ESTIMATES OF GROUND-WATER RECHARGE TO THE COLUMBIA PLATEAU REGIONAL AQUIFER SYSTEM, WASHINGTON, OREGON, AND IDAHO, FOR PREDEVELOPMENT AND CURRENT LAND-USE CONDITIONS

By H.H. Bauer and J.J. Vaccaro

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4108

A contribution of the
REGIONAL AQUIFER-SYSTEM
ANALYSES PROGRAM

Tacoma, Washington
1990

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425, Federal Center, Bldg. 41
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

[Plates are located in pocket at end of report]

TABLES

CONVERSION FACTORS

For the convenience of readers who may prefer to use metric units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound units	By	To obtain SI units
inch (in.)	25.4	millimeter (mm)
foot (ft)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
	0.02832	cubic meters per second (m^3/s)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 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.

degree Fahrenheit (°F) to degree Celsius (°C): °C = 5/9 (°F - 32)

ESTIMATES OF GROUND-WATER RECHARGE TO THE COLUMBIA PLATEAU REGIONAL AQUIFER SYSTEM, WASHINGTON, OREGON, AND IDAHO, FOR PREDEVELOPMENT AND CURRENT LAND-USE CONDITIONS

By H.H. Bauer and J.J. Vaccaro

ABSTRACT

Estimates of time-averaged ground-water recharge to the Columbia Plateau regional aquifer system were computed for predevelopment and current land-use conditions for 1956-77. The estimates were computed using a deep-percolation model. Recharge estimates were made for individual cells within 53 zones. The zones ranged in size from 20 to 2,392 square miles.

The deep-percolation model uses precipitation, temperature, streamflow, soils, land-use, and altitude data to compute transpiration, soil evaporation, snow accumulation, snowmelt, sublimation, and evaporation of intercepted moisture. Daily changes in soil moisture, plant interception, and snowpack are computed and accumulated. Deep percolation is computed when soil moisture exceeds field capacity.

Total recharge for predevelopment land-use conditions for the 53 modeled zones was estimated to be 2,588 cubic feet per second (1.65 inches per year) on average. Recharge for current land use was estimated to be 6,083 cubic feet per second (3.88 inches per year) on average.

Estimates of recharge for areas outside of the zones, but within the study area, were computed using a second-order polynomial regression equation. The equation relates the estimates of long-term zone estimates to average annual precipitation.

Estimates of average recharge rate for the total area within the ground-water model boundaries (32,800 square miles) for predevelopment and current land-use conditions were 5,998 cubic feet per second (2.48 inches per year) and 9,492 cubic feet per second (3.93 inches per year), respectively.

INTRODUCTION

A study of the Columbia Plateau regional aquifer system was begun in October 1982 as one of the 29 studies of the U.S. Geological Survey's Regional Aquifer-System Analyses Program (RASA). The Columbia Plateau aquifer system underlies about 50,600 square miles of the Columbia Plateau (fig. 1) in central and eastern Washington, north-central and eastern Oregon, and a small part of northwestern Idaho. The aquifer system is composed of the Columbia River Basalt Group (Miocene age), all of the intercalated sediments collectively assigned to the Ellensburg Formation (Miocene age), and the unconsolidated sediments (Miocene to Holocene age) overlying the basalts.

The Columbia Plateau aquifer system is a major source of ground water for municipal, industrial, domestic, and agricultural uses. Concurrent with ground-water usage, imported and native surface water is used for irrigation in several areas on the plateau. The surface water is almost fully appropriated, and the demand for more irrigation water is increasing. The Columbia Plateau aquifer system is the probable new source of irrigation water. The use of water for irrigation has resulted in ground-water-level rises in areas of surface-water irrigation, in ground-water-level declines (locally as much as 200 feet) in areas of ground-water pumpage, and in changes in chemical quality. Certain deep basalt layers are also under consideration as the national site for a high-level nuclear waste repository.

Purpose and Scope

The objective of the RASA program is to aid in the effective management of the nation's important ground-water resources by providing information on the geohydrology and geochemistry of the regional aquifer systems (Bennett, 1979). This general objective is met by (1) describing the geologic framework, (2) describing the hydraulic characteristics, (3) describing the water budget, (4) describing the flow system, (5) providing a means of estimating water levels through numerical ground-water modeling, and (6) describing the water-quality characteristics and geochemistry of the regional aquifer system.

The purpose of this report is to describe the method used to estimate ground-water recharge, to document the estimates of ground-water recharge, to describe the factors controlling recharge, and to discuss sources of error in estimating recharge. Recharge through the unsaturated zone is the main source of water to the Columbia Plateau aquifer system. Recharge simulations and regression estimates were made for a 32,800-square-mile area of the Columbia Plateau aquifer system for which a numerical ground-water model is being constructed (see fig. 2). Simulations were made for both predevelopment (prior to appreciable agriculture) and for current land-use conditions. Current land-use conditions represent averaged or composite land uses based on 1975 and 1979 Landsat data and field surveys, and are described in the later subsection "Land Use."

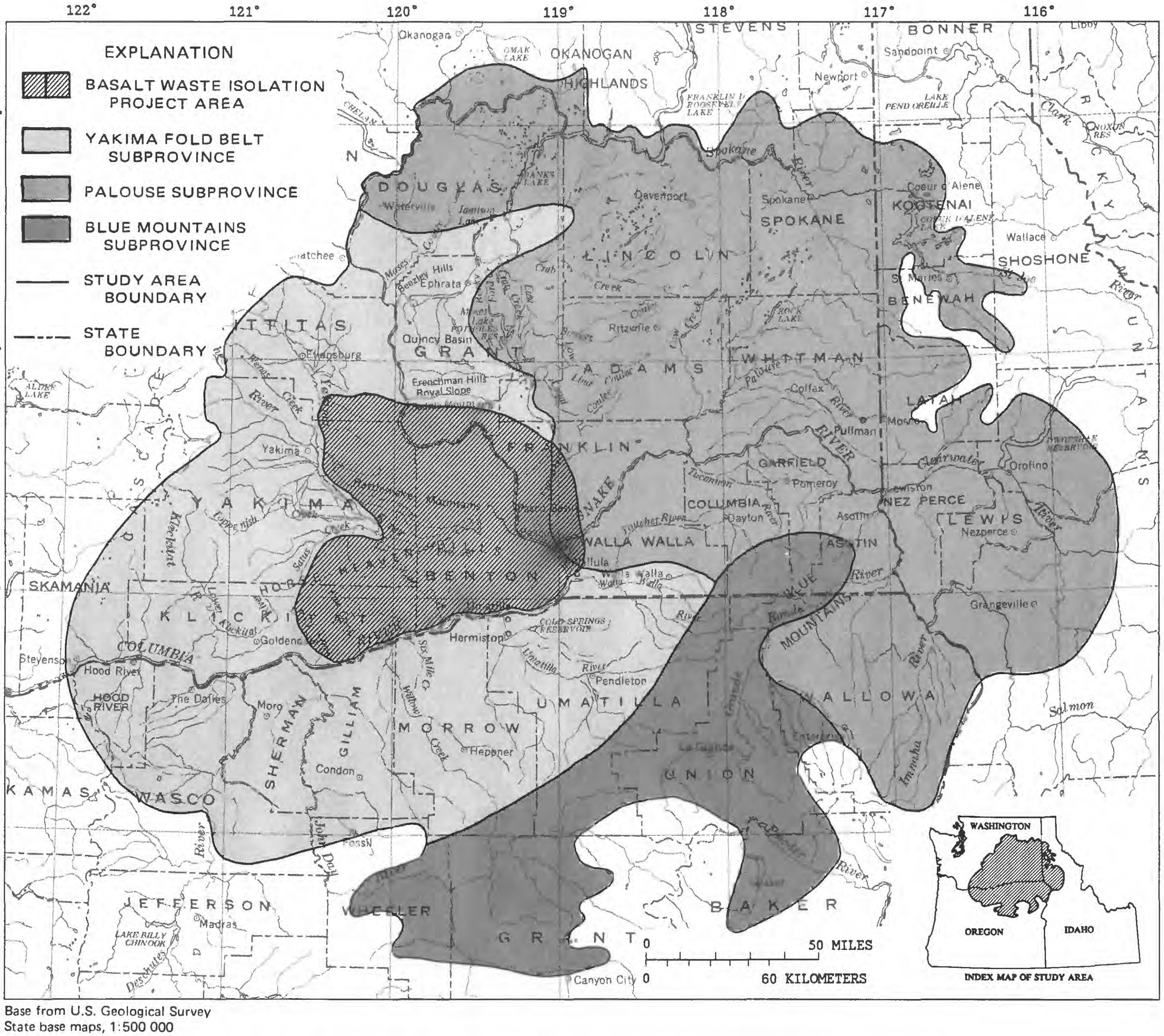

Figure 1.--Location of the study area and physiographic subprovinces of the Columbia Plateau.

Base from U.S. Geological Survey
State base maps, 1:500 000

Figure 2.--Zones, with reference numbers, where recharge was estimated using the daily deep percolation model.

Estimating recharge to the ground-water system from river-discharge analysis was not possible for this study. Streamflows in the Columbia and Snake Rivers, two of the major drains to the regional aquifer system, are highly regulated and are of such great magnitude that meaningful seepage or base-flow analysis could not be done. Instead, the approach of estimating percolation beyond the root zone (deep percolation) by calculating water budgets for discrete land areas was used. A daily deep-percolation model was developed. The computed deep-percolation values are used to estimate ground-water recharge.

The deep-percolation model was developed early in the study, and is documented by Bauer and Vaccaro (1987). During model development, the data base needed for the recharge estimation was developed, and a data-base management system was established. The data base, which includes meteorological, altitude, soil, land-use, streamflow, and irrigation data, also supplied information for other tasks in this RASA study.

Deep-percolation simulations were made for individual small areas (cells) within drainage basins having continuous streamflow records for at least 3 years and also for areas having little surface runoff, many of which have irrigated croplands. These drainage basins and areas with little surface runoff are herein collectively referred to as "zones." The area covered by the model was divided into 53 zones (fig. 2). The zones ranged in size from 20 to 2,392 square miles, totaling 20,375 square miles. Attributes for each of the zones, listed by reference number, are given in appendix A. (Zone reference numbers are used throughout the report.) Fifty zones were divided into rectangular cells. The cells ranged in size from 0.25 to 1 square mile. Most cells had an area of 1 square mile; however, smaller cell sizes were chosen where croplands vary considerably from one quarter section to another or where there were severe topographic variations. For some zones corresponding to drainage basins, small areas outside the basins were included because they otherwise would not have been modeled. For such instances, the model adjusts the streamflow values according to the ratio of the total area to the watershed area.

The computed amounts of daily deep percolation were accumulated for each cell of each zone to calculate annual deep percolation. The values of annual deep percolation for each cell were averaged over the simulation period to provide an average value for each cell. These average annual values of deep percolation were used as estimates of the distribution of long-term average annual recharge rates, hereafter referred to as recharge estimates. Recharge estimates from the modeled zones were used to make regression estimates, based on average annual precipitation, for those areas not simulated. The deep-percolation model was used to estimate recharge by other investigators at four zones; zones 43, 47, and 51 by E.L. Bolke (U.S. Geological Survey, written commun., 1986) and zone 39 by W.E. Lum (U.S. Geological Survey, written commun., 1986).

