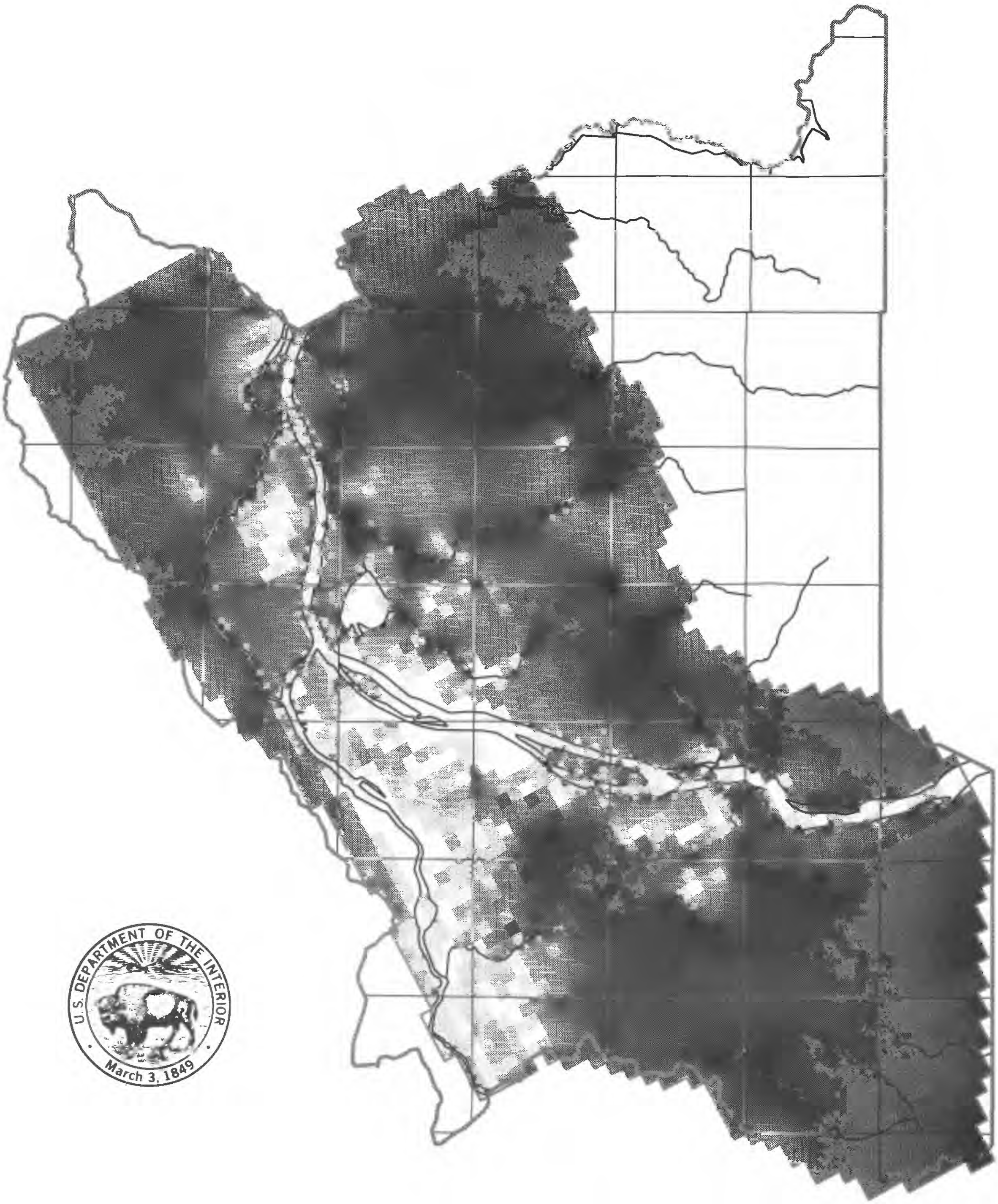

ESTIMATION OF GROUND-WATER RECHARGE FROM PRECIPITATION, RUNOFF INTO DRYWELLS, AND ON-SITE WASTE-DISPOSAL SYSTEMS IN THE PORTLAND BASIN, OREGON AND WASHINGTON

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 92-4010

Prepared in cooperation with
CITY OF PORTLAND BUREAU OF WATER WORKS,
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Portland, Oregon
1994

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ILLUSTRATIONS

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Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09294	square meter
acre	4,047.	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
gallon per day (gal/d)	0.003785	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The average recharge rate in the Portland Basin in northwestern Oregon and southwestern Washington is estimated to be about 22.0 inches per year. Of that amount, precipitation accounts for about 20.8 inches per year, runoff into drywells accounts for 0.9 inches per year, and on-site waste disposal accounts for about 0.4 inches per year. In areas of urban development, however, drywells and on-site waste-disposal systems are a substantial source of recharge, contributing about 38 percent and 17 percent of the total, respectively.

The highest recharge rates (about 49 inches per year) generally are found in the Cascade Range; the lowest recharge rates (near zero) are found along and between the Columbia and Willamette Rivers. Higher recharge rates occur locally in discrete areas owing to recharge from runoff into drywells and on-site waste-disposal systems in urbanized parts of the study area. In these urbanized areas, recharge ranges from 0 to 49 inches per year.

INTRODUCTION

The greater metropolitan area of Portland, Oregon, and Vancouver, Washington, has grown considerably during the last 25 years. The population of the metropolitan area has increased more than 50 percent during this time and is currently (1990) about 1 million. The development of ground-water resources and changes in land-use practices associated with the increase in population will ultimately affect the quantity and quality of available water. In recognition of the need to protect and manage the ground-water resources, the Oregon Water Resources Department, in association with the City of Portland Bureau of Water Works, began a cooperative study with the U.S. Geological Survey in 1987 to describe the ground-water flow system in the Portland Basin of Oregon and Washington. This effort was later merged with a similar study being done by the U.S. Geological Survey in cooperation with the Intergovernmental Resource Center (the council of governments for Clark and Skamania Counties, Washington).

The study area is located in northwestern Oregon and southwestern Washington (fig. 1). The study area, referred to as the "Portland Basin" in this report, encompasses about 1,310 square miles (mi^2) and is bounded approximately by the Lewis River to the north, the Clackamas River to the south, the Cascade Range to the east, and the Tualatin Mountains to the west. Included in the study area is most of Multnomah County and parts of Clackamas, Columbia, and Washington Counties, Oregon, as well as all of Clark County and part of Skamania County, Washington. The topography is characterized by flat-lying, alluvial lands along the Columbia River and

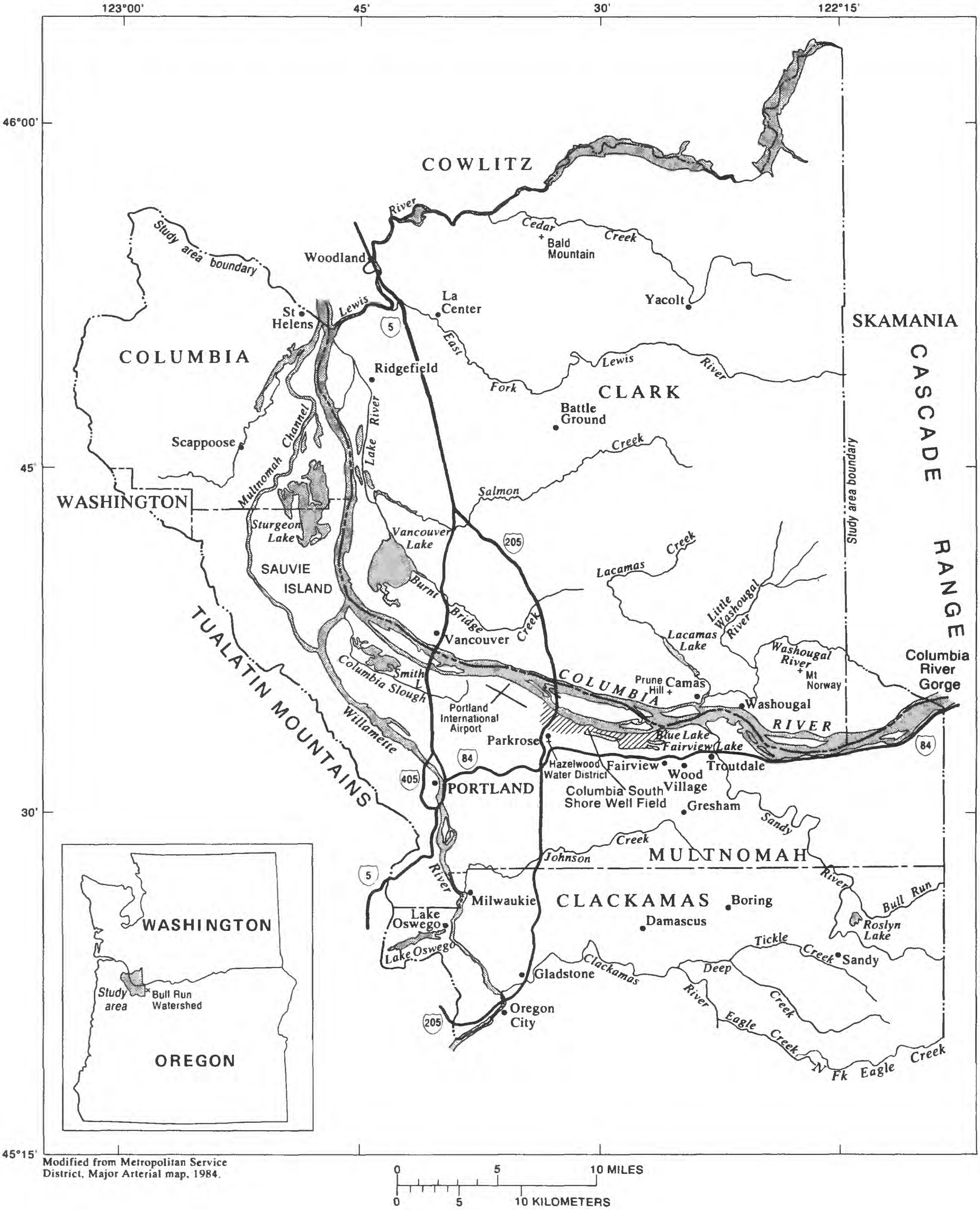


Figure 1. Location and general features of the Portland Basin study area.

its tributaries that are broken by low, rolling hills or buttes with benches and hilly areas. Altitude of the land surface ranges from about 10 feet (ft) along the Columbia River to about 3,000 ft in the Cascade Range.

The climate is temperate with dry, moderately warm summers and wet, mild winters, although topography produces considerable variations in the climate. The average temperature in the Portland Basin is about 52 degrees Fahrenheit (°F) and ranges from about 40°F in January to about 66°F in July. Precipitation ranges from about 36 inches per year (in/yr) near Portland to about 100 in/yr in the Cascade Range. About 50 percent of the land in the study area is forest land, about 26 percent is classified as urban land, about 17 percent consists of agricultural land, and about 7 percent is for other uses.

Although previous ground-water investigators in the Portland Basin did not quantify the recharge, they qualitatively state that the primary source of ground-water recharge is infiltration of precipitation (Piper, 1942; Griffin and Swenson, 1956; Brown, 1963; Mundorff, 1964; Hogenson and Foxworthy, 1965). In the urbanized parts of the basin, however, other sources locally contribute a large percentage of the total recharge to the ground-water system. Two of the most significant sources are runoff from impervious surfaces to drywells (sumps) and effluent from on-site waste-disposal (septic) systems. About 26 percent (340 mi^2) of the basin is covered by commercial, industrial, and residential development where recharge from precipitation has been reduced by increases in impervious surfaces and the subsequent diversion of runoff to storm sewers, canals, and natural drainages.

Purpose and Scope

This report presents the estimated rates and spatial distributions of ground-water recharge in the Portland Basin. Recharge rates estimated during this study can be used as input to a ground-water flow model for a part of the Portland Basin which is being developed concurrently (McFarland and Morgan, in press). The results are presented only for that part of the Portland Basin within the boundary of part of the ground-water-flow-model grid that contains active cells (hereafter referred to as the model-grid area).

Sources of recharge include precipitation, runoff into drywells (sumps), and on-site waste-disposal systems (cesspools and septic systems). Recharge from agricultural irrigation was not estimated. Although locally important, recharge from irrigation is insignificant on a regional scale. The total quantity of water used for agricultural purposes in the Portland Basin is about 18 cubic feet per second (ft^3/s) from ground water (Collins and Broad, 1993) and an estimated 25 ft^3/s from surface water (T.M. Broad, U.S. Geological Survey, written commun., 1991). Logically, after losses for interception, soil-moisture storage, and evapotranspiration, the amount of recharge from agricultural irrigation would be expected to be small. The exclusion of irrigation recharge from the calculation results in a more conservative estimate (or underestimate) of recharge. Recharge gains and losses from streams and rivers also were not included in this study because estimates of these recharge components will be facilitated by use of the ground-water flow model.

Approach

For the purposes of this report, ground-water recharge is defined as the deep percolation of water below the root zone that may be added to the unconfined aquifer at some later time. Recharge from each of three sources--precipitation, drywells, and on-site waste-disposal effluent--was estimated. A computer model was used to estimate deep percolation of precipitation in three basins of the study area. The results from these three subbasins were analyzed by using a multiple-linear regression of climatic and physical factors used in the model to derive an equation for calculating recharge for any part of the Portland Basin. Drywell locations were compiled from existing inventories, and estimates of recharge were based on collection area, precipitation, runoff, and evapotranspiration. Recharge from on-site waste-disposal systems was estimated from an inventory of the distribution and capacity of septic systems and cesspools provided by local government agencies. Recharge amounts from precipitation, runoff into drywells, and on-site waste-disposal systems were then summed to determine the total recharge.

