00	0.00	0.00
910802	--	0.19	0.00	0.00	0.00	0.00	0.00	0.00
910809	--	0.00	0.00	0.03	--	--	--	0.00
910812	--	--	--	--	0.00	0.00	0.00	--
910816	--	0.06	0.00	0.00	0.00	0.00	0.00	0.00
910822	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910829	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910905	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910913	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
911004	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
911025	--	0.00	0.00	0.00	0.00	0.11	--	0.00
911029	--	--	--	--	0.00	0.00	0.00	0.00
911105	--	0.00	0.00	0.00	0.00	0.46	0.00	0.01
911112	--	0.00	0.00	0.00	0.00	0.25	0.00	0.00
911119	--	0.00	0.00	0.11	0.43	1.50	0.00	0.03
911127	--	4.02	0.00	0.11	2.65	1.63	0.00	0.18

Table A2.--*Water levels in soils in the Clover catchment--Continued*

Date[1]	Water levels above bottom of piezometer at indicated locations, in feet[2]							
	PNMN	T1BT	T1MD	T1TP	T2BT	T2MD	T2TP	CEDR
911210	--	4.72	0.82	0.05	2.68	2.30	0.00	0.00
911219	--	4.74	0.78	0.05	2.71	2.40	0.49	0.52
911231	--	4.83	0.90	0.00	2.76	2.58	0.86	1.20
920114	--	4.84	0.77	0.02	2.77	2.53	0.79	1.24
920124	--	5.00	1.31	0.05	2.88	3.09	1.60	1.61
920131	2.09	5.07	1.57	0.22	2.78	3.51	2.06	1.81
920210	1.63	4.94	0.89	0.07	2.87	2.64	1.27	1.41
920225	1.79	4.95	0.97	0.00	2.89	2.95	1.56	1.45
920306	1.87	4.96	1.09	0.00	2.93	3.08	1.70	1.48
920310	1.38	--	--	--	--	--	--	--
920321	1.35	4.82	0.62	0.00	2.83	2.36	0.94	1.21
920415	1.91	4.90	0.88	0.00	2.89	2.78	1.15	1.36
920423	1.26	--	--	--	--	--	--	--
920514	0.00	--	--	--	--	--	--	--
920522	0.00	--	--	--	--	--	--	--
920603	0.00	--	--	--	--	--	--	--
920609	0.00	--	--	--	--	--	--	--
920623	0.00	--	--	--	--	--	--	--
920701	0.00	--	--	--	--	--	--	--
920721	0.00	--	--	--	--	--	--	--
920728	0.00	--	--	--	--	--	--	--
920820	0.00	--	--	--	--	--	--	--
920827	0.00	--	--	--	--	--	--	--
920917	0.00	--	--	--	--	--	--	--
920929	0.00	--	--	--	--	--	--	--
921009	0.00	--	--	--	--	--	--	--
921021	0.00	--	--	--	--	--	--	--
921102	0.00	--	--	--	--	--	--	--
921117	0.00	--	--	--	--	--	--	--
921125	0.78	--	--	--	--	--	--	--
921212	1.88	--	--	--	--	--	--	--
921222	1.85	--	--	--	--	--	--	--

Table A2.--*Water levels in soils in the Clover catchment--Continued*

Date[1]	Water levels above bottom of piezometer at indicated locations, in feet[2]							
	PNMN	T1BT	T1MD	T1TP	T2BT	T2MD	T2TP	CEDR
930106	1.41	--	--	--	--	--	--	--
930122	2.00	--	--	--	--	--	--	--
930129	1.85	--	--	--	--	--	--	--
930208	1.37	--	--	--	--	--	--	--
930219	0.95	--	--	--	--	--	--	--
930305	1.67	--	--	--	--	--	--	--
930317	1.90	--	--	--	--	--	--	--
930325	1.65	--	--	--	--	--	--	--
930406	1.65	--	--	--	--	--	--	--
930413	2.01	--	--	--	--	--	--	--
930422	1.79	--	--	--	--	--	--	--
930429	2.21	--	--	--	--	--	--	--
930519	0.39	--	--	--	--	--	--	--
930527	0.00	--	--	--	--	--	--	--
930616	1.26	--	--	--	--	--	--	--
930629	0.00	--	--	--	--	--	--	--
930712	0.00	--	--	--	--	--	--	--
930723	0.00	--	--	--	--	--	--	--
930805	0.00	--	--	--	--	--	--	--
930812	0.00	--	--	--	--	--	--	--
930910	0.00	--	--	--	--	--	--	--
931007	0.00	--	--	--	--	--	--	--

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 3.

Table A3.--*Water levels in soils in the Beaver catchment*

[--, indicates no data]

Date[1]	Water levels above bottom of piezometer at indicated locations, in feet[2]					
	TLBT	TLMD	TLTP	TUBT	TUMD	TUTP
920107	0.00	0.00	0.28	0.00	0.00	0.12
920117	0.00	0.08	0.08	0.00	0.08	0.00
920128	0.34	0.48	0.46	0.97	1.21	1.20
920129	--	--	--	1.04	1.24	1.30
920213	0.00	0.00	0.17	0.32	0.52	0.15
920220	0.08	0.00	0.20	--	--	--
920226	--	--	--	0.42	0.67	0.39
920311	0.00	0.14	0.00	0.62	0.27	0.00
920331	0.00	0.00	0.00	0.00	0.00	0.00
920414	0.00	0.00	0.00	--	--	--
920428	0.00	0.00	0.11	0.02	0.17	0.00
920512	0.00	0.00	0.00	0.00	0.00	0.00
920521	0.00	0.00	0.00	0.00	0.00	0.00
920602	0.00	0.00	0.00	0.00	0.00	0.00
920612	0.00	0.00	0.00	0.00	0.00	0.00
920622	0.00	0.00	0.00	0.00	0.00	0.00
920702	0.00	0.00	0.00	0.00	0.00	0.00
920710	0.00	0.00	0.00	0.00	0.00	0.00
920720	0.00	0.00	0.00	0.00	0.00	0.00
920729	0.00	0.00	0.00	0.00	0.00	0.00
920807	0.00	0.00	0.00	0.00	0.00	0.00
920818	0.00	0.00	0.00	0.00	0.00	0.00
920827	0.00	0.00	0.00	0.00	0.00	0.00
920915	0.00	0.00	0.00	0.00	0.00	0.00
920930	0.00	0.00	0.00	0.00	0.00	0.00
921008	0.00	0.00	0.00	0.00	0.00	0.00
921020	0.00	0.00	0.00	0.00	0.13	0.00
921103	0.00	0.00	0.10	0.18	0.00	0.00
921118	0.00	0.00	0.00	0.00	0.00	0.00
921128	0.00	0.00	0.06	0.04	0.00	0.00
921211	0.00	0.00	0.23	0.46	0.32	0.34
921221	0.06	0.00	0.18	0.22	0.11	0.39
930108	--	--	--	0.00	0.00	0.00
930121	0.09	0.00	0.31	0.04	0.49	0.50

Table A3.--*Water levels in soils in the Beaver catchment-Continued*

Date[1]	Water levels above bottom of piezometer at indicated locations, in feet[2]					
	TLBT	TLMD	TLTP	TUBT	TUMD	TUTP
930129	0.06	0.00	0.20	0.37	0.76	0.55
930205	0.00	0.00	0.05	0.15	0.42	0.00
930212	0.00	0.00	0.00	0.02	0.18	0.00
930223	0.00	0.00	0.00	0.00	0.00	0.00
930308	0.00	0.00	0.00	0.00	0.00	0.00
930319	0.00	0.00	0.00	0.00	0.00	0.00
930324	0.04	0.02	0.19	0.45	0.78	0.39
930407	0.03	0.00	0.08	0.05	0.53	0.00
930414	0.03	0.00	0.16	0.25	0.58	0.00
930423	0.00	0.00	0.27	0.34	0.87	0.62
930430	0.00	0.00	0.15	0.25	0.58	0.24
930518	0.00	0.00	0.00	0.25	0.00	0.00
930527	0.00	0.00	0.00	0.00	0.00	0.00
930611	0.08	0.00	0.00	0.00	0.00	0.00
930629	0.00	0.00	0.00	0.00	0.00	0.00
930713	0.00	0.00	0.00	0.00	0.00	0.00
930723	0.00	0.00	0.00	0.00	0.00	0.00
930804	0.00	0.00	0.00	0.00	0.00	0.00
930813	0.00	0.00	0.00	0.00	0.00	0.00
930930	0.00	0.00	0.00	0.00	0.00	0.00

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 4.

Table A4.--*Water levels in soils in the Vaughn catchment*

[--, indicates no data]

	Water levels above bottom of piezometer at indicated locations, in feet[2]							
Date[1]	TLBT	TLMD	TLTP	LYBT	LYMD	LYTP	TUBT	TUMD
920107	2.62	0.10	0.00	--	--	--	2.30	0.00
920117	1.49	0.10	0.00	--	--	--	1.58	0.00
920129	3.57	0.52	0.00	--	--	--	3.05	1.17
920204	3.09	0.15	0.02	--	--	--	--	--
920213	2.66	0.25	0.03	--	--	--	2.36	0.00
920220	2.78	0.00	0.00	--	--	--	--	--
920226	--	--	--	--	--	--	2.54	0.21
920303	--	--	--	2.24	0.00	0.00	--	--
920311	1.71	0.00	0.00	--	--	--	--	--
920319	--	--	--	1.21	0.00	0.00	1.56	0.00
920331	0.59	0.00	0.00	0.40	0.00	0.00	0.91	0.00
920414	0.42	0.00	0.00	0.00	0.00	0.00	0.46	0.00
920424	0.00	0.00	--	--	--	--	--	--
920428	0.25	0.00	0.00	0.10	0.00	0.00	--	--
920512	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
920521	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920602	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920612	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920622	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920702	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920710	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920720	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920729	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920807	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920818	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920827	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920914	0.00	--	--	--	--	--	--	--
920915	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920930	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
921008	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
921020	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.03
921103	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
921118	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
921128	0.00	0.00	0.00	--	0.00	0.00	0.00	0.00

Table A4.--*Water levels in soils in the Vaughn catchment--Continued*

Date[1]	Water levels above bottom of piezometer at indicated locations, in feet[2]							
	TLBT	TLMD	TLTP	LYBT	LYMD	LYTP	TUBT	TUMD
921211	0.58	0.02	0.05	0.71	0.00	0.00	1.14	0.55
921221	1.50	0.00	0.03	2.10	0.00	0.00	2.41	0.00
930108	0.00	0.00	--	0.78	0.00	0.00	0.00	0.00
930119	0.00	0.05	0.08	0.63	0.00	0.00	0.00	0.00
930125	3.47	0.35	0.14	3.01	0.03	0.16	3.00	1.21
930126	3.32	0.13	0.07	2.71	0.02	0.02	2.84	0.86
930128	3.00	0.03	0.04	2.49	0.00	0.02	2.65	0.37
930202	--	--	--	2.26	0.00	0.00	--	--
930205	2.56	0.00	0.00	2.14	0.00	0.00	2.00	0.00
930212	1.13	0.00	0.00	1.54	0.00	0.00	0.91	0.00
930223	0.06	0.00	0.00	0.67	0.00	0.00	0.00	0.00
930308	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00
930319	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930322	0.00	0.10	0.13	0.00	0.00	0.00	0.00	0.00
930323	2.87	0.15	0.04	2.39	0.03	0.07	2.71	0.96
930324	--	--	--	2.45	0.00	0.00	--	--
930405	2.02	0.00	0.00	1.91	0.00	0.00	1.79	0.00
930414	2.74	0.00	0.00	2.26	0.00	0.00	2.41	0.00
930423	2.60	0.00	0.00	2.19	0.00	0.00	2.30	0.00
930430	2.68	0.00	0.00	2.21	0.00	0.00	2.35	0.00
930518	0.60	0.00	0.00	0.87	0.00	0.00	--	0.00
930527	0.20	0.00	0.00	0.13	0.00	0.00	0.27	0.00
930611	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930628	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930713	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930723	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930804	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930813	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	--

[1]Dates are listed as year, month day.

[2]Locations of piezometers are shown on figure 5.

