HYDROGEOLOGY AND A MATHEMATICAL MODEL OF GROUND-WATER FLOW IN THE PULLMAN-MOSCOW REGION, WASHINGTON AND IDAHO

by

John Leach Smoot
Dale R. Ralston

Department of Geology

WATER for IDAHO

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

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LARRY KIRKLAND

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In cooperation with:

Cities of Moscow, Idaho and Pullman, Washington
University of Idaho
Washington State University

U.S. Geological Survey
Water Resources Division
Tacoma, Washington

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

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ABSTRACT

Increasing pumpage rates and declining ground-water levels in the Columbia River Basalts of the Pullman-Moscow area of Washington and Idaho indicate a need for ground-water management. A three-dimensional numerical computer model of ground-water flow is constructed to guide this management. Basalt aquifer thicknesses of 0 to 3500 feet are determined by a magnetotelluric geophysical survey in support of the study.

The model incorporates a Grande Ronde Basalt layer, a Wanapum Basalt layer, and an overlying surficial loess layer. A recharge rate of 139 cubic feet per second to the upper layer of the ground-water flow model is calculated using a recharge model developed by the U.S. Geological Survey. Ground-water discharge is modeled as stream inflow and seepage where a layer is incised by a river. Cross-sectional models distributed across the domain of the three-dimensional model along flow lines provide an efficient means of obtaining hydraulic coefficient input for the three-dimensional model. The three-dimensional model is calibrated using the time-average method and evaluated through a history match procedure. The model incorporates numerous assumptions and simplifications; model predictions therefore are indicative only of general trends for the future.

The model suggests that it is possible for ground-water levels to stabilize if ground-water pumpage stabilizes at a constant level. Ground-water level declines will continue into the foreseeable future as long as ground-water pumpage continues to increase.

2.5×10^9 gpy ⇒ 6.85×10^6 gpd /90 ⇒ 7.61% of recharge now being used.
⇒ 10.6 cfs ⇒ 7669 ~ 7670 AF/yr ≃ 12 mi² 1 ft deep in H_2O
Moscow + UI ≃ 1100×10^7 ≃ 3374 AF ≃ 5.27 mi² 1 ft deep.

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CHAPTER I

INTRODUCTION

Statement of the Problem

The Pullman-Moscow area of northern Idaho and eastern Washington depends on ground water as the principal source of water. Primary pumpage occurs from the Miocene Grande Ronde Formation of the Yakima Basalt Subgroup and associated interbedded sediments. Water levels in wells in the deeper basalts have declined slowly but steadily since the wells were first drilled. The presence of the cities of Moscow, Idaho and Pullman, Washington, as well as the University of Idaho and Washington State University, implies a steady demand for ground water in the future.

The water supply in the region has long been a concern. The trend in recent years has been toward the development of mathematical models to simulate the ground-water system. These efforts began with the image well model of Jones and Ross (1969). Later modeling was conducted by Barker (1979). Barker's model underpredicted water level declines in the area; Barker's water levels predicted for the year 2000 were reached in 1985.

Representatives of the two universities, the two cities, the Washington State Department of Ecology, and the United States 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 a predictive tool to guide future management decisions. As a result, municipal and university officials entered into an agreement with the

United States Geological Survey to help support the present effort to construct a new model of the Pullman-Moscow area. The study plan included the collection of additional hydrogeologic data. A critical part of the study was a magnetotelluric geophysical survey to delineate the thickness of the basalt aquifer in the basin. Hydrogeologic data were input into an updated version of the U.S. Geological Survey modular model that was applied to the basin. The model was used to predict future water level behavior under various pumping scenarios. This report presents the details of field data collection, model construction, model operation, and an analysis of results.

Purpose and Objectives

The purpose of this study is to develop and construct a numerical ground-water model to be utilized to guide ground-water management in the Pullman-Moscow region. The general approach was to construct, calibrate, and operate a numerical model of the ground-water system in the Pullman-Moscow basin. Specific objectives include:

1) Discuss the hydrogeology of the Pullman-Moscow area.
2) Define data needs and collect of data for the digital model.
3) Construct and calibrate the digital model.
4) Operate the model under various management plans, evaluate their impacts, and evaluate the potential for future ground-water use and development based on model results.

Geographic Setting

Location

The Pullman-Moscow region is located in Whitman County, Washington and Latah County, Idaho (fig. 1). The area is located near the edge of the Columbia Plateau within the Palouse subprovince. The city of Pullman, Washington is about 85 miles south of Spokane, Washington.

Surface Water

The Snake River is the main surface water body in the region. No other large surface water bodies exist within the basin. The U.S. Army Corps of Engineers operates Lower Granite Lock and Dam southwest of Pullman. Pool elevation upstream from the dam is 740 feet above sea level. Average annual discharge through the dam for the years 1978 to 1984 was 57,500 cubic feet per second (Blazs, personal communication, 1986). The Palouse River is the only other major river; its average annual discharge at Colfax, Washington for the period 1964 to 1984 was 394 cubic feet per second (Blazs, personal communication, 1986).

Several perennial streams drain the area in addition to the Snake and Palouse Rivers. These include the South Fork of the Palouse River, Paradise Creek, Fourmile Creek, and Union Flat Creek (fig. 1). Streamflow measurements indicate that these streams gain or lose water from the ground-water system, depending on location and stream stage. A small amount of lawn and pasture irrigation is derived from these streams. The upper reaches of these streams flow on the loessial soils of the basin, whereas the lower reaches are incised into the basalt bedrock.

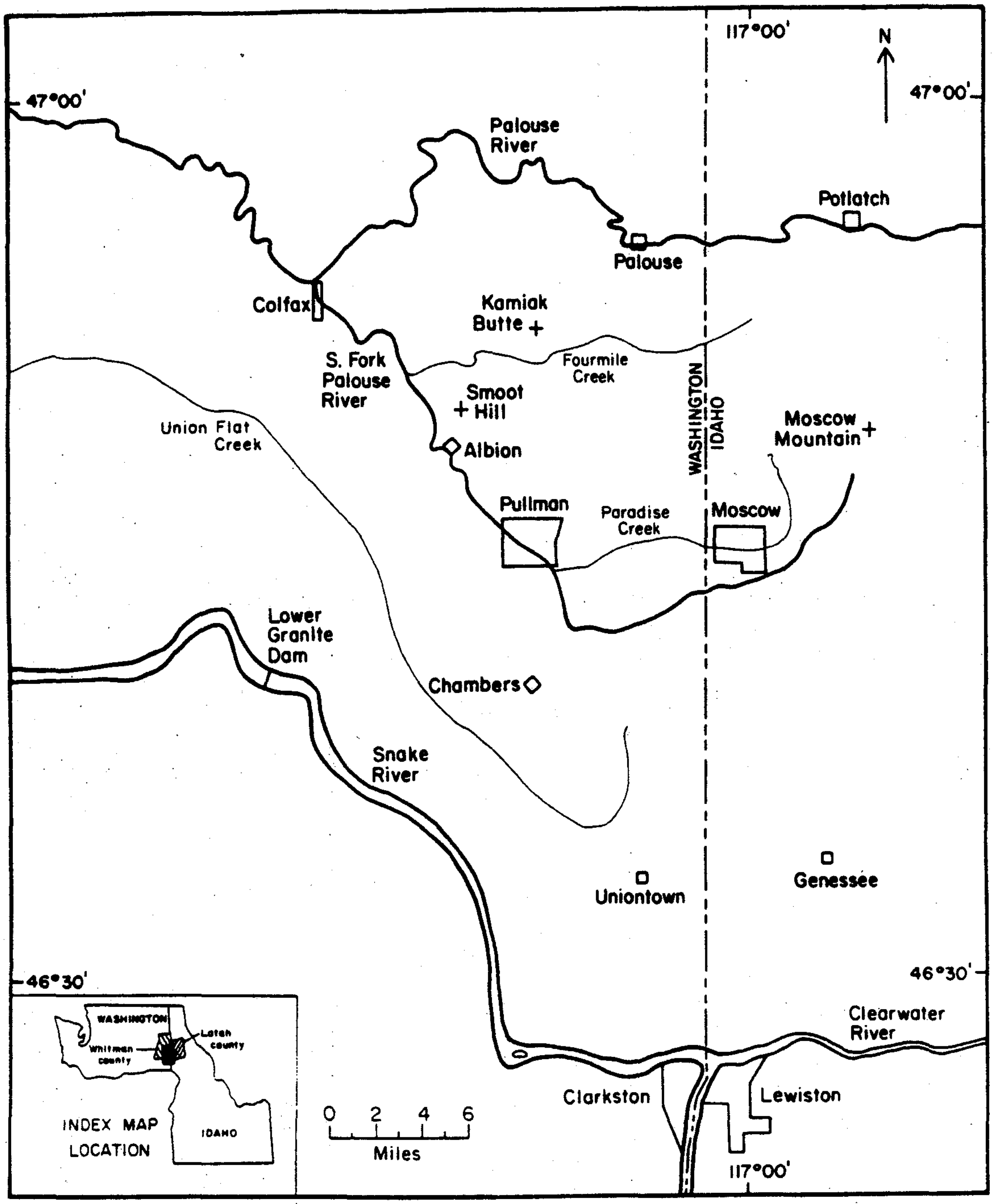


Figure 1. Location of Pullman-Moscow region.

Precipitation

Long term records indicate an average annual precipitation of 24 inches in Moscow and 22 inches in Pullman (HISARS, 1986). Precipitation may be more than double this amount in the highlands east of Moscow because of orographic effects. Precipitation falling on the basin generally is low intensity and seasonal. About 65% of the precipitation falls during the months of November through April followed by dry conditions during the summer. Table 1 shows long-term average monthly conditions for Pullman and Moscow.

Table 1. Average Monthly Precipitation for Moscow and Pullman (Inches).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
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
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

+1951-1980. (HISARS, 1986)
*1956-1977.

Land Use

Dryland farming constitutes the major land use within the basin. 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; no irrigated agriculture exists. The urban areas of Moscow and Pullman account for only a few percent of the land use within the basin.

Previous Investigations

Eyck and Warnick (1984) provide a comprehensive listing of documents that deal with ground water and water supply in the Pullman-Moscow area. Ground-water investigations in the Pullman-Moscow region began in the late 1800's. Russell (1897) makes the initial hydrogeologic reconnaissance of the area. DeMotte and Miles (1933) incorrectly postulate the independence of the Moscow and Pullman aquifer systems. Foxworthy and Washburn (1963) and Walters and Glancy (1969) constitute two of the most significant works on the basic hydrogeology of the area.

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

The theory of the magnetotelluric geophysical technique used in this study is described by Vozoff (1972). Instrumentation and field procedures are described by Stanley and Frederick (1979) and Stanley and Tinkler (1982). Klein and Sneddon (1985) discuss the preliminary results of the magnetotelluric survey; Klein and others (1987) prepared the final report on the magnetotelluric investigation. Bockius (1985) conducts a magnetic geophysical survey to better delineate the buried basalt-granite contact in the Idaho portion of the basin.

Barker Ground-Water Flow Model

Barker (1979) models the basalt aquifer in the region under the support of the United States Geological Survey. A computer program written by Pinder (1971) constitutes the basis for his two-dimensional, finite-difference model of the basalt aquifer. The model covers an area within a radius of about 8 miles of Pullman (fig. 2). The edge of the basalt flows form much of the model boundary, with Union Flat Creek forming the western boundary.

Barker's modeled aquifer consists of what he termed the "primary aquifer system". This corresponds to what has since been termed the Grande Ronde Basalt Formation. The Grande Ronde Basalt constitutes most of the basalt in the model area and is the primary supplier of water to wells. The much thinner overlying Wanapum Basalt Formation is not included as part of Barker's "primary aquifer system".

Barker (1979, p. 105) lists several problems with his model. He notes that inaccurate pumpage records could lead to inaccurate predictions of drawdown, because water level declines are related directly to pumpage rates. Barker questions the accuracy of his pumpage information. He also indicates the possibility of inaccuracy in his storativity value of 5×10^{-3}, particularly with respect to the potential change from confined to unconfined storativity in the future.

Recent water level records indicate that Barker's model is not a good tool for water level predictions. The model predicts declining

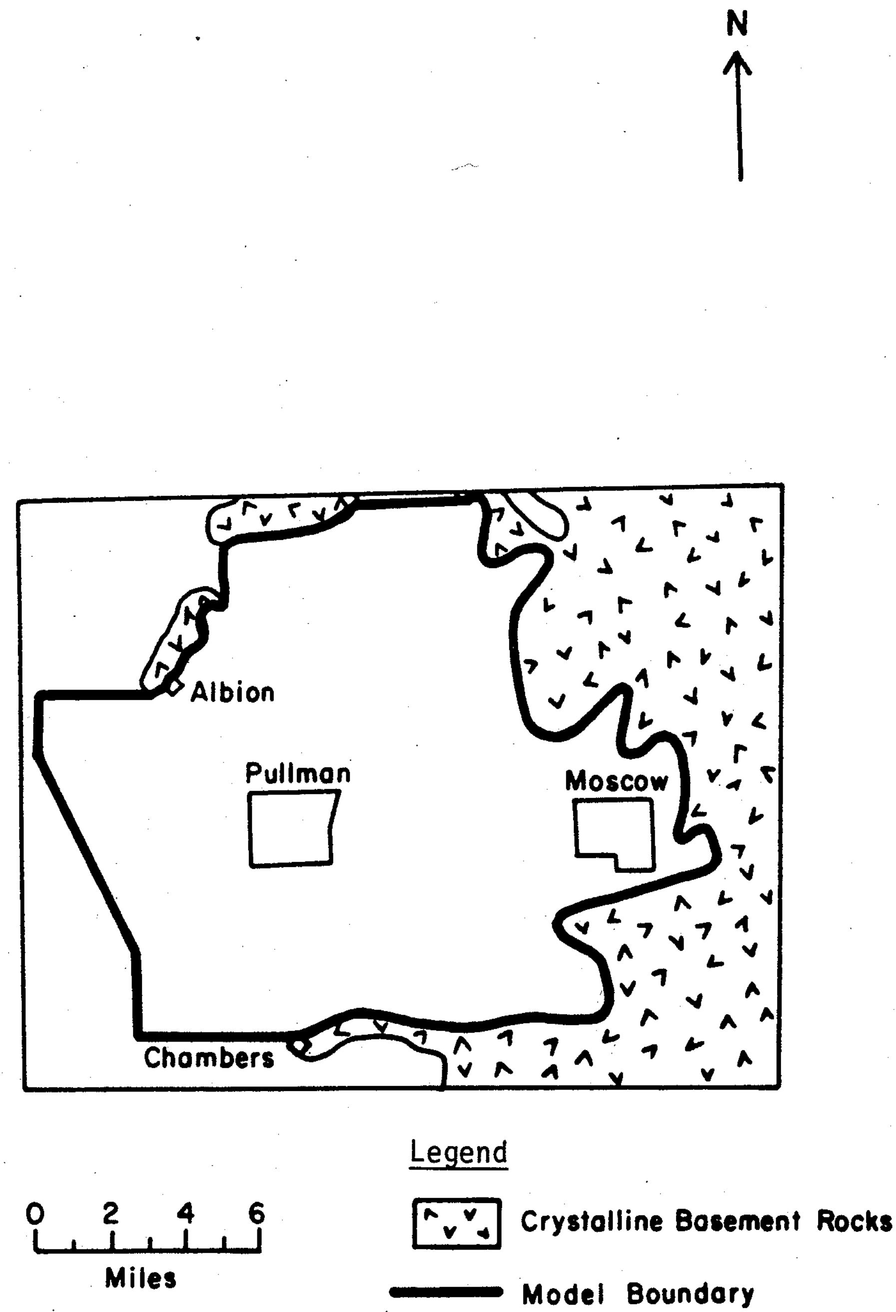


Figure 2. Location of the previous ground-water flow model by Barker (modified from Barker, 1979).

water levels in the deep Grande Ronde Basalt aquifer through the year 2000. By 1985, actual water levels in Moscow and Pullman had dropped below levels predicted for the year 2000. This error may be explained partially by Barker's perceived inaccuracies of pumpage and storativity; however, the discrepancy may be more the result of problems with his conceptual model of the ground-water flow system.

Barker uses local water level information to assume that Union Flat Creek west of Pullman is a hydrogeologic boundary. This assumption implies that the stream channel fully penetrates the aquifer and can be replaced in the mathematical model by a constant head boundary. Barker's results indicate that the flux from this constant head boundary is the major source of water for pumpage in the model. Data collected since Barker's work indicate that the Snake River rather than Union Flat Creek is the regional hydrogeologic boundary on the southwestern side of the region.

CHAPTER II

HYDROGEOLOGY

Introduction

The occurrence and movement of ground water in the Pullman-Moscow region is dependent on the hydrogeology of the region, including the nature of the geologic units and their water bearing characteristics, as well as recharge to and discharge from the ground-water system. The development of a conceptual model that integrates all hydrogeologic information is an essential step in understanding the basin. The impacts of pumpage in a ground-water basin can be investigated through an understanding of the hydrogeologic framework of the system. The hydrogeologic framework is the integration of geologic and hydrologic information that describes water flow within the subsurface.

Geology

The Pullman-Moscow area consists of an irregular buried surface of pre-Tertiary crystalline rocks overlain by Columbia River basalts and interbeds that are capped by Pleistocene loess. The crystalline basement rocks primarily are granites, although some metamorphic rocks occur in the northern part of the basin. The granites are Cretaceous in age and appear to be related to the Idaho Batholith.

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 (Bush, personal communication, 1987). A series of eruptions over millions of years produced the layers that make up the existing basalt sequence. The thickness of the layers or flows averages 40 to 80 feet, although layers 200 feet thick have been observed.

Basalt flows fracture at the surface as they cool from the molten state. Three sets of joints commonly occur; two are in the vertical direction and one is in the horizontal direction. Columnar hexagonal joints that form columns 0.5 to 6 feet in width and blocky joints about 0.5 feet in diameter occur in the vertical direction (Newcomb, 1965, p. 19). Platy fractures occur in the horizontal direction. In addition, regional fractures hundreds or thousands of feet long may intersect several flows.

The basalt flows in the Pullman-Moscow basin are classified into the Wanapum and Grande Ronde Formations of the Yakima Basalt Subgroup of the Columbia River Basalt Group (Swanson and others, 1979). Wanapum and Grande Ronde Basalt may be differentiated geochemically by their magnesium and titanium concentrations. Wanapum Basalt tends to be high in titanium and low in magnesium concentrations, whereas Grande Ronde Basalt tends to have high magnesium concentrations and low titanium concentrations. The Wanapum Basalt is separated from the Grande Ronde Basalt by the Vantage Member (interbed) of the Ellensburg Formation. The Vantage Member is composed of siltstone, claystone, and tuffaceous rocks (Swanson and others, 1979, p. 25).

Do not confuse with Fe and manganese

Numerous sedimentary interbeds like the Vantage Member commonly are mixed with the basalt, particularly near the margins of the Columbia Plateau. Basalt flows are known to have dammed streams that existed during the eruption process. The dams produced lakes where sediment deposition occurred. 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 driller's logs for wells east of Moscow report hundreds of feet of clay. Examination of the clays reveals both lateritic and swelling clays. Lateritic clays probably derive from soils whereas swelling clays probably derive from lake bed deposits.

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 reverse direction in the Idaho portion of the basin. This reversal may be the result of compaction of clay interbeds due to loading by overlying basalt flows.

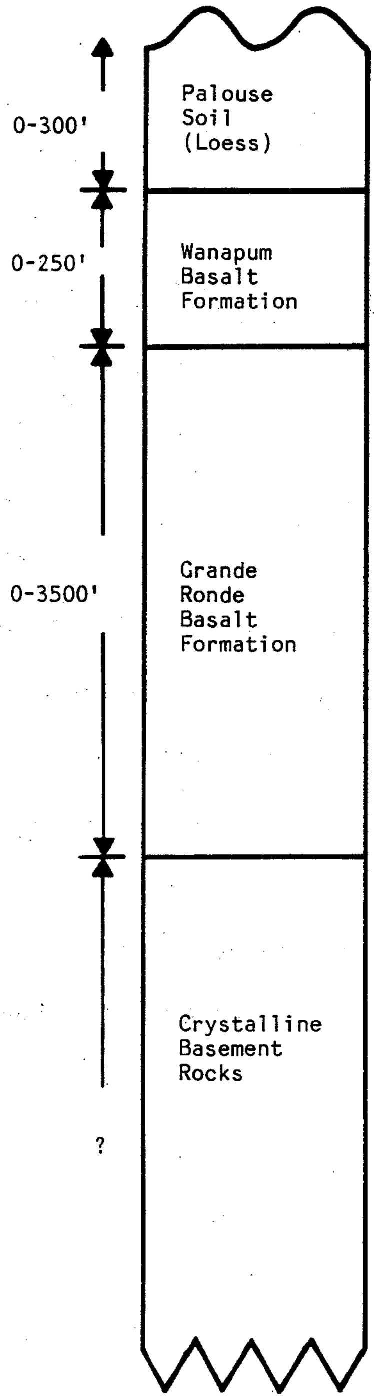
Pleistocene loess covers the relatively flat surface of the Wanapum Basalt Formation. The loess originated in the Pasco Basin of Washington. Loess deposition occurred as large dunes which form the present topography. Thicknesses of the loess range from several hundred feet to zero where streams penetrate through to the underlying basalt. Large thicknesses correspond to the crests of the loessial dunes. The loess is fine-grained and contains a well-developed silt-loam soil that plays a major role in subsequent discussion of ground-water recharge and discharge.

Water-Bearing Characteristics of Geologic Units

The loess, basalt, crystalline, and metamorphic 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. Water availability within the loess is sufficient for stock and domestic purposes. Small springs are common in the loess, particularly along stream valleys at the contact of the loess and underlying Wanapum basalt.

Basalts constitute the major producing aquifers in the basin. Most of the water occurs in the fractured zones between the basalt flows. Wells that penetrate one or more of these zones are the best producers. The deepest wells are at Moscow; they fully penetrate the basalt flows into the underlying crystalline rocks. Near Moscow, sandy interbeds can be a significant source of water.

The crystalline and metamorphic rocks underlying the basalt can be assumed to have negligible permeability. They generally yield small quantities of water for domestic use and for stock watering along the



WATER BEARING CHARACTERISTICS

Local stock and domestic supplies via wells and springs (less than 30 gallons per minute).

Most rural domestic wells; older municipal wells (less than 1500 gallons per minute).

Major municipal supplier (less than 3000 gallons per minute).

Local domestic supplies from wells (less than 20 gallons per minute).

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

eastern margin of the basin; however a few prolific wells do exist in these rocks.

Ground-Water Flow System

Definition of Hydrostratigraphic Units

Three hydrostratigraphic units are delineated based on the correlation of hydrogeologic properties with mappable geologic units. The eoloian Palouse soil overlies unconformably the Wanapum Basalt. The contact between the Wanapum Basalt Formation and the Grande Ronde Basalt Formation was determined from borehole sample geochemistry and maps of surface exposures. The large thickness of Grande Ronde Basalt was not subdivided for several reasons. First, a logical division that could be mapped does not exist in the Grande Ronde Basalt; the available field data simply do not support more detailed hydrostratigraphy. Second, the inclusion of four or more layers is not believed to be justifiable for this study.

Structural contour maps that describe the topography of the top surface of the Wanapum Basalt Formation and Grande Ronde Basalt Formation are shown in figures 4 and 5. These maps incorporate available literature, surface outcrop, and borehole geochemistry data. Both maps reveal the regional dip of the basalts to the northwest.