The deep-percolation model was applied to only about 65 percent of the area within the ground-water model boundaries because of lack of streamflow or soil-type data. This area included most of the irrigated land, about 80 percent of the dryland cropland, and most of the area receiving less than 11 inches of precipitation per year. Estimates of recharge for the remaining area within the ground-water model were made from regression equations. The regression equations were developed by relating the 1956-77 average annual precipitation to estimated recharge for each cell in the 53 zones.

Owing to the small size of the cells within modeled zones, most of the illustrations presented in this report show averaged or aggregated quantities over the ground-water model cells, which are 2-minutes longitude by 2.5-minutes latitude in size. Use of this cell size is good for presentation of data because of the large size of the study area and because the values can be directly compared and used with the ground-water model data input and computed output.

DESCRIPTION OF THE STUDY AREA

The Columbia Plateau aquifer system lies in the Columbia Intermontane physiographic province (Freeman and others, 1945). The study area (fig. 1) is bordered by the Blue Mountains on the south, by the Cascade Range on the west, by the Okanogan Highlands on the north, and by the Rocky Mountains on the east. The plateau has been further divided into three informal subprovinces (fig. 1). Together, these subprovinces form a structural and topographic basin. The Yakima Fold Belt subprovince, located in the western part of the study area, is characterized by long, narrow, east-west-trending anticlines, with intervening broad-to-narrow synclinal basins. The rolling topography of the Palouse subprovince is underlain by undeformed basalts that slope gently to the southwest. The northern part of the Blue Mountains subprovince is a high, dissected plateau, whereas the southern part is a major anticline with some exposed pre-Columbia River Basalt Group rocks.

The study area is completely in the drainage of the Columbia River. Major tributary rivers to the Columbia River in the study area include the Snake, Yakima, John Day, Umatilla, Klickitat, and Deschutes Rivers. These rivers, and their associated tributaries, drain the bordering forested mountainous areas, which locally receive more than 100 inches of precipitation per year.

Precipitation varies greatly over the plateau. The mean annual precipitation distribution, 1956-77, is shown in figure A, plate 1 and figure G, plate 2 (Nelson, 1990). At intermediate altitudes, where precipitation ranges from 15 to 25 inches per year, the vegetation includes both grasslands and forest. At lower altitudes in the central part of the plateau, precipitation is as low as 6.5 inches a year, and sage, grass, dryland wheat, and irrigated agriculture predominate.

The predominant economic activities on the plateau are agriculture and its associated industries. There are currently about 4,200 square miles of irrigated croplands, of which about 75 percent are irrigated by surface water, on the plateau (Wukelic and others, 1981). The major source of surface water is the Columbia River, with the Yakima River providing the next largest amount. There are also about 12,000 square miles of dryland crops (Wukelic and others, 1981), most of which have the potential for conversion to irrigated lands, on the plateau. In addition, there are about 5,000 to 7,000 square miles of sagebrush and grasslands with the potential for conversion to irrigated croplands (Pacific Northwest River Basins Commission, 1971).

DAILY DEEP PERCOLATION MODEL

Theory

The physical processes of soil-moisture accumulation, evaporation from soil, evaporation of intercepted moisture, transpiration, surface runoff, snow accumulation, sublimation, and melting are simulated to determine, as a residual, the amount of moisture that percolates beyond the root zone (deep percolation) and eventually to the water table. Using actual daily values of precipitation, maximum and minimum temperatures, and stream discharge, simulations are made for periods spanning as many years as possible. Computing estimates for individual days is particularly important where precipitation is infrequent. For certain arid to semiarid areas, no recharge would result from calculations using long-term average monthly or long-term average daily values. In reality, infrequent intervals of relatively large amounts of precipitation wet the soils sufficiently for deep percolation to occur.

In a dry area where the water table is far below land surface and the amount of deep percolation is small, it may take many years before percolating water reaches the water table. Conversely, in a humid area with a water table near land surface, it may take only a few hours for water to reach the water table. This study attempts to estimate only average recharge rates and areal distribution; no attempt is made to estimate temporal distribution.

The model does daily simulations for any specified number of grid cells for each zone so that different soils, land uses, precipitation patterns, elevations, slopes, and aspects of an area are accounted for. The conceptual processes simulated by the model are illustrated in figures 3 and 4.

The following briefly describes the methodology and flow of the model for any given day and cell. For more detailed information see Bauer and Vaccaro (1987).

Water-budget calculations are made for a conceptual control volume that includes the vegetation covering the land surface down to the maximum prevalent root depth. The root zone is divided into 6-inch layers, each of which has its own physical characteristics. The daily water budget for the conceptual control volume may be expressed as

$$PRCP = RCH + EVINT + EVSOL + EVSNW + PTR + RO + \Delta INT + \Delta SNW + \Delta SM \qquad (1)$$

where:

- PRCP = precipitation
- RCH = water percolating beyond the root zone
- EVINT = evaporation of moisture intercepted by the foliage surfaces
- EVSOL = evaporation from bare soil
- EVSNW = evaporation from snowpack (sublimation)
- PTR = transpiration
- RO = surface runoff
- ΔINT = change of moisture on the foliage surface
- ΔSNW = change of snowpack
- ΔSM = change of soil water in the root zone

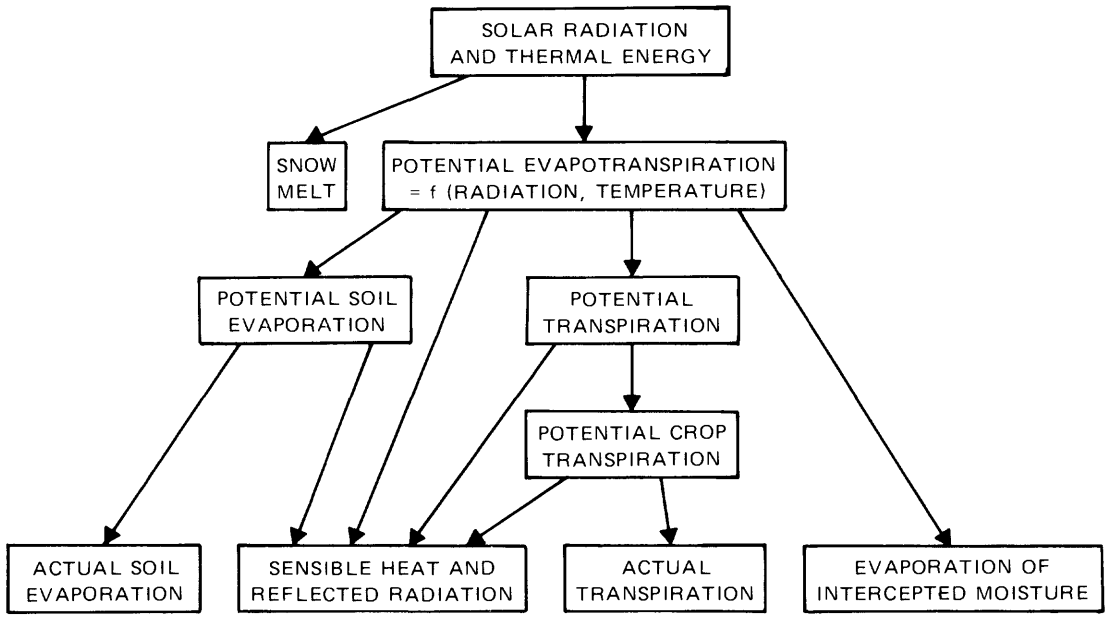

Figure 3.--Conceptual energy balance.

Components of the budget for each cell for each day are determined as follows. Daily precipitation and maximum and minimum temperatures are estimated for each cell from selected weather stations by a distance-weighted method. If the altitudes of the cells are much different from the weather stations, further corrections to temperature may be made using monthly lapse rate for maximum and minimum temperatures. Similarly, precipitation may be adjusted using annual rainfall data (see the subsection Precipitation and Temperature).

If the average daily temperature for a cell is less than 32 °F, all of the precipitation is assumed to be snow and is added to snowpack. When precipitation is rain, some of it is intercepted by foliage and leaf litter. The amount intercepted is dependent on the current maximum interception capacity for the particular land use and also on the amount left from the previous day. Intercepted water evaporates with little resistance (compared with evapotranspiration losses from soil) and is allowed to evaporate at the potential rate.

Potential evapotranspiration (PET) is the amount of evapotranspiration that would occur, water nonlimiting, over a fully grown, fully covered field of alfalfa. The method of Jensen and Haise (Jensen, 1974) was used to compute PET because it is well-suited for arid to semiarid areas of the Columbia Plateau and because the data requirements of daily temperatures, solar radiation, and altitude are readily obtainable. The value of PET at a cell is calculated using the cell values of temperature, altitude, and computed incident solar radiation. Incident solar radiation is optionally corrected for the effects of land slope and aspect.

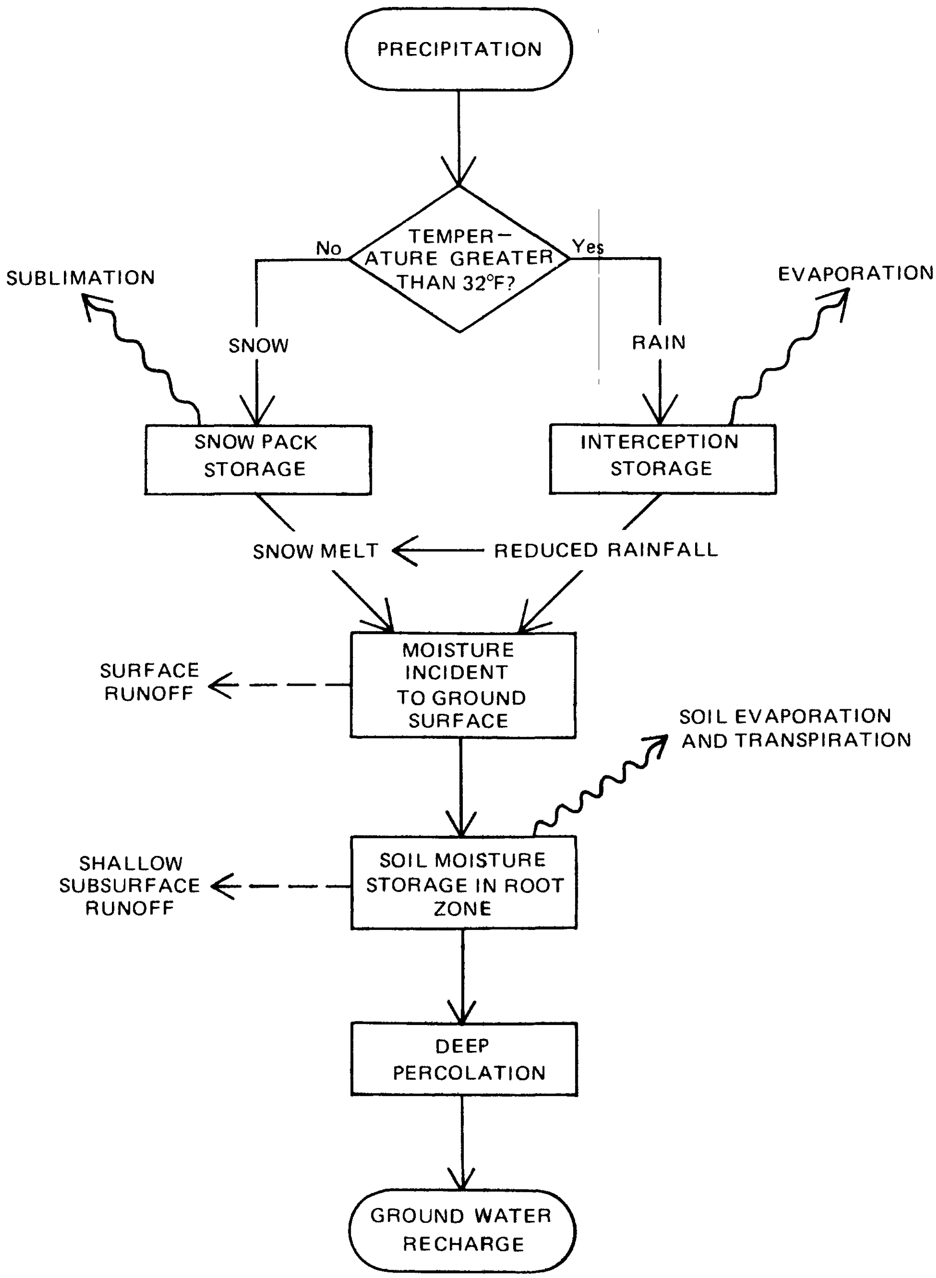

Figure 4.--Conceptual water balance.