Table A5.--*Maximum water levels in soils between data-collection visits in the Clover catchment*

[--, indicates no data]

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]							
From date	To date	PNMN	T1BT	T1MD	T1TP	T2BT	T2MD	T2TP	CEDR
910206	910207	--	0.00	0.00	--	0.00	0.00	0.00	0.00
910207	910213	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910213	910221	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910221	910227	--	0.00	--	0.00	0.00	0.00	0.00	0.00
910227	910305	--	5.10	[3]1.59	0.11	2.95	1.76	0.00	1.82
910305	910306	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910306	910314	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910314	910327	--	4.98	0.00	0.00	2.91	0.68	1.92	1.49
910327	910405	--	5.25	1.98	1.02	2.99	3.58	2.92	2.46
910405	910411	--	5.08	1.55	0.16	2.97	2.49	2.35	1.84
910411	910426	--	4.93	0.92	0.06	--	2.93	1.58	1.45
910426	910514	--	4.90	0.77	0.00	[3]2.84	1.70	0.85	0.90
910514	910528	--	4.75	0.43	0.00	2.78	1.14	0.61	0.65
910528	910605	--	4.88	0.48	0.00	2.70	1.37	0.58	0.57
910605	910614	--	3.64	0.00	--	1.59	0.95	0.00	0.04
910614	910624	--	4.23	0.00	[3]0.00	2.47	1.46	0.00	0.03
910624	910705	--	3.24	0.00	0.00	1.35	0.38	0.00	0.02
910705	910711	--	1.81	0.00	0.00	0.08	0.00	0.00	0.00
910711	910718	--	0.00	0.00	0.00	0.13	0.00	0.00	0.01
910718	910726	--	0.74	0.00	0.00	0.11	0.00	0.00	0.04
910726	910802	--	0.22	0.00	0.00	0.08	0.00	0.00	0.05
910802	910809	--	0.12	0.00	0.03	--	--	--	0.02
910809	910812	--	--	--	--	[3]0.09	[3]0.00	[3]0.00	--
910812	910816	--	[3]0.00	[3]0.00	[3]0.00	0.00	0.00	0.00	[3]0.06
910816	910822	--	0.06	0.00	0.00	0.00	0.00	0.00	0.00
910822	910829	--	0.00	0.00	0.00	0.00	0.00	0.00	0.02
910829	910905	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
910905	910913	--	0.00	0.00	0.00	0.00	0.00	0.00	0.02
910913	911004	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
911004	911025	--	0.00	0.00	0.00	0.00	1.20	0.00	0.00
911025	911029	--	--	--	--	0.00	0.00	0.00	0.00
911029	911105	--	[3]0.00	[3]0.00	[3]0.00	0.00	1.14	0.00	0.01
911105	911112	--	0.00	0.00	0.00	0.00	0.49	0.00	0.06
911112	911119	--	0.00	0.00	0.10	0.42	2.05	0.00	0.05
911119	911127	--	4.06	0.00	0.27	2.69	1.82	0.00	0.17
911127	911210	--	4.88	1.09	0.10	2.81	2.68	0.00	0.08
911210	911219	--	4.86	0.88	0.00	2.78	2.53	0.48	0.57

Table A5.--*Maximum water levels in soils between data-collection visits in the Clover catchment--Continued*

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]							
From date	To date	PNMN	T1BT	T1MD	T1TP	T2BT	T2MD	T2TP	CEDR
911231	920114	--	4.98	1.20	0.00	2.87	2.77	1.16	1.45
920114	920124	--	4.95	1.43	0.07	2.96	3.37	1.66	1.63
920124	920131	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920131	920210	2.41	5.13	1.78	0.37	2.97	0.00	2.39	1.93
920210	920225	2.49	5.09	1.48	0.15	2.99	0.00	2.30	1.70
920225	920306	2.25	0.00	1.18	0.00	2.96	3.17	1.71	1.50
920306	920310	1.88	--	--	--	--	--	--	--
920310	920321	2.06	[3]4.98	[3]1.13	[3]0.00	[3]2.93	[3]2.90	[3]1.65	[3]1.51
920321	920415	1.96	5.01	1.08	0.00	2.99	2.86	1.29	1.37
920415	920423	2.64							
920423	920514	2.19							
920514	920522	0.00							
920522	920603	0.00							
920603	920609	0.00							
920609	920623	0.00							
920623	920701	0.00							
920701	920721	0.00							
920721	920728	0.00							
920728	920820	0.00							
920820	920827	0.00							
920827	920917	0.00							
920917	920929	0.05							
920929	921009	0.06							
921009	921021	0.07							
921021	921102	0.00							
921102	921117	0.04							
921117	921125	1.27							
921125	921212	2.28							
921212	921222	2.41							
921222	930106	1.90							
930106	930122	2.17							
930122	930129	0.00							
930129	930208	1.88							
930208	930219	1.39							
930219	930305	1.88							
930305	930317	2.15							
930317	930325	2.59							
930325	930406	2.38							
930406	930413	2.48							

Table A5.--*Maximum water levels in soils between data-collection visits in the Clover catchment--Continued*

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]							
From date	To date	PNMN	TIBT	TIMD	T1TP	T2BT	T2MD	T2TP	CEDR
930413	930422	2.27							
930422	930429	2.35							
930429	930519	2.32							
930519	930527	0.99							
930527	930616	1.71							
930616	930629	1.26							
930629	930712	0.00							
930712	930723	0.00							
930723	930805	0.00							
930805	930812	0.00							
930812	930910	0.00							
930910	931007	0.00							

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 3.

[3]Maximum water level is not recorded for previous time period; therefore, add the time period of previous record to that of this record.

Table A6.--*Maximum water levels in soils between data-collection visits in the Beaver catchment*

[--, indicates no data]

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]					
From date	To date	TLBT	TLMD	TLTP	TUBT	TUMD	TUTP
920107	920117	0.08	0.20	0.18	0.00	0.10	0.21
920117	920128	0.26	0.53	0.51	0.99	1.39	1.53
920128	920129	--	--	--	0.00	0.00	0.00
920129	920213	[3]0.69	[3]0.10	[3]0.71	1.12	1.22	1.31
920213	920220	0.10	0.00	0.20	--	--	--
920220	920226	--	--	--	[3]0.86	[3]1.14	[3]0.00
920226	920311	[3]0.61	[3]0.00	[3]0.65	0.00	0.69	0.39
920311	920331	0.00	0.00	0.10	0.00	0.22	0.00
920331	920414	0.00	0.00	0.00	--	--	--
920414	920428	0.42	0.00	0.47	[3]0.00	[3]0.00	[3]0.00
920428	920512	0.00	0.00	0.09	0.00	0.18	0.00
920512	920521	0.00	0.00	0.00	0.00	0.00	0.00
920521	920602	0.00	0.00	0.00	0.00	0.00	0.00
920602	920612	0.00	0.00	0.00	0.00	0.00	0.00
920612	920622	0.00	0.00	0.00	0.00	0.00	0.00
920622	920702	0.00	0.08	0.31	0.00	0.60	0.00
920702	920710	0.00	0.00	0.00	0.00	0.48	0.00
920710	920720	0.00	0.00	0.00	0.00	0.00	0.00
920720	920729	0.00	0.00	0.00	0.00	0.00	0.00
920729	920807	0.00	0.00	0.00	0.17	0.68	0.00
920807	920818	0.00	0.00	0.00	0.00	0.00	0.00
920818	920827	0.00	0.00	0.00	0.00	0.00	0.00
920827	920915	0.00	0.07	0.00	0.00	0.37	0.00
920915	920930	0.07	0.08	0.48	0.69	0.85	0.00
920930	921008	0.00	0.07	0.00	0.05	0.00	0.00
921008	921020	0.13	0.10	0.00	0.00	0.65	0.00
921020	921103	0.14	0.10	0.49	0.48	0.89	0.10
921103	921118	0.11	0.06	0.39	0.21	0.62	0.00
921118	921128	0.28	0.00	0.44	0.11	0.58	0.00
921128	921211	0.20	0.04	0.33	0.57	0.61	0.38
921211	921221	0.14	0.06	0.30	0.46	0.35	0.48
921221	930108	--	--	--	0.22	0.11	0.39
930108	930121	[3]0.25	[3]0.10	[3]0.50	0.04	0.55	0.50
930121	930129	1.34	0.58	0.92	1.31	1.25	0.55
930129	930205	0.00	0.00	0.21	0.15	0.76	0.56
930205	930212	0.00	0.00	0.09	0.15	1.23	0.00
930212	930223	0.00	0.00	0.00	0.03	0.18	0.00

Table A6.--*Maximum water levels in soils between data-collection visits in the Beaver catchment--Continued*

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]					
From date	To date	TLBT	TLMD	TLTP	TUBT	TUMD	TUTP
930308	930319	0.00	0.00	0.00	0.00	0.00	0.00
930319	930324	0.55	0.08	0.61	0.79	1.08	0.53
930324	930407	0.11	0.08	0.19	0.45	0.83	0.39
930407	930414	0.22	0.00	0.42	0.51	0.88	0.17
930414	930423	0.25	0.00	0.34	0.41	0.86	0.62
930423	930430	0.29	0.00	0.37	0.55	0.91	0.73
930430	930518	0.00	0.00	0.17	0.00	0.69	0.36
930518	930527	0.00	0.00	0.00	0.00	0.00	0.00
930527	930611	0.08	0.00	0.00	0.00	0.00	0.00
930611	930629	0.00	0.00	0.00	0.00	0.00	0.00
930629	930713	0.00	0.00	0.00	0.00	0.00	0.00
930713	930723	0.00	0.00	0.00	0.00	0.00	0.00
930723	930804	0.00	0.00	0.00	0.00	0.00	0.00
930804	930813	0.00	0.00	0.00	0.00	0.00	0.00
930813	930930	0.00	0.00	0.00	0.00	0.00	0.00

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 4.

[3]Maximum water level is not recorded for previous time period; therefore, add the time period of previous record to that of this record.

Table A7.--*Maximum water levels in soils between data-collection visits in the Vaughn catchment*

[--, indicates no data]

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]							
From date	To date	TLBT	TLMD	TLTP	LYBT	LYMD	LYTP	TUBT	TUMD
920107	920117	2.70	2.07	0.00	--	--	--	2.41	0.00
920117	920129	3.63	0.89	0.49	--	--	--	3.16	1.49
920129	920204	3.37	0.21	0.10	--	--	--	--	--
920204	920213	3.14	0.00	0.00	--	--	--	[3]3.50	[3]1.16
920213	920220	2.78	0.00	0.00	--	--	--	--	--
920220	920226	--	--	--	--	--	--	[3]0.00	[3]0.94
920226	920303	[3]--	[3]--	[3]--	--	--	--	--	--
920303	920311	[3]3.15	[3]0.00	[3]0.19	--	--	--	[3]--	[3]--
920311	920319	--	--	--	[3]2.24	[3]0.00	[3]0.00	[3]2.51	[3]0.00
920319	920331	[3]1.69	[3]0.00	[3]0.00	1.29	0.00	0.00	0.00	0.00
920331	920414	0.56	0.00	0.00	0.39	0.00	0.00	0.00	0.00
920414	920424	1.04	0.26	--	--	--	--	--	--
920424	920428	0.42	0.00	[3]0.00	[3]1.05	[3]0.00	[3]0.00	[3]1.49	[3]0.00
920428	920512	0.66	0.00	0.00	0.61	0.00	0.00	--	--
920512	920521	0.00	0.00	0.00	0.00	0.00	0.00	[3]0.10	[3]0.00
920521	920602	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920602	920612	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920612	920622	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920622	920702	0.00	0.21	0.00	0.00	0.00	0.00	0.36	0.00
920702	920710	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920710	920720	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920720	920729	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920729	920807	0.00	0.09	0.00	0.00	0.00	0.00	0.15	0.00
920807	920818	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920818	920827	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920827	920914	0.00	--	--	--	--	--	--	--
920914	920915	0.00	[3]0.00	[3]0.00	[3]0.00	[3]0.00	[3]0.00	[3]0.00	[3]0.00
920915	920930	0.00	0.36	0.24	0.00	0.00	0.01	0.24	0.00
920930	921008	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
921008	921020	0.00	0.19	0.19	0.00	0.10	0.00	0.00	0.17
921020	921103	0.48	0.81	0.35	0.18	0.35	0.10	0.81	0.48
921103	921118	0.22	0.23	0.18	0.00	0.00	0.00	0.00	0.12
921118	921128	0.43	0.35	0.24	--	0.00	0.00	0.00	0.00
921128	921211	0.59	0.32	0.05	[3]0.71	0.00	0.00	3.88	0.54
921211	921221	1.51	0.11	0.06	2.17	0.07	0.07	2.43	0.55
921221	930108	1.90	0.00	--	2.11	0.00	0.00	2.42	0.64

Table A7.--*Maximum water levels in soils between data-collection visits in the Vaughn catchment--Continued*

Time period[1]		Maximum water level during time period above bottom of piezometer at indicated locations, in feet[2]							
From date	To date	TLBT	TLMD	TLTP	LYBT	LYMD	LYTP	TUBT	TUMD
930119	930125	3.44	0.69	0.25	3.01	0.17	0.69	3.03	1.39
930125	930126	3.50	0.35	0.07	3.05	0.02	0.17	3.01	1.23
930126	930128	3.32	0.13	0.00	2.74	0.02	0.02	2.84	0.89
930128	930202	--	--	--	2.53	0.00	0.01	--	--
930202	930205	[3]3.02	[3]0.00	[3]0.00	2.25	0.00	0.00	[3]2.66	[3]0.36
930205	930212	2.55	0.00	0.00	2.16	0.00	0.00	1.99	0.00
930212	930223	1.13	0.00	0.00	1.54	0.00	0.00	0.92	0.00
930223	930308	0.06	0.00	0.00	0.67	0.00	0.00	0.00	0.00
930308	930319	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00
930319	930322	0.02	0.14	0.16	0.12	0.00	0.04	0.00	0.00
930322	930323	2.81	0.32	0.08	2.39	0.03	0.42	2.71	--
930323	930324	--	--	--	2.49	0.00	0.08	--	[3]0.96
930324	930405	[3]2.98	[3]0.15	[3]0.05	2.48	0.00	0.00	[3]2.61	0.97
930405	930414	2.83	0.00	0.00	2.28	0.00	0.00	2.57	0.29
930414	930423	2.76	0.00	0.00	2.26	0.00	0.00	2.47	0.00
930423	930430	2.79	0.00	0.00	2.29	0.00	0.00	2.55	0.00
930430	930518	2.68	0.00	0.00	2.21	0.00	0.00	--	0.00
930518	930527	0.67	0.00	0.00	0.87	0.00	0.00	[3]2.39	0.00
930527	930611	0.50	0.00	0.00	0.37	0.00	0.00	0.26	0.00
930611	930628	0.07	0.00	0.00	0.00	0.00	0.00	0.11	0.00
930628	930713	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930713	930723	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930723	930804	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930804	930813	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
930813	930930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 5.