A magnetotelluric investigation of the Pullman-Moscow area (Klein and others, 1987) was done in support of the modeling effort in order to help define the hydrogeologic framework. This geophysical technique identifies the depth to electrical basement, which is considered to be the contact between the Grande Ronde Basalt and crystalline rocks at

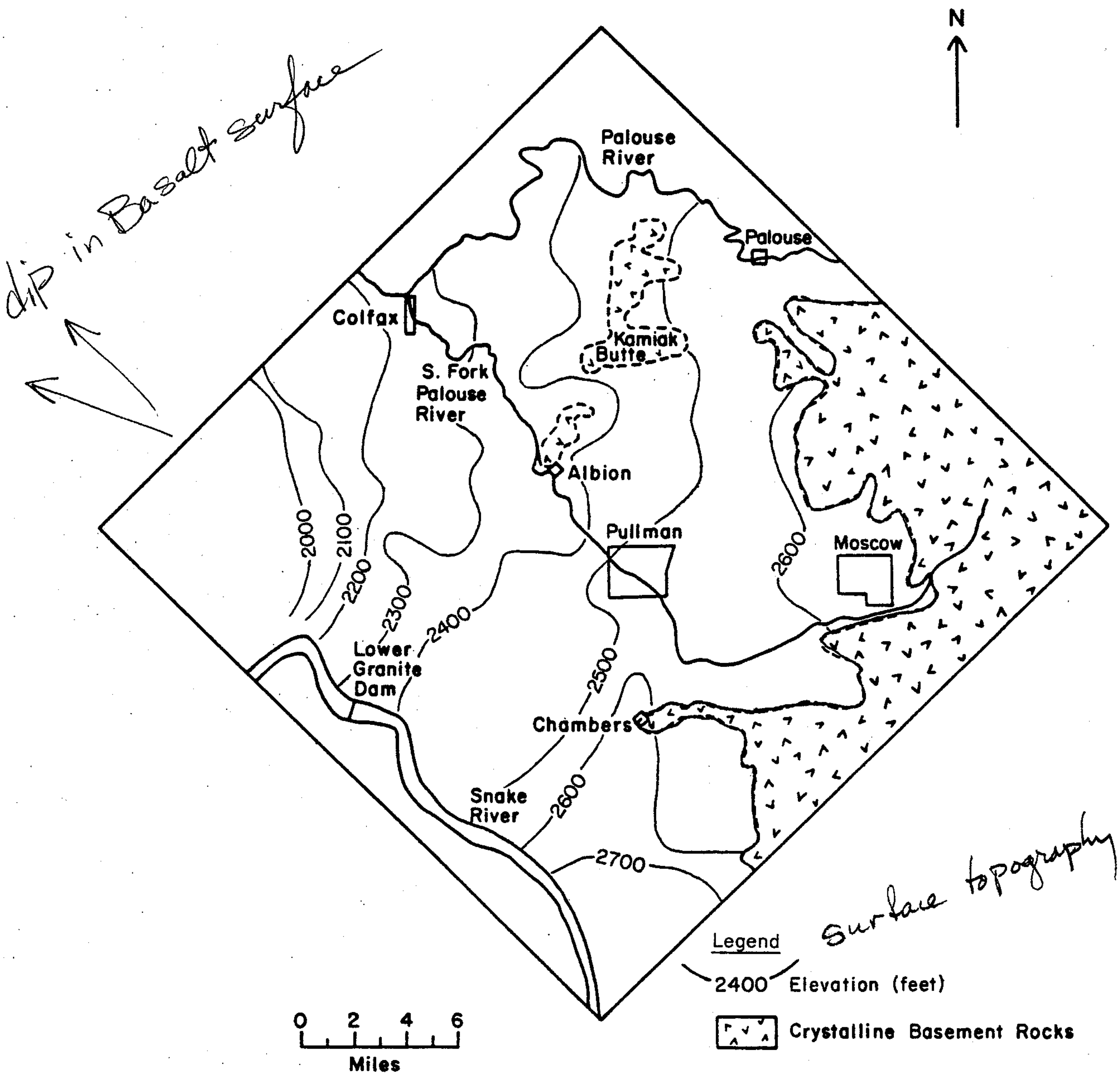


Figure 4. Structural contour map of the top of the Wanapum Basalt Formation (modified from Ringe, 1968).

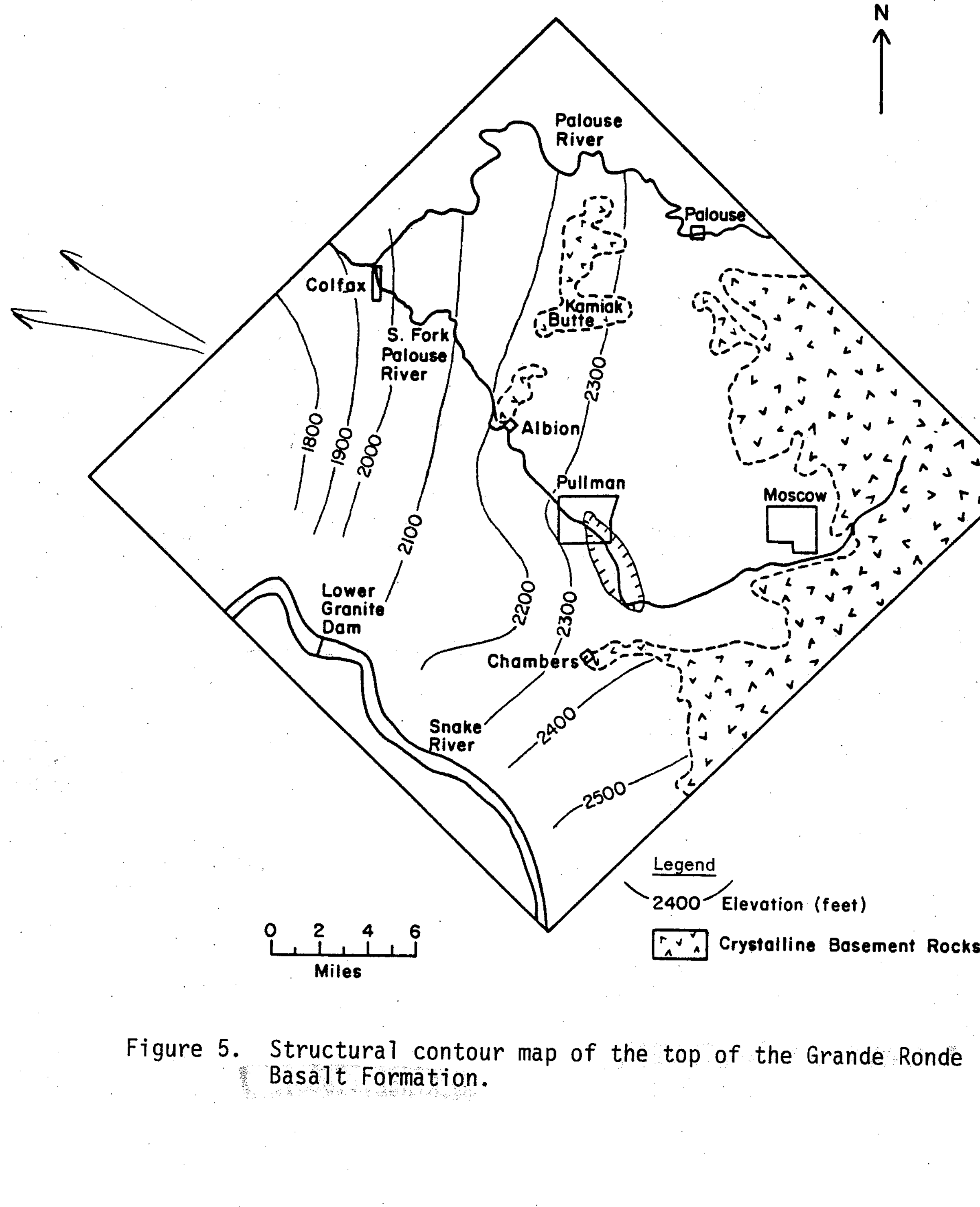


Figure 5. Structural contour map of the top of the Grande Ronde Basalt Formation.

depth. This contact defines the lower limit of the aquifer in the Pullman-Moscow region. Twenty-four magnetotelluric soundings were obtained distributed uniformly across the basin. The first sounding was taken east of Moscow to determine the characteristics of the crystalline rocks. The second sounding was taken near Moscow well 9, which completely penetrates through the basalt, to check the characteristics of a known thickness of basalt. The work at the rest of the soundings incorporated this information.

The final product of the soundings is a contour map of basalt thickness (fig. 6). The total thickness of the basalt is about 1,300 feet at Moscow and 2,000 feet at Pullman. A zone between Moscow and Pullman has a thickness greater than 2,000 feet. The basalt thickens significantly to the northwest where thicknesses are in excess of 3,000 feet.

A map of the elevation of the basalt-crystalline rock contact is derived by subtracting the thickness map from the map of the upper Wanapum surface (fig. 7). This procedure provides another tool for viewing the results of the magnetotelluric investigation. The internal basement low shown on figure 7 may be a result of sounding spacing and location.

The structural contour maps and the surface topographic map define the three hydrostratigraphic units that comprise the hydrogeologic framework. Land surface and the top of the Wanapum Formation define the thickness of the loess unit. The top of the Wanapum Formation and the top of the Grande Ronde Formation define the thickness of the Wanapum Basalt unit. The top of the Grande Ronde Formation and the crystalline

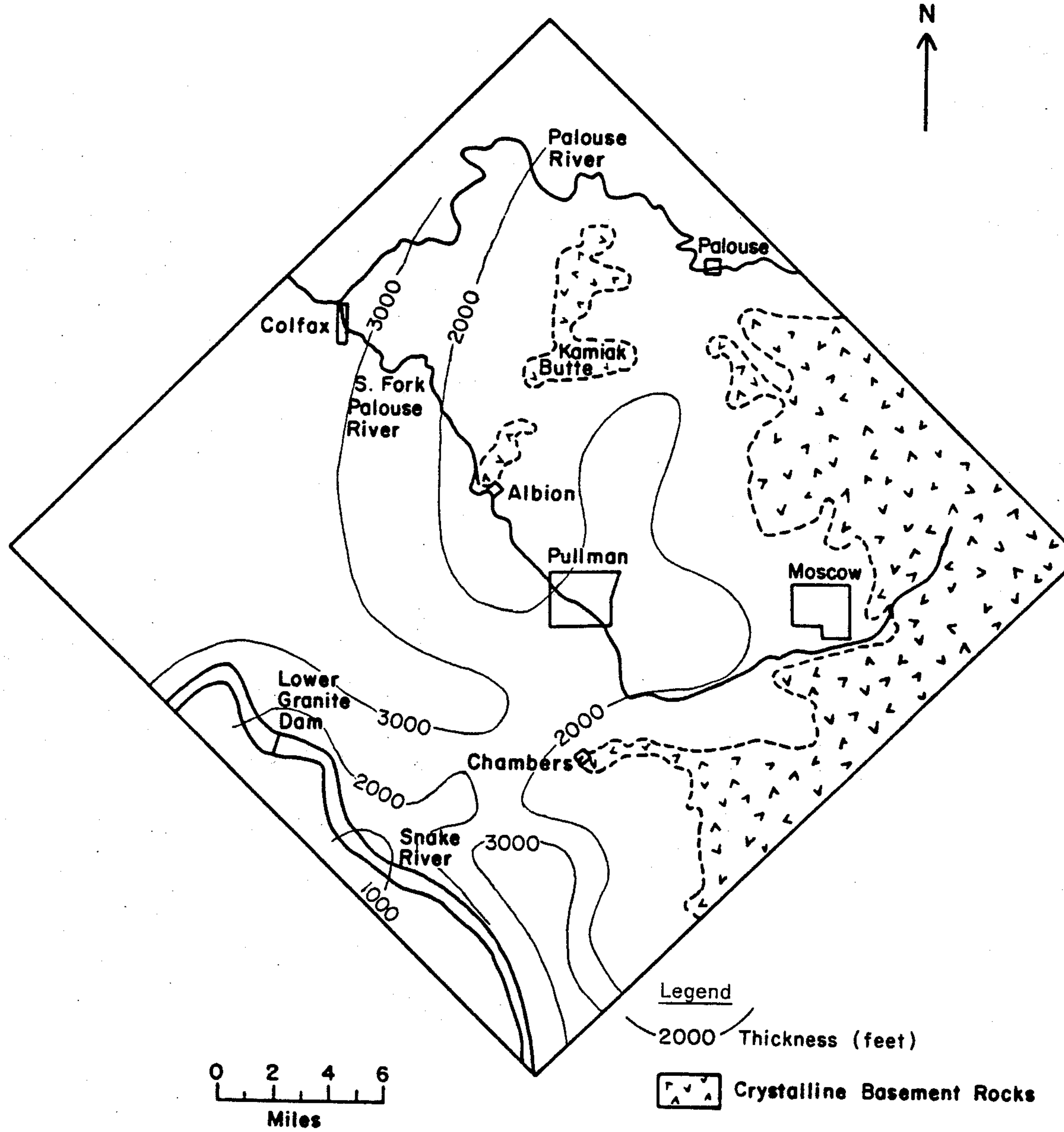


Figure 6. Thickness of the basalt (modified from Klein and others, 1987).

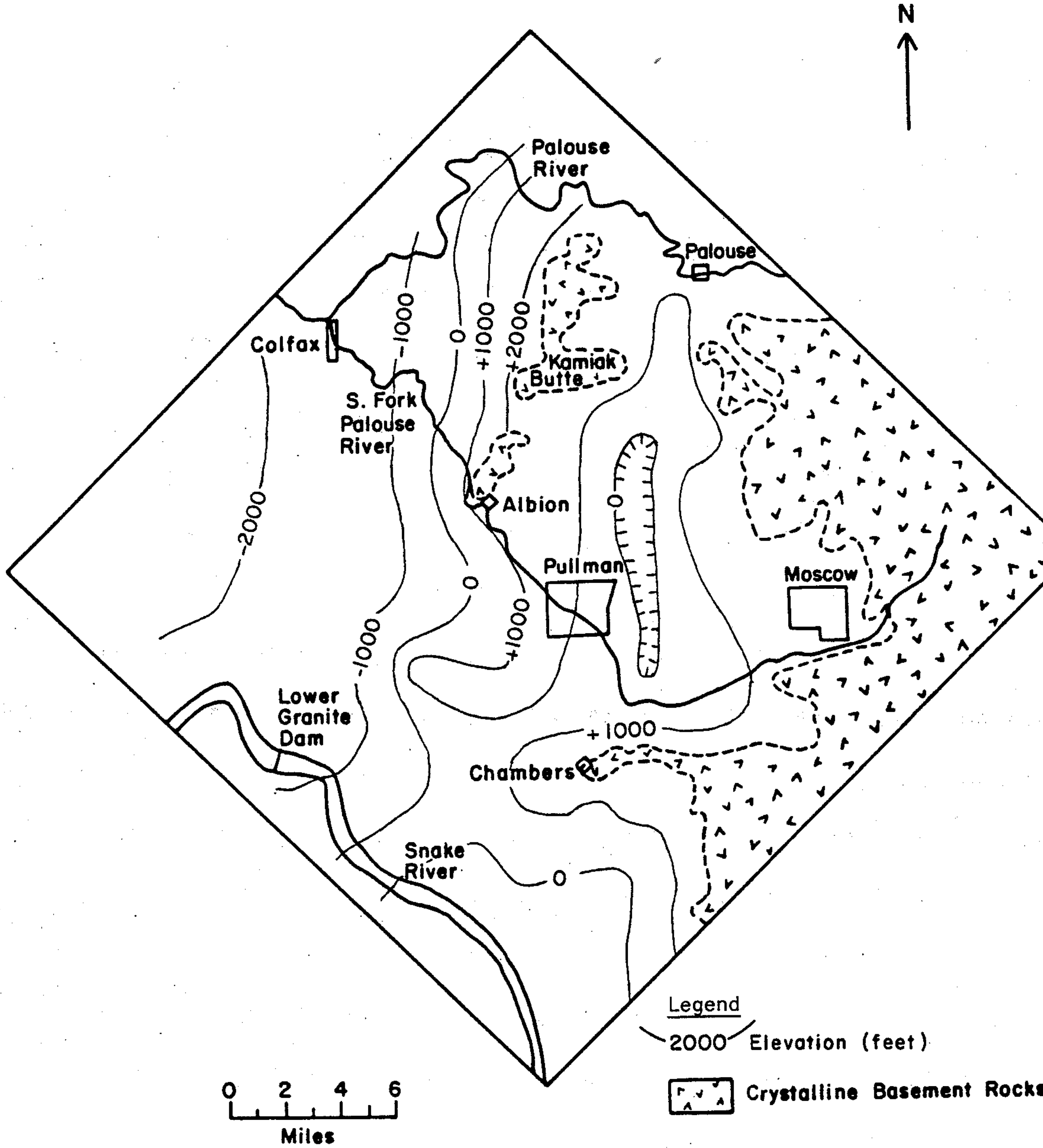


Figure 7. Structural contour map of the top of the crystalline basement rocks.

Recharge

rock contact define the thickness of the Grande Ronde Basalt unit. The perspective view in figure 8 shows the relative thickness of each layer (not to scale). The Snake River Canyon cuts through the upper two layers and much of the third.

Ralston now says from streams I agree! XI-9-89

Recharge

Most of the recharge to the ground-water system appears to occur from infiltration of precipitation through the surficial loess. Water levels in the unconfined aquifer 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 when high precipitation and little evapotranspiration occur simultaneously. High intensity, low duration precipitation events may produce recharge at other times of the year. Extensive long-term cultivation by heavy machinery may have created a low permeability zone beneath the ploughed horizon in the soil (Williams, personal communication, 1985). Williams and Allman (1969) indicate that bioturbation is an important mechanism in infiltration through the loess. Observations by Williams suggest that maximum recharge through the loess occurs in low areas where the relief is most gentle. Surface runoff and shallow subsurface lateral flow accumulates in these areas during spring snow melt (Williams, personal communication, 1985).

Ground-Water Flow

Ground water in the Pullman-Moscow region appears to flow generally to the west. Maps by Bauer and others (1985) reveal that ground water flows toward the Snake River from both sides of the river. This

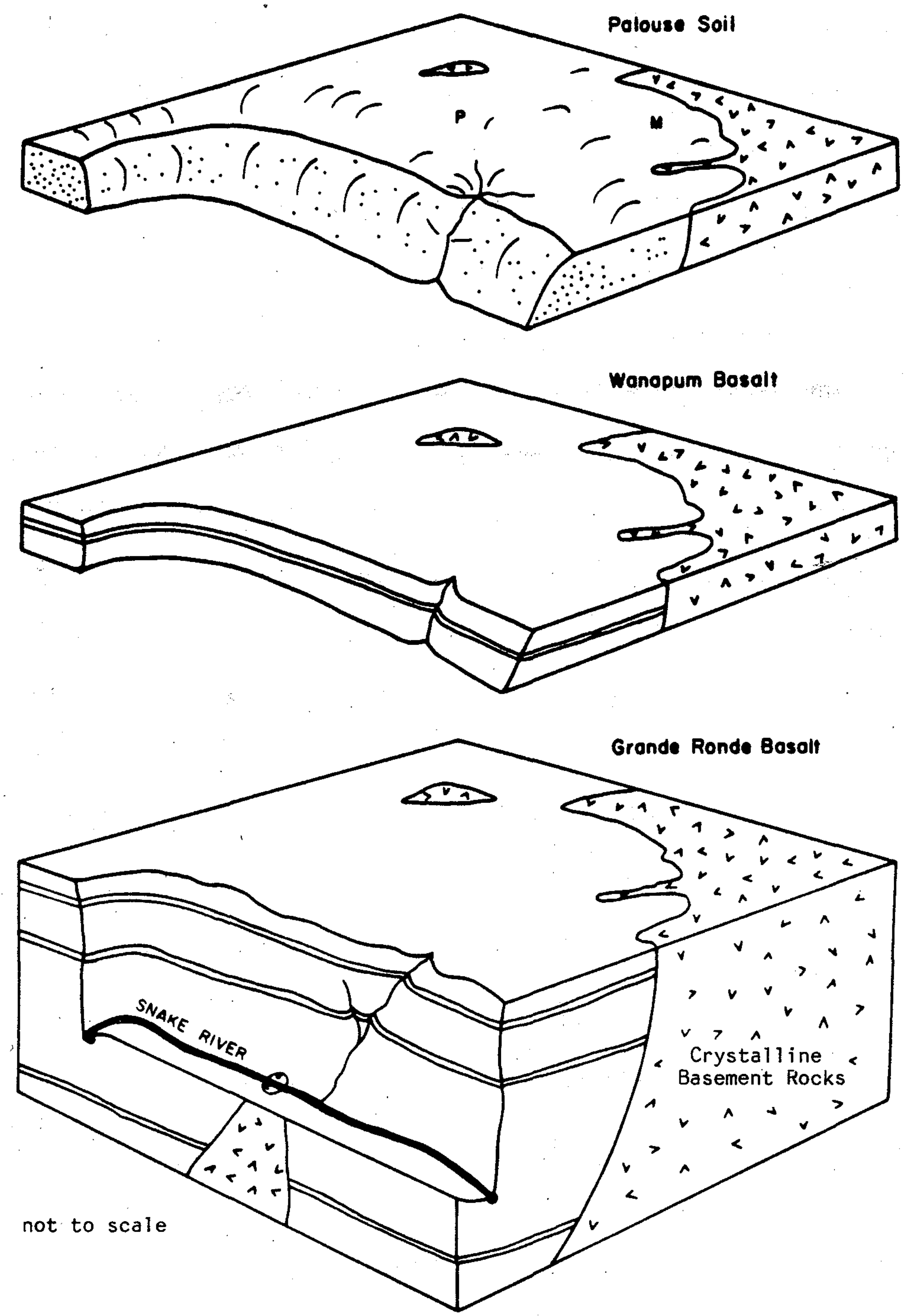


Figure 8. Three-dimensional perspective of the layered aquifer system.

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. Wells in the Grande Ronde Basalt along the Snake River have water levels similar to river stage. Water levels in the deepest wells in the basin near Moscow have water levels about 1500 feet higher than the river.

The basalt flow interiors and fine-grained sedimentary interbeds are important controls on the vertical movement of ground water. Thinner fractured basalt flow interiors would be expected to permit significant downward movement of water. Thicker basalt flows have more massive centers that probably impede flow. Lenses of sticky clay may limit the downward movement of water. The magnitude of such vertical leakage is dependent on the areal extent, thickness, and continuity of the lenses. More vertical leakage may occur as the percentage of coarse-grained material in the interbeds increases.

Discharge

The Snake River appears to be the regional ground-water discharge area in the Moscow-Pullman region. Ground water flowing toward the river may discharge as small streams, springs, and seeps along the canyon wall, or it may discharge directly into the river. The rate of discharge directly to the river is unknown; field observations indicate that the canyon wall is a seepage face (Lum, personal communication, 1986). The large surface area of the sides of the Snake River Canyon relative to the area of the Snake River and the preferential horizontal flow paths between the basalt flows imply that a significant portion of the discharge from the basin may discharge through the sides of the canyon. The rate of discharge is unknown, but it probably does not vary much throughout the year; The deep regional flow system appears to be insensitive to seasonal fluctuations in precipitation. Ground water also discharges to the Palouse River along the northwest side of the region. The Palouse River is incised only into the upper Grande Ronde Basalt; therefore, discharge to the Palouse River is probably much less than discharge to the Snake River.

Ground-water discharge also occurs to small streams from local flow systems in the loess and in the Wanapum Basalt Formation. During the late summer and fall, total stream flow probably is the result of discharge from the shallower ground-water systems. This ground-water component of flow is termed baseflow and is present throughout the year. Surface runoff from precipitation and snow melt is a seasonal component of stream-flow. Streamflow measurements by the U.S. Geological Survey in October, 1984, quantify the average annual component of streamflow attributable to direct connection with the ground-water system (fig. 9). This information is important in the modeling of ground water-surface water interactions.

Ground-Water Pumpage

The Pullman-Moscow area has a history of pumpage increases (fig. 10). Moscow and Pullman are the pumpage centers of the basin, but the municipalities and universities maintain separate wells. Older municipal wells in Moscow and numerous domestic wells bottom in the Wanapum basalt. Most of the municipal and university wells obtain water from the Grande Ronde Basalt Formation.

