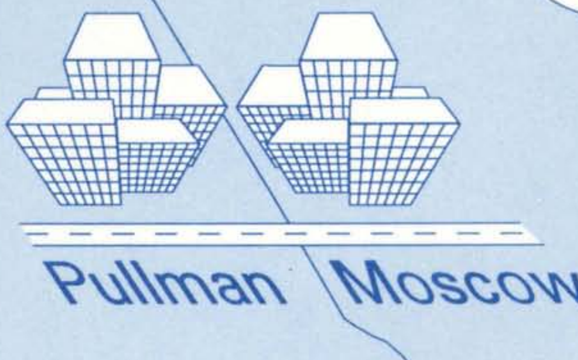
Geohydrology and Numerical Model Analysis of Ground-Water Flow in the Pullman-Moscow Area, Washington and Idaho

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 89-4103



m. DeAngelo

Prepared in cooperation with the

UNIVERSITY OF IDAHO, WASHINGTON STATE UNIVERSITY, and the CITIES OF MOSCOW, IDAHO, and PULLMAN, WASHINGTON

GEOHYDROLOGY AND NUMERICAL MODEL ANALYSIS OF GROUND-WATER FLOW IN THE PULLMAN-MOSCOW AREA, WASHINGTON AND IDAHO

by W.E. Lum II, U.S. Geological Survey, Tacoma, Washington
J.L. Smoot, Batelle Pacific Northwest Laboratory, Richland, Washington
D.R. Ralston, University of Idaho, Moscow, Idaho

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 89-4103

Prepared in cooperation with the

UNIVERSITY OF IDAHO, WASHINGTON STATE UNIVERSITY
and the CITIES OF MOSCOW, IDAHO, and PULLMAN, WASHINGTON

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. 810
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

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 unit	By	To obtain metric unit
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
	0.028317	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

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.

GEOHYDROLOGY AND NUMERICAL MODEL ANALYSIS OF GROUND-WATER FLOW IN THE PULLMAN-MOSCOW AREA, WASHINGTON AND IDAHO

By W.E. Lum II, J.L. Smoot, and D.R. Ralston

ABSTRACT

The Pullman-Moscow area of southeastern Washington and northern Idaho depends on ground water as the principal source of water, but increasing pumpage rates and declining ground-water levels indicate a need for ground-water management. Using data from a study done by the U.S. Geological Survey in the 1970's and up-to-date data collected for this study, a three-dimensional numerical computer model of the ground-water-flow system was constructed to provide an understanding of the geohydrology of the study area.

The ground-water-flow model incorporates three layers--an overlying surficial loess layer, a Wanapum Basalt layer, and a Grande Ronde Basalt layer. A ground-water-system recharge rate was estimated using a methodology developed by the U.S. Geological Survey. Ground-water discharge was modeled as ground-water pumping, flow to rivers and streams, and flow out of seepage faces, where a layer is incised by a river valley. Three cross-sectional flow models, distributed across the domain of the three-dimensional model along estimated flow lines in the Grande Ronde Basalt, were used to obtain hydraulic coefficient input for the three-dimensional model. The three-dimensional model was calibrated using the time-averaged method for the period 1974-85, and was evaluated by simulating historical pumpage rate changes (1890-1985) and comparing simulated with observed water-level changes.

Model results suggest that ground-water levels would stop declining if ground-water pumpage were to stabilize at a constant level. However, ground-water levels will continue to decline in the foreseeable future as long as ground-water pumpage continues to increase.

Further study of the recharge, movement, and discharge of ground water in the area is needed to increase the accuracy of any ground-water-flow model to predict the response of the flow system to future pumping stresses.

INTRODUCTION

The Pullman-Moscow area of southeastern Washington and northern Idaho depends on ground water as the principal source of water. Primary pumpage is from the Miocene Grande Ronde Formation of the Yakima Basalt Subgroup of the Columbia River Basalt Group and associated interbedded sediments. Water is used for municipal supplies for the city of Pullman, Wash. (about 85 miles south of Spokane); the Washington State University (located in Pullman); the city of Moscow, Idaho (about 8 miles east of Pullman); and the University of Idaho (located in Moscow). Water levels in wells in the deeper basalts have declined slowly but steadily since the wells were first drilled in the 1890's. Because of the declining water levels, there has been local concern that water availability might limit development in the area.

To try to understand the response of the ground-water-flow system to pumping and to help develop a management strategy to protect the ground water, two mathematical models were developed by other investigators prior to this study. These efforts began with the image-well model of Jones and Ross (1969). Later modeling was done by the U.S. Geological Survey (Barker, 1979). The model described by Barker simulated that water levels would continue to decline in the area even if pumping rates of ground water did not increase. That model also simulated that the rate of water-level decline from 1976 to 2000 would average about 1.5 feet per year if pumping of ground water increased at a rate of 3 percent per year (Barker, 1979).

Between 1976 and 1985, average annual pumpage of ground water has increased at a rate of only about 1 percent per year. Water levels in Pullman and Moscow have continued to decline. However, the rate of decline continued unabated at about 1.5 feet per year, a rate of decline that had been associated with a much higher rate of increase in ground-water pumping (Barker, 1979). The continuing decline and its rate prompted renewed local concern.

Representatives of the two universities, the two cities, the State of Washington Department of Ecology, and the U.S. Geological Survey met in 1984 to discuss the area's water problems. The group acknowledged the deficiency in knowledge of the system and the need for an updated predictive tool to guide future management decisions. As a result, the cities of Pullman and Moscow and the University of Idaho and Washington State University entered into a cooperative agreement with the U.S. Geological Survey to help support this effort to collect new geohydrologic data and then to construct a new model of the ground-water system in the Pullman-Moscow area. A critical part of the study was a magnetotelluric geophysical survey conducted by personnel of the U.S. Geological Survey to delineate the thickness of the basalt in the basin. Geohydrologic data were used to construct an updated model using the U.S. Geological Survey modular ground-water-flow program (McDonald and Harbaugh, 1988). The model was used to calculate future water-level changes under various pumping scenarios. This report presents the details of field data collection, data interpretation, model construction, model operation, and an analysis of results.

Purpose and Scope

The purpose of this report is to document the results of a study to: 1) define the geohydrology of the area around Pullman, Wash., and Moscow, Idaho; and 2) construct and calibrate a three-dimensional ground-water-flow model for the area to calculate the effect of changes in the rate of withdrawal on the ground-water system. This study updates the work done in the 1970's by the U.S. Geological Survey (Barker, 1979). Data collected for this study included:

1) Water-level measurements in all wells measured during 1974-75 and reported on by Barker (1979).
2) Rate of ground-water withdrawal for all water users in the study area through 1985.
3) Data on the lateral extent, thickness, and hydraulic characteristics of all geologic units present in the study area.

Specific objectives of the study included:

1) Defining data needs and collecting data to update the current understanding of the ground-water-flow system of the area;
2) Defining the thickness of the basalt in the study area using a magnetotelluric geophysical technique;
3) Constructing and calibrating a three-dimensional numerical model of the flow system;
4) Operating the model under various management plans, and evaluating their impacts on the geohydrologic features of the area; and
5) Comparing the results of the model presented in this report with results of a two-dimensional finite-difference ground-water-flow model by Barker (1979).

Previous Investigations

Ground-water investigations in the Pullman-Moscow area began in the late 1800's. Russell (1897) made the first geohydrologic reconnaissance of the area. DeMotte and Miles (1933) investigated the source of the artesian water levels in Moscow and Pullman. Barker (1979), Foxworthy and Washburn (1963), and Walters and Glancy (1969) defined the basic geohydrology of the area.

Barker (1979), Foxworthy and Washburn (1963), Ross (1965), Lin (1967), Ringe (1968), Brown (1976), and Cotton (1982) provided discussions of the geology of the area. Swanson and others (1979) and Drost and Whiteman (1986) discussed the stratigraphy and geology of the Columbia River Basalt Group. Swanson and others (1980) and Hooper and Webster (1982) provided surficial geologic maps of the area. Ross (1965), Jones and Ross (1972), Crosthwaite (1975), Barker (1979), and Whiteman (1986) provided information on wells, water levels in the basin, and the ground-water-flow system. Bauer and others (1985) showed the regional ground-water levels in the basalt. Williams and Allman (1969) discussed mechanisms for recharge and infiltration in the surficial loessial soils. Jones and Ross (1972) and Barker (1979) did the previous ground-water-modeling studies.

The results of a magnetotelluric geophysical survey done by the Geologic Division of the U.S. Geological Survey to provide data on basalt thickness for this study were described by Klein and others (1987). Bockius (1985) did a magnetic geophysical survey to better delineate the buried basalt-granite contact in the Idaho part of the basin. Eyck and Warnick (1984) provided a comprehensive listing (a lengthy annotated bibliography) of documents about ground water and water supply in the Pullman-Moscow area.

Well-Numbering System

Idaho and Washington identify wells on the basis of the township and range system, but divide the sections differently. Idaho wells are referenced to the Boise baseline and meridian, and Washington wells are referenced to the Willamette baseline and meridian. Both States identify the township, range, and section of the well and use letter codes to divide the quarter-quarter sections. In Washington, quarter-quarter sections are divided by letters in a similar manner to which sections are numbered in a township. Letters begin in the northeast corner and wind around in alphabetical order. In Idaho, quarter sections are lettered counter-clockwise. The same method is used for quarter-quarter and quarter-quarter-quarter sections. This letter code is then added to the township-range-section number to provide a location for the well. If there is more than one well in the smallest subdivision, then these several wells are numbered usually in order of drilling. Examples of the well-numbering systems are shown in figure 1, for Washington well 15/45-25F1 and Idaho well 40/5-31bdb3.

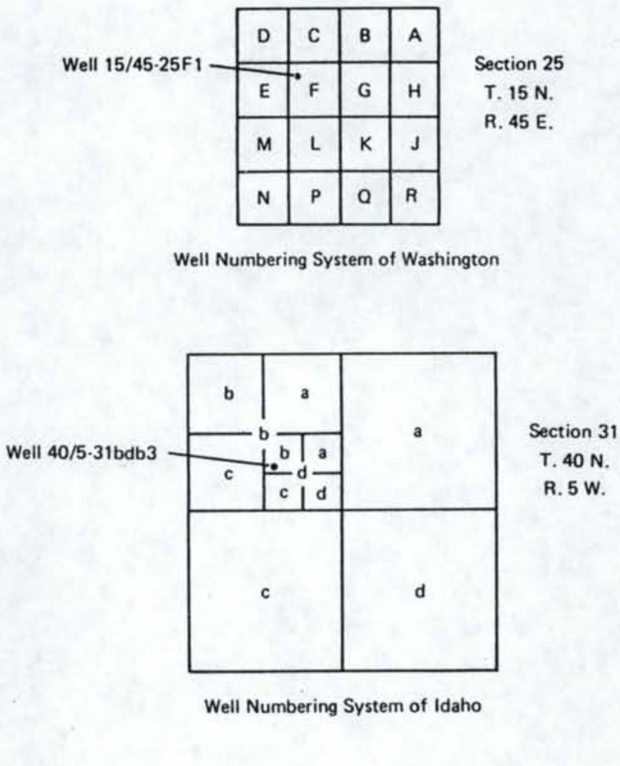


Figure 1.--Well-numbering systems of Washington and Idaho.

DESCRIPTION OF THE STUDY AREA

The study area is located in southeast Washington and northern Idaho, and includes parts of Whitman County, Washington, and Latah County, Idaho. The total area investigated is about 750 mi^2. About 150 mi^2 near Pullman and Moscow was investigated in detail, and the remainder of the study area at a reconnaissance level.

Physiography and Land Use

Pullman and Moscow lie within a shallow elliptical basin bordered on the north, east, and south by a broken horseshoe-shaped ring of mountains and hills of granite, gneiss, and quartzite. The physiographic divide on the east side of the basin is the crest of the Moscow Mountains, in Idaho. The northern margin of the basin is a semicircle of prominent hills, including Kamiak Mountain and Smoot Hill (fig. 2). A series of lower hills ending near Chambers marks the southern border.

The basin floor consists of a moderately dissected lava plain that has a thick cover of wind-deposited silt, or loess. Altitudes in this area range from 2,225 feet above sea level near Albion, Washington, to about 2,550 feet in Moscow, Idaho. The rounded, loess-covered hills generally rise 200 to 300 feet above the narrow intervening stream channels. From the air, the hilltops show a marked concordance, and if connected, they would form a fairly even surface having a gentle westward slope (after Foxworthy and Washburn, 1963).

The gentle slope is interrupted southwest of Pullman by the canyon of the Snake River. The loess-covered hills are gently rounded to within about 1 to 2 miles of the river. Altitudes of the tops of the hills are about 2,200 feet near Lower Granite Dam to about 2,900 feet between Uniontown and Clarkston. The altitude of the river behind Lower Granite Dam is about 740 feet; below the dam it is about 640 feet. The intervening canyon wall is extremely steep. The land surface in this canyon is vertical in places, and slopes of 25 percent are common.

The canyon probably has a significant effect on ground-water flow in the area. Numerous small springs and seeps occur in the canyon along its steeply sloping walls. Abundant native grasses and isolated, dense stands of shrubs may indicate subirrigation from regional ground-water discharge.

The urban areas of Moscow and Pullman account for only a few percent of the land area within the basin. Dryland farming of the loess constitutes the major land use in the study area. The primary crops are wheat, peas, and lentils. Rainfall is ample for the crops because the large soil-moisture storage capacity carries the crops through the dry summer; little irrigated agriculture exists. In parts of Whitman County, Wash., the common farming practice is to alternate fallow years with crop-growing years. The fallow year allows an increase in moisture stored in the soil zone to be used by crops the next year. In eastern Whitman County, however, generally east of a line through Colfax, Pullman, and Chambers (fig. 2), there is sufficient precipitation and resultant increased soil moisture to allow a crop to be grown every year (Robert Allen, U.S. Department of Agriculture, Pullman, Wash., oral commun., 1985).

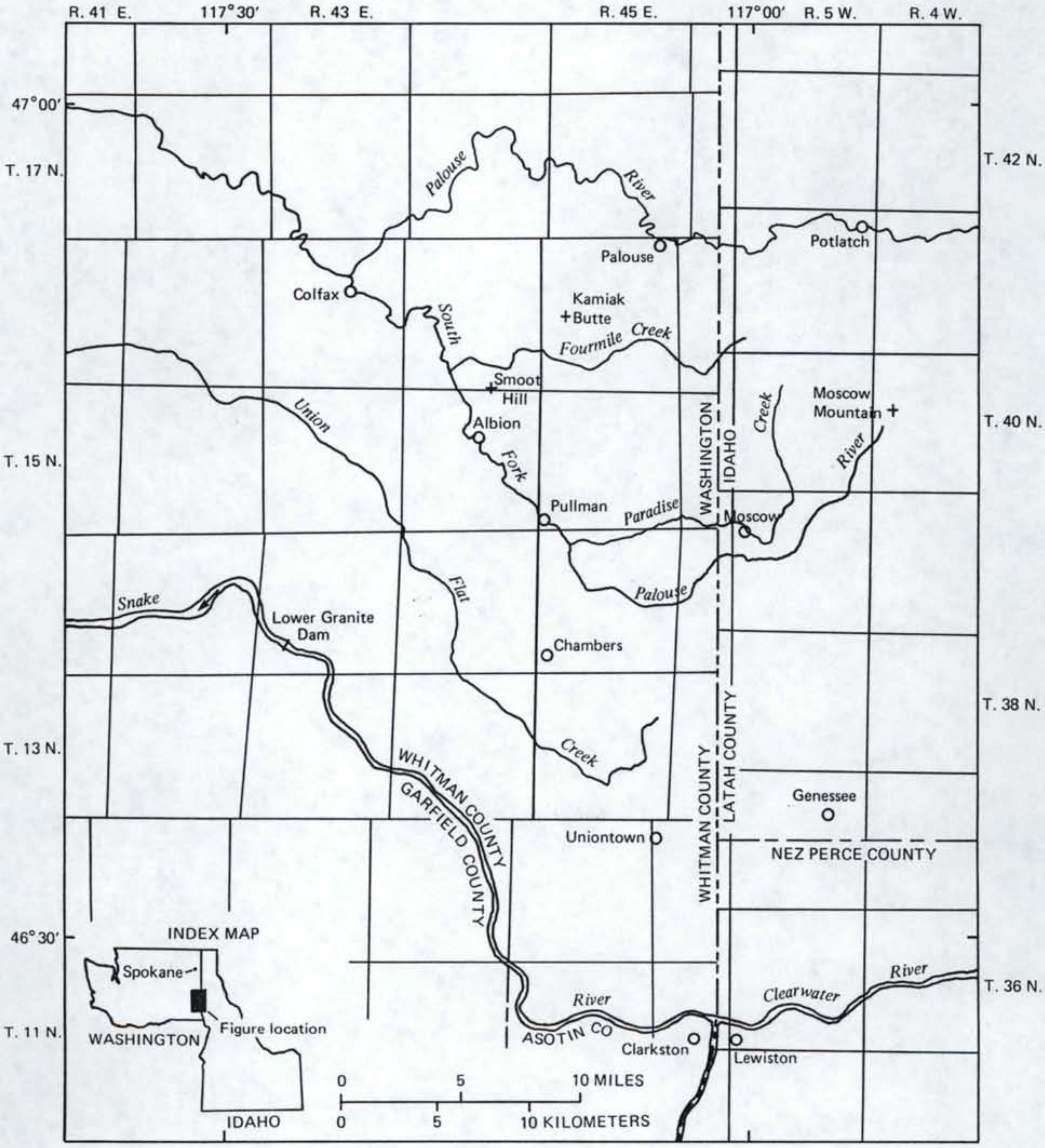


Figure 2.--Location of Pullman-Moscow area.

Precipitation

Average annual precipitation gradually increases west to east in the region. Long-term records indicate an average annual precipitation of about 22 inches in Pullman and about 24 inches in Moscow ([U.S.] National Oceanic and Atmospheric Administration, 1987a and 1987b). East of Moscow, precipitation abruptly increases to about 40 inches per year as the altitude abruptly increases near Moscow Mountain. Precipitation falling on the basin generally is of low intensity and is seasonal. Most of the precipitation falls between November and April, with dry conditions during the summer. Table 1 shows average monthly precipitation for Pullman and Moscow.

Table 1.--Average monthly precipitation for Pullman, Wash., and Moscow, Idaho, 1956-77 and 1951-80, respectively

	Average monthly precipitation, in inches											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Pullman	3.1	2.1	2.1	1.6	1.5	1.6	0.5	1.0	1.1	1.7	2.8	3.1
Moscow	3.2	2.1	2.0	2.0	2.0	1.7	0.7	1.1	1.1	1.8	3.0	3.3

Surface-Water Resources

The Snake River is the largest surface-water body in the study area. The U.S. Army Corps of Engineers operates Lower Granite Lock and Dam on the Snake River southwest of Pullman. Pool elevation upstream from the dam is about 740 feet above sea level. Average annual discharge through the dam for the years 1978 to 1985 (period of available records) was 56,250 ft^3/s (U.S. Geological Survey, 1987). The Palouse River is the only other major river; its average annual discharge at Colfax, Wash., for the period of available records (1964-72 and 1976-86) was 388 ft^3/s (U.S. Geological Survey, 1988).

Several perennial streams also drain the area, including the South Fork Palouse River, Paradise Creek, Fourmile Creek, and Union Flat Creek (fig. 2). A small amount of lawn and pasture irrigation is derived from these streams. The cities of Pullman and Moscow put treated sewage effluent into the South Fork Palouse River and Paradise Creek, respectively. In Moscow, some treated sewage effluent is also used for irrigation.

The upper reaches of streams in the study area generally flow on the loessial soils of the basin, whereas the lower reaches are incised into the basalt bedrock. The Snake and the Palouse Rivers are incised deeply in the basalt.

GEOHYDROLOGY

The occurrence and movement of ground water in the Pullman-Moscow area is dependent on the geohydrology of the area, including the nature of the geologic units and their water-bearing characteristics, and sources of recharge to and discharge from the ground-water system. The development of a model of ground-water flow can improve the understanding of the system by integrating all pertinent geohydrologic information. Such a model can then be used to evaluate the effects of ground-water withdrawals (pumping).

Geology and Structure

The geology of the Pullman-Moscow area consists of an irregular buried surface of pre-Tertiary crystalline rocks (Klein and others, 1987), overlain by the Miocene Columbia River Basalt Group and interbeds that are capped by Pleistocene Palouse Loess (Swanson and others, 1980). The geologic units are shown diagrammatically in figure 3. The crystalline basement rocks primarily are granites, although some metamorphic rocks occur in the northern part of the basin.

Miocene basalts interbedded with sediments overlie the crystalline rocks. Basaltic lava was extruded from fissures located near Pullman and elsewhere in southeastern Washington and northeastern Oregon (Swanson and others, 1980). A series of flows over millions of years produced the layers that make up the existing basalt sequence. The thickness of the layers averages 40 to 80 feet, although layers 200-feet thick have been observed.

Basalt flows fracture at the surface as they cool and solidify from the molten state. Three sets of joints commonly occur, two in the vertical direction and one in the horizontal direction. Columnar hexagonal joints that form columns 0.5 to 6 feet in width, and blocky joints fracturing parts of the basalt into pieces commonly about 0.5 foot in diameter, occur in the vertical direction (Newcomb, 1965). Platy fractures occur in the horizontal direction irregularly throughout most of the thickness of a flow. In addition, regional fractures hundreds or thousands of feet long may intersect several flows and have widely varying widths.

The basalt flows in the Pullman-Moscow basin are classified into the Wanapum and Grande Ronde Basalts of the Yakima Basalt Subgroup of the Columbia River Basalt Group (Swanson and others, 1979). Wanapum and Grande Ronde Basalts can be differentiated geochemically by magnesium and titanium concentrations--the Wanapum Basalt contains large concentrations of titanium and small concentrations of magnesium, and the Grande Ronde Basalt contains large concentrations of magnesium and small concentrations of titanium. The Wanapum Basalt is separated from the Grande Ronde Basalt by the Vantage Member (interbed) of the Miocene Ellensburg Formation. The Vantage Member occurs widely throughout the Columbia Plateau and is composed of siltstone, claystone, and tuffaceous rocks (Swanson and others, 1979).

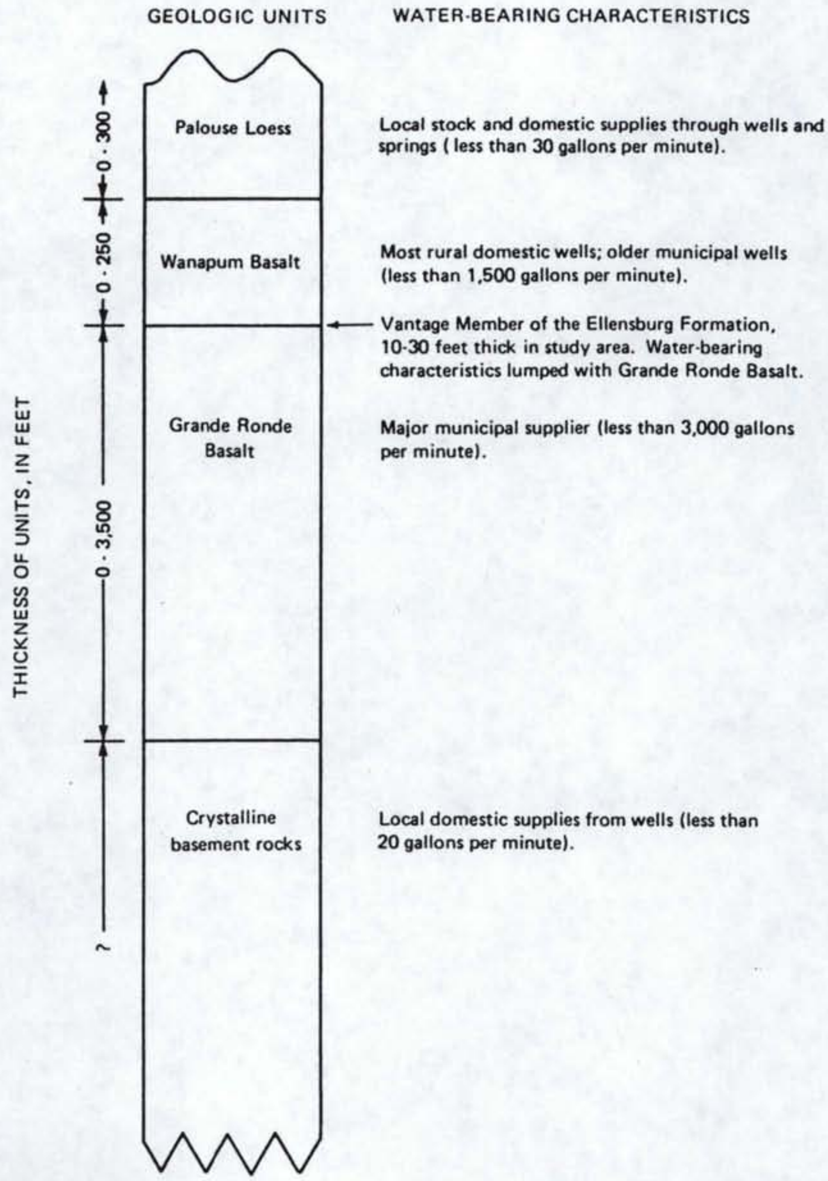


Figure 3.--Stratigraphy and water-bearing characteristics of the geologic units in the Pullman-Moscow area.

Numerous sedimentary interbeds like the Vantage Member commonly are mixed with the basalt, particularly near the margins of the Columbia Plateau. They were produced in lakes created when basalt flows dammed streams that existed during the eruption process. Soils also may have formed on the interbeds or on the basalt surfaces. Subsequent lava flows may have covered the sediments and created new lakes. Interbeds commonly are encountered during well drilling near Moscow and Pullman. Lithologies include clays, sands, and gravels. Laterally, the interbeds tend to thin and become finer to the west, but their spatial distribution has not been mapped adequately. Some drillers' logs for wells east of Moscow report hundreds of feet of clay.

Little structural deformation of the basalt flows has been detected in the Pullman-Moscow area. Foxworthy and Washburn (1963) note the possibility of broad flexures in the basalt. Some subsidence appears to have occurred to the west (Brown, 1976). The basalts generally dip a few degrees to the northwest. Cross sections by Brown do not reveal any structure other than the regional dip. The dip increases northwest of Pullman (Walters and Glancy, 1969). This increase may be the result of greater subsidence in that area. The basalts dip in the opposite direction in the Idaho part of the basin, possibly because of compaction of clay interbeds due to loading by overlying basalt flows and interbeds.