After PET is reduced by evaporation of intercepted moisture, it is divided into potential soil evaporation and potential crop transpiration. The proportion going to each of these components depends on the type of vegetation (land use) and its stage of growth. During certain periods, such as after a plant has gone into a dormant stage, the sum of the potential crop transpiration and potential soil evaporation may be less than PET. This excess PET is considered to be converted to unavailable thermal and radiant energy (see fig. 3).

Moisture that reaches the soil surface (incident moisture) partly infiltrates and partly runs off as surface water. Surface runoff for each cell is computed by the modified U.S. Soil Conservation Service (SCS) method of Wight and Neff (1983). This method was developed for rangeland in eastern Montana and is based on the SCS curve number (CN) technique for determining surface runoff from small watersheds. Measured daily stream discharge (minus base flow) is apportioned to each cell in proportion to the SCS computed surface runoff.

After these abstractions, any surplus moisture from precipitation and snowmelt is assumed to infiltrate the soil profile. If this infiltration exceeds the difference between the available water capacity (the amount of water in excess of the wilting point that can be held by capillary action under the force of gravity) and the current soil-moisture content, the excess is assumed to go to deep percolation and ultimately to ground-water recharge. Some upward movement of moisture from below the root zone from capillary action may occur when the root zone becomes dry. However, infiltration experiments have shown that movement of water from moist to dry soil during a period of several months is limited in extent and amount if no additional moisture is added and if the soil is not in contact with a free-water surface (Chow, 1964). In addition, experiments have shown that significant amounts of evaporation from bare soil for a period of several months is limited to 4 to 8 inches below the surface (Chow, 1964). Errors from neglecting upward movement of moisture from below the root zone, therefore, are probably small and can be compensated for by overestimating the root depth by about 6 inches.

Soil evaporation is estimated from the relation presented by Saxton and others (1974) and is assumed to occur only from the top 12 inches of the soil profile at a rate that decreases with decreasing soil-moisture content. The amount of water extracted for crop transpiration is based on empirical relations of the ratio of actual to potential transpiration versus soil moisture for different soil types (see fig. 5). Soil moisture within the root zone is then reduced by these amounts.

These processes are summarized in figures 3 and 4. After the final adjustment to soil moisture is simulated for an individual day, the next day's simulation begins, using new daily values of Julian day, precipitation, maximum and minimum temperatures, and stream discharge. To simulate the processes, the above sequence of simulation has been assumed, although in reality all of these processes occur simultaneously.

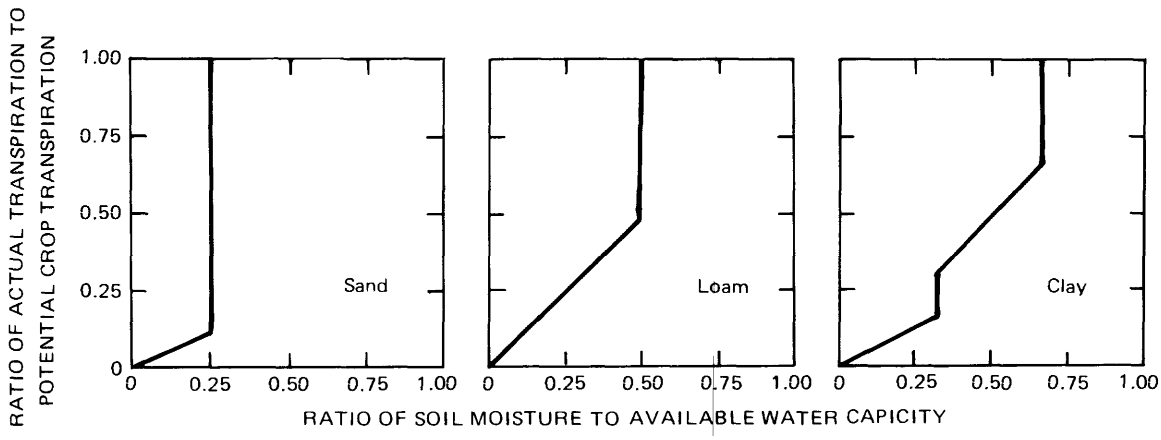

Figure 5.--Relation between actual and potential transpiration, based on soil texture and soil moisture (after Leavesley and others, 1983).

Data

Precipitation and Temperature

Daily precipitation and maximum-minimum air temperatures for the period 1956-77 (U.S. Department of Commerce, written commun., 1984) were compiled, checked, and stored for 103 weather stations, 89 of which had air-temperature and precipitation data. Fourteen stations had precipitation data only. This period was chosen because sufficient data exhibiting climate variability were available. Missing daily values in this period for these stations were calculated by correlation and interpolation methods to give a continuous daily 22-year temperature and precipitation data base. The precipitation data were used to construct a 22-year average annual rainfall map, which was presented in Nelson (1990). The isohyets, weather station locations, and identifying reference numbers used in this study are shown on plates 1 and 2. The mean annual precipitation, temperature values, and station characteristics are listed in appendix B.

Daily values of precipitation and maximum-minimum temperatures at weather stations were used in the model to estimate daily values for each cell within a modeled zone. Cell values were estimated by one of two distance-weighted interpolation schemes using data from nearby weather stations (described by Bauer and Vaccaro, 1987). Adjustments to the daily precipitation for a cell were made by multiplying it by the ratio of average annual weather-station precipitation to the average annual cell precipitation. The average annual precipitation at each cell was estimated from the digitized data of the annual rainfall map and a surface-fitting method described in IMSL (1982).

Daily maximum and minimum temperatures for a cell were adjusted by applying the regional average monthly maximum and minimum temperature-lapse rates to the altitude differences between the cell and the selected weather stations. Regional monthly lapse rates given in table 1 were established by regression of average monthly maximum and minimum air temperatures with the altitudes of each of the 89 temperature stations.

Table 1.--Regional average monthly maximum and minimum temperature lapse rates per 1,000 feet altitude change

[Values in degrees Fahrenheit]

Month	Maximum	Minimum
January	1.7	2.0
February	2.4	2.2
March	3.7	2.8
April	3.9	3.2
May	3.9	3.5
June	3.9	3.8
July	3.2	4.1
August	3.0	3.9
September	2.8	3.4
October	2.4	2.5
November	2.2	2.1
December	1.7	1.9

Soils

The available water capacity for each soil layer within the root zone must be known in order to establish the maximum amount of water that can be evapotranspired from the soil. Further, the soil texture (sand, clay, loam, and combinations thereof) affects the rate of evapotranspiration. In general, the finer textured soils have slower rates of evapotranspiration for a given soil-moisture content because of the greater capillary forces. Empirical relations given by Leavesley and others (1983) are used in the model to determine the ratio of actual to potential transpiration for different soil textures and soil-moisture contents (see fig. 5).

The best sources of quantitative regional soil data are the county soil surveys prepared by the SCS, which present detailed soil series maps and tables of physical and engineering properties of the various soil series. Typically, an eastern Washington county contains approximately 100 to 200 different soil series and each county map has its own unique set of map symbols. In addition to available water capacity and texture, many other parameters are used by the SCS to characterize a soil series, resulting in many more soil classifications than are needed for estimating recharge. For this reason, and because basins and zones commonly spanned several counties, a simpler soil classification scheme was necessary.

Soil categories based on selected intervals of available water capacities and total depth were established for recharge computations. It was not necessary also to base the categories on texture, because water-holding capacity and texture are well-correlated. Twenty soil categories were used for zones 1-21 that were established for a concurrent project (T.A. Zimmerman, Battelle Northwest Laboratory, written commun., 1985).

Twenty-four somewhat different categories were used for zones 22-53, on the basis of different available water-capacity intervals and total depth intervals. Total depths for the categories of zones 22-53 ranged from 1.0 to 5.0 feet in 1-foot increments, and available water capacities ranged from 7.5 to 30 percent by volume in 4.5-percent increments. Model cells were first assigned a soil series by overlaying the model grid on the SCS county soil series maps and coding the SCS soil series symbol. Each cell was then assigned one of the 24 categories, depending on the available water capacity and total depth of the particular soil series. Area-weighted averages of water-holding capacity, clay, silt, and sand contents were computed for each soil category from the soil series data, for the purpose of assigning a particular numerical value of available water capacity and soil texture to each of the 24 categories.

The physical characteristics of the two sets of soil categories are in appendix C. Figure B on plate 1 shows distribution of available water capacity in the upper 5 feet of soil as averaged over ground-water model blocks. Discussion of how soils affect recharge estimates is presented in the later section, Factors Controlling Recharge and Sources of Error.

Land Surface

Land-surface data requirements depend on the model options selected. The minimum requirement is the altitude of each weather station. In this case daily PET is calculated for each station (assuming a horizontal land surface) and the cell values of PET are distance-interpolated from a specified number of nearest weather stations. Cell values of maximum and minimum air temperatures likewise are obtained from interpolating data from the weather stations.

For improved estimates of PET, altitudes for selected cells and regional monthly temperature-lapse rates are read in. For these cells maximum and minimum daily temperatures are adjusted by the monthly maximum and minimum temperature lapse rates, and PET is calculated using the cell altitudes. Further, since the Jensen-Haise PET method involves a solar-radiation term, the model computes the effects of a sloping land surface on the incident solar radiation if slope and aspect data are included for those cells. The authors chose to use altitude, slope, and aspect data for all cells for zones that were not in level terrain.

Digital elevation models (DEMS) at a scale of 1:250,000 (Elassal and Caruso, 1983) were obtained for 13 areas of 1-degree latitude by 1-degree longitude. These data covered most of the study area and were used to compute average altitude, slope, and aspect for each recharge cell for zones having significant land-surface relief. For zones 1-21, altitude, slope, and aspect on 660-foot centers were provided by T.A. Zimmerman (Battelle Northwest Laboratory, written commun., 1985), who also obtained the basic altitude data from the same DEMS. These data were averaged to arrive at an input value for each cell in zones 1-21.