Acknowledgments

The authors would like to thank the many individuals and groups who provided assistance and cooperation. Kelly T. Redmond, formerly the State Climatologist for Oregon, provided climatic data and technical assistance. The U.S. Department of Agriculture, Soil Conservation Service, Portland, Oregon, provided soil mapping and information on soil properties. Clint L. Moshofsky, formerly of the U.S. Geological Survey, contributed significantly to the analysis of recharge from drywells and on-site waste-disposal systems. Michael E. Pappalardo, also formerly of the U.S. Geological Survey, did the statistical analysis of soil properties. In addition, we would like to acknowledge the following colleagues for their contributions to the study: Frank A. Bond, Tyson M. Broad, Michael E. Darling, Larry L. Hubbard, Robert L. Moffatt, Lenore Y. Nakama, and James M. Wilkinson.

ESTIMATION OF RECHARGE FROM PRECIPITATION

Three techniques were used conjunctively to estimate recharge from precipitation: a deep percolation model, regression analysis, and regionalization of the results to the grid cells that will be used in the ground-water flow model.

Deep Percolation Model

Recharge from precipitation for three selected subbasins in the study area was calculated by using a modified version of the Deep Percolation Model for Estimating Ground-Water Recharge (hereafter referred to as the DPM). The model was developed by Bauer and Vaccaro (1990) for use in the Columbia Plateau Regional Aquifer System Analysis to estimate long-term average ground-water recharge from precipitation in areas with variable weather, soils, and land uses. A brief description of the model is provided below; a detailed explanation of the theory and use of the model is provided in the model documentation by Bauer and Vaccaro (1987).

Model Description

According to Bauer and Vaccaro (1987, p. 2), "The model is based on practical and easily implemented physical relations presented in Wight and Neff (1983), Saxton and others (1974), and Leavesley and others (1983)." These physical processes include changes in soil moisture, soil evaporation, plant transpiration, surface-water runoff, snow cover, and interception and evaporation of precipitation from the foliar cover. The major factors that control recharge from precipitation are simulated on a daily basis. The DPM then calculates the average annual amount of precipitation that percolates below the root zone over discrete areal blocks for each year and the average for the total period simulated. Though the DPM does not require calibration, it does compare the input base-flow estimates with precipitation and streamflow measurements. For any given day of the simulation, a base-flow value that is too small may result in an observed surface-runoff value (calculated as the streamflow minus the base flow) that exceeds the quantity that can be supplied by that day's precipitation. These precipitation "deficits" are accumulated over the simulation period and recorded with the other results.

The DPM was modified for this study to better reflect the prevailing conditions of the basins being modeled. Modifications included increasing the number of available soil types, increasing the number of available land-use types, adjustments of growth curves for local plant types, calculation of impervious area from land-use type, and routing of a part of incident precipitation to runoff on the basis of the percentage of impervious area in a cell. All modifications were tested by using a sample data set to verify the proper functioning of the DPM.

Model boundaries were selected to coincide with drainage divides so as to include the entire drainage basin contributing to stream discharge above the location of the streamflow-gaging station for each subbasin. Discretization of the subbasins was accomplished by using rectilinear grids with the y-axes oriented in a north-south direction, and a uniform grid-cell spacing of 1,640 ft (a cell area of 0.10 mi^2).

Subbasin Selection and Description

The subbasins selected for detailed analysis were Salmon and Cedar Creeks in Washington and Johnson Creek in Oregon (fig. 2). These three subbasins were selected because each was representative of a particular domain of climatic, topographic, and land-use conditions found throughout the Portland Basin (table 1). Criteria for selection also included readily defined drainage divides and the availability of extended records of daily streamflow discharge. An additional factor in the choice of subbasins was the availability of daily precipitation and maximum and minimum temperature data. The locations of and selected data for the hydrologic data sites (weather and streamflow-gaging stations) are presented in figure 2 and table 2, respectively. Weather stations are referenced with the unique index number used in the climatic data reports of the U.S. Department of Commerce, National Climatic Data Center. Streamflow-gaging-station numbers used in this report are those used in data and water-supply reports of the U.S. Geological Survey.

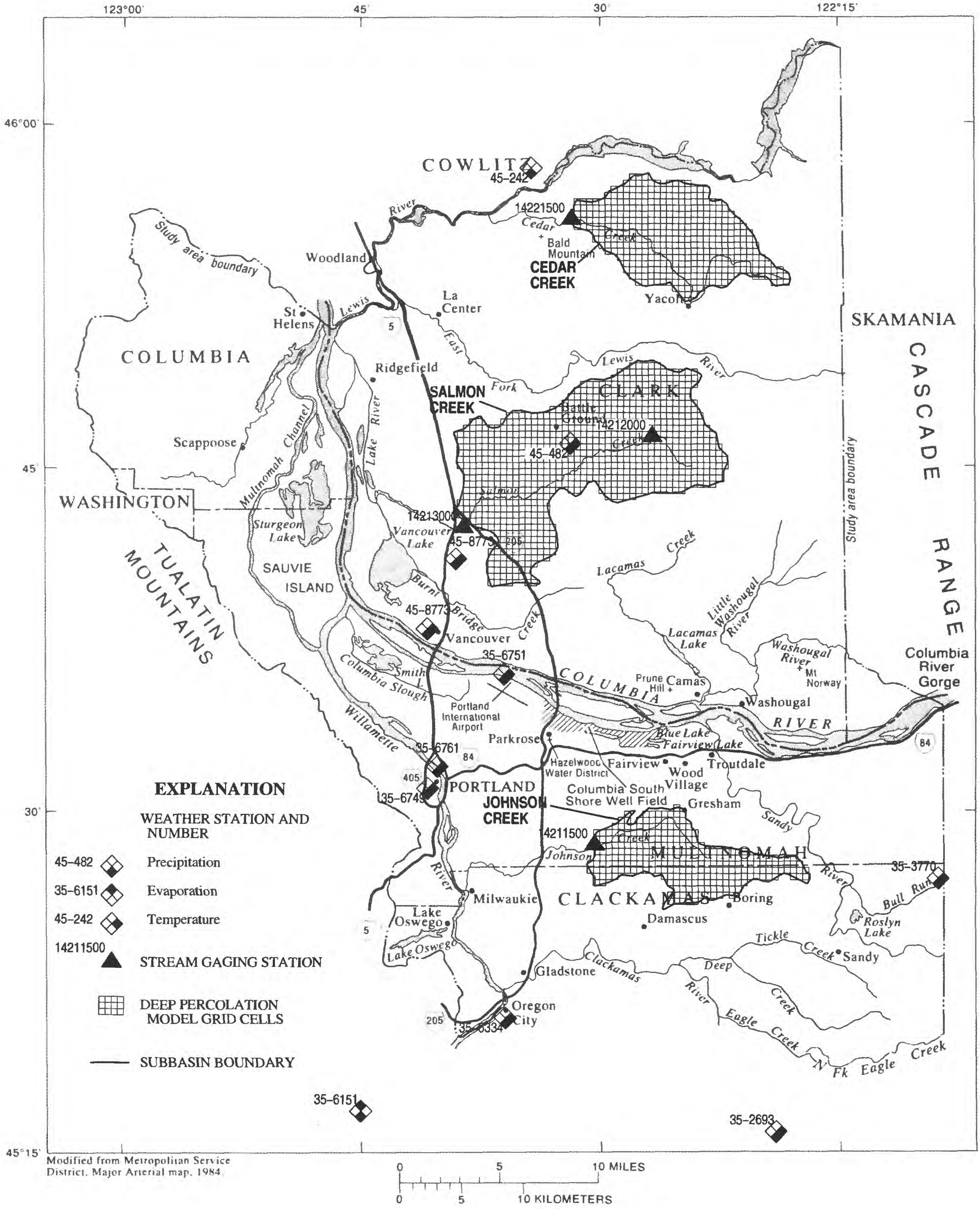


Figure 2. Location of hydrologic data sites and subbasins used with the Deep Percolation Model.

Table 1.--Selected data for drainage-basin simulations

[mi^2, square miles; in/yr, inches per year]

Drainage-basin name	Period of simulation	Area above gaging station (mi^2)	Number of model-grid cells	Mean altitude (feet)	Average precipitation (in/yr)	Land use, in percent		
						Forest	Agriculture	Urban
Salmon Creek	1949-74	80	824	500	60	38	20	42
Cedar Creek	1952-68	39	403	900	100	87	5	8
Johnson Creek	1949-83	27	280	500	55	26	49	25

Table 2.--Locations of and selected data for hydrologic-data sites

[--, not applicable; WB is Weather Bureau]

Index or station number [1]	Station name	Altitude (feet)	Longitude (decimal degree)	Latitude (decimal degree)	Period of record	Data type [2]	Drainage-basin simulation(s) for which data are used
			Weather stations				
45-8773	Vancouver, Washington [3]	100	122.683	45.633	1949-74	P T --	Salmon Creek
45- 482	Battle Ground, Washington	300	122.533	45.767	1949-74	P T --	Cedar and Salmon Creeks
45- 242	Ariel Dam, Washington	220	122.567	45.967	1952-68	P -- --	Cedar Creek
35-6751	Portland WB AP, Oregon	20	122.600	45.600	1949-83	P T --	Johnson Creek
35-6761	Portland WB City, Oregon [4]	30	122.667	45.533	1949-73	P T --	Johnson Creek
35-6749	Portland KGW-TV, Oregon [4]	190	122.683	45.517	1973-83	P T --	Johnson Creek
35-6334	Oregon City, Oregon	170	122.600	45.350	1949-83	P T --	Johnson Creek
35-2693	Estacada 2 SE, Oregon	410	122.317	45.267	1949-83	P T --	Johnson Creek
35-3770	Headworks Portland Water Bureau, Oregon	750	122.150	45.450	1949-83	P T --	Johnson Creek
35-6151	North Willamette Experiment Station, Oregon	150	122.750	45.283	1979-88	P -- E	--
			Streamflow-gaging stations				
14213000	Salmon Creek near Vancouver, Washington	75	122.642	45.708	[5] 1949-74	-- -- --	Salmon Creek
14221500	Cedar Creek near Ariel, Washington	287	122.528	45.932	[6] 1952-68	-- -- --	Cedar Creek
14211500	Johnson Creek at Sycamore, Oregon	228	122.507	45.478	1949-83	-- -- --	Johnson Creek
14212000	Salmon Creek near Battle Ground, Washington	356	122.443	45.774	[7] 1949-74	-- -- --	Cedar and Salmon Creeks

1 Index or station number: see figure 2 for location.
2 P = daily precipitation values, T = daily maximum/minimum temperature values, E = daily pan evaporation.
3 In November 1963, this station was moved to 122.650 degrees longitude, 45.683 degrees latitude at an altitude of 210 feet. The station number remained the same; however, the station name was changed to Vancouver, Washington 4 NNE.
4 Data from the Portland WB City, Oregon and Portland KGW-TV, Oregon; stations were combined to create a continuous data record.
5 A correlative estimate was made for the periods 1949-50 and 1952-74 from the records from the Salmon Creek station near Battle Ground, Washington.
6 A correlative estimate was made for the period 1956-60 from the records from the Salmon Creek station near Battle Ground, Washington.
7 Used for correlative estimates only.

Data Requirements

The data requirements for the DPM include climate, land-surface altitude, soil properties, and land-use information. Though not required, streamflow measurements, base-flow estimates, and information describing the slope and aspect of the land surface also were used in the DPM for increased reliability.

Climatic data obtained from the weather-station network of the U.S. Department of Commerce (1949-84) included daily precipitation totals, daily minimum and maximum temperatures, average July maximum temperatures, and daily percentage of possible sunshine (the ratio of actual to possible sunshine duration for a given day). Selection of weather stations was based on their proximity to the subbasins and the length and continuity of the data record. Average annual precipitation data were obtained by digitizing 15-year average annual lines of equal precipitation from a map of local precipitation patterns of the Portland area (Wantz and others, 1983). A triangulated irregular network was then used to interpolate average annual precipitation values between lines of equal precipitation; these values were then discretized by assigning area-weighted mean values to individual model-grid cells. Temperature data used in the calculation of average monthly temperature lapse rates were provided by the Oregon Department of Environmental Quality (L.D. Brannock, Oregon Department of Environmental Quality, written commun., 1988).

Information on land-surface features was obtained from the U.S. Geological Survey (USGS) National Mapping Division 1:250,000-scale Digital Elevation Model for Vancouver, Washington, 1974. A geographic information system was then used to calculate values of land-surface altitude, slope, and aspect. Altitude, slope, and aspect were then weighted by area in a model-grid cell and averaged to determine a single value for each parameter for the entire grid cell.

Soil maps were digitized from soil surveys of the U.S. Department of Agriculture, Soil Conservation Service (1972, 1982, 1983, 1985, 1986), for Clackamas, Columbia, and Multnomah Counties, Oregon, and Clark County, Washington, and from the Washington State Department of Natural Resources (1983). The 144 basic soil types were clustered into 27 groups to facilitate use in the DPM. The groups were clustered on the basis of similarity of soil depth, available soil-water capacity (the difference between the amount of soil water at field capacity and the amount at wilting point), and texture. Representative values of the properties for each soil group were obtained by averaging the attributes of soil types in each group. Each model-grid cell was accorded the soil group that had the largest areal extent in the cell and was then assigned the values of the properties associated with that soil group.