Other investigators have speculated on the presence of structural features in the Pullman and Moscow area that may have an effect on ground-water flow. Barker (1979) provided a definitive discussion on all the theories, but concluded that more data collection (test drilling and possibly more geophysical surveys) is necessary to determine the nature of these features, their location, and their effect on the ground-water system.

The geophysical study done by Klein and others (1987) was intended to provide some information about these features. The results indicate that there are considerable variations in the altitude of the bedrock-basalt interface (see fig. 7, p. 16). However, no specific features were identified that relate directly to the 'barrier zone' of Barker (1979). (Barker's investigation is discussed on page 58.) Test drilling to determine water-level variations with depth, aquifer permeabilities, and stratigraphic information to better define the features postulated by Barker was not included in this study.

Pleistocene Palouse Loess covers the relatively flat surface of the Wanapum Basalt. The loess originated in the Pasco basin about 95 miles west of the study area. Loess was deposited as large dunes that form the present topography. Thickness of the loess ranges from several hundred feet at the crests of the loessial dunes to zero where streams penetrate through to the underlying basalt. The loess is fine-grained and contains a well-developed silt-loam soil.

Water-Bearing Characteristics of Geologic Units

The loess, basalt, and crystalline basement rocks all contain sufficient saturated permeable material to yield water to wells and springs (fig. 3). The loess has a high water-holding capacity. Unconfined ground water occurs in the loess, with the water table conforming roughly to the topography (Williams and Allman, 1969). Water levels fluctuate in response to the annual wet and dry cycle of precipitation. No long-term declines in water levels in wells open to the loess were reported by well owners during this study. Sufficient water is available in the loess for some stock and domestic supplies. Small springs are common at the contact of the loess and underlying basalt, particularly along stream valleys.

Basalts constitute the major producing aquifers in the basin. Most of the water is present in the fractured zones near the tops and bottoms of the basalt flows. Wells that penetrate one or more of these zones have the highest yields. The deepest wells in the area are at Moscow; they fully penetrate the basalt flows and are completed in the underlying crystalline rocks. Near Moscow, sandy interbeds can be a significant source of water.

The crystalline and metamorphic rocks underlying the basalt are generally less permeable than the basalt. They yield only small quantities of water for domestic use and for stock watering along the eastern margin of the study area. The source of water to these wells was not investigated for this study.

Geohydrologic Units

Three geohydrologic units were defined on the basis of the correlation of hydrologic properties with mappable geologic units. They are the Palouse Loess, the Wanapum Basalt, and the Grande Ronde Basalt. The loess ranges in thickness from 0 to 300 feet in the study area and unconformably overlies the Wanapum Basalt. The Wanapum Basalt is as much as 250 feet thick in the study area. The contact between the Wanapum Basalt and the Grande Ronde Basalt (where the Vantage Member of the Ellensburg Formation usually occurs) was determined from borehole-sample geochemistry and maps of surface exposures.

Structure contour maps of the top of the Wanapum Basalt and Grande Ronde Basalt are shown in figures 4 and 5, respectively. These maps incorporate information from available literature (see Previous Investigations section) and borehole geochemistry data (B.W. Drost, U.S. Geological Survey, written commun., 1986). The maps indicate that the regional dip of the basalts is to the northwest.

The Vantage Member is treated as part of the Grande Ronde Basalt for convenience of mapping, the same approach used for the Columbia Plateau Regional Aquifer-System Analysis (RASA) model (J.J. Vaccaro, U.S. Geological Survey, oral commun., 1986).

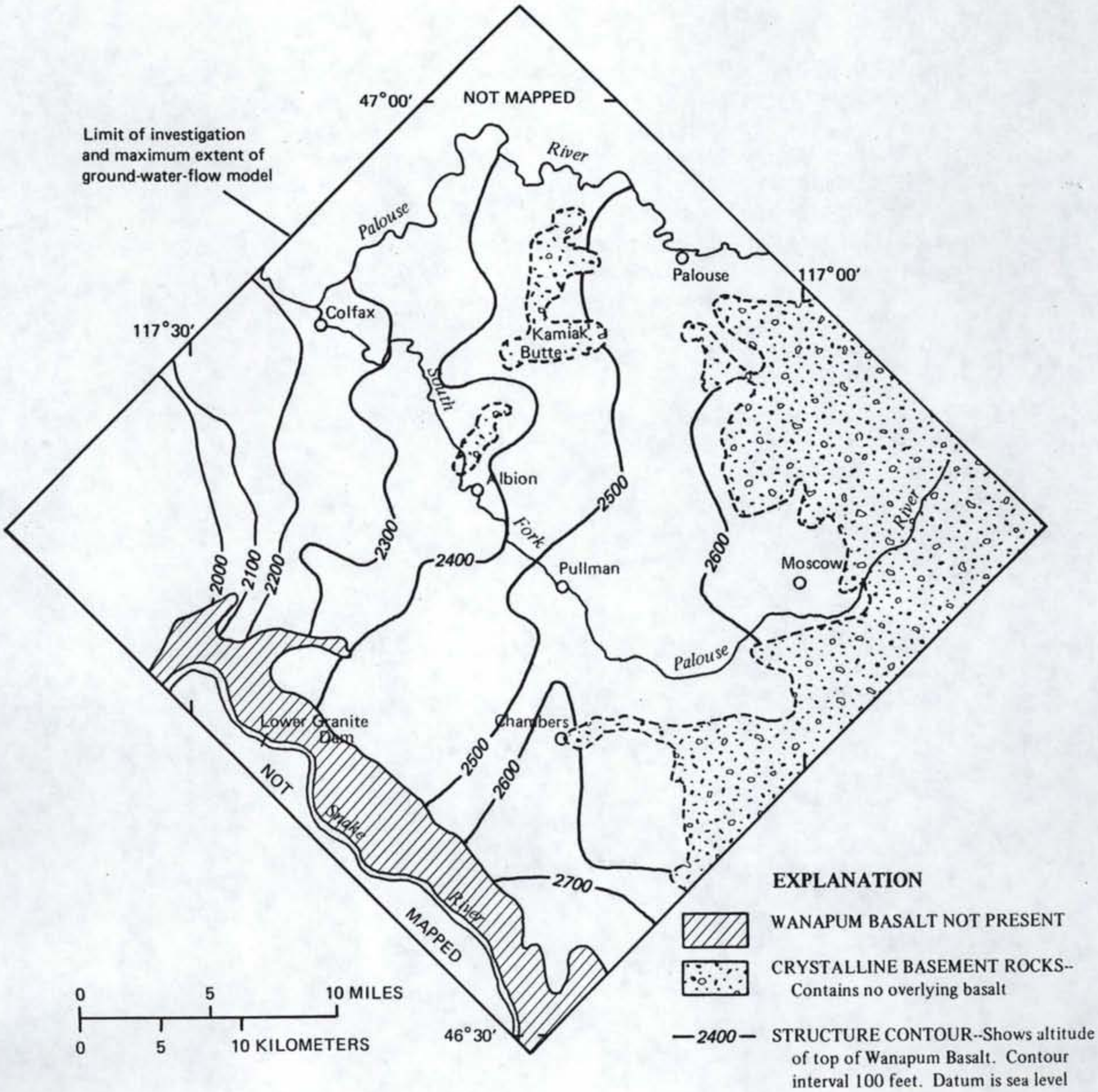


Figure 4.--Altitude of the top of the Wanapum Basalt.

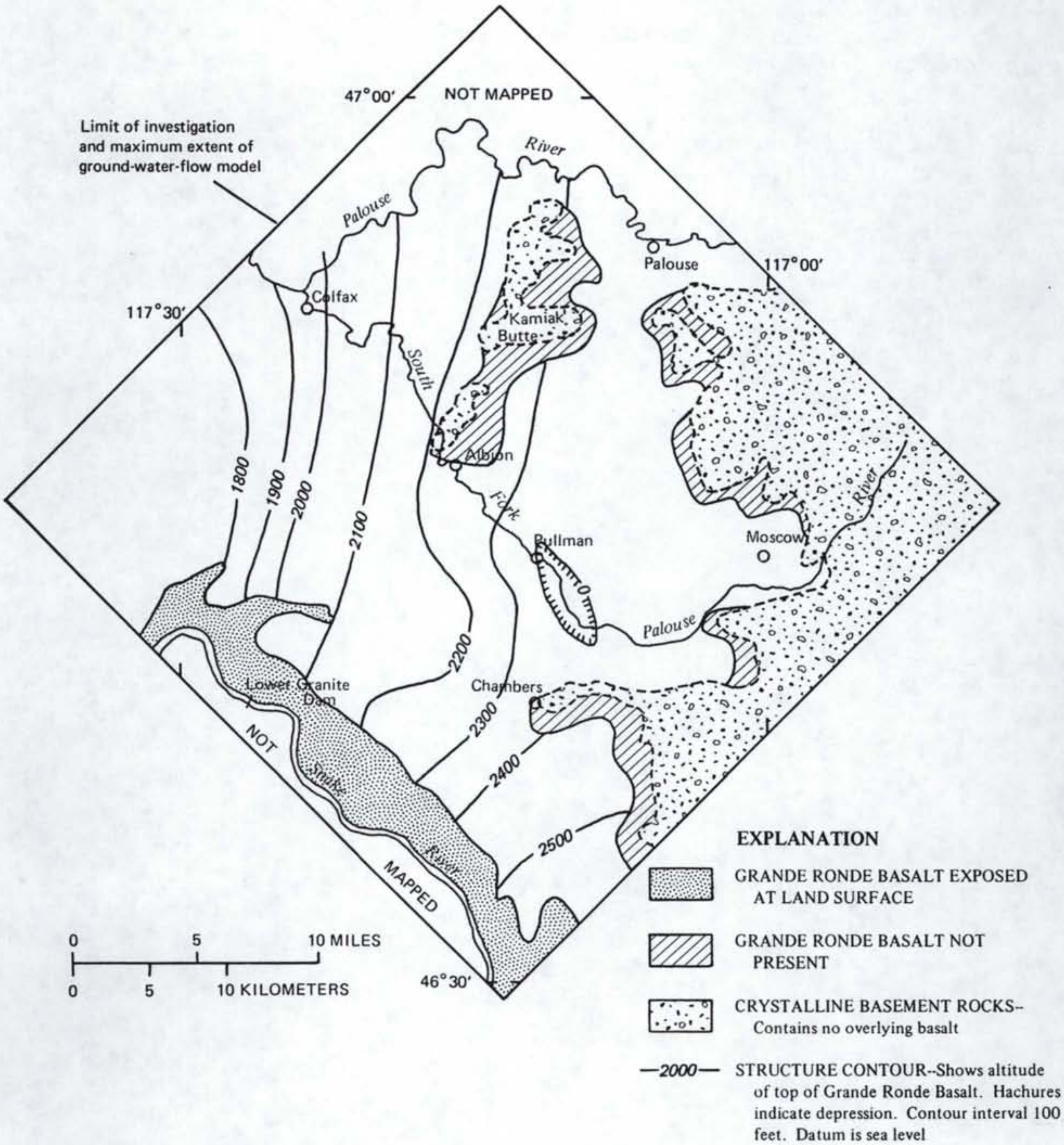


Figure 5.--Altitude of the top of the Grande Ronde Basalt.

A magnetotelluric geophysical investigation of the Pullman-Moscow area (Klein and others, 1987) was done in support of this study to help define the geohydrologic framework. This geophysical technique identifies the depth to the contact between the Grande Ronde Basalt and crystalline rocks. This contact defines the lower limit of the basalt in the Pullman-Moscow area. Twenty-four magnetotelluric soundings were obtained, distributed across the study area. A contour map of the thickness of the Wanapum and Grande Ronde Basalts plus interbedded deposits was developed from the soundings (fig. 6). The thickness of the basalt is about 1,300 feet near Moscow and 2,000 feet near Pullman, and greater than 2,000 feet between Moscow and Pullman. Thickness is greater in the western part of the study area, and is in excess of 3,500 feet west of Colfax.

A map of the altitude of the contact between basalt and crystalline rock (fig. 7) was derived by subtracting the thickness of basalt from the top of the Wanapum Basalt unit. The area in figure 7 where the top of the crystalline rocks is shown to be below sea level is not supported by any data other than magnetotelluric surveys, and may be a result of errors in interpretation or incorrect sounding spacing or location (D.P. Klein, U.S. Geological Survey, oral commun., 1987). The basalt may be thinner than what is shown in figure 7 (by an unknown amount) in that area.

The structure contour maps and the surface topographic map define the geometry of the three geohydrologic units that comprise the geohydrologic framework in the study area. The perspective view in figure 8 shows the relation between the layers. The Snake River canyon cuts through the upper two layers and much of the third.

Recharge

Most of the recharge to the ground-water system appears to be from infiltration of precipitation through the surficial loess. Water levels in the loess are responsive to seasonal fluctuations of precipitation; water levels indicate that recharge to the loess occurs during the late fall, winter, and spring, coincident with high precipitation and low evapotranspiration. High-intensity, short-duration precipitation events may produce recharge at other times of the year. Observations by Williams suggest that maximum recharge through the loess occurs in valleys between the rolling hills made of loess, where the relief is most gentle. Surface runoff and shallow subsurface lateral flow accumulate in these areas during spring snowmelt (R.E. Williams, University of Idaho, oral commun., 1985).

Deep percolation of water below the soil zone and rooting depth of crops (essentially recharge) has been calculated as part of the U.S. Geological Survey RASA program in a study of the Columbia River Plateau in Washington, Idaho, and Oregon. The recharge is calculated for river/stream drainage basins and uses daily records (usually over a 22-year period) of temperature, precipitation, streamflow, and crop and noncrop water-demand data. The resulting rate of recharge represents a long-term average (Bauer and Vaccaro, 1987). Using this methodology, the recharge for two basins in the study area, under both predevelopment conditions (before farming) and current farming practices, was calculated and is shown below:

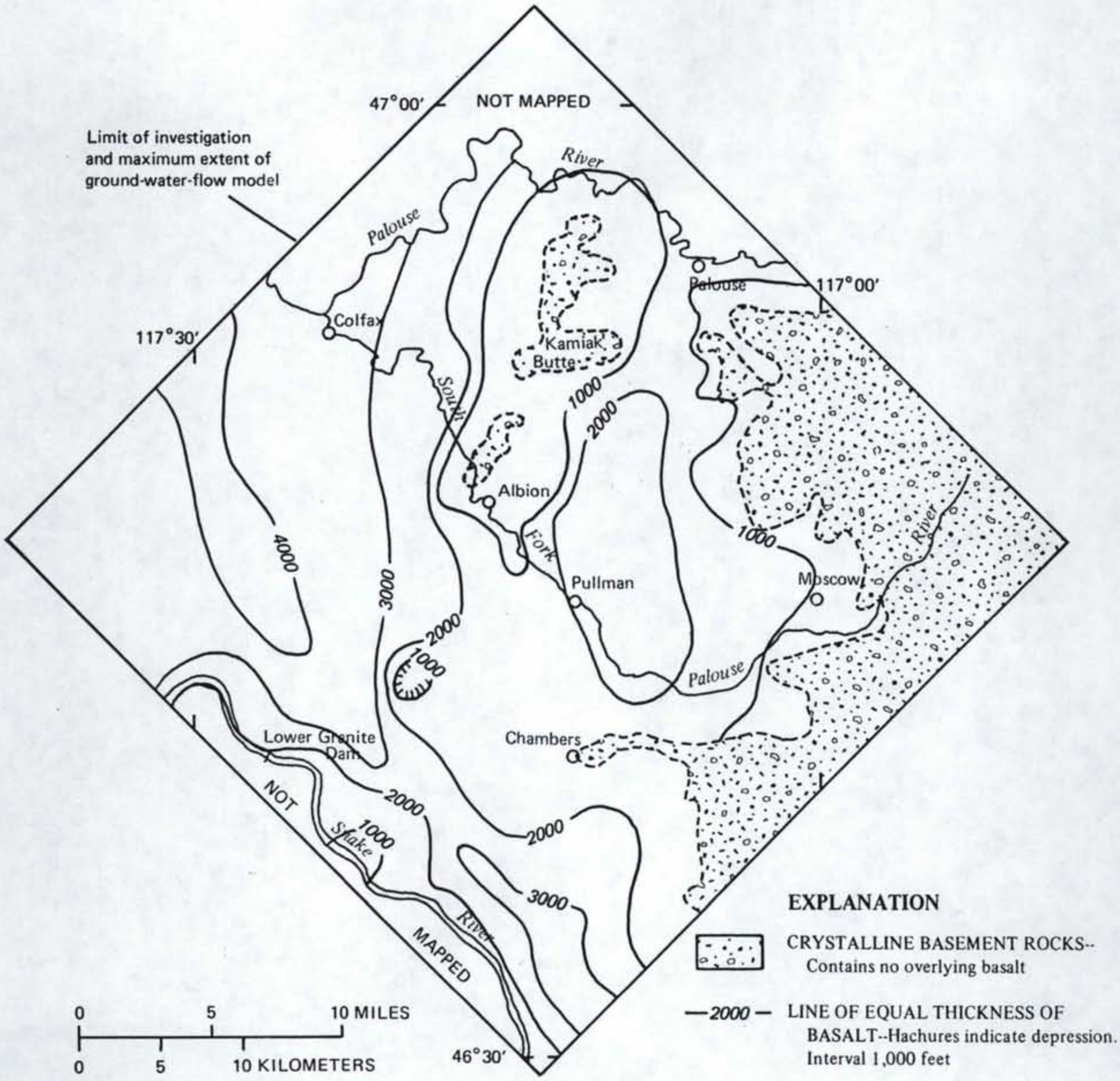


Figure 6.--Thickness of the basalt (modified from Klein and others, 1987).

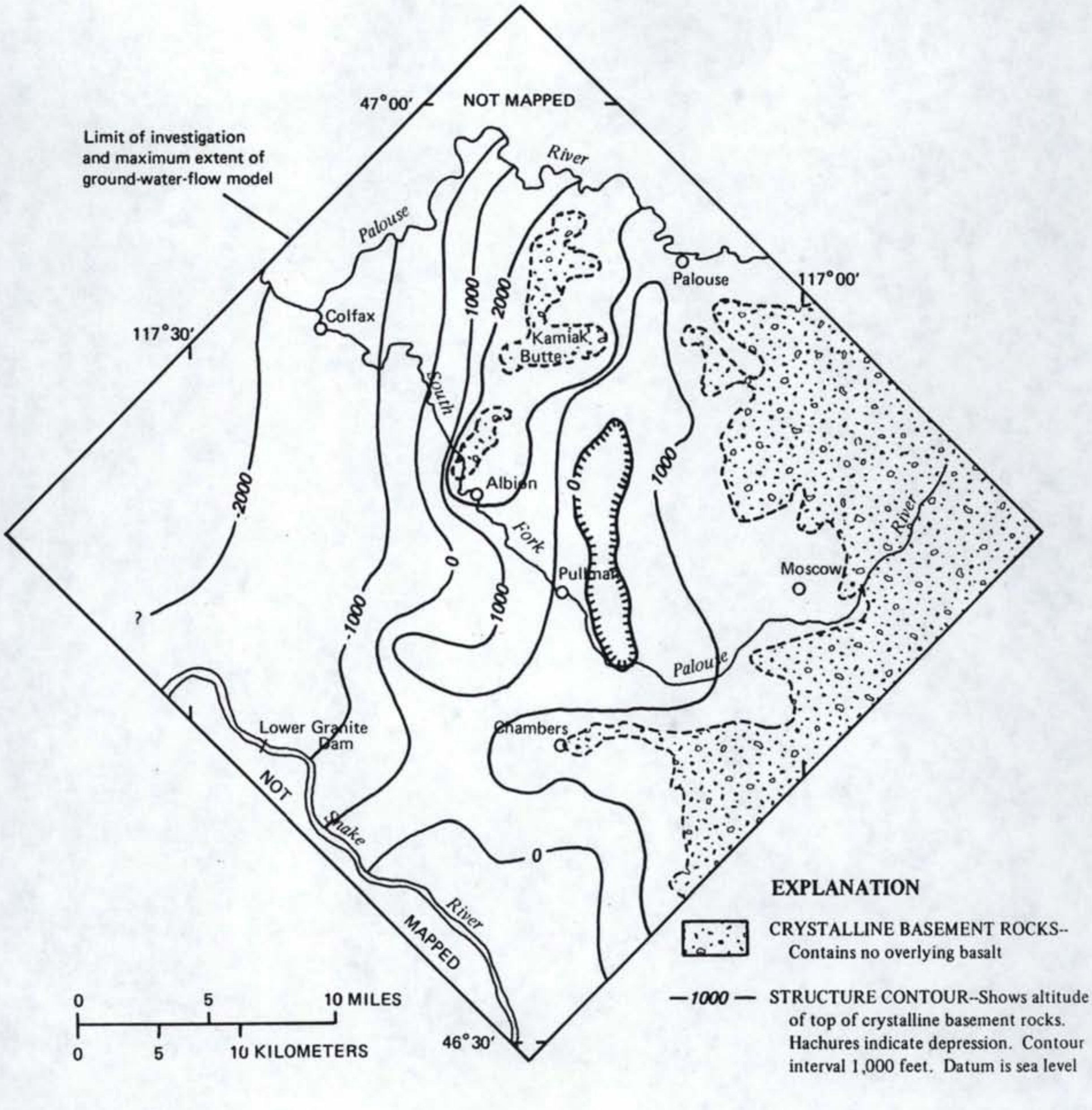


Figure 7.--Altitude of the top of the crystalline basement rocks.

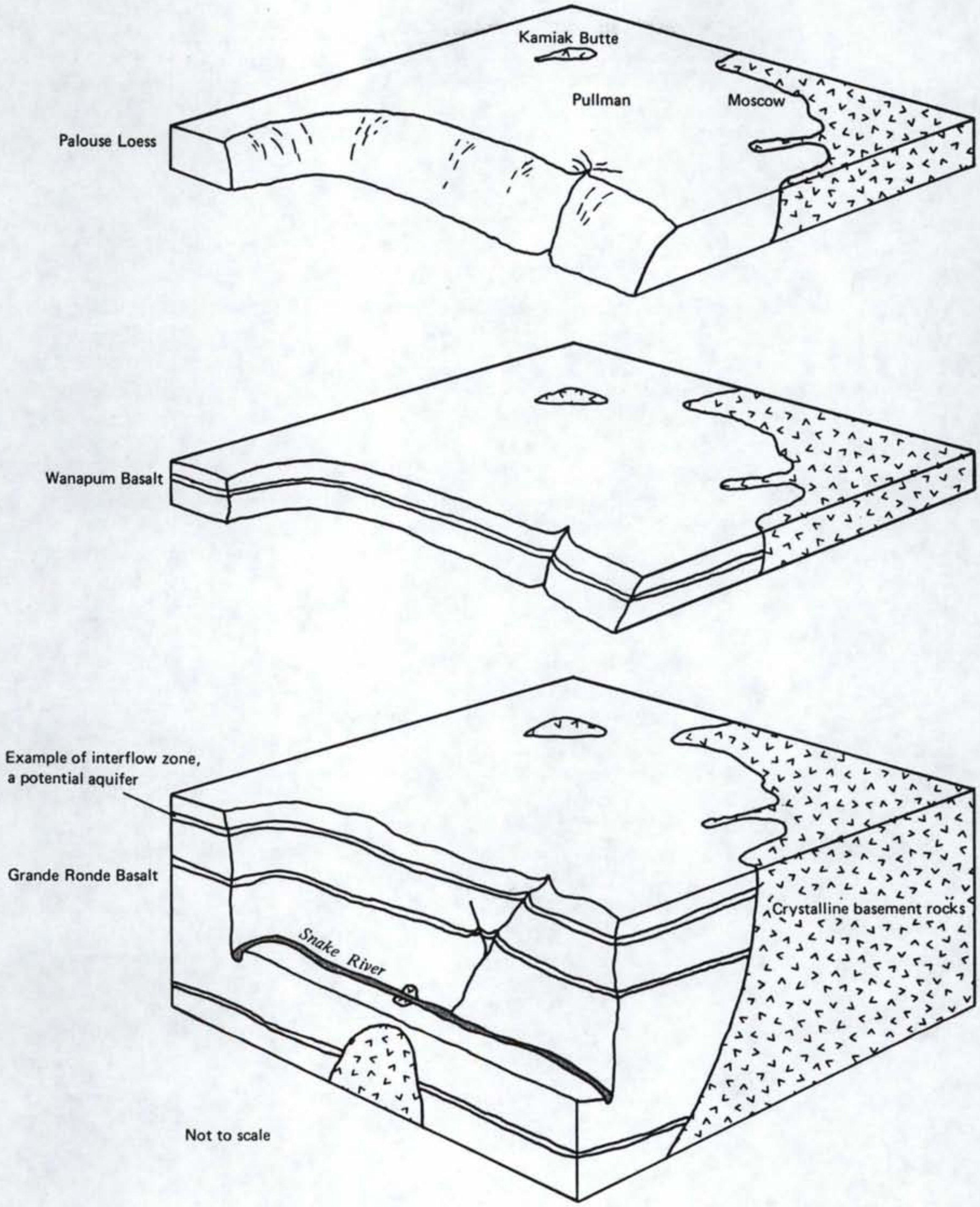


Figure 8.--Three-dimensional perspective of the layered aquifer system.

Basin	Recharge, in inches per year: Predevelopment land use	Recharge, in inches per year: Current farming practice
South Fork Palouse River	4.13	2.79
Union Flat Creek	2.98	3.65

The recharge rate in Union Flat Creek basin has increased under the current farming practice of alternating fallow and crop years. During the fallow year, soil moisture increases and more water gets below the root zone to become recharge (Bauer and Vaccaro, 1989). The practice of growing a crop every year, common in the South Fork Palouse River basin, has actually caused a 32-percent decrease in the average recharge rate. The relationships of increased recharge in areas where fields are fallow or crop in alternate years and decreased recharge where crops are grown every year are common in the areas of the Columbia Plateau where dryland farming is the dominant agricultural technique (Bauer and Vaccaro, 1989). As will be shown later, recharge from local rainfall is the source of most ground water under Pullman and Moscow. A net reduction in recharge in the area may have a significant impact on the ground-water system.

Ground-Water Movement

Recharge to the ground-water system in the Pullman-Moscow study area is principally by infiltration of precipitation. The water moves vertically and laterally in the loess and in the Wanapum and Grande Ronde Basalts; flow is generally from east to the west and northwest (Bauer and others, 1985; Whiteman, 1986). This observation is in agreement with the earliest recorded water-level measurements by Russell (1897), which indicate a gradient from Moscow to Pullman. Water levels currently are lower in the Grande Ronde Basalt than in the Wanapum Basalt and loess, indicating that downward flow of ground water also is occurring.