Land Use

Land-use classification of the Columbia Plateau for 1975 (see table 2), compiled from Landsat data, was provided by T.A. Zimmerman (Battelle Northwest Laboratory, written commun., 1985) and is documented by Wukelic and others (1981). A land-use type was identified for each rectangular area (pixel) measuring 154 feet in the east-west direction and 206 feet in the north-south direction (table 2). The distribution of land use over the project area is shown in figure C on plate 1. (The 154-foot by 206-foot pixel size was too small to present on a convenient scale. The pixels shown in figure C are 1,500 feet on a side, derived from the smaller pixels.)

Table 2.--Classes of land use for the Columbia Plateau, based on 1975 Landsat data (from Wukelic and others, 1981)

Land use	Area of the land use within the Landsat coverage (square miles)
Snow	28
Commercial/residential	216
Sand/barren	197
Water	698
Irrigated agriculture	3,366
Grass	3,930
Sagebrush	9,887
Forest	10,332
Dryland agriculture	12,015

Land-use assignments to the recharge cells were done by computer in a manner such that the frequency distribution of the cell land uses for a zone closely matched the frequency distribution of the pixel land uses for the zone. All land uses are represented under this criterion, even though some cells may have land-use assignments that may not be the predominant land uses for those cells. To have used the predominant land use in every cell would have meant that certain infrequent land uses that are widely but sparsely distributed may not have been represented. The results for model zones 26 and 50 are shown in table 3. Because there is some error in classifying land use using Landsat data and because of changes in land-use patterns since 1975, the land use for some cells was re-assigned when more reliable information was available.

Table 3.--A comparison of the percentages of land-use types in zones 26 and 50 as derived from pixel land-use data and from cell land-use assignments

	Percentage of total land use			
	Zone 26		Zone 50	
	Pixels	Cells	Pixels	Cells
Water	0.5716	0.7326	0.0	0.0
Sagebrush	62.0647	62.8205	9.0369	8.3821
Commercial/residential	.1924	.3663	.0014	.0
Sand/barren	.0293	.0	.0	.0
Irrigated agriculture	4.5141	4.3956	.7700	1.1695
Grass	.3133	.3663	1.5126	2.1442
Dryland agriculture	30.2647	29.8535	1.4776	1.5595
Forest	2.0500	1.4652	87.2015	86.7446
Zone error (percentage of total)		3		2

Further delineation of Landsat data was necessary for agricultural areas. If Landsat data indicated irrigated agriculture, then additional information was used to determine one of the following typical irrigated land uses: 1) grass (pasture), 2) winter wheat (supplementally irrigated), 3) orchard, 4) alfalfa, 5) row crops, 6) corn, or 7) potatoes. If Landsat data indicated dryland agriculture, then one of the following typical dryland crops was determined: 1) winter wheat, 2) peas-lentils, or 3) spring wheat. Additional land-use information was provided by the several ongoing projects in the U.S. Geological Survey's Pacific Northwest District (written commun., 1984), by the State of Washington Department of Ecology (written commun., 1983-86), and from published crop-type information (U.S. Army Corps of Engineers, 1980; Washington Department of Ecology, 1974). The areal distribution of land-use classifications in selected modeled zones is presented later in the report.

To estimate recharge for predevelopment conditions, it was necessary to reconstruct predevelopment land uses. The 1975 land uses of sage, forest, grassland, and sand/barren were assumed to be unchanged since predevelopment times. The land uses of commercial/residential, irrigated agriculture, and dryland agriculture had to be converted into one of the predevelopment land uses. Generally, the currently existing sagebrush areas are in proximity to the irrigated, commercial, and residential areas and (or) lie within the same precipitation regime (see figs. C and D on plate 1). Similarly, dryland agriculture is associated with grasses. Therefore, for predevelopment land uses, direct conversion of pixel data was made from commercial, residential, and irrigated to sagebrush; and from dryland agriculture to grassland.

Surface Runoff

Modeled areas were selected primarily on the basis of availability of stream-discharge data for at least 3 consecutive years. In certain other areas, where streamflow data were lacking but where average annual precipitation was less than 13 inches and topography showed poorly developed drainage patterns, simulations were made under the assumption that daily surface runoff was zero.

Much of the project area did not fall into either of these two categories. Streamflow for certain ungaged drainage basins was estimated from data from adjacent gaged basins. Crest-stage data for ephemeral streams were used to estimate mean daily discharges for some basins when no other data were available. This was done by assuming an exponential decay of streamflow with time where the time constant is estimated as a function of drainage area (Linsley and others, 1975). The type of runoff information used in each of the modeled areas (fig. 2) is given in appendix A.

Stream discharge at a gage was assumed to be the total of all the surface runoff from all the cells in the basin plus ground-water discharge to the stream above the gage. Ground-water discharge rates were estimated by inspection of streamflow hydrographs. These rates are subtracted from total stream discharges during simulations. A part of the total daily surface runoff is assigned to each model cell during simulation. This is done by first computing surface runoff according to the method of Wight and Neff (1983) from precipitation, antecedent soil moisture, and the Soil Conservation Service runoff curve number (CN2 number). CN2 numbers are empirical values that are a measure of runoff potential. They are determined from published tables relating the value of CN2 to land use, slope, soil type, and vegetative condition (see table 4). To automate the process of inputing CN2 numbers, a tabling procedure was incorporated into the original model code. This procedure uses soil texture and land-slope data.

Estimates of the ground-water discharge component (base flow) of a stream can be ambiguous. Slow drainage from waterlogged soil layers to temporary springs and seeps or springtime snowmelt may completely "mask" the base-flow component. The procedure used to eliminate this problem was to initially make low estimates of monthly base flow. If base flow is underestimated, surface runoff will be overestimated. During the daily deep percolation simulations, surface runoff is subtracted either from moisture incident to the ground surface or from root-zone soil moisture; but if moisture is not available from either of these sources, a "deficit" is accumulated. If the "deficit" is greater than acceptable error limits, the monthly base flows are adjusted upward and the deep percolation re-simulated. This process is repeated until the "deficit" is within reasonable error limits.

Table 4.--Surface runoff curve numbers, CN2 (from Wight and Neff, 1983)

Range site	Range condition		
	Fair	High-fair and good	Excellent
Wetland	95	95	95
Very shallow	95	90	85
Saline subirrigated	90	90	85
Subirrigated	90	90	85
Shale	90	85	90
Dense clay	90	85	80
Alkali clay	90	85	80
Saline upland	90	85	80
Igneous	90	80	75
Shallow clayey	85	80	75
Shallow sandy	90	75	70
Shallow loamy	90	75	70
Thin claypan	80	75	70
Shallow igneous	80	75	70
Steep clayey	80	75	70
Clayey	80	75	65
Gravelly loamy	80	75	65
Steep loamy	80	75	65
Overflow	90	70	60
Loamy overflow	80	70	60
Clayey overflow	80	70	60
Coarse upland	80	70	60
Limey upland	80	70	60
Shallow breaks	80	70	60
Stoney	80	70	60
Steep stoney	80	70	60
Lowland	80	70	60
Saline lowland	80	70	60
Loamy lowland	80	65	55
Loamy	80	65	55
Sandy lowland	75	60	50
Sandy	75	60	50
Gravelly	70	55	45
Sands	70	55	40
Choppy sands	70	55	40

Irrigation

Estimation of recharge in irrigated areas requires that the rate of water application be known or estimated. Maps showing surface-water irrigation areas and application rates were compiled for this study. The grid system for each modeled area was overlaid on application maps, and an application rate was coded for each cell that had surface-water-irrigated agriculture. The application rates also included the estimated canal losses, distributed over the area, for each irrigation district. Application rates for ground-water irrigation were based on estimates made by Cline, Knadle, Collins, and Van Metre (U.S. Geological Survey, written commun., 1985) for individual crop types. The distribution of ground-water-supplied and surface-water-supplied irrigation application waters is shown in figure D on plate 1. Application rates varied from 0.5 ft/year to a maximum of 6.0 ft/year. Most of the irrigated croplands in the study area were included in the 53 model zones.

ESTIMATES OF RECHARGE

Modeled Zones

Recharge was estimated for predevelopment land-use conditions in 53 zones and for current land-use conditions in the 50 zones where land use has changed. The 50 zones included most of the irrigated croplands and about 80 percent of the dryland croplands within the ground-water model boundaries. Figure C on plate 2 outlines each of the basins and zones for which simulations were made and shows the resulting estimated recharge for each zone for both land-use conditions (these data are also presented in table 5). The model zones cover about 65 percent of the 32,800 square miles included in the ground-water model boundaries.

The distribution of estimated recharge for the ground-water model grid for predevelopment and current land-use simulations is shown in figures E and F on plate 1. Recharge values for the ground-water model cells were obtained by averaging the values of the recharge cells, weighted by area, that lie within the ground-water model cells. This smoothed the local variation while preserving the total estimated recharge. Zones 43, 47, and 51, located in Oregon, generally used cell sizes larger than the ground-water model cells. The estimated recharge for the ground-water model cells encompassed by these zones was obtained by overlaying the ground-water model grid system on a map of the recharge distribution for these zones and assigning values.

The area-weighted average of the recharge estimates for the modeled zones for predevelopment land uses is 2,588 ft^3/s or 1.65 in./yr (fig. E, plate 1); the area-weighted average of the recharge estimates for current conditions is 6,038 ft^3/s or 3.88 in./yr (fig. F, plate 1). Most of the increase in recharge estimates from predevelopment to current conditions occurred in irrigated land-use areas (see figs. D, E, and F on plate 1). The estimated recharge for predevelopment and current conditions for the identified land use is shown in table 6, which shows in general how the introduction of agriculture, all of which is irrigated except for most dryland winter wheat, some spring wheat, and some peas and lentils, has increased recharge. Note that as previously described, predevelopment land-use conditions for irrigated, residential, and commercial areas were assumed to be sage, and dryland agriculture was assumed to be grassland. Areas of large changes in recharge estimates between the two land-use types (see fig. F on plate 2) correspond to the distribution of irrigated areas (see fig. C on plate 1). This is further illustrated in figure A, plate 2, which shows the detailed grid system used for the deep percolation simulation of zone 41, and figure B, plate 2, which shows current land uses for zone 41.

Changes were less pronounced and varied over dryland agricultural areas. Regression relations between recharge and precipitation for grassland and for dryland agriculture are shown in figure 6. In general, because of its shallower root system, grassland allows somewhat more deep percolation.