[3]Maximum water level is not recorded for previous time period; therefore, add the time period of previous record to that of this record.

Table A8.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Clover catchment, downstream area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]							
	T1BT			T1MD		T1TP		
Date[1]	0.9	2.9	4.8	0.9	2.9	0.9	1.9	3.9
910205	--	--	--	28.4	35.4	31.0	27.0	27.1
910206	45.2	41.9	37.1	28.2	35.4	30.6	26.9	27.5
910213	--	--	--	28.4	35.0	30.6	27.1	27.1
910314	--	--	--	--	--	30.8	27.3	27.3
910327	45.3	41.7	37.8	27.7	28.7	30.1	27.1	26.9
910405	--	--	--	--	--	34.6	29.6	27.9
910411	--	--	--	--	--	31.4	28.1	27.3
910426	--	--	--	25.6	28.1	27.1	25.3	25.7
910514	45.4	--	--	25.4	27.4	24.8	23.5	22.1
910528	45.8	41.6	36.1	25.5	27.6	25.4	24.2	22.1
910605	42.2	40.7	35.8	24.6	26.5	22.2	22.2	23.8
910614	41.1	40.9	37.3	24.9	26.2	22.4	22.2	23.9
910624	40.5	40.9	35.7	24.4	25.8	23.7	22.1	23.4
910705	37.5	37.6	--	20.3	22.6	14.5	16.9	17.4
910711	35.8	33.0	31.8	17.7	20.2	10.8	13.7	15.3
910718	33.9	31.3	30.4	16.7	18.7	7.9	11.2	13.7
910726	32.3	29.6	--	15.8	18.4	7.9	9.8	12.9
910802	26.9	26.4	27.1	11.7	15.1	6.6	7.9	11.0
910809	30.1	27.4	26.8	17.7	16.5	8.4	9.1	11.0
910816	24.7	24.6	25.5	11.1	13.7	6.4	7.7	9.9
910822	20.5	22.4	23.8	8.2	12.2	6.5	7.2	9.3
910829	25.5	24.8	24.5	17.8	15.1	8.8	9.4	10.5
910905	25.0	24.1	24.9	13.2	14.5	9.7	9.2	10.7
910913	19.7	21.9	24.0	11.4	11.0	7.6	8.0	9.7
911004	12.6	17.6	21.0	8.7	10.3	6.7	7.1	8.7
911025	23.8	22.4	--	17.2	14.4	9.4	10.3	10.2
911029	--	--	23.5	--	--	--	--	--
911105	29.1	25.2	25.0	22.0	16.7	16.9	13.2	12.3
911112	30.9	29.3	28.4	22.6	18.8	22.8	18.7	14.2
911119	33.7	32.0	29.7	25.0	22.3	25.8	23.3	17.9
911127	38.8	36.2	35.2	28.0	26.1	30.5	26.7	24.8
911210	44.0	38.3	35.8	25.3	27.6	24.5	25.2	23.8
911219	44.9	38.5	35.7	27.6	27.9	24.6	26.0	23.7
911231	45.2	39.6	36.3	27.4	27.9	24.1	25.8	24.8
920114	47.0	40.5	38.0	27.9	28.2	23.7	24.7	24.2
920124	48.1	40.7	37.3	28.8	29.5	25.9	26.9	26.4
920131	48.1	40.3	38.0	28.6	31.4	26.2	28.7	26.7

Table A8.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Clover catchment, downstream area--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]							
	T1BT			T1MD		T1TP		
Date[1]	0.9	2.9	4.8	0.9	2.9	0.9	1.9	3.9
920210	47.1	40.2	37.3	27.1	28.7	23.1	26.5	25.1
920225	47.2	41.0	38.0	26.4	29.2	24.4	27.4	25.6
920306	48.0	40.8	38.0	27.9	29.4	25.6	27.4	25.4
920321	47.5	41.1	37.5	26.7	28.3	23.1	25.9	24.6
920415	47.9	41.1	37.4	27.1	28.7	26.9	26.5	24.7

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 3.

Table A9.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Clover catchment, center area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]						
	T2BT		T2MD			T2TP	
Date[1]	0.9	1.9	0.9	1.9	3.9	0.9	2.9
910206	41.1	39.1	44.1	36.5	35.1	31.8	36.7
910213	--	--	43.9	36.9	35.5	32.5	37.2
910327	42.0	39.4	43.4	36.8	35.1	32.1	32.1
910405	--	--	46.1	38.1	35.7	--	--
910426	--	--	--	--	--	--	36.9
910514	41.5	39.3	40.5	35.4	34.8	26.6	28.8
910528	41.4	39.3	40.0	35.6	33.7	27.3	28.6
910605	39.9	--	39.5	35.1	35.3	25.0	35.5
910614	39.6	37.9	39.0	34.8	36.2	27.3	35.8
910624	39.6	38.2	38.7	34.2	33.5	26.0	35.0
910705	35.3	35.3	33.3	30.8	32.4	19.1	23.1
910711	32.5	32.9	27.8	27.8	30.3	14.2	20.2
910718	29.6	30.3	24.4	25.3	24.9	11.8	18.3
910726	26.9	28.7	19.4	23.6	22.1	10.3	17.2
910802	21.2	24.4	13.2	19.0	22.7	8.6	13.5
910812	20.5	22.7	11.3	17.2	21.6	11.0	12.7
910816	15.8	20.0	9.7	15.7	20.6	8.2	11.5
910822	11.9	17.3	9.3	14.3	19.5	7.1	10.5
910829	23.4	22.7	11.3	16.0	20.7	18.0	13.5
910905	19.1	21.5	11.6	15.4	19.9	13.5	12.9
910913	13.9	18.5	9.5	14.3	23.2	9.5	11.7
911004	9.9	15.7	8.6	13.5	17.9	7.8	10.4
911029	21.8	21.2	15.9	17.6	19.8	18.2	12.7
911105	30.6	26.8	21.3	20.0	23.2	23.6	14.5
911112	32.0	32.4	30.8	27.5	27.1	26.1	20.6
911119	35.4	35.2	36.8	33.0	29.7	29.2	25.0
911127	39.9	37.5	37.2	33.4	32.1	29.3	27.1
911210	41.0	38.9	36.7	33.0	32.5	29.3	26.4
911219	41.5	39.1	38.3	34.6	33.9	29.7	27.4
911231	42.2	39.6	37.1	34.2	33.8	29.3	28.1
920114	43.4	40.0	38.1	34.9	34.9	27.6	28.9
920124	42.9	40.5	40.7	35.9	35.6	30.8	31.3
920131	43.9	40.6	46.4	38.4	38.3	31.6	34.2
920210	43.7	40.0	41.1	36.6	36.3	29.2	31.6
920225	42.8	39.7	42.4	37.4	37.0	30.1	32.5
920306	42.8	40.0	43.8	37.4	36.6	30.7	32.3
920321	43.3	40.7	40.8	37.0	36.0	29.2	30.5
920415	43.6	40.5	43.1	36.8	36.3	29.9	30.8

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 3.

Table A10.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Clover catchment at the CEDR and PNMN locations*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]					
	CEDR			PNMN		
Date[1]	0.9	1.9	3.9	0.9	1.9	2.8
910205	29.8	28.6	28.9	--	--	--
910213	28.8	27.3	29.0	--	--	--
910327	28.1	26.8	28.4	--	--	--
910426	25.9	25.4	28.3	--	--	--
910514	25.3	24.1	28.2	--	--	--
910528	24.6	24.8	--	--	--	--
910605	23.1	22.5	28.0	--	--	--
910614	23.3	22.2	27.7	--	--	--
910624	24.5	23.5	28.2	--	--	--
910705	19.0	19.9	27.2	--	--	--
910711	17.0	18.1	26.1	--	--	--
910716	--	--	--	24.2	24.2	25.6
910718	13.7	15.8	20.8	23.4	24.0	25.6
910726	11.3	13.0	18.8	19.6	22.6	24.5
910802	8.5	9.7	16.9	14.8	18.5	21.6
910809	8.7	8.9	16.3	--	--	--
910812	--	--	--	16.2	18.3	21.5
910816	6.6	7.3	15.2	12.8	15.3	19.8
910822	6.3	6.9	14.6	9.6	12.9	18.2
910829	9.0	8.2	15.1	14.9	16.8	20.2
910905	8.6	7.7	14.6	13.9	15.5	19.3
910913	7.1	7.1	14.2	10.7	13.2	17.8
911004	6.2	6.0	13.3	7.8	11.4	16.2
911024	--	--	--	17.2	16.9	19.1
911029	8.9	9.3	14.0	--	--	--
911105	14.4	9.7	15.1	25.8	20.4	22.8
911112	--	--	16.3	--	--	--
911119	14.4	12.8	16.7	--	--	--
911120	--	--	--	38.9	32.5	31.6
911127	19.0	17.7	20.8	39.0	35.1	38.7
911210	21.2	18.5	22.7	44.6	39.8	42.1
911219	21.1	19.8	23.8	44.9	40.5	41.8
911231	22.2	20.7	24.6	44.8	40.6	41.7
920114	24.4	22.4	26.4	45.2	40.7	41.9
920124	26.0	24.5	27.3	48.7	43.3	43.2
920131	27.4	28.9	30.5	49.0	43.4	44.1
920210	26.6	26.7	28.4	47.0	42.2	42.9
920225	26.8	27.5	28.6	48.3	43.2	43.9
920306	27.1	26.7	28.6	49.2	43.5	43.7
920321	25.4	25.8	28.2	47.1	41.7	43.2

Table A10.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Clover catchment at the CEDR and PNMN locations--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]					
	CEDR			PNMN		
Date[1]	0.9	1.9	3.9	0.9	1.9	2.8
920415	24.8	24.7	28.3	46.6	42.7	43.8
920423	--	--	--	46.1	41.2	43.1
920514	--	--	--	36.8	34.0	37.4
920522	--	--	--	29.0	29.0	33.2
920603	--	--	--	19.7	22.3	25.9
920609	--	--	--	14.2	19.5	23.6
920623	--	--	--	12.4	17.3	22.1
920701	--	--	--	21.9	21.1	24.5
920713	--	--	--	19.1	20.6	23.8
920721	--	--	--	13.5	15.8	21.4
920728	--	--	--	11.1	14.5	20.4
920820	--	--	--	9.7	12.5	19.0
920827	--	--	--	9.2	10.8	18.8
920917	--	--	--	10.9	10.7	17.2
920929	--	--	--	20.2	15.8	20.2
921009	--	--	--	17.8	14.8	21.3
921021	--	--	--	23.6	18.8	23.5
921102	--	--	--	30.1	24.0	25.4
921117	--	--	--	31.6	28.9	30.4
921125	--	--	--	35.6	33.6	35.4
921212	--	--	--	44.7	42.6	42.1
921222	--	--	--	44.5	42.3	42.3
930106	--	--	--	43.0	39.8	40.1
930122	--	--	--	44.9	42.9	42.3
930129	--	--	--	44.6	42.9	42.6
930208	--	--	--	42.5	41.4	40.5
930219	--	--	--	40.3	37.8	37.7
930305	--	--	--	42.0	41.8	41.7
930317	--	--	--	41.6	42.5	42.6
930325	--	--	--	44.8	42.8	42.1
930406	--	--	--	44.6	42.6	42.5
930413	--	--	--	46.0	43.7	43.2
930422	--	--	--	45.1	43.2	42.7
930429	--	--	--	47.0	43.9	43.5
930519	--	--	--	38.1	37.7	37.3
930528	--	--	--	35.8	34.7	36.0
930616	--	--	--	42.1	39.4	40.2
930629	--	--	--	35.0	34.0	35.7
930712	--	--	--	26.6	27.4	30.9
930723	--	--	--	24.3	26.6	28.3
930805	--	--	--	18.7	22.2	26.6

Table A10.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Clover catchment at the CEDR and PNMN locations--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]					
	CEDR			PNMN		
Date[1]	0.9	1.9	3.9	0.9	1.9	2.8
930812	--	--	--	12.7	17.9	23.7
930910	--	--	--	8.6	12.6	19.5
931007	--	--	--	12.7	13.4	19.7

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 3.