Land-use information was acquired from the USGS 1:250,000-scale Land-Use and Land-Cover Digital Data Map for Vancouver, Washington, 1974. The 24 land-use categories from the map were reclassified and grouped into 10 land-use types for use with the DPM. Land-use types included grass, orchard/deciduous forest, deciduous/evergreen forest mix, evergreen forest, residential, transportation, industrial, commercial, sand/bare ground, and surface water. As with the soil groups, the dominant land use in a model-grid cell was used to determine a land-use type for each cell. The percentage of impervious area was assigned to each land use from values published by the U.S. Department of Agriculture, Soil Conservation Service (1975) as follows: commercial, 85 percent; industrial, 72 percent; transportation, 50 percent; residential (one-half acre average lot size assumed), 25 percent; and all other land uses, 0 percent.

Daily streamflow at the streamflow-gaging stations at Salmon, Cedar, and Johnson Creeks were obtained from L.L. Hubbard (U.S. Geological Survey, written commun., 1988). To augment records of the Salmon and Cedar Creek stations for periods of missing record, correlative estimates of streamflow were made from records from the Salmon Creek streamflow-gaging station near Battle Ground, Washington (see table 1). Monthly base-flow estimates for each basin were determined by using hydrograph-separation techniques as described by Freeze and Cherry (1979).

Estimated Recharge

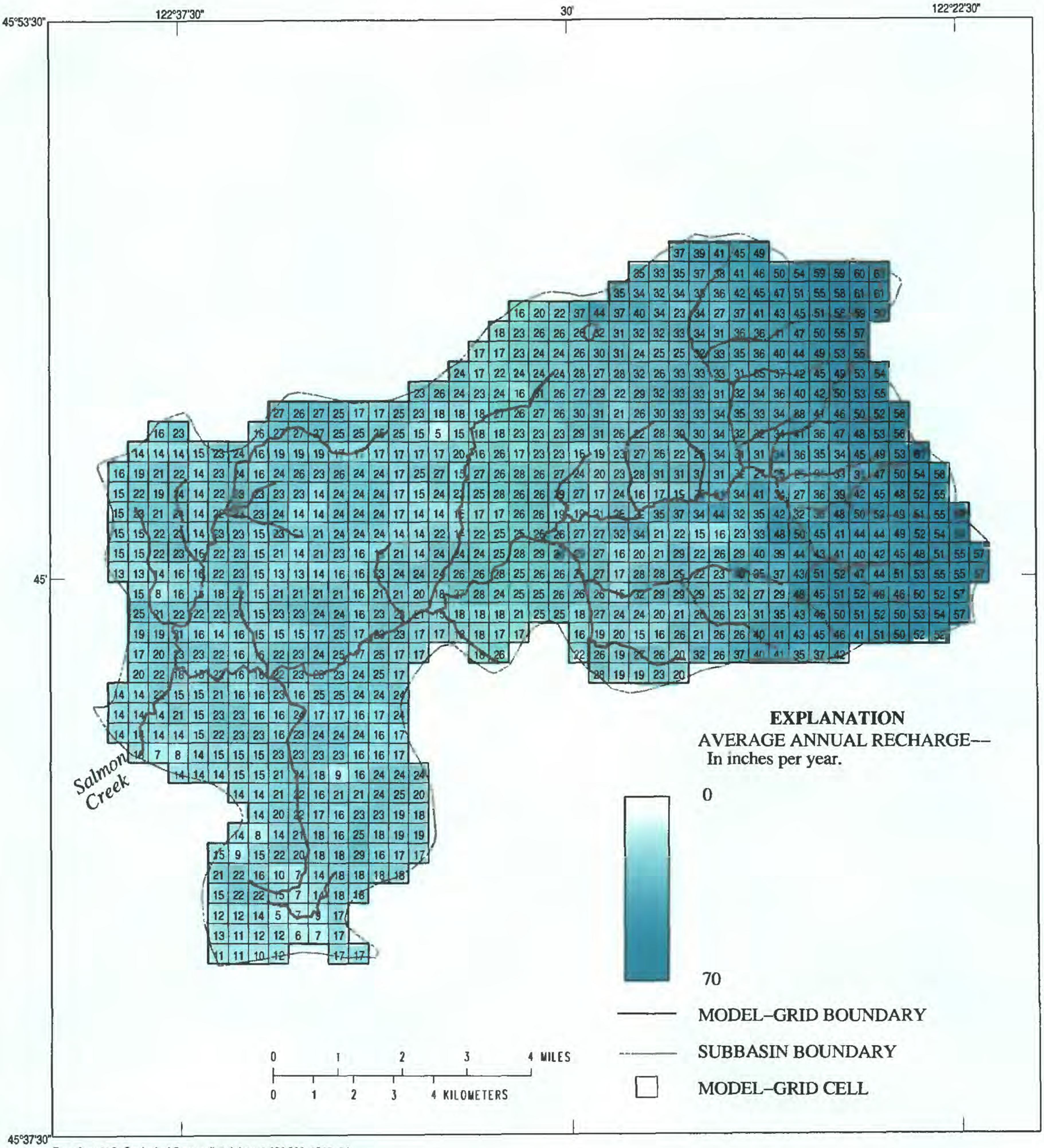
The results of the DPM simulation of average annual recharge from precipitation for the Salmon, Cedar, and Johnson Creek subbasins are shown in figures 3, 4, and 5, respectively, and are summarized in figure 6. The average annual deficit for any of the subbasin simulations was less than 2 percent of the average annual recharge.

The means of the average recharge for the DPM grid cells for the Salmon, Cedar, and Johnson Creek subbasins are 27, 52, and 20 in/yr, respectively. The distribution of recharge in the Salmon and Cedar Creek subbasins generally increases with altitude; however, the Johnson Creek subbasin shows no obvious trend in the distribution of recharge with altitude.

The average monthly water budgets for recharge, runoff, evapotranspiration, and precipitation calculated with the DPM for the three subbasins are shown in figure 7. Soil-moisture changes can be estimated as the difference between the precipitation and the sum of recharge, runoff, and evapotranspiration. Several common trends are evident (fig. 7). Maximum recharge occurs in November to January during the period of maximum precipitation and minimum evapotranspiration. Minimum recharge occurs in July through September during the period of minimum precipitation and maximum evapotranspiration. Recharge generally exceeds surface runoff throughout the year for all three subbasins, and both recharge and runoff are highly correlated with precipitation. Soil moisture accumulates during fall and early winter, whereas soil-moisture losses occur in late winter, spring, and early summer.

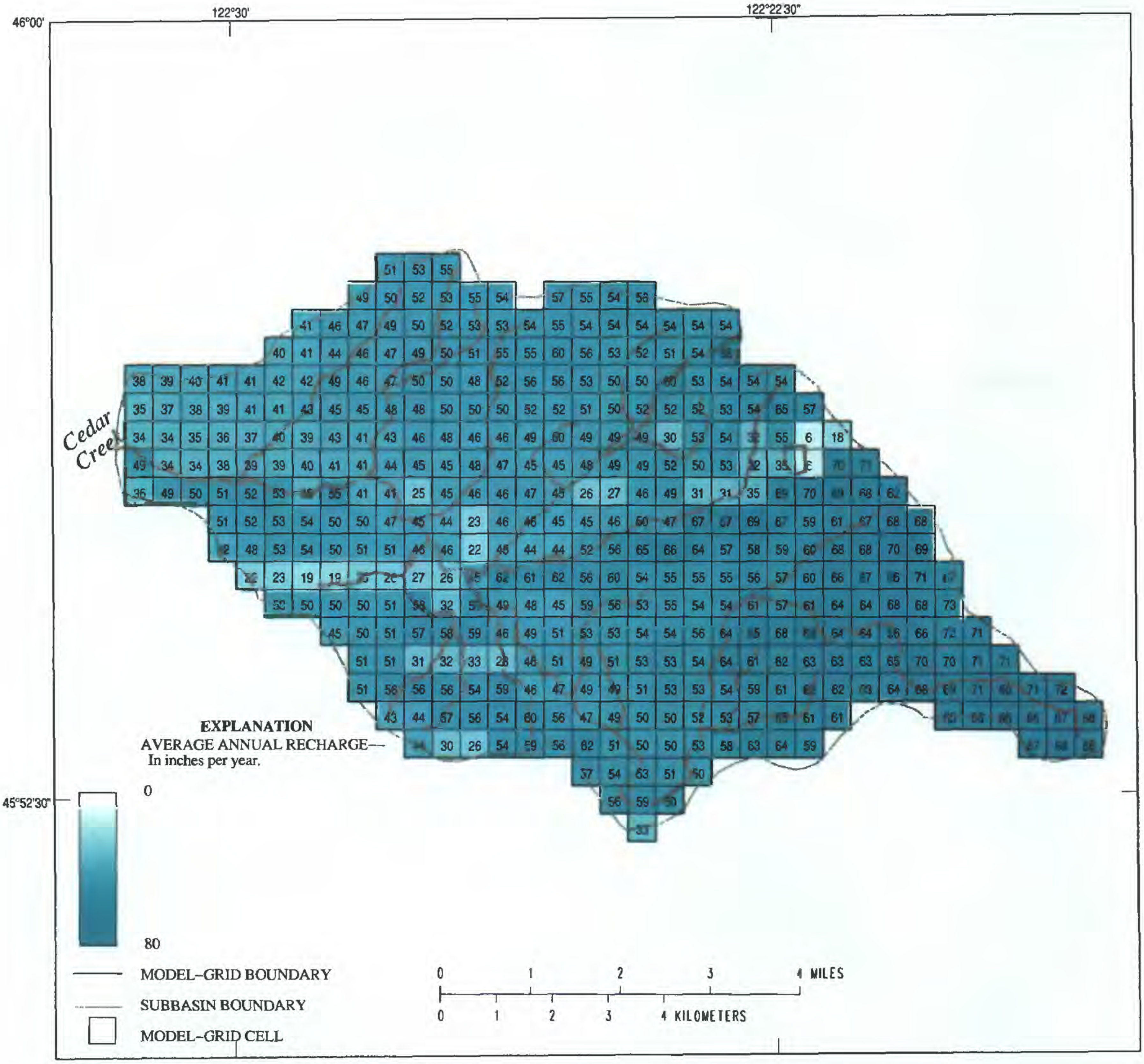
Sensitivity and Uncertainty Analyses

A sensitivity analysis was done with model runs on the Salmon Creek subbasin by using a 5-year subset of the simulation period to test the basin-wide response of the DPM to variations in major system parameters. Parameters tested included soil depth, available soil-water capacity, root depth, plant transpiration, interception capacity, foliar cover,



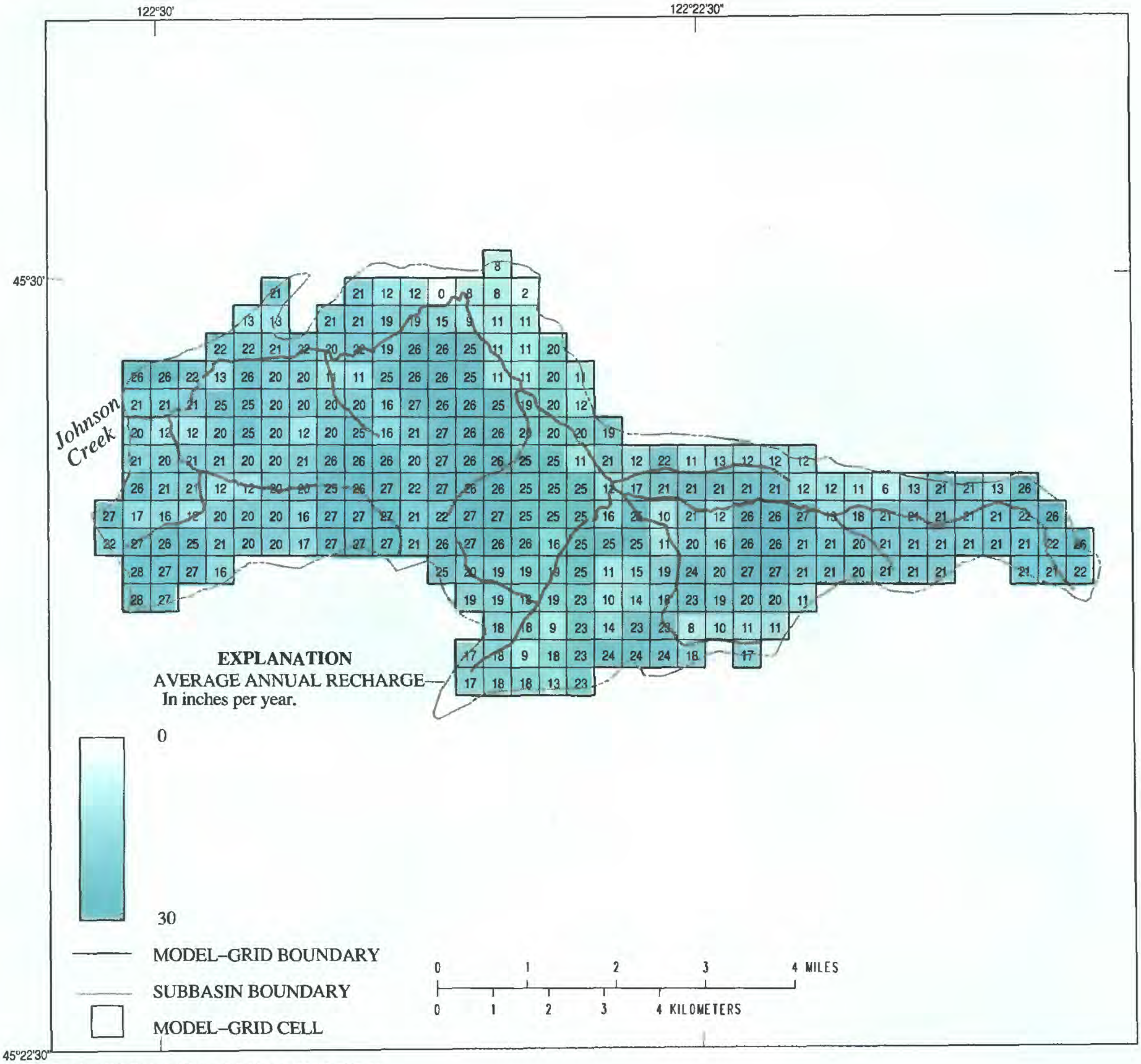
Base from U.S. Geological Survey digital data, 1:100,000, 1978-84
and 1:24,000 topographic quadrangles, 1970-86
Universal Transverse Mercator projection,
Zone 10

Figure 3. Distribution of average annual recharge from precipitation for the Salmon Creek subbasin as computed with the Deep Percolation Model.