Table 5.--Summary of estimated recharge and data used for predevelopment and current land-use conditions

[in inches per year]

Zone reference number	Average precipitation	Average current irrigation	Average potential evapotranspiration	Average actual evapotranspiration		Average stream discharge		Average recharge	
				Predevelopment	Current	Surface runoff	Base flow	Predevelopment	Current
1	7.29	23.74	43.06	6.74	18.56	*0.06	0	0.43	12.27
2	8.91	.32	35.93	7.62	7.83	.10	0	1.25	1.35
3	9.34	.29	39.92	7.75	7.97	*.13	0	1.37	1.45
4	6.61	0	42.45	6.09	6.09	*.07	0	.38	.38
5	8.77	0	36.14	7.54	7.54	*0	0	1.18	1.18
6	8.64	.67	37.32	7.66	8.07	.12	0	.66	.93
7	8.26	0	39.43	6.62	6.66	.19	0	1.31	1.29
8	6.95	.23	41.89	6.61	6.73	*0	0	.30	.29
9	7.64	6.50	38.92	7.24	12.47	.10	0	.43	1.56
10	7.93	0	40.25	7.39	7.47	*0	0	.45	.41
11	7.76	0	41.49	7.24	7.28	*0	0	.44	.43
12	7.41	22.02	41.72	7.28	22.11	.07	0	.15	7.26
13	8.19	9.86	42.15	7.66	15.13	*0	0	.47	2.83
14	7.95	7.20	42.82	7.36	11.56	.14	0	.23	2.83
15	6.98	2.73	40.56	6.52	9.23	.16	.04	.13	.66
16	8.31	4.30	40.56	7.71	10.68	*.16	0	.39	1.78
17	8.09	5.31	41.19	7.39	11.54	*.40	0	.26	1.50
18	12.05	.13	40.47	8.64	8.75	2.44	1.29	1.30	1.33
19	10.09	0	40.71	8.57	8.54	1.26	1.20	.83	.87
20	9.19	1.48	41.04	7.49	8.77	.76	.06	.87	1.16
21	17.27	.08	36.16	9.92	10.00	3.61	3.15	5.39	5.39
22	22.75	1.83	28.69	10.58	11.65	3.56	5.08	10.52	11.11
23	22.32	0	36.13	14.05	14.05	2.82	3.55	6.01	6.00
24	9.64	2.51	44.24	9.19	11.64	.13	0	.57	.51
25	10.33	1.54	43.43	8.92	10.68	*0	0	1.36	1.20
26	12.61	.77	41.32	10.24	11.13	.29	.32	2.30	2.11
27	12.54	.27	41.32	10.24	10.90	.65	.25	1.68	1.35
28	10.05	.11	39.09	8.75	9.10	.07	0	1.16	1.01
29	21.80	0	37.45	14.37	14.94	4.30	1.70	3.51	2.97
30	10.09	1.62	41.64	8.41	9.71	*.22	0	1.42	1.81
31	8.69	3.92	42.49	7.91	10.81	*0	0	.73	1.79
32	7.78	30.15	41.41	7.11	19.08	*.05	0	.58	18.71
33	11.12	17.43	34.73	8.33	18.71	*0	0	2.74	9.72
34	10.24	3.59	43.09	8.89	12.01	*.25	0	1.04	1.58
35	8.94	3.96	44.78	8.23	10.68	.28	0	.24	1.86
36	10.26	0	40.00	8.93	9.32	*.11	0	1.17	.85
37	24.30	0	27.92	11.71	11.71	3.32	9.24	10.65	10.65
38	8.24	6.82	44.9	8.06	13.89	.10	0	.13	1.21
39	22.42	0	34.5	16.03	16.54	2.39	2.28	4.13	2.79
40	8.15	18.64	40.41	7.32	16.30	*.21	0	.57	10.07

Table 5.--Summary of estimated recharge and data used for predevelopment and current land-use conditions--Con.

Zone reference number	Average precipitation	Average current irrigation	Average potential evapotranspiration	Average actual evapotranspiration		Average stream discharge		Average recharge	
				Predevelopment	Current	Surface runoff	Base flow	Predevelopment	Current
41	8.04	21.02	41.71	7.13	17.10	*.04	0	.82	11.89
42	9.12	1.99	44.55	8.14	9.76	*.07	0	.84	1.30
43	9.04	1.97	42.47	9.04	11.02	*0	0	.01	.01
44	8.61	26.68	39.91	8.09	25.10	*0	0	.44	10.33
45	18.28	.37	38.75	12.33	13.18	3.16	1.54	3.30	2.93
46	21.06	0	38.51	12.64	12.98	2.11	4.06	6.79	6.50
47	16.49	.84	42.98	12.89	13.91	2.40	1.86	1.53	1.55
48	20.96	0	36.21	15.59	14.84	2.57	0	2.98	3.65
49	12.93	5.20	40.13	11.45	14.53	*.02	0	1.45	3.33
50	37.65	.28	35.72	15.08	15.53	10.05	24.47	15.06	15.19
51	11.35	.66	41.21	11.15	11.81	*0	0	.29	.29
52	11.34	.15	41.85	10.01	9.58	.46	0	.90	1.63
53	8.93	23.84	37.60	8.03	20.73	*0	0	.84	11.15

*Stream runoff assumed to be zero from all land surfaces within the zone; however, the presence of surface-water bodies results in surface-runoff output for those areas during model simulations.

Table 6.--Estimated recharge for predevelopment and current land-use conditions in the modeled zones

Land use	Area[1] (square miles)	Predevelopment recharge: Cubic feet per second	Predevelopment recharge: Inches per year	Area (square miles)	Current recharge: Cubic feet per second	Current recharge: Inches per year
Forest	1,841	1,031	7.61	1,841	1,033	7.62
Grass	10,129	831	1.11	3,095	283	1.24
Sage	8,256	468	.77	5,490	409	1.01
Irrigated winter wheat			.00	820	1,192	19.72
Dryland winter wheat			.00	6,639	362	.74
Orchard (irrigated)			.00	210	183	11.88
Alfalfa (irrigated)			.00	1,202	1,179	13.32
Row crops (irrigated)			.00	425	710	22.66
Water	108		.00	230	0	.00
Corn (irrigated)			.00	152	129	11.54
Potato (irrigated)			.00	178	197	14.95
Sand/barren	102	13	1.77	91	12	1.74
Pea-lentil			.00	36	6	2.32
Dryland spring wheat			.00	26	2	1.27
Totals for modeled zones	20,436	2,343		20,436	5,697	
Area-weighted averages for modeled zones			1.56			3.79

[1]Area based on the constant-model cell size as listed in Appendix A except for zones 43, 47, and 51; these zones had a slightly variable cell size, which was used in the calculations of area.

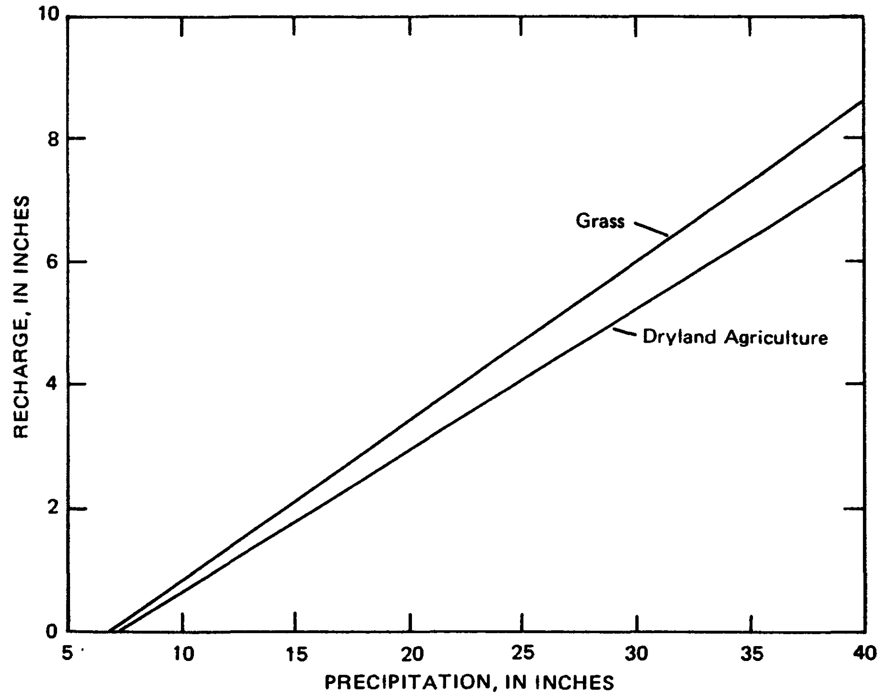

Figure 6.--Regession relations between estimated recharge and precipitation for two land uses.

Estimated recharge ranges widely over the project area, from 0.0 to about 30 in./yr for predevelopment conditions and from 0.0 to about 54 in./yr for current conditions. The highest predevelopment estimated recharge rates are in areas of high altitude (up to 6,000 feet), particularly along the west and southwest margins of the project area where precipitation is high (as much as 45 in./yr) and potential evapotranspiration is low (as low as 27 in./yr). Areas of little or no estimated recharge occur near the central part of the study area where land surface is only a few hundred feet above sea level, where precipitation is as low as 6.0 in./yr, and potential evapotranspiration is as high as 44 in./yr. Generally, estimated recharge rates parallel the precipitation amounts in areas of high precipitation (fig. E, plate 1). In areas of low precipitation, estimated recharge is generally small, but is less closely related to precipitation than in the areas of high precipitation. The cause of this effect will be discussed later.

Regression Estimates

Because streamflow and (or) soils data were not available for large parts of the study area, alternative methods for estimating recharge within the ground-water model boundaries were developed.

Linear regression of estimated predevelopment recharge versus the 1956-77 average annual precipitation for all cells of all the modeled zones produced a good correlation coefficient of 0.90. The plotted values of estimated predevelopment recharge versus average annual precipitation, however, showed a definite upward-curving trend.

A regression equation based on a second-order polynomial for all data was tested and had a slightly better correlation coefficient of 0.92. (The regression estimates and statistics on the cell data are given in table 7.)

Table 7.--Statistics and regressions for estimated predevelopment recharge and mean annual precipitation for all modeled zones

Statistics of recharge computed at cells

		Percentile	Cell recharge
Number of cells	29,759	10	0.00
Number of cells with water	229	20	.09
Number of cell data points	29,530	30	.21
Maximum cell recharge	29.68	40	.36
Minimum cell recharge	.0	50	.56
Mean cell recharge	1.82	60	.84
Mean cell precipitation	11.43	70	1.34
Median cell precipitation	8.94	80	2.35
Maximum cell precipitation	45.43	90	4.63
Minimum cell precipitation	5.0		

Regression parameters for estimated recharge versus mean annual precipitation:

	Linear regression	Second-order polynomial regression
Correlation coefficient	0.90	0.92
Recharge intercept at zero precipitation	-3.72 inches	-1.28 inches
Precipitation intercept at zero recharge[1]	7.67 inches	6.49 inches
Slope	.48	Not applicable
Slope parameters	Not applicable	0.1416 0.00865 ~~0.2163, 0.0363~~

[1]Recharge is zero for values of precipitation below this value.

The polynomial regression equation was chosen to estimate recharge for predevelopment and current land-use conditions for the nonmodeled area. The nonmodeled areas generally had average annual precipitation greater than 11 inches. The correlation is even better in this higher precipitation range. For example, the linear correlation coefficient between estimated recharge and average annual precipitation is only 0.35 for less than 11.0 inches of precipitation, but is 0.65 between 11.0 and 22.0 inches of precipitation.

The nonmodeled area was discretized using the ground-water model grid system. The 22-year average annual precipitation was then estimated for each of these cells, on the basis of the digitized data from the annual rainfall map and a surface-fitting routine described in IMSL (1982). The regression equation used these precipitation values to estimate recharge. Figures D and E, plate 2, show the distributions of recharge estimates for predevelopment and current land-use conditions, respectively, for all cells of the ground-water model. Figure F, plate 2, shows the changes in estimated recharge from predevelopment to current land-use conditions. For this study, it was reasonable to assume that the regression equation was applicable to both predevelopment and current land-use conditions for the nonmodeled areas, because almost no irrigated land lies outside of the modeled zones. The results and comparisons of applying the regression equations to several modeled zones are presented in table 8. The estimates of recharge for both land-use conditions in the area within the ground-water model boundary are summarized below.