Fractures within the basalt flows and fine-grained sedimentary interbeds are important controls on the vertical movement of ground water. Sedimentary interbeds are more common in the eastern part of the study area. Near Moscow, which is near the eastern edge of basalt flows, interbeds make up as much as 50 percent of the thickness of water-bearing materials (Lin, 1967; and Jones and Ross, 1972). Thinner basalt flows may be present in those areas, and thus may have interiors that are more fractured and permit significant downward movement of water. To the west, thicker basalt flows have more massive centers that probably impede flow. Interbeds consisting of poorly permeable clay may slow the downward movement of water. The magnitude of such vertical leakage is dependent on the areal extent, thickness, and continuity of the clay layers. More vertical leakage may occur as the percentage of coarse-grained material in the interbeds increases.

The Snake River appears to be a ground-water-discharge area for the Moscow-Pullman area. Water levels in shallow wells in the Grande Ronde Basalt along the Snake River are similar to river surface altitude. Water levels in the deepest wells in the basin, near Moscow, are about 1,500 feet higher than the river. Ground water flowing toward the river may discharge as small streams, springs, and seeps along the canyon wall, or it can discharge directly into the river. The rate of discharge directly to the river is unknown. The surface area of the walls of the Snake River canyon is significantly larger than the area of the Snake River and the preferential flow paths between the basalt flows is horizontal; for these reasons, a significant part of the discharge from the basin may be through the sides of the canyon and may represent discharge from the regional ground-water-flow system.

The small seasonal fluctuations in water levels in deep wells in the study area indicate that the deep regional flow system probably is insensitive to the seasonal fluctuations in precipitation. The rate of discharge from the sides of the canyon is unknown, but probably is fairly constant. Ground water also discharges to the Palouse River along the northwest edge of the study area. The Palouse River is incised only into the upper part of the Grande Ronde Basalt. Being at a higher altitude than the Snake River, the Palouse River probably receives much less ground-water discharge than does the Snake River.

Ground water discharges to small streams from local flow systems in the loess and in the Wanapum Basalt. During the late summer and fall, discharge from the shallower ground-water systems probably is the sole source of streamflow. This ground-water component of flow is termed baseflow and is present throughout the year.

Ground-Water Pumpage

The Pullman-Moscow area has a history of pumpage increases (fig. 9). The cities of Moscow and Pullman are the pumpage centers of the basin, and the municipalities and universities maintain separate wells. In Moscow, older municipal wells and numerous domestic wells are finished in the Wanapum Basalt. As shown in figure 9, pumpage from the Wanapum Basalt has decreased substantially after about 1965. This was due to poor water quality and declining water levels. Currently, only about 3 percent of water pumped for municipal uses comes from the Wanapum Basalt. All other municipal and university wells in Pullman and Moscow obtain water from the Grande Ronde Basalt.

The rate of ground-water pumpage has increased in the study area from about 27,000 ft^3/d (about 200,000 gal/d) to about 260,000 ft^3/d (about 2,000,000 gal/d) during the period 1891-1945. The average annual rate of increase for that period is about 4½ percent. From 1946 to 1975, ground-water pumpage increased to about 820,000 ft^3/d (about 6,100,000 gal/d), an average annual increase of about 4 percent. From 1976 to 1985, the rate of increase in ground-water pumpage slowed significantly to about 1 percent per year. Total ground water pumped in 1985 was about 910,000 ft^3/d (about 6,800,000 gal/d).

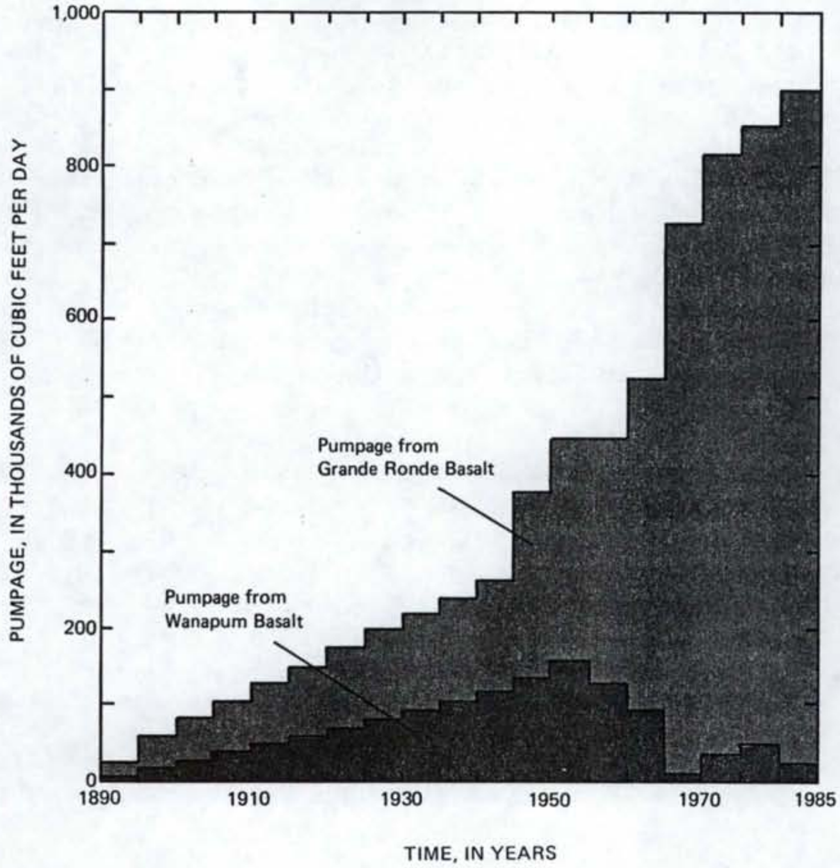


Figure 9.--Five-year average pumpage from wells operated by Pullman, Moscow, Washington State University, and the University of Idaho.

Historical Water-Level Changes

Prior to the drilling of wells, the ground-water system in the Pullman-Moscow area was in a state of dynamic equilibrium, with ground-water recharge equalling ground-water discharge. Discharge of ground water from pumping that started before 1900 produced an imbalance in the system. The initial response of the system was a reduction in the volume of water stored in the basalt. This is common; any development of ground-water resources causes a response, usually the drawdown of water levels. In many basins, a sustained decline in water levels causes a decrease in natural discharge and (or) an increase in natural recharge. Streams near Moscow and Pullman may be affected by the lowered ground-water levels; streamflow may be reduced. The adjustment to the pumpage can produce a new equilibrium if there is a reduction in natural discharge or an increase in the capture of recharge equal to the pumpage. Ground-water modeling, which will be discussed subsequently, will be used to indicate the extent to which a new equilibrium might be achieved in the Pullman-Moscow area.

Water-level declines caused by pumpage from the Grande Ronde Basalt Formation have been documented in Moscow and Pullman (Barker, 1979, and numerous other references; see Previous Investigations). Hydrographs reveal a history of water-level decline that is similar for the two communities (fig. 10). The rate of decline was about 1.5 feet annually for the period 1946-85. Water-level declines of as much as 20 feet in the Grande Ronde Basalt for the period 1974-85 occurred within a radius of several miles of Moscow and Pullman (fig. 11).

The history of ground-water-level changes is different for the overlying Wanapum Basalt. Pumpage from the Wanapum Basalt near Moscow caused water levels to decline in that unit from the 1890's into the 1960's; significant reductions in pumpage since about 1965 (see Ground-Water Pumpage, p. 19) reportedly allowed water levels to recover several tens of feet in the Wanapum Basalt (Gary Presol, City Engineer, Moscow, Idaho, written commun., 1985). The recovery of water levels during the period 1974-85 is shown in figure 12.

Water levels in the loess fluctuate in response to the annual precipitation cycle and are reported by well owners not to have changed significantly during 1974-85.

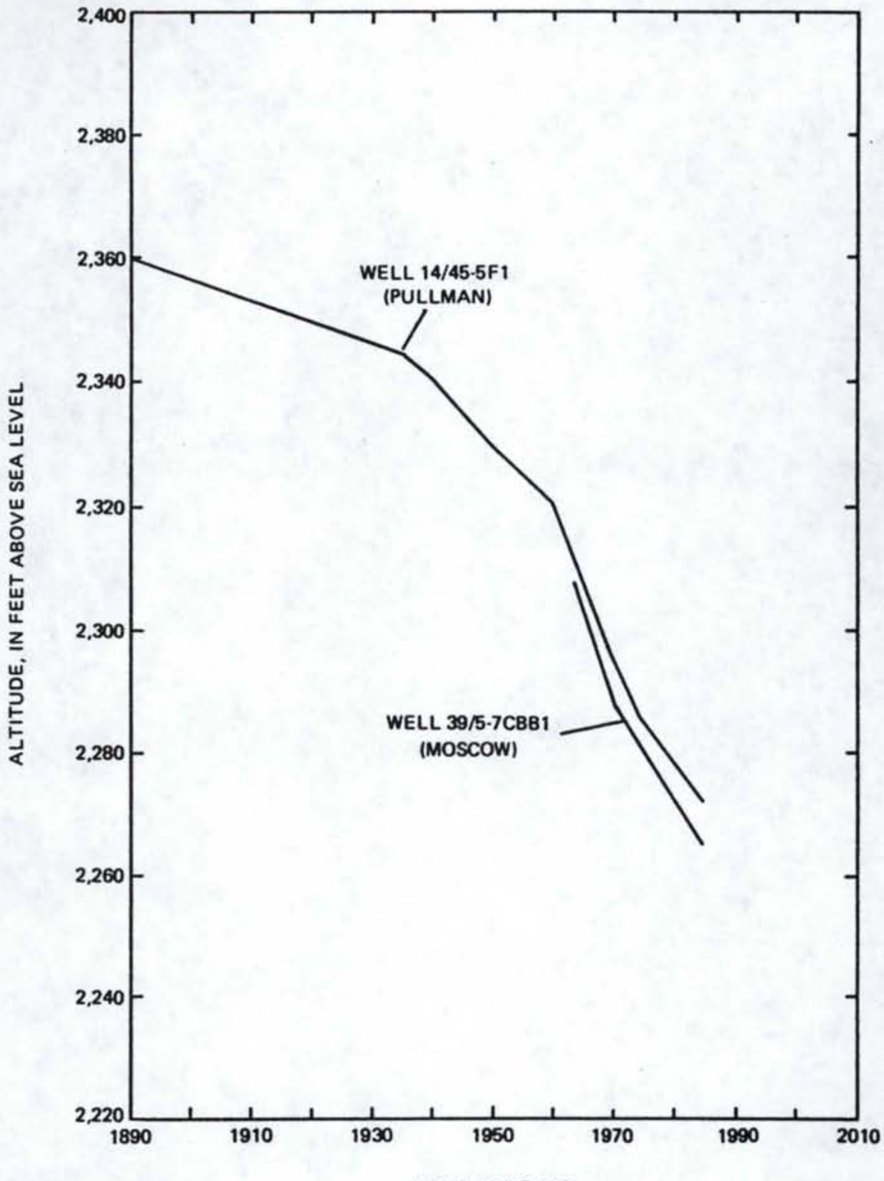


Figure 10.--Ground-water-level declines in wells in Pullman and Moscow, 1890-1985.

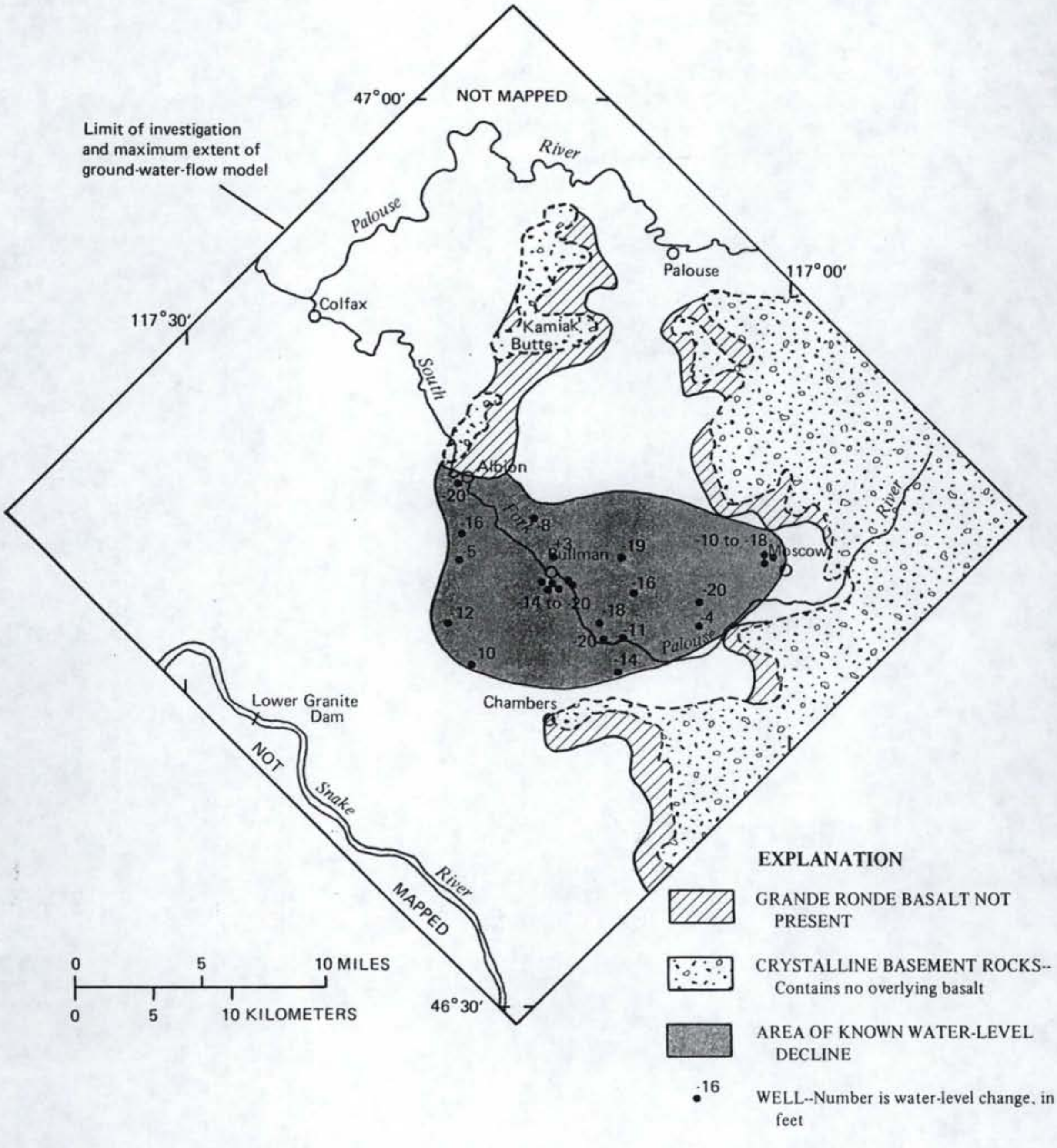


Figure 11.--Water-level changes in the Grande Ronde Basalt, 1974-1985.

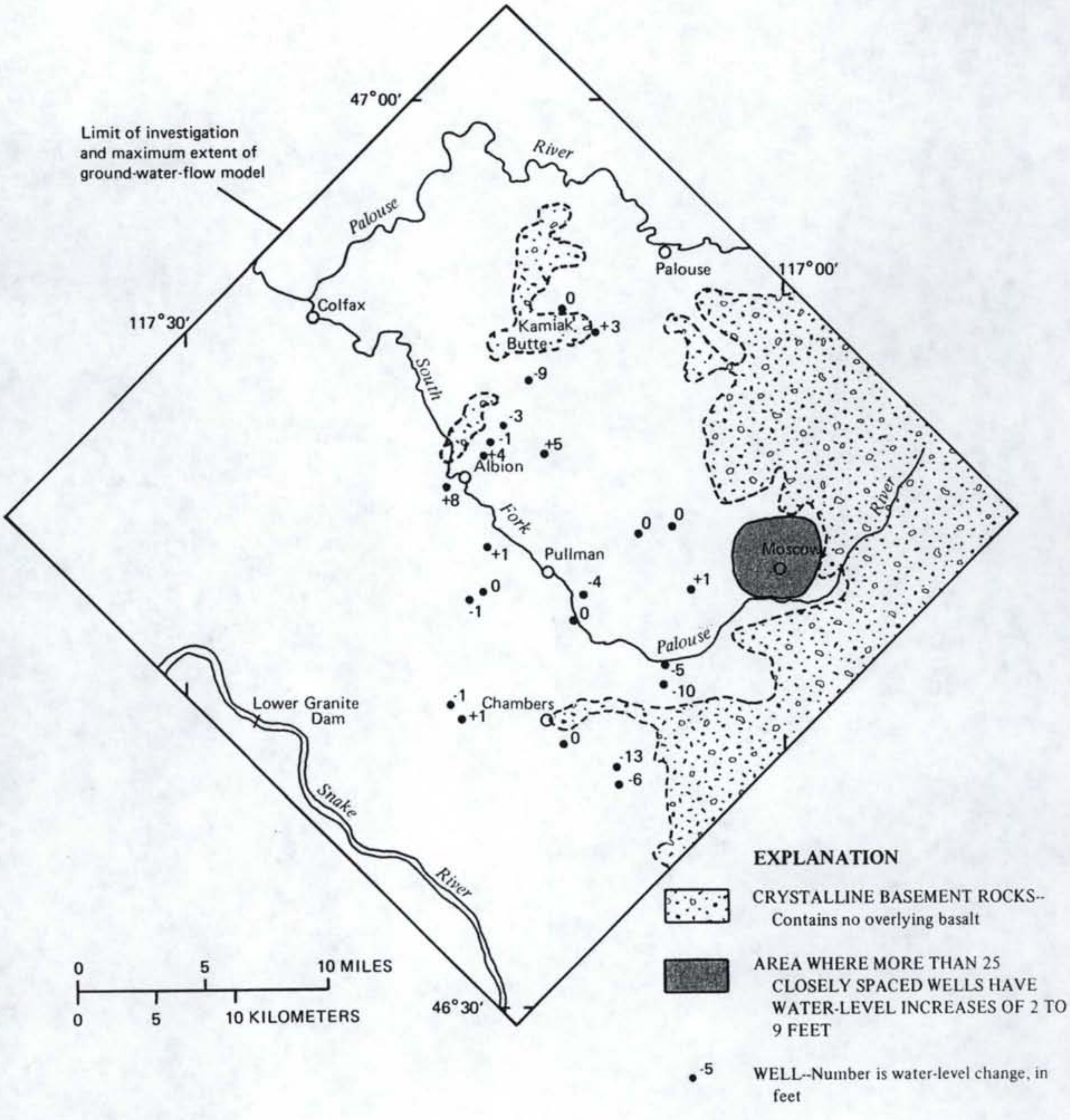


Figure 12.--Water-level changes in the Wanapum Basalt, 1974-1985.

NUMERICAL GROUND-WATER-FLOW MODEL

A numerical ground-water-flow model is a mathematical representation of the geohydrologic framework of the area investigated, the hydraulic properties of the materials present, and the hydraulic connection to the surrounding ground-water-flow system. Input to the model describes thickness and extent of zones or layers that compose the ground-water-flow system. Such layers commonly represent aquifers or geohydrologic units. Hydraulic properties of these layers are simulated by assigning values to model cells created by superimposing a grid on each layer. Hydraulic conditions must be described along the boundaries of the model. Model construction is completed when the data that describe the hydraulic properties and boundary conditions of each layer within the model have been collected, analyzed, compiled, and input to the numerical model.

For this study, one three-dimensional model and three two-dimensional cross-sectional models were constructed. The computer program used is that of McDonald and Harbaugh (1988). The cross-sectional models were used to evaluate various changes to the three-dimensional model of ground-water flow in the study area and as an aid to calibrate the three-dimensional model. The three-dimensional model was calibrated to simulate time-averaged conditions in the study area during 1974-85, and was evaluated by simulating historical water-level changes during 1890-1985. The calibrated model then was used to simulate water-level changes that would result from hypothetical pumping rates.

Three-Dimensional Model Construction

A three-dimensional numerical ground-water model was used to simulate the movement of ground water in the Palouse Loess, Wanapum Basalt, and Grande Ronde Basalt. Details of construction of the model are described below.

Discretization of Space

A regular grid mesh was used in this study to divide the study area into one-half-mile-square cells. This grid size adequately represents the distribution of values of hydraulic properties without creating too large a grid, or a grid with too many cells for available computer storage space. The grid is oriented northwest-southeast in order to make it coincide with several major streams and rivers that flow northwestward (fig. 13). These streams include the Snake River, Union Flat Creek, and the South Fork Palouse River.

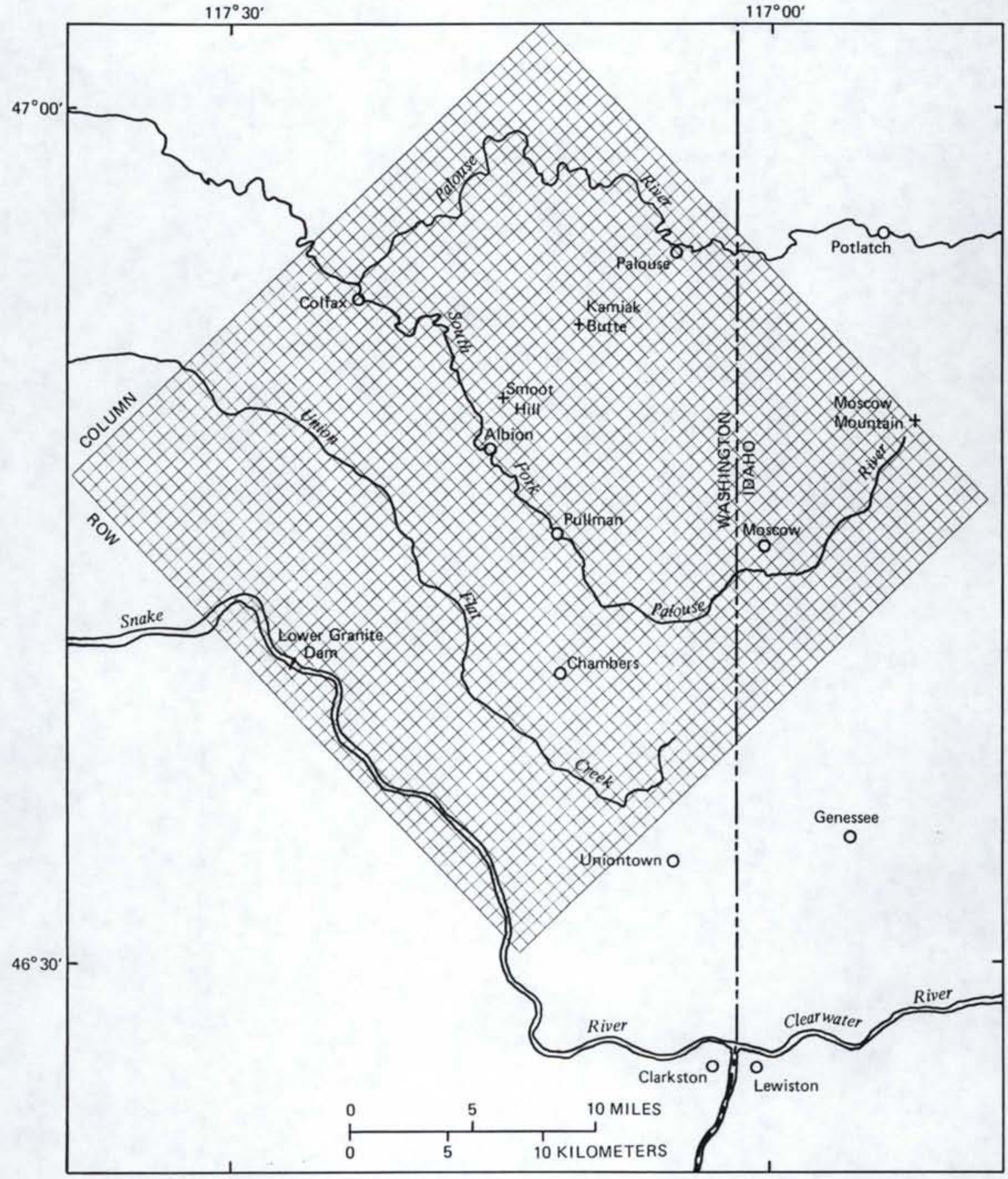


Figure 13.--Location and orientation of the modeled area.

Model Layers

The model includes three geohydrologic units that are represented in the model by layers. The top layer represents the Palouse Loess; the middle layer represents the Wanapum Basalt; and the bottom layer represents the Grande Ronde Basalt. For the purposes of this report the hydraulic characteristics of all interbeds are lumped with the basalt formation they are contained within. The Vantage Member of the Ellensburg Formation is considered part of the Grande Ronde Basalt. The rationale for the selection of these units is in the section titled "Geohydrologic Units." These units are shown in the idealized cross section of figure 14. The layers do not have the same areal extent. The loess laps onto the crystalline basement rocks, and both the loess and Wanapum Basalt are missing in parts of the Snake River canyon.

The loess and the Wanapum Basalt (each less than 300 feet thick) were assigned as individual model layers. The much thicker Grande Ronde (up to 3,000 feet thick) was also assigned to one model layer. It was not subdivided for two significant reasons. First, a mappable logical division (a 'marker' bed or single basalt flow) could not be found in the Grande Ronde Basalt; second, data indicate that in the Pullman and Moscow area the basalt probably acts as one hydrologic unit.