Base from U.S. Geological Survey digital data, 1:100,000, 1978–84
and 1:24,000 topographic quadrangles, 1971–86
Universal Transverse Mercator projection,
Zone 10

Figure 4. Distribution of average annual recharge from precipitation for the Cedar Creek subbasin as computed with the Deep Percolation Model.



Base from U.S. Geological Survey digital data, 1:100,000, 1978–84
and 1:24,000 topographic quadrangles, 1975–85
Universal Transverse Mercator projection,
Zone 10

Figure 5. Distribution of average annual recharge from precipitation for the Johnson Creek subbasin as computed with the Deep Percolation Model.

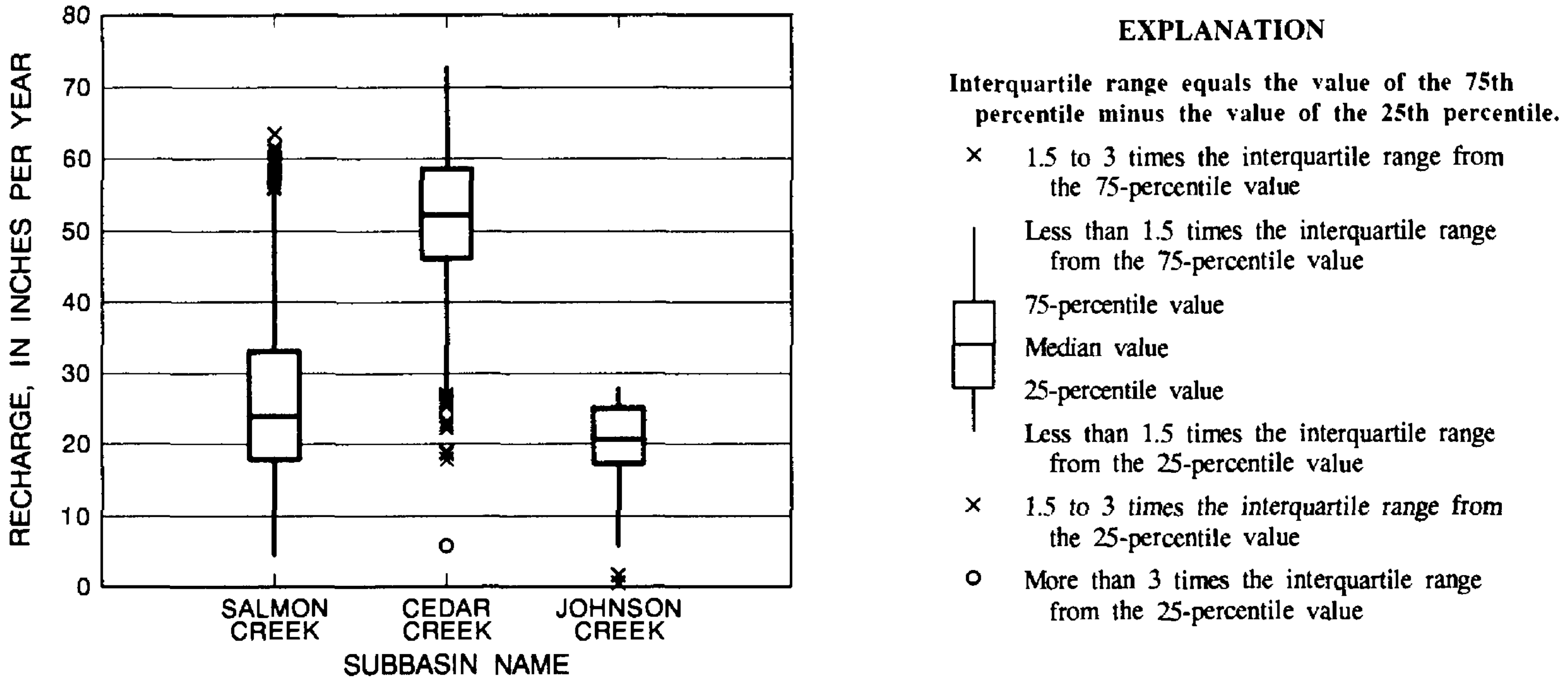


Figure 6. Average annual recharge calculated for the Deep Percolation Model grid cells.

impervious area, and land-surface altitude. Runoff data, base-flow estimates, and average annual precipitation also were tested. The Salmon Creek subbasin was chosen because it incorporates the largest variation of climate, topography, and land use of the three subbasins.

The DPM was run with input parameters for the Salmon Creek subbasin for a 5-year period (1949-53) to calculate baseline estimates of recharge for use in the sensitivity and uncertainty analyses. For each sensitivity model run, a single input parameter was varied by using either the maximum or minimum expected value of the parameter. The response of the model estimate of the average annual recharge for the Salmon Creek subbasin was then compared with the baseline estimate. The ratio of percentage of change in the parameter to the percentage of change in the average annual recharge for the subbasin determines the sensitivity of the model; larger values indicate greater sensitivity. The uncertainty of the recharge estimate was calculated for each model input parameter. Uncertainty is expressed as the change in the average annual recharge for the subbasin that results from using the maximum and minimum values of a model input parameter equal to the upper and lower bounds of its uncertainty.

The results of the sensitivity analysis of the Salmon Creek subbasin are summarized in figure 8. Recharge is most sensitive to changes in average annual precipitation and runoff to streamflow and least sensitive to changes in soil depth and foliar cover.

The results of the uncertainty analysis are shown in figure 9. Uncertainty in average annual precipitation and in the available soil-water capacity contribute most to the errors in the recharge estimate, whereas foliar cover and soil depth appear to have little effect.

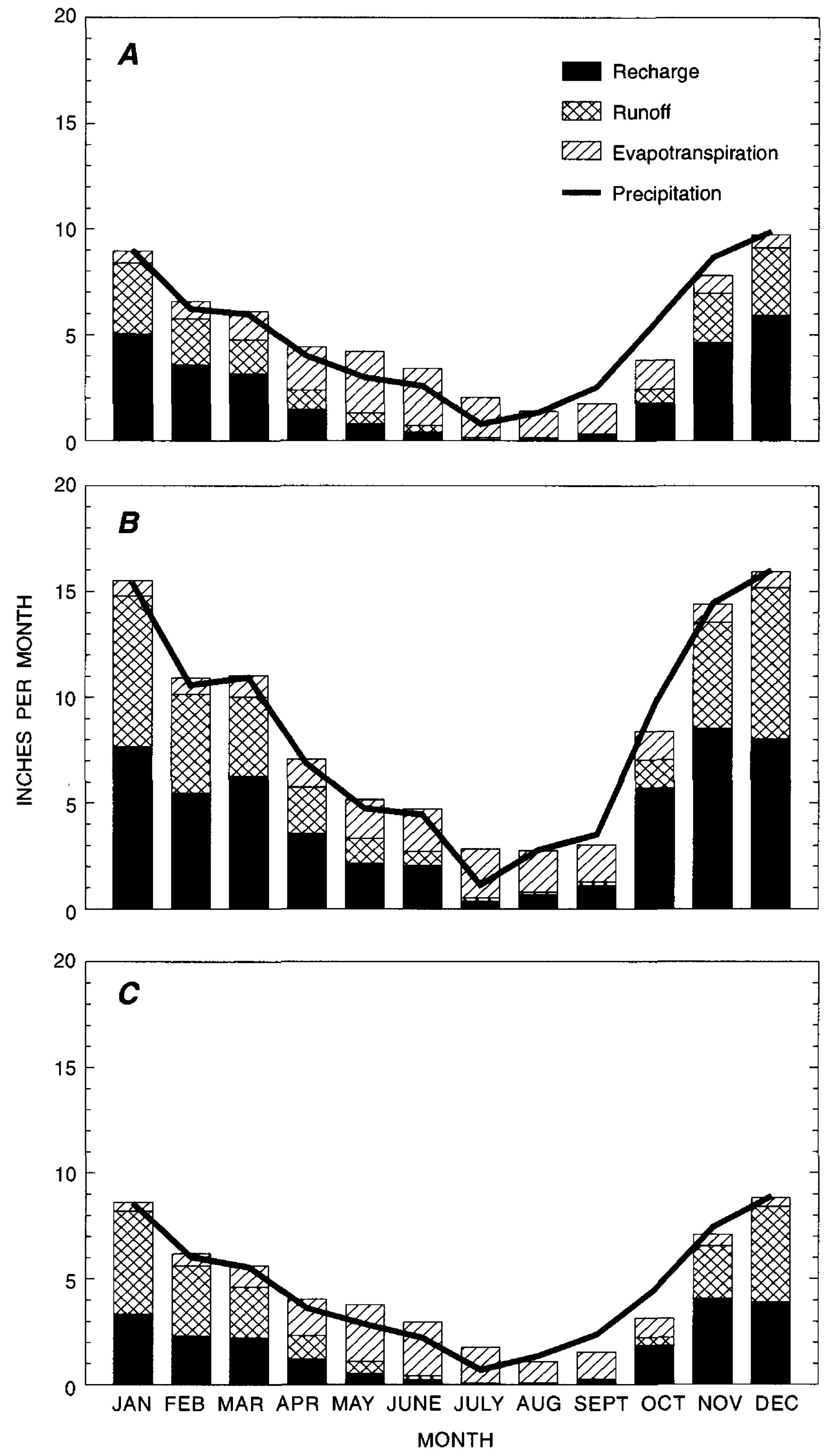


Figure 7. Average monthly water budget for *(A)* Salmon Creek Subbasin, 1949-74; *(B)* Cedar Creek Subbasin, 1952-68; and *(C)* Johnson Creek Subbasin, 1949-83.

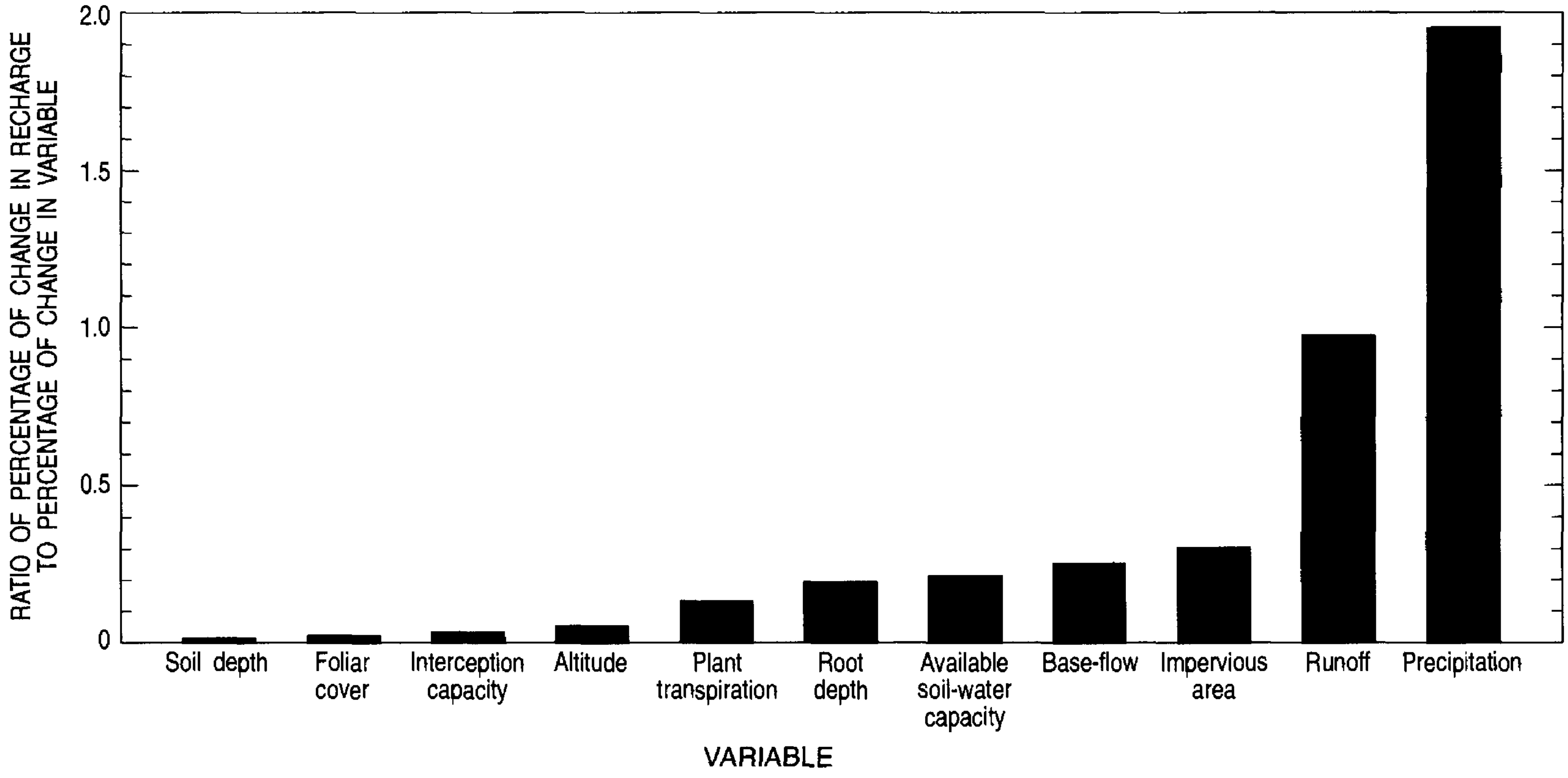


Figure 8. Sensitivity analysis for Salmon Creek Subbasin.