Land-use condition	Recharge in estimate, cubic feet per second	Area-weighted recharge, in inches per year
Predevelopment	5,998	2.48
Current	9,492	3.93
Change	3,494	1.45

Table 8.--Comparison of model-estimated recharge and regression-predicted recharge for three model zones

[in inches per year]

Zone	Number of cells	Precipi-tation	Average long-term recharge: Model Mean	Model Low	Model High	Regression Mean	Regression Low	Regression High	Model minus regression Mean	Model minus regression Low	Model minus regression High
1	2,949	7.29	0.43	0.0	2.21	0.24	0.0	0.71	0.19	-0.43	1.99
15	1,149	6.98	.13	.0	4.44	.52	.21	2.07	-.40	-1.77	2.46
46	433	21.06	6.79	.0	29.68	6.53	2.15	23.00	.26	-4.23	6.98

FACTORS CONTROLLING RECHARGE AND SOURCES OF ERROR

Sensitivity tests were performed on two zones, a semiarid zone (52) and a temperate zone (23) (table 9). The purpose of the tests was twofold: 1) to determine which factors are important for controlling recharge on the Columbia Plateau, and 2) to assess the effect that data errors have on estimated recharge. It is evident from the results shown in table 9 that the amount of precipitation is the most critical factor, whereas significant errors in stream discharge have little effect on the amount of estimated recharge. This is reasonable because precipitation is the largest component of the water budget. For example, 10 percent of the total precipitation represents 1.13 inches of moisture for zone 52, whereas 10 percent of runoff for this zone represents only 0.046 inch of moisture.

The effect of raising temperature is to increase potential evapotranspiration for all days of the year. During periods of large soil-moisture deficits, this will have little effect on the budget components. However, during the spring months, when soil moisture is near field capacity, additional moisture will be evapotranspired, leaving less that can go to deep percolation.

Table 9.--Sensitivity of estimated recharge to various input data for a semiarid zone and a temperate zone

Change made to input data	Semiarid, zone 52 (average annual precipitation = 11.34 in./yr)			Temperate, zone 23 (average annual precipitation = 22.32 in./yr)		
	Estimated recharge (in./yr)	Change (in./yr)	Percentage change	Estimated recharge (in./yr)	Change (in./yr)	Percentage change
None	0.90	--	--	6.01	--	--
Daily precipitation increased 10 percent	1.30	+0.40	+44	7.49	+1.48	+25
Daily maximum and minimum temperatures increased by 5 °F	.78	-.12	-13	5.23	-.78	-13
Daily surface runoff reduced 10 percent	.91	+.01	+1	6.13	+.12	+2
	(surface runoff = 4 percent of precipitation)			(surface runoff = 13 percent of precipitation)		
Available water capacity increased by 10 percent	.77	-.13	-14	5.63	-.38	-6
Interception capacity of plants reduced by 10 percent	.91	+.01	+1	6.04	+.03	+1
PET calculated _not_ using lapse rates altitudes slopes and aspects	.88	-.02	-2	5.29	-.72	-12

The effect of increasing the available water capacity of the soils is to reduce significantly the estimated recharge for both zones; however, the impact is much greater on the semiarid zone. For nonirrigated areas, where most of the incident moisture occurs as precipitation during the winter months, much of the water evapotranspired during the spring and summer months is actually water that has been absorbed and stored in the soil during the winter months. Generally, over the warm dry season the vegetation is capable of using more water than is available in the root zone. If the root zone can store more water, a greater amount will be transpired during the warm dry season, leaving less that can go to deep percolation. The potential for any deep percolation is small for areas receiving annual amounts of precipitation approximately equivalent to the total available water capacity of the root zone. Thus, for these areas deep percolation will occur only during periods of abnormally high precipitation and (or) low potential evapotranspiration. Inspection of table 5 shows that even though zone 4 has the lowest average annual precipitation, it does not have the smallest estimated recharge. This is due to the presence of large areas of sandy soils that have small available water capacity (see fig. B, plate 1).

The effect of not using lapse-rate corrections to temperature is negligible for zone 52, but is significant for zone 23 (see table 9). Zone 52 is topographically "smooth" with nearby weather stations at both higher and lower altitudes. Zone 23, on the other hand, is in mountainous terrain with nearby weather stations mainly at the lower altitudes. With no lapse-rate correction to temperatures, PET was overestimated for much of zone 23, resulting in a smaller amount of estimated recharge.

The effects of changing land uses on computed recharge is pronounced (see table 10). Of three land uses tested, sagebrush, having the deepest root system and therefore able to tap a larger quantity of stored soil moisture, allows the least amount of deep percolation, whereas grassland allows the greatest amount of deep percolation because of its shallow root system. Dryland winter wheat allows a greater amount of deep percolation than sagebrush, even though reported root depths are comparable. However, dryland winter wheat is grown on a 2-year cycle. During this cycle the land is kept free of vegetation, from early summer of one year to the autumn of the following year. Only a small part of stored soil moisture can be evaporated during the dry months of the fallow period, the remainder being available to percolate downward with the addition of winter precipitation.

Table 10.--Comparison of estimated recharge for different assumed land uses in a semiarid zone and in a temperate zone

Land use	Computed average annual recharge, in inches: Semiarid (zone 52)	Computed average annual recharge, in inches: Temperate (zone 23)
Sagebrush	0.51	5.82
Grass	1.13	7.61
Dryland wheat	.73	7.16

The control that the temporal variability of climate, the soil type, and land use have on recharge has been discussed above. Climatic variation is the reason for operating the deep percolation model for many years to arrive at estimates of recharge that represent long-term, time-averaged estimates. The timing of precipitation in relation to the soil-moisture conditions is critical. For example, an unusual short period of heavy precipitation in an arid area would result in a much greater amount of deep percolation than would occur for more normal weather conditions, even though the average precipitation over a period of time is about the same. This can be seen both in the data and in simulation results shown in table 11 for zone 4, one of the most arid zones. Clearly, the annual precipitation quantity alone does not entirely account for recharge quantities.

Errors in the different input data sets produce varying degrees of error in the recharge estimates. From table 9 it can be seen that the magnitude of error resulting from data input errors is also dependent upon the climatic and topographic regime. Because of the wide climatic variations in the project area, it is difficult to estimate the error of estimated recharge presented in this report.

Table 11.--Water budget and factors controlling estimated predevelopment recharge in zone 4 for selected years

Year	Water-budget items[1] (values in inches per year)								
	PRCP	RCH	RO	EVINT	EVSOL	EVSNW	PTR	ΔINT	ΔSNW	ΔSM
1958	8.70	0.40	0.09	2.84	1.80	0.07	2.69	0.03	0.0	0.78
1962	7.18	.06	.09	2.50	2.05	.05	2.53	.00	.00	-.09
1970	7.16	1.27	.08	1.74	1.27	.26	2.93	-.04	.00	-.35
1973	8.41	2.01	.10	1.80	.89	.15	1.23	.04	.06	2.12

[1]PRCP, precipitation; RCH, water percolating beyond the root zone; RO, surface runoff; EVINT, evaporation of moisture intercepted by the foliage surfaces; EVSOL, evaporation from bare soil; EVSNW, evaporation from snowpack (sublimation); PTR, transpiration; ΔINT, change of moisture on the foliage surface; ΔSNW, change of snowpack; ΔSM, change of soil water in the root zone.

Some additional errors can be expected from the empirical relations used in the model. In the development of the model, however, a "conservative" approach was used toward necessary assumptions in the formulation of certain relations. For example, experiments have shown that evaporation from a bare soil surface removes moisture mainly from the upper 6 to 8 inches (Chow, 1964) of the soil profile during periods of up to several months. In the model, moisture is removed down to 12 inches. This generally results in slightly more evaporation and, thus, less estimated recharge.

Another conservative factor influencing the estimated recharge values in this report is that the average annual precipitation for the 22-year period used for many of the zones was slightly less than the 100-year average annual precipitation.

The authors believe that the values presented are the most comprehensive regional estimates made to date, and that a maximum error of about 25 percent can be assumed for most zones presented in this report.

SUMMARY AND CONCLUSIONS

Long-term, time-averaged ground-water recharge estimates were simulated for a 22-year period using a daily deep-percolation model. Estimates were made for both predevelopment and current land-use conditions. Recharge estimates were made for individual cells within 53 zones ranging in size from 20 to 2,392 square miles.

Zones were generally chosen on the basis of surface-drainage areas above a stream gage. Cell size was generally 1 square mile or less. Simulations for most zones were made for the 1956-77 period; however, streamflow-data limitations dictated shorter simulation periods for many zones.

Predevelopment recharge for the 53 zones was estimated to be 2,588 ft^3/s or 1.65 in./yr on average. Recharge for current land-use conditions was estimated at 6,083 ft^3/s or 3.88 in./yr on average. The zones covered about 65 percent of the area within the ground-water model boundary.

Recharge was estimated for the remaining 35 percent of the area by a second-order polynomial regression equation developed from the long-term cell estimates for all zones. The regression equation related average annual precipitation to long-term average recharge.

Estimates of average recharge rate for the total area within the ground-water model boundaries (32,800 square miles) for predevelopment and current land-use conditions were 5,998 ft^3/s (2.48 in./yr) and 9,492 ft^3/s (3.93 in./yr), respectively.

A sensitivity analysis showed that errors in precipitation data produce the largest errors in recharge estimates, whereas errors in stream-discharge data produced the least error. Errors in recharge produced by errors in available water-capacity data depend upon the amount of precipitation received. Larger percentage errors are produced in more arid zones.

REFERENCES CITED

Bauer, H.H., and Vaccaro, J.J., 1987, Documentation of a deep percolation model for estimating ground-water recharge: U.S. Geological Survey Open-File Report 86-536, 180 p.

Bennett, G.D., 1979, Regional ground-water systems analysis, in Water Spectrum: U.S. Army Corps of Engineers, v. 2, no. 4, p. 36-42.

Chow, Ven Te, 1964, Handbook of applied hydrology, a compendium of water resources technology: New York, McGraw-Hill Book Co. (section N, 38 p.).

Elassal, A.A., and Caruso, V.M., 1983, USGS digital cartographic data standards: Digital elevation models, U.S. Geological Survey Circular 895-B, 40 p.

Freeman, O.W., Forrester, J.O., and Lupher, R.L., 1945, Physiographic divisions of the Columbia Intermontane Province: Annual Association American Geographer, v. 35, no. 2, p. 50-75.

IMSL, 1982, Interpolation, Chapter I, in International mathematics and science library reference manual, vol. 2: Houston, Texas, IMSL, Inc.

Jensen, M.E., editor, 1974, Consumptive use of water and irrigation water requirements: ASCE, Irrigation and Drainage Division, 215 p.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system: Users's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4283, 245 p.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H., 1975, Hydrology for engineers: New York, McGraw-Hill Book Co., 482 p.

Nelson, L.M., 1990, Surface-water resources for the Columbia Plateau, southeastern Washington, northeastern Oregon, and northwestern Idaho: U.S. Geological Survey Water-Resources Investigations Report 88-4105, 4 sheets (in press).