Pullman ≅ 12 miles horizontal from Snake

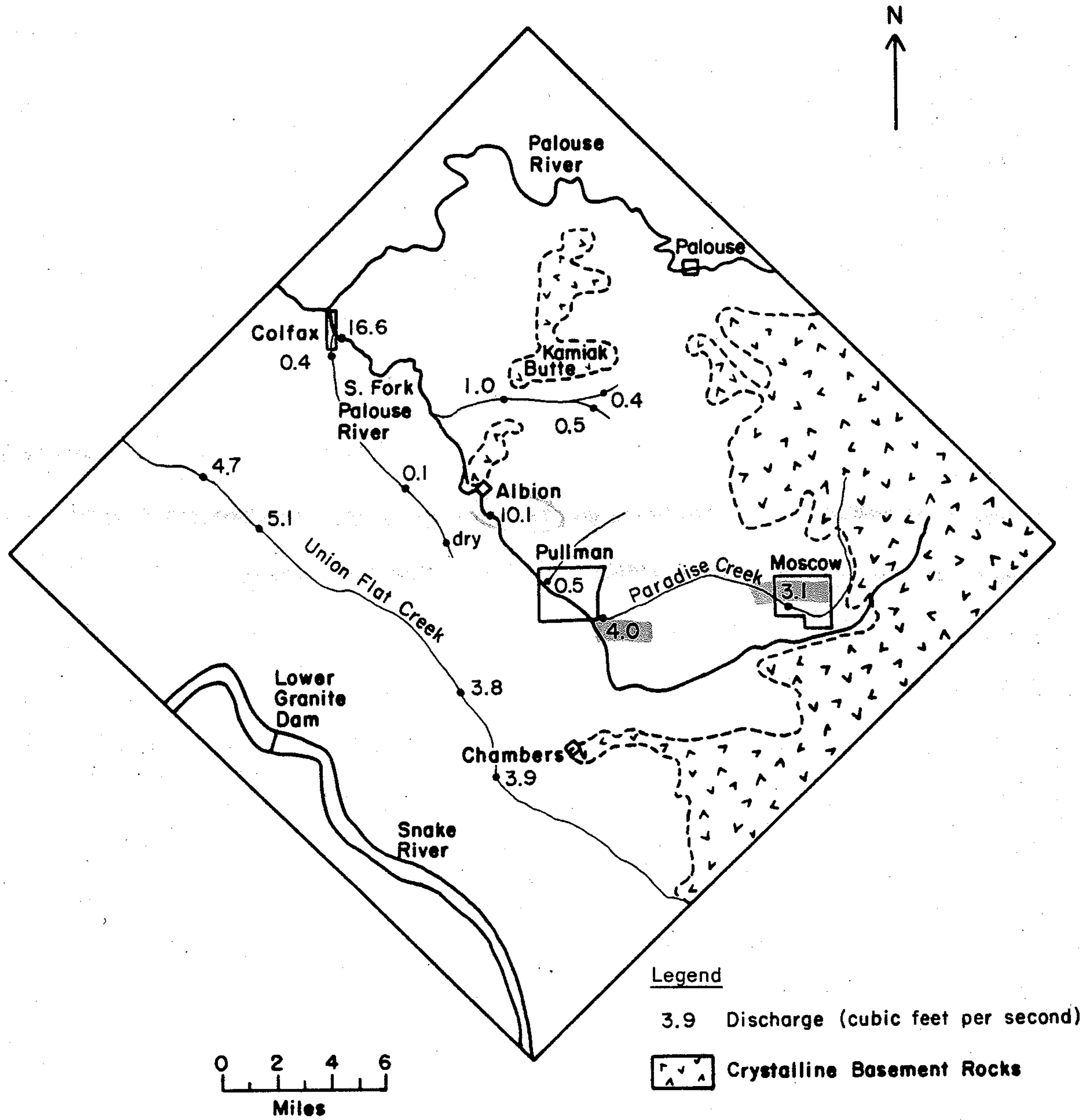


Figure 9. Streamflow measurements, October, 1984 (Blazs, personal communication, 1984).

Low flow season yet still has enough to meet regional needs (at Albion).

South Fork of Palouse?

$$\frac{9 \times 10^5 \text{ cf per day}}{3600 \times 24 \frac{\text{sec}}{\text{day}}} = 10.416 \text{ cfs} \times 0.646 \text{ mgd} = 6.73 \times 10^6 \text{ gpd}$$

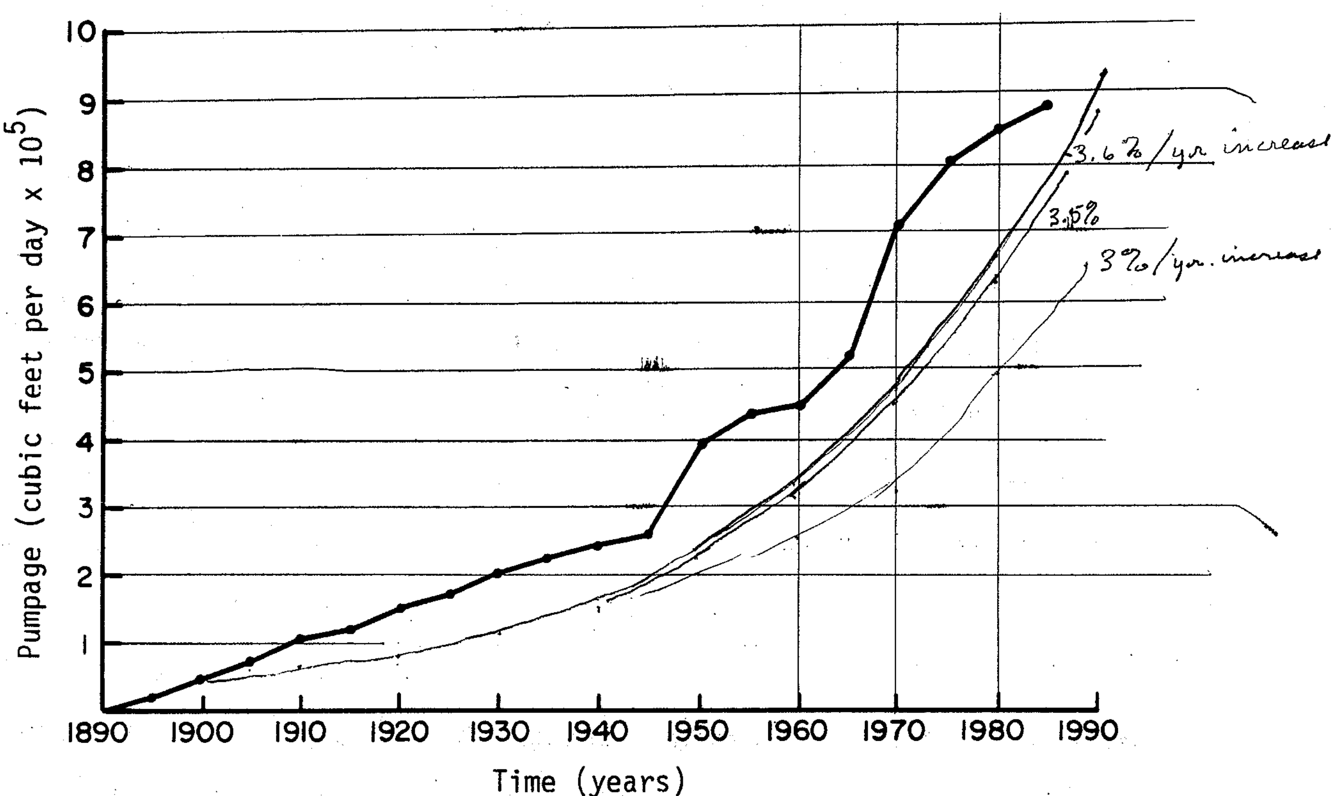


Figure 10. Plot of five-year averages of total pumpage for major wells operated by Pullman, Moscow, Washington State University, and the University of Idaho.

Water Level Declines

Prior to the drilling of wells, ground-water resources in the Pullman-Moscow area were in a state of dynamic equilibrium with ground-water recharge equalling ground-water discharge. Consumptive discharge from pumpage produced an imbalance in the system. The initial response of the system was a reduction in the volume of water stored in the basalt aquifers as a result of water level declines. In many basins, a decline in water levels causes a decrease in natural discharge and/or an increase in natural recharge. This adjustment can produce a new equilibrium if there is a reduction in natural discharge or an increase in the capture of recharge equal to the consumptive pumpage. Ground-water modeling may be used to indicate the extent to which a new equilibrium might be achieved in the Pullman-Moscow area.

Water level declines from pumpage in the Grande Ronde Basalt Formation have been documented in Moscow and Pullman. Hydrographs reveal a history of water level decline that is similar for the two communities (fig. 11). The recent rate of decline is about 1.5 feet annually. Measurable water level declines for the period 1974 to 1985 occurred within a radius of several miles of the pumping centers of Moscow and Pullman (fig. 12). The area over which water levels have declined for the complete history of pumpage is not known. When the area of water level decline reaches the Snake River Canyon, seepage out the canyon wall should decrease. Streams near Moscow and Pullman also should be affected by the lowered ground-water levels. The amount of reduction in natural ground-water discharge caused by pumpage in the Pullman-Moscow area may be estimated using the ground-water flow model.

Which? Ones must be in Grande Ronde.

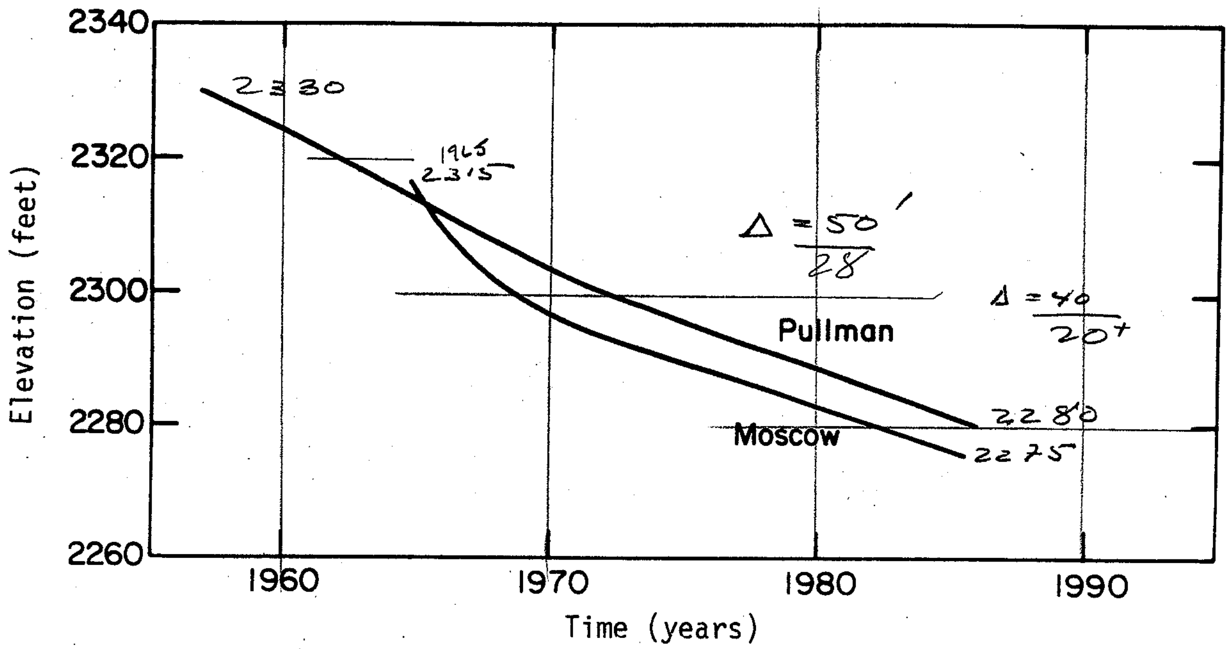


Figure 11. Hydrographs of recent ground-water level declines at Pullman and Moscow.

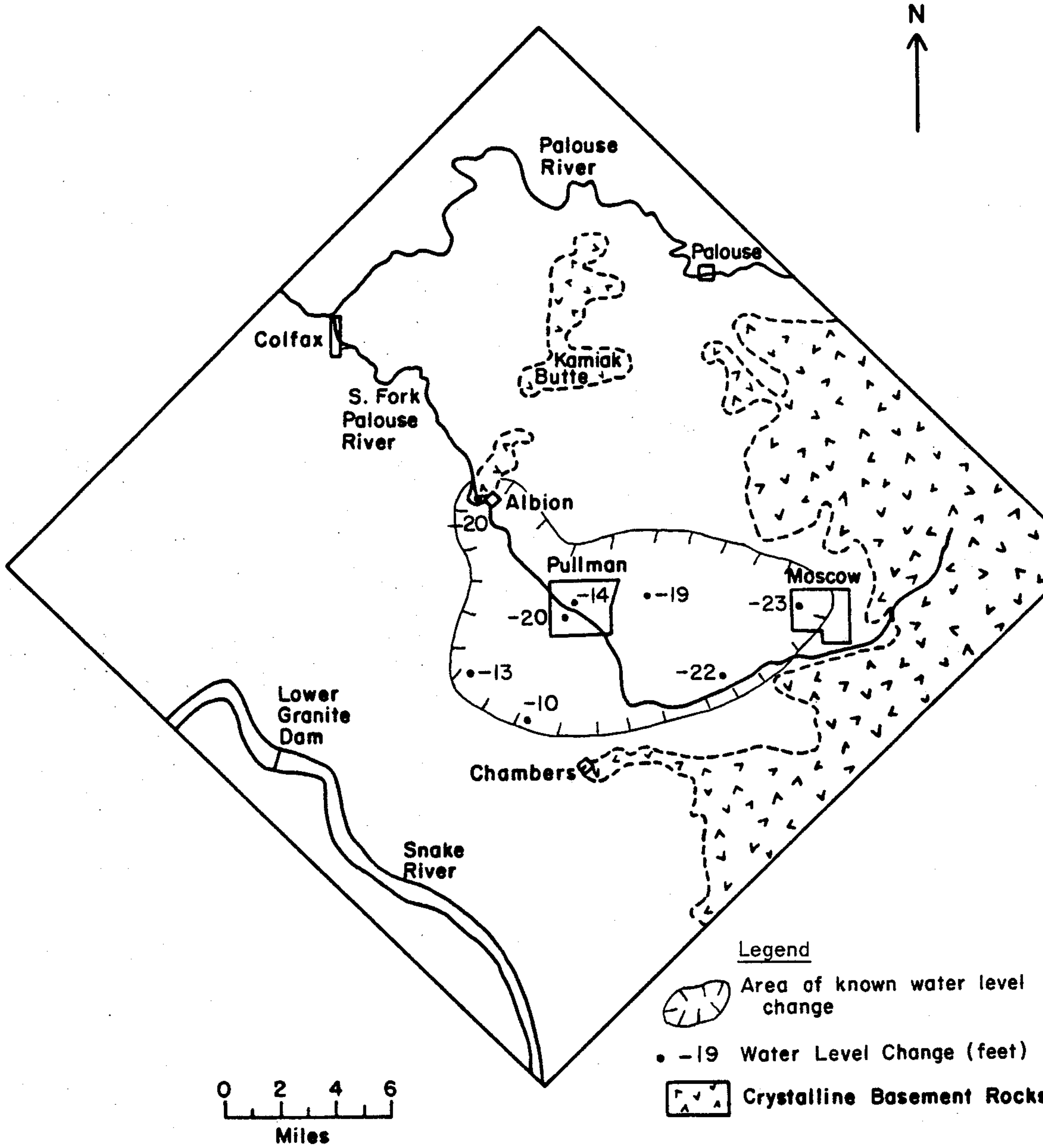


Figure 12. Water level decline in the Grande Ronde Basalt Formation, 1974-85.

The history of ground-water level decline is different for the overlying Wanapum Basalt Formation and loessial Palouse soils. Pumpage from the Wanapum Basalt Formation in Moscow caused water levels to decline in that unit from the 1890's into the 1960's; subsequent cessation in pumpage allowed water levels to recover several ten's of feet in the Wanapum Formation. Water levels in the loess fluctuate in response to the annual precipitation cycle. Water level comparisons between the present study and Barker's (1979) study indicate that water levels in the loess have changed very little over the last decade.

CHAPTER III

MODEL CONSTRUCTION

Introduction

A numerical ground-water model is a mathematical representation of a hydrogeologic framework. Most models approximate the solution of a partial differential equation that describes ground-water flow via finite difference or finite element numerical techniques. A three-dimensional model describes separate subsurface zones or layers that comprise the ground-water flow system. Such layers often are termed hydrostratigraphic units. Hydrogeologic properties of these layers are simulated by assigning values to model cells created by superimposing a grid on each layer. This procedure is termed discretization of space. Boundary conditions are needed to describe the hydraulic conditions along the edges, top, and bottom of the hydrogeologic framework. Model construction is completed when the data that describe the hydrogeologic properties of each zone within the model domain have been collected, analyzed, compiled, and input to the numerical model. Model calibration involves the adjustment of input data in order to reproduce historic water level data. In summary, the modeling procedure transforms the conceptual hydrogeologic framework into a discretized mathematical domain that can be used to simulate the response of a ground-water flow system to superimposed hydraulic stresses. The pumping of ground water from wells is the stress of major interest.

Discretization of Space

A regular grid mesh containing one-half mile square blocks is utilized in this study to discretize the hydrogeologic framework. This size facilitates adequate representation of the distribution of values of hydraulic properties without creating too large a grid. The grid is oriented northwest-southeast in order to make it coincide with the major surface streams that strike in that direction (fig. 13). These streams include the Snake River, Union Flat Creek, and the South Fork of the Palouse River. The grid is intended to extend far enough to include all of the hydrogeologic boundaries or extend far enough that boundaries have little influence on model results in the Pullman and Moscow areas. Zones or portions of zones that occur outside of assigned hydrogeologic boundaries are deactivated by the computer program.

Hydrostratigraphic Units

The model includes three horizontal hydrostratigraphic units. The top layer represents the loess; the second layer represents the Wanapum Basalt Formation; and the third layer represents the Grande Ronde Basalt Formation. The rationale for the selection of these units is presented in the section entitled "Definition of Hydrostratigraphic 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 or metamorphic rocks, while both the loess and Wanapum Basalt are missing at the Snake River Canyon.

The three hydrostratigraphic units of the hydrogeologic framework described previously were assembled into the numerical model. The

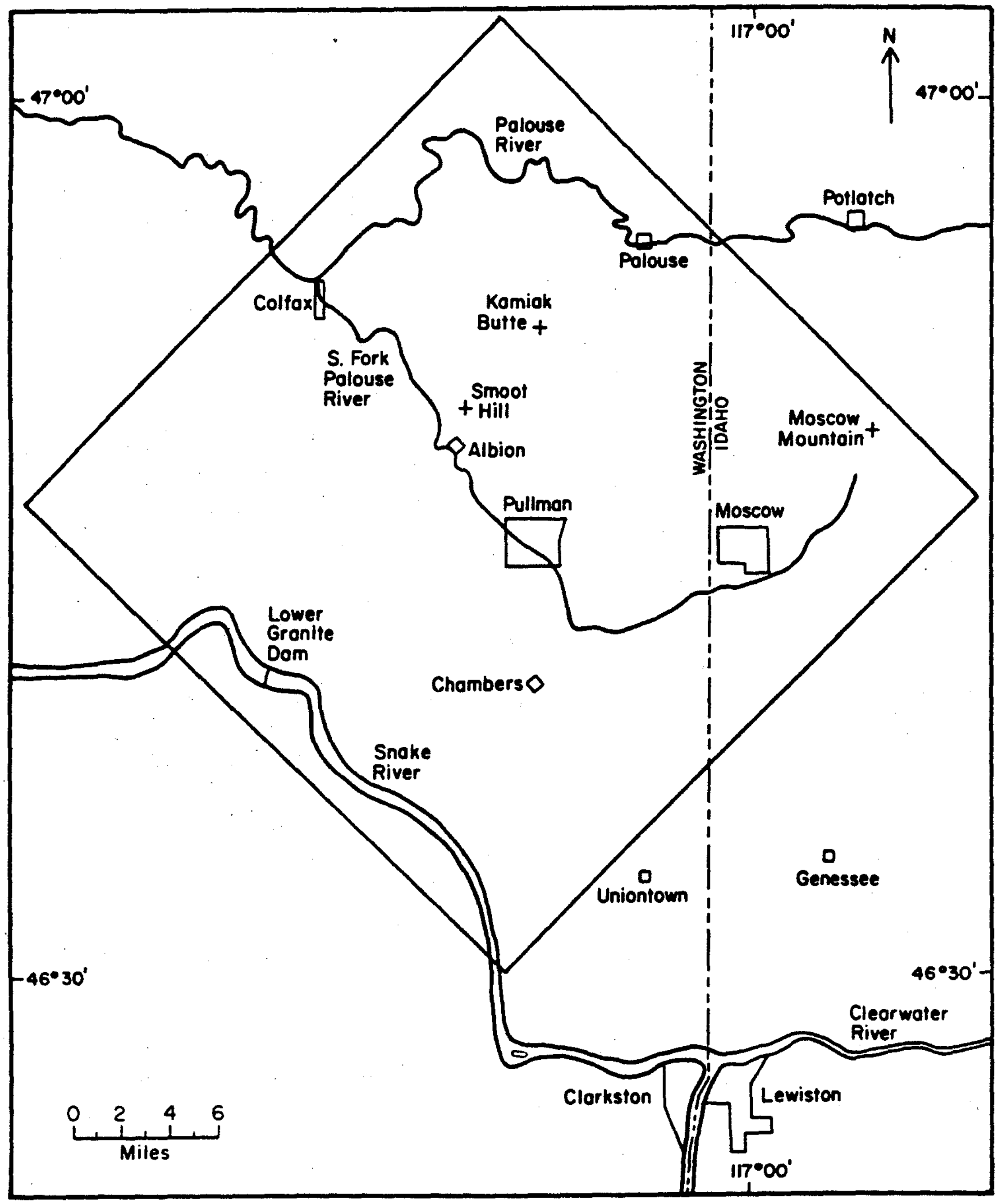
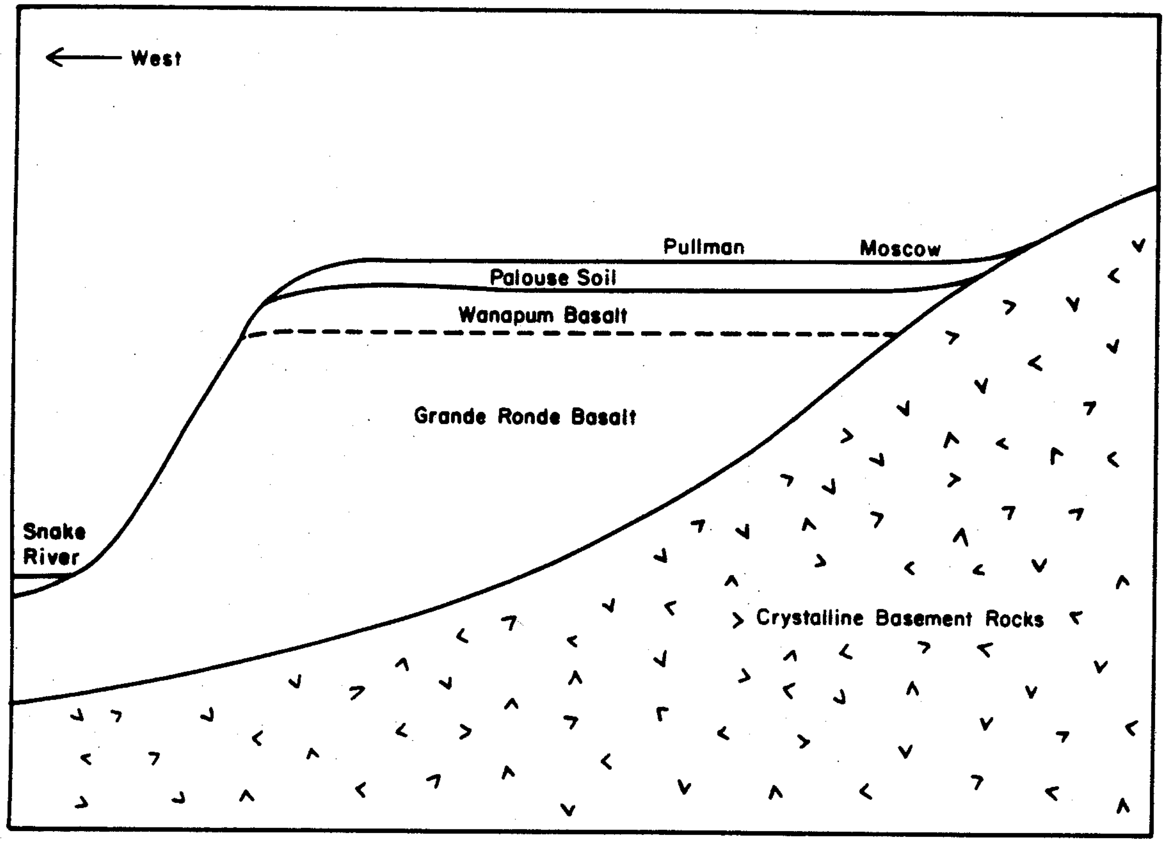


Figure 13. Location and orientation of the model grid.