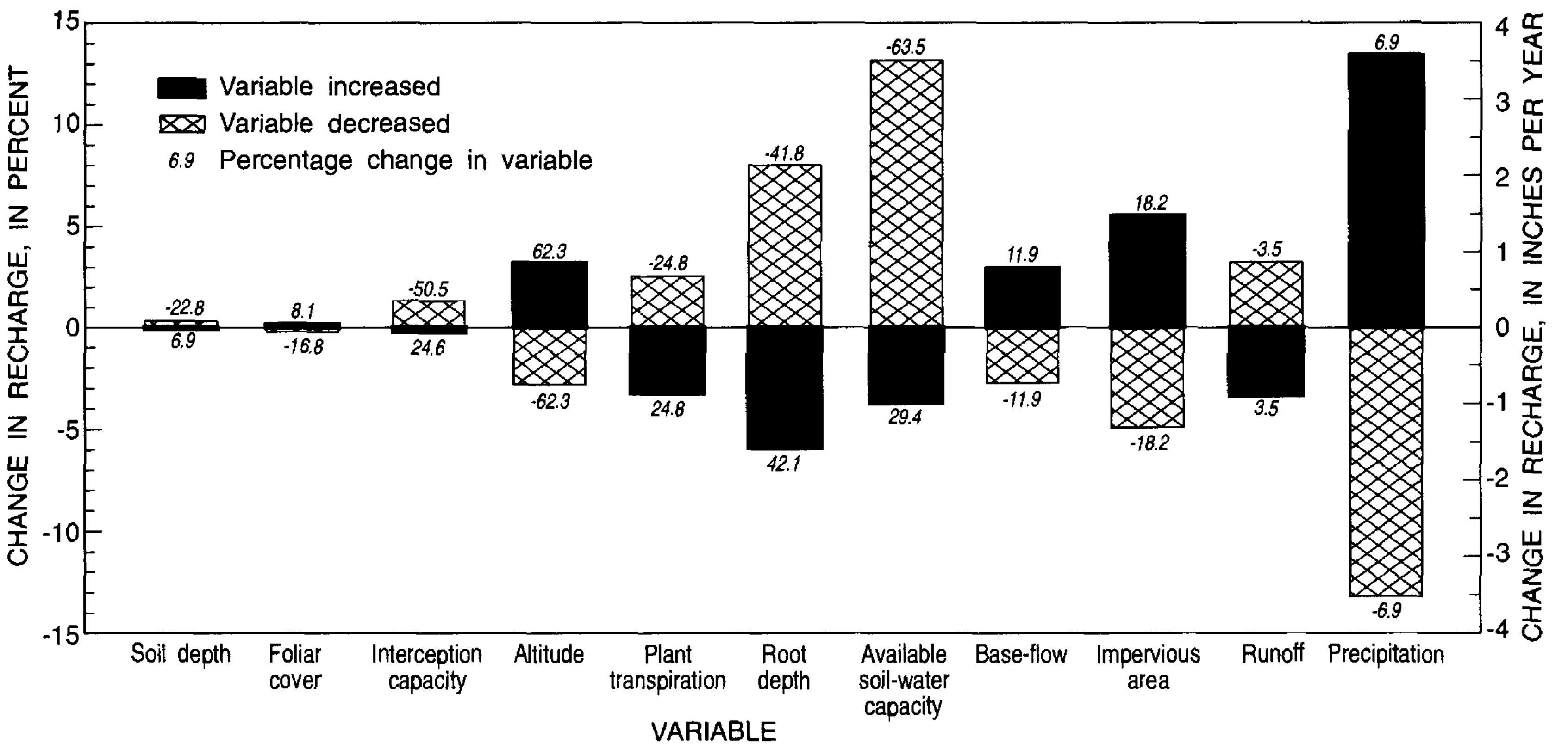


Figure 9. *Uncertainty analysis for Salmon Creek Subbasin.*

Regression Analysis

The DPM was not used to calculate recharge from precipitation over the entire study area because of the lack of necessary data for many of the drainage basins. Instead, a regression analysis from results of the DPM simulation for the three subbasins was used to derive an equation for calculating the average annual recharge from precipitation for any part of the study area from readily available climatic and physical parameters.

The multiple-linear regression analysis used the average annual recharge calculated with the DPM as the response variable. Explanatory variables chosen from among the spatially distributed input parameters for the DPM included average annual precipitation, runoff, impervious area, land-surface altitude, slope, aspect, soil depth, available soil-water capacity, soil texture, root depth, plant transpiration, interception capacity, and foliar cover. The average annual recharge calculated with the DPM for each cell in the three subbasins, along with the input parameters for the cells, were used as observations in the regression.

A regression equation that accounts for the largest part of the total variation in the response variable with the fewest number of explanatory variables was selected. Criteria for the selection of an equation included maximizing the adjusted R^2 (the coefficient of determination adjusted for the number of explanatory variables used in the regression) and minimizing the Mallow's Cp statistic (a measure of total squared error). The number of explanatory variables used in the regression equation was determined by noting when the introduction of additional explanatory variables failed to substantially increase the adjusted R^2. Mallow's Cp was used to select between equations with the same number of explanatory variables having similar adjusted R^2 values (see Draper and Smith, 1981).

All possible regression equations that use the explanatory variables were examined. The best equation, which uses average annual precipitation, percentage of impervious area, and land-surface altitude as the explanatory variables, is:

$$RCHG = (0.48212)PRCP - (0.35418)IMPRV + (0.0097444)ALT - 4.7906$$

where

RCHG is recharge, in in/yr;
PRCP is precipitation, in in/yr;
IMPRV is impervious area, in percentage of cell; and
ALT is altitude of land surface, in feet above sea level.

The adjusted R^2 of 0.91, indicates that 91 percent of the variation in recharge, as determined with the DPM, can be explained by precipitation, impervious area, and altitude of land surface. The p-values (the probability that a particular value was obtained by chance) for the regression equation, the three explanatory variables, and the intercept are less than 0.0001. The mean square error for the regression model is 4.9 in/yr; however, this does not incorporate the uncertainty inherent in the estimates of recharge calculated with the DPM.

Regionalization

A portion of the study area was discretized into a rectilinear grid identical to that being used in subsequent ground-water model studies. This discretization facilitates the direct transfer of recharge data from this study to be used as input to the flow model. The grid (fig. 10) has an area of 981 mi^2 and consists of 3,040 active cells with a uniform grid-cell spacing of 3,000 ft (a cell area of 0.32 mi^2). The y-axis is oriented in a direction 28.8 degrees west of north to align the rectilinear grid with the major directions of ground-water flow.

The predictors of recharge used in the regression equation--average annual precipitation, impervious area, and land-surface altitude--were estimated for each model grid cell. Average annual precipitation (fig. 11) was determined in a manner similar to that used to estimate precipitation for the DPM. Impervious-area values were determined from the USGS 1:250,000-scale Land-Use and Land-Cover Digital Data Map for Vancouver, Washington, 1974, by using the percentages of impervious area based on the land-use categories presented in the data-requirements section for the DPM. Impervious area was then area-weighted in a model-grid cell to yield the percentage of impervious area (fig. 12). Land-surface altitude was derived by electronically scanning topographic contours from the USGS 1982 1:100,000-scale maps for Oregon City, Oregon, and Vancouver, Washington, and converting to digital data. The altitude data were discretized by a process identical to that used for precipitation (fig. 13). Average annual recharge for each model cell was calculated by using the regression equation and appropriate input data. This results in a distribution of recharge in which the recharge value is a point estimate for any land-surface area in the cell.

Use of the regression equation produced negative values of recharge for 82 of the 3,040 cells in the model-grid area. This generally occurs for cells that have a large percentage of impervious area, small values of precipitation, and low land-surface altitudes. The recharge values for these cells were set to zero. The estimated volume rate of recharge from precipitation (excluding recharge from precipitation over surface-water areas) in the area of the ground-water flow-model grid (981 mi^2) for the Portland Basin is 1,440 ft^3/s. The average recharge from precipitation for the model-grid cells ranges from 0 to 49 in/yr with a mean of 20.8 in/yr. Except in areas with significant impervious area, the areal distribution of recharge from precipitation (pl. 1, fig. A) is similar to that for precipitation.

In a similar study using the DPM, Bauer and Vaccaro (1990, p. 28) assumed a maximum error of about 25 percent for their estimates of ground-water recharge. The results of the uncertainty analysis of the DPM and the mean square error for the regression equation used in this study indicate that about ±25 percent for recharge greater than or equal to 8 in/yr or ±2 in/yr for recharge less than 8 in/yr is a reasonable estimate of the uncertainty in the estimates of ground-water recharge from precipitation.

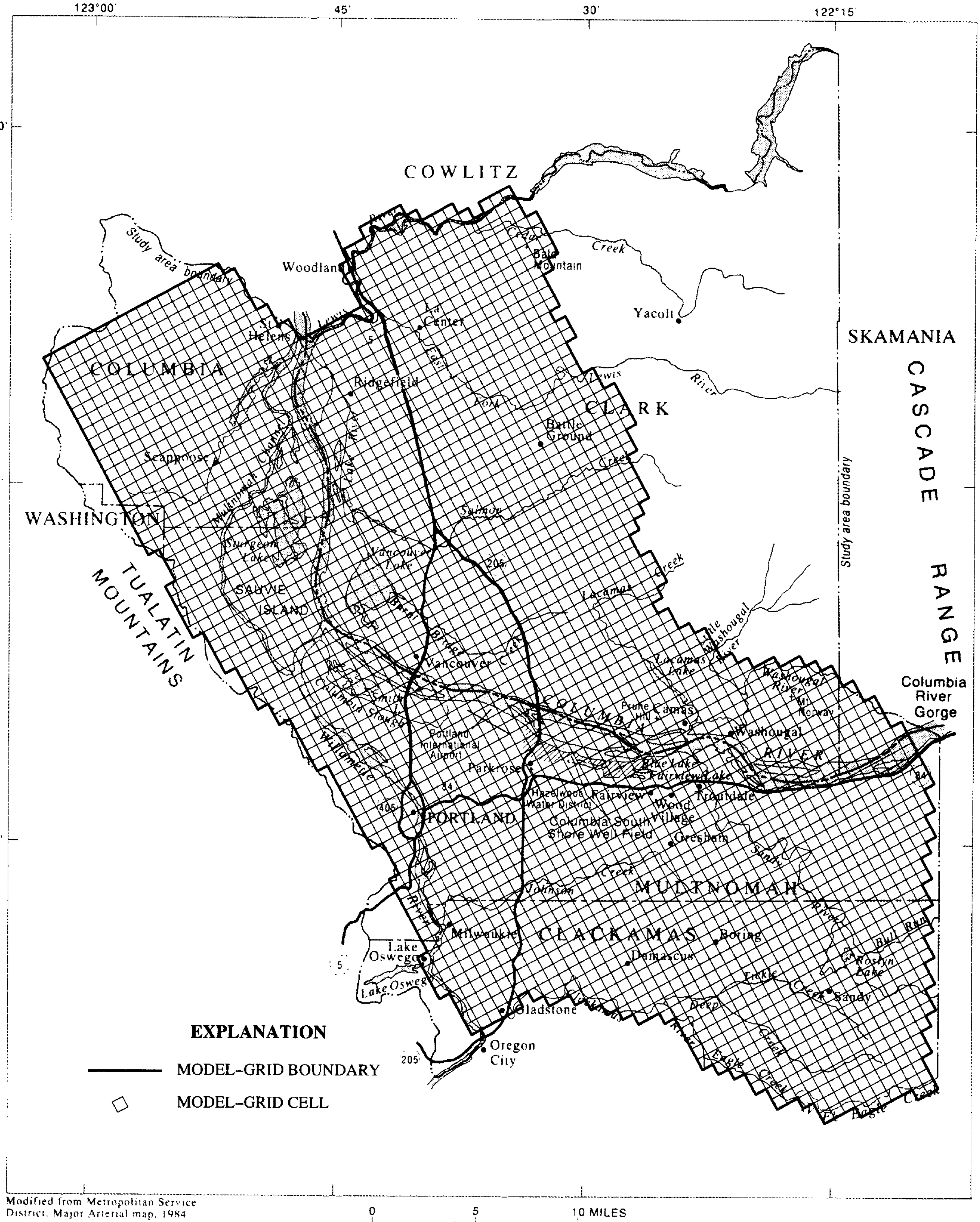


Figure 10. Ground-water flow model grid.