Pacific Northwest River Basins Commission, 1971, Comprehensive framework study, Appendix IX, Irrigation: Vancouver, Washington, 345 p.

Saxton, K.E., Johnson, H.P., and Shaw, R.H., 1974, Modeling evapotranspiration and soil moisture: Transactions of the American Society of Agricultural Engineers, v. 17, no. 4, p. 673-677.

U.S. Army Corps of Engineers, 1980, Columbia Basin water withdrawal environmental review: Appendix C, Economics, pt. IV, Appendix H, Agricultural data, pt. 1.

Washington (State) Department of Ecology, 1974, Inventory and reconnaissance of irrigation districts in the State of Washington: URS/Hill, Ingman, Chase and Co., 3 volumes.

Wight, J.R., and Neff, E.L., 1983, Soil-vegetation-hydrology studies, vol. II. A user manual for ERHYM: U.S. Department of Agriculture, Agricultural Research Station, Agricultural Research Results, ARR-W-29, January 1983, 38 p.

Wukelic, G.E., Foote, H.P., Blair, S.C., and Begei, C.D., 1981, Monitoring land- and water-use dynamics in the Columbia Plateau using remote-sensing computer analysis and interpretation techniques, RHO-BW-CR-122P/PNL-1047: Rockwell Hanford Operations and Pacific Northwest Laboratory, Richland, Washington, 50 p.

APPENDIX A. Attributes for the zones which were modeled

Zone reference number	Name[1]	Average latitude (decimal degree)	Area (square miles)	Years[2] of simulation	Runoff[3] record	Altitude[4] data	Number of: Nodes	Number of: Cells	Cell[5] size (square miles)	Dry-land[6] cells	Irrigated cells
1	BWIP1	46.5	729	1956-77	N	Y	3,151	2,949	0.25	169	1,191
2	BWIP2	46.8	115	56-76	P	Y	365	310	.375	0	3
3	BWIP3	46.8	146	56-77	N	Y	469	395	.375	0	5
4	BWIP4	46.6	188	56-77	N	Y	581	507	.375	0	0
5	BWIP5	46.8	20	56-77	N	Y	73	54	.375	0	0
6	BWIP6	46.7	112	56-73	P	Y	357	303	.375	0	5
7	BWIP7	46.7	58	67-78	P	Y	193	156	.375	11	0
8	BWIP8	46.5	234	56-77	N	Y	718	632	.375	7	12
9	BWIP9	46.6	161	63-76	P	Y	492	436	.375	30	90
10	BWIP10	46.6	55	56-77	N	Y	181	149	.375	38	0
11	BWIP11	46.5	51	56-77	N	Y	173	138	.375	22	0
12	BWIP12	46.3	541	56-76	P	Y	1,579	1,462	.375	214	733
13	BWIP13	46.2	211	56-77	N	Y	671	571	.375	60	141
14	BWIP14	46.2	260	56-73	P	Y	790	701	.375	239	123
15	BWIP15	46.1	425	63-68	S	Y	1,266	1,149	.375	854	102
16	BWIP16	46.0	256	56-77	N	Y	760	692	.375	215	94
17	BWIP17	46.0	52	56-77	N	Y	176	139	.375	68	26
18	BWIP18	46.8	387	63-68	D	Y	1,665	1,565	.25	179	14
19	BWIP19	45.8	68	64-68	S	Y	352	278	.25	40	0
20	BWIP20	45.9	277	63-68	D	Y	1,218	1,124	.25	257	58
21	BWIP21	46.2	571	63-72	D	Y	1,632	1,537	.375	1	4
22	Ahtanum	46.5	122	61-67	D	Y	552	487	.25	2	17
23	Asotin	46.23	167	60-77	D	Y	204	167	1.0	30	0
24	Bowers Coulee	47.0	1,020	56-76	S	N	1,134	1,020	1.0	758	150
25	Canniwai	47.5	347	56-77	N	N	442	347	1.0	117	67
26	Cow Creek	47.2	546	62-69	D	N	657	546	1.0	161	35
27	Crab Creek	47.45	1,019	56-77	D	N	1,126	1,019	1.0	612	31
28	Douglas Creek	46.6	601	56-77	D	Y	672	601	1.0	406	15
29	Dry Creek	46.15	46	56-66	D	Y	226	182	.25	125	0
30	East Banks	47.5	482	56-77	N	N	550	482	1.0	222	41
31	East High Canal	47.3	293	56-77	N	N	346	293	1.0	69	105
32	Eastlow Canal	47.00	504	56-77	N	N	599	504	1.0	18	266
33	Ellensburg	47.0	362	56-77	N	N	425	362	1.0	3	193
34	Eureka Flat	46.35	409	56-77	N	N	501	409	1.0	240	68
35	Farrier Coulee	47.15	43	62-73	D	N	217	172	.25	148	16
36	Jameson Lake	47.7	293	56-77	N	N	338	293	1.0	179	0
37	Naneum Creek	47.2	85	57-77	S	Y	390	338	.25	0	0
38	Providence Coulee	46.9	31	56-76	D	N	162	122	.25	73	36
39	Pullman-Moscow	46.7	130	60-77	D	Y	592	525	.25	430	0
40	Quincy	47.1	872	56-77	N	Y	945	872	1.0	69	314

APPENDIX A. Attributes for the zones which were modeled--continued

Zone reference number	Name[1]	Average latitude (decimal degree)	Area (square miles)	Years[2] of simulation	Runoff[3] record	Altitude[4] data	Number of: Nodes	Number of: Cells	Cell[5] size (square miles)	Dryland[6] cells	Irrigated cells
41	Royal Slope	46.9	321	56-77	N	Y	1,396	1,285	.25	134	470
42	Rye Grass Flat	46.65	711	56-77	N	N	787	711	1.0	496	47
43	Six Mile Creek	45.6	624	56-77	N	N	35	24	V	0	3
44	Toppenish	46.4	346	56-77	N	N	397	346	1.0	40	213
45	Touchet River	46.30	734	1956-77	D	Y	835	734	1.0	543	9
46	Tucannon River	46.40	433	59-77	D	Y	515	433	1.0	197	0
47	Umatilla River	45.55	2,392	56-77	S	Y	143	120	V	39	22
48	Union Flat Creek	46.6	185	56-70	D	N	239	185	1.0	113	0
49	Walla Walla	46.0	726	56-77	N	N	814	726	1.0	508	115
50	S-N Fork Walla Walla River	45.85	128	56-77	D,S	Y	581	513	.25	8	6
51	Willow Creek	45.4	856	56-77	N	Y	85	64	V	0	11
52	Wilson Creek	47.7	427	56-72	D	Y	494	427	1.0	288	21
53	Yakima	46.6	203	56-77	N	N	246	203	1.0	10	110

[1] Name refers to location of zone or feature within area and BWIP refers to zones in the Basalt Waste Isolation Project study area.

[2] Years is the calendar years for which the model was operated for.

[3] Runoff record shows the type of streamflow data used in the model, where: N = assumed no surface runoff, D = observed daily values, S = synthesized record using standard techniques, and P = daily values synthesized from peak value data.

[4] Y = all cells for zone had altitude, slope, and aspect data; N = none of the cells had such data.

[5] Size of cells that zones were subdivided into (for zones 1-21, and 39, cell sizes varied slightly), and V = variable size blocks.

[6] Number of cells in a zone that had dryland agriculture; assumed to be winter wheat on 2-year cycle.

APPENDIX B. Weather stations used in this study, and mean annual precipitation and temperature values for the period 1956-77 (U.S. Department of Ecology, National Climatic Data Center, written commun., 1982)

Zone reference number	Index number	Station	Station altitude (feet)	Longitude (--decimal	Latitude degree--)	Mean annual precipitation (inches)	Temperature, in degree Fahrenheit Minimum	Maximum	Mean
1	35-197	Antelope	2,680	120.7167	44.9167	12.23	37.1	62.1	49.6
2	35-265	Arlington	285	120.2000	45.7167	8.56	42.7	66.3	54.5
3	35-858	Boardman	300	119.7000	45.8333	7.87	41.5	65.2	53.4
4	35-897	Bonneville Dam	60	121.9500	45.6333	75.64	44.0	60.6	52.3
5	35-1028	Brightwood	1,065	122.0167	45.3667	87.89	(a)	(a)	(a)
6	35-1765	Condon	2,830	120.1833	45.2333	13.40	36.0	59.8	47.9
7	35-1924	Cove	2,920	117.8000	45.3000	16.32	33.8	60.1	47.0
8	35-2440	Dufur	1,330	121.1333	45.4500	11.57	35.7	63.1	49.4
9	35-2597	Elgin	2,655	117.9167	45.5667	24.25	33.3	62.0	47.7
10	35-2672	Enterprise	3,790	117.2667	45.4333	12.82	29.2	58.1	43.7
11	35-3038	Fossil	2,650	120.2167	45.0000	13.80	34.0	62.0	48.0
12	35-3250	Gibbon	1,740	118.3667	45.7000	23.93	(a)	(a)	(a)
13	35-3402	Government camp	3,980	121.7500	45.3000	88.26	35.6	50.6	42.1
14	35-3827	Heppner	1,950	119.5500	45.3500	13.29	38.6	62.8	50.7
15	35-3847	Hermiston 2 S	624	119.2833	45.8167	8.57	40.4	65.4	52.9
16	35-4003	Hood River Exp Sta	500	121.5167	45.6833	30.59	40.0	61.1	50.5
17	35-4161	Ione 18 S	2,130	119.8500	45.3167	11.60	(a)	(a)	(a)
18	35-4411	Kent	2,720	120.7000	45.2000	11.12	36.8	59.5	48.2
19	35-4622	La Grande	2,755	118.0833	45.3167	17.26	35.3	60.8	48.1
20	35-5545	Mikkalo 6 W	1,550	120.3500	45.4667	10.19	40.7	62.8	51.8
21	35-5593	Milton Freewater	970	118.4167	45.9500	13.20	42.8	65.2	54.0
22	35-5610	Minan 7 NE	3,615	117.6000	45.6833	26.82	27.3	56.7	42.0
23	35-5711	Monument 2	1,995	119.4167	44.8167	13.12	34.6	64.4	49.5
24	35-5734	Moro	1,870	120.7167	45.4833	10.58	37.9	59.8	48.9
25	35-6468	Parkdale 2 SSE	1,890	121.5833	45.5000	44.97	39.0	58.2	48.6
26	35-6540	Pendleton Brch Exp S	1,487	118.6333	45.7167	15.68	37.7	63.7	50.7
27	35-6546	Pendleton WSO A P	1,492	118.8500	45.6833	11.73	42.1	63.7	52.9
28	35-6634	Pilot Rock 1 SE	1,720	118.8167	45.4833	13.63	37.6	64.4	51.0
29	35-8000	Spout Spgs Ski Lodge	5,035	118.0500	45.7500	35.38	(a)	(a)	(a)
30	35-8407	The Dalles	102	121.2000	45.6000	13.51	42.9	65.1	54.0
31	35-8726	Ukiak	3,355	118.9333	45.1333	16.77	28.8	59.3	44.0
32	35-8746	Union Exp Sta	2,765	117.8833	45.2167	13.74	35.7	59.7	47.7
33	35-8985	Walla Walla 13 ESE	2,400	118.0500	46.0000	41.77	35.9	58.8	47.3
34	35-9068	Wasco	1,264	120.7000	45.5833	11.01	(a)	(a)	(a)
35	35-9219	Weston 5 ESE	3,200	118.3333	45.8000	26.09	(a)	(a)	(a)
36	45-217	Appleton	2,336	121.2667	45.8167	31.50	36.6	57.3	46.9
37	45-294	Asotin 14 SW	3,500	117.2500	46.2000	19.20	(a)	(a)	(a)
38	45-668	Bickleton	3,000	120.3000	46.0000	13.93	36.7	57.8	47.2
39	45-969	Bumping Lake	3,440	121.3000	46.8667	36.90	31.3	54.2	42.8
40	45-1350	Chelan	1,120	120.0333	47.8333	10.31	40.2	59.9	50.1