Table A11.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Beaver catchment, downstream area*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TLBT			TLMD			TLTP		
Date[1]	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.9
920107	30.9	28.3	28.8	34.8	24.1	21.7	39.3	24.1	32.5
920117	32.0	28.8	30.2	34.5	26.0	21.9	39.9	24.3	33.6
920128	35.9	33.1	34.6	38.8	28.1	25.7	41.8	27.7	38.1
920213	31.3	26.2	32.8	33.8	26.1	18.8	39.3	25.0	34.3
920220	32.6	30.8	31.9	35.6	27.9	24.4	42.0	19.1	36.8
920311	30.9	28.6	28.7	31.3	26.3	22.5	40.2	24.7	33.2
920331	27.8	26.8	26.8	28.9	30.1	20.1	33.6	21.7	28.1
920414	31.2	29.2	29.5	32.5	26.7	22.4	40.3	23.3	32.9
920428	27.4	27.6	27.4	30.0	24.9	21.3	37.1	22.4	31.4
920512	25.6	25.4	26.0	26.1	22.5	19.4	29.9	19.4	28.3
920521	22.0	23.1	23.5	18.2	17.9	16.0	22.0	16.1	23.8
920602	17.8	19.8	20.8	13.9	14.9	14.1	15.8	13.0	20.3
920612	16.3	18.7	19.5	14.8	13.8	13.4	15.5	11.8	18.9
920622	15.7	17.3	17.8	13.1	12.1	12.1	14.0	10.4	17.0
920702	22.1	22.0	20.7	19.7	14.4	12.2	19.2	11.8	18.2
920710	25.6	23.0	21.2	23.0	15.7	13.1	23.8	12.9	19.3
920720	17.7	18.4	17.6	13.5	12.1	10.6	14.9	10.0	15.4
920729	14.9	15.7	14.7	11.3	10.5	9.4	12.2	8.9	14.1
920807	21.6	20.7	16.2	15.0	11.7	10.2	15.6	10.3	14.8
920818	14.7	14.7	12.6	11.2	9.8	8.6	12.4	8.9	12.6
920827	19.2	18.8	15.8	12.8	10.4	8.7	14.6	9.7	13.4
920915	15.3	14.5	12.4	12.1	9.9	8.6	13.1	8.7	12.9
920930	23.8	22.6	20.6	21.5	13.9	10.4	21.7	12.6	17.1
921008	22.5	21.2	19.3	19.6	13.5	10.1	19.8	11.8	16.7
921020	31.0	25.7	22.1	31.8	18.4	13.8	29.9	15.9	19.2
921103	29.0	26.9	26.6	31.5	24.6	20.2	36.8	21.8	26.0
921118	30.2	27.6	27.6	31.5	25.9	22.6	37.0	24.3	32.7
921128	29.5	27.0	28.2	32.0	25.8	22.6	40.9	22.5	32.1
921211	33.2	29.7	32.0	36.1	28.2	24.8	40.8	26.9	35.6
921221	30.5	28.7	30.4	32.9	26.5	23.8	40.5	24.8	34.4
930121	31.7	29.5	31.5	33.4	27.4	24.1	41.2	27.8	34.4
930129	30.0	28.4	30.1	30.7	26.0	23.3	38.4	24.7	34.3
930205	28.2	27.3	28.0	28.7	24.8	22.1	36.6	23.4	32.1
930212	28.1	26.8	27.1	28.9	24.8	21.6	36.0	22.5	31.6
930223	27.6	26.8	26.4	29.6	25.0	21.7	35.7	23.3	30.8
930308	27.8	27.1	26.8	29.0	24.5	22.1	34.9	23.4	32.0
930319	28.4	26.7	28.6	29.3	24.9	22.6	35.2	23.3	32.9
930324	27.8	27.6	29.7	29.8	25.4	23.5	36.2	23.9	34.0
930407	28.7	27.4	30.1	30.2	25.7	23.2	37.6	24.9	34.1
930414	28.4	27.5	29.1	29.5	25.2	22.8	38.2	23.8	33.8

Table A11.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Beaver catchment, downstream area--Continued*

Date[1]	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TLBT			TLMD			TLTP		
	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.9
930423	28.6	28.3	30.5	31.1	26.7	23.5	39.8	25.5	35.0
930430	27.4	27.1	28.5	29.6	25.4	22.5	37.9	24.4	33.6
930518	23.6	24.9	25.3	24.1	21.2	18.8	28.3	19.9	26.8
930527	25.2	24.8	25.4	21.8	20.7	17.9	25.3	18.8	25.8
930611	27.4	26.8	26.9	28.6	24.4	21.4	34.7	22.7	29.8
930629	22.6	23.1	24.1	20.6	19.2	17.6	24.6	18.0	25.5
930713	19.0	20.7	21.3	15.2	15.9	14.6	17.6	14.7	22.2
930723	22.1	21.9	22.4	17.5	16.9	15.2	19.7	15.5	22.1
930804	25.0	23.1	22.7	18.0	16.7	14.2	19.6	15.2	21.0
930813	21.6	20.5	20.0	13.8	14.3	12.9	16.9	13.0	19.5
930909	14.9	15.5	14.5	10.9	11.1	10.5	12.8	10.9	16.4
930930	12.9	13.3	12.3	9.8	9.9	9.2	11.2	9.4	14.4

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 4.

Table A12.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Beaver catchment, upstream area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TUBT			TUMD			TUTP		
Date[1]	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.9
920107	35.0	32.7	33.7	25.7	24.9	26.1	27.9	25.8	23.2
920117	36.1	33.5	33.2	27.7	25.9	26.9	29.8	25.9	21.7
920129	43.1	43.1	40.7	30.9	33.8	35.1	34.3	34.3	33.6
920226	38.3	39.1	37.9	26.4	29.6	31.5	28.4	25.2	27.2
920311	36.5	36.1	35.5	24.1	27.2	28.0	28.3	25.7	22.3
920331	31.4	30.4	31.0	19.2	22.3	24.3	22.1	16.4	17.0
920428	33.7	32.1	32.8	21.9	24.6	26.4	27.1	17.9	19.0
920512	30.3	28.1	29.8	18.6	21.9	24.3	22.6	16.4	16.9
920521	24.4	23.7	26.6	15.5	18.6	21.5	20.1	14.3	15.1
920602	18.0	19.0	23.0	13.0	15.8	18.6	16.3	12.2	13.3
920612	20.4	18.4	21.6	11.9	13.9	16.6	13.2	12.1	12.8
920622	16.1	15.3	19.3	10.8	12.4	14.7	14.6	10.5	11.5
920702	23.8	19.1	20.5	12.7	12.8	15.7	16.9	13.6	13.8
920710	27.3	21.5	22.6	13.3	13.4	14.8	23.7	15.6	15.4
920720	14.4	13.6	17.0	10.6	10.0	12.6	14.9	11.3	11.9
920729	12.8	12.0	15.3	10.0	10.2	11.5	11.9	9.1	9.9
920807	15.8	12.6	16.3	9.7	9.6	12.0	12.5	12.5	11.7
920818	12.3	11.1	13.7	9.0	8.7	10.5	9.2	8.8	9.1
920827	11.8	11.2	13.4	9.1	8.6	10.3	9.0	8.5	8.7
920915	11.3	10.5	12.9	8.9	8.5	9.6	8.4	8.0	8.2
920930	24.5	15.8	17.3	10.8	11.2	12.4	14.2	12.1	12.6
921008	18.1	14.0	16.6	9.8	10.1	11.2	15.3	11.3	11.5
921020	34.9	23.7	22.2	13.7	11.5	13.2	28.4	17.3	15.3
921103	32.4	27.9	27.1	20.7	18.7	19.9	21.6	16.8	16.4
921118	35.0	30.2	31.4	24.1	23.0	22.9	29.1	18.3	18.5
921128	34.1	30.2	31.7	23.7	23.0	24.1	27.5	17.3	18.9
921211	39.9	37.5	36.4	25.3	26.1	26.4	32.6	22.6	25.3
921221	37.2	34.7	35.2	26.4	25.7	25.5	29.7	22.6	24.3
930108	31.2	29.2	--	23.1	23.4	24.3	26.2	18.0	20.1
930121	39.9	36.6	35.7	27.5	27.0	27.2	35.0	23.4	25.5
930129	37.3	36.5	36.8	26.0	28.6	29.6	25.9	26.0	26.7
930205	35.4	34.3	35.2	22.3	26.3	27.8	23.3	20.3	23.0
930212	33.7	31.2	33.2	22.3	25.4	26.9	24.2	18.0	20.9
930223	32.8	29.8	31.9	22.9	25.0	25.6	25.8	17.2	18.5
930308	31.8	29.2	31.5	22.4	24.5	25.5	23.7	17.6	18.2
930319	32.7	29.9	31.9	23.1	24.4	25.6	27.0	18.3	18.9
930324	36.8	36.3	35.8	26.0	28.8	30.2	29.0	21.7	24.5
930407	35.6	33.0	34.6	26.7	27.9	28.8	30.1	19.8	22.4
930414	36.0	35.2	35.4	25.8	27.8	29.5	30.3	21.6	24.0
930423	37.6	35.3	36.1	27.0	29.1	30.8	31.6	23.7	25.8

Table A12.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Beaver catchment, upstream area--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TUBT			TUMD			TUTP		
Date[1]	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.9
930430	35.9	34.5	35.6	24.7	28.0	29.4	29.6	22.1	24.9
930518	30.4	28.2	30.9	19.8	23.7	25.7	24.5	16.8	18.5
930527	28.2	26.7	28.9	18.9	22.8	25.0	21.9	16.7	17.4
930611	32.9	29.4	31.4	23.4	25.2	25.6	26.9	18.6	19.1
930629	24.0	23.7	26.4	18.0	16.5	21.9	24.7	15.6	16.0
930713	17.4	18.7	23.4	13.7	16.0	18.7	20.8	12.7	13.6
930723	20.9	19.8	23.8	14.8	16.4	18.0	25.7	13.2	13.9
930804	15.9	17.0	21.2	12.8	13.8	16.0	18.6	14.1	14.2
930813	13.5	13.9	19.1	11.5	11.6	13.9	15.9	11.3	12.1
930909	11.8	11.5	15.2	9.4	9.5	10.7	13.2	8.6	9.0
930930	11.0	10.7	13.7	8.8	8.9	9.8	7.1	7.5	7.7

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 4.

Table A13.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Vaughn catchment, downstream area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TLBT			TLMD			TLTP		
Date[1]	0.9	1.9	2.8	0.9	1.9	2.9	0.9	1.9	2.7
920107	47.7	41.2	37.7	30.7	24.5	26.0	41.2	31.9	30.8
920117	35.0	31.5	31.0	32.5	25.5	25.6	40.9	33.2	32.2
920129	--	--	--	34.7	31.6	31.9	41.3	35.5	34.2
920213	50.3	43.7	40.2	--	26.9	26.5	40.9	33.4	32.9
920220	50.6	44.0	40.8	33.3	28.2	28.2	41.6	35.0	34.4
920311	37.2	35.3	33.8	28.4	24.9	25.0	38.3	32.2	31.7
920331	28.4	28.0	29.5	24.2	22.5	22.2	33.7	28.1	28.4
920414	28.6	27.5	--	29.9	23.8	23.6	37.5	29.5	29.4
920424	26.8	27.5	28.3	28.2	25.1	--	--	--	--
920428	26.4	27.2	27.3	28.3	25.1	24.6	38.1	31.1	31.0
920512	24.8	25.7	25.0	27.1	24.4	24.0	36.8	30.5	30.8
920521	20.8	22.6	22.4	24.2	22.1	22.0	33.1	27.4	28.1
920602	17.5	20.3	20.6	22.5	20.5	20.5	31.7	25.7	26.6
920612	16.1	18.8	19.6	20.2	18.7	18.5	30.7	24.0	25.2
920622	13.8	16.3	17.5	18.0	16.8	16.5	28.6	22.2	23.2
920702	15.8	16.2	16.9	18.9	16.7	16.1	28.4	21.5	22.1
920710	16.0	15.9	16.0	18.5	16.1	15.5	27.9	21.3	21.5
920720	11.9	12.9	13.6	15.0	13.6	13.5	26.2	18.6	19.7
920729	9.9	11.1	11.9	14.0	12.2	12.5	22.9	17.4	17.2
920807	15.4	15.4	13.4	16.0	14.6	14.0	24.8	18.2	17.4
920818	9.5	10.0	10.1	13.2	13.0	12.2	21.7	16.7	18.8
920827	8.9	9.2	9.5	12.1	11.6	11.4	20.3	15.4	15.4
920914	9.2	9.4	9.6	--	--	--	--	--	--
920915	8.9	9.5	9.5	11.7	10.4	10.9	19.5	15.8	14.6
920930	12.3	11.9	11.4	16.0	13.9	12.6	23.5	17.0	16.6
921008	10.0	10.5	10.3	13.9	12.4	12.1	22.3	16.2	16.4
921020	16.4	15.2	12.1	19.0	16.2	14.1	26.9	18.9	17.9
921103	22.0	20.3	17.9	26.5	22.6	19.0	34.4	25.2	24.7
921118	23.3	22.2	21.2	28.2	24.5	23.9	38.3	30.1	28.4
921128	23.3	21.5	21.1	26.9	24.7	24.3	38.0	30.2	30.9
921211	26.8	24.1	25.3	29.2	26.4	27.1	38.2	31.5	32.1
921221	24.9	25.7	26.5	28.5	25.6	26.0	38.3	31.2	32.0
930108	21.9	21.2	21.7	26.7	24.1	23.7	36.9	30.0	30.7
930119	30.5	26.9	24.1	31.9	27.1	26.0	40.2	33.3	32.4
930120	50.9	43.3	38.3	--	--	--	--	--	--
930128	--	--	--	29.7	26.6	26.6	38.7	31.3	31.4
930205	48.1	42.2	36.3	26.8	23.7	24.0	36.1	29.5	30.3
930212	26.3	27.4	28.5	25.9	23.6	23.5	35.7	28.8	30.0
930223	22.5	22.5	22.9	26.1	22.9	22.9	35.4	28.4	29.5
930308	21.5	21.9	22.1	26.9	24.2	23.4	36.8	30.1	30.5

Table A13.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Vaughn catchment, downstream area--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TLBT			TLMD			TLTP		
Date[1]	0.9	1.9	2.8	0.9	1.9	2.9	0.9	1.9	2.7
930319	22.1	40.5	21.6	27.1	24.2	23.3	36.9	30.3	30.5
930323	45.8	40.5	35.6	30.0	27.6	27.7	39.5	32.5	32.6
930405	37.6	35.4	33.3	27.9	25.1	25.0	37.5	31.3	31.4
930414	47.2	42.1	36.3	27.7	25.5	25.1	37.7	31.6	31.4
930423	44.7	41.3	36.9	29.6	26.1	25.6	40.1	32.5	32.1
930430	46.8	41.9	37.4	27.8	24.9	25.1	39.3	31.7	31.4
930518	23.6	25.0	27.0	24.3	22.2	22.7	35.6	28.0	29.9
930527	21.5	23.3	24.7	24.5	22.6	22.6	35.7	28.9	29.9
930611	22.8	22.9	23.8	26.8	24.5	24.8	38.1	31.6	31.2
930628	15.1	18.4	19.1	23.5	21.1	21.9	34.0	27.1	28.8
930713	11.5	15.2	16.2	18.8	18.1	18.7	29.0	23.4	25.5
930723	13.4	15.3	15.9	19.7	18.1	17.7	29.8	22.6	23.8
930804	11.4	13.9	14.7	17.8	16.2	15.7	27.3	21.1	21.7
930813	9.2	11.6	12.9	14.2	13.8	13.5	25.6	19.0	19.6
930909	8.2	9.3	10.0	12.2	11.0	11.6	20.5	15.5	15.2
930930	8.0	8.8	9.1	11.1	10.3	10.7	18.6	14.5	14.1

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 5.