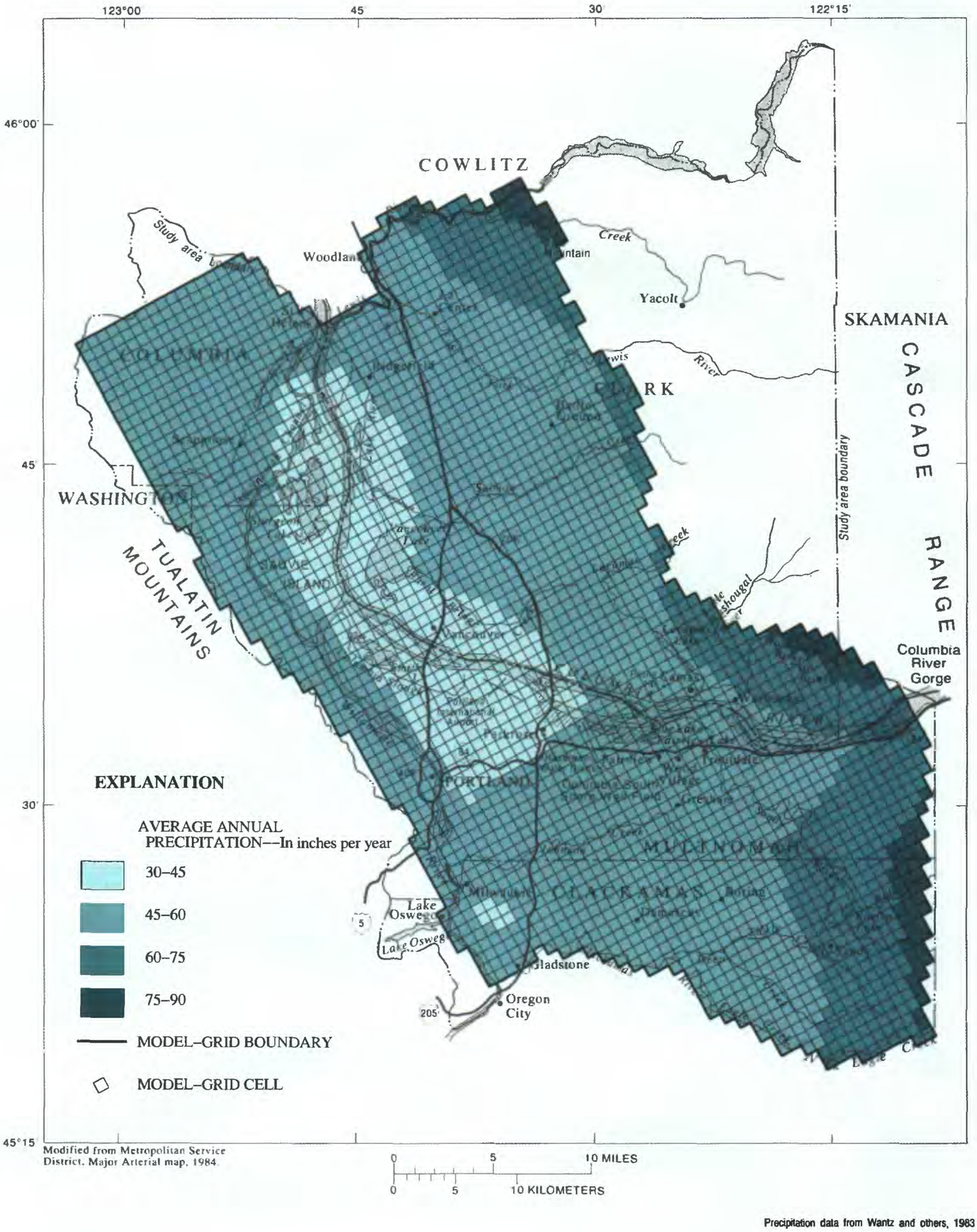


Figure 11. Distribution of average annual precipitation.

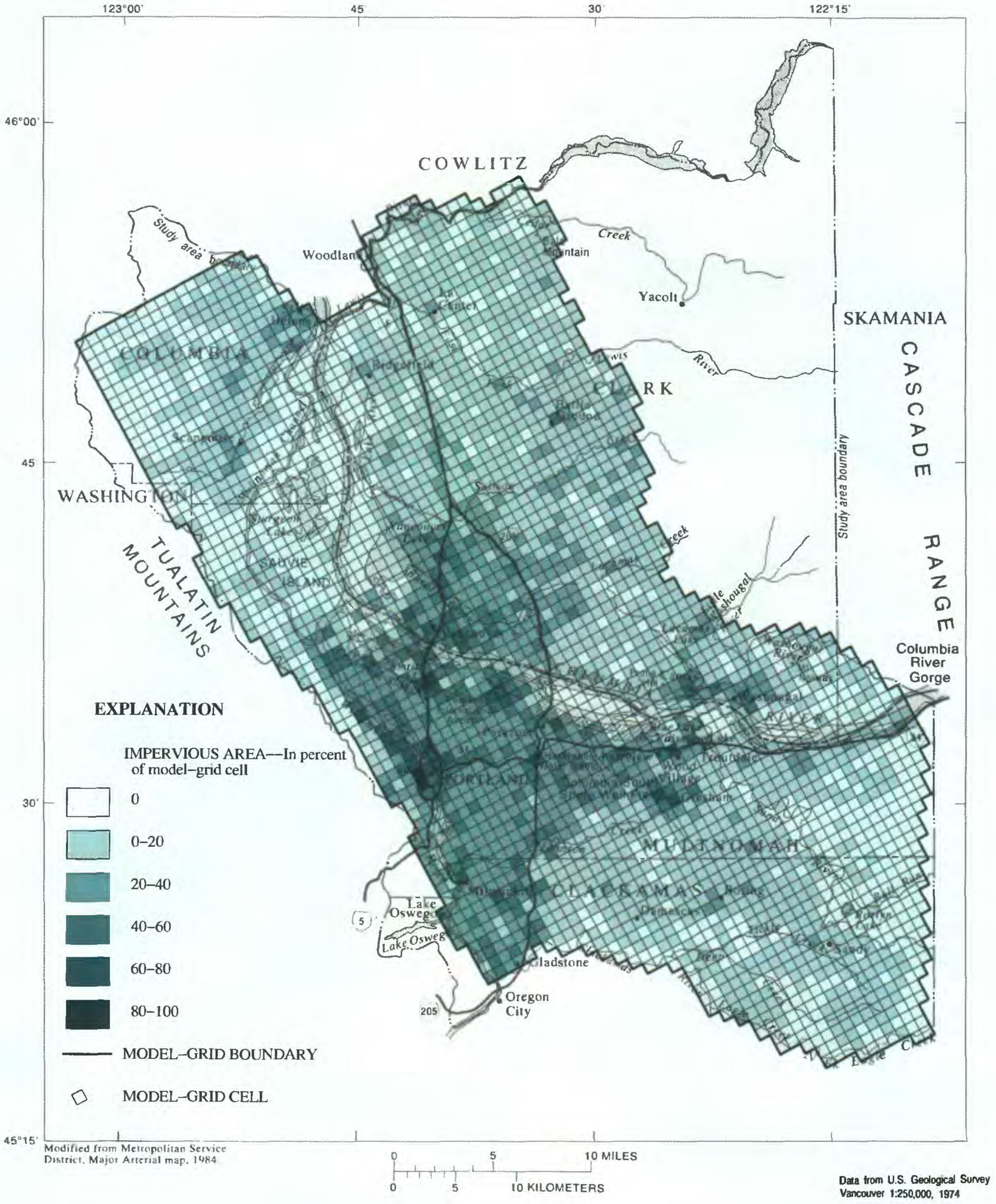


Figure 12. Distribution of impervious area.

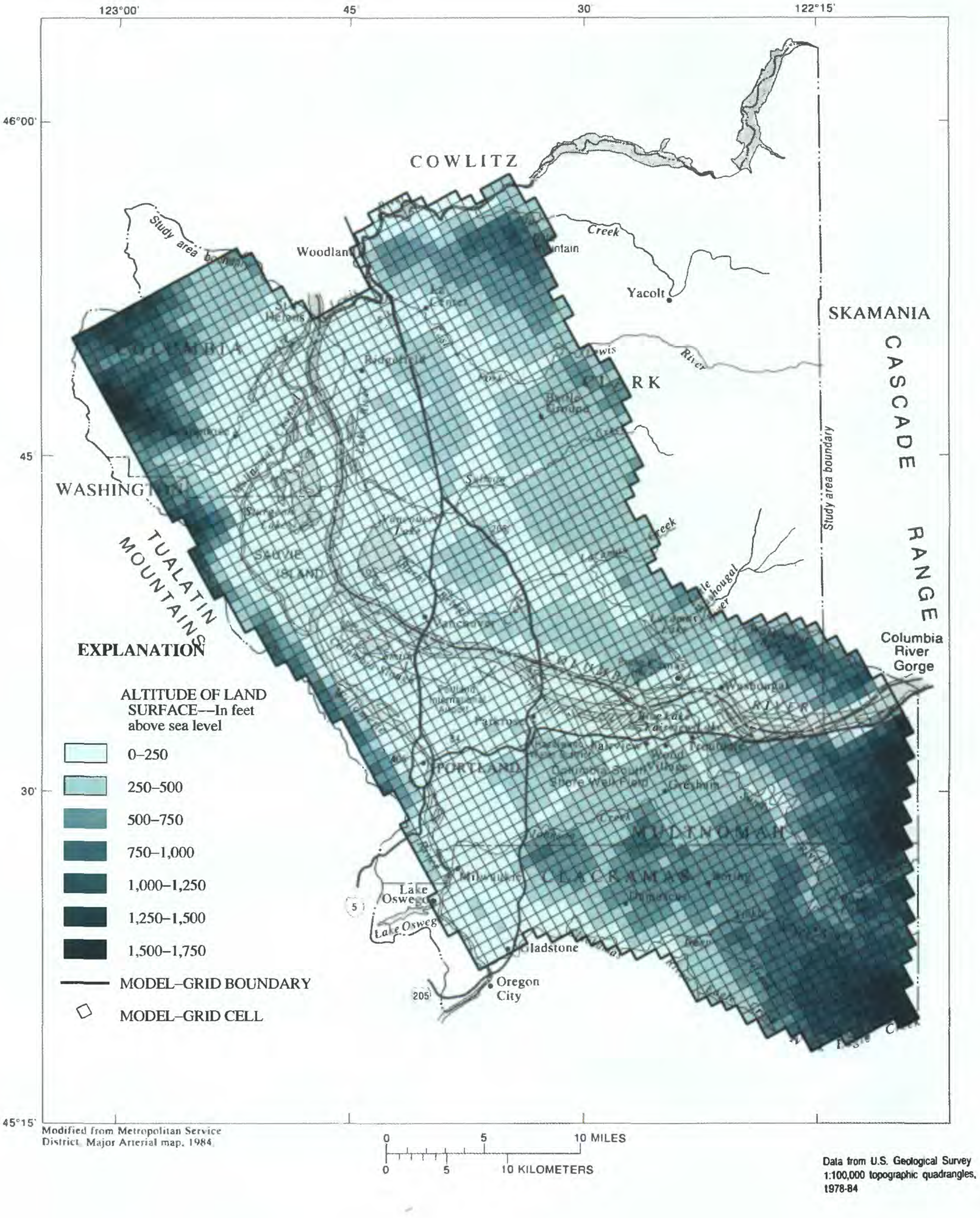


Figure 13. Altitude of land surface.

ESTIMATION OF RECHARGE FROM RUNOFF INTO DRYWELLS

In the urbanized parts of the Portland-Vancouver area, soils and shallow geologic formations are generally permeable and conducive to infiltration of runoff from impervious surfaces such as rooftops, streets, and parking lots. The runoff flows into the shallow ground-water system by gravity through shallow, large-diameter drywells (sumps). This direct path from the surface to the water table allows water to bypass the natural processes of filtration, bioretardation, and evapotranspiration of water that infiltrates through the unsaturated zone. The magnitude and distribution of this source of recharge and its associated effect on the ground-water flow regime of the Portland Basin had not been evaluated before this study. The following sections describe the estimates of recharge from drywells, including the availability of data, the methodology and assumptions used, and the resulting distribution of ground-water recharge.

Data Availability

All county, municipal, State, and Federal agencies with jurisdiction in the study area were contacted to determine the availability and type of data describing the locations of drywells. Agencies contacted included city and county public-works departments, local sanitary-sewer districts, the Oregon Water Resources Department, the Oregon Department of Environmental Quality, the Washington Department of Ecology, and the U.S. Environmental Protection Agency. The availability of data on the number and locations of drywells varied greatly throughout the study area. Typically, only qualitative information regarding prevalent building practices was available and there were virtually no records of individual domestic drywells. Data-collection efforts, therefore, were focused on urban areas without storm drains or combined sewers.