Cross-section not to scale

Figure 14. Idealized cross-section through the Pullman-Moscow area.

elevation of land surface and the elevation of the top of the Wanapum Formation define the thickness of the loess unit. The elevation of the top of the Wanapum Formation and the elevation of the top of the Grande Ronde formation define the thickness of the Wanapum Basalt unit. The elevation of the top of the Grande Ronde Formation and the elevation of the crystalline rock contact define the thickness of the Grande Ronde Basalt unit. In this manner the thicknesses of each layer are defined throughout the model. Refer to figure 8 for a perspective view of the three layers.

Boundary Conditions

The loess hydrostratigraphic unit is modeled with no-flow boundaries on all sides. Some of this boundary corresponds to the topographic divide along the eastern and southern edges of the model area. The loess is cut by the Snake River and Palouse River and there is no flow across these boundaries. Elsewhere, flow in the loess is very localized with respect to topography; consequently the no-flow boundary was believed to be justified on a regional scale.

Two different types of boundary conditions are used to define the edges of the Wanapum and Grande Ronde hydrostratigraphic units: constant head boundaries and no-flow boundaries (fig. 15). 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 this contact has been studied extensively (Ross, 1965; Bockius, 1985). The low permeability of the crystalline rocks justifies a no flow boundary at the contact of the basalt rocks with the crystalline rocks.

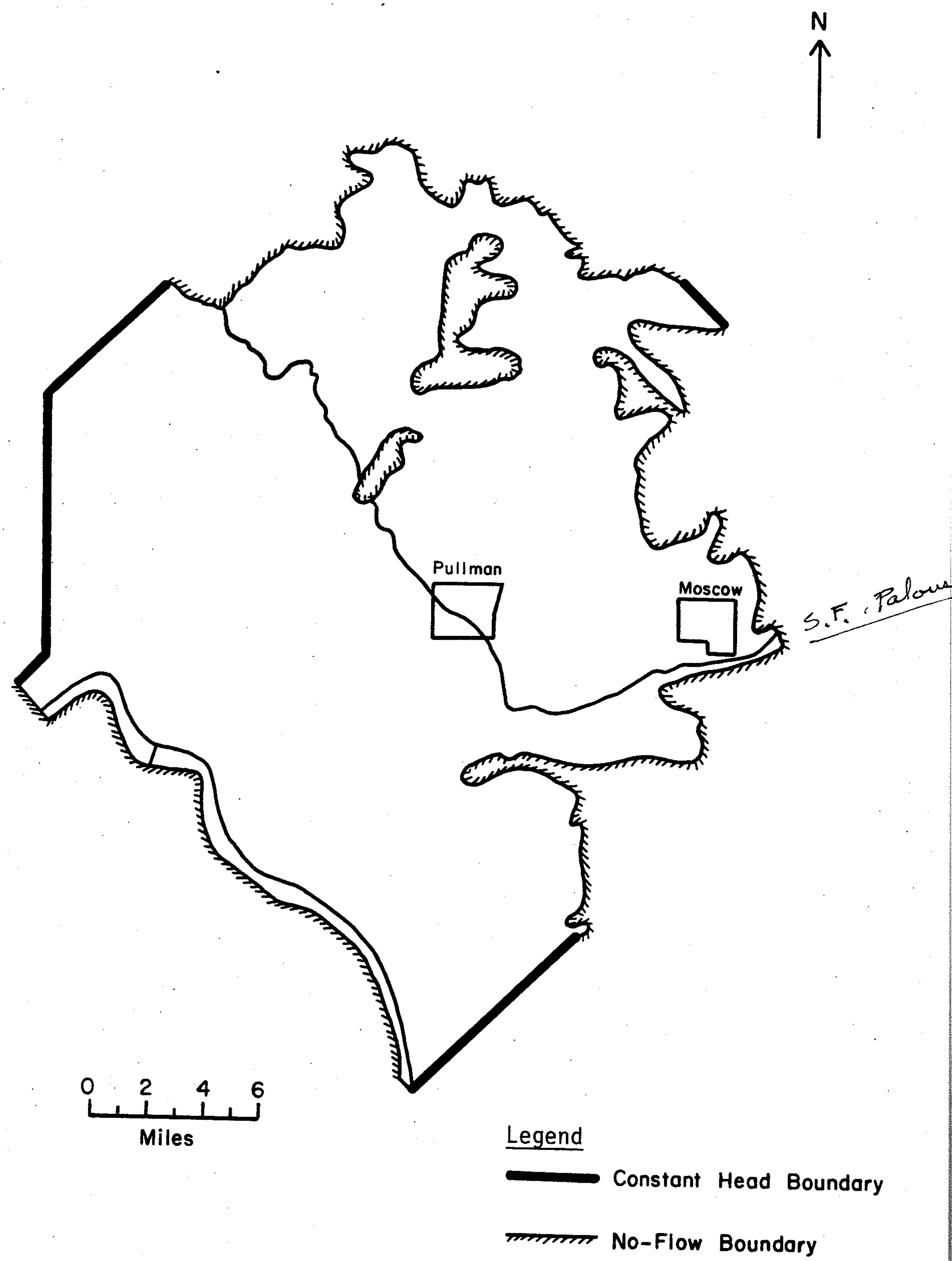


Figure 15. Boundary conditions imposed on the basalt hydrostratigraphic units of the three-dimensional model.

No-flow boundaries also are used along the west and southwest side of the Snake River. A horizontal no-flow boundary beneath the Snake River can be deduced because of upward vertical flow beneath the Snake River. This conclusion is based on the assumption that ground water flows towards the Snake River from either side. Consequently, the boundary is actually located in the center of the river due to symmetry. Similar conditions are assumed for the Palouse River. However, the assumption for the Palouse River is less well supported by field data. The small size of the river implies that it is not a regional discharge area and there may be underflow. In spite of this uncertainty, the boundary is designated as no flow because it is sufficiently distant from the pumping centers of Moscow and Pullman that the effects of errors will be significantly dissipated over the intervening distance. The choice of the no-flow boundary along the Palouse River would cause greater water level declines resulting from pumpage in the model because underflow along the Palouse River would not exist as a source of water to wells in the model.

The remaining segments of the model boundary are designated as constant head boundaries (fig. 15). A constant head boundary creates a ground-water gradient into or out of the aquifer system, depending on the hydraulic heads in the region near the boundary. The model uses this gradient to calculate a flux into or out of the appropriate hydrostratigraphic unit at the location of the boundary. Care must be exercised with constant head boundaries because model pumpage can artificially induce unrealistically large fluxes into the model with a subsequent underprediction of water level decline. This problem is discussed previously in connection with Barker's (1979) model. The effect that a constant head boundary has on stresses imposed on a ground-water model may be investigated by replacing the constant head boundary with a constant flux boundary and observing the difference in hydraulic heads calculated by the model.

The northwestern edge of the model and segments along the northeast and southeast sides of the model are designated as constant head boundaries. These boundary conditions are imposed on the segments of the boundary that connect the more obvious hydrologic boundaries discussed previously. However, sufficient water level data exists to adequately define 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 out of the model area to the northwest and into the model on the northeast and southeast. The quantity of the flux across each boundary is not known.

Data Inputs

Hydraulic Properties of Hydrostratigraphic Units

Loess. Most infiltration of water in the Pullman-Moscow area is into the surficial loess soil. Hydraulic conductivities of loess can range from several feet to several hundredths of a foot per day (Freeze and Cherry, 1979). McGary and Lambert (1962) note a slightly greater range. The loess may be approximated as homogeneous and isotropic, although the characteristics of earth slumps and mud flows in the loess suggest that years of cultivation has compacted a low permeability zone beneath the ploughed horizon. Long term infiltration rates of several inches per hour near Moscow (Williams and Allman, 1969) indicate that portions of the loess are on the higher end of the published scale for hydraulic conductivity. Clayey layers that occur within the loess could limit the vertical hydraulic conductivity. A value of 5 feet per day is assumed for the horizontal hydraulic conductivity of the loess; 0.05 feet per day is obtained for the vertical hydraulic conductivity by assuming an anisotropy ratio of 0.01.

Basalt. Basalt flows comprise the majority of the hydrogeologic framework in the Pullman-Moscow region. Table 2 lists values of saturated hydraulic conductivity for basalts as compiled by Rockwell Hanford Operations, U.S. Geological Survey, and University of Idaho researchers. Hydraulic conductivity data compiled for the eastern edge of the Columbia Plateau (Lum, personal communication, 1986) suggest a hydraulic conductivity of 2 feet/day as an average for the entire thickness of basalt. This value is very near the median value of 1.7 feet/day as identified by the RASA project in the Columbia Plateau (Vaccaro, personal communication, 1986). The value of hydraulic conductivity probably is greater than the median near the margins of the plateau where thinner, less massive basalts have a greater percentage of the flows composed of flow tops.

Pumping test data indicate that the horizontal hydraulic conductivity is at least an order of magnitude greater than 2 feet/day in the upper Grande Ronde Basalt near Pullman and Moscow (table 2). This value probably reflects thin basalt flows at the margin of the basin.

Table 2. Hydraulic Coefficients

⇒ years to move several feet!

Source of Data	K_h (ft/day)	K_v (ft/day)	S
Barker (1979)	--	--	0.005
Lum, personal comm. (1986)	0.03-22.0	0.00001-0.001	0.000001-0.001
Luzier and Skrivan (1973)	--	--	0.0015-0.006
Mac Nish and Barker (1976)	--	--	0.00047-0.00475
Ralston, personal comm. (1986)	--	--	0.003-0.02
Strait and Spane (1982a)	2.6-10.9	--	--
Strait and Spane (1982b)	1.6- 3.1	--	--
Strait and Spane (1982c)	0.00000021-0.0000049	--	--
Tanaka and others (1974)	--	--	0.0025

K_h - Horizontal hydraulic conductivty
K_v - Vertical hydraulic conductivity
S - Storage coefficient

The effective vertical hydraulic conductivity of the sequence of basalt flows is much more difficult to define. In a layered system, the smallest vertical hydraulic conductivity controls ground-water flow. In the Pullman-Moscow area, these controlling layers consist of flow centers and clay interbeds. Field measurements of vertical hydraulic conductivity do not exist for either the flow interiors or clay interbeds in the area. However, 1×10^{-4} feet per day is a reasonable estimate of vertical hydraulic conductivity for both lithologies (Freeze and Cherry, 1979); initial inputs of vertical hydraulic conductivity incorporated this value.

Different horizontal and vertical hydraulic conductivities may be assigned to each block in the model. Initially, homogeneous hydrostratigraphic units were defined by assigning average values of hydraulic conductivity to each group of cells that constitute a hydrostratigraphic unit. Zones of increasing hydraulic conductivity were introduced to the basalt layers in the model in order to implement the conceptual model of increasing hydraulic conductivity in the basalts as they thin toward the margin of the Columbia Plateau. The final version of the Grande Ronde layer has seven zones.

Recharge Model

Recharge to the ground-water system is evaluated using the U.S. Geological Survey recharge model (Bauer and Vaccaro, 1985). The recharge model simulates the physical processes of soil moisture accumulation, evaporation from the soil, evaporation of intercepted moisture, plant transpiration, surface runoff, and the accumulation and melting of snow. The difference between these terms and precipitation incorporates error and the rate of deep percolation of water beneath the root zone into the ground-water system.

The model calculates the rate of deep percolation on a daily basis. As many years as possible are simulated for the Pullman-Moscow area using measured daily values of precipitation, maximum and minimum air temperature, and stream discharge rates. Calculations based on average monthly or average yearly values of these parameters tend to negate the impacts of high intensity, short duration events that could cause deep percolation.

The recharge model uses a one-half mile square grid system, similar to the one used in the three-dimensional model, to divide the surface into blocks. These blocks are small enough to account for most variations in soil type, vegetation, land use, elevation, slope, aspect, and precipitation. The recharge model calculates the water budget for a control volume that extends from the plant-covered surface down to the maximum root depth. The root zone is divided into 6 inch layers, each of which has its own separate physical characteristics.

The precipitation rate is interpolated to each cell in the model from data collected at several precipitation guages utilizing a distance weighted method; the interpolation includes an adjustment for elevation. If the average daily air temperature falls below 32^{o}F, all of the precipitation is assumed to be snow and is allowed to be intercepted by the existing plant cover. Potential evapotranspiration is computed based on the Jensen-Haise method (Jensen, 1973). Potential evapotranspiration is calculated based on that which would occur in a fully covered field of mature alfalfa, water nonlimiting. Slope and aspect are also included in this calculation. The alfalfa number is adjusted to the actual cropping pattern in the Pullman-Moscow area via a coefficient (Vaccaro, personal communication, 1986). Surface runoff for each cell in the grid is computed on the basis of the modified Soil Conservation Service method of Wight and Neff (1983).

Any water not accounted for by evapotranspiration and runoff is assumed to infiltrate the soil profile. If the amount of infiltrated water is greater than the difference between the total water holding capacity and the soil moisture content that exists at the time of calculation, the extra water is assumed to constitute deep percolation and becomes part of the ground-water resource. Under dry conditions, however, plant roots may extract water from below the root zone (Hammel, personal communication, 1986).

Preliminary applications of the recharge model in the Pullman-Moscow area revealed an average recharge rate of 7.4 inches across the basin. This rate appeared to be large (Ralston, personal communication, 1986). Review of the recharge model by U.S. Geological Survey, University of Idaho, and Washington State University researchers revealed that the root depth of crops in the Palouse area was underestimated and crop fallow conditions were overestimated. Loessial soils allow for wheat rooting depths that approach 6 feet compared with 3 feet on an average across the nation (Vaccaro, personal communication, 1986). The recharge model is very sensitive to this variable. Rerunning of the recharge model with a 6 foot rooting depth reduced the recharge rate to an average of 3.6 inches/year to the surface of the basin. This recharge rate is assumed to be a known quantity for operation of the ground-water flow model.

Figure 16 shows the distribution of recharge over the basin based on average precipitation and current land use patterns. Orographic effects on the distribution of recharge can be seen clearly. Lowest values of recharge occur in the Snake River Canyon at elevations below 1000 feet. Recharge increases to near average in the interior of the basin and is greatest in the eastern mountains. The areas of depression in the contours may be related to soil type. The areal variations in recharge are incorporated into the ground-water flow model. Recharge to the ground-water flow model is supplied to the loess layer present at the

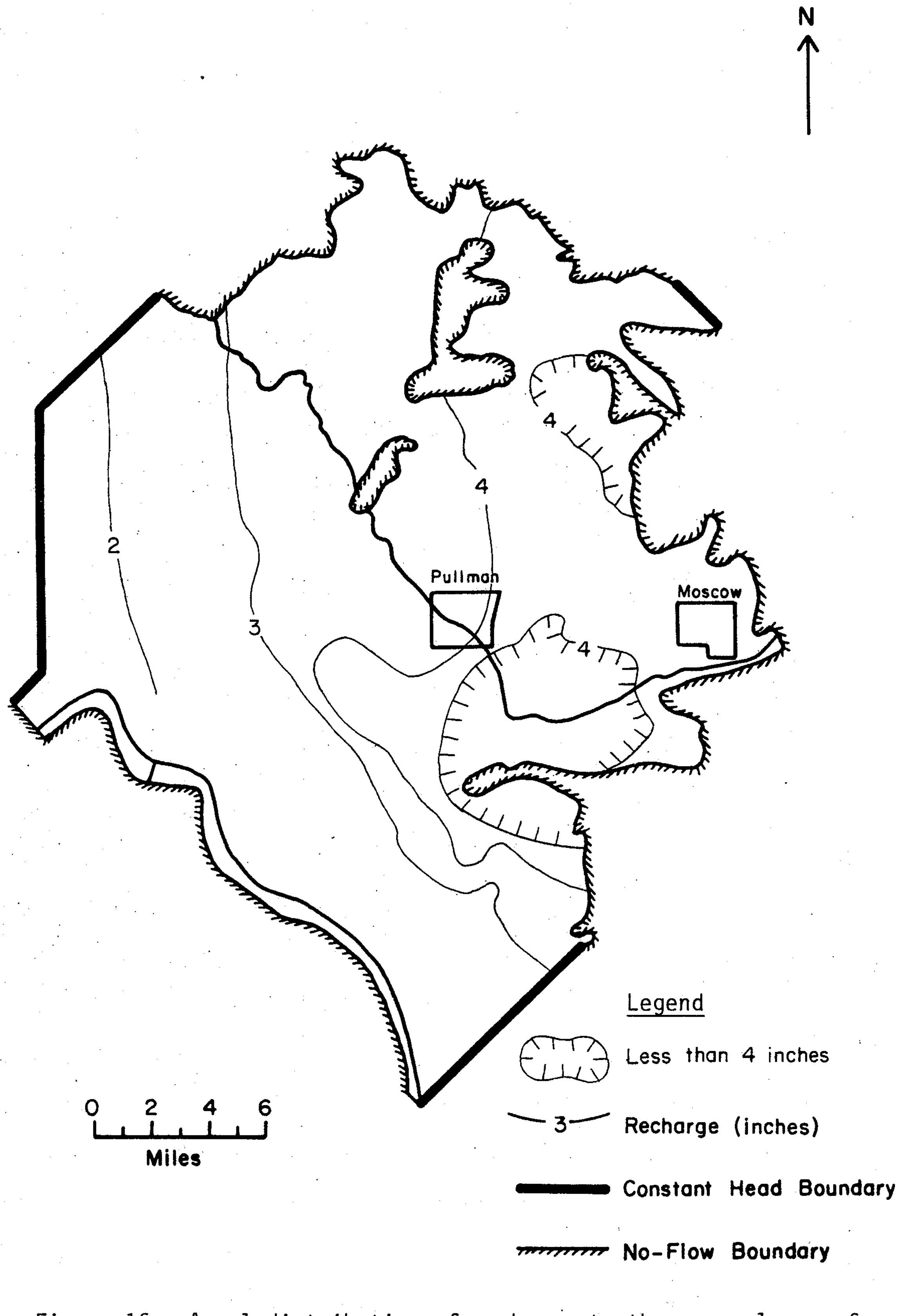


Figure 16. Areal distribution of recharge to the upper layer of the three-dimensional ground-water flow model.

surface except in those areas where the Wanapum or Grande Ronde hydrostratigraphic units are exposed, such as along the Snake River Canyon. To the east, the loess overlies the crystalline basement rocks and extends to the topographic drainage divide.

Hydraulic Connection of Ground Water With Rivers

The River Package is used to simulate river and stream reaches within the ground-water flow model (McDonald and Harbaugh, 1984). River reaches are simulated in the model on a cell by cell basis. Input includes the layer, row, and column in the grid in which the stream flows, the stream stage elevation, the conductance of the riverbed material, and river bottom elevation (McDonald and Harbaugh, 1984). Conductance is the hydraulic conductivity divided by the distance over which the head gradient is calculated. This allows the model to compute a flux either into or out of a river depending on the head gradient from the corresponding layer to the river. The River Package is modified to group the cells that comprise each stream so that the flux may be summed for each stream (Hansen, personal communication, 1985). These fluxes may then be compared to flow measurements of area streams obtained in October, 1984 (fig. 9).

River conductance is based on vertical hydraulic conductivity since most of the communication between the basalt flows and the rivers is assumed to be in the vertical direction. The distance (dz) over which the head gradient is calculated is assumed to be the distance from the cell center to the river bottom. Conceptual and numerical difficulties arise when the cell center elevation is greater than the river bottom elevation. This inconsistency occurs where streams are deeply incised into a layer. In order to correct this problem, conductance is recalculated based on river bottom and the elevation of the bottom of the hydrostratigraphic unit that is deeply incised. The river conductance calculation is described in detail in Appendix A on page 104.

Seepage Faces

Saturated basalt faces along canyons where water is evapotranspired are termed seepage faces. Seepage faces occur along streams and rivers. The major seepage face in the modeled area is along the Snake River Canyon. The average river level is about 1,700 feet below the loess surface in the Pullman-Moscow area. Smaller seepage faces in the basalt occur along the Palouse River, the South Fork Palouse River, and Union Flat Creek. Seepage faces are significant to the ground-water model because they account for a significant portion of the regional ground-water discharge.

Field investigations revealed that portions of the canyon wall of the Snake River are saturated (Lum, personal communication, 1986). There are areas along the canyon wall where there is dense plant cover and the ground is saturated just below the surface. Other portions of the canyon wall appear dry and have little plant cover. For modeling purposes, the canyon wall is assumed to be saturated completely; therefore the average flux out the canyon wall in the model should be less than potential evapotranspiration because the portions of the canyon wall that appear dry are evapotranspiring water at less than the potential rate.

The Drain and Well Packages (McDonald and Harbaugh, 1984) are used in the model to describe areas where water discharges along a seepage face. The drains produce a gradient dependent flux based on the head in the adjacent hydrostratigraphic unit and the head assigned to the drain. Drains are used to model seepage faces along the interior stream valleys. Drains initially were used to simulate the seepage face along the Snake River canyon, but problems occurred. The great thickness of Grande Ronde hydrostratigraphic unit did not allow head dependent fluxes to be modeled adequately. The cell-center head calculated by the model generally was below canyon level in the thick Grande Ronde unit, and the drains were mostly inoperational; consequently the drains are replaced in the three-dimensional model by a constant flux implemented by a well function for each cell corresponding to the seepage face. This implementation utilizes the Well Package of the three-dimensional model (McDonald and Harbaugh, 1984).

The Drain Package is modified to calculate fluxes for specified sets of drains along interior streams (Hansen, personal communication, 1985). Drain conductance is calculated similarly to the river conductance except that drain conductance is based solely on horizontal hydraulic conductivity. In the case of interior streams that cut the basalt, the drain conductance must be multiplied by two to account for the seepage face along both stream banks. The model calculates a head gradient and computes fluxes through the drain based on Darcy's Law. The drain conductance calculation is described in detail in Appendix A on page 104.

Cross-Sectional Model Contruction

Cross-sectional models are two-dimensional slices through the three-dimensional model that are constructed for several reasons. They are used during the initial phase of modeling to gain understanding of the three-dimensional movement of water in the hydrogeologic system. The cross-sectional models also are used as a calibration tool for the three-dimensional model, particularly for vertical hydraulic conductivity. The cross-sectional models provide a cost-effective means of acomplishing that objective. Multiple layers are introduced easily into the Grande Ronde Basalt to investigate the distribution of hydraulic head within this hydrostratigraphic unit. The rationale is to facilitate comparisons between measured water levels for the upper Grande Ronde Basalt Formation and cross-sectional model results.

The cross-sectional models are located on the basis of flow lines drawn perpendicularly to contours of regional hyraulic head distribution. The location of the section lines is shown in figure 17. Good coverage is attained for the interior of the basin. The great thickness of the Grande Ronde unit is modeled as 200 foot thick layers to facilitate simulation of the vertical hydraulic head distribution in the formation and to obtain a more accurate representation of the seepage face in the Snake River Canyon (fig. 18a). The 200 foot division is chosen arbitrarily; it does not represent the actual layering in the Grande Ronde. The exact number of layers depends on the depth to basement along each section, but the average number is 18 layers in the Grande Ronde Formation. The layering allows five or six drains to simulate the seepage face. The flux from these drains forms the basis for the well flux that simulates the seepage face in the three-dimensional model.