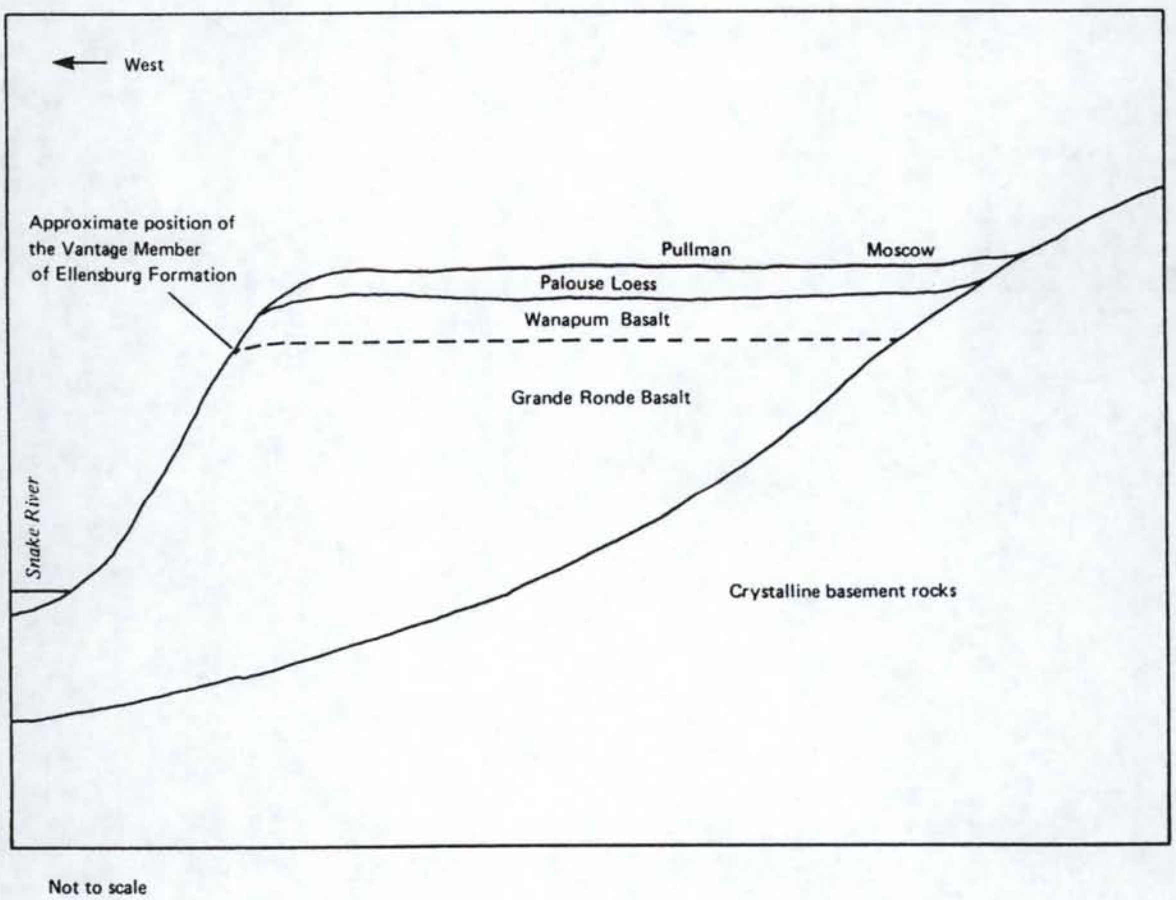


Figure 14.--Idealized geologic section through the Pullman-Moscow area showing the geohydrologic units.

Hydraulic Properties of Model Layers

Most infiltration of water in the Pullman-Moscow area is into the surficial loess soil. Hydraulic conductivities of loess can range from less than 0.01 foot per day (ft/d) to about 10 ft/d (Freeze and Cherry, 1979). McGary and Lambert (1962) note a slightly greater range. The loess may be approximated as homogeneous and isotropic, although field observations of the characteristics of earth slumps and mudflows in the loess that years of cultivation have compacted a zone beneath the plowed soil horizon. This zone of compacted material may have different hydraulic characteristics, but they are not known. Long-term infiltration rates of several inches per hour near Moscow (Williams and Allman, 1969) indicate that parts of the loess are highly permeable. Clayey layers that occur within the loess could limit the vertical hydraulic conductivity. On the basis of these limited data, the horizontal hydraulic conductivity of the loess was estimated to be 5 ft/d. The vertical hydraulic conductivity of the loess was estimated to be 0.05 ft/d by assuming an anisotropy ratio of 0.01.

Basalt flows comprise most of the geohydrologic framework in the Pullman-Moscow area. Table 2 lists values of hydraulic properties for basalts as compiled by Rockwell Hanford Operations, U.S. Geological Survey, and University of Idaho researchers. Horizontal hydraulic conductivity data compiled for the eastern edge of the Columbia Plateau near the study area suggest a hydraulic conductivity of 2 ft/d as an average for the entire thickness of basalt. This value was used in the initial data input to the model, and is near the median value of 1.7 ft/d identified by the RASA project for the Columbia Plateau (J.J. Vaccaro, U.S. Geological Survey, oral commun., 1986).

Table 2.--Hydraulic properties for the Columbia River Basalt Group

Source of data	Hydraulic conductivity, in feet per day		Storage coefficient
	Horizontal	Vertical	
Barker (1979)	0.09-26	--	0.005
Luzier and Skrivan (1973)	0.5-80	--	0.0015-0.006
MacNish and Barker (1976)	2.9	0.004	0.00047-0.00475
Strait and Spane (1982a)	2.6-10.9	--	--
Strait and Spane (1982b)	1.6-3.1	--	--
Tanaka and others (1974)	7.4	--	0.0025

Near the margins of the plateau where thinner, less massive basalt flows compose a greater percentage of the total thickness, the value of hydraulic conductivity probably exceeds the median value. There, flows composed of broken or vesicular basalt and interbedded materials are more common. Pumping-test data indicate that the horizontal hydraulic conductivity in the upper Grande Ronde Basalt near Pullman and Moscow is at least an order of magnitude greater than the average of 2 ft/d.

The effective (or bulk value) vertical hydraulic conductivity of the sequence of basalt flows is more difficult to define. In a layered system, the layer with the lowest vertical hydraulic conductivity controls ground-water flow. In the Pullman-Moscow area, these controlling layers probably are the centers of the basalt flows and the clay interbeds, for which there are no field measurements of vertical hydraulic conductivity. However, 0.001 ft/d (an anisotropy ratio of 0.0005) is assumed to be a reasonable estimate of vertical hydraulic conductivity for both lithologies (Freeze and Cherry, 1979), and this value was used as initial input to the model.

Boundary Conditions

The loess geohydrologic unit is modeled with no-flow boundaries on all horizontal sides (fig. 15a). Part of this boundary is formed by the topographic divide along the eastern and southern edges of the model area. It is assumed that little or no ground water leaves or enters the model at those areas. No-flow boundaries are also used where the loess is cut through by the Snake and Palouse Rivers. The bottom of the loess is hydraulically connected to the Wanapum or Grande Ronde Basalt layers, if present; if underlain by basement rocks, there is a no-flow boundary.

Two types of boundary conditions are used to represent the edges of the Wanapum and Grande Ronde geohydrologic units: no-flow boundaries and constant-head boundaries (fig. 15b and c). No-flow boundaries are imposed around the eastern half of the model where the basalt flows pinch out against the crystalline rocks. The location of these pinch outs has been studied extensively (Ross, 1965; Bockius, 1985). Although small quantities of ground water are present in these basement rocks, their relatively lower permeability justifies a no-flow boundary at the contact with the basalt. A no-flow boundary also underlies the basalt layers where they are in direct contact with the basement rocks. No-flow boundaries also are used along the west and southwest sides of the study area near the Snake River. A horizontal no-flow (streamline) boundary beneath the Snake River is assumed because ground-water flow is upward to the Snake River. This conclusion is based on the assumption that ground water flows towards the Snake River from either side.

Boundary conditions similar to those for the Snake River are assumed for the Palouse River. The smaller size of the Palouse River suggests that it may not be a regional discharge area and that there may be underflow of ground water. Despite this uncertainty, however, the boundary is designated as no-flow (streamline) because it was thought to be sufficiently distant from the pumping centers of Moscow and Pullman that the effects of drawdown would be insignificant. The use of the no-flow boundary along the Palouse River may cause greater simulated water-level declines resulting from pumpage in the model because underflow along the Palouse River does not exist as a potential source of water to wells in the model.

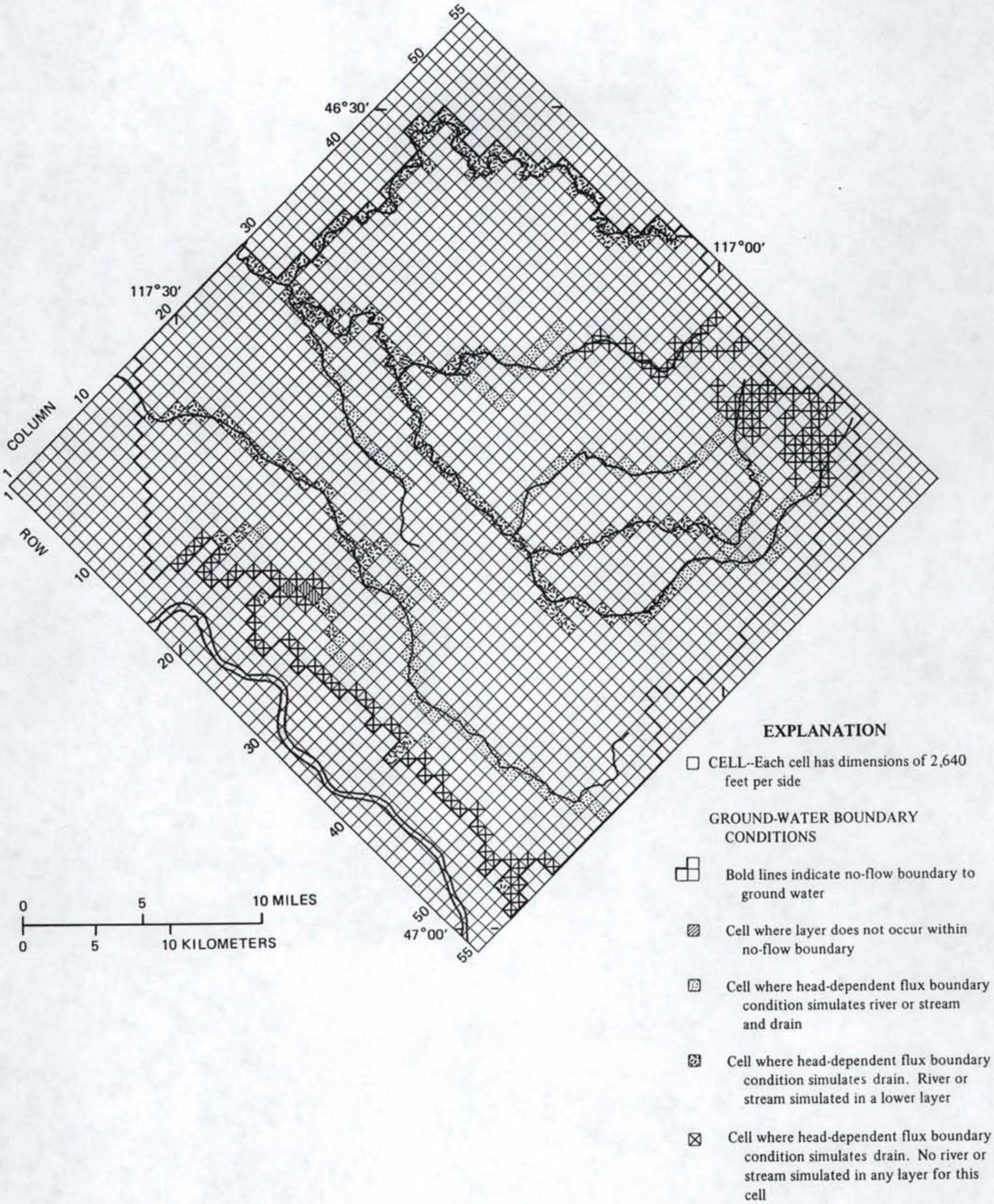


Figure 15a.--Grid used to subdivide the study area for the ground-water model and boundary conditions for the loess geohydrologic unit.

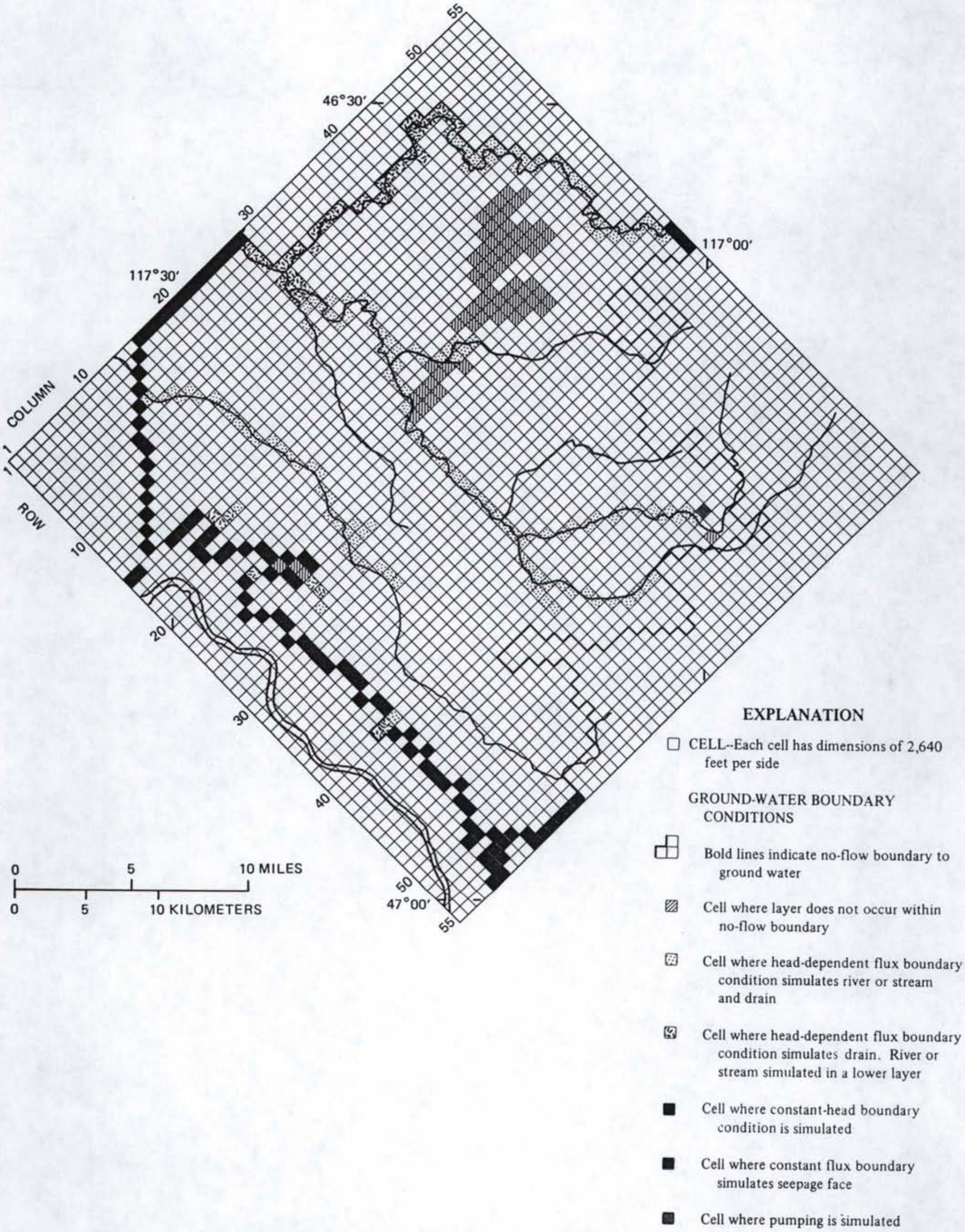


Figure 15b.--Grid used to subdivide the study area for the ground-water model and boundary conditions for the Wanapum geohydrologic unit.

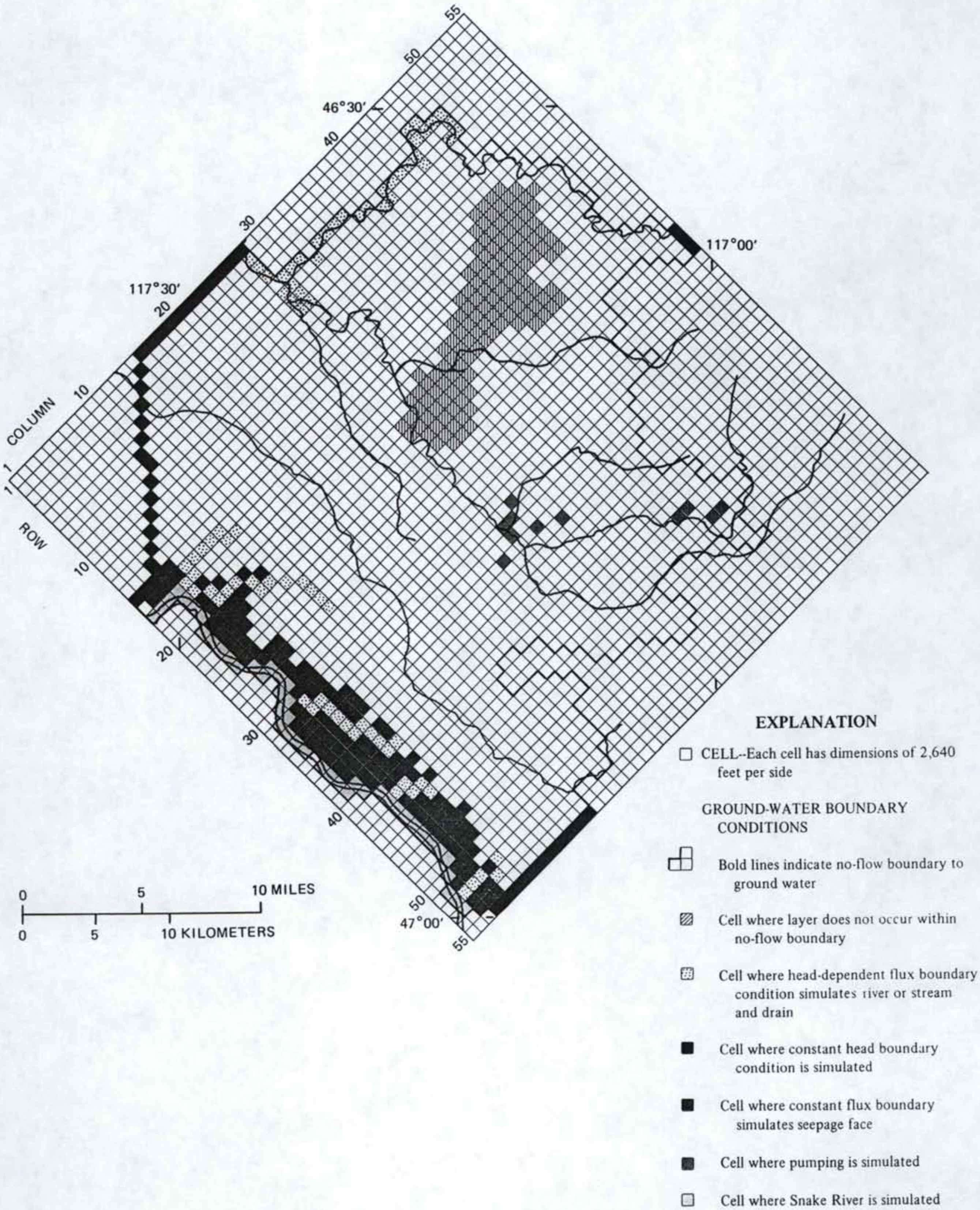


Figure 15c.--Grid used to subdivide the study area for the ground-water model and boundary conditions for the Grande Ronde geohydrologic unit.

The remaining segments of the model boundary for the Wanapum and Grande Ronde layers are designated as constant head (fig. 15b and c). A constant-head boundary creates a ground-water gradient into or out of the modeled area, depending on the hydraulic heads near the boundary. The model uses this gradient to calculate a flux into or out of the appropriate geohydrologic unit at the location of the boundary. The northwestern edge of the model and segments along the northeast and southeast sides of the model are designated constant-head boundaries. Sufficient water-level data exist to define adequately the head distribution along the constant-head boundaries. These boundaries are also distant from the pumping centers; consequently, the same rationale that is used for the no-flow boundary along the Palouse River applies to these areas. Regional water-level information indicates that ground water flows into the model area on the northeast and southeast and out of the model area to the northwest. The modeled area extends far enough that effects of pumpage in the Pullman and Moscow areas should have little influence on conditions at the edges (lateral boundaries).

Recharge to the Model

Recharge to the ground-water-flow model as a result of precipitation is applied to the uppermost active model layer. This most commonly is the loess layer, but can be the Wanapum or Grande Ronde layers if they are at the surface. Recharge was calculated for two basins, South Fork Palouse River and Union Flat Creek, using the deep percolation model by Bauer and Vaccaro (previously discussed, p. 14), for both current land-use and farming practices and predevelopment (before farming) conditions. In these two basins, these calculated values of recharge were used in the ground-water-model. In areas outside these two basins, a regression equation (Bauer and Vaccaro, 1989) was used to allocate recharge as a function of long-term average annual precipitation and current farming practices. In areas where farming is not occurring, recharge was set to predevelopment rates.

Recharge is input to the ground-water-flow model for each cell to incorporate the areal variations in recharge. Figure 16a shows the distribution of average annual recharge over the study area under predevelopment conditions; recharge under current land-use and farming practices is shown in figure 16b. Lowest values of recharge occur in the Snake River canyon. Recharge generally increases toward the interior of the area and is greatest in the east where precipitation is also greatest, due to orographic effects in the mountains.

For predevelopment conditions (fig. 16a) the average annual recharge applied over the area of the three-dimensional model was about 150 ft^3/s and for current conditions and farming practices (fig. 16b) about 136 ft^3/s. There has been a net decrease in recharge to the ground-water system in the study area of about 10 percent and the areal distribution has been changed. This apparently is due, at least in part, to the practice of growing a crop every year in parts of the study area (Bauer and Vaccaro, 1989). Crops use more water than did the natural vegetation, resulting in a decrease in the amount of water that gets below the root zone and becomes recharge. In the South Fork Palouse River basin, where both Pullman and Moscow are located and where crops are grown every year, there has been a reduction in recharge of about 13 ft^3/s, or 32 percent, from predevelopment recharge. By comparison, average pumpage during 1981-85 for the same area was about 10 ft^3/s (6,700,000 gal/d). The reduction in recharge exceeds the amount of pumpage from the same area.

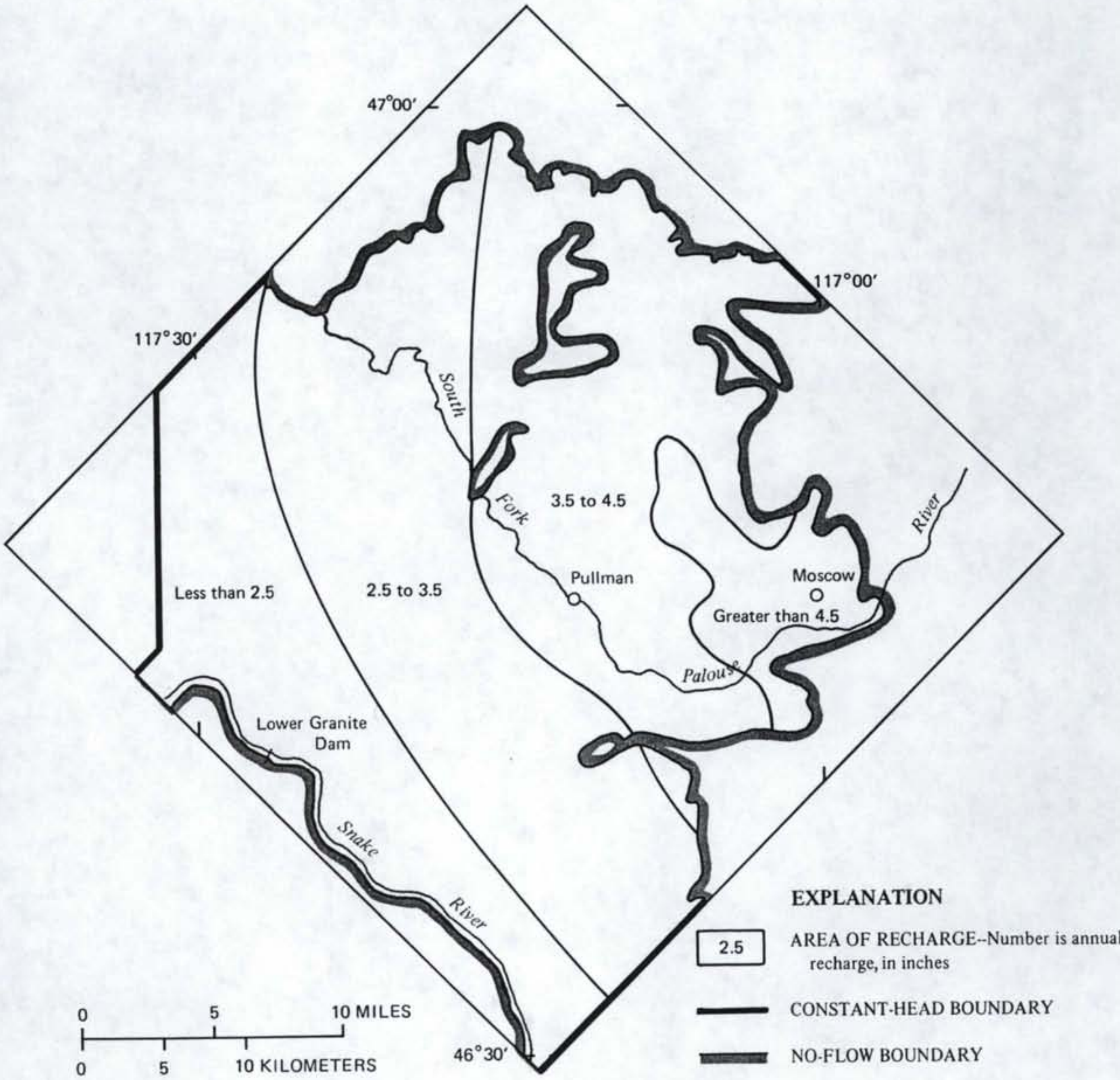


Figure 16a.--Areal distribution of recharge to the three-dimensional ground-water-flow model based on predevelopment conditions

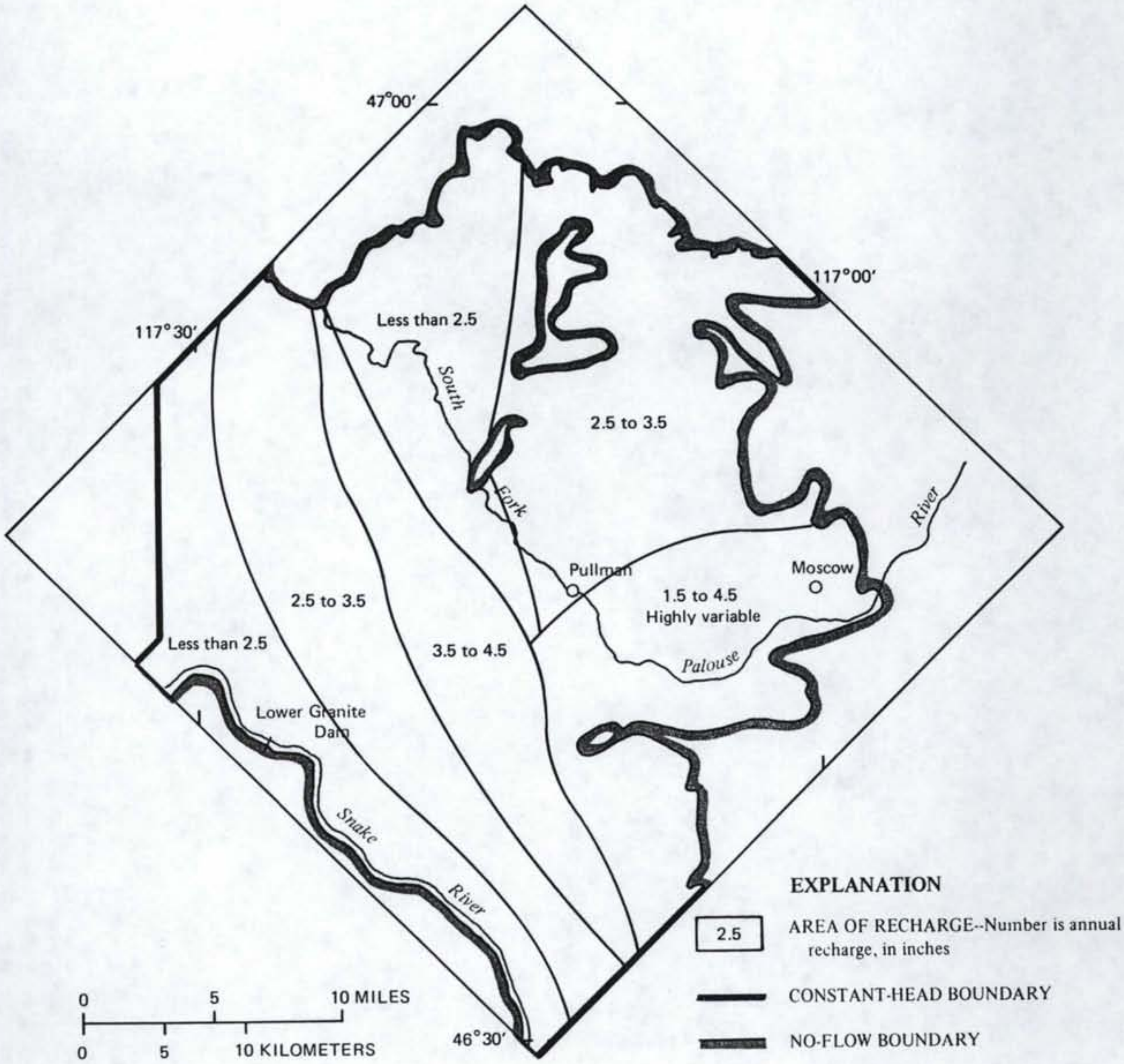


Figure 16b.--Areal distribution of recharge to the three-dimensional ground-water-flow model based on current land use and farming practices.