Drywells in mid-Multnomah County, Oregon, in the City of Portland, were inventoried in 1985 (Brown and Caldwell, 1986). The resolution of the inventory was one-quarter of a standard section (0.25 mi^2). An inventory for the rest of Multnomah County was compiled from unpublished maps provided by the public-works departments of Multnomah County and the City of Gresham.

Drywells in Clark County, Washington, were inventoried as part of a statewide program to assess the effects of underground wastewater injection on water quality (B.D. Bowen, Washington Department of Ecology, written commun., 1988). As in Multnomah County, this inventory was compiled at quarter-section resolution. The area of the inventory included only the urbanized parts of the county that coincided with heavily concentrated commercial and industrial development. These are the areas where impervious surfaces intercept significant quantities of precipitation, and runoff is diverted to drywells. The rest of the county is sparsely populated with virtually no commercial or industrial presence.

Where soil conditions allow, drywells also are commonly used to dispose of runoff from residential rooftops and driveways. In this study, it was assumed that the total area of residential impervious surfaces was small enough that it could be ignored in the estimates of recharge.

In the 88-mi^2 area inventoried (fig. 14), nearly 5,700 drywells were found. Almost two-thirds of this total (3,720) are in Multnomah County where the mean drywell density of 84 per square mile is nearly twice that in Clark County (46 drywells per square mile).

Few data are available on the volume of runoff to drywells that recharges the ground-water system each year in the study area. In Multnomah County, two previous studies addressed the suitability of using drywells for storm-water disposal in localized areas (Kramer, Chin and Mayo Incorporated, 1984; Century West Engineering, 1985). A more regional assessment of the effects of drywells on ground-water quality was done by Brown and Caldwell (1986), but none of these studies included an attempt to quantify the volume of recharge to the ground-water system from drywells. Information on recharge volumes from drywells in Clark County is similarly sparse.

Method of Estimation

The following assumptions were made in order to estimate the average annual quantity of recharge from runoff to drywells in the study area:

(1) If drywells are present in a quarter section, all runoff from impervious surfaces in the quarter section was routed to the drywells.

(2) All runoff routed to drywells was available to the flow system as recharge.

(3) The quantity of runoff available to drywells was equal to precipitation on impervious surfaces less detention-storage losses from those surfaces.

It was originally believed that drywell density might provide an index to the quantity of recharge contributed by individual quarter sections; however, there is no apparent relation between the number of drywells per quarter section and the percentage of impervious area in a quarter section (fig. 15). This conclusion is supported by information provided by local drainage engineers that drywell density is more closely related to soil characteristics and other design constraints than to the volume of runoff generated from impervious surfaces in a given area (C.L. Moshofsky, Clark County, Washington, Public Service Department, written commun., 1989). This information was the basis for assuming that recharge rates from runoff into drywells were directly related to impervious area and precipitation and unrelated to drywell density.

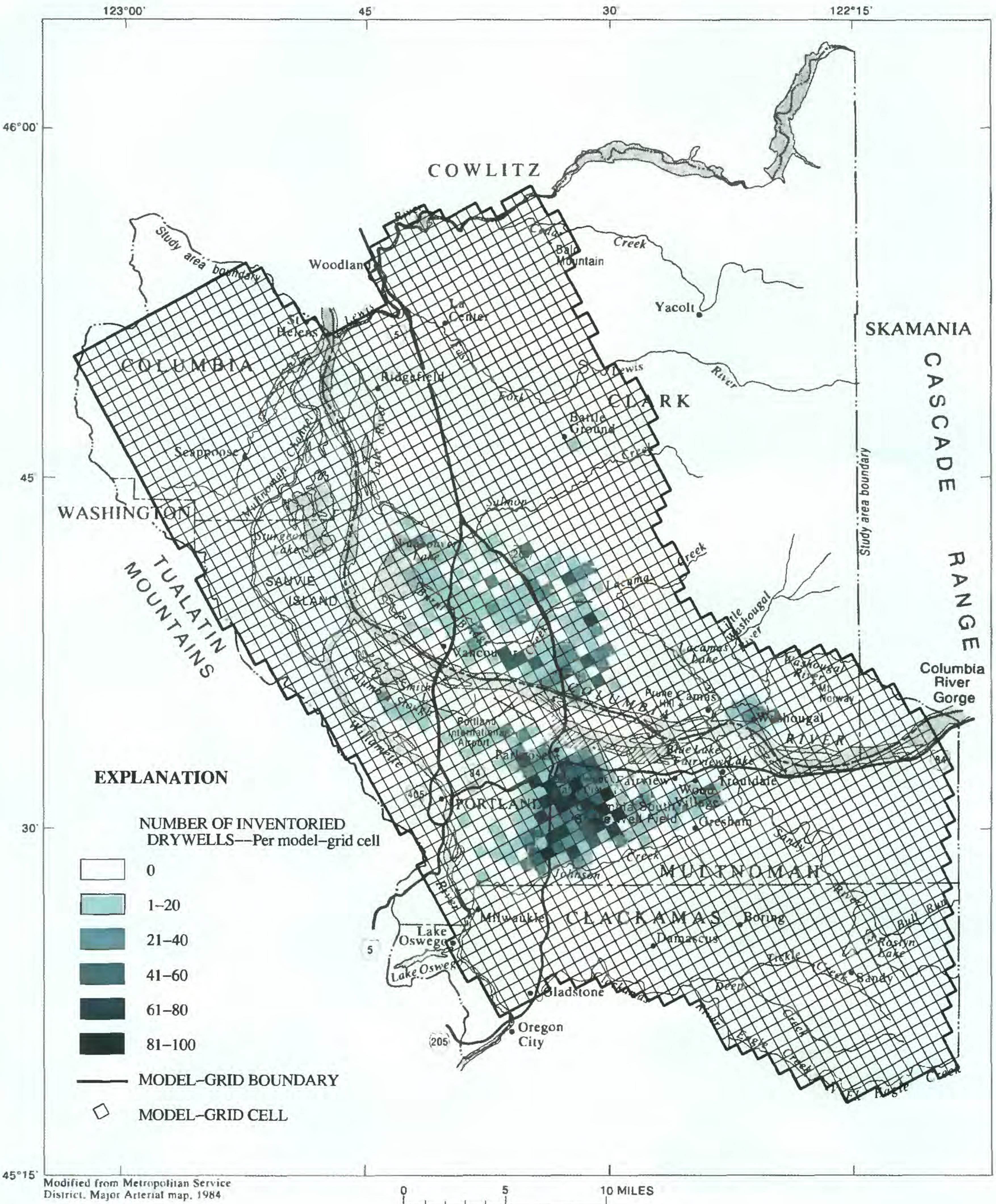


Figure 14. Distribution of drywells.

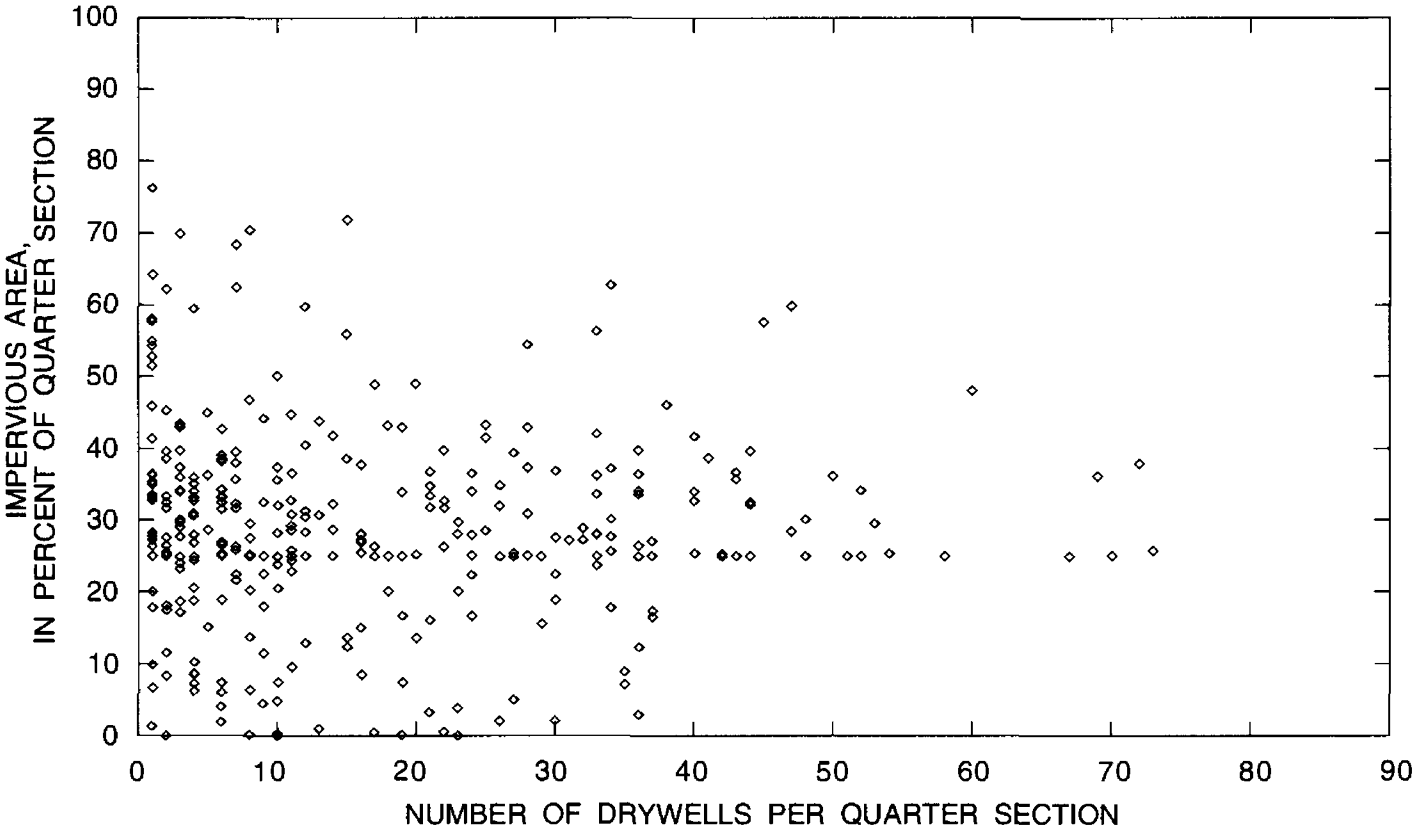


Figure 15. Relation between impervious area and number of drywells.

A mass-balance approach was used to estimate the percentage of average annual precipitation lost to detention storage and ultimately to evaporation. The mass balance was calculated by using a simple "bucket model," wherein the amount of daily precipitation available for runoff to drywells was computed as the precipitation in excess of detention-storage requirements with detention storage being depleted at the daily pan-evaporation rate.

The percentages of impervious areas for quarter sections containing drywells were estimated from the USGS 1:250,000-scale Land-Use and Land-Cover Digital Data Map for Vancouver, Washington, 1974, by using the same percentages of impervious area for urban classifications as were used in estimating recharge from precipitation. In Multnomah and Clark Counties, the mean percentage of impervious area in the 88-mi^2 area of inventoried drywells was 29 percent. The mean for the 44 mi^2 that lie within Multnomah County was 31 percent, and the mean for the remaining 44 mi^2 in Clark County was 26 percent.

Daily pan-evaporation and precipitation data from the North Willamette Agricultural Experiment Station (NWES) were obtained for calendar years 1979-88 (K.T. Redmond, State of Oregon, Office of the State Climatologist, written commun., 1989) and used in the bucket model. The NWES is 15 mi south of downtown Portland (see fig. 2 and table 2) and has an average precipitation of 42 in/yr (1979-88) and a pan evaporation of 44 in/yr (1979-88).

Use of the bucket model required an estimate of the average detention-storage capacity of impervious surfaces in the study area, expressed as depth of water in inches. In attempting to simulate rainfall-runoff relations in several urban basins in the Portland-

Vancouver area, Laenen (1980) found that impervious-area detention-storage values of 0.05 to 0.10 inches yielded good results; however, he also noted that the models were generally insensitive to this parameter (Antonius Laenen, U.S. Geological Survey, oral commun., 1989).

Use of detention-storage values of 0.05 and 0.10 inches and climatic data from the NWES showed that 23 and 26 percent, respectively, of precipitation incident on impervious surfaces would be lost to evaporation annually during the 1979-88 period. For estimation of recharge from drywells, it was assumed that 74 percent of average annual precipitation falling on impervious surfaces would run off to drywells (where drywells were used).

Precipitation in each quarter section was estimated from the 15-year average annual precipitation map used to estimate regional recharge. Precipitation in the drywell recharge area ranged from 37 to 62 in/yr with a mean of 48 in/yr.

Estimated Recharge

Recharge rates were first computed by quarter section, then aggregated to the model-cell format for consistency with estimates of recharge from precipitation. The distribution of drywell recharge in the model grid is shown in figure B on plate 1. The estimated average volume rate of recharge from drywells is 61.7 ft^3/s, of which nearly one-half (27.1 ft^3/s) occurs in Clark County, Washington. Rates of recharge from drywells for model-grid cells in the 88-mi^2 area of inventoried drywells range from 0 to 26 in/yr and have a mean of 9.4 in/yr.

ESTIMATION OF RECHARGE FROM ON-SITE WASTE-DISPOSAL SYSTEMS

In many parts of the study area, on-site waste-disposal systems (OWDS's) [septic tanks and cesspools] are still used to dispose of commercial and domestic wastewater. Effluent from OWDS's, like surface runoff diverted to drywells, bypasses most or all of the near-surface unsaturated zone and the processes of evapotranspiration, filtration, and bioretardation that would otherwise affect water infiltrating from the surface. This makes OWDS's, like drywells, efficient conduits for ground-water recharge--particularly where water tables are shallow and soils are highly permeable.