Lateral zonation for both horizontal and vertical hydraulic conductivity is incorporated into the construction of the cross-sectional models (fig. 18b). This procedure allows different hydraulic properties

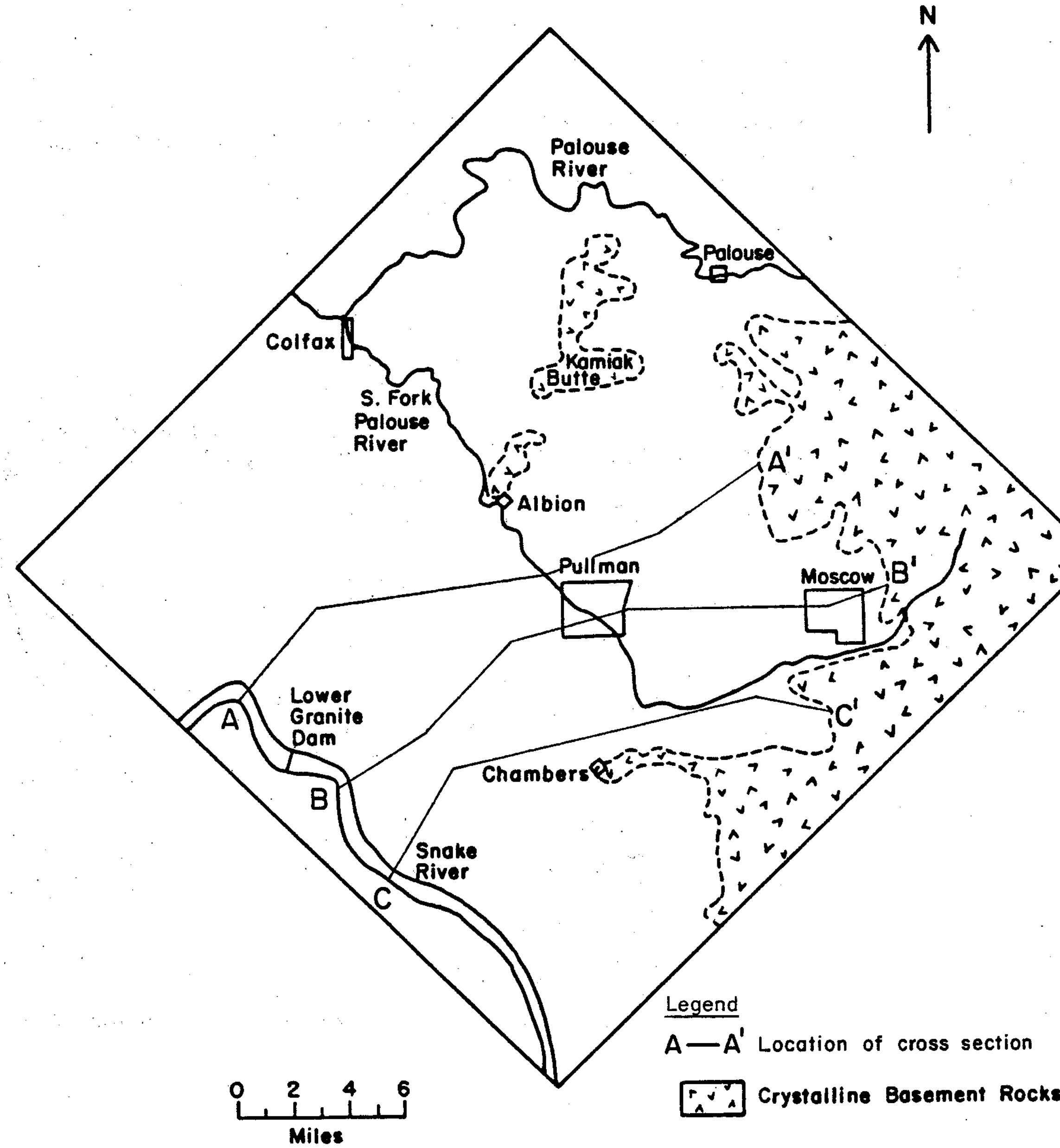


Figure 17. Location of cross-sectional models in the domain of the three-dimensional model.

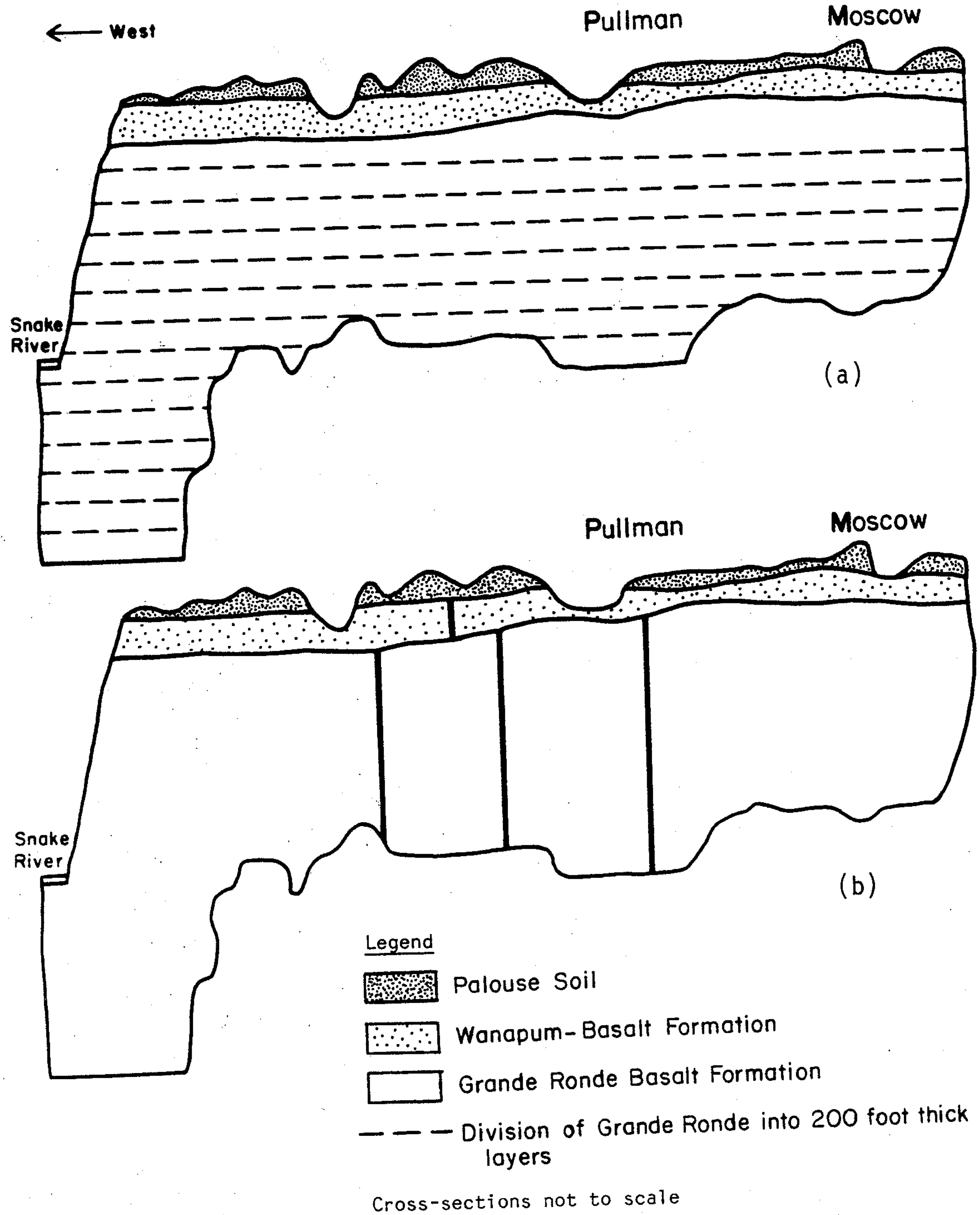


Figure 18. Construction of cross-sectional models: a) layering, b) zonation.

to be entered for each zone. The inclusion of zonation 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; the final version has four zones in the Grande Ronde layer and two in the Wanapum layer. Inability to match observed hydraulic heads with cross-sectional model calculated hydraulic heads led to the inclusion of more zones. Greater complexity within the hydrogeologic framework of the model was required to match the irregular head distribution indicated by the measured water levels.

CHAPTER IV

MODEL CALIBRATION

Introduction

The calibration phase of modeling has the purpose of achieving the closest possible agreement between the numerical model and the physical world that it represents. Konikow (1978, p. 88) notes that "...in practice, the calibration of a deterministic ground-water flow model is frequently acomplished 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, p. 109) 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 acompanied by a verification process. Verification is not well defined in the hydrogeologic literature. According to Wang and Anderson (1982, p. 110), verification is achieved by demonstrating that the model is capable of reproducing an 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 the uniqueness of the model solution. Konikow (1978 p. 88) puts the debate in perspective by stating that "...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 calibration procedure for the Pullman-Moscow ground-water flow model consists of several steps. The cross-sectional models are calibrated to predevelopment conditions. The resulting hydraulic conductivity distributions are applied with little adjustment to a time-average calibration of the three-dimensional model (Prych, 1985, p. 43). The time-average calibration matches the model to average conditions over a selected period of time. The model then is run transiently with no adjustments in hydraulic coefficients to check the results of the calibration by comparing historical water level declines with model calculated water level declines. The ability to match historic water level records provides a measure of verification or reassurance that the model calibration is reasonable. This process would appear to satisfy Wang and Anderson's (1982) definition of verification but does not identify a unique model solution that satisfies Wang and Williams' (1984) definition of calibration.

Cross-Sectional Model Calibration

Cross-sectional models are calibrated to predevelopment hydraulic heads. Predevelopment hydraulic heads are known accurately only for wells at Pullman and Moscow. Wells are considered to penetrate a formation if the elevation of the bottom of the hole is beneath the elevation of the top of the formation. The earliest wells in Moscow tapped the Wanapum Basalt Formation and flowed at land surface. The head was 2,570 feet ± 20 feet (Russell, 1897). Early wells in Pullman tapped the Upper Grande Ronde Basalt Formation where the head was approximately 2,360 feet ± 20 feet (Russell, 1897). In addition to the data points at

Pullman and Moscow, a well is available for calibration near the edge of the Snake River canyon. This well is located near the breaks of the canyon; it penetrates the upper portion of the Grande Ronde Basalt Formation. 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; consequently it is considered acceptable for calibration purposes. The shallow depth to water in this well (200 feet) implies that most of the canyon wall should be a seepage face; therefore all of the drains that simulate the seepage face should be operational in the calibrated cross-sectional models.

Calibration of the cross-sectional models was achieved by varying horizontal hydraulic conductivity and the corresponding vertical hydraulic conductivity ratio for all zones in the basalt hydrostratigraphic units. Horizontal and vertical hydraulic conductivity was held constant in the Palouse soil at 5 and 0.5 feet per day, respectively. The horizontal hydraulic conductivity for basalt was varied between 0.1 and 50 feet/day. This range is compatible with reported data for the Columbia River Basalts (Table 2). The vertical hydraulic conductivity was obtained through a multiplier of horizontal hydraulic conductivity. This multiplier ranged between 0.1 and 0.0001. This procedure produced vertical hydraulic conductivities similar to reported values (Table 2). This range is intended to bound the probable distribution of hydraulic conductivity. The purpose of the cross-sectional modeling is to reduce the degrees of freedom for input to the three-dimensional model. Figure 19a shows the four zones and their hydraulic conductivity values in the calibrated model for section B-B'.

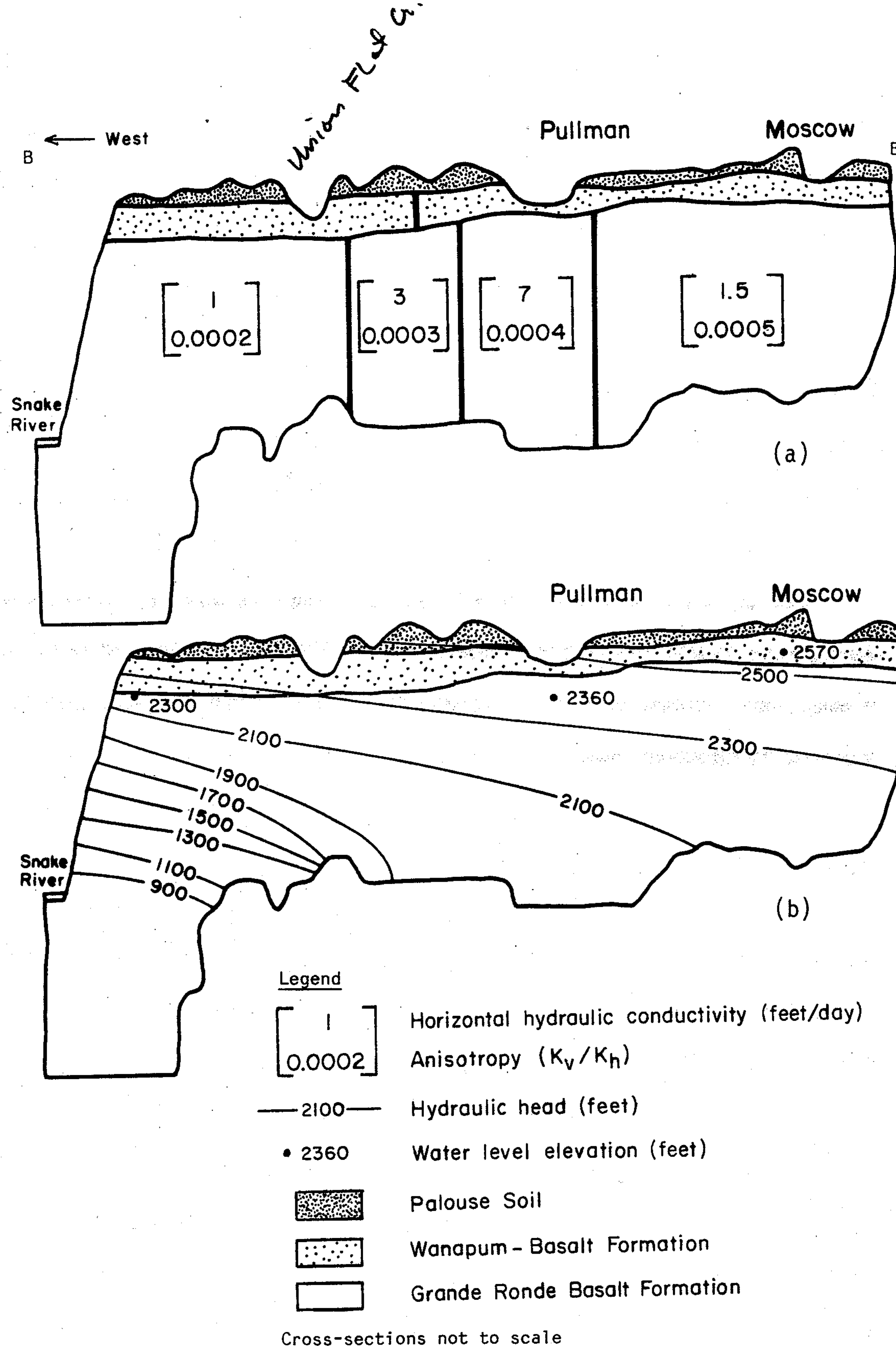


Figure 19. Calibrated cross-sectional model B-B': a) calibrated hydraulic conductivity distribution, b) calibrated hydraulic head distribution.

Contoured values of the cross-sectional model head output match well with reported and/or measured water level measurements along cross-section B-B' (fig. 19b). The contour lines are based on the multi-layer output from the cross-sectional models. The water level at Moscow represents the Wanapum Basalt and the water level at Pullman represents the upper Grande Ronde Basalt, while the water level near the Snake River canyon probably represents a composite Wanapum-upper Grande Ronde water level because the borehole is uncased and bottoms in the Grande Ronde Formation. The 200 foot thick model layers in the Grande Ronde Formation provide reasonable resolution of the hydraulic head distribution of the model output.

Similar hydraulic conductivity distributions resulted from the A-A' and C-C' cross sections. Points on the A-A' and C-C' cross sections that correspond approximately to Pullman and Moscow are calibrated to Russell's (1897) reported values 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 were calibrated to be below the top of the respective layers. This decision was arbitrary. Cross sections A-A' and C-C' both have zonations similar to cross section B-B'.

The magnitude of the fluxes calculated by the cross-sectional models provides additional input for model calibration. The majority of the flux toward the Snake River is expected to discharge along the canyon wall rather than into the river because of the large surface area of the canyon wall. The average flux out the seepage face calculated from cross-sectional modeling is about 20 inches per year. This flux compares to a potential evapotranspiration rate of 35-40 inches per year based on the recharge model. The flux calculated by the recharge model is considered reasonable based on limited examinations of the canyon wall (Lum, personal communication, 1986). Fluxes through the drains in the canyon for each of the several hydrostratigraphic units that crop out in the canyon wall are summed for each cross section and averaged across the length of the face. This sum is used as an initial approximation of the flux out the seepage face for input into the 3-D model.

Time-Averaged Three-Dimensional Model Calibration

The model calibration technique incorporates the method of time-averaging (Prych, 1984, p. 43). Time-averaging is a method of approximating average conditions over a discrete time interval of transient conditions in a ground-water flow system. This allows calibration to recent time intervals when data more often are complete. Utilization of a model to simulate time-average conditions requires that the change in storage of water in the aquifer be incorporated into the model as an implicit flux, either as an adjustment to the recharge for each model cell affected by pumpage or as a separate well function for each model cell affected by pumpage. This change in storage flux will be opposite in sign to the water level change in each model cell. The model is then run with the explicit storage coefficient equal to zero using the option for steady-state since storage is accounted for with the implicit flux.

Hydraulic Coefficients

The time-average calibration honors the cross-sectional model results. The hydraulic conductivity distributions obtained from the cross-sectional models are transferred to the three-dimensional model (fig. 20). Initially there was some iteration between operation of the three-dimensional model and the cross-sectional models. Minor changes in hydraulic coefficients necessary in the three-dimensional model were checked by rerunning the cross-sectional models to determine if they were still reasonable. Changes that significantly disrupted the head patterns in the cross-sectional models were disallowed. The horizontal hydraulic conductivity was varied by less than a factor of two in the transition from the steady-state cross-sectional models to the three-dimensional model under time-average conditions. The vertical hydraulic conductivity ratio was varied by an order of magnitude. Given that little is known about this coefficient, an order of magnitude is a relatively small variation.

A single value of storage coefficient is used for the basalt hydrostratigraphic units in the time-average calibration. The final value used is 1×10^{-4}. This is a reasonable value for confined storativity in the basalts. There is most likely some distribution of storativity in the basalts in the Pullman-Moscow area, but this distribution is unknown.

Hydraulic Head Distribution

A reasonable match is obtained between heads produced by the three-dimensional model for the second layer and measured water levels for the Wanapum Basalt Formation (fig. 21). Measured water levels are

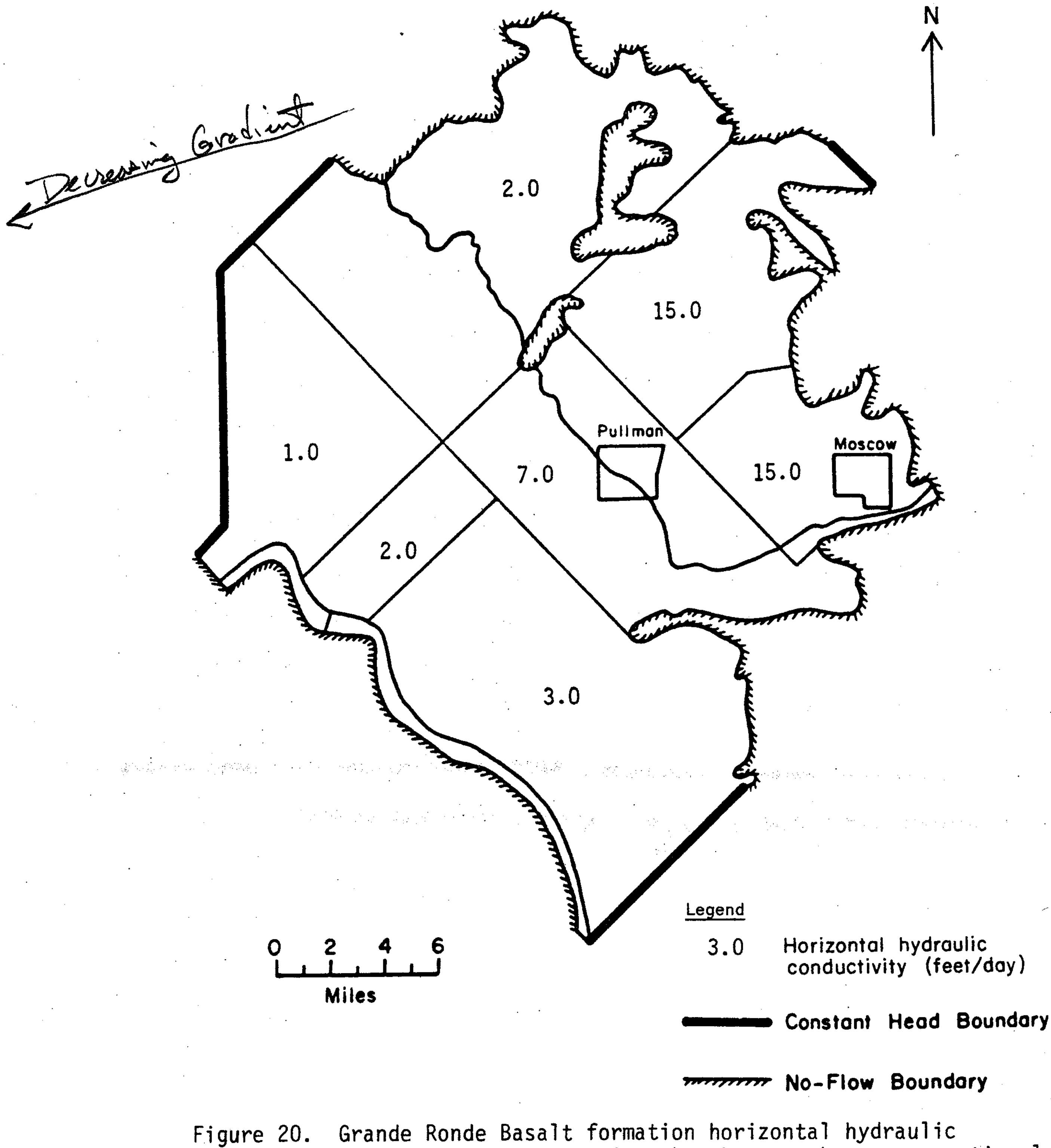


Figure 20. Grande Ronde Basalt formation horizontal hydraulic conductivity distribution that honors the cross-sectional model calibration and the time-average three-dimensional model calibration.