Hydraulic Connection of Ground Water With Rivers

Rivers may either contribute water to the modeled area or drain water from it, depending on the simulated head gradient between the river and the model layer. River reaches are simulated on a cell-by-cell basis (see figures 15a, b, and c). Input data to the model include the layer, row, and column in the grid through which the stream flows, the stream-stage altitude, a conductance value, and a river-bottom altitude (McDonald and Harbaugh, 1988). Conductance is proportional to the hydraulic conductivity and thickness of the material underlying the river.

River conductance for this model is based on vertical hydraulic conductivity of the loess or basalt, because most of the hydraulic connection between the model layer and the rivers is assumed to be in the vertical direction. McDonald and Harbaugh (1988) describe a riverbed lined with a lower-permeability material. That material can be any thickness and is assumed to be the limiting factor in water movement in and out of the river. In the Pullman-Moscow area, the lowest permeability material that the water moving to or from a river must flow through is probably the interior of a basalt flow or a clayey interbed deposit.

Drains

Ground water flowing horizontally in an aquifer may discharge as a spring (a point of ground-water discharge) or seep (discharge over a wider area) where the aquifer is truncated by a valley. Drains were used to simulate discharge from the ground-water system in those places. For example, if the altitude of the drain in a valley is below the simulated water table altitude in a model cell, then discharge from the ground water is simulated to occur.

Drains are placed in all cells where the aquifers are incised and the physical conditions exist for discharge to occur. Typically, intermittant stream reaches were simulated by a drain and perennial reaches were simulated by a drain and river in each cell. Input data to the model include layer, row, and column in the model grid system, the drain altitude, and a conductance value (McDonald and Harbaugh, 1988). Drain conductance for this model is based on the horizontal hydraulic conductivity of the layer where the drain occurs.

Seepage Faces

Seepage faces commonly occur along streams and rivers where the water table is near the surface. Water is available to be evapotranspired by vegetation or it may seep into streams or rivers. Some seepage faces can be simulated with drains (described above).

Field investigations revealed areas along the canyon wall of the Snake River where plant cover is dense and where the soil and rock material is saturated just below the surface. Other parts of the canyon wall appear dry and have substantially less plant cover. The canyon wall of the Snake River represents a major seepage face in the modeled area. This seepage face may extend from river level (about 740 feet above sea level) to near the top of the canyon, some 1,700 feet higher. For modeling purposes, the canyon wall is assumed to act as a seepage face. Minor seepage faces occur along the Palouse River, the South Fork Palouse River, and Union Flat Creek.

Drains initially were used to simulate the seepage face along the Snake River canyon in the three-dimensional model. The drains produce a gradient-dependent flux based on the head in the adjacent geohydrologic unit and the head assigned to the drain. However, the great thickness of Grande Ronde geohydrologic unit did not allow gradient-dependent fluxes to be represented adequately, because in some cases the model-calculated head for those cells was below the bottom of the canyon and the drains were inoperative. Consequently, the drains were replaced in the three-dimensional model by a constant flux boundary for each cell corresponding to the seepage face. The method of determining the flux rate is discussed in the section Time-Averaged Three-Dimensional Model Calibration (p. 44).

Cross-Sectional Model Construction

The cross-sectional models used in this study are two-dimensional slices constructed through the three-dimensional flow system. They were used during the initial phase of modeling to gain understanding of the three-dimensional movement of water, and to help calibrate the three-dimensional model. Multiple model layers were introduced easily into the Grande Ronde Basalt in the cross-sectional models to investigate the distribution of hydraulic head within this thick geohydrologic unit. Simulating many layers facilitated comparisons between measured water levels in wells open only to the upper part of the Grande Ronde Basalt and water levels calculated by the three-dimensional model that represent the average for the entire thickness of the Grande Ronde Basalt.

The cross-sectional models were located along flow lines drawn perpendicular to contours of regional hydraulic-head distribution (not shown). The regional hydraulic-head distribution was obtained from Whiteman (1986) for the Grande Ronde Basalt. The location of the section lines is shown in figure 17. The flow lines chosen for the Grande Ronde Basalt do not fit the hydraulic-head distribution in the overlying Wanapum Basalt. Ground-water flow in the Wanapum Basalt generally represents a local flow system and that in the Grande Ronde Basalt represents a regional flow system (see Freeze and Cherry, 1979); therefore, flow lines in the two basalt geohydrologic units may be different. This may compromise the results of the cross-sectional models.

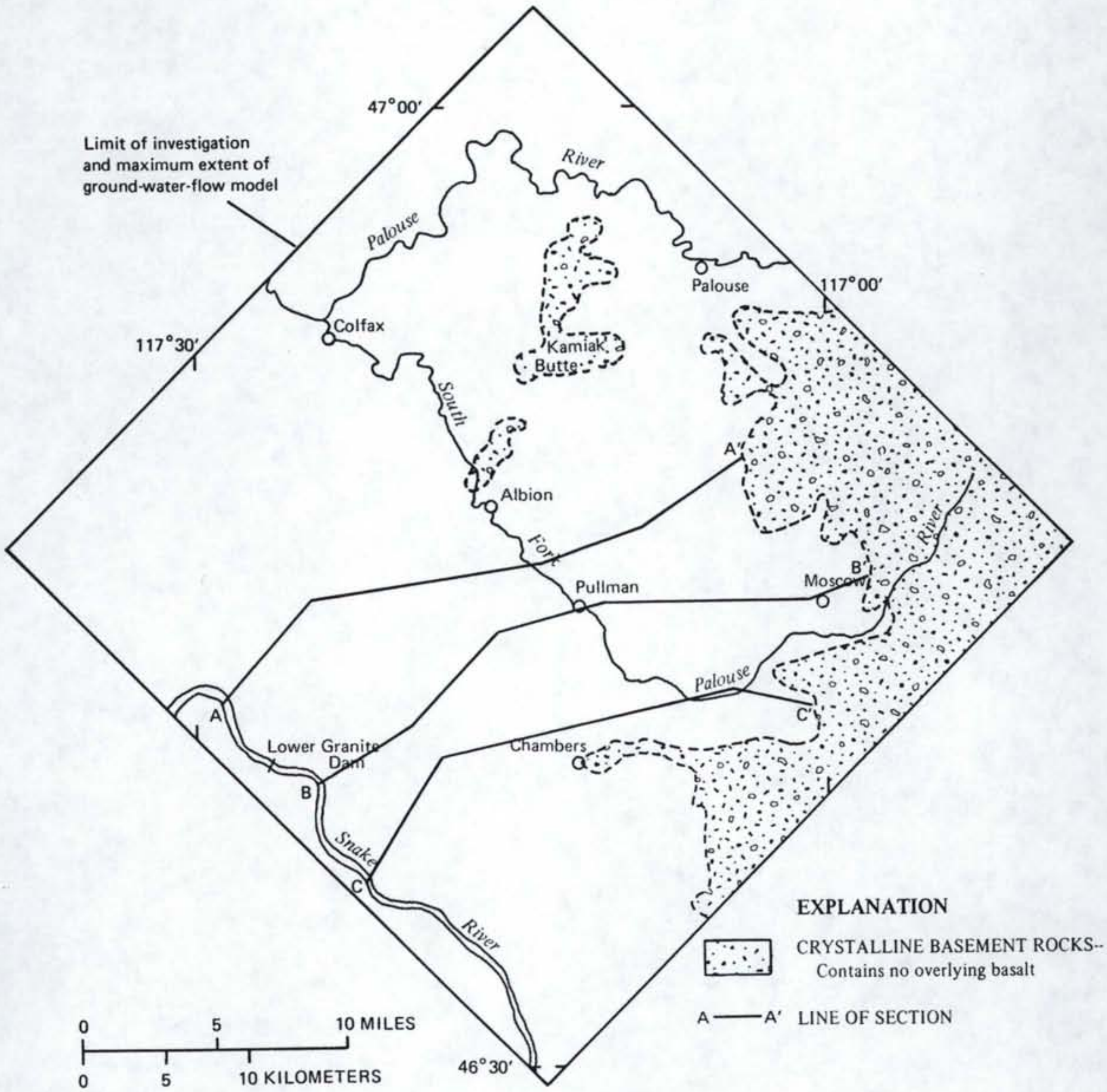


Figure 17.--Location of cross-sectional models in the domain of the three-dimensional model.

An example of the cross-sectional model is shown in figure 18 using cross-section B-B'. Boundaries of the cross-sectional models are similar to those of the three-dimensional model. A recharge flux (predevelopment rate, figure 16a, calculated using Bauer and Vaccaro, 1987) is applied to the uppermost active layer. The east and west edges are no-flow boundaries (fig. 18) where the geohydrologic units pinch out onto the basement rocks or where vertical flow probably occurs upward to the Snake River, respectively. The great thickness of the Grande Ronde unit was modeled as a series of 200-foot-thick layers, each with a drain at the canyon, to facilitate simulation of the vertical hydraulic-head distribution in the formation, and to obtain a more accurate representation of the seepage faces in the Snake River canyon. The 200-foot division was chosen arbitrarily (basalt flows may be thinner); it does not represent the actual layering in the Grande Ronde. The exact number of layers used in the Grande Ronde Basalt depends on the depth to basement along each section, but the average number for the three cross-sectional models is 18 layers. The layering allows drains to simulate the seepage face along the canyon. The flux from these drains forms the basis for the well flux that simulates the seepage face in the three-dimensional model (see Cross-Sectional Model Calibration, p. 40). The loess and Wanapum Basalt each were simulated as single layers as in the three-dimensional model.

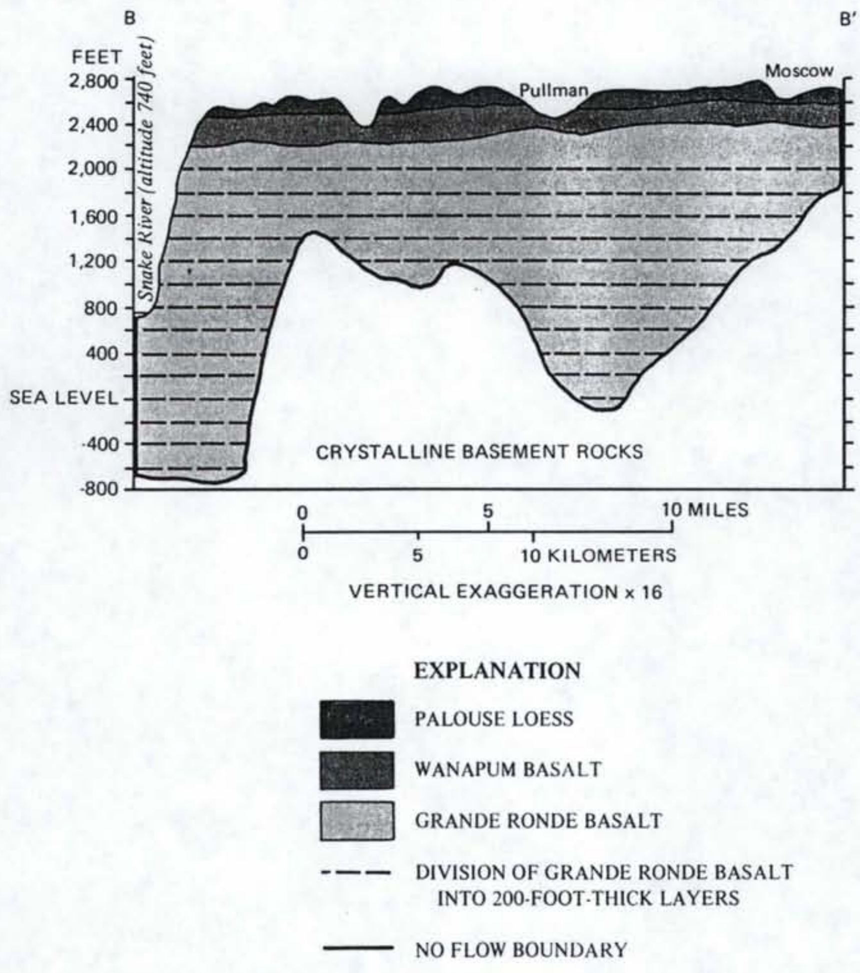


Figure 18.--Diagrammatic sketch of cross-sectional model B-B', showing layering.

Calibration of Models

The purpose of the calibration phase of modeling is to achieve the closest possible agreement between the numerical model and the physical world that it represents. Konikow (1978) notes that "...in practice, the calibration of a deterministic ground-water-flow model is frequently accomplished through a trial-and-error adjustment of the model's input data (aquifer properties, sources and sinks, and boundary and initial conditions) to modify the model's output". Wang and Anderson (1982) augment this definition by indicating that a model is considered calibrated when output hydraulic heads are in agreement with those heads measured in the field.

The calibration process may be accompanied by a verification process. Verification is not well defined in the geohydrologic literature. According to Wang and Anderson (1982), verification is achieved by demonstrating that the model is capable of reproducing a historical hydrologic event for which field data are available. Konikow (1978) notes that the verification data should be distinct in time from the calibration data. Wang and Williams (1984) indicate that the goal of verification is to determine that the model has not been uniquely tuned to the calibration data set.

For this study, three cross-sectional models were calibrated independently to reproduce steady-state predevelopment conditions, and the three-dimensional model was calibrated to reproduce time-averaged conditions during 1974-85. The three-dimensional model then was used to simulate historical drawdown in the area due to pumping during 1890-1985. This last step was intended to be a verification of the model, but much back-tracking, iterating from the cross-sectional to three-dimensional time-averaged to three-dimensional historical drawdown models, occurred. The calibrated models are a product of all the available data sets, so the model does not strictly fit the calibrated and verified criteria discussed above. Konikow (1978) states that "...a model that has been calibrated only to reproduce historical data should not be considered a verified model. Nevertheless, a calibrated model can be used to analyze or predict future aquifer responses. The accuracy of its predictions is the best measure of a model's reliability."

The cross-sectional and three-dimensional models initially were constructed using the best estimates for all input data. Then, each cross sectional model was calibrated. Hydraulic coefficients were reevaluated, changed as appropriate, and then checked by rerunning the cross-sectional models. The areal distribution of hydraulic coefficients was mapped from results of the cross-sectional models and used as input data to the three-dimensional model. The three-dimensional model first was calibrated to match average conditions during 1974-85, a time-average steady-state simulation (Prych, 1983). If a change in hydraulic coefficients was required in the three-dimensional model, the change also was made in the appropriate cross-sectional model and checked to be sure the change did not alter significantly the calibration of that model. Iterating through this process is time-consuming, but is designed to keep all hydraulic coefficients in a range of reasonable values. The least-known values of hydraulic coefficients were those most likely to be changed. The least known and better known input data are listed below.

Least known input data:

1) Vertical hydraulic conductivity
2) Horizontal hydraulic conductivity
3) River and drain conductance values
4) Storage coefficient

Better known input data:

1) Thickness and extent of the Grande Ronde Basalt
2) Thickness and extent of the Wanapum Basalt
3) Recharge rate
4) Boundary conditions

When the cross-sectional models were calibrated, the range of uncertainty in the 'least known' input data was large, and the data were adjusted through all possible values considered reasonable on the basis of a literature search. Data from the calibrated cross-sectional models were used as input to the three-dimensional model also, but during calibration of the three-dimensional model, the adjustments were smaller. Horizontal hydraulic conductivity was changed only within a factor of 2 in the three-dimensional model from that determined in the cross-sectional models. Vertical hydraulic conductivity values (the least well-known hydraulic characteristic) were changed only within a factor of 10 from that of the cross-sectional models. When the three-dimensional model was run to simulate water-level change caused by historic changes in pumping (1890-1985), only the storage coefficient was changed, by as much as a factor of 10, to improve the fit of calculated to observed water levels.

Cross-Sectional Model Calibration

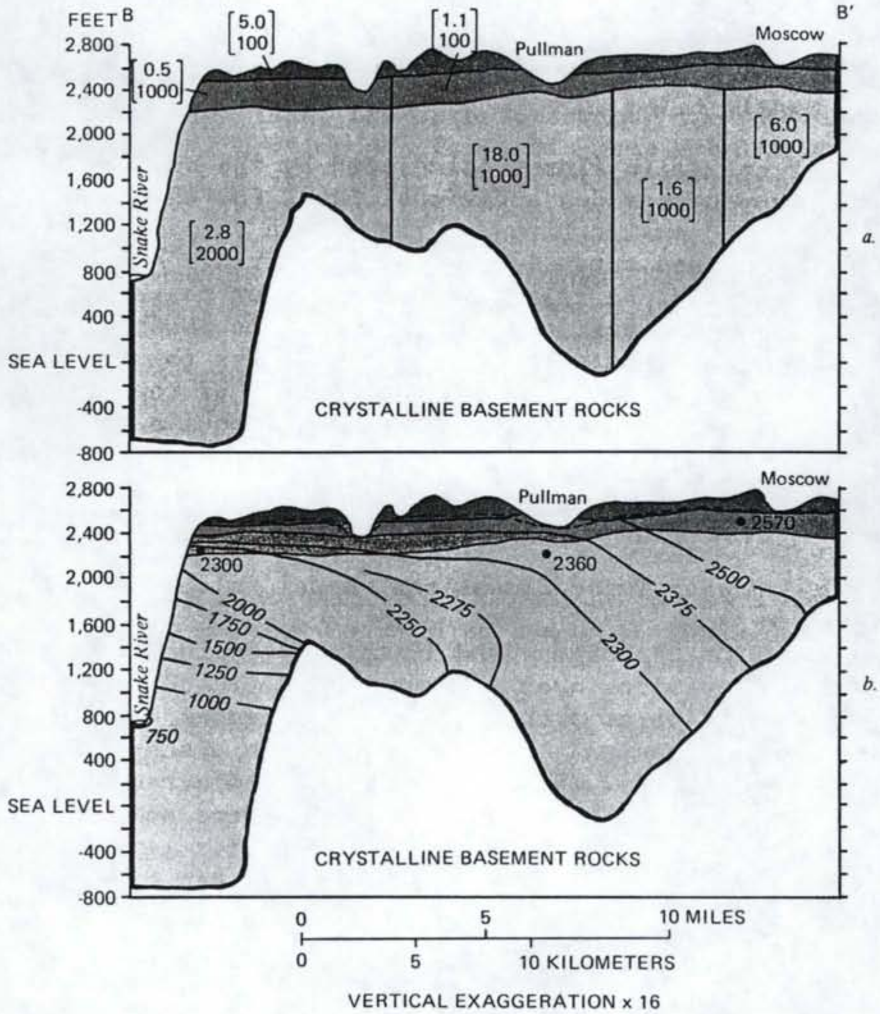
Cross-sectional models constructed for this study are calibrated to simulate predevelopment (no pumpage) conditions. Predevelopment recharge rates were used. One of the criteria used to determine if the models were calibrated was that simulated water levels closely match observed water levels. Predevelopment water levels are known approximately for only a few wells near Pullman and Moscow. The earliest wells in Moscow tapped the Wanapum Basalt and flowed at land surface. The potentiometric head was 2,570 feet ± 20 feet (Russell, 1897). Early wells in Pullman tapped the upper part of the Grande Ronde Basalt where the head was approximately 2,360 feet ± 20 feet (Russell, 1897). A well located near the edge of the Snake River canyon (14/43-25N2, table 7, end of report) was used as another calibration data point for model B-B'. The water level in this well is assumed to approximate predevelopment conditions within several tens of feet because of its distance from the pumping centers. This well penetrates the Wanapum Basalt and the upper part of the Grande Ronde Basalt (total depth 350 feet). The shallow depth to water in this well (about 121 feet) implies that most of the canyon wall may be a seepage face; therefore, another cross-sectional model calibration criterion was that all of the drains that simulate the seepage face should be active.

The cross-sectional models were calibrated by varying horizontal and vertical hydraulic conductivity of the basalt geohydrologic units. Horizontal and vertical hydraulic conductivity were held constant in the Palouse Loess soil at 5 and 0.05 ft/d, respectively. The horizontal hydraulic conductivity for basalt was varied between 0.1 and 50 ft/d. This range is compatible with reported data for the Columbia River Basalt Group (table 2). The vertical hydraulic conductivity was estimated to be a (smaller) multiple of horizontal hydraulic conductivity. The vertical hydraulic conductivity ranged between 10 and 10,000 smaller than the horizontal hydraulic conductivity (representing an anisotropy ratio). This range is intended to bound the probable distribution of hydraulic conductivities. The cross-sectional models were constructed to allow investigation of changes in both horizontal and vertical hydraulic conductivity values. In each cross-sectional model the basalts were divided vertically into distinct zones of similar hydraulic properties, four for the Grande Ronde Basalt and two for the Wanapum Basalt. The inclusion of these zones was an evolutionary process that occurred during initial operation of the cross-sectional models. The original version of the cross-sectional models had no zonation, but because observed water levels could not be matched with hydraulic heads calculated by the cross-sectional models, the zones were added. Figure 19a shows the zones and their values of hydraulic conductivity for the calibrated model for section B-B'. Similar zones were used in models A-A' and C-C', which are not shown.

The zones of differing hydraulic characteristics used in the calibrated cross-sectional models probably represent natural changes in the rock materials. On the basis of the results of the three cross-sectional models, the horizontal hydraulic conductivity of the Grande Ronde Basalt is lower in the western part of the study area than in the east. In the west, the basalt flows are thicker and may be less fractured, and thus have a lower conductivity. In the east, the opposite occurs. Basalt flows are thinner and fractured and have a higher hydraulic conductivity. To the west, the interflow zones may contain finer grained sediments. In the calibrated cross-sectional models the vertical hydraulic conductivity of the basalts (including the interbeds) was a smaller fraction of the horizontal value; thus, vertical hydraulic conductivity is lower, reflecting the geology.

Contours of the hydraulic heads simulated by the cross-sectional model match well with reported and (or) observed water levels along cross-section B-B' (fig. 19b). The contour lines are based on the multilayer output from the cross-sectional models. The water level at Moscow represents the Wanapum Basalt at one point, and the water level at Pullman represents the upper Grande Ronde Basalt at one point; the water level near the Snake River canyon probably represents a composite water level of the Wanapum and upper Grande Ronde at one point.

Points on cross-sections A-A' and C-C' that correspond approximately to Pullman and Moscow are calibrated to water-level values reported by Russell (1897) of 2,360 and 2,570 feet, respectively. Predevelopment water levels on the western end of these cross sections near the Snake River are unknown. Water levels in the upper Grande Ronde and Wanapum near the canyon are calibrated to be just above the top of the respective layers. This decision was based on the best available data.



EXPLANATION

PALOUSE LOESS

WANAPUM BASALT

GRANDE RONDE BASALT

[0.5 / 1000] ZONES OF CALIBRATED HYDRAULIC CONDUCTIVITY--Upper number is horizontal hydraulic conductivity, in feet per day. Lower number is ratio of horizontal to vertical hydraulic conductivity, anisotropy

—*1500*— WATER-LEVEL CONTOUR--Shows altitude of calculated hydraulic head. Contour interval in feet, is variable. Datum is sea level

•2360 MEASURED WATER-LEVEL SITE--Number is altitude in feet above sea level

——— NO-FLOW BOUNDARY

- - - - WATER TABLE

Figure 19.--Calibrated cross-sectional model B-B': a) calibrated hydraulic conductivity distribution, b) calibrated hydraulic head distribution.

The results of the cross-sectional models were used to map the areal distribution of hydraulic characteristics. This was used as input to the three-dimensional model.