Throughout most of the Portland Basin, population densities and levels of commercial development are low enough that OWDS's do not contribute significant volumes of recharge to the ground-water system. More than 74 percent of the study area is low-population-density rural residential, farm, or forest land with less than 60 people per square mile. Use of the U.S. Environmental Protection Agency (1980) estimate of OWDS discharge of 45 gallons per day per capita yields OWDS recharge rates in these areas of about 0.06 in/yr. This amount is far below the uncertainty limits of recharge from precipitation so that the contribution of recharge from OWDS's in these areas was ignored for this study.

The two sizable unsewered areas that coincide with areas of high-population density and concentrated commercial development (fig. 16) are a potentially significant source of recharge to the shallow ground-water system. In 1987, the mid-Multnomah County area had approximately 47,000 residential and commercial OWDS's in a 39-mi^2 area (fig. 16) [City of Portland Bureau of Environmental Services, unpub. data, 1988]. This area is also the location of a sewering project with the goal of eliminating all OWDS's by the year 2003 (CH2M-Hill, 1984). The vicinity of Burnt Bridge Creek in Clark County is another unsewered area with a significant population. Although similar in extent to the mid-Multnomah County area, OWDS's in the Burnt Bridge Creek area numbered only about 10,200 in 1987 (Washington Department of Ecology, unpub. data, 1988). Although new development in the Burnt Bridge Creek area must be connected to sewers, there are currently (1992) no plans to force existing OWDS users to hook up to the sewer system.

Twenty percent of the population in the Portland Basin relies on OWDS's and resides in a 73-mi^2 area that is only 6 percent of the Portland Basin. The potential effect of recharge from OWDS's in this area on the ground-water flow system, particularly the shallow aquifers, is significant. In this study, data-collection efforts were focused on the mid-Multnomah County and southwestern Clark County urban areas identified as being substantially unsewered and having large populations using OWDS's.

Data Availability

All data used to estimate recharge were compiled from existing files and reports from Federal, State, and local agencies and consulting firms. The principal source of data on the locations of OWDS's in the mid-Multnomah County area was an inventory by quarter section (0.25 mi^2) maintained by the City of Portland's Department of Environmental Services. Additional information on the distribution of OWDS's was obtained from the Cities of Gresham and Troutdale. Together, these inventories were estimated to contain 90 to 95 percent of the functioning OWDS's in the Portland metropolitan area; the remaining 5 to 10 percent are scattered throughout the area with no locally significant concentrations (C.L. Moshofsky, U.S. Geological Survey, written commun., 1989). Inventories of OWDS's also were completed by quarter section in the Burnt Bridge Creek area in southwestern Clark County by the Southwest Washington Health Department (C.L. Addy, Southwest Washington Health Department, oral commun., 1988). Whereas the inventory of OWDS's for the Portland metropolitan area differentiated between commercial and residential systems, the Clark County inventory did not.

Method of Estimation

Annual recharge volumes in each quarter section were calculated by multiplying estimated effluent rates for residential and commercial OWDS's by the number of OWDS's in the quarter section.

Residential OWDS's were estimated to discharge 117 gallons per day (gal/d) on the basis of an average of 2.6 persons per household (CH2M-Hill, 1985) and a per capita discharge of 45 gal/d (U.S. Environmental Protection Agency, 1980).

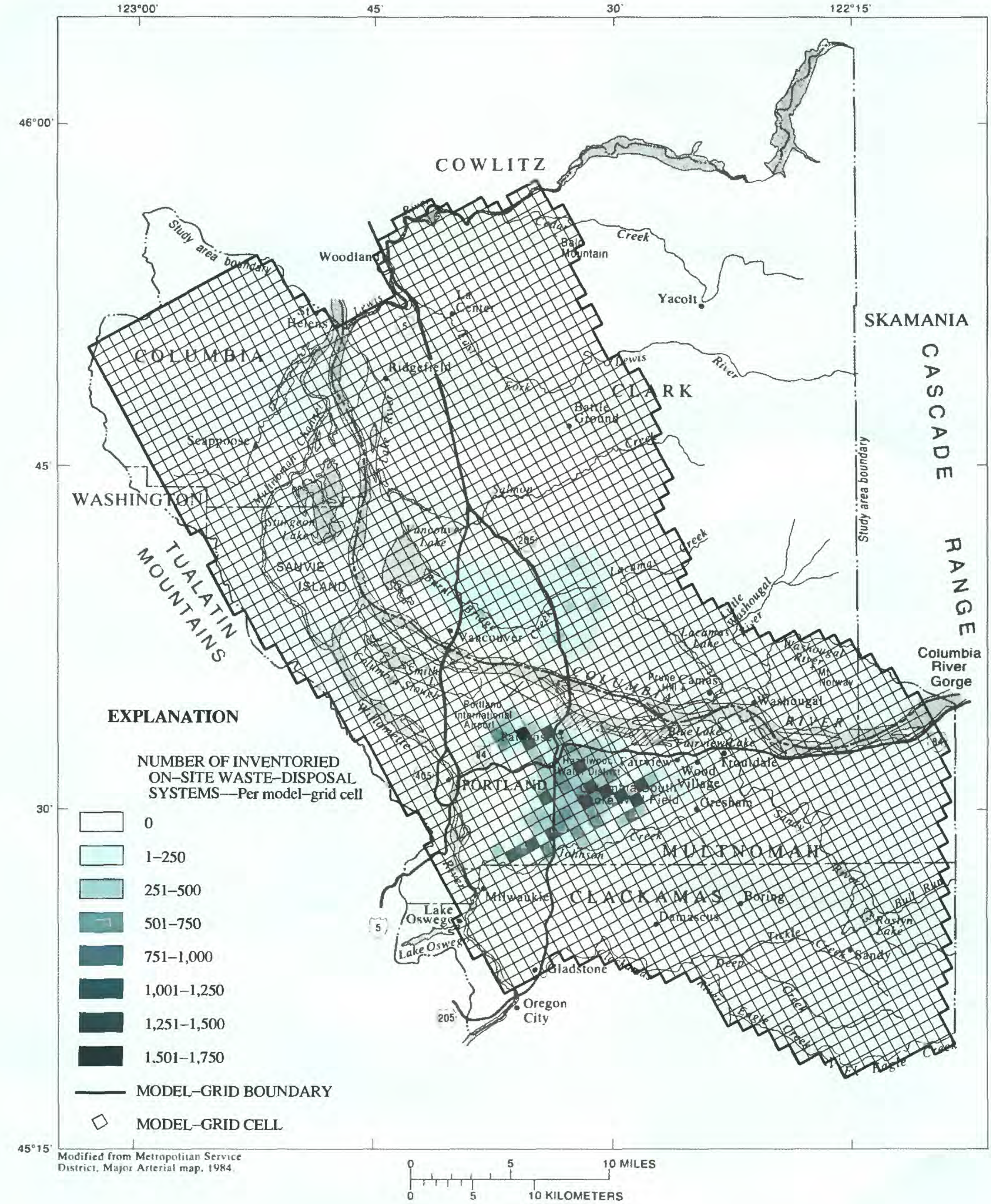


Figure 16. Distribution of on-site waste-disposal systems.

Many factors control commercial wastewater-discharge rates, including the type of establishment, the number of employees, and the number of people served (U.S. Environmental Protection Agency, 1980). Because data needed to reliably account for these factors in estimating industrial/commercial OWDS discharge rates were not available, the average effluent-discharge volume rate for commercial OWDS's was estimated indirectly from data published in a mid-Multnomah County sewer implementation plan (CH2M-Hill, 1985). In this study, it was estimated that 50,459 residential and 3,133 commercial OWDS's functioning in mid-Multnomah County in 1985 discharged a total of 16.7 million gallons per day (Mgal/d). It was assumed that if the 50,459 residential OWDS's discharged an average of 117 gal/d, they would generate 5.9 Mgal/d of the 16.7 Mgal/d total. The remaining 10.8 Mgal/d was assumed to be generated by the 3,133 commercial OWDS's discharging at an average rate of 3,400 gal/d. It was further assumed that the percentage of commercial systems in Clark County was the same as in mid-Multnomah County, because residential and commercial systems were not differentiated in the Clark County inventory. The mean percentage of commercial systems in mid-Multnomah County in 1987 was about 6 percent.

Estimated Recharge

The estimated 1987 ground-water recharge rates from residential and commercial OWDS's are listed by county in table 3.

Table 3.--Estimated 1987 ground-water recharge from on-site waste-disposal systems

[Mgal/d = million gallons per day, ft^3/s = cubic feet per second]

Waste-disposal system		Discharge	
Type	Number	Mgal/d	ft^3/s
CLARK COUNTY			
Commercial	556	1.89	2.93
Residential	9,656	1.13	1.75
Total	10,212 1/	3.02	4.68
MULTNOMAH COUNTY			
Commercial	2,751	9.35	14.5
Residential	44,135	5.16	7.99
Total	46,886 2/	14.5	22.5
Grand total	57,098	17.5	27.2

1/ Washington Department of Ecology, unpub. data, 1988.
2/ City of Portland Bureau of Environmental Services, unpub. data, 1988.

Recharge rates from OWDS's were first computed by quarter section, then aggregated to the model-cell format for consistency with estimates of recharge from precipitation and drywells. The estimated distribution of recharge in the model grid from OWDS discharge is shown in figure C on plate 1. The average volume rate of recharge is 27.2 ft^3/s, of which 4.68 ft^3/s occurs in Clark County. Rates of recharge from OWDS's for model-grid cells in the 73-mi^2 area of mid-Multnomah and southwestern Clark Counties range from 0 to 26 in/yr and have a mean of 5.0 in/yr.

TOTAL RECHARGE FROM PRECIPITATION, RUNOFF INTO DRYWELLS, AND ON-SITE WASTE-DISPOSAL SYSTEMS

The volume rate of recharge from all sources averaged over the model-grid area of 981 mi^2--precipitation (excluding recharge from precipitation over surface-water areas), runoff into drywells, and effluent from on-site waste-disposal systems--is about 1,530 ft^3/s. The average rate of recharge from these sources for the model-grid cells is 22.0 in/yr. The distribution of recharge summed from the individual recharge components--precipitation, runoff into drywells, and on-site waste-disposal systems--is presented in figure D on plate 1. (Differences between the sum of the individual recharge components and the total recharge are due to rounding.)

The lowest recharge occurs along and between the Columbia and Willamette Rivers and is near zero. The Cascade Range generally has the highest recharge, about 49 in/yr. Recharge in urban areas of Multnomah and Clark Counties containing drywells and on-site waste-disposal systems varies from 0 to as much as 49 in/yr in localized areas.

The dominant component of recharge is precipitation, which accounts for 94 percent of the total recharge in the model-grid area. Recharge from drywells is only 4 percent of the total recharge. In the 88-mi^2 area of inventoried drywells, however, drywell recharge, makes up 38 percent of the recharge, with rates as large as 26 in/yr for individual grid cells. Recharge from on-site waste-disposal systems contributes less than 2 percent of the total recharge to the model-grid area. In the 73-mi^2 area of heavily concentrated OWDS's, however, recharge from this source accounts for approximately 17 percent of the total, with a maximum rate of 26 in/yr for individual cells.

SUMMARY AND CONCLUSIONS

Average annual ground-water recharge from precipitation, runoff into drywells, and on-site waste-disposal systems was estimated for a part of the Portland Basin.

Ground-water recharge from precipitation was estimated for three subbasins by using a modified version of the Deep Percolation Model. The three subbasins and their respective average recharge rates are Salmon Creek, Washington, 27 in/yr; Cedar Creek, Washington, 52 in/yr; and Johnson Creek, Oregon, 20 in/yr. The results from the Deep Percolation Model then were regressed against the input parameters to derive an equation by which recharge from precipitation for the study area could be calculated. Average annual precipitation, percentage of impervious area, and land-surface altitude account for 91 percent of the variation in recharge.

Estimates of ground-water recharge from runoff into drywells were made on the basis of precipitation, percentage of impervious area, and evaporation. The number of drywells per quarter section was compiled from data available from city, county, State, and Federal agencies. In an 88-mi^2 urbanized area of Multnomah and Clark Counties, nearly 5,700 drywells were identified.

Ground-water recharge from on-site waste-disposal systems at about 57,000 sites in mid-Multnomah County, Oregon, and southwestern Clark County, Washington, was estimated. The distribution of on-site waste-disposal systems in the counties was provided by local, State, and Federal agencies and consulting firms.

The average recharge rates from precipitation, drywells, and on-site waste-disposal effluent in the Portland Basin are 20.8, 0.9, and 0.4 in/yr, respectively; average volume rates of recharge (excluding recharge over surface-water areas) for the same categories are 1,440 ft^3/s, 61.7 ft^3/s, and 27.2 ft^3/s, respectively. The sum of the average recharge rates from all sources is estimated to be about 22.0 in/yr, and 1,530 ft^3/s is the average volume rate for all sources. Recharge rates are near zero along and between the Columbia and Willamette Rivers. Recharge rates are largest, about 49 in/yr, in the Cascade Range, although discrete areas of large recharge also are found in urbanized parts of the Portland Basin. The largest component of recharge is generally from precipitation, however, in urbanized areas recharge from drywells and on-site waste-disposal systems can have significant local effect.

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