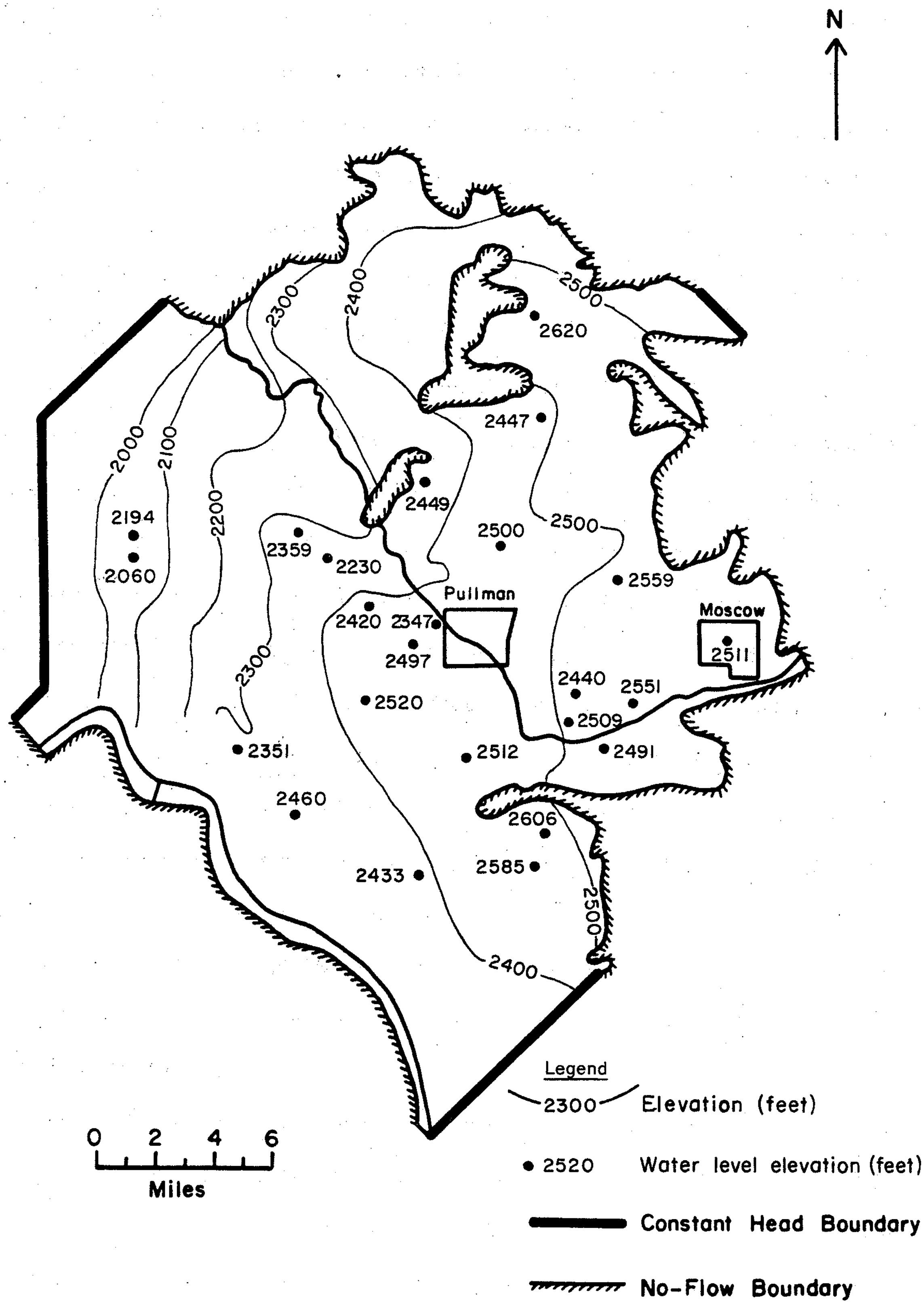


Figure 21. Calibrated distribution of hydraulic head for the Wanapum Basalt Formation.

presented as the average water level for the period 1974 to 1985. The contour lines represent the distribution of hydraulic head in the model. Most of the measured water levels are in general agreement with the contours of model output. Cases where measured water levels are greater than model output probably reflect wells that penetrate only the upper portion of the Wanapum Basalt Formation. The model calculated water levels are representative of fully penetrating wells. Because water levels tend to drop with increasing well depth, the partially penetrating well will tend to have a higher water level. Measured water levels that are lower than model output may be the result of 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 tend to be smoothed out by the regional nature of the three-dimensional ground-water flow model.

A reasonable calibration also is achieved for the Grande Ronde hydrostratigraphic unit (fig. 22). The contours represent model output hydraulic head values for the lower model layer. Water levels in the Grande Ronde Formation generally are for wells that penetrate the upper part of the formation except for two deep wells at Moscow. The three-dimensional model calculates water levels for the center of the Grande Ronde layer; therefore the average measured water levels for the period 1974 to 1985 presented on figure 22 are adjusted based upon the vertical gradients in the cross-sectional models so that they are comparable directly to heads produced by the three-dimensional model for the Grande Ronde hydrostratigraphic unit. The correction factor lowers measured

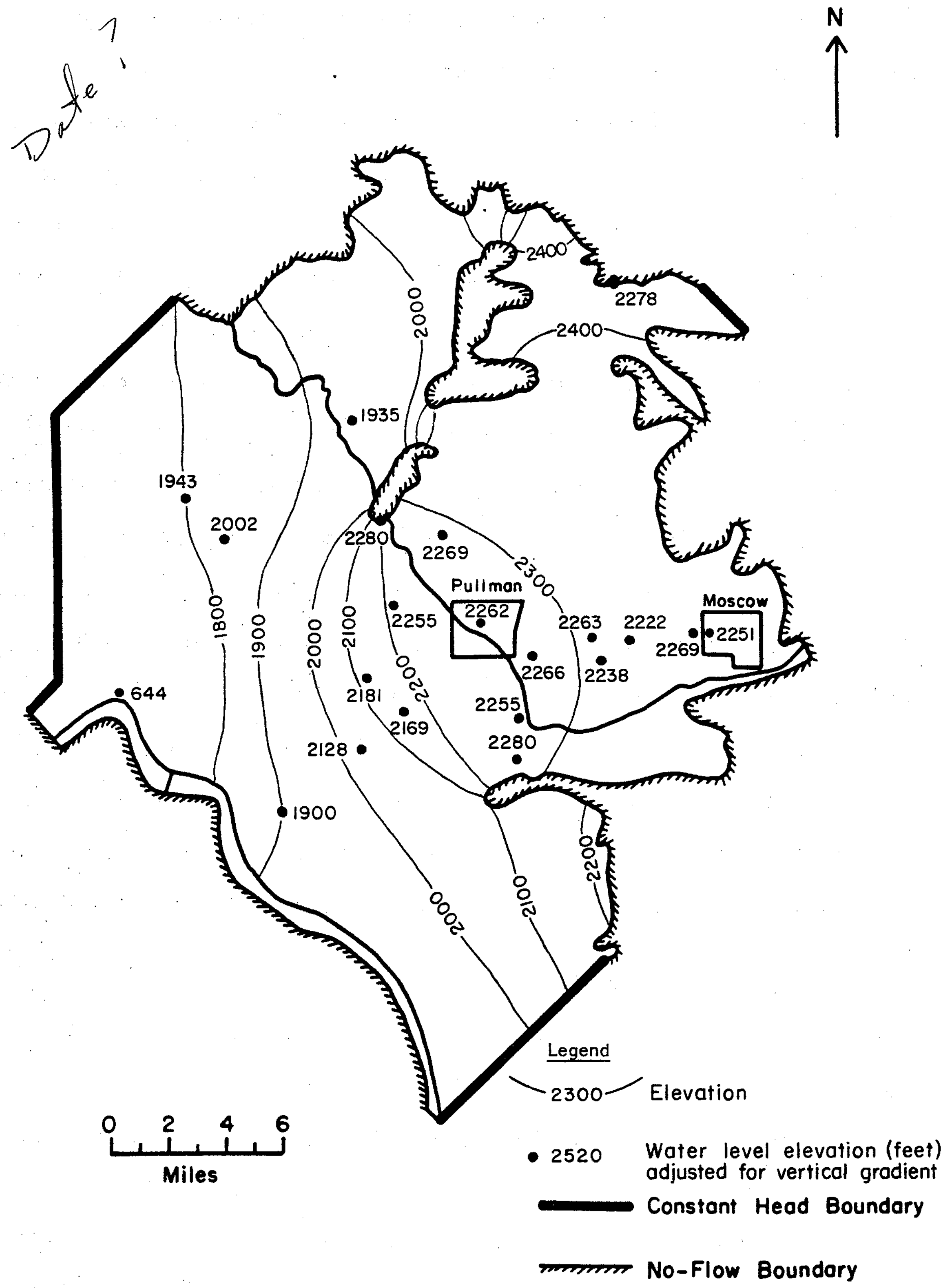


Figure 22. Calibrated distribution of hydraulic head for the Grande Ronde Basalt Formation.

water levels by a few ten's of feet near Moscow and Pullman and by several hundred feet near the canyon.

The match between model calculated hydraulic heads and measured water levels tends to be best around Pullman (fig. 22). Most measured water levels fall within the interval marked by the enclosing contours. Near Moscow, the measured values are several tens of feet less than the model calculated value of approximately 2300 feet. Several factors probably cause this discrepancy. There could be error in the correction factor that was applied to these water levels. This cannot explain all of the difference because the correction factor near Moscow was less than 20 feet. The model output suggests that there is a water level difference of about 60 feet between Moscow and Pullman. Such a gradient is necessary to move water towards the Snake River according to the conceptual model of the ground-water flow system. However, this head difference does not appear in the measured water level data for the Grande Ronde Formation. This may result from the measurement of water levels from fully penetrating wells in Moscow and partially penetrating wells in Pullman.

Water Budget Analysis of Time-Average Model

The water budget of the calibrated time-average model presented in Table 3 is reasonable based on knowledge of the hydrogeology of the system. The total recharge to the model is about 139 cubic feet per second. This number is calculated from the recharge distribution over the surface area of the model (fig. 16). The flux of water into the model from recharge is balanced by the flux of water out of the model through wells, drains, rivers, and the constant head boundaries. Almost

48 cubic feet per second leaves the model through the three constant head boundary segments. These boundaries are distant from the pumping centers, and analyses of the fluxes across these boundaries indicate that they have little effect on the model results. Changing the constant head boundaries to constant flux boundaries produces changes in model calculated heads of several tens of feet near the boundaries and only several feet near the pumping centers. The drain flux includes drains along the creeks and the extreme upper reaches of streams east of Moscow. The well flux includes both ground-water pumpage and the flux out the seepage face along the Snake River Canyon. About 31 cubic feet per second reaches the Grande Ronde Basalt layer in the model. The fluxes between layers are summarized in figure 23.

~3+ pumpage

The river discharge summation is divided into the discharges for individual streams (Table 4). These numbers may be compared directly to the streamflow measurements on figure 9. The discharges are generally within an order of magnitude of each other. Such a fit is reasonable given the simplified mathematical treatment of the streams in the model. The agreement of the stream discharges provides additional evidence to support model calibration.

Table 3. Water Budget of Time-Average Model

Summary

	IN (cfs)	OUT (cfs)	SUM (cfs)
Storage	0.0	0.0	0.0
Constant Heads	11.4	59.0	-47.6
Wells	0.1	38.0	-37.9
Drains	0.0	30.1	-30.1
Recharge	138.9	0.0	138.9
Rivers	1.4	24.6	-23.2

much too high
not all = real
well pumpage
10.4 cfs actual

0.12 percent discrepancy

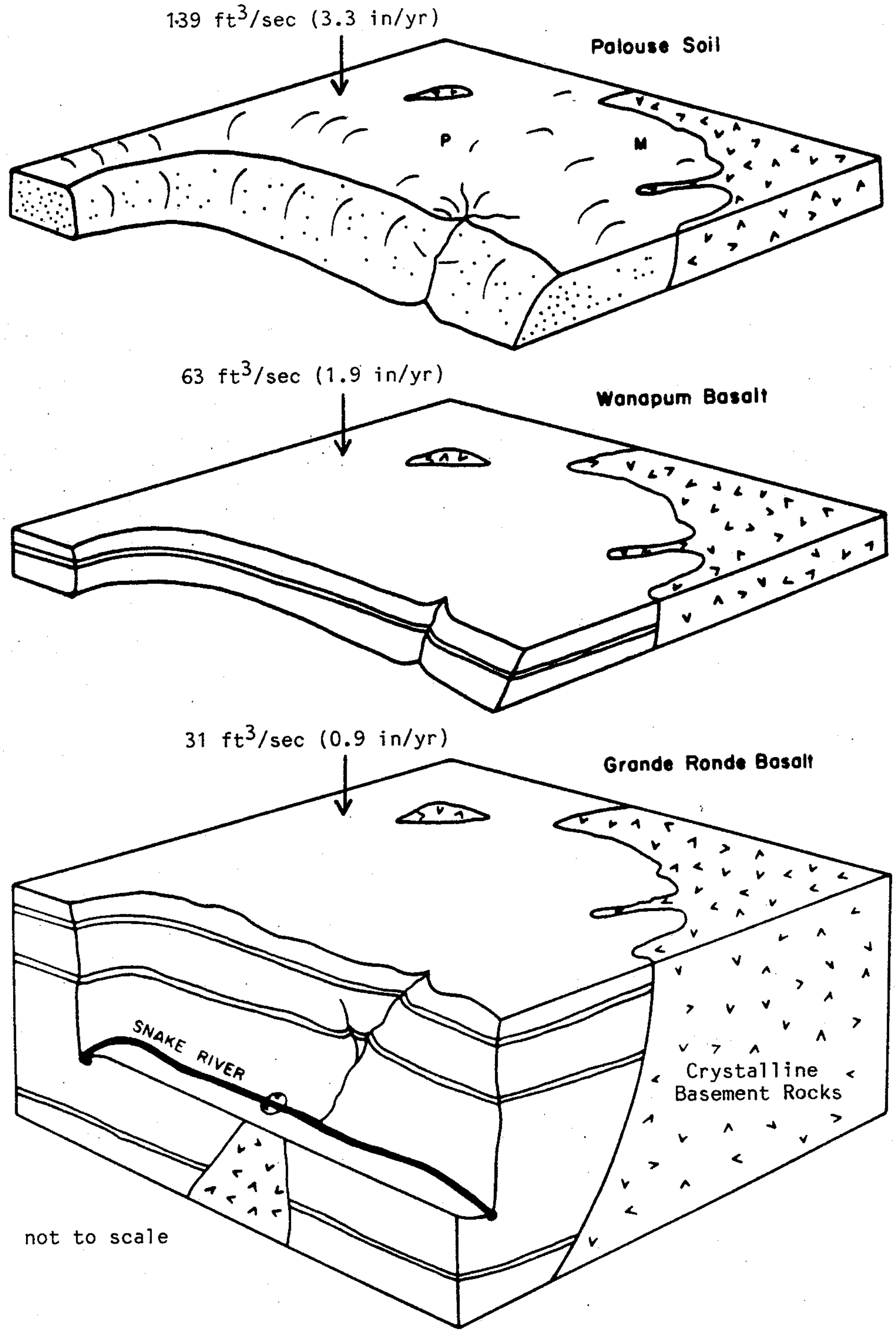


Figure 23. Layer fluxes in the three-dimensional model.

NOTE: this is not = streamflow!

Year round average or October?

Table 4. Discharge From Model to Rivers (cfs)

Snake River	3.0
S. Fork Palouse above Pullman	1.6
S. Fork Palouse below Pullman	4.6
Palouse River	0.1
Union Flat Creek	3.5
Paradise Creek	1.5
Fourmile Creek	5.3
Missouri Flat Creek	4.4
Spring Flat Creek	1.5

The model appears to be relatively insensitive to changes in storativity over a reasonable range for confined basalt aquifers (1×10^{-3} to 1×10^{-6}). The relative insensitivity of the Pullman-Moscow model to changes in storativity indicates that much of the water pumped from the ground-water system does not come from storage within the aquifer. The source of this water is most likely the result of losses from streams and a reduction in discharge to the Snake River canyon.

Evaluation of Time-Average Calibration

The final step of model construction is an evaluation of the ability of the calibrated model to predict historical water level records. Hydraulic heads computed by the model over time are compared to historical hydrographs for the time period from predevelopment through 1974, the beginning of the time-average calibration period, and then checked against the 1974 to 1985 time-average calibration period. Initial comparison of model results with historic data showed unacceptable differences. Hydrologic coefficients were changed and then checked by rerunning the cross-sectional models and the time-average three-dimensional model. The history match was then rechecked. Storativity was the primary target during these adjustments because it is the least known of the hydrologic coefficients.

The model simulation begins in 1890 with one well in Pullman, one well in Moscow, and a pumpage rate of less than 1 acre-foot per year. Pumpage is increased over time and wells added to the appropriate cell according to the historical record. Washington State University well 1 (14/45-5F1) and University of Idaho well 3 (39/5-7cbb1) penetrate the Grande Ronde Formation and were chosen for comparison to model results. The wells were chosen based upon completeness of water level records and the fact that they are representative of wells in each municipality.

The historical hydrographs and hydrographs calculated by the model for Pullman and Moscow are shown in figure 24. The shapes of the hydrographs are of primary importance. The differences in the absolute water level elevations between calculated and observed hydrographs result primarily from limitations inherent in representing the Grande Ronde Formation as a single model layer. Most wells in the area penetrate only the upper portion of the Grande Ronde hydrostratigraphic unit. Consequently, the water level record for most wells is for the upper part of the formation, whereas the model calculates water levels representing the complete thickness of the hydrostratigraphic unit.

The curves presented in figure 24 may be used to predict short-term water level declines below present levels for both cities. The rate of water level change is more important for management purposes than is the absolute magnitude of the water level elevation.

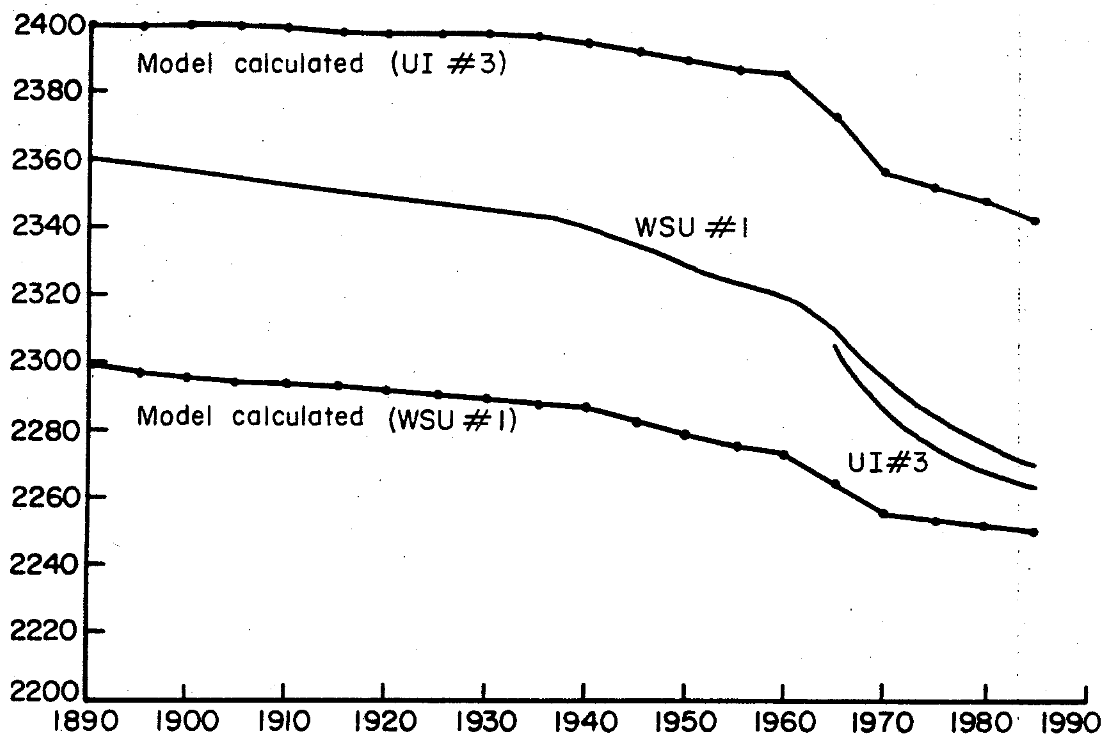


Figure 24. History match evaluation of the calibrated model results for the Grande Ronde Basalt Formation.

CHAPTER V

PREDICTIVE SCENARIOS

Introduction

The common perception among water users in the Pullman-Moscow area is that water consumption and the corresponding pumpage has remained essentially constant over the past decade. Pumpage data indicate that annual ground-water pumpage has continually increased. An analysis of five-year averages of pumpage conducted in order to smooth out the effect of extreme years indicates a nearly steady increase of about 1.7 percent per year since the 1940's (fig. 10). A future decrease in the pumpage rate in the area is not likely; therefore the model predictions focus on water use at or above the 1985 rate of 7,600 acre-feet per year.

Six different projections were examined in order to bracket potential future pumpage patterns (Table 5). Three projections are based on stable pumping rates, and three projections are for various rates of growth in pumpage. These projections are intended to bracket water use based upon the extremes of 3 percent pumpage growth per year and a stabilization of pumpage rates at the 1985 level of 7,600 acre-feet per year.

Table 5. Pumpage Projection Scenarios for 1990 and 2000

Group I: Constant Future Pumpage	Future Pumpage Rates (acre-feet/year) 1990	2000
1. Maintain 1985 rate:	7,600	7,600
2. 125 percent 1985 rate:	9,500	9,500
3. 200 percent 1985 rate:	15,000	15,000
Group II: Continual Growth in Pumpage Rates.		
4. 1%/year growth from 1985 rate:	8,000	8,800
5. 2%/year growth from 1985 rate:	8,400	10,200
6. 3%/year growth from 1985 rate:	8,800	11,800

Constant Pumpage Scenarios

The ground-water impacts of future pumpage at three different constant rates are investigated with the model. These rates are listed as Group I in Table 5. The model results indicate 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 into the future. The elevation of the stabilized water levels and the length of time required to achieve this stabilization are dependent on the pumping rate. Larger pumpage rates increase the depth at which any water level stabilization occurs and increase the time required for such stabilization to occur.

Pumpage at 100 Percent of 1985 Level

The first projection scenario is for a constant pumpage rate at the 1985 level of about 7,600 acre-feet per year. The model results indicate that water levels stabilize in a short time with little additional water level decline (fig. 25, curve a). A reasonable interpretation of this

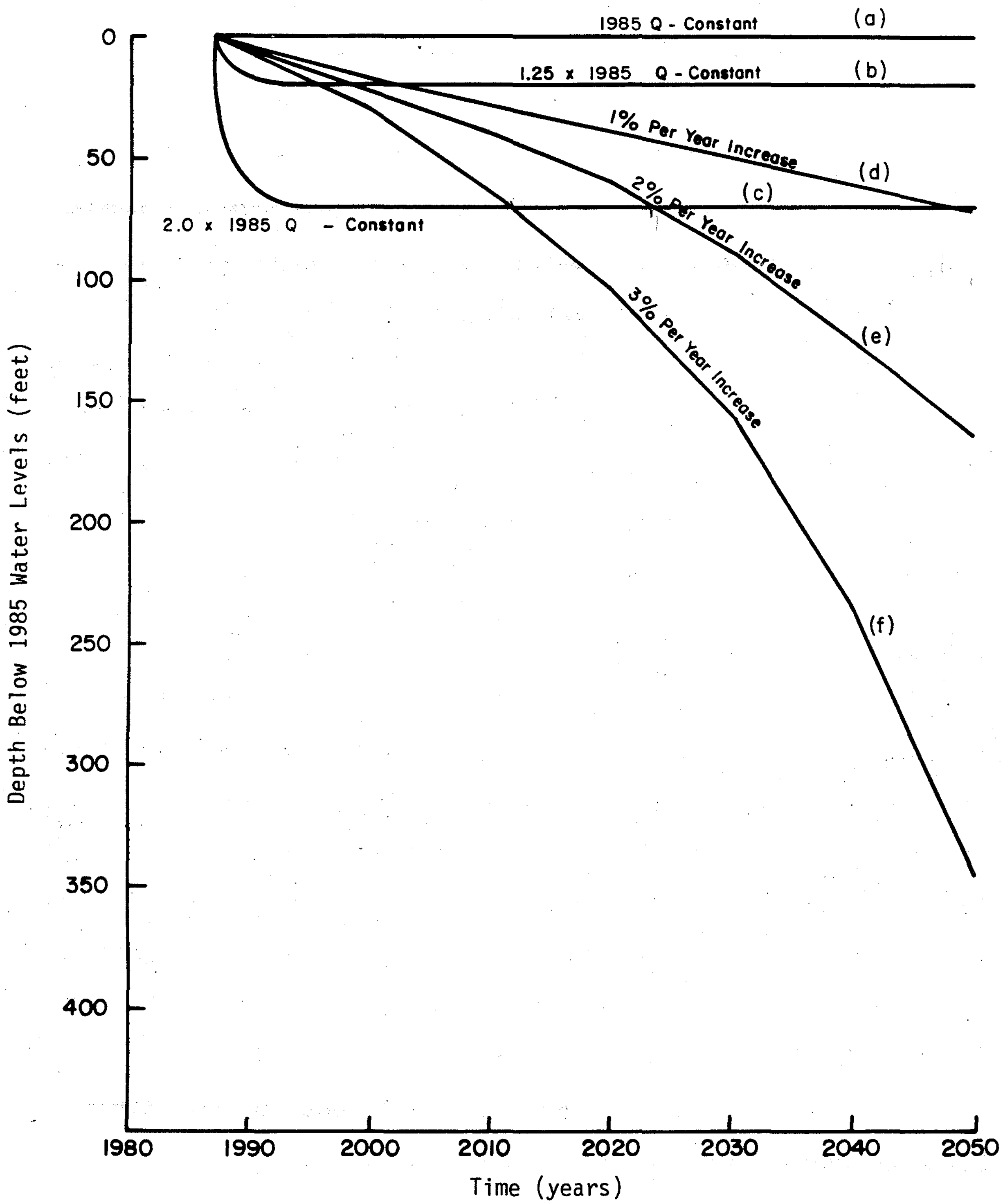


Figure 25. Future ground-water level projections for Pullman and Moscow.

model prediction is that water levels will stabilize within a few decades with perhaps as much as several ten's of feet of additional water level decline. Some lag time is involved in the response of the physical system beyond that predicted by the model because of the single layer representation of the Grande Ronde Formation. The important implication of this predictive scenario is that a stabilization of water levels will occur without extensive water level decline.