The magnitude of the drain fluxes calculated by the cross-sectional models at the Snake River canyon provides additional input for the three-dimensional model calibration. Field examinations of the canyon seepage face indicate that the discharge of ground water is probably occurring; however, the quantity of discharge cannot be calculated directly or measured. Average annual precipitation in this part of the study area is about 17 in./yr and the potential evapotranspiration rate is at least 40 in./yr (Bauer and Vaccaro, 1989). The average rate of flux out the seepage face of the Snake River canyon, calculated from cross-sectional modeling, is equivalent to about 25 in./yr. This flux is used for input into the three-dimensional model as an initial approximation of the flux out the Snake River canyon seepage face.

Time-Averaged Three-Dimensional Model Calibration

The model-calibration technique used in this study incorporates a method averaging hydrologic conditions over a known period (Prych, 1983). Time-averaging allows calibration of a three-dimensional model to recently collected data, which are commonly more complete than historical data. The period chosen was 1974 to 1985. Barker (1979) had collected data in 1974, and data on all aspects of the ground-water-flow system were collected for this study in 1985. All transient conditions (changing water levels or pumping rates) are averaged over the same period so that they can be accounted for in what then becomes a steady-state simulation. Recharge rates based on current land-use and farming practices were simulated.

The hydraulic-conductivity distributions for both the Wanapum and Grande Ronde Basalts, obtained from the cross-sectional models, were transferred to the three-dimensional model. The loess was assigned the same values used in the cross-sectional modeling. The horizontal hydraulic conductivities of the basalts were varied by no more than a factor of 2 in the transition from the steady-state cross-sectional models to the three-dimensional model under time-averaged conditions. The vertical hydraulic conductivity ratio was varied by one order of magnitude. Given that little is known about this ratio, an order of magnitude is a reasonable variation.

A uniform value of storage coefficient was used for the basalt geohydrologic units in the time-average calibration. The final value used was 0.001. This is a reasonable value for confined aquifers in the basalts. There is most likely some nonuniform distribution of storage coefficient in the basalts in the Pullman-Moscow area, but this distribution is unknown.

A trial-and-error approach was used to calibrate the model. The goal was to simulate as closely as possible the observed average water levels for 1974-1985 and base flow in streams in the study area. The better known input data for the model (thickness and extent of the geohydrologic units, recharge, and boundary conditions) were not altered during calibration. The input data least well known (hydraulic coefficients including horizontal and vertical hydraulic conductivity and the storage coefficient) were altered within a range that was considered reasonable on the basis of a literature search.

Initially, the seepage face near the Snake River was simulated using drains. As previously described (p. 37), this was not adequate. A constant flux boundary was substituted, with a rate of discharge equal to 25 in./yr withdrawn from the seepage face, the rate determined from the cross-sectional modeling. During the calibration process, this rate eventually was reduced to a rate equal to about 10 in./yr. This lesser rate is reasonable, based on field observations that significant but unmeasurable discharge probably is occurring at the seepage face. Evapotranspiration of water at the seepage face could occur because the rate is smaller than the estimated potential evapotranspiration rate (40 in./yr) less precipitation (about 17 in./yr).

All changes to hydraulic coefficients and discharge rate at the seepage face of the Snake River canyon were evaluated during this calibration process. If horizontal hydraulic conductivity of the Wanapum Basalt was changed in one zone in the three-dimensional model, the change also was made in the appropriate cross-sectional model. Only if the change helped calibrate both models would it be accepted and left in the input data sets.

Values of horizontal hydraulic conductivity in the calibrated model for the Wanapum Basalt ranged from 0.4 ft/d to 0.6 ft/d; for the Grande Ronde Basalt, the range was from 0.4 ft/d to 12.0 ft/d. The ratio of horizontal to vertical hydraulic conductivity, the anisotropy of the geohydrologic unit, was 500:1 for the Wanapum and ranged from 2,000:1 to 5,000:1 for the Grande Ronde. The range of resulting vertical hydraulic conductivity was 0.0008 to 0.0012 ft/d for the Wanapum and 0.0001 to 0.0025 for the Grande Ronde. The distribution of calibrated values for hydraulic characteristics for the Wanapum Basalt is shown in figure 20 and for the Grande Ronde in figure 21.

Eventually, after iterating between the cross-sectional models and the three-dimensional model, a reasonable match was obtained between simulated heads produced by the three-dimensional model and observed water levels for the Wanapum Basalt (fig. 22). The observed water levels shown are the average water levels for 1974 to 1985. The contour lines show the distribution of simulated water levels (for fully penetrating wells) in the model. Most of the measured water levels are in general agreement with the simulated water levels. Where measured water levels are greater than simulated water levels, the wells may penetrate only the upper part of the Wanapum Basalt. Because water levels are known to decrease with increasing well depth in most of the study area, a partially penetrating well may have a higher water level. Measured water levels that are lower than model output may be from wells along a narrow stream valley. Because most of the stream valleys are small relative to the half-mile-square model cells, the model-calculated water level for a cell might be dominated by nearby uplands rather than the stream valley. Local effects and water levels tend to be smoothed out by the regional nature of the three-dimensional ground-water-flow model.

A reasonable match also was achieved for the Grande Ronde geohydrologic unit (fig. 23). The contours represent simulated water levels. Observed water levels in the Grande Ronde Basalt generally are from wells that penetrate the upper part of the basalt, except for two deep wells at Moscow. The three-dimensional model calculates the average water levels over the thickness of the cell. To correct for partial penetration of the wells, the average measured water levels for 1974 to 1985 presented in figure 23 are adjusted using the results of the cross-sectional models. The corrected water

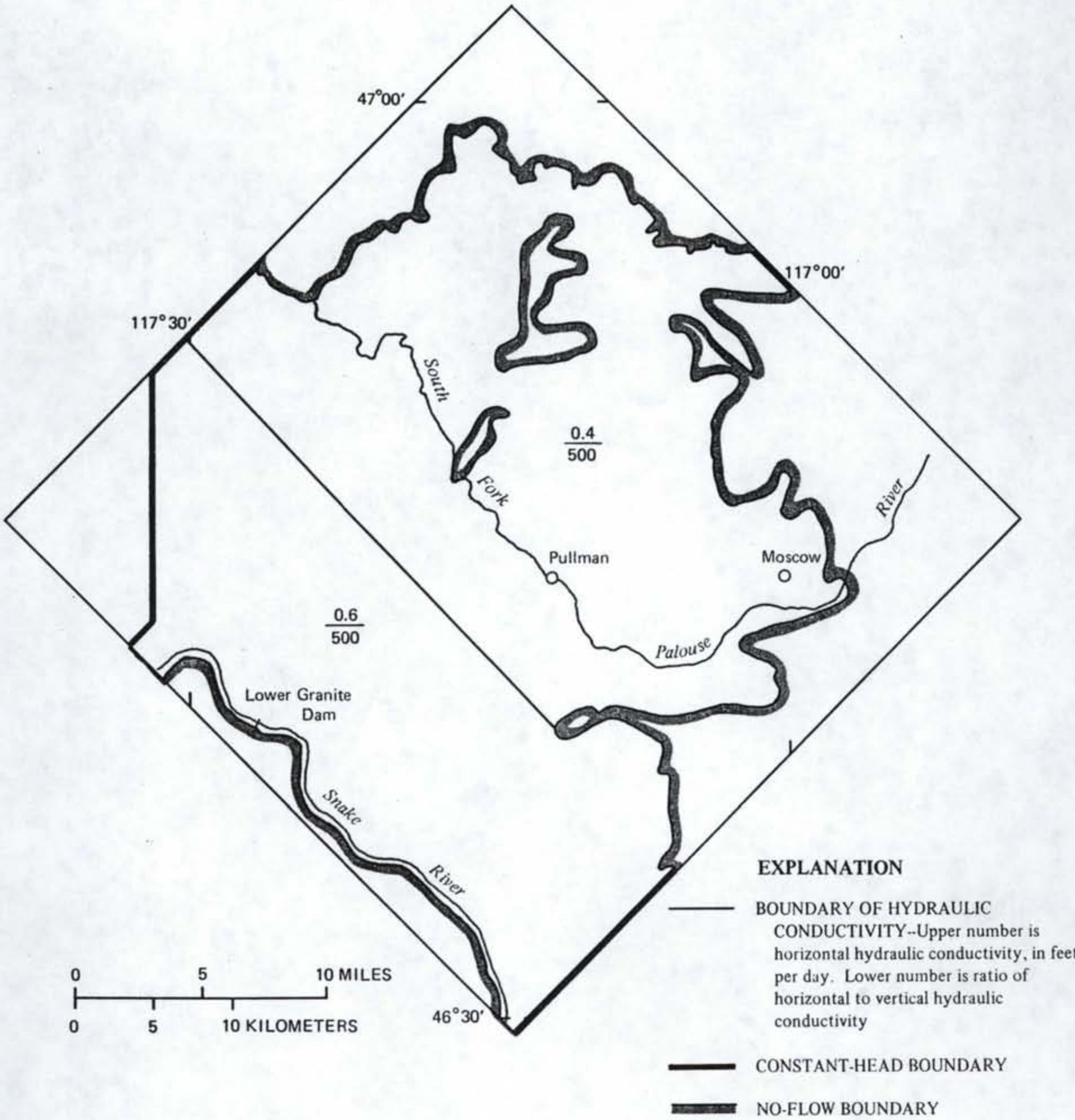


Figure 20.--Distribution of horizontal hydraulic conductivity and ratio of horizontal to vertical hydraulic conductivity for the Wanapum geohydrologic unit. Based on the cross-sectional model calibration and the time-averaged three-dimensional model calibration.

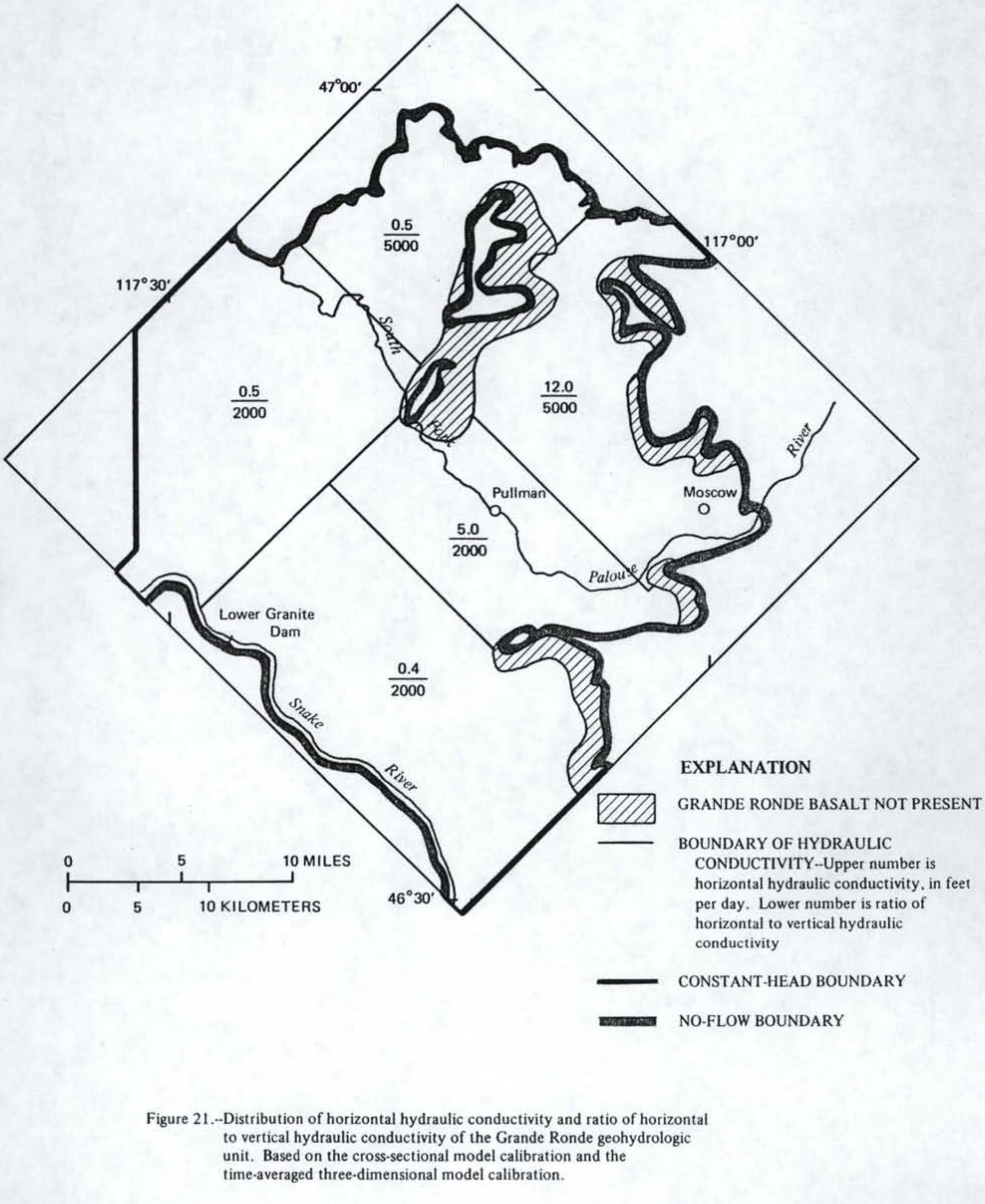


Figure 21.--Distribution of horizontal hydraulic conductivity and ratio of horizontal to vertical hydraulic conductivity of the Grande Ronde geohydrologic unit. Based on the cross-sectional model calibration and the time-averaged three-dimensional model calibration.

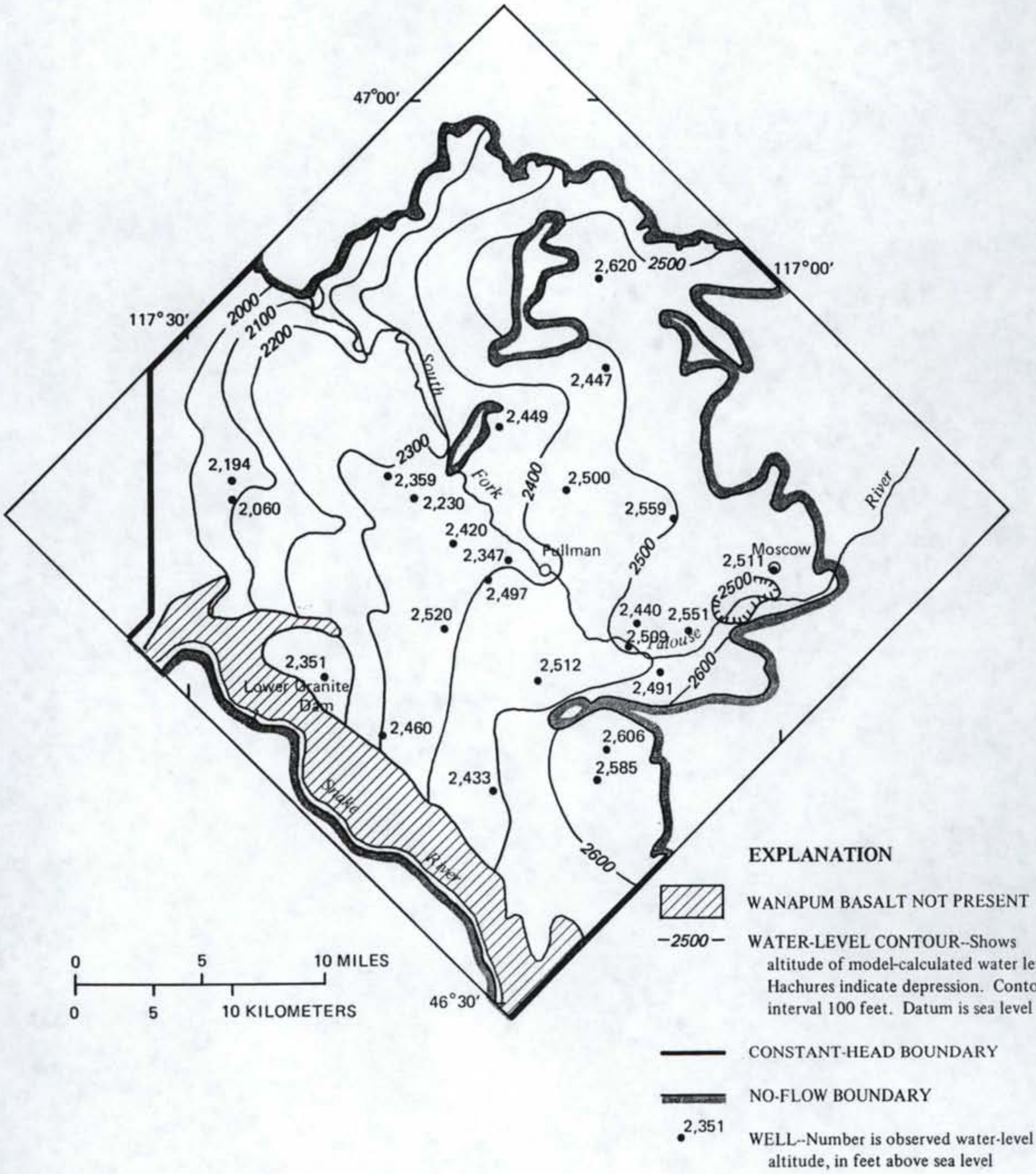


Figure 22.--Calibrated distribution of hydraulic head for the Wanapum geohydrologic unit for time-averaged conditions, 1974-1985.

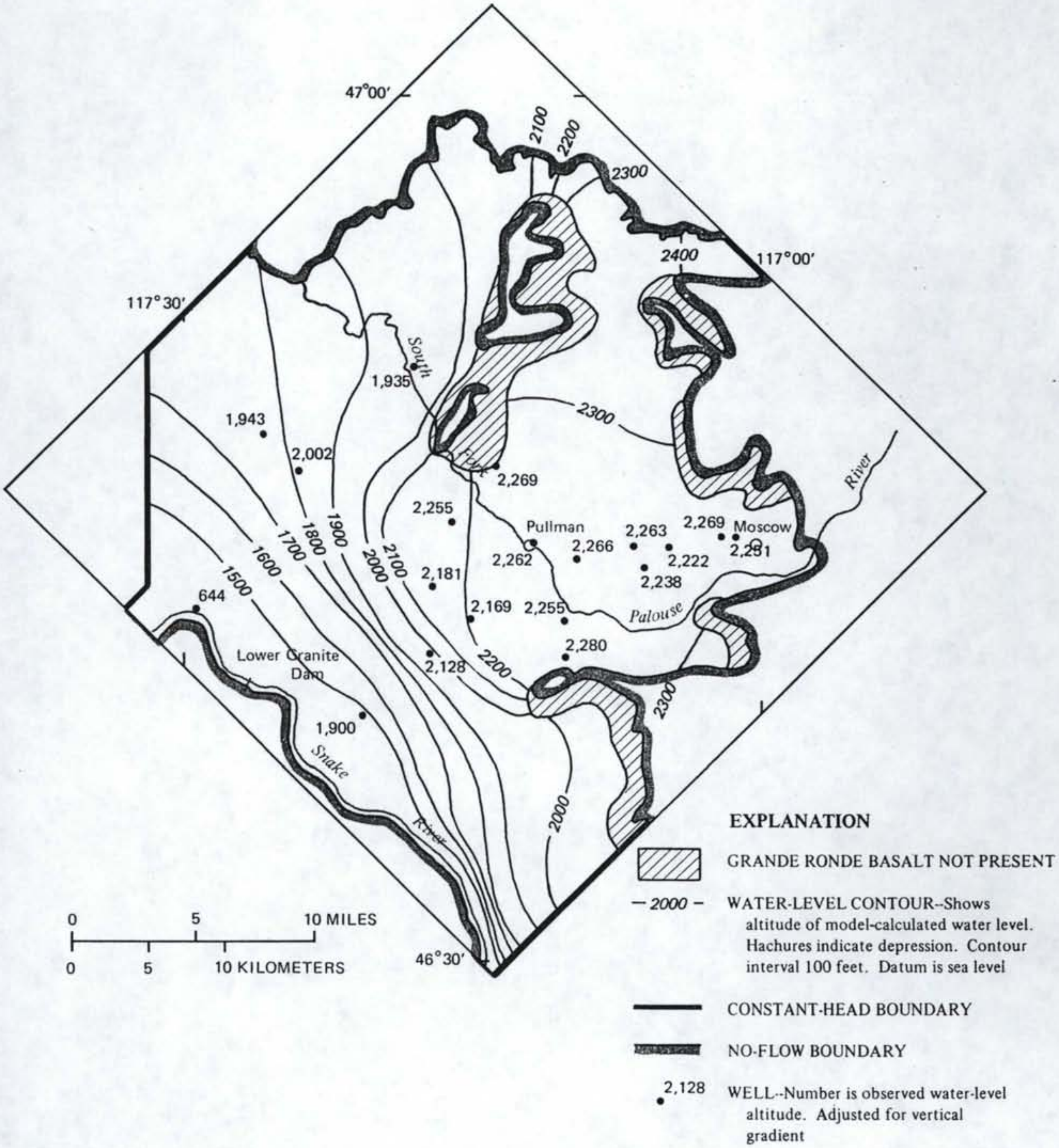


Figure 23.--Calibrated distribution of hydraulic head for the Grande Ronde geohydrologic unit for time-averaged conditions, 1974-1985.

levels for wells are comparable directly to water levels calculated by the three-dimensional model for the Grande Ronde geohydrologic unit. The correction factor for partial penetration lowers measured water levels by a few feet near Moscow and Pullman, where vertical gradients are low, and by several hundred feet near the canyon, where vertical gradients are high.

The model output suggests that there is a water-level difference of about 40 feet between Moscow and Pullman. However, this head difference does not appear in the measured water-level data for the upper part of the Grande Ronde; water levels in Moscow and Pullman are nearly the same. This difference between the simulated and observed hydrologic conditions is not understood at this time.

Barker (1979) found that a similar gradient between Moscow and Pullman was calculated at first by the model constructed for his study. In trying to correct this perceived error, Barker chose to simulate some type of undefined geologic structure that was controlling the hydrology of the area between Pullman and Union Flat Creek (the 'barrier zone'). Other investigators had speculated that feeder dikes or geologic structures may exist in that area; Barker speculated that the geologic features may have reduced hydraulic conductivity (see Barker, 1979, for an in-depth discussion). Barker reduced the hydraulic conductivity of the primary aquifer system by a factor of about 0.01 in that area. He then was able to adjust other input data in that model so that it simulated the observed (small or nonexistent) gradient in the Grande Ronde Basalt between Moscow and Pullman.

The 'barrier zone' concept was extensively investigated for this study, but even with new geophysical data and new water-level data, the existence, location, nature, and hydraulic characteristics of any geologic feature that may coincide with the 'barrier zone' of Barker are uncertain. Neither the cross-sectional models nor the three-dimensional model described in this report incorporates a feature that specifically correlates with the 'barrier zone.' In general, however, the results of the calibrated models discussed in this report indicate that the hydraulic conductivity of the Grande Ronde Basalt is highest east of Pullman and decreases to the west (fig. 21), in agreement with Barker's findings.

Simulated discharge of ground water to streams also was compared with measured streamflow values during calibration of the model. The results are discussed as part of the next section of the report.

Water-Budget Analysis of Time-Averaged Model

The water budget of the calibrated time-averaged model is presented in table 3. Recharge to the model is about 136 ft^3/s, calculated from the recharge distribution over the surface area of the model (fig. 16b) and based on current land-use and farming practices. About 13 ft^3/s enters the model on the south and northeast constant-head boundaries. The flux of water into the model from recharge and constant-head boundaries is balanced by the flux of water out of the model through wells, drains, rivers, and the constant-head boundaries. More than 19 ft^3/s leaves the model through the three constant-head boundary segments simulating the regional flow system at those locations.

Table 3.--Summary of water budget for time-averaged simulation

	Quantity of water, in cubic feet per second		
	In	Out	Sum
Constant-head boundaries	12.8	-19.3	-6.5
Wells, pumpage	0	-9.4	-9.4
Snake River and seepage face	0	-40.5	-40.5
Drains	0	-41.6	-41.6
Rivers	.3	-38.4	-38.1
Recharge	136	0	+136
Sum	+149	-149	0

The drain flux includes drains along the creeks and the extreme upper reaches of streams east of Moscow. Although not shown in table 3, about 32 ft^3/s leaks downward from the overlying layers and reaches the Grande Ronde Basalt layer in the model. Discharge from the Grande Ronde Basalt is mostly to the Snake River and its associated seepage face. Average pumpage from wells during 1974-85 was 9.4 ft^3/s.

Simulated streamflow in reaches of selected rivers and streams is shown in table 4. The sum of the simulated river flux and the simulated drain flux represents the quantity of water that the model calculates is flowing from the ground-water system toward a river valley and into a river. Streamflow measurements in the same reach are shown for comparison. In general, measured streamflow is less than the model-calculated value. This may be due to inaccuracies in simulating these rivers and drains and because the model does not account for any evapotranspiration losses that may occur in the river valley.

Table 4.--Simulated average flow into selected rivers and measured stream discharges in study area

[Values are in cubic feet per second]

River reach	Simulated average flow into reach [1] (net flow)	Measured stream discharge in October 1984
Snake River	-40.5	--
South Fork Palouse River:		
above Pullman, Wash.	-5.1	1.4
mouth to Pullman, Wash	-11.8	[2]15
Sum of South Fork Palouse River	-16.9	[2]17
Palouse River	-10.3	--
Union Flat Creek	-20.5	4.7
Paradise Creek	-4.0	[2]4.0
Fourmile Creek	-6.8	--
Missouri Flat Creek	-6.3	.5
Spring Flat Creek	-5.4	.4

[1] This is the net sum of simulated discharge to the river reach and to the drains immediately adjacent to the river reach. Negative values represent net loss from the model to the stream.

[2] Ungaged sewage plant effluent included in this measured discharge.

Simulation of Historical Water-Level Changes Due to Pumping of Ground Water

When the model had been calibrated, it was verified (or evaluated) by simulating historical changes in the rate of pumping of ground water in the area and comparing the resulting water levels with records of water-level change during 1890-1985. Washington State University well 1 (14/45-5F1) and University of Idaho well 3 (39/5-7cbbl) penetrate the Grande Ronde Basalt and were chosen for comparison of model results with observed conditions. The wells were chosen on the basis of completeness of water-level records and the fact that they are representative of wells in each municipality. A three-dimensional model simulation that begins in 1890 with one well in Pullman, one well in Moscow, and a combined pumping rate of about 200,000 gal/d reproduces historical water-level declines in the study area. During the simulation, pumping was increased over time and new wells were added according to historical records.

Recharge to the model for this simulation was varied with time. Pre-development recharge (fig. 16a) was simulated from 1890 to 1945 as farming in the area was gradually increasing. For 1946-1960 an arithmatic average of pre-development and current (fig. 16b) recharge was applied to the model, representing the transition period to current land-use and farming practices. For 1961-1985, recharge based on figure 16b values representing current land-use and farming practices was applied to the model.