Table A14.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Vaughn catchment, isotope sampling area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	LYBT			LYMD			LYTP		
Date[1]	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.7
920220	52.3	48.1	44.5	22.7	22.0	20.7	30.7	26.7	25.5
920303	53.5	48.5	44.7	22.0	20.4	19.7	29.6	25.4	24.0
920319	41.0	41.9	39.9	20.9	18.9	18.7	26.3	23.7	22.5
920331	30.2	33.6	34.3	17.2	16.1	16.8	22.5	21.3	20.5
920414	28.7	30.2	36.7	22.5	17.4	17.9	28.1	23.9	22.0
920428	26.4	31.1	30.7	21.3	19.9	18.5	25.6	24.1	22.7
920512	24.2	27.8	26.6	16.9	16.7	18.1	24.2	22.6	21.4
920521	22.3	25.5	24.0	13.4	15.0	16.0	20.2	19.7	18.9
920602	21.7	24.2	22.4	12.8	13.5	14.5	17.5	17.3	17.0
920612	20.9	23.3	21.7	12.8	13.1	13.7	17.9	16.5	15.8
920622	19.0	22.0	20.3	10.7	12.1	12.2	14.8	13.9	13.6
920702	20.6	22.5	20.5	10.4	10.1	11.6	16.7	14.4	13.3
920710	21.7	23.1	20.8	10.2	10.1	10.9	16.5	13.4	12.5
920720	16.6	19.5	18.5	9.0	8.7	9.5	12.7	11.1	10.7
920729	13.5	16.9	17.0	8.1	8.3	8.8	11.4	10.0	9.5
920807	14.4	16.7	16.9	9.5	8.7	8.7	12.6	10.6	10.4
920818	11.9	14.9	15.1	8.5	7.6	7.8	11.0	9.6	9.3
920827	9.8	13.0	13.9	7.7	7.9	7.6	--	--	--
920829	--	--	--	--	--	--	10.3	9.1	8.6
920915	9.2	12.2	12.7	7.8	6.9	7.2	10.0	8.8	8.7
920930	14.6	14.6	14.8	9.6	8.5	8.3	14.9	11.1	10.4
921008	12.6	13.9	14.1	8.3	8.1	7.9	13.0	10.1	9.7
921020	14.5	15.2	14.6	10.7	8.3	8.7	18.1	12.2	10.8
921103	22.3	24.6	21.8	18.4	13.8	12.8	25.5	20.7	15.2
921118	20.8	25.2	23.8	20.2	17.9	18.2	27.2	23.8	18.0
921128	19.7	25.5	24.0	18.8	17.7	18.7	27.2	24.7	22.8
921211	21.2	29.3	29.7	20.7	18.8	21.3	28.1	26.5	25.1
921221	44.5	43.8	40.4	19.1	17.3	19.9	27.6	26.0	24.9
930108	25.2	34.3	33.7	16.7	16.9	17.9	25.1	23.8	22.9
930119	24.7	32.1	32.4	20.2	18.3	20.0	28.9	26.3	24.2
930128	53.5	47.3	43.2	18.6	18.3	19.8	27.1	25.6	25.1
930205	48.7	45.1	41.5	15.7	17.6	18.1	24.2	23.1	23.0
930212	36.6	41.1	37.5	15.7	16.1	18.2	23.9	22.3	22.3
930223	26.8	33.5	33.0	14.9	15.3	17.4	24.9	22.2	22.2
930308	22.4	28.7	29.4	15.3	16.0	18.0	24.9	23.6	22.9
930319	20.7	26.4	26.7	15.6	16.4	17.9	25.8	24.3	23.2
930323	49.4	45.3	40.9	19.0	18.2	21.3	28.1	27.2	27.6
930405	44.4	44.4	39.6	16.3	17.5	18.9	25.9	24.3	24.0
930414	48.0	46.1	41.9	18.7	17.5	19.1	26.1	24.3	24.4
930423	47.6	45.7	41.5	17.7	19.4	19.5	27.3	22.7	24.3

Table A14.--*Soil moistures measured in situ by the time-domain reflectometry (TDR) method in the Vaughn catchment, isotope sampling area--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	LYBT			LYMD			LYTP		
Date[1]	0.9	1.9	2.9	0.9	1.9	2.9	0.9	1.9	2.7
930430	48.2	45.8	42.1	15.5	16.9	18.9	25.9	24.4	24.0
930518	26.3	35.8	35.1	13.5	14.9	16.9	21.2	20.6	20.3
930527	22.2	29.1	30.0	14.0	16.1	17.3	20.9	21.1	20.3
930611	21.6	27.6	26.8	13.7	17.0	18.5	24.9	23.5	22.0
930628	18.5	23.8	22.6	13.1	15.1	15.8	18.5	18.8	18.7
930713	--	21.4	20.3	10.4	13.0	13.2	15.4	15.4	15.1
930723	18.2	21.7	52.5	10.2	12.6	12.7	15.5	14.6	14.2
930804	16.0	21.9	20.3	10.7	11.6	11.4	14.0	12.9	12.7
930813	15.9	19.5	18.6	8.4	10.1	10.1	12.0	11.3	10.8
930909	11.3	14.0	14.3	6.3	7.5	7.9	12.0	9.5	9.0
930930	8.7	11.7	12.7	6.0	7.0	7.3	9.6	-1.5	8.7

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 5.

Table A15.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Vaughn catchment, upstream area*

[--, indicates no data]

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TUBT			TUMD			TUTP		
Date[1]	0.9	1.9	2.8	0.9	1.9	2.9	0.9	1.9	2.9
920107	--	--	--	24.0	26.6	28.8	31.3	31.0	42.9
920117	56.3	49.4	45.0	24.9	26.9	28.1	33.3	32.0	42.5
920129	--	--	--	29.7	33.7	35.8	36.5	34.9	44.4
920213	--	--	--	25.7	24.2	27.2	33.7	32.7	42.8
920226	--	--	--	24.2	26.9	30.3	33.0	32.4	43.7
920319	55.7	49.3	45.3	20.2	23.8	26.4	28.3	30.2	99.9
920331	48.2	43.4	42.1	18.3	21.3	24.1	19.7	25.3	40.6
920414	46.1	40.8	40.5	23.5	24.3	25.9	23.9	27.4	41.5
920512	42.8	33.3	35.8	19.0	23.0	25.5	22.9	28.4	44.3
920521	38.0	27.6	32.3	16.5	20.2	23.3	20.1	25.1	41.4
920602	31.8	23.8	30.0	15.7	18.7	22.0	16.7	22.5	40.5
920612	32.3	23.3	28.8	13.5	16.4	19.8	15.2	20.8	36.9
920622	30.0	21.2	27.4	11.8	14.8	17.8	13.7	19.6	36.0
920702	31.3	21.7	27.7	14.6	16.0	17.9	15.7	20.5	36.3
920710	31.2	22.3	28.1	14.0	15.1	17.1	15.2	20.7	37.7
920720	26.5	20.2	25.2	9.5	11.4	14.4	12.6	17.3	30.5
920729	21.8	16.9	23.6	8.1	10.3	12.7	10.8	15.6	28.0
920807	20.9	15.9	22.4	12.7	13.3	13.4	14.6	18.3	31.1
920818	17.3	14.8	21.2	8.4	10.0	11.5	11.0	14.9	23.6
920827	14.9	12.7	20.4	7.3	9.2	10.7	9.7	13.9	23.1
920915	13.6	10.7	18.0	7.1	8.9	10.3	9.6	13.3	22.2
920930	15.1	13.6	18.2	12.3	13.2	13.5	13.2	16.4	23.2
921008	14.5	12.6	18.8	10.0	11.3	12.2	11.7	15.2	22.8
921020	18.9	15.9	20.3	16.6	14.4	15.6	16.3	17.6	24.3
921103	29.2	22.2	29.5	19.6	21.2	22.5	22.2	27.2	34.1
921118	32.0	25.2	30.3	20.0	22.6	25.5	27.0	30.3	39.2
921128	31.6	23.2	30.6	19.7	23.3	26.4	25.2	29.6	36.5
921211	40.0	41.0	38.3	21.9	25.4	30.1	27.0	31.8	40.1
921221	--	--	--	21.3	24.6	28.8	25.9	29.9	37.1
930108	34.3	24.5	31.4	18.8	22.1	26.0	25.0	29.3	36.2
930119	36.6	26.5	31.3	25.0	25.5	28.9	29.5	32.4	40.7
930128	--	--	--	21.7	25.3	30.1	26.8	30.4	38.5
930205	53.0	48.5	45.1	17.6	22.0	26.3	23.6	28.6	36.8
930212	44.6	43.5	39.8	17.3	20.9	25.1	22.6	27.9	36.7
930223	34.4	25.1	30.3	18.1	21.0	25.1	22.7	28.0	36.8
930308	32.6	22.4	29.3	18.2	21.8	25.8	24.7	28.8	37.5
930319	33.3	23.3	29.5	18.8	22.5	26.1	25.0	29.4	38.0
930323	--	--	--	22.8	26.5	31.6	28.3	32.3	40.1
930405	50.7	46.9	43.2	19.5	23.1	26.8	25.1	29.3	39.4
930414	--	--	--	20.4	23.1	28.4	26.0	28.1	37.6

Table A15.--*Soil moistures measured in situ by the time-domain reflectometry method (TDR) in the Vaughn catchment, upstream area--Continued*

	Average soil moisture, in percent by volume, at indicated locations, from surface to indicated depths, in feet[2]								
	TUBT			TUMD			TUTP		
Date[1]	0.9	1.9	2.8	0.9	1.9	2.9	0.9	1.9	2.9
930423	--	--	--	23.2	24.1	27.9	27.6	30.9	40.7
930430	--	--	--	19.6	23.0	27.5	25.3	29.3	39.5
930518	45.6	42.7	38.8	16.1	20.0	24.4	20.2	26.6	37.3
930527	40.1	24.8	34.8	16.8	20.6	24.9	18.6	26.9	37.5
930611	37.1	21.5	31.9	19.7	22.4	25.6	25.5	29.7	39.2
930628	29.5	17.4	27.9	15.8	18.8	23.1	19.1	25.2	36.8
930713	27.1	16.0	25.7	12.2	15.5	19.8	14.7	20.6	35.8
930723	29.0	15.9	26.1	13.1	15.6	19.6	15.1	20.5	36.4
930804	26.7	15.7	25.4	12.3	14.5	18.2	14.3	19.5	33.7
930813	22.7	17.2	23.6	8.2	11.3	14.6	11.4	16.9	31.5
930909	16.9	14.7	19.9	6.8	9.3	11.5	9.8	14.3	25.0
930930	13.3	11.7	17.9	6.4	8.5	10.4	9.1	12.7	21.8

[1]Dates are listed as year, month, day.

[2]Locations of piezometers are shown on figure 5.