Discretion must be exercised in literal interpretation of the model results. The model is based upon a series of assumptions and simplifications with respect to a very complex hydrogeologic system. The accuracy of the three-dimensional model results are discussed in a section entitled "Limitations of Model Predictions".

Pumpage at 125 Percent of 1985 Level

The second projection scenario is for a constant pumpage rate at 125 percent of 1985 levels, about 9,500 acre-feet per year. The model results indicate that water levels will stabilize in about five years with additional water level declines of about twenty feet (fig. 25, curve b). A reasonable interpretation of this model result is that water levels would stabilize within several decades with perhaps as much as several ten's of feet of additional water level decline. Both the stabilization period and the decline of water levels would be greater than for the first option. The important implication of this predictive scenario is that a stabilization of water levels will occur.

Pumpage at 200 Percent of 1985 Level

The third projection scenario is for a constant pumpage rate at 200 percent of 1985 levels. This pumpage rate is about 15,000 acre-feet per year. The model results indicate that water levels will stabilize within about ten years with an additional water level decline of about 70 feet (fig. 27, curve c). A reasonable interpretation of this model result is that water level stability is possible for the area even with a pumpage rate twice that of 1985. Again, care must be taken to consider the model results in the perspective of the assumptions and simplifications involved in model construction.

Increasing Pumpage Rate Scenarios

Annual pumpage rate increases are representative of historical water use trends over the last 40 years. Pumpage rate scenarios that incorporate one percent, two percent, and three percent annual increases are investigated using the model. All three scenarios indicate that water level declines will accompany increases in pumping rates. Figure 25 (d,e,f) shows that the rate of water level decline is proportional to the rate of pumpage increase.

Pumpage Increase at 1 Percent Per Year

The first projection scenario represents a pumpage rate increase of one percent annually from 1985 levels. The pumpage rate will double by the year 2050 at this rate of increase. The model results indicate that water level declines will continue as long as pumpage rates increase (fig. 27, curve d). The rate of decline illustrated is about 1 to 1.5 feet per year. The model results indicate that equilibrium conditions between recharge and discharge will not occur. The error inherent in this model prediction increases with time into the future. The important implication of this predictive scenario is that water level declines will occur as long as pumpage increases annually, even at the relatively low level of one percent per year.

Pumpage Increase at 2 Percent Per Year

The historical trend of pumpage rate increases in the basin has been an average annual increase of about 1.7 percent since the 1940's. On this basis, the two percent curve shown in figure 27 may be the most indicative of current trends in the basin. The two percent scenario suggests that water level declines would average 2 to 3 feet per year in the Pullman and Moscow areas into the foreseeable future. The rate of annual water level decline would gradually increase in the future.

Pumpage Increase at 3 Percent Per Year

The third projection scenario represents a relatively rapid three percent annual rate of pumpage increase from 1985 levels. The model results indicate that water level declines would occur at rates greater that experienced to date (fig. 25, curve f). Water levels would decline on the order of 30 to 40 feet per decade over the next several decades. The error inherent in this model prediction is probably greater than the other predictive runs because it is the greatest deviation from present conditions.

Limitations of Model Predictions

The model incorporates many simplifying assumptions about the treatment of the aquifer 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 important is the representation of the Grande Ronde Formation as a single layer. These simplifications may allow the model to achieve recharge-discharge equilibrium sooner and with less drawdown than would be experienced in the field.

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 for all scenarios. However, the amount of drawdown was small, leading to the conclusion 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 do not account for discontinuities that might impede flow and lengthen the time required for equilibrium to be established. Similar problems may apply to leakage from streams.

Recharge and discharge amounts and locations represented in the model control predictive pumpage scenarios. The pattern of ground-water level declines in the region and the extent to which equilibrium will be established are dependent on the interrelationship of ground-water levels and stream and seep areas.

The use of a single layer to represent the Grande Ronde Formation is significant for several reasons. This model characteristic makes it difficult to compare model results with field data. The single representation probably results in underestimation of the time required for equilibrium conditions to occur.

The limitations described above suggest that only general conclusions should be drawn from model results. This does not lessen the value of the model but rather provides the proper perspective for interpretation of predicted water level patterns.

Implications of Findings on Ground Water as a Resource Base

Ground water presently constitutes the sole water supply source for the cities of Moscow, Idaho, and Pullman, Washington, Washington State University, and the primary supply for the University of Idaho. Recycled waste water is used to irrigate a portion of the University of Idaho campus. The future reliability of ground water as a water supply source thus is very important to the area.

Conclusions

The predictive runs of the model suggest that the cities and universities can rely on the existing ground-water resource without extensive additional water level declines if pumpage rates are stabilized and held constant. Conversely, the model runs suggest that continued water level declines will accompany any continual pattern of increased annual pumpage. The rates of future water level decline are directly related to the rates of increased ground-water usage.

The model results suggest that several avenues of action are warranted in the area. First, a continued effort is needed to upgrade the hydrogeologic knowledge in the area. A greater understanding is needed on locations, controls for, and magnitudes of both recharge and discharge. Second, the cities and universities should begin planning for measures to curtail continual water level decline in the region. Activities should include water conservation, recharge enhancement, use of treated waste water, and use of water from the Wanapum Formation where ever possible. The model results indicate that there is time for long-term resource planning. Resource planning should be a cooperative effort between hydrogeological specialists and representatives of the major water users.

Note * the recommendation!

Surface H_2O for irrigation and other uses where + Grey H_2O, rain/ppt H_2O use.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Predictive runs of the computer model of the ground-water system in the Pullman-Moscow area 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 which 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) Magnetotelluric studies indicate that the basalt thickness ranges from 1,300 feet in Moscow and 2,000 feet in Pullman to more than 3,000 feet northwest of Pullman.

2) Results of a recharge model suggest that the average rate of recharge in the Pullman-Moscow area is about 3.6 inches per year with about 1 inch per year reaching the Grande Ronde Basalt Formation, the primary aquifer unit.

3) Most of the discharge from the ground-water resource in the Pullman-Moscow area is to streams within the area and seepage along the canyon walls of the Snake River and to a lesser extent, the Palouse River.

4) The computer model constructed for the Pullman-Moscow area uses one layer to represent the surficial loess, one layer for the Wanapum

Basalt, and one layer for the Grande Ronde Basalt. Cross-sectional models using multiple layers for the Grande Ronde Basalt are used for model calibration.

5) The calibrated three-layer model has hydraulic coefficient ranges as follows:

Horizontal hydraulic conductivity	0.6-15.0 feet/day
Vertical hydraulic conductivity	0.0001-0.0075 feet/day
Storativity	0.0001

6) Model operation suggests that recharge-discharge equilibrium will be achieved with limited additional water level decline if pumpage is stabilized at 1985 rates or up to twice 1985 rates.

7) Model operation suggests that water level decline will persist into the future as long as annual increases in pumpage occur. The run with two percent annual increase in pumpage approximates current annual pumpage increases and current annual water level decline.

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

Recommendations

The present modeling study is another step in the process of understanding the basin. Much information has resulted from the present study. However, much more data collection is needed to strengthen the assumptions and simplifications of the present study. The cities and universities should implement a plan for the collection of more hydrogeologic information. Such a plan should include the systematic collection of water level and pumpage data with the establishment of a clearing house to tabulate total pumpage for the region.

Further study of the recharge, movement, and discharge of ground water in the area is needed. Particular emphasis should be on evaluation of the recharge distribution calculated for this study and on the nature of ground-water discharge along the Snake River canyon. A lysimeter should be installed to provide detailed data on water movement through the loess. A detailed examination of ground-water discharge characteristics along the Snake River canyon would add much to the understanding of the resource.

Perhaps the most important recommendation is for continued cooperation and communication between the four primary water users. The Pullman-Moscow area has a common ground-water resource. Management of the resource must involve both cities and both universities with input from the two state water management agencies. Further analysis of the ground-water situation will likely be necessary within 10 years. Continued cooperation between local agencies and agencies such as the United States Geological Survey will lead to a better understanding and awareness of the advantages and constraints of ground water as a water source in the Pullman-Moscow region.