The observed and simulated water levels for Pullman and Moscow are shown in figure 24. There is a close correlation between observed and simulated water levels. Barker's (1979) simulated historical water-level decline for Pullman is shown for comparison. (Barker's model is discussed later on pages 58-60.) Differences (as much as 10-30 feet) in the absolute water-level altitude between simulated and observed hydrographs may result from limitations inherent in representing the Grande Ronde Basalt as a single model layer. Most wells in the area penetrate only the upper part of the Grande Ronde geohydrologic unit. Consequently, the water-level record for most wells is for the upper part of the formation, whereas simulated water levels represent the average over the model layer.

Figure 25 shows a more detailed comparison between simulated and observed drawdown in one well each in Pullman and Moscow during 1975-85. Available records show that the average increase in pumping rate in the area for that period was about 1 percent per year. Model runs simulating both 1 and 1½ percent annual increases are shown, and simulated drawdown compares well with measured drawdown.

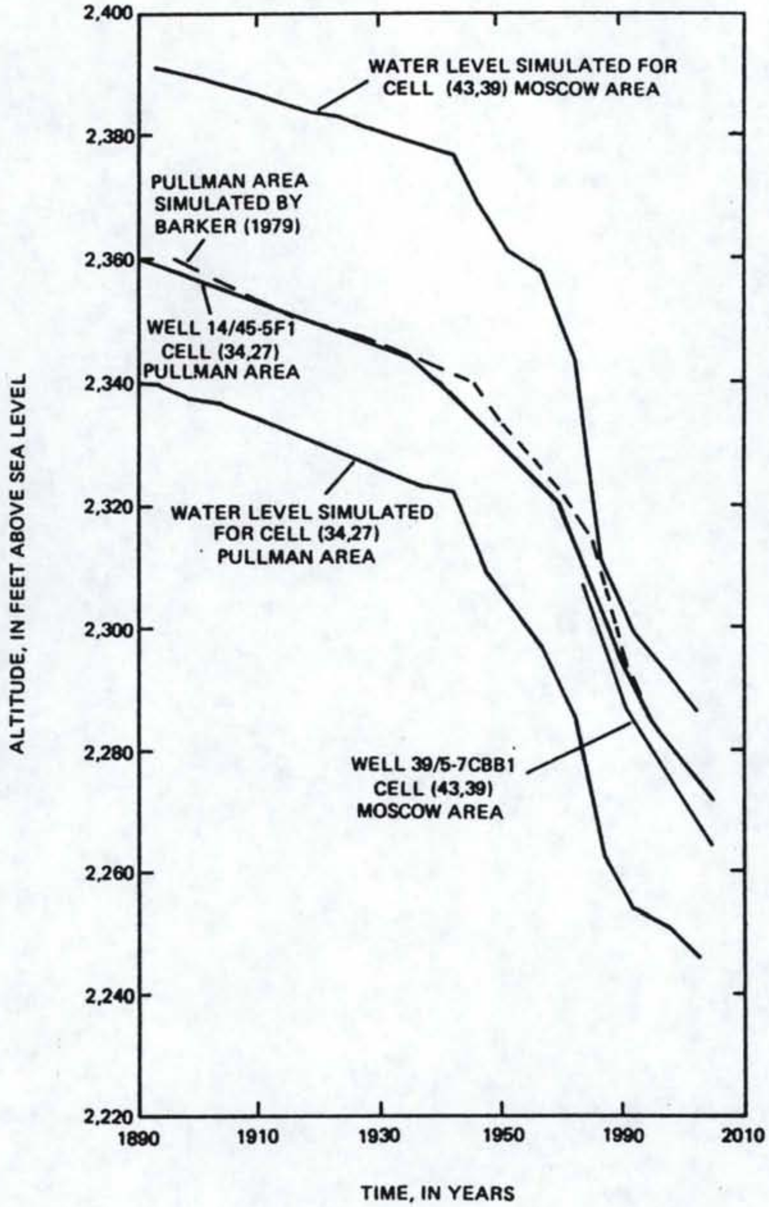


Figure 24.--Comparison of observed and simulated water levels in wells in the Pullman and Moscow area, 1890-1985.

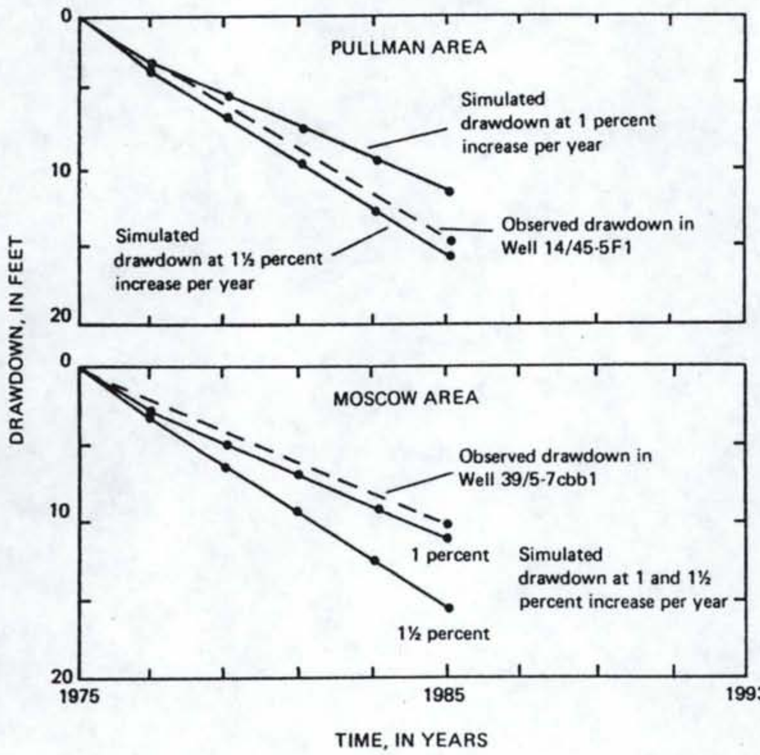


Figure 25.--Comparison of observed and simulated water levels in wells in the Pullman and Moscow area, 1975-1985.

Estimated Effects Due To Pumping Of Ground Water

A common misperception among water users in the Pullman-Moscow area was that water consumption and the corresponding pumpage had remained essentially constant over the period 1976-85. Available pumpage data indicate that annual ground-water pumpage has continually increased (see fig. 9). An analysis of 5-year averages of pumpage (5-year averages are used to smooth out year-to-year variations) indicates increases of about 4½-percent per year during 1891-1945, 4-percent per year during 1946-1975, and 1-percent per year during 1976-85. Model projections are based on water use at or above the 1981-85 average rate of about 6,700,000 gal/d.

Six projections of water pumpage were examined. Three were based on stable pumping rates and three were for various rates of increase in pumpage. These projections were intended to bracket water use on the basis of the extremes of a stabilization of pumpage at the 1981-85 average rate and 2-percent pumpage growth per year. The distribution of pumpage remains the same as in 1981-85 in all simulations. If pumpage increased in Pullman at a rate of 2 percent annually, it was assumed to increase by the same amount in Moscow.

Constant-Pumpage-Rate Scenarios

The effects on the ground-water system of future pumpage at three constant rates were investigated with the model. The model simulation of future conditions indicates that ground-water levels will decline and then stabilize at annual pumpage rates as great as twice the 1985 rate if pumpage is held constant at the increased rate into the future. The altitude of the stabilized water levels and the length of time required to achieve this stabilization depend on the pumping rate--the larger the pumping rates, the greater the depth at which any water-level stabilization occurs and the more time required for stabilization.

The first scenario is for a constant pumpage rate equal to the average 1981-85 rate of about 6,700,000 gal/d. The model results indicate that water levels near both Pullman and Moscow stabilize in a few years with little additional water-level decline below 1985 levels (fig. 26, curve a). The actual response of the physical system may take longer than predicted by the model because of the single-layer representation of the Grande Ronde Basalt; it may take several years for water-level declines to stabilize.

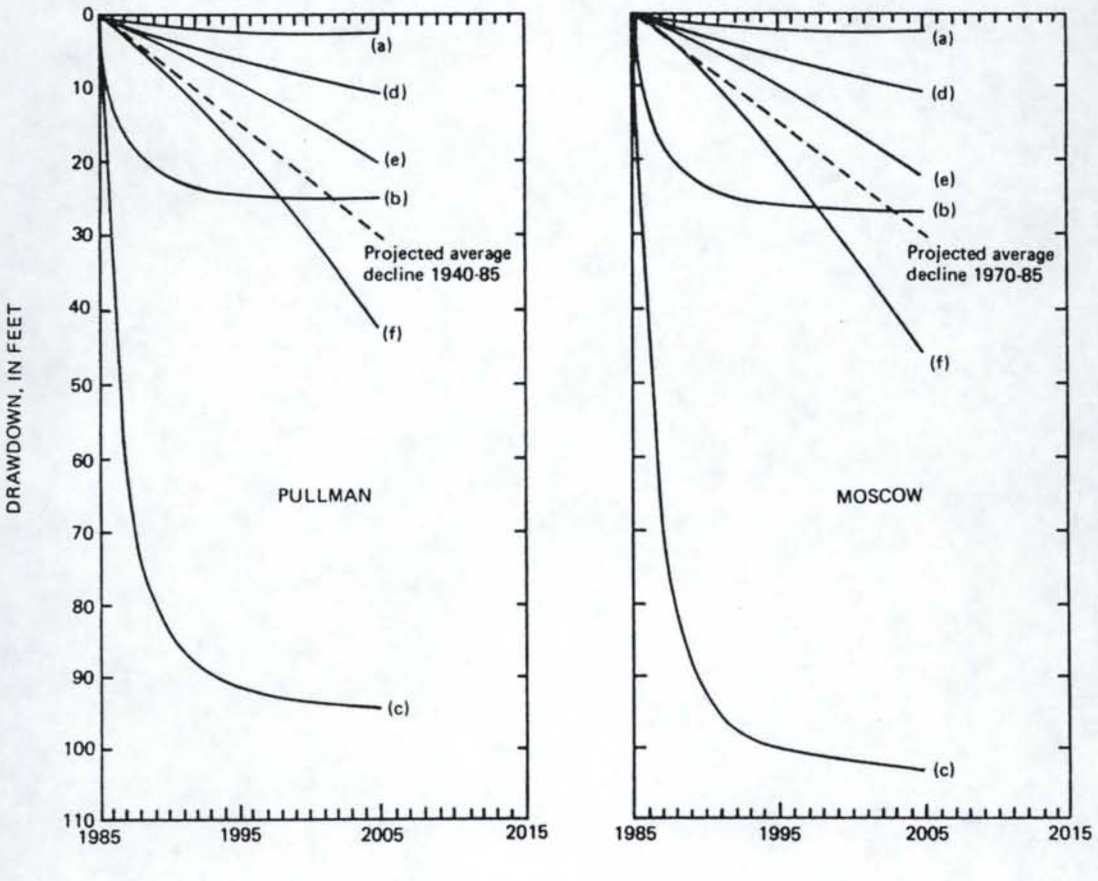


Figure 26.--Simulated water levels at a constant pumpage rate equal to: (a) the 1981-1985 average rate; (b) 125 percent of the 1981-85 average rate; and (c) 200 percent of the 1981-85 average rate; and at an annual pumpage rate increase from each preceeding year of: (d) ½ percent; (e) 1 percent; and (f) 2 percent; starting with the 1981-1985 average rate.

The second scenario assumed constant pumpage rate at 125 percent of average 1981-85 rates, about 8,500,000 gal/d. The model results indicate that water levels will stabilize in about 5 years with water-level declines of about 20-30 feet (fig. 26, curve b). Both the stabilization period and the decline of water levels are greater than for the first scenario.

The third scenario assumes a constant pumpage rate equal to 200 percent of average 1981-85 rates. This pumpage rate is about 13,400,000 gal/d. The model results indicate that water levels will stabilize, possibly within about 10 years, with a water-level decline of about 90-110 feet (fig. 26, curve c).

Increasing-Pumpage-Rate Scenarios

Annual pumpage rate increases are representative of historical water-use trends over the last 100 years. Pumpage rate scenarios that incorporate ½-, 1-, and 2-percent annual increases (from each preceding year) were investigated using the model. All three scenarios indicate that water-level declines will accompany increases in pumping rates. Figure 26 (curves d,e,f) shows that the rate of water-level decline is proportional to the rate of pumpage increase.

The first scenario assumes a pumping rate increase of ½ percent annually. The initial rate was the average for 1981-85. At this rate of increase, the pumpage rate would be double that of the 1981-1985 average in about 140 years. The model results indicate that even at this seemingly small rate of increase, water levels would continue to decline in the study area (fig. 26, curve d). The rate of decline would be about 0.5 ft/yr in both Pullman and Moscow. Equilibrium between recharge and discharge did not occur for this scenario. Water-level declines are simulated to occur as long as pumpage increases annually, even at the relatively low rate of ½ percent per year.

In a scenario assuming a pumpage rate increase of 1 percent annually from average 1981-85 rates, the pumpage rate will double in about 70 years. The model results indicate that water-level declines will continue as long as pumpage rates increase (fig. 26, curve e). The simulated rate of decline is about 1 ft/yr.

In a scenario assuming a pumping rate increase of 2 percent annually from 1981-85 rates, the pumping rate will double in about 35 years. This scenario suggests that water-level declines would average 2 to 2.3 ft/yr in the Pullman and Moscow areas (fig. 26, curve f). The rate of annual water-level decline gradually would increase.

Sources of Pumped Water

In all these scenarios, the water budget calculated by the model was examined to determine the source of the additional water being pumped. The major source of some of that water (about 40-50 percent) is reduced flow from aquifers in the model to simulated streams and rivers or reduced flow out of simulated drains. Perennial reaches of streams in the study area could have a reduced flow in late summer or could become intermittent reaches, going dry earlier and staying dry longer as pumping of ground water increases. About 20-30 percent of the increased pumpage comes from aquifer storage. The remaining water pumped (about 20-25 percent) was derived from reduced outflow from the model (or increased inflow to the model) at the constant-head boundaries.

The simulated flow of ground water to the Snake River remained virtually unaffected by increased pumping. The implication is that sufficient water was captured from other sources of recharge (or reduced discharge) such as streams, rivers, and drains closer to the pumping centers than the Snake River.

A COMPARISON OF MODEL RESULTS WITH THOSE OF A PREVIOUS STUDY

Barker (1979) constructed a two-dimensional finite-difference ground-water-flow model of a part of the area investigated for this study (fig. 27). His model was calibrated to simulate accurately the observed water-level changes in the upper part of what is referred to in this report as the Grande Ronde geohydrologic unit (fig. 24).

Barker (1979) simulated the upper Grande Ronde as a heterogeneous aquifer with a fixed thickness of 1,000 feet. The average thickness of the Grande Ronde for this report in the same area is about 2,000 feet, but varies considerably. Aquifer hydraulic conductivities in most of Barker's model ranged from 4 to 26 ft/d. In this report, Grande Ronde hydraulic conductivities ranged from 5 to 12 ft/d for the same area. Barker reduced hydraulic conductivities in the 'barrier zone' to 0.1 to 1.0 ft/d. In this report, hydraulic conductivities between Pullman and the Snake River are as low as 0.4 ft/d. Calibrated storage coefficient values are 0.005 (Barker, 1979) and 0.001 (this report).

Significant differences between the two models occur in how recharge to the ground-water system is calculated and how much recharge is occurring in the area. Barker used a head-dependent 'leakance' flux as recharge to the Grande Ronde Basalt. During model calibration, the 'leakance' was adjusted as one of the unknowns. This is a common technique that allows a two-dimensional model (which Barker described) to simulate approximately the three-dimensional flow. Barker had no other independent method to calculate recharge. Simulating conditions for 1975, the 'leakance' recharge rate to the Grande Ronde amounted to 0.67 in./yr. In this report, using the Bauer and Vaccaro (1987) methodology (and current conditions of land use), recharge to the loess is about 2.8 in./yr and the ground-water-flow model calculates that about 2 in./yr gets into the Grande Ronde geohydrologic unit in the area modeled by Barker (1979).

There are similarities in the results of the two models in that they predict similar responses of water levels in the Grande Ronde Basalt to historical changes in the pumping rate of ground water. Table 5 shows the observed water-level decline in Pullman and Moscow (1896-1975) and a comparison of simulated water-level declines in Pullman and Moscow from Barker's study and this report.

Barker (1979) summarized three scenarios of future pumping rates. Using the model described in this report, those same rates of change in pumping rate were simulated. Similar water-level declines in Pullman and Moscow are estimated by simulating no increase in the rate of pumping in both models. Simulating increases in pumping of 3 and 4.6 percent per year with both models points to a discrepancy between the models. The model in this report predicts considerably more drawdown than did Barker (table 6). An examination of the simulated water budgets leads to an explanation of this discrepancy. By the year 2000, when pumping is either two or three times what it was in 1975

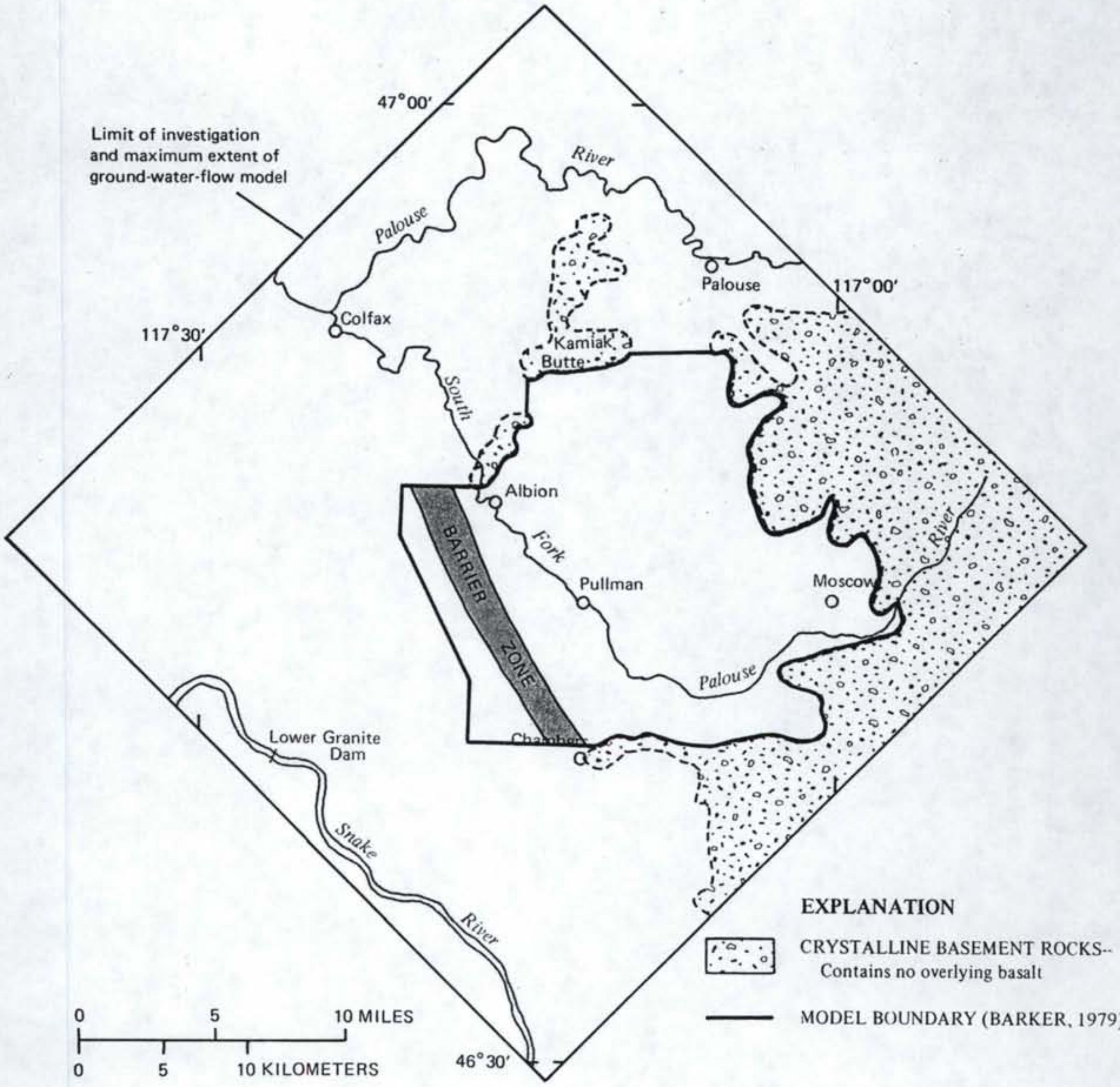


Figure 27.--Location of the ground-water-flow model boundaries and the 'barrier zone' of Barker (1979).

(at 3- and 4.6-percent increases per year, respectively) Barker (1979) predicts that about 90 percent of the additional water pumped will be from storage in the aquifer. The model described in this report, simulating similar pumpage scenarios, calculates that about 9 to 15 percent of the water will come from storage, and the remainder will be drawn toward the pumping centers from streams and drains. This results in larger predicted drawdowns in water levels.

Pumping of ground water increased in the Pullman-Moscow area by an average annual rate of 1 percent during 1976-85. Observed drawdown in the Grande Ronde Basalt for 1974-85 ranged from 14-20 feet near Pullman and 10-18 feet near Moscow (see fig. 11). To correspond to the period simulated by the models (1976-85), drawdown during 1976-85 is estimated to be about 12-16 feet and 8-25 feet, respectively. The model in this report calculated that drawdown was about 11 feet in both cities during 1976-85, assuming a 1-percent increasing rate of pumpage. Barker (1979) does not simulate an equivalent increase in pumpage. However, in a scenario of 3-percent per year increase, water-level drawdown in Pullman and Moscow was simulated to be about 13 feet (Barker, 1979). At a lesser rate of increase, simulated drawdown would be smaller.

Table 5.--Observed and simulated water-level declines in the Grande Ronde geohydrologic unit, 1896-1975

	Water-level decline, in feet		
		Simulated, for model cell	
	Observed (well data)	Barker, 1979	This report
Pullman	about 75	70-75	87
Moscow	about 60-80	80-85	91

Table 6.--Simulated water-level declines in the Grande Ronde geohydrologic unit, 1975-2000

Percent increase per year in pumping rate over that of 1971-75	Water-level decline, in feet			
	Barker 1979		This report	
	Pullman	Moscow	Pullman	Moscow
0	8.5	8.5	4.5	5.0
3	30-40	30-40	93	96
4.6	40-50	50-60	170	177

LIMITATIONS OF THE MODEL

Discretion must be exercised in use of the model results. The three-dimensional ground-water-flow model incorporates many simplifying assumptions about the flow system. Most important are the assumptions of constant heads along some boundaries, homogeneous blocks of aquifer material both laterally and with depth, and the simplified treatment of streams and rivers. Particularly critical to the model developed in this study is the representation of the Grande Ronde Basalt as a single layer. These simplifications may allow the model to achieve recharge-discharge equilibrium sooner and with less drawdown than would be experienced under actual conditions in the study area.

The use of constant-head boundaries was tested by replacing the constant-head boundary with a constant-flux boundary. This change produced some additional drawdown over most of the model for all future pumping scenarios. The additional drawdown was small (1 to 3 feet), but was apparent at all model boundaries, indicating that the effects of pumping in Pullman and Moscow may have wider (areal) impact on the ground-water system than previously thought. Conversely, because the amounts of drawdowns were small, it indicates that the constant-head boundaries are far enough away that they have little impact on predicted water levels at Pullman and Moscow.

The model representation of half-mile-square homogeneous blocks of aquifer material does not account for discontinuities (such as faults, dikes, poorly permeable interbeds) that might impede flow and lengthen the time required for equilibrium to be established. Similar problems may apply to leakage from streams.

Using a single layer to represent the Grande Ronde Basalt makes it difficult to compare model results with field data. The single-layer representation may result in underestimation of the time required for equilibrium conditions.

Simulated drawdown matches observed drawdown closely in Pullman and Moscow for the period 1891-1985. It is probable that the simulated rates and amounts of drawdown in the three scenarios where pumpage increased every year are reasonably accurate projections for the period 1985-2005. The total drawdown and time to equilibrium of the scenarios where pumping did not change from the average rate of 1981-85 and the step-increased rates of 1.25x and 2.00x have a large potential error, the time to equilibrium being the most uncertain.

SUGGESTIONS FOR FUTURE INVESTIGATIONS

This study is a step in the long process of understanding the geohydrology of the basin. Much information has resulted from the study; however, more data collection is needed to strengthen the assumptions and simplifications of this study. The systematic collection of water-level and pumpage data for the area and dissemination of that information to the public may be helpful in increasing public awareness of the value of the resource. Further examination of the recharge, movement, and discharge of ground water in the area is needed, with emphasis on evaluating the recharge distribution calculated for this study. Lysimeter studies could provide detailed data on water movement through the loess, which is useful in quantifying recharge rates. A detailed examination of ground-water discharge characteristics along the Snake River canyon would add much to the understanding of the resource.

Further investigation of the 'barrier zone' of Barker (1979) is warranted because of the importance of knowing if it limits water movement into and (or) out of the Pullman area. Information on water-level change with depth below land surface is needed throughout the area to help understand if the Grande Ronde Basalt is acting as a single aquifer.

CONCLUSIONS

Increasing pumpage rates and declining ground-water levels in the Columbia River Basalt Group of the Pullman-Moscow area of Washington and Idaho indicate a need for ground-water management. A three-dimensional numerical computer model of the ground-water-flow system was constructed to provide an understanding of the geohydrology of the study area. The ground-water-flow model incorporates an overlying surficial loess layer, a Wanapum Basalt layer, and a Grande Ronde Basalt layer. A ground-water-system recharge rate was estimated using a methodology developed by the U.S. Geological Survey. Ground-water discharge was modeled as ground-water pumping, flow to rivers and streams, and flow out of seepage faces, where a layer is incised by a river valley. Three cross-sectional flow models distributed across the domain of the three-dimensional model along estimated flow lines in the Grande Ronde Basalt provide an efficient means of obtaining hydraulic coefficient input for the three-dimensional model. The three-dimensional model was calibrated using the time-averaged method for 1974-85 and evaluated by simulating historical pumpage rate changes (1890-1985) and comparing simulated with observed water-level changes.

Predictive runs of the computer model of the ground-water system suggest that the cities and the universities can rely on existing ground-water resources into the future without extensive additional water-level declines if pumpage rates are stabilized. This general conclusion is based on a model that uses all available data and current modeling procedures, but incorporates a number of simplifying assumptions. Continued data collection and periodic model updating are necessary to maintain the model as a viable management tool.