Table A16.--*Monthly computed water-budget summaries for the Clover catchment*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
								1991 Water year									
October	1990	3.40	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.44	1.87	1.09	0.00	51.3	0.00	0.00
November	1990	11.15	0.41	0.00	4.97	0.09	0.00	0.00	0.00	0.11	0.11	5.12	1.38	0.00	46.7	0.41	-0.53
December	1990	4.12	0.31	0.00	3.08	0.34	0.00	0.00	0.09	0.07	0.07	-0.28	0.83	0.00	35.2	0.92	0.00
January	1991	4.21	0.45	0.00	3.41	0.13	0.00	0.00	0.00	0.16	0.16	0.17	0.84	0.00	39.4	0.46	-0.51
February	1991	5.24	0.76	0.00	4.06	0.28	0.00	0.00	0.00	0.39	0.39	-0.28	0.84	0.00	47.2	0.92	-0.0
March	1991	4.96	1.35	0.00	2.85	0.32	0.00	0.00	0.00	0.61	0.61	-0.07	1.33	0.00	44.2	0.99	-0.07
April	1991	6.40	2.38	0.00	3.88	0.25	0.00	0.00	0.00	1.20	1.20	-0.09	1.28	0.00	49.6	1.28	-0.12
May	1991	2.08	3.35	0.00	0.45	0.00	0.00	0.00	0.00	1.90	1.90	-0.94	1.12	0.00	54.3	0.00	-0.45
June	1991	1.46	3.67	0.00	0.04	0.00	0.00	0.00	0.00	2.24	2.24	-1.63	0.85	0.00	58.7	0.00	-0.04
July	1991	0.26	5.44	0.00	0.00	0.00	0.00	0.00	0.00	3.89	3.49	-3.37	0.15	0.00	65.3	0.00	0.00
August	1991	1.91	4.19	0.00	0.00	0.00	0.00	0.00	0.00	2.96	1.42	0.01	0.48	0.00	64.5	0.00	0.00
September	1991	0.02	3.03	0.00	0.00	0.00	0.00	0.00	0.00	2.20	1.13	-1.13	0.02	0.00	58.9	0.00	0.00
Totals:		45.21	26.45	0.00	22.73	1.41	0.00	0.00	0.09	16.19	13.17	-0.62	10.19	0.00	51.3	4.98	-1.77
								1992 Water year									
October	1991	1.66	1.52	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.34	0.81	0.52	0.00	50.0	0.00	0.00
November	1991	6.51	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.13	5.05	1.33	0.00	46.8	0.00	0.00
December	1991	3.08	0.32	0.00	0.51	0.19	0.00	0.00	0.00	0.12	0.12	1.53	0.73	0.00	43.9	1.02	0.00
January	1992	6.13	0.38	0.00	2.92	0.24	0.00	0.00	0.00	0.12	0.12	1.85	1.00	0.00	44.3	2.15	0.00
February	1992	3.09	0.78	0.00	2.57	0.32	0.00	0.00	0.00	0.38	0.38	-1.04	0.86	0.00	46.6	2.48	0.00
March	1992	1.73	1.76	0.00	0.86	0.29	0.00	0.00	0.00	1.10	1.10	-1.11	0.61	0.00	47.9	1.02	-0.02
April	1992	4.64	2.52	0.00	2.14	0.15	0.00	0.00	0.00	1.34	1.34	0.10	1.34	0.00	51.2	0.29	-0.42
May	1992	0.08	4.38	0.00	0.10	0.00	0.00	0.00	0.00	3.15	3.15	-3.15	0.08	0.00	56.4	0.00	-0.10
June	1992	2.38	4.60	0.00	0.00	0.00	0.00	0.00	0.00	3.17	3.04	-1.11	0.45	0.00	61.7	0.00	0.00
July	1992	1.21	4.22	0.00	0.01	0.00	0.00	0.00	0.00	2.95	2.66	-1.77	0.32	0.00	63.6	0.00	-0.01
August	1992	0.84	4.16	0.00	0.00	0.00	0.00	0.00	0.00	2.97	1.66	-0.99	0.17	0.00	63.6	0.00	0.00
September	1992	1.82	2.48	0.00	0.00	0.00	0.00	0.00	0.00	1.67	0.75	0.64	0.43	0.00	57.4	0.00	0.00
Totals:		33.17	27.53	0.00	9.10	1.18	0.00	0.00	0.00	18.10	14.77	0.83	7.83	0.00	52.8	6.95	-0.55

Table A16.--*Monthly computed water-budget summaries for the Clover catchment--Continued*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
								1993 Water year									
October	1992	2.60	1.02	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.59	1.14	0.88	0.00	51.9	0.00	0.00
November	1992	5.71	0.41	0.00	0.01	0.01	0.00	0.00	0.00	0.16	0.16	4.51	1.02	0.00	45.3	0.01	0.00
December	1992	3.45	0.32	0.00	0.89	0.22	0.00	0.00	0.00	0.13	0.13	1.58	0.63	0.00	39.3	1.49	0.00
January	1993	3.67	0.45	0.00	1.81	0.26	0.00	0.00	0.00	0.26	0.26	0.76	0.57	0.00	40.3	2.37	0.00
February	1993	0.26	0.92	0.00	0.31	0.29	0.00	0.00	0.00	0.62	0.62	-1.14	0.19	0.00	42.1	1.57	0.00
March	1993	4.38	1.49	0.00	1.64	0.32	0.00	0.00	0.00	0.73	0.73	0.59	1.09	0.00	46.2	1.81	0.00
April	1993	5.61	1.90	0.00	2.53	0.33	0.00	0.00	0.00	0.65	0.65	0.12	1.98	0.00	48.9	2.48	0.00
May	1993	3.53	3.63	0.00	0.64	0.24	0.00	0.00	0.00	2.08	2.08	-0.76	1.35	0.00	57.9	1.02	-0.01
June	1993	1.91	3.65	0.00	0.13	0.13	0.00	0.00	0.00	2.28	2.28	-1.51	0.88	0.00	58.4	0.28	0.00
July	1993	1.31	3.13	0.00	0.00	0.00	0.00	0.00	0.00	2.02	2.02	-1.42	0.70	0.00	59.6	0.00	0.00
August	1993	0.00	3.83	0.00	0.00	0.00	0.00	0.00	0.00	2.80	2.79	-2.79	0.00	0.00	62.6	0.00	0.00
September	1993	0.00	2.93	0.00	0.00	0.00	0.00	0.00	0.00	2.14	1.68	-1.68	0.00	0.00	58.5	0.00	0.00
Totals:		32.43	23.69	0.00	7.95	1.80	0.00	0.00	0.00	14.47	13.99	-0.59	9.29	0.00	51.0	11.04	-0.01
								Average monthly values									
October		2.55	1.21	0.00	0.00	0.00	0.00	0.00	0.00	0.68	0.45	1.27	0.83	0.00	51.1	0.00	0.00
November		7.79	0.41	0.00	1.66	0.03	0.00	0.00	0.00	0.13	0.13	4.90	1.24	0.00	46.3	0.14	-0.18
December		3.55	0.32	0.00	1.49	0.25	0.00	0.00	0.03	0.10	0.10	0.94	0.73	0.00	39.5	1.15	0.00
January		4.67	0.43	0.00	2.71	0.21	0.00	0.00	0.00	0.18	0.18	0.93	0.81	0.00	41.3	1.66	-0.17
February		2.86	0.82	0.00	2.31	0.30	0.00	0.00	0.00	0.46	0.46	-0.82	0.63	0.00	45.3	1.66	-0.02
March		3.69	1.53	0.00	1.79	0.31	0.00	0.00	0.00	0.82	0.82	-0.20	1.01	0.00	46.1	1.27	-0.03
April		5.55	2.27	0.00	2.85	0.24	0.00	0.00	0.00	1.06	1.06	0.04	1.53	0.00	49.9	1.35	-0.18
May		1.90	3.79	0.00	0.39	0.08	0.00	0.00	0.00	2.38	2.38	-1.62	0.85	0.00	56.2	0.34	-0.19
June		1.92	3.97	0.00	0.06	0.04	0.00	0.00	0.00	2.56	2.52	-1.41	0.72	0.00	59.6	0.09	-0.01
July		0.93	4.26	0.00	0.00	0.00	0.00	0.00	0.00	2.96	2.72	2.19	0.39	0.00	62.8	0.00	0.00
August		0.92	4.06	0.00	0.00	0.00	0.00	0.00	0.00	2.91	1.96	-1.25	0.21	0.00	63.6	0.00	0.00
September		0.61	2.81	0.00	0.00	0.00	0.00	0.00	0.00	2.00	1.19	-0.72	0.15	0.00	58.3	0.00	0.00
Totals:		36 94	25.89	0.00	13.26	1.46	0.00	0.00	0.03	16.25	13.98	-0.13	9.10	0.00	51.7	7.66	-0.78

Table A16.--*Monthly computed water-budget summaries for the Clover catchment--Continued*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															

[1]PRCP = observed precipitation;

POTET = potential evapotranspiration (may be less than sum of evaporation and transpiration components, as dicussed in report),

CHGINT = change in moisture stored on foliage (zero when throughfall data is used, as in this investigation),

RO = observed, or estimated direct runoff,

RCH = soil water that percolates below the root zone (recharge),

SOLPEV = potential soil evaporation over bare soil areas (none in this investigation),

EVSOL = evaporation from bare soil areas (none in this investigation),

EVSNW = sublimation of snow,

PPLTR = foliage-type-dependent potential transpiration,

TR = transpiration,

CHGSM = change in soil moisture,

EVINT = interception loss computed from input throughfall, or DPM-simulated throughfall if not input,

CHGSNW = change in snowpack,

AVTMP = average temperature,

SYMRO = DPM-simulated direct runoff,

DEFCIT = if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity - evaporation and transpiration components - observed direct runoff, if the following is positive: rain + snowmelt - (available water-holding capacity + specific yield - starting soil moisture) - observed direct runoff - recharge..

Table A17.--*Monthly computed water-budget summaries for the Beaver catchment*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
									1992 Water year								
October	1991	2.14	1.54	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.59	0.65	0.90	0.00	51.0	0.00	0.00
November	1991	7.50	0.44	0.00	0.27	0.54	0.00	0.00	0.00	0.08	0.08	3.96	2.65	0.00	46.2	0.48	0.00
December	1991	5.08	0.33	0.00	0.88	2.10	0.00	0.00	0.01	0.05	0.05	-0.08	2.10	0.00	41.3	2.08	0.02
January	1992	11.25	0.37	0.00	4.73	1.92	0.00	0.00	0.00	0.09	0.09	1.95	2.56	0.00	42.5	2.57	0.00
February	1992	4.62	0.77	0.00	2.86	0.70	0.00	0.00	0.00	0.32	0.32	-0.87	1.61	0.00	45.8	3.34	0.00
March	1992	0.98	1.89	0.00	0.33	0.00	0.00	0.00	0.00	1.21	1.21	-1.23	0.66	0.00	49.5	2.25	0.00
April	1992	5.25	2.54	0.00	0.79	1.10	0.00	0.00	0.00	1.22	1.22	0.10	2.03	0.00	51.8	0.80	0.00
May	1992	0.13	4.66	0.00	0.05	0.00	0.00	0.00	0.00	3.33	3.09	-3.11	0.13	0.00	59.2	0.00	-0.03
June	1992	1.69	4.85	0.00	0.00	0.00	0.00	0.00	0.00	3.33	1.58	-0.57	0.68	0.00	64.1	0.00	0.00
July	1992	1.02	4.42	0.00	0.00	0.00	0.00	0.00	0.00	3.03	1.47	-0.93	0.48	0.00	66.1	0.00	0.00
August	1992	1.41	4.33	0.00	0.00	0.00	0.00	0.00	0.00	3.03	1.09	-0.03	0.34	0.00	66.2	0.00	0.00
September	1992	2.05	2.54	0.00	0.00	0.00	0.00	0.00	0.00	1.66	0.82	0.54	0.69	0.00	59.1	0.00	0.00
Totals:		43.12	28.70	0.00	9.91	6.36	0.00	0.00	0.01	18.31	11.62	0.39	14.83	0.00	53.6	11.53	-0.01
									1993 Water year								
October	1992	3.46	1.04	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.55	1.32	1.58	0.00	53.0	0.01	0.00
November	1992	6.05	0.44	0.00	0.20	0.77	0.00	0.00	0.00	0.15	0.15	3.20	1.68	0.00	44.5	0.81	0.05
December	1992	4.03	0.34	0.00	0.91	1.95	0.00	0.00	0.00	0.09	0.09	-0.49	1.49	0.00	37.8	1.51	0.09
January	1993	6.01	0.43	0.00	2.72	1.19	0.00	0.00	0.00	0.11	0.11	0.91	1.10	0.00	36.0	1.88	-0.02
February	1993	0.44	0.88	0.00	0.18	0.61	0.00	0.00	0.00	0.53	0.53	-1.19	0.31	0.00	39.8	0.43	0.00
March	1993	4.88	1.57	0.00	1.15	0.00	0.00	0.00	0.00	0.73	0.73	1.36	1.64	0.00	46.6	1.66	0.00
April	1993	3.91	1.98	0.00	1.70	0.00	0.00	0.00	0.00	0.88	0.88	-0.63	1.96	0.00	50.0	3.73	0.00
May	1993	2.60	3.81	0.00	0.48	0.00	0.00	0.00	0.00	2.19	2.18	-1.22	1.40	0.00	59.6	0.12	-0.25
June	1993	2.30	3.83	0.00	0.20	0.00	0.00	0.00	0.00	2.32	2.30	-1.12	1.08	0.00	60.4	0.00	-0.17
July	1993	1.47	3.24	0.00	0.07	0.00	0.00	0.00	0.00	2.03	1.78	-1.22	0.92	0.00	61.2	0.00	-0.07
August	1993	0.24	3.99	0.00	0.00	0.00	0.00	0.00	0.00	2.87	1.57	-1.52	0.19	0.00	65.0	0.00	0..00
September	1993	0.00	3.03	0.00	0.00	0.00	0.00	0.00	0.00	2.22	0.57	-0.57	0.00	0.00	61.1	0.00	0.00
Totals:		35.39	24.59	0.00	7.61	4.52	0.00	0.00	0.00	14.69	11.44	-1.17	13.35	0.00	51.3	10.16	-0.37