APPENDIX B. Weather stations used in this study, and mean annual precipitation and temperature values for the period 1956-77 (U.S. Department of Ecology, National Climatic Data Center, written commun., 1982)--continued

Zone reference number	Index number	Station	Station altitude (feet)	Longitude (--decimal	Latitude degree--)	Mean annual precipitation (inches)	Temperature, in degree Fahrenheit		
							Minimum	Maximum	Mean
41	45-1400	Chief Joseph Dam	820	119.6500	48.0000	9.45	38.8	61.4	50.1
42	45-1504	Cle Elum	1,930	120.9500	47.1833	24.65	34.5	57.8	46.1
43	45-1586	Colfax 1 NW	1,955	117.3833	46.8833	19.29	36.4	60.0	48.2
44	45-1690	Connel 1 W	1,020	118.8833	46.6667	7.58	(a)	(a)	(a)
45	45-1691	Connel 12 SE	1,078	118.7667	46.5000	9.45	38.4	64.2	51.3
46	45-1767	Coulee Dam 1 SW	1,700	119.0000	47.9500	10.08	39.7	59.7	49.7
47	45-1968	Dallesport FAA AP	240	121.1500	45.6167	12.75	42.8	64.3	53.6
48	45-2007	Davenport	2,460	118.1500	47.6500	15.10	34.8	58.0	46.4
49	45-2030	Dayton 1 WSW	1,557	118.0000	46.3167	18.16	39.6	62.6	51.1
50	45-2505	Ellensburg	1,480	120.5500	46.9667	9.47	35.8	59.9	47.9
51	45-2542	Eltopia 8 WSW	700	119.1667	46.4000	8.09	39.3	63.6	51.5
52	45-2614	Ephrata FAA AP	1,259	119.5167	47.3167	7.11	41.0	61.8	51.4
53	45-3183	Glenwood 2	1,850	121.2833	46.0000	35.06	(a)	(a)	(a)
54	45-3226	Goldendale 2 E	1,800	120.7667	45.8167	16.39	38.4	61.1	49.8
55	45-3502	Harrington 5 S	2,170	118.2500	47.4167	12.18	(a)	(a)	(a)
56	45-3512	Harrington 4 EN E	2,266	118.1833	47.4833	12.82	(a)	(a)	(a)
57	45-3529	Hartline	1,910	119.1000	47.6833	10.38	36.7	60.5	48.6
58	45-3546	Hatton 9 ESE	1,430	118.6500	46.7500	9.79	37.5	63.2	50.4
59	45-3883	Ice Harbor Dam	368	118.8667	46.2500	9.07	42.2	65.7	53.9
60	45-4077	Kahlotus 5 SSW	1,550	118.6000	46.5833	10.43	(a)	(a)	(a)
61	45-4154	Kennewick	390	119.1000	46.2167	7.35	42.4	65.9	54.2
62	45-4338	La Crosse	1,480	117.8833	46.8167	13.33	37.3	62.1	49.7
63	45-4394	Lake Cle Elum	2,250	121.0667	47.2444	37.27	34.6	54.5	44.5
64	45-4406	Kachess	2,270	121.2000	47.2667	52.84	34.5	54.1	44.3
65	45-4414	Keechleus	2,475	121.3389	47.3222	69.03	33.1	51.6	42.3
66	45-4679	Lind 3 NE	1,630	118.5833	47.0000	9.18	37.2	62.9	50.1
67	45-4971	Mansfield 7 W	2,500	119.8000	47.8167	10.54	38.4	60.0	49.2
68	45-5231	McNary Dam	361	119.3000	45.9500	7.33	43.8	64.8	54.3
69	45-5325	Methow 2	1,160	120.0000	48.0000	10.59	(a)	(a)	(a)
70	45-5326	Methow 2 S	1,170	120.0167	48.1000	10.93	37.3	60.6	48.9
71	45-5387	Mill Creek Dam	1,175	118.2667	46.0833	17.82	(a)	(a)	(a)
72	45-5613	Moses Lake	1,070	119.3000	47.1000	7.46	37.1	61.7	49.4
73	45-5659	Mt. Adams Ranger Sta	1,960	121.5333	46.0000	43.64	35.4	59.3	47.4
74	45-5688	Moxee CITY 10 E	1,550	120.1667	46.5167	7.79	36.0	61.0	48.5
75	45-5832	Nespelem 2 S	1,090	118.9833	48.1333	12.68	34.3	61.2	47.7
76	45-6039	Odessa	1,540	118.6833	47.3333	9.72	35.9	63.1	49.5
77	45-6215	Othello 6 ESE	1,190	119.0500	46.8000	7.82	38.6	62.6	50.6
78	45-6610	Pomeroy	1,810	117.6167	46.4667	15.44	38.9	62.7	50.8
79	45-6747	Priest Rapids Dam	460	119.9000	46.6500	6.67	44.4	65.6	55.0
80	45-6768	Prosser 4 NE	903	119.7500	46.2500	7.68	38.5	63.5	51.0

APPENDIX B. Weather stations used in this study, and mean annual precipitation and temperature values for the period 1956-77 (U.S. Department of Ecology, National Climatic Data Center, written commun., 1982)--continued

Zone reference number	Index number	Station	Station altitude (feet)	Longitude (--decimal	Latitude degree--)	Mean annual precipitation (inches)	Temperature, in degree Fahrenheit Minimum	Maximum	Mean
81	45-6789	Pullman 2 NW	2,545	117.2000	46.7667	21.95	36.8	57.5	47.1
82	45-6880	Quincy 1 S	1,274	119.8500	47.2167	7.95	37.2	62.1	49.7
83	45-7015	Richland	373	119.2667	46.3167	6.55	42.4	66.9	54.7
84	45-7038	Rimrock Reservoir	2,730	121.1333	46.6500	24.72	32.6	56.0	44.3
85	45-7059	Ritzville 1 SSE	1,830	118.3667	47.1167	11.20	36.1	60.8	48.4
86	45-7180	Rosalia	2,400	117.3667	47.2333	16.98	36.1	57.8	46.9
87	45-7267	St. John	1,945	117.5833	47.1000	15.06	36.2	60.4	48.3
88	45-7342	Satus Pass 2 SS W	2,610	120.6500	45.9500	19.28	36.4	59.5	48.0
89	45-7727	Smyrna	560	119.6667	46.8333	7.87	39.9	65.2	52.6
90	45-7938	Spokane WSO AP	2,356	117.5333	47.6333	16.61	37.2	57.3	47.3
91	45-7956	Sprague	1,920	117.9833	47.3000	14.75	34.9	60.6	47.8
92	45-8009	Stampede Pass W SCMO	3,958	121.3333	47.2833	94.53	33.5	45.3	39.4
93	45-8207	Sunnyside	747	120.0000	46.3167	6.44	39.0	65.3	52.1
94	45-8442	Tieton Headwork S	2,280	121.0000	46.6711	20.26	33.5	56.7	45.1
95	45-8931	Walla Walla WSO CI	949	118.3333	46.0333	15.91	44.8	63.7	54.2
96	45-8959	Wapato	841	120.4167	46.4333	7.82	38.7	63.1	50.9
97	45-9012	Waterville	2,620	120.0667	47.6500	10.38	38.2	59.8	49.0
98	45-9058	Wellpinit	2,490	118.0000	47.9000	15.78	36.2	58.5	47.3
99	45-9079	Wenatchee Exp Sta	800	120.3500	47.4333	11.69	38.1	60.6	49.3
100	45-9082	Wenatchee FAA A P	1,229	120.2000	47.4000	10.75	38.8	60.5	49.6
101	45-9200	Whitman Mission	632	118.4500	46.0500	15.56	41.8	64.0	52.9
102	45-9238	Wilbur	2,160	118.7000	47.7500	11.14	36.5	60.1	48.3
103	45-9465	Yakima WSO AP	1,064	120.5333	46.5667	9.14	36.4	61.1	48.8

[a] No temperature data.

APPENDIX C. Physical characteristics of the two sets of soil categories used in this study

	Zones 1-21			Zones 22-53		
Soil category	Layers[1]	Texture[2]	Available water capacity for each layer (inches)	Layers[1]	Texture[2] range	Available water-capacity range for each layer[3] (inches)
1	None	--	--	0-3	1.2-1.8	0.0 - 0.45
2	3	1.5	0.72	3-5	1.3-2.0	0.0 - 0.45
3	4	1.4	.66	0-3	1.5-1.9	0.45- 0.75
4	5	1.5	.70	5-7	1.1-1.5	0.0 - 0.45
5	3	2.0	1.02	0-3	1.8-2.0	0.75- 1.05
6	3	2.1	1.20	7-8	1.3-2.0	0.0 - 0.45
7	5	2.0	1.02	3-5	1.3-1.8	0.45- 0.75
8	5	2.1	1.14	0-3	1.6-2.1	1.05- 1.35
9	5	2.2	1.26	9-10	1.0-2.3	0.0 - 0.45
10	7	1.7	.90	0-3	(2)	1.35- 1.80
11	10	1.1	.36	5-7	1.5-1.9	0.45- 0.75
12	10	1.3	.60	3-5	1.5-2.2	0.75- 1.05
13	8	2.2	1.08	7-9	1.3-1.8	0.45- 0.75
14	8	2.4	1.20	3-5	1.8-2.3	1.05- 1.35
15	8	3.0	1.44	5-7	1.6-2.1	0.75- 1.05
16	10	3.0	1.56	9-10	1.3-1.6	0.45- 0.75
17	None	--	--	3-5	(2)	1.35- 1.80
18	None	--	--	7-9	1.5-2.0	0.75- 1.05
19	None	--	--	5-7	1.7-2.6	1.05- 1.35
20	4	1.5	.69	9-10	1.5-2.4	0.75- 1.05
21	4	2.3	1.15	5-7	(2)	1.35- 1.8
22	9	1.3	.54	7-9	2.0-2.4	1.05- 1.35
23	8	2.4	1.18	9-10	1.9-2.3	1.05- 1.35
24	9	3.0	1.53	7-9	(2)	1.35- 1.80

[1] Each layer is 6 inches and zones 22-53 will have some specific values in the listed range.

[2] Texture represents soil particle size where 1.0 = sand, 2.0 = loam, 3.0 = clay, 1.5 = sandy loam, and other combinations thereof. For zones 22-53 a particular texture and available water capacity were determined for each soil category in each zone by weight-averaging the textures and capacities of all soil series falling into the given available water-capacity range. No texture values given where no soils occurred in the given capacity range.

[3] Each of the zones 22-53 will have some specific value in the listed range.