Specific conclusions are listed below:

(1) Model simulations suggest that recharge-discharge equilibrium will be achieved with limited additional water-level decline if pumpage is stabilized at 1981-1985 average rates.

(2) Model simulations suggest that water-level declines will persist into the future as long as annual increases in pumpage occur.

(3) Average annual increases in pumpage at a rate of about 2 percent will result in water-level declines of more than 2 ft/yr in both Pullman and Moscow.

(4) In every case of increasing pumpage, the source of the extra water pumped was reduced flow to streams and drains and reduced water in storage in aquifers simulated in the model. The closer the stream/drain is to the pumping center, the more it is affected. The ground-water flow to the Snake River is virtually unaffected by pumping near Pullman and Moscow.

(5) Results of a model simulating ground-water recharge indicate that the average rate of recharge to the ground-water system in the Pullman-Moscow area is about 2.8 in./yr with about 2 in./yr reaching the Grande Ronde Basalt.

(6) Current farming practices used near Pullman and Moscow where a crop is grown every year have reduced the amount of recharge to the ground-water system. The reduced recharge may have contributed significantly to water-level declines in the study area.

(7) Most of the discharge from the ground-water system in the Pullman-Moscow area is to streams within the area and seepage along the canyon walls of the Snake River and the Palouse River.

(8) Magnetotelluric studies indicate that the basalt thickness ranges from 1,300 feet in Moscow and 2,000 feet in Pullman to more than 4,000 feet northwest of Pullman.

(9) The calibrated three-dimensional ground-water-flow model has hydraulic coefficient ranges as follows:

Loess:	
Horizontal hydraulic conductivity	5.0 feet/day
Vertical hydraulic conductivity	0.05 feet/day
Basalt:	
Horizontal hydraulic conductivity	0.4-12.0 feet/day
Vertical hydraulic conductivity	0.0001-0.0025 feet/day
Storage coefficient	0.001

(10) A program of continued data collection and model updating is needed for the area. Particular emphasis is needed on gaining a better understanding of locations and amounts of recharge and discharge.

REFERENCES CITED

Barker, R.A., 1979, Computer simulation and geohydrology of a basalt aquifer system in the Pullman-Moscow Basin, Washington and Idaho: Washington Department of Ecology Water-Supply Bulletin 48, 119 p.

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.

Bauer, H.H., and Vaccaro, J.J., 1989, Estimates of ground-water recharge to the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho, for predevelopment and current land-use conditions: U.S. Geological Survey Water-Resources Investigations Report 88-4108, in press.

Bauer, H.H., Vaccaro, J.J., and Lane, R.C., 1985, Maps showing ground-water levels in the Columbia River Basalt and overlying materials, spring 1983, southeastern Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4360, scale 1:500,000, 4 sheets.

Bockius, S.H., 1985, Geophysical mapping of the extent of basaltic rocks in the Moscow groundwater basin: M.S. Thesis, University of Idaho, Moscow, Idaho, 83 p.

Brown, J.C., 1976, Well construction and stratigraphic information: Pullman test and observation well, Pullman, Washington: College of Engineering Research Report 76/15-6, Washington State University, Pullman, Washington, 35 p.

Cotton, W.R., Jr., 1982, Hydrochemistry of ground water near Pullman, Washington: M.S. Thesis, Washington State University, 89 p.

Crosthwaite, E.G., 1975, Basic ground-water data for the Moscow Basin, Idaho: U.S. Geological Survey Open-File Report, Boise, Idaho, 96 p.

DeMotte, H., and Miles, W.F., 1933, A study of the Pullman artesian basin: Undergraduate Honors Thesis in Civil Engineering and Geology, Washington State University, Pullman, Washington, 35 p.

Drost, B.W., and Whiteman, K.J., 1986, Surficial geology, structure, and thickness of selected geohydrologic units in the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4326, scale 1:500,000, 11 sheets.

Eyck, G.T., and Warnick, C., 1984, Catalog of water reports pertinent to the municipal water supply of Pullman, Washington, and Moscow, Idaho - a summary: Idaho Water and Energy Resources Research Institute, University of Idaho, Moscow, Idaho, 56 p.

Foxworthy, B.L., and Washburn, R.L., 1963, Ground water in the Pullman area, Whitman County, Washington: U.S. Geological Survey Water-Supply Paper 1655, 71 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Hooper, P.R., and Webster, G.D., 1982, Geology of the Pullman, Moscow West, Colton, and Uniontown 7½-minute quadrangles, Washington and Idaho: State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, Geologic Map GM-26, scale 1:62,500, 1 sheet.

Jones, R.W., and Ross, S.H., 1969, Detailed ground water investigation of Moscow Basin: Research Technical Completion Report, Project A-011-IDA, Idaho Water Resources Research Institute, Moscow, Idaho, 11 p.

----1972, Moscow basin ground water studies, Idaho Bureau of Mines and Geology, Pamphlet No. 153, 95 p.

Klein, D.P., Sneddon, R.A., and Smoot, J.L., 1987, A magnetotelluric study of the thickness of volcanic and sedimentary rock in the Pullman-Moscow Basin of eastern Washington: U.S. Geological Survey Open-File Report 87-140, 30 p.

Konikow, L.F., 1978, Calibration of ground-water models: Proceedings of the Specialty Conference on Verification of Mathematical and Physical Models in Hydraulic Engineering, American Society of Civil Engineers, College Park, Maryland, August 9-11, 1978, p. 87-93.

Lin, C., 1967, Factors affecting ground water recharge in the Moscow Basin, Latah County, Idaho: M.S. Thesis, Washington State University, Pullman, Washington, 86 p.

Luzier, J.E., and Skrivan, J.A., 1973, Digital simulation and projection of water-level declines in basalt aquifers of the Odessa-Lind area, east-central Washington: U.S. Geological Survey Open-File Report, 56 p.

MacNish, R.D., and Barker, R.A., 1976, Digital simulation of a basalt aquifer system, Walla Walla River basin, Washington and Oregon: Washington Department of Ecology Water-Supply Bulletin 44, 51 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, 586 p.

McGary, L.M., and Lambert, T.W., 1962, Reconnaissance of ground-water resources of the Jackson Purchase region, Kentucky: U.S. Geological Survey Hydrologic Atlas 13.

Newcomb, R.C., 1965, Geology and ground-water resources of the Walla Walla River basin, Washington-Oregon: Washington Division of Water Resources Water-Supply Bulletin 21, 151 p.

Prych, E.A., 1983, Numerical simulation of ground-water flow in lower Satus Creek Basin, Yakima Indian Reservation, Washington: U.S. Geological Survey Water-Resources Investigations Report 82-4065, 78 p.

Ringe, L.D., 1968, Geomorphology of the Palouse Hills, southeastern Washington: M.S. Thesis, Washington State University, Pullman, Washington, 73 p.

Ross, S.H., 1965, Contributions to the geohydrology of Moscow Basin, Latah County, Idaho: M.S. Thesis, University of Idaho, Moscow, Idaho, 119 p. and plates.

Russell, I.C., 1897, A reconnaissance in southeastern Washington: U.S. Geological Survey Water-Supply Paper 4, 96 p.

Strait, S.R., and Spane, F.A., Jr., 1982a, Preliminary results of hydrologic testing the composite middle Sentinel Bluffs Basalt flow bottom at borehole RRL-2, SD-BWI-TI-095, Rockwell Hanford Operations, Richland, Washington, 36 p.

----1982b, Preliminary results of testing the composite Umtanum Basalt flow top at borehole RRL-2 (3,568-3,781 feet), SD-BWI-TI-105, Rockwell Hanford Operations, Richland, Washington, 45 p.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.

Swanson, D.A., Wright, T.L., Camp, V.E., Gardner, J.N., Helz, R.T., Price, S.M., Reidel, S.P., and Ross, M.E., 1980, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla quadrangles, southeast Washington and adjacent Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1139, scale 1:250,000, 2 sheets.

Tanaka, H.H., Hansen, A.J., Jr., and Skrivan, J.A., 1974, Digital-model study of ground-water hydrology, Columbia Basin Irrigation Project area, Washington: Washington Department of Ecology Water-Supply Bulletin 40, 60 p.

U.S. Geological Survey, 1987, Water Resources Data, Washington--water year 1985: U.S. Geological Survey Water-Data Report WA-85-1, 460p.

-----1988, Water Resources Data, Washington--water year 1986: U.S. Geological Survey Water-Data Report WA-86-1, 517p.

[U.S.] National Oceanic and Atmospheric Administration, 1987a, Climatological Data, Idaho, Annual Summary 1986: v. 89, 34 p.

-----1987b, Climatological Data Washington, Annual Summary 1986: v. 90, 36 p.

Walters, K.L., and Glancy, P.A., 1969, Reconnaissance of geology and of ground-water occurrence and development in Whitman County, Washington: Washington Department of Water Resources Water-Supply Bulletin 26, 169 p.

Wang, H.F., and Anderson, M.P., 1982, Introduction to groundwater modeling: finite difference and finite element methods: San Francisco, Calif., W.H. Freeman and Company, 237 p.

Wang, C.P., and Williams, R.E., 1984, Aquifer testing, mathematical modeling, and regulatory risk: Ground Water, v. 22, no. 3, p. 285-296.

Whiteman, K.J., 1986, Ground-water levels in three basalt hydrologic units underlying the Columbia Plateau in Washington and Oregon, spring 1984: U.S. Geological Survey Water-Resources Investigations Report 86-4046, scale 1:500,000, 4 sheets.

Williams, R.E., and Allman, D.W., 1969, Factors affecting infiltration and recharge in a loess covered basin: Journal of Hydrology, v. 8.

Table 7.--Records of selected wells in the study area

Local well number: Numbered by township, range, section, and 40-acre subdivision, as described on page 4.

Model cell location: Model cell location (row number, column number) of well.

Well owner: Name of owner or tenant.

Altitude of land surface (ft): Altitude of land-surface datum, in feet, with reference to sea level (National Geodetic Vertical Datum of 1929).

Well depth (ft): As measured, in feet below land-surface datum, by U.S. Geological Survey personnel or other agencies or as reported by well drillers or owners.

Depth to water below LSD: Measured (or reported, R) depth to water surface below land surface datum (LSD). Measured in spring 1985 unless specified: W, means winter 1985 measurement; A, means airline measurement.

Water-level altitude: Altitude of water level in feet above sea level for water-level measurement in previous column. +, well flows at land surface.

Altitude of cased interval: Altitude above sea level in feet of interval in well that is cased.

Altitude of open interval: Altitude above sea level of interval in well that is open to formation.

FMT YLD WTR: Geohydrologic unit yielding water to well, U, means unconsolidated loess; W, means Wanapum Basalt; GR, means Grande Ronde Basalt; and B, means granitic basement rocks.

Percent of formation that well penetrates: Percent that open well interval is of total thickness of geohydrologic unit.

-- : Data not available.

WELL NUMBER	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FEET)	WELL DEPTH (FEET)	DEPTH TO WATER BELOW LSD (FEET)	WATER LEVEL ALTITUDE (FEET)	ALTITUDE OF CASED INTERVAL (FEET)	ALTITUDE OF OPEN INTERVAL (FEET)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
13/44-05C1	(34,10)	J. RYAN	2,540	--	80. R	2,460	--	--	W	--
13/44-11H1	(41,13)	J. DAVIS	2,455	130	11.18	2,444	--	--	W	98
13/44-12P1	(42,13)	J. DAVIS	2,440	70	7.29	2,433	2,425-2,440	2,370-2,425	W	92
13/44-12P2	(42,13)	J. DAVIS	2,505	165	61.59	2,443	2,487-2,505	2,340-2,487	GR	1
13/45-01B1	(49,26)	R. HOOD	2,740	--	20.47	2,720	--	--	B	--
13/45-03M2	(46,21)	E. DRUFFEL	2,618	100	18.85	2,599	--	--	W	28
13/45-05D1	(42,18)	G. SENTER	2,558	190	4.04	2,554	2,538-2,558	2,368-2,538	W	--
13/45-10L1	(47,20)	P. KIRPIS	2,663	137	78.47	2,585	2,613-2,663	2,526-2,613	W	26
14/43-24M1	(27,10)	YOUNG	2,430	165	78.94	2,351	2,290-2,430	2,265-2,290	W	52
14/43-24M2	(--,--)	YOUNG	2,420	8	6.00	2,414	--	--	U	--
14/43-24R1	(29,11)	H. WEGNER	2,350	162	7.68	2,342	2,343-2,350	2,188-2,343	W	86
14/43-25N1	(29, 9)	A. TOWNSEND	2,480	250	37.65	2,442	2,460-2,480	2,230-2,460	W	74
14/43-25N2	(29, 8)	A. TOWNSEND	2,420	350	121.	2,299	--	--	GR	3
14/44-01E1	(31,24)	R. HARLOW	2,565	375	108.22	2,457	--	--	GR	4
14/44-01J1	(32,25)	HENDRICKS	2,660	200	0.00	2,660	--	--	U	--
14/44-01L1	(32,24)	B. BELL	2,620	275	221.18	2,399	--	--	W	75
14/44-01M3	(31,23)	195 & WWPUL	2,535	--	46.40	2,489	--	--	W	--
14/44-02J1	(31,24)	R. HARLOW	2,530	--	11.64	2,518	--	--	U	--
14/44-02M2	(30,22)	D. BLOOMFIELD	2,498	102	34.26	2,464	2,468-2,498	2,396-2,468	W	29
14/44-09J2	(30,19)	KIEFER	2,485	286	210.	2,275	2,467-2,485	2,199-2,167	GR	--
14/44-14P2	(33,19)	WSU DAIRY #2	2,550	432	286. A	2,264	2,200-2,550	2,120-2,200	GR	2
14/44-16F1	(30,17)	E. BROCH	2,405	160	120.02	2,285	--	--	GR	--
14/44-21R1	(33,15)	HATLEY	2,340	150	13.41	2,327	--	--	GR	--
14/44-23A1	(35,19)	R. WILBURN	2,560	90	40. R	2,520	--	--	W	4
14/44-28A1	(33,15)	V. RUMLEY	2,385	111	43.71	2,341	--	--	W	66
14/44-31A1	(32,13)	BREWER	2,460	--	3.72W	2,456	--	--	W,U	--
14/44-34C1	(35,15)	N. HATLEY	2,455	200	0.00	2,455	2,437-2,455	2,255-2,437	W	83

WELL NUMBER	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FEET)	WELL DEPTH (FEET)	DEPTH TO WATER BELOW LSD (FEET)	WATER LEVEL ALTITUDE (FEET)	ALTITUDE OF CASED INTERVAL (FEET)	ALTITUDE OF OPEN INTERVAL (FEET)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
14/45-01F1	(39,33)	PUL. TEST	2,470	982	213.61	2,256	2,270-2,470	1,488-2,270	GR	35
14/45-03H3	(38,31)	WWP	2,460	259	198.94	2,261	2,282-2,460	2,201-2,282	GR	7
14/45-03P1	(38,29)	S. JORSTAD	2,460	--	19.65	2,440	--	--	W	--
14/45-04D1	(35,29)	WSU #6	2,535	702	267. A	2,268	2,143-2,535	1,833-2,143	GR	17
14/45-04N1	(36,28)	WSU	2,390	95	DRY	--	--	--	W	100
14/45-05D1	(33,27)	PULLMAN #1	2,342	164	67.22	2,275	2,308-2,342	2,178-2,308	GR	5
14/45-05D3	(33,27)	PULLMAN #3	2,340	167	69.37	2,271	2,300-2,340	2,173-2,300	GR	5
14/45-05F1	(34,27)	WSU #1 (OBS)	2,364	145	92.87	2,271	2,304-2,364	2,219-2,304	GR	3
14/45-05F4	(34,28)	WSU #4	2,364	275	95. A	2,269	--	--	GR	7
14/45-06D4	(32,26)	H. WOO	2,515	220	168.21	2,347	2,475-2,515	2,295-2,475	W	100
14/45-07E1	(34,24)	H. COLE	2,530	82	33.21	2,497	2,522-2,530	2,448-2,522	W	30
14/45-08E1	(35,25)	PULLMAN #5	2,447	712	175.45	2,271	--	--	GR	21
14/45-08J4	(36,26)	J. ASKINS	2,420	223	147.65	2,272	--	--	GR	4
14/45-09E1	(37,27)	M. WISE	2,415	67	9.05W	2,406	2,395-2,415	2,348-2,395	W	71
14/45-09E2	(37,27)	H. NEIL	2,420	240	142.97	2,277	2,398-2,420	2,180-2,398	GR	4
14/45-10P1	(39,28)	H. STRATTON	2,540	--	31.45	2,509	--	--	W	--
14/45-15B1	(40,28)	G. LEONARD	2,610	213	147.62	2,462	2,515-2,610	2,397-2,515	W	57
14/45-16E1	(38,26)	W. STRATTON	2,400	110	DRY	--	2,360-2,400	2,290-2,360	W	100
14/45-16G1	(39,26)	WSU SPILLMAN	2,480	400	215. A	2,265	2,448-2,480	2,080-2,448	GR	9
14/45-16R1	(40,26)	G. WISE	2,418	195	142.87	2,275	2,243-2,418	2,223-2,243	GR	4
14/45-19G1	(37,22)	J. BENSCOTER	2,575	198	13.50	2,562	--	--	W	70
14/45-20A1	(39,24)	JACOBSON	2,550	--	37.77	2,512	--	--	W	--
14/45-21H2	(41,25)	SEARS	2,440	--	166.86	2,273	--	--	GR	--
14/45-22P2	(42,25)	A. FAIRBANKS	2,464	250	185.67	2,278	2,444-2,464	2,214-2,444	GR	14
14/45-23A1	(43,28)	R. DRUFFEL	2,480	--	0.00	2,480	--	--	U	--
14/45-23R1	(44,28)	R. MEYER	2,520	80	38.74	2,481	2,474-2,520	2,440-2,474	W	42
14/45-24F1	(44,29)		2,505	--	13.96	2,491	--	--	W	--
14/45-26J2	(45,26)	WEBER FARM	2,545	223	42.99	2,502	2,483-2,545	2,318-2,483	W	100
14/45-26J1	(45,26)	WEBER FARM	2,545	--	9.34	2,536	--	--	U	--
14/45-36Q2	(48,26)	J. WHITMAN	2,680	127	4.44	2,676	2,623-2,680	2,553-2,623	W	0

WELL NUMBER	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FEET)	WELL DEPTH (FEET)	DEPTH TO WATER BELOW LSD (FEET)	WATER LEVEL ALTITUDE (FEET)	ALTITUDE OF CASED INTERVAL (FEET)	ALTITUDE OF OPEN INTERVAL (FEET)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
14/46-07N1	(43,32)	J. BRADEN	2,570	100	16.41	2,554	--	--	W	27
14/46-07N3	(43,32)	J. BRADEN	2,570	353	306.62	2,263	2,505-2,570	2,217-2,505	GR	6
14/46-19F1	(45,30)	L. BROWN	2,485	180	11.52W	2,473	--	--	GR	3
15/43-08B1	(10,18)	KINCAID	2,100	--	157.49	1,943	--	--	GR	--
15/43-16J1	(14,17)	J. GHILCHRIST	2,100	138	97.82	2,002	--	--	GR	--
15/43-18H1	(11,15)	R. MILLER	2,270	160	75.93	2,194	2,180-2,270	2,110-2,180	W	--
15/43-18R1	(11,14)	M. MILLER	2,140	130	80. R	2,060	--	--	W	20
15/43-21A1	(--,--)		2,230	30	24.33	2,206	--	--	U	--
15/44-01G1	(23,33)	A. CLARK	2,380	157	18.56	2,371	2,340-2,380	2,213-2,340	W	0
15/44-01N1	(23,32)	G. CLARK	2,450	73	0.85	2,449	2,415-2,450	2,377-2,415	W	0
15/44-11F1	(23,30)	V. BIDDLE	2,435	140	0.--	2,435	--	--	W	0
15/44-11F2	(23,30)	V. BIDDLE	2,430	225	FLOWING	2,430+	--	--	B	--
15/44-15G2	(23,27)	ALBION #1	2,390	290	180. R	2,210	--	--	GR	100
15/44-15G3	(23,27)	ALBION #2	2,400	--	112.	2,288	--	--	GR	--
15/44-21D1	(22,24)	M. MCCROSKEY	2,355	177	125.44	2,230	2,335-2,355	2,178-2,335	W,U	95
15/44-24D1	(26,28)	J. MORRISON	2,380	35	7.92	2,372	--	--	U	--
15/44-24E1	(26,28)	J. MORRISON	2,375	135	120.19	2,255	--	--	W	100
15/44-24F1	(27,29)	J. MORRISON	2,390	165	21.50	2,378	--	--	W	100
15/44-26L1	(27,25)	M. HARLOW	2,390	160	120.97	2,269	2,370-2,390	2,230-2,370	GR	0
15/44-35E1	(28,24)	V. MICHAELSON	2,412	300	130.15	2,282	2,373-2,412	2,112-2,373	GR	11
15/44-35F1	(28,25)	V. MICHAELSON	2,435	96	14.86	2,420	--	--	W	36
15/45-06E	(23,34)	A. CLARK	2,480	--	76.77	2,403	--	--	W	--
15/45-07Q1	(26,33)	G. LAWSON	2,525	150	48.30	2,477	--	--	W	37
15/45-08L1	(27,34)	H. ROSSEBO	2,480	124	22.05	2,458	2,440-2,480	2,360-2,440	W	39
15/45-08M2	(27,34)	R. HOWELL	2,495	290	210. R	2,285	2,440-2,495	2,205-2,440	GR	3
15/45-10M1	(30,36)	R. GILLESPE	2,510	200	180. R	2,330	--	--	W	100
15/45-16B1	(29,35)	R. WHITMORE	2,500	200	21.62	2,478	--	--	W	100
15/45-16K1	(30,34)	R. WHITMORE	2,520	--	18.70	2,501	--	--	W	--
15/45-19E2	(28,30)	G. LAWSON	2,445	110	18.95	2,426	--	--	W	63
15/45-20H2	(30,32)	D. PORT	2,530	130	30.56	2,500	--	--	W	50

WELL NUMBER	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FEET)	WELL DEPTH (FEET)	DEPTH TO WATER BELOW LSD (FEET)	WATER LEVEL ALTITUDE (FEET)	ALTITUDE OF CASED INTERVAL (FEET)	ALTITUDE OF OPEN INTERVAL (FEET)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
15/45-24C1	(35,38)		2,540	350	60.	2,480	--	--	GR	15
15/45-25A2	(37,37)	M. BOYD	2,650	215	114.10	2,536	--	--	W	63
15/45-25Q1	(38,36)	L. BOYD	2,609	264	50. R	2,559	2,544-2,609	2,345-2,544	W	100
15/45-30G4	(30,29)	USDA AG EXP	2,520	371	249.40	2,271	--	--	GR	10
15/45-32C2	(32,29)	PULLMAN #6	2,430	518	152.10	2,278	2,196-2,430	1,912-2,196	GR	17
15/45-32N2	(33,28)	PULLMAN #4	2,356	954	73.22	2,283	1,957-2,356	1,402-1,957	GR	35
15/45-34L2	(36,31)	WSU WHITLAOW #5	2,510	396	238. A	2,272	2,210-2,510	2,114-2,210	GR	9
15/45-35F1	(37,33)	MOS-PUL AIRPT	2,531	172	7.00	2,524	--	--	W	100
15/46-06L1	(33,43)	T. QUIST	2,620	--	29.20	2,591	--	--	W	--
15/46-06P2	(33,42)	S. FLEENOR	2,625	100	53.02	2,572	--	--	W	31
15/46-08L1	(35,43)	F. FLEENOR	2,700	280	13.99	2,686	--	--	B	--
15/46-20N1	(38,39)	H. NELSON	2,570	--	5.87	2,563	--	--	U	--
16/43-25D1	(10,27)	NELSON	2,140	20	17. R	2,123	--	--	U	--
16/44-29F1	(14,30)	R. COCKING	2,135	500	400. R	1,735	--	--	GR	22
16/45-10A2	(21,47)	F. ELLS	2,630	50	11.52	2,628	--	--	W	--
16/45-15P1	(23,44)	M. KUEHNER	2,495	100	7.99W	2,487	--	--	U,W	--
16/45-22K1	(24,43)	E. RUPP	2,470	165	42.02	2,428	2,442-2,470	2,305-2,442	W	100
16/45-27Q3	(26,41)	L. THOMPSON	2,460	--	12.98	2,447	--	--	W	--
16/45-28H1	(24,41)	J. REDFIELD	2,450	--	95.02	2,355	--	--	W	--
16/45-29J1	(23,39)	D. HARLOW	2,430	--	56.75	2,373	--	--	W	--
39/05-07DAD2	(45,40)	MOSCOW #2	2,568	320	49.	2,511	--	--	W	100
39/05-07DAD3	(45,40)	MOSCOW #3	2,568	261	58.	2,502	--	--	W	100
39/05-07BDA2	(43,39)	MOSCOW #8	2,620	1,458	367.	2,253	--	--	GR	100
39/05-07CBB1	(43,39)	UI #3	2,567	1,336	294.65	2,272	--	--	GR	100
39/05-08BDB1	(45,41)	MOSCOW #6	2,600	1,308	334. R	2,266	--	--	GR	78
39/05-16DDB1	(49,41)	D. GENTRY	2,620	55	37.00	2,583	--	--	W,U	--
39/05-30AAB1	(48,36)	D. SINCLAIR	2,620	--	3.00	2,617	--	--	U	--

WELL NUMBER	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FEET)	WELL DEPTH (FEET)	DEPTH TO WATER BELOW LSD (FEET)	WATER LEVEL ALTITUDE (FEET)	ALTITUDE OF CASED INTERVAL (FEET)	ALTITUDE OF OPEN INTERVAL (FEET)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
39/06-12DBA1	(43,38)	MOSCOW #9	2,538	1,252	287.	2,251	--	--	GR	93
39/06-12DAA1	(43,38)	UI #4	2,554	747	284.66	2,255	--	--	GR	47
40/05-30CA 1	(40,43)	F. WARD	2,638	--	125.38	2,513	--	--	W	--
40/05-31DB 1	(41,42)	K. ROGERS	2,635	--	30. R	2,605	--	--	W,U	--
40/06-19CB 1	(36,43)	C. LADWIG	2,770	258	12.17	2,758	--	--	W,U	0
40/06-25DA 1	(39,42)	D. CLARK	2,680	--	27.74	2,652	--	--	W	--
40/06-36AD 1	(40,41)	A. CARSON	2,610	135	0.00	2,610	--	--	W	40