Table A17 --*Monthly computed water-budget summaries for the Beaver catchment--Continued*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
		Average monthly values:															
October		2.80	1.29	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.57	0.99	1.24	0.00	52.0	0.01	0.00
November		6.77	0.44	0.00	0.23	0.66	0.00	0.00	0.00	0.11	0.11	3.58	2.17	0.00	45.4	0.65	0.02
December		4.55	0.33	0.00	0.89	2.03	0.00	0.00	0.00	0.07	0.07	-0.29	1.79	0.00	39.5	1.79	0.05
January		8.63	0.40	0.00	3.72	1.55	0.00	0.00	0.00	0.10	0.10	1.43	1.83	0.00	39.3	2.23	-0.01
February		2.53	0.82	0.00	1.52	0.65	0.00	0.00	0.00	0.42	0.42	-1.03	0.96	0.00	42.8	1.89	0.00
March		2.93	1.73	0.00	0.74	0.00	0.00	0.00	0.00	0.97	0.97	0.07	1.15	0.00	48.1	1.95	0.00
April		4.58	2.26	0.00	1.25	0.55	0.00	0.00	0.00	1.05	1.05	-0.27	2.00	0.00	50.9	2.27	0.00
May		1.37	4.24	0.00	0.27	0.00	0.00	0.00	0.00	2.76	2.64	-2.16	0.76	0.00	59.4	0.06	-0.14
June		2.00	4.34	0.00	0.10	0.00	0.00	0.00	0.00	2.83	1.94	-0.84	0.88	0.00	62.2	0.00	-0.09
July		1.24	3.83	0.00	0.03	0.00	0.00	0.00	0.00	2.53	1.62	-1.08	0.70	0.00	63.7	0.00	-0.03
August		0.82	4.16	0.00	0.00	0.00	0.00	0.00	0.00	2.95	1.33	-0.77	0.26	0.00	65.6	0.00	0.00
September		1.03	2.79	0.00	0.00	0.00	0.00	0.00	0.00	1.94	0.70	-0.02	0.34	0.00	60.1	0.00	0.00
Totals:		39.25	26.64	0.00	8.76	5.44	0.00	0.00	0.00	16.50	11.53	-0.39	14.09	0.00	52.5	10.84	-0.19

[1]PRCP = observed precipitation;
POTET = potential evapotranspiration (may be less than sum of evaporation and transpiration components, as dicussed in report),
CHGINT = change in moisture stored on foliage (zero when throughfall data is used, as in this investigation),
RO = observed, or estimated direct runoff,
RCH = soil water that percolates below the root zone (recharge),
SOLPEV = potential soil evaporation over bare soil areas (none in this investigation),
EVSOL = evaporation from bare soil areas (none in this investigation),
EVSNW = sublimation of snow,
PPLTR = foliage-type-dependent potential transpiration,
TR = transpiration,
CHGSM = change in soil moisture,
EVINT = interception loss computed from input throughfall, or DPM-simulated throughfall if not input,
CHGSNW = change in snowpack,
AVTMP = average temperature,
SYMRO = DPM-simulated direct runoff,
DEFCIT = if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity - evaporation and transpiration components - observed direct runoff, if the following is positive: rain + snowmelt - (available water-holding capacity + specific yield - starting soil moisture) - observed direct runoff - recharge.

Table A18.--*Monthly computed water-budget summaries for the Vaughn catchment*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
									1992 Water year								
October	1991	2.16	1.54	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.71	0.08	1.37	0.00	51.2	0.00	0.00
November	1991	7.58	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.08	3.24	4.26	0.00	46.3	0.00	0.00
December	1991	4.86	0.33	0.00	0.52	0.31	0.00	0.00	0.00	0.04	0.04	1.33	3.10	0.00	41.6	0.03	-0.45
January	1992	11.75	0.37	0.00	4.63	2.42	0.00	0.00	0.00	0.10	0.10	1.39	3.23	0.00	42.7	1.87	-0.02
February	1992	5.12	0.77	0.00	1.86	2.19	0.00	0.00	0.00	0.32	0.32	-1.44	2.25	0.00	46.0	1.06	-0.06
March	1992	0.81	1.90	0.00	0.06	0.00	0.00	0.00	0.00	1.25	1.25	-1.22	0.78	0.00	49.6	0.00	-0.06
April	1992	4.66	2.55	0.00	0.00	0.00	0.00	0.00	0.00	1.27	1.27	1.06	2.32	0.00	51.9	0.00	0.00
May	1992	0.50	4.67	0.00	0.00	0.00	0.00	0.00	0.00	3.25	3.20	-3.10	0.40	0.00	59.3	0.00	0.00
June	1992	1.43	4.86	0.00	0.00	0.00	0.00	0.00	0.00	3.31	1.77	-1.15	0.81	0.00	64.2	0.00	0.00
July	1992	0.67	4.42	0.00	0.00	0.00	0.00	0.00	0.00	3.13	1.24	-0.90	0.34	0.00	66.2	0.00	0.00
August	1992	0.66	4.34	0.00	0.00	0.00	0.00	0.00	0.00	3.10	0.65	-0.21	0.22	0.00	66.2	0.00	0.00
September	1992	1.36	2.54	0.00	0.00	0.00	0.00	0.00	0.00	1.66	0.35	0.41	0.60	0.00	59.2	0.00	0.00
Totals:		41.56	28.73	0.00	7.08	4.92	0.00	0.00	0.00	18.45	10.96	-0.49	19.69	0.00	53.7	2.96	-0.59
									1993 Water year								
October	1992	3.24	1.04	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.39	1.09	1.76	0.00	53.2	0.00	0.00
November	1992	5.96	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.13	3.54	2.29	0.00	44.6	0.00	0.00
December	1992	4.42	0.34	0.00	0.00	1.77	0.00	0.00	0.00	0.09	0.09	0.53	2.02	0.00	37.9	0.55	0.00
January	1993	6.16	0.43	0.00	1.73	1.52	0.00	0.00	0.00	0.13	0.13	1.39	1.38	0.00	36.3	2.16	0.00
February	1993	0.54	0.88	0.00	0.03	1.19	0.00	0.00	0.00	0.53	0.53	-1.73	0.51	0.00	40.2	0.66	0.00
March	1993	5.45	1.58	0.00	0.20	1.54	0.00	0.00	0.00	0.72	0.72	0.71	2.27	0.00	46.8	1.05	0.00
April	1993	6.99	1.98	0.00	0.28	2.53	0.00	0.00	0.00	0.58	0.58	-0.43	4.05	0.00	50.0	0.75	-0.02
May	1993	3.67	3.81	0.00	0.05	0.11	0.00	0.00	0.00	2.05	2.05	-0.67	2.16	0.00	59.6	0.01	-0.04
June	1993	1.89	3.83	0.00	0.00	0.00	0.00	0.00	0.00	2.41	2.41	-1.50	0.98	0.00	60.4	0.00	0.00
July	1993	1.28	3.24	0.00	0.00	0.00	0.00	0.00	0.00	2.03	1.93	-1.59	0.94	0.00	61.2	0.00	0.00
August	1993	0.24	3.99	0.00	0.00	0.00	0.00	0.00	0.00	2.81	1.49	-1.49	0.24	0.00	65.1	0.00	0.00
September	1993	0.00	3.04	0.00	0.00	0.00	0.00	0.00	0.00	2.22	0.40	-0.40	0.00	0.00	61.1	0.00	0.00
Totals:		39.84	24.60	0.00	2.30	8.66	0.00	0.00	0.00	14.30	10.86	-0.54	18.62	0.00	51.4	5.17	-0.07

Table A18.--*Monthly computed water-budget summaries for the Vaughn catchment--Continued*

Month	Year	PRCP	POTET	CHGINT	RO	RCH	SOLPEV	EVSOL	EVSNW	PPLTR	TR	CHGSM	EVINT	CHGSNW	AVTMP	SYMRO	DEFCIT
		All values in inches of water except AVTMP, which is in degrees Farenheit[1]															
		Average monthly values:															
October		2.70	1.29	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.55	0.58	1.57	0.00	52.2	0.00	0.00
November		6.77	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	3.39	3.28	0.00	45.5	0.00	0.00
December		4.64	0.33	0.00	0.26	1.04	0.00	0.00	0.00	0.07	0.07	0.93	2.56	0.00	39.8	0.29	-0.22
January		8.95	0.40	0.00	3.18	1.97	0.00	0.00	0.00	0.11	0.11	1.39	2.30	0.00	39.5	2.01	-0.01
February		2.83	0.83	0.00	0.94	1.69	0.00	0.00	0.00	0.43	0.43	-1.58	1.38	0.00	43.1	0.86	-0.03
March		3.13	1.74	0.00	0.13	0.77	0.00	0.00	0.00	0.98	0.98	-0.25	1.53	0.00	48.2	0.52	-0.03
April		5.82	2.27	0.00	0.14	1.27	0.00	0.00	0.00	0.93	0.93	0.32	3.19	0.00	51.0	0.37	-0.01
May		2.08	4.24	0.00	0.03	0.06	0.00	0.00	0.00	2.65	2.62	-1.88	1.28	0.00	59.4	0.00	-0.02
June		1.66	4.34	0.00	0.00	0.00	0.00	0.00	0.00	2.86	2.09	-1.32	0.89	0.00	62.3	0.00	0.00
July		0.97	3.83	0.00	0.00	0.00	0.00	0.00	0.00	2.58	1.58	-1.25	0.64	0.00	63.7	0.00	0.00
August		0.45	4.16	0.00	0.00	0.00	0.00	0.00	0.00	2.96	1.07	-0.85	0.23	0.00	65.7	0.00	0.00
September		0.68	2.79	0.00	0.00	0.00	0.00	0.00	0.00	1.94	0.37	0.01	0.30	0.00	60.2	0.00	0.00
Totals:		40.70	26.67	0.00	4.69	6.79	0.00	0.00	0.00	16.37	10.91	-0.52	19.16	0.00	52.6	4.07	-0.33

[1]PRCP = observed precipitation;
POTET = potential evapotranspiration (may be less than sum of evaporation and transpiration components, as dicussed in report),
CHGINT = change in moisture stored on foliage (zero when throughfall data is used, as in this investigation),
RO = observed, or estimated direct runoff,
RCH = soil water that percolates below the root zone (recharge),
SOLPEV = potential soil evaporation over bare soil areas (none in this investigation),
EVSOL = evaporation from bare soil areas (none in this investigation),
EVSNW = sublimation of snow,
PPLTR = foliage-type-dependent potential transpiration,
TR = transpiration,
CHGSM = change in soil moisture,
EVINT = interception loss computed from input throughfall, or DPM-simulated throughfall if not input,
CHGSNW = change in snowpack,
AVTMP = average temperature,
SYMRO = DPM-simulated direct runoff,
DEFCIT = if the following is negative: rain + snowmelt + starting soil moisture in excess of available water-holding capacity - evaporation and transpiration components - observed direct runoff, if the following is positive: rain + snowmelt - (available water-holding capacity + specific yield - starting soil moisture) - observed direct runoff - recharge.

APPENDIX B--Data input instructions for the modified Deep Percolation Model used in this investigation

DATA INPUT INSTRUCTIONS FOR THE MODIFIED DEEP PERCOLATON MODEL (DPM) USED IN THIS INVESTIGATION

The modified source code, written in FORTRAN 77 was permanently stored on 8 mm archive tape dg09 (using the "tar" command) at the Tacoma, Washington, office of the Water Resources Division of the U.S. Geological Survey. The logical tape number is 8 and the direcotry containing the main programs and all subroutines is source.pub.

For each catchment there is a unique main program main.clr.f, main.bvr.f, and main.vgn.f for the Clover, Beaver, and Vaughn clatchments, respectively. Similarly, the subroutines datain.clr.f and iopen.clr.f, datain.bvr.f and iopen.bvr.f, and datain.vgn.f and iopen.vgn.f are also unique to the Clover, Beaver, and Vaughn catchments, respectively. The differences arise from different dimensions, certain arrays, and data file pathnames (see "Source Code Adjustments Requied by User", below). All other subroutines are common to all catchments.

Input data are of three types: (1) a BASIC DATA input file for time- and location-independent information about the drainage area (basin) and for specification of various computational and output options, (2) a CELL ATTRIBUTES input file for geographic, surface, and subsurface information for the unique subareas (cells) of the drainage area, and (3) daily TIME-SERIES input files of weather variables. In addition, certain minor source code adustments are required relating to array dimensions and file pthnames for each drainage basin that the DPM is used on.

There are three or five output files, depending on user-specified options.

BASIC DATA INPUT FILE:

A line-by-line description of the data items is given below. All data items are read free format; the variable names used in the source code areas are given in parentheses.

(1) Text on this line will appear as title in the main output file (limit of 80 characters).

(2) Starting year (IYRSTRT), starting month (MOSTRT), ending year (IYREND), and ending month (MOEND) of the simulation period, and the ending month of the annual water-budget summaries (MOBDGT).

(3) The number of subareas (NEL), also referred to as cells or blocks, that make up the basin; and the state plane projection system zone number (KZONE) when longitude and latitude are used to locate cells. KZONE is set = 0 if cell locations are given as x-y feet from some arbitrary origin. If KZONE=0, weather-data station locations must also be given in x-y feet from this origin.

(4) Total number of precipitation weather stations (NWSP); throughfall data stations (NWSTF); temperature weather stations (NWST); and incoming solar radiation data stations (NWSR) that are used to interpolate values to cells. Any number of stations for each of these weather variables may be used, but at least one is required for each except for throughfall, which can be optionally computed by the DPM.

(5) For the first of the NWSP precipitation stations: longitude (XP(1)) and latitude (YP(1)) in decimal degrees (or feet from origin used in 3, above); and long-term average annual precipitation (ANPWS(1)) in inches. If NWSP > 1 the next line will be for XP(2), YP(2), ANPWS(2), etc.

(6) For the first of the NWSTF throughfall stations: longitude (XP(1)) and latitude (YP(1)) in decimal degrees (or feet from origin used in 3, above); and land-use number (1-15) at this location (LTFWS(1). Throughfall is highly dependent on land-use and generally cannot be simply distance-interpolated to other locations. Therefore a land-use number is attached to the throughfall data collection station, and data from the station will be interpolated only to cells having the same land-use number. If a cell has a land use different from any of the throughfall data collection stations, then throughfall is computed by the DPM based on a maximum daily moisture capacity of the foliage, daily precipitation, and daily PET (see Bauer and Vaccaro, 1987). If NWSTF > 1 the next line will be for XTF(2), YTF(2), LTFWS(2), etc.

(7) For the first of NWST temperature stations: longitude (XT(1)) and latitude (YT(1)) in decimal degrees (or feet from origin used in 3, above); long-term average daily minimum temperature for the warmest month of the year (TNJAVWS(1)) in degrees Fahrenheit; and long-term average daily maximum temperature for the warmest month of the year (TXJAVWS(1)) in degrees Fahrenheit. If NWST > 1 the next line will be for XT(2), YT(2), TNJAVWS(2), TXJAVWS(2), etc.

(8) For the first of the NWSR solar radiation data sites: longitude (XR(1)) and latitude (YR(1)) in decimal degrees (or feet from origin used in 3, above). If NWSR > 1 the next line will be for XR(2), YR(2), etc.

(9) The maximum number of nearest weather stations to a cell from which to interpolate daily values to a cell for: precipitation (NVALP); throughfall (NVALTF); temperature (NVALT); and solar radiation (NVALR).

(10) The maximum radius from a cell that a data station must lie within to be used for data interpolation to the cell, in miles, for precipitation (DMAXP); throughfall (DMAXTF); temperature (DMAXT); and solar radiation (DMAXR). If fewer than NVALP precipitation stations lie within DMAXP miles of a cell, only those will be used for interpolation.

(11) Average lattitude of the basin (AVLAT), in decimal degrees.

(12) Monthly lapse rates, 12 values, for minimum daily temperature (RATEMN(1-12)) in °F/1,000 ft. A lapse rate is coded as 0 if no altitude adjustment is to be made to the distance-weighted interpolations.

(13) Same as (12) for maximum daily temperature (RATEMX(1-12).

(14) A constant sublimation rate for snowpack (SBLRATE), in inches of water per day (published rates vary from .0028-.0114); and a constant snowmelt coefficient (SNMCOEF) in inches of water per degrees Celsius per day (generally ranges from about 0.002-0.090).

(15) Minimum daily potential evapotranspiration, 12 values, one for each month (PETMIN(1-12)) in inches of water per day. These values are used to account for some evaporation if theoretical potential evapotranspiration = 0 when temperature is below freezing and there is no snowpack. If not deemed important, these values may be set to 0.0

(16) Ratio of maximum observed incoming daily short-wave solar radiation (clear sky) to extraterrestrial short-wave solar radiation, 12 values, one for each month (SLRXFMX(1-12)).

(17) Initial conditions for all cells for: soil-moisture (STRTSMS) as fraction of available water capacity; soil saturation (STRTSAT) as fraction of specific yield; and snowpack (STRTSNW) as inches of water. Cell-by-cell initial conditions can also be read in from separate file indicated in subroutine IOPEN.F77 (see below for user-required editing of source-code in the MAIN program and subroutines DATAIN.F77 and IOPEN.F77). In this case, initial conditions from this data record will be reset.

(18) Parameter (DSUM) specifies whether the average basin-budget output has monthly averages only (DSUM=0) or daily and monthly averages (DSUM=1).

(19) The number of cells (10 maximum) for which daily soil-moisture and soil-saturation values are to be output (NSSBLKS). Soil moistures for all specified cells for all days are in one output file. The same applies for the saturation values in a separate output file.

(20) Cell index (or sequence) numbers for the NSSBLKS in 19, above (NSS(1-NSSBLKS)). Index numbers are from those assigned in the cell attribute file, discussed below.

(21) Number of different soil types (NSOLAS), maximum of 24.

(22) For the first soil type: sequence number (IS), starting with 1; depth, as number of 6-inch layers (NLAYER(1)); soil texture (SOLTEX(1)) (1=sand, 2=silt, 3=clay—use decimal values for mixtures); available water capacity (AVLCAP(1)), as decimal fraction by volume; specific yield (SPCYLD(1)), as decimal fraction by volume; lateral permeability of soil (SOLPRM(1)), in feet per day; soil-limiting transpiration coefficient (SLMFAC(1) which, when multiplied by soil moisture, specifies maximum daily transpiration), in inches per day. If SLMFAC is set = 0.0, then soil-water-limited transpiration is determined from "hard wired" empirical soil texture relationships taken from Leavesly and others (1983). If NSOLAS > 1 the next line will be for IS=2, NLAYER(2), SOLTEX(2), etc.

(23) Parameter (IROOT) that determines type of moisture extraction from soil by plants when SLMFAC (in 22 above) is not specified. Root mass may be assumed to be evenly distributed (IROOT = 0) or decrease exponentially with depth (IROOT = 1), and transpiration potential is divided among soil layers in proportion to root mass. IROOT is set to 0 for even distribution, or > 0 for exponential ditribution. (IROOT = 0 will usually result in somewhat higher transpiration rate than if IROOT = 1). If SLMFAC > 0.0 in 22, above, any value may be coded for IROOT because it is then not used in the program.

(24) Number of different land uses in a basin for which other than default values of plant characteristics defined in source code are to be used (MDLNDS).

(25) For the first of the modified land uses: land-use number (ILND) (see Bauer and Vaccaro, 1987, for land-use numbers); maximum root depth (RDMAX(ILND)) in inches; maximum foliar cover (FCMAX(ILND)) decimal fraction; maximum interception storage capacity (MAXINT(ILND)) inches of water; starting and ending dates of two irrigation periods IRRST1(ILND), IRREND1(ILND), IRRST2(ILND), IRREND2(ILND)) "compressed" month-day (i.e. 0609 for June 9); and type of irrigation scheduling (IRRSCD(ILND)) 0 for constant daily rate or 1 for rate proportional to growth stage. If any of these parameters are set to 0, the default value in the appropriate land-use subroutine is used (default for irrigation is no irrigation). If there is only one irrrigation period, use IRRST1 for begining and IRREN2 for end and arbitrary intermediate values such that IRRST2=IRREND1+1). If MDLNDS > 0 the next line will be these parameters for the next modified land use.

(26) Drainage area to the streamgage (BSNARA) in square miles (BSNARA does not have to equal the total area being simulated because it is used only to compute runoff per unit area); time between centroid of a storm to centroid of storm streamflow at gage (LAGDYS) in whole days.

CELL ATTRIBUTES INPUT FILE:

The first record is not read and, therefore, can be used as a comment line such as for an abbreviated heading line for the columns in this tabular file. Each subsequent record specifies the spacially dependent physical attributes for each unique subarea (or cell) within the basin. The data elements on each record are itemized below. The variable name used in the source code for each data element (or column) is given in parenthesis. Each data element (except for cell index number) is represented by a single-dimension array in the source code that the user must dimension to the number of cells in the common blocks in the MAIN program and in subroutine DATAIN (described below).

(1) Cell index number (usually I, or NE), must be sequential starting with I=1.

(2) Longitude, or distance east of arbitrary origin, to the centroid of the cell (GX(I)), in decimal degrees or feet.

(3) Latitude, or distance north of arbitrary origin, to the centroid of the cell (GY(I)), in decimal degrees or feet.

(4) Area (AREA(I)), in square miles.

(5) Soil-type sequence number that corresponds with "IS" in 22, above (NSOIL(I)).

(6) Land use index number (LANDUS(I). See Bauer and Vaccaro, 1987, for description of land uses and associated index numbers.

(7) Long-term average annual precipitation (ANPBLK(I)) (usually obtained from isohyet map), in inches of water. This is used to make "orographic" corrections to distance-interpolated precipitation values. If ANPBLK(I) is set to 0.0 then no orographic correction is made for this cell.

(8) Altitude (ALTBLK(I)) in feet above sea level.

(9) Land surface slope (SLPBLK(I)) in decimal degrees from horizontal (used in computing amount of solar radiation incident on cell—important only in steep terrain; in most cases it may be set to 0.0 and have little effect on the results).

(10) Land surface aspect (ASPECT(I)) in degrees clockwise from north (same comment as in parenthesis in 9, above).

(11) Annual amount of irrigation (APPLD(I)) in inches.

(12) Saturated vertical conductivity of the subsoil material (VKSAT(I)) in inches per year. This value is generally unknown but is of primary importance. If it is known that the soils never saturate, simply set VKSAT(I) to a large value (such as 9999). If the soils saturate, then values of VKSAT must be "calibrated" to minimize the deficit term in the output (see discussion in Water Budget section in main body of report). Negative deficits are computed on days when precipitation minus evapotranspiration plus saturated moisture stored in the soil is less than the observed storm runoff (streamflow minus baseflow), suggesting that lower VKSAT values be used. Positive deficits are computed on days when precipitation minus evapotranspiration minus unsaturated pore space exceeds the observed storm runoff, suggesting that a higher value of VKSAT be used.

(13) One-half the average spacing between the smallest (probably intermittent) drainage channels in the subarea (EFFLNGTH(I)), in feet. This somewhat subjective parameter is used together with the hydraulic conductivity of the soil (specified in the basic data set), the average land surface slope (see 14, below), and VKSAT(I) (see 12, above) to compute saturated soil-water discharge to the stream channels, which, in turn, is used to allocate the total measured direct runoff from the basin to the cells.

(14) The average slope between the smallest drainage channels of of 13, above (EFFSLP(I)) as the ratio of vertical to horizontal.

DAILY TIME-SERIES DATA INPUT FILES:

Each of the data files in the following 5 groups has one data record for each day of the budget period starting with the first day of the starting month and ending with the last day of the ending month specified on line 2 of the BASIC DATA FILE (except possibly for the streamflow data set, described below). All files are read free format. The first three values on each record represent the date as year, month, and day (for example, 1994 10 15). The files and subsequent values on each record in the files are as follows:

Precipitation Files:

One file for each of the precipitation stations is required. The total number of stations is specified on line 4 of the BASIC DATA FILE. At least one station is required. On each record there is one value of daily precipitation, in inches, following the date.

Throughfall Files:

Same as for precipitation files, except that the date is followed by one daily value of the ratio of throughfall to precipitation (precipitation at location of throughfall station), in inches. There is no requirement on the number of files (for example, may be none).

Streamflow File:

Only one streamflow file is allowed, but is not required (for example, runoff may not occur in a highly pervious area). On each record following the date, there is one value of mean daily discharge and one value of the estimated ground-water discharge component of the daily discharge, both in cubic feet per second. If LAGDYS > 0 (specified on last line in the BASIC DATA FILE) then LAGDYS number of additional daily streamflow records beyond last day of simulation must be included.

Temperature Files:

Same as for precipitation files except that the date is followed by the daily minimum and then the daily maximum temperature in degrees Fahrenheit. At least one station is required.

Incoming Solar Radiation Files:

Same as for precipitation files except that the date is followed by one daily value of daily incoming solar radiation, in langleys (calories per square centimeter). At least one station is required.

SOURCE CODE ADJUSTMENTS REQUIRED BY USER:

The main program, MAIN.F77, and two subroutines, DATAIN.F77 and IOPEN.F77, require certain modifications before compiling:

MAIN.F77:

This is the main fortran source code that directs the flow of the DPM. A certain number of common blocks need to be appropriately dimensioned before compilation. Instructions for dimensioning are contained in the first comment statements in MAIN.F77. Many comment lines, which are also included throughout the code, would help a user to better understand the flow of the program.

DATAIN.F77:

This subroutine reads information from the basic data file and from the cell attributes file and performs certain one-time computations. Several common blocks require dimensioning. Instructions for dimensioning are contained in the first comment statements in the subroutine.

IOPEN.F77:

This subroutine opens the necessary input and output files. File pathnames need to be supplied in the source code of this subroutine. Instructions are contained in the first comment statements in the subroutine.

OUTPUT FILES:

Three output files are created for each simulation, and two additional output files are optional.

Main Output File:

Examples of this file are presented in Tables A16 through A18 in appendix A of this report. The monthly budget items tabulated are averages of all the subareas or cells in the basin. An additional option for these files is to have daily (DSUM = 1, item 18 of of the BASIC DATA FILE) as well as monthly budget summarries.

Cell Monthly File:

For each month of the simulation period, the monthly totals of the water-budget items are printed for each cell.

Cell Summary File:

For each cell, budget summaries are printed for (1) simulation-period totals, (2) simulation-period monthly averages, and (3) if the simulation is for more than one year, the simulation-period annual averages.

Unsaturated Soil-Moisture File (optional):

For selected cells (item 19 in the BASIC DATA FILE), calculated daily values of soil moisture in excess of the wilting point up to field capacity in inches of water, are printed. For each day of the simulation, the date and daily values for all the selected cells are printed on one record.

Saturated Soil-Moisture File (optional):

For the same cells selected for the UNSATURATED SOIL-MOISTURE FILE, above, calculated daily values of soil moisture in excess of field capacity (saturated soil moisture), in inches of water, are printed. For each day of the simulation, the date and daily values for all selected cells are printed on one record.

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