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APPENDIX A

THREE-DIMENSIONAL MODEL INPUT AND OUTPUT PROCESSOR SOFTWARE

```
C     A PROGRAM TO SUM THE FLUXES ALONG THE THREE SEGMENTS OF CONSTANT
C     HEAD BOUNDARY IN EACH LAYER OF THE 3-D MODEL.  INPUT TO THE
C     PROGRAM IS CELL BY CELL OUTPUT FROM THE 3-D MODEL.
C
C     CHBSUM - FLUX SUMMATION ALONG A CONSTANT HEAD BOUNDARY SEGMENT.
C     IGROUP - NUMBER OF CONSTANT HEAD CELLS IN THE 3D MODEL.
C     RATE   - FLUX THROUGH INDIVIDUAL CONSTANT HEAD CELLS.
C
      DIMENSION IGROUP(6), CHBSUM(12)
      READ (4,30) (IGROUP(I),I=1,6)
      III = 1
      DO 20 I = 1,6
      DO 10 II = 1,IGROUP(I)
      READ (5,40) RATE
      IF (RATE .LE. 0.0) CHBSUM(III) = CHBSUM(III) + RATE
      IF (RATE .GT. 0.0) CHBSUM(III + 1) = CHBSUM(III + 1) + RATE
10    CONTINUE
      III = III + 2
20    CONTINUE
      LYR = 2
      LYRR= 3
      WRITE (6,50) LYR,CHBSUM(1), CHBSUM(2)
      WRITE (6,50) LYRR,CHBSUM(7), CHBSUM(8)
      WRITE (6,60) LYR,CHBSUM(3), CHBSUM(4)
      WRITE (6,60) LYRR,CHBSUM(9), CHBSUM(10)
      WRITE (6,70) LYR,CHBSUM(5), CHBSUM(6)
      WRITE (6,70) LYRR,CHBSUM(11), CHBSUM(12)
30    FORMAT(6I3)
40    FORMAT(78X,G15.7)
50    FORMAT('  NW CORNER LYR ',I2,5X,2E15.3//)
60    FORMAT('  EAST SIDE LYR ',I2,5X,2E15.3//)
70    FORMAT('  SOUTH     LYR ',I2,5X,2E15.3//)
      STOP
      END
```

```
C     A PROGRAM TO CALCULATE LAYER TO LAYER FLUXES IN THE 3D MODEL.
C
C     DZ12 -  DISTANCE BETWEEN NODE CENTERS IN LAYERS 1 AND 2.
C     DZ23 -  DISTANCE BETWEEN NODE CENTERS IN LAYERS 2 AND 3.
C     HED  -  UNFORMATTED OUTPUT HEADS FROM 3D MODEL.
C     HEAD -  FORMATTED HEADS FROM 3-D MODEL.
C     QP   -  POSITIVE FLUX.
C     QN   -  NEGATIVE FLUX.
C
      DIMENSION HEAD(3,55,55), HED(55,55), DZ12(55,55), DZ23(55,55)
C
      QP12 = 0.
      QN12 = 0.
      QP23 = 0.
      QN23 = 0.
C
      QSUM12 = 0.0
      QSUM23 = 0.0
C
      DO 10 K=1,3
      READ(3)
      READ(3) HED
      DO 10 I=1,55
      DO 10 J=1,55
      HEAD(K,I,J)=HED(J,I)
10    CONTINUE
C
      READ (4,20) ((DZ12(I,J),J=1,55),I=1,55)
      READ (4,20) ((DZ23(I,J),J=1,55),I=1,55)
20    FORMAT (4(12E10.2/),7E10.2)
C
C
      DO 40 K=1,2
      DO 40 I=1,55
      DO 40 J=1,55
      FLOW2 = 0.0
      FLOW3 = 0.0
C     AREA OF A CELL BOTTOM
      AREA = 6969600.00
      IF (HEAD(K,I,J) .LE. 0.0) GO TO 30
      IF (HEAD(K+1,I,J) .LE. 0.0) GO TO 30
C     FLUX = (HEAD(K) - HEAD(K+1)) * VCONT * AREA
       IF (K.EQ.1) FLOW2 = (HEAD(K,I,J)-HEAD(K+1,I,J))*DZ12(I,J)*AREA
       IF (K.EQ.2) FLOW3 = (HEAD(K,I,J)-HEAD(K+1,I,J))*DZ23(I,J)*AREA
       IF (FLOW2 .GT. 0.0) QP12 = QP12 + FLOW2
       IF (FLOW2 .LT. 0.0) QN12 = QN12 + FLOW2
       IF (FLOW3 .GT. 0.0) QP23 = QP23 + FLOW3
       IF (FLOW3 .LT. 0.0) QN23 = QN23 + FLOW3
30    CONTINUE
40    CONTINUE
C
```

```
      QSUM12 = QP12 + QN12
      QSUM23 = QP23 + QN23 .
C
      WRITE (6,50)
      WRITE (6,60) QP12,QN12,QSUM12
      WRITE (6,140)
      WRITE (6,70) QP23,QN23,QSUM23
      WRITE(6,140)
C
50    FORMAT (25X,'IN',15X,'OUT',13X,'SUM')
60    FORMAT (1H ,'FLUX TO LAYER 2 ',3E16.5)
70    FORMAT (1H ,'FLUX TO LAYER 3 ',3E16.5)
C
      QD1N = 0.0
      QD2N = 0.0
      QD3N = 0.0
C
      READ(5,110) ND
      IF (ND .GT. 1000) GO TO 150
      DO 90 N=1,ND
      READ(5,80) K,I,J,Q
80    FORMAT(10X,3I5,E16.5)
      IF (K .EQ. 1 .AND. Q .LT. 0.0) QD1N = QD1N + Q
      IF (K .EQ. 2 .AND. Q .LT. 0.0) QD2N = QD2N + Q
      IF (K .EQ. 3 .AND. Q .LT. 0.0) QD3N = QD3N + Q
90   CONTINUE
C
      QR1P = 0.0
      QR1N = 0.0
      QR2P = 0.0
      QR2N = 0.0
      QR3P = 0.0
      QR3N = 0.0
      QR1S = 0.0
      QR2S = 0.0
      QR3S = 0.0
C
      READ (5,110) NR
      DO 100 N=1,NR
      READ(5,80) K,I,J,Q
      IF (K .EQ. 1 .AND. Q .GE. 0.0) QR1P = QR1P + Q
      IF (K .EQ. 1 .AND. Q .LT. 0.0) QR1N = QR1N + Q
      IF (K .EQ. 2 .AND. Q .GE. 0.0) QR2P = QR2P + Q
      IF (K .EQ. 2 .AND. Q .LT. 0.0) QR2N = QR2N + Q
      IF (K .EQ. 3 .AND. Q .GE. 0.0) QR3P = QR3P + Q
      IF (K .EQ. 3 .AND. Q .LT. 0.0) QR3N = QR3N + Q
100   CONTINUE
      QR1S=QR1P+QR1N
      QR2S=QR2P+QR2N
      QR3S=QR3P+QR3N
```

```
      K=1
      WRITE(6,120)K,QD1N
      WRITE(6,130)K,QR1P,QR1N,QR1S
      K=2
      WRITE(6,140)
      WRITE(6,120)K,QD2N
      WRITE(6,130)K,QR2P,QR2N,QR2S
      K=3
      WRITE(6,140)
      WRITE(6,120)K,QD3N
      WRITE(6,130)K,QR3P,QR3N,QR3S
  110 FORMAT(I5)
  120 FORMAT(1H ,'DRAINS IN LYR',I3,16X,E16.5)
  130 FORMAT(1H ,'RIVERS IN LYR',I3,3E16.5)
  140 FORMAT(1H )
  150 CONTINUE
      STOP
      END
```

```
C     A PROGRAM TO PRODUCE ZONED HORIZONTAL AND VERTICAL HYDRAULIC
C     CONDUCTIVITY MATRICES.
      DIMENSION KHTWO(55,55), KHTHR(55,55), KVZNS(55,55) , VPRMS(3,4)
      REAL KHGR(55,55), KHWA(55,55), KVWA(55,55), KVGR(55,55), KH(2,8)
C
C     KH(I,J)     = UP TO 8 VALUES OF KH FOR ZONES(I,J) INPUT MATRIX, L3.
C                   KH(1,J) FOR WANAPUM AND KH(2,J) FOR GRANDE RONDE.
C     KHGR(I,J)   = KH MATRIX FOR GRANDE RONDE.
C     KHTWO(I,J) = J SUBSCRIPTS TO IDENTIFY KH(1,J) FOR WANAPUM.
C     KHTHR(I,J) = J SUBSCRIPTS TO IDENTIFY KH(2,J) FOR GRANDE RONDE.
C     KHWA(I,J)   = KH MATRIX FOR WANAPUM.
C     KVGR(I,J)   = KV/KH RATIO MATRIX FOR GRANDE RONDE.
C     KVWA(I,J)   = KV/KH RATIO MATRIX FOR WANAPUM.
C     KVZNS(I,J) = 4 ZONES TO VARY KV/KH RATIOS.
C     VPRMS(I,J) = KV/KH RATIOS FOR 4 ZONES IN EACH OF 3 LAYERS.
C
      READ (10,30)((VPRMS(I,J),J=1,4),I=1,3)
      READ (11,40)((KH(I,J),J=1,8),I=1,2)
      READ (12,50)((KHTWO(I,J),J=1,55),I=1,55)
      READ (13,50)((KHTHR(I,J),J=1,55),I=1,55)
      READ (14,50)((KVZNS(I,J),J=1,55),I=1,55)
C
      DO 20 J=1,55
      DO 20 I=1,55
         KVWA(I,J) = VPRMS(2,KVZNS(I,J))
         KVGR(I,J) = VPRMS(3,KVZNS(I,J))
         KHWA(I,J) = KH(1,KHTWO(I,J))
         KHGR(I,J) = KH(2,KHTHR(I,J))
20    CONTINUE
C
      WRITE (15,60)((KHWA(I,J),J=1,55),I=1,55)
      WRITE (16,60)((KHGR(I,J),J=1,55),I=1,55)
      WRITE (17,70)((KVWA(I,J),J=1,55),I=1,55)
      WRITE (18,70)((KVGR(I,J),J=1,55),I=1,55)
30    FORMAT (4F10.0)
40    FORMAT (8F5.1)
50    FORMAT (55I1)
60    FORMAT (20F6.1 / 20F6.1 / 15F6.1)
70    FORMAT (20F6.4 / 20F6.4 / 15F6.4)
      STOP
      END
```

```
C     A PROGRAM TO MULTIPLY A MATRIX.
C     READ THICKNESS AND HYDRAULIC CONDUCTIVITY AND PROGRAM WILL
C     CALCULATE A TRANSMISSIVITY MATRIX.
C
      DIMENSION THICK(55,55), TRANS(55,55)
      REAL K(55,55)
      READ (4,20)((THICK(I,J),J=1,55),I=1,55)
      READ (5,20)((K(I,J),J=1,55),I=1,55)
C
      DO 10 J=1,55
      DO 10 I=1,55
         TRANS(I,J)  = THICK(I,J)*K(I,J)
10    CONTINUE
C
      WRITE (6,20)((TRANS(I,J),J=1,55),I=1,55)
20    FORMAT (20F6.0 / 20F6.0 / 15F6.0)
      STOP
      END
```

```
C     A PROGRAM TO PICK HEADS ALONG THE LINES OF THREE CROSS
C     SECTION MODELS FROM 3-D MODEL OUTPUT.
C     HED  -  UNFORMATTED OUTPUT HEADS FROM 3D MODEL.
C     HEAD -  FORMATTED HEADS FROM 3-D MODEL.
C     HLYR -  HEADS FOR EACH LAYER ALONG THE LINE OF SECTION.
C     INUM -  NUMBER OF COLUMNS IN EACH CROSS SECTION MODEL.
C
      DIMENSION HEAD(3,55,55), HED(55,55), HLYR(3,40,3), INUM(3)
      INTEGER XCOL
      DO 10 K=1,3
      READ(4)
      READ(4) HED
      DO 10 I=1,55
      DO 10 J=1,55
      HEAD(K,I,J)=HED(J,I)
10    CONTINUE
      DO 30 ISET = 1,3
         READ (5,80) INUM(ISET)
         DO 30 JCOL=1,INUM(ISET)
            READ (5,90) I,J,XCOL
            DO 20 K=1,3
               HLYR(K,XCOL,ISET) = HEAD(K,I,J)
20          CONTINUE
C
         IF (ISET .EQ. 1) WRITE (6,100) I,J,XCOL,HLYR(1,XCOL,ISET),
     .                    HLYR(2,XCOL,ISET),HLYR(3,XCOL,ISET)
         IF (ISET .EQ. 2) WRITE (7,100) I,J,XCOL,HLYR(1,XCOL,ISET),
     .                    HLYR(2,XCOL,ISET),HLYR(3,XCOL,ISET)
         IF (ISET .EQ. 3) WRITE (8,100) I,J,XCOL,HLYR(1,XCOL,ISET),
     .                    HLYR(2,XCOL,ISET),HLYR(3,XCOL,ISET)
30    CONTINUE
      WRITE (9,40) ((HLYR(K,XCOL,3),XCOL=1,20),K=1,3)
      WRITE (9,70)
      WRITE (9,40) ((HLYR(K,XCOL,3),XCOL=21,40),K=1,3)
      WRITE (9,70)
      WRITE (9,70)
      WRITE (9,70)
      WRITE (9,40) ((HLYR(K,XCOL,2),XCOL=1,20),K=1,3)
      WRITE (9,70)
      WRITE (9,60) ((HLYR(K,XCOL,2),XCOL=21,39),K=1,3)
      WRITE (9,70)
      WRITE (9,70)
      WRITE (9,70)
      WRITE (9,40) ((HLYR(K,XCOL,1),XCOL=1,20),K=1,3)
      WRITE (9,70)
      WRITE (9,50) ((HLYR(K,XCOL,1),XCOL=21,32),K=1,3)
```

```
40     FORMAT (20F6.0)
50     FORMAT (12F6.0)
60     FORMAT (19F6.0)
70     FORMAT (1H )
80     FORMAT (I5)
90     FORMAT (3I5)
100    FORMAT (3I5,3F10.0)
       STOP
       END
```

```
C     A PROGRAM TO COMPUTE THE DIFFERENCE AND DIFFERENCE SQUARED
C     FOR OBSERVED HEADS RELATIVE TO THE FOUR SURROUNDING NODE
C     CENTER COMPUTED HEADS.
C
C     COEFI  - FEET IN I DIRECTION TO WELL FROM UPPER LEFT NODE CTR
C     COEFJ  - FEET IN J DIRECTION TO WELL FROM UPPER LEFT NODE CTR
C     DIFF   - HEAD OBSERVED MINUS HEAD CALC FOR WELL LOC
C     DIFFSQ - DIFF SQUARED
C     HEAD(K,I,J) - HEAD CALCULATED BY MODEL
C     HEADOB - HEAD OBSERVED IN WELL
C     HEADC  - HEAD CALCULATED FOR WELL LOCATION
C     NUMWEL -  NUMBER OF WELLS
C     SLJT   - SLOPE IN J DIR ALONG TOP OF REP BLOCK
C     SLJB   - SLOPE IN J DIR ALONG BOTTOM OF REP BLOCK
C     SLIL   - SLOPE IN I DIR ALONG LEFT OF REP BLOCK
C     SLIR   - SLOPE IN I DIR ALONG RIGHT OF REP BLOCK
C     SLIA   - SLOPE AVERAGE IN I DIRECTION
C     SLJA   - SLOPE AVERAGE IN J DIRECTION
C     SUMDIF - SUM OF DIFF FOR NUMWEL
C     SUMSQ  - SUM OF DIFFSQ FOR NUMWEL
C
C     I,J,K FOR WELL IS ALWAYS NEAREST NODE CENTER TO LEFT AND UP
C     REP BLOCK IS THE CELL SIZED BLOCK FORMED BY CONNECTING FOUR
C     ADJACENT NODE CENTERS
C
C        I,J           I,J+1
C         .              .
C
C            *
C           WELL
C
C
C         .              .
C        I+1,J         I+1,J+1
C
C     PROGRAM READS MODEL OUTPUT HEADS FOR ALL K,I,J
C     IN DO LOOP 1 TO NUMWEL:
C     PROGRAM READS WELL K,I,J,COEFI,COEFJ,HEADOB
C     CALCULATES SLOPES IN I AND J DIR
C     CALCULATES AVERAGE SLOPE IN I AND J DIR
C     CALCULATES HEAD FOR WELL LOCATION
C     CALCULATES DIFFERENCE BETWEEN OBSERVED AND CALCULATED
C     SUMS THE DIFF
C     SQUARES THE DIFF
C     SUMS THE SQUARES
C     WRITES THE K,I,J,COEFI,COEFJ,HEADOB,HEADC,DIFF,DIFFSQ
C     END LOOP
C     WRITES SUMDIF
C     WRITES SUMSQ
C     END
C
C
```

```
      DIMENSION HEAD(3,55,55),HED(55,55)
C
C
      DO 10 K=1,3
      READ(4)
      READ(4) HED
      DO 10 I=1,55
      DO 10 J=1,55
      HEAD(K,I,J)=HED(J,I)
10    CONTINUE
C
C
C
      DO 100 ISET = 1,2
C
      SUMDIF=0.0
      SUMSQ=0.0
C
      READ(5,30) NUMWEL
C
C     WRITES TITLE FOR OUTPUT
C
      WRITE(6,70)
C
      DO 20 IWEL=1,NUMWEL
      DIFF=0.0
      DIFFSQ=0.0
      SLIT=0.0
      SLIB=0.0
      SLJL=0.0
      SLJR=0.0
      SLIA=0.0
      SLJA=0.0
      COEFI=0.0
      COEFJ=0.0
      HEADOB=0.0
      K=0
      I=0
      J=0
      READ(5,40)K,I,J,COEFI,COEFJ,HEADOB
C
      SLJT=(HEAD(K,I,J+1)-HEAD(K,I,J))/2640.
      SLJB=(HEAD(K,I+1,J+1)-HEAD(K,I+1,J))/2640.
      SLJA=(SLJT+SLJB)/2.
C
      IF(SLJT .GT. 1.0 .OR. SLJT .LT. -1.0) SLJA=SLJB
      IF(SLJB .GT. 1.0 .OR. SLJB .LT. -1.0) SLJA=SLJT
C
C
      SLIL=(HEAD(K,I+1,J)-HEAD(K,I,J))/2640.
      SLIR=(HEAD(K,I+1,J+1)-HEAD(K,I,J+1))/2640.
      SLIA=(SLIL+SLIR)/2.
```

```
      IF (SLIL .GT. 1.0 .OR. SLIL .LT. -1.0) SLIA=SLIR
      IF (SLIR .GT. 1.0 .OR. SLIR .LT. -1.0) SLIA=SLIL
C
      HEADC=HEAD(K,I,J)+(SLIA*COEFI+SLJA*COEFJ)
      DIFF=HEADOB-HEADC
      SUMDIF=SUMDIF+DIFF
      DIFFSQ=DIFF*DIFF
      SUMSQ=SUMSQ+DIFFSQ
C
      WRITE(6,50)K,I,J,COEFI,COEFJ,HEADOB,HEADC,DIFF,DIFFSQ
C     WRITE(6,80)K,I,J,HEAD(K,I,J),HEAD(K,I+1,J),
C    .HEAD(K,I,J+1),HEAD(K,I+1,J+1)
C     WRITE(6,90)SLJT,SLJB,SLJA,SLIL,SLIR,SLIA
C
20    CONTINUE
C
      WRITE(6,60)SUMDIF,SUMSQ
C
30    FORMAT(I10)
40    FORMAT(3I5,3F10.0)
50    FORMAT(3I5,5F10.2,G10.2)
60    FORMAT(/'   SUM OF THE DIFFERENCES=',G10.2,/'   SUM OF THE SQUARES
     . OF THE DIFFERENCES=',G10.2///)
70    FORMAT('   K    I    J      COEFI     COEFJ     HEADOB    HEADC
     .  DIFF      DIFFSQ'/)
80    FORMAT(3I5,4F10.0)
90    FORMAT(15X,6F10.4/)
C
100   CONTINUE
      STOP
      END
```

```
C     PROGRAM TO COMPUTE SOURCE/SINK TERMS FOR TIME-AVERAGE SIMULATION.
C     SINK TERM FOR EACH NODE REPRESENTS THE AVERAGE RATE OF RELEASE OF
C     WATER FROM STORAGE FOR THE TIME AVERAGE PERIOD.
C
C     AREA OF CELL - 2640 * 2640 SQUARE FEET.
C     CORRECTION FACTOR - CONVERTS NODAL FLUX FROM CUBIC FEET PER
C       11 YEARS TO CUBIC FEET PER DAY.
C     ISINK - WATER LEVEL CHANGE FOR 11 YEARS
C     S - STORAGE OF LAYER
C     SOURCE/SINK - WELL FUNCTION REPRESENTING:  WATER LEVEL CHANGE *
C       STORATIVITY * AREA OF CELL * CORRECTION FACTOR.
C
      DIMENSION ISINK(55,55,3), SINK(55,55,3), S(3)
C
      CORR = 1.0/(365. * 11.0)
C
      TOTP2 = 0.0
      TOTN2 = 0.0
      TOTP3 = 0.0
      TOTN3 = 0.0
C
      READ (3,60) ((ISINK(I,J,2),J=1,55),I=1,55)
      READ (4,60) ((ISINK(I,J,3),J=1,55),I=1,55)
      READ (5,70) (S(I),I=2,3)
C
      DO 40 I=1,55
      DO 40 J=1,55
      SINK(I,J,2) = ISINK(I,J,2) * 2640. * 2640. * CORR * S(2)
      SINK(I,J,3) = ISINK(I,J,3) * 2640. * 2640. * CORR * S(3)
      IF (J .GT. 34) GO TO 10
      GO TO 30
10    IF (I .GT. 34) GO TO 20
      GO TO 30
20    SINK(I,J,2) = SINK(I,J,2) *  1.0
      SINK(I,J,3) = SINK(I,J,3) *  1.0
30    CONTINUE
40    CONTINUE
C
      DO 50 K=2,3
      DO 50 I=1,55
      DO 50 J=1,55
      IF(SINK(I,J,K) .NE. 0.0) WRITE(63,80)K,I,J,SINK(I,J,K)
      IF(SINK(I,J,2) .GT. 0.0) TOTP2 = TOTP2 + SINK(I,J,2)
      IF(SINK(I,J,2) .LT. 0.0) TOTN2 = TOTN2 + SINK(I,J,2)
      IF(SINK(I,J,3) .GT. 0.0) TOTP3 = TOTP3 + SINK(I,J,3)
      IF(SINK(I,J,3) .LT. 0.0) TOTN3 = TOTN3 + SINK(I,J,3)
50    CONTINUE
C
      WRITE (100,90) TOTP2,TOTN2, TOTP3, TOTN3
C
```

```
60    FORMAT(55I2)
70    FORMAT(2F10.0)
80    FORMAT(3I10,F10.0)
90    FORMAT(' WELLS REPRESENTING TIME AVERAGE CHANGE'/,
     .' LYR 2 WELLS',2F10.0,' LYR 3 WELLS',2F10.0)
C
      STOP
      END
```

```
C     A PROGRAM TO CALCULATE VCONT FOR 3D MODEL FROM LAYER THICKNESS,
C     KV RATIO AND KH FOR EACH LAYER.  BASED ON HARMONIC MEAN OF KV'S.
C
      COMMON THICK(55,55,3),
     .       HALFTH(55,55,3),
     .       KH(55,55,3),
     .       KV(55,55,3),
     .       VC(55,55,3)
      REAL KH1,KVR1,KH,KV
C
C     THICK(I,J,K)  - LYR THICKNESS
C     HALFTH(I,J,K) - LYR HALF-THICKNESS
C     KH(I,J,K)     - LYR HORIZ CONDUCTIVITY
C     KV(I,J,K)     - LYR TO LYR VERT. CONDUCTIVITY ANISOTROPHY RATIO
C                     MULT BY KH TO GET VERT HYD COND
C     VC(I,J,K)     - CALC VCONT
C
      READ(60,90) THK1,KH1,KVR1
      READ(61,92) ((THICK(I,J,2),J=1,55),I=1,55)
      READ(62,92) ((THICK(I,J,3),J=1,55),I=1,55)
      READ(63,92) ((KH(I,J,2),J=1,55),I=1,55)
      READ(64,92) ((KH(I,J,3),J=1,55),I=1,55)
      READ(65,92) ((KV(I,J,2),J=1,55),I=1,55)
      READ(66,92) ((KV(I,J,3),J=1,55),I=1,55)
C
      DO 10 I=1,55
      DO 10 J=1,55
      THICK(I,J,1) = THK1
      KH(I,J,1)    = KH1
      KV(I,J,1)    = KVR1
      DO 10 K=1,3
      KV(I,J,K) = KV(I,J,K) * KH(I,J,K)
      HALFTH(I,J,K) = THICK(I,J,K) / 2.0
10    CONTINUE
C
C     CALCULATE VCONT.
C
      DO 80 I=1,55
      DO 80 J=1,55
C
C     CALCULATE HARMONIC MEAN KV = D/((D/KV)+(D/KV)).
C
      TOP = HALFTH(I,J,1) + HALFTH(I,J,2)
      DEN = (HALFTH(I,J,1)/KV(I,J,1)) + (HALFTH(I,J,2)/KV(I,J,2))
      IF(DEN .LE. 0.0) GO TO 20
      KV(I,J,1) = TOP / DEN
20    CONTINUE
      TOP = HALFTH(I,J,2) + HALFTH(I,J,3)
      DEN = (HALFTH(I,J,2)/KV(I,J,2)) + (HALFTH(I,J,3)/KV(I,J,3))
      IF(DEN .LE. 0.0) GO TO 30
      KV(I,J,2) = TOP / DEN
30    CONTINUE
```

```
C     CALCULATE VCONT FROM HARMONIC MEAN KV AND D BETWEEN NODE CENTERS
C
      HTH = HALFTH(I,J,1) + HALFTH(I,J,2)
      IF(HTH .LE. 0.0) GO TO 40
      VC(I,J,1) = KV(I,J,1)/HTH
      GO TO 50
40    CONTINUE
      WRITE(70,96) I,J,HTH
50    CONTINUE
C
      HTH = HALFTH(I,J,2) + HALFTH(I,J,3)
      IF(HTH .LE. 0.0) GO TO 60
      VC(I,J,2) = KV(I,J,2)/HTH
      GO TO 70
60    CONTINUE
      WRITE(70,98) I,J,HTH
70    CONTINUE
C
80    CONTINUE
C
      WRITE(67,94) (((VC(I,J,K),J=1,55),I=1,55),K=1,2)
C
90    FORMAT(3F10.0)
92    FORMAT(2(20F6.0/)15F6.0)
94    FORMAT(4(12E10.3/)7E10.3)
96    FORMAT('  PROBLEM IN VCONT 1-2',2I5,F10.1)
98    FORMAT('  PROBLEM IN VCONT 2-3',2I5,F10.1)
      STOP
      END
```

```
C     A PROGRAM TO GENERATE INPUT DATA SETS SIMULATING SEEPAGE FACES
C     AND RIVERS.
C
C     ANIS      -  HORIZONTAL TO VERTICAL ANISOTROPY OF LAYER.
C     COND1     -  LATERAL HYDRAULIC CONDUCTIVITY OF LAYER #1.
C     CDR       -  UNIQUE NODAL DRAIN CONDUCTANCE (SEE COMMENT C1).
C     CRIV      -  UNIQUE NODAL RIVER CONDUCTANCE (SEE COMMENT C2).
C     DEPTH     -  RIVER DEPTH. UNIQUE TO IRCH OF RIVER.
C     DRCOND    -  UNIT CELL NODAL DRAIN CONDUCTANCE. UNIQUE TO LAYER.
C     HEIGHT    -  HEIGHT OF SEEPAGE FACE IN STREAM VALLEY OR
C                  CANYON FACE WHERE LAYER IS TERMINATED.
C     IRATIO    -  RATIO OF LENGTH OF REACH IN CELL TO CELL WIDTH.
C     IRCH      -  REACH OF RIVER IDENTIFIER. RANGE 2 TO 18.
C     KH        -  HORIZONTAL HYDRAULIC CONDUCTIVITY FOR WANAPUM
C                  AND GRANDE RONDE LAYERS.
C     KVR       -  HORIZONTAL TO VERTICAL RATIO OF HYDRAULIC
C                  CONDUCTIVITY.
C     M         -  THE CALCULATED VERTICAL DISTANCE FROM A RIVER
C                  BOTTOM TO THE CELL CENTER.
C     MTYPE     -  RIVER OR DRAIN IDENTIFIER, RANGE 1 TO 8.
C     PAIR      -  2.0 MULTIPLIER.  STREAMS INCISING ONE OR SEVERAL
C                  LAYERS NECESSITATES A PAIR OF DRAINS IN EACH CELL
C                  TO SIMULATE THE SEEPAGE FACE ON EITHER BANK.  EACH
C                  LAYER INCISED BY A STREAM WILL HAVE TWO DRAINS.
C                  PAIR ENABLES ONE INPUT VALUE FOR DRAIN PAIRS.
C     RATIO     -  REAL EQUIVALENT OF IRATIO.
C     RCOND     -  UNIT CELL NODAL RIVER CONDUCTANCE.
C                  UNIQUE TO LAYER AND IRCH.
C     RIVALT    -  ALTITUDE OF RIVER IN CELL.
C     THKWA     -  THICKNESS OF WANAPUM FOR HEIGHT OF SEEPAGE FACE
C                  IN CANYON TYPE 7.
C     TOP       -  IN DESCENDING ORDER: ALSD, TOP WANAPUM, TOP GRANDE
C                  RONDE, TOP OF THE CRYSTALLINE BASEMENT.
C     WACENT    -  ALTITUDE OF WANAPUM FORMATION CENTER.
C     WELL      -  WELL FUNCTION TO SIMULATE DRAIN FLUX AT SNAKE CANYON.
C     WID       -  RIVER WIDTH, UNIQUE TO IRCH OF RIVER.
C
C
C                  TYPE  RIVER   DRAIN    EXPLANATION
C
C                   1      1       1      UPPER REACHES OF SMALL STREAMS
C                                         (FLOWING ON LOESS).
C
C                   2      2      1,2     LOWER REACHES OF SMALL STREAMS
C                                         (FLOWING ON WANAPUM BASALT).
C
C                   3      3     1,2,3    PALOUSE RIVER& SNAKE CANYON ED
C                                         (FLOWING ON GRANDE RONDE WITH
C                                         LAYERS PRESENT AT CELL LOCATIO
C
C                   4      3       -      SNAKE RIVER.
C
```

```
C                      5      -      3        SNAKE CANYON.  SEEPAGE FACE IN
C                                             RONDE (SIMULATED BY WELLS).
C
C                      6      -      1        EXTREME UPPEROF SMALL STREAMS
C
C                      7      -      1,2      EDGE OF SNAKE CANYON (LOESS AN
C                                             WANAPUM TERMINATE).
C
C                      8      3      3        SNAKE RIVER TRIBUTARY CANYONS
C                                             WITH SMALL STREAMS.
C
C                    NOTE:  DUE TO UNMANAGEABLE SENSITIVITY OF DRAINS
C                    TO NODE CENTER HEAD VALUES, SOME DRAINS ARE REPLACED
C                    WITH WELLS IN THE 3-DIMENSIONAL MODEL.
C                    A WELL IS WRITTEN FOR TYPE 3 NEAR SNAKE CANYON,
C                    TYPE 5, TYPE 7 LAYER 2, AND TYPE 8.
C
C
      INTEGER MTYPE(55,55),IRCH(55,55),IRATIO(55,55)
      REAL M,KH,KVR
      COMMON WID(18),HEIGHT(3),DEPTH(18)
      COMMON RIVALT(55,55),RATIO(55,55),WACENT(55,55),TOP(55,55,4)
      COMMON RCOND(55,55,3),DRCOND(55,55,3),KH(55,55,3)
      COMMON KVR(55,55,3), THKWA(55,55)
C
      READ(50,260) ((MTYPE(I,J),J=1,55),I=1,55)
      READ(50,260) ((IRCH(I,J),J=1,55),I=1,55)
      READ(50,260) ((IRATIO(I,J),J=1,55),I=1,55)
C
      READ(51,270) ((RIVALT(I,J),J=1,55),I=1,55)
      READ(51,270) (((TOP(I,J,K),J=1,55),I=1,55),K=1,4)
      READ(51,270) ((THKWA(I,J),J=1,55),I=1,55)
C
      READ(52,280) (WID(I),I=1,18)
      READ(52,280) (HEIGHT(I),I=1,3)
      READ(52,280) (DEPTH(I),I=1,18)
      READ(52,280) COND1
      READ(52,280) ANIS1
      READ(52,280) ET
      READ(52,280) SEEP
C
      READ(53,270) ((KH(I,J,2),J=1,55),I=1,55)
      READ(54,270) ((KH(I,J,3),J=1,55),I=1,55)
      READ(55,270) ((KVR(I,J,2),J=1,55),I=1,55)
      READ(56,270) ((KVR(I,J,3),J=1,55),I=1,55)
C
      READ(57,270) ((WACENT(I,J),J=1,55),I=1,55)
C
C     COEFFICIENTS TO ALTER CONDUCTANCE ON A GLOBAL BASIS.
      DRCOEF  = 1.0
      RIVCOF = 1.0
C
```

```
      PAIR = 2.0
      WEL3 = 0.0
      WEL2 = 0.0
C
C
      DO 100 I=1,55
      DO 100 J=1,55
      RATIO(I,J) = IRATIO(I,J) * 0.1
      IF (RATIO(I,J) .LE. 0.001) RATIO(I,J) = 1.0
100   CONTINUE
C
C
C     DRAIN CONDUCTANCE = {CELL WIDTH * LATERAL HYDRAULIC CONDUCTIVITY /
C     CELL HALF WIDTH (DISTANCE OVER WHICH HEAD IS DISSIPATED) *
C     CORRECTION COEFFICIENT}.  ONE VALUE PER CELL.
C
C     LATER COMPUTED TO INCLUDE SEEPAGE FACE HEIGHT.  RATIO OF CELL
C     WIDTH TO SEEPAGE FACE HEIGHT DEPENDENT ON PARTICULAR CELL
C     CHARACTERISTICS.
C
      DO 110 I=1,55
      DO 110 J=1,55
      DRCOND(I,J,1) = 2640.0 * COND1 * DRCOEF / 1320.0
      DRCOND(I,J,2) = (2640.0 * KH(I,J,2) * DRCOEF) / 1320.0
      DRCOND(I,J,3) = (2640.0 * KH(I,J,3) * DRCOEF) / 1320.0
110   CONTINUE
C
C
C     RIVER BED CONDUCTANCE = {CELL WIDTH * VERTICAL HYDRAULIC
C     CONDUCTIVITY *  CORRECTION COEFFICIENT}.  (VERTICAL HYDRAULIC
C     CONDUCTIVITY = HORIZONTAL HYDRAULIC CONDUCTIVITY * ANISOTROPY.)
C
C     LATER COMPUTED TO INCLUDE PARTICULAR CELL CHARACTERISTICS:
C     RATIO OF NODAL RIVER REACH LENGTH TO CELL WIDTH, RIVER WIDTH,
C     LENGTH OF FLOW PATH FROM CELL CENTER TO BOTTOM OF RIVER (RBOT).
C
      DO 120 I=1,55
      DO 120 J=1,55
      RCOND(I,J,1) = COND1 * ANIS1 * 2640.0 * RIVCOF
      RCOND(I,J,2) = KH(I,J,2) * KVR(I,J,2) * 2640.0 * RIVCOF
      RCOND(I,J,3) = KH(I,J,3) * KVR(I,J,3) * 2640.0 * RIVCOF
120   CONTINUE
C
C
      DO 250 I=1,55
      DO 250 J=1,55
      MT = 0
      MT = MTYPE(I,J)
      IF (MT .EQ. 0) GO TO 220
      IF (MT .NE. 1) GO TO 130
```

```
C                                                               TYPE 1
C
C                                                               DRAIN
      LYR = 1
      ELEV = RIVALT(I,J) + 5.0
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HEIGHT(LYR)
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C
C
C                                                               RIVER
      LYR = 1
      RBOT = RIVALT(I,J) - DEPTH(IRCH(I,J))
      THK = (TOP(I,J,LYR) - TOP(I,J,LYR + 1)) / 2.0
      CTR = TOP(I,J,LYR) - THK
      M = RBOT - CTR
      IF (M .LT. 1.0) M=(RBOT - TOP(I,J,LYR + 1))/2.0
      IF (M .GT. 75.0) M = 5.0
      IF (M .LT. 1.0) M = 1.0
      CRIV = (WID(IRCH(I,J)) * RCOND(I,J,LYR) * RATIO(I,J)) / M
      WRITE(61,310) LYR,I,J,RIVALT(I,J),CRIV,RBOT,IRCH(I,J),M,MT
C
      GO TO 220
130   CONTINUE
      IF (MT .NE. 2) GO TO 140
C                                                               TYPE 2
C
C                                                               DRAIN
      LYR = 1
      ELEV = TOP(I,J,LYR + 1) + 5.0
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HEIGHT(LYR)
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C                                                               DRAIN
      LYR = 2
      HGT = TOP(I,J,LYR) - RIVALT(I,J)
      IF (HGT .LT. 10.0) HGT = 10.0
      ELEV = RIVALT(I,J) + (HGT / 2.0)
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HGT
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C                                                               RIVER
      LYR = 2
      RBOT = RIVALT(I,J) - DEPTH(IRCH(I,J))
      THK = (TOP(I,J,LYR) - TOP(I,J,LYR + 1)) / 2.0
      CTR = TOP(I,J,LYR) - THK
      M = RBOT - CTR
      IF (M .LT. 1.0) M=(RBOT - TOP(I,J,LYR + 1))/2.0
      IF (M .LT. 1.0) M = 1.0
      CRIV = (WID(IRCH(I,J)) * RCOND(I,J,LYR) * RATIO(I,J)) / M
      WRITE(61,310) LYR,I,J,RIVALT(I,J),CRIV,RBOT,IRCH(I,J),M,MT
C
```

```
      GO TO 220
140   CONTINUE
      IF(MT .NE. 3) GO TO 170
C                                                          TYPE 3
C
C                                                          DRAIN
      LYR = 1
      ELEV = TOP(I,J,LYR + 1) + 5.0
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HEIGHT(LYR)
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C
C
C                                                          DRAIN
      LYR = 2
      HGT = TOP(I,J,LYR) - TOP(I,J,LYR+1)
      IF (HGT .LT. 10.0) HGT = 10.0
      ELEV = TOP(I,J,LYR + 1) + (HGT / 2.0)
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HGT
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C                                                          DRAIN
      LYR = 3
      HGT = TOP(I,J,LYR) - RIVALT(I,J)
      IF (HGT .LT. 10.0) HGT = 10.0
      ELEV = RIVALT(I,J) + (HGT / 2.0)
      IF (J .LE. 12) GO TO 150
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HGT
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
      GO TO 160
150   CONTINUE
C                                                          WELL
      C = 0.0
      WRITE(60,300) LYR,I,J,ELEV,C,IRCH(I,J),MT
      WELL = 2640.0 * 2640.0 * ET * RATIO(I,J)
      WELL = -1.0 * WELL
      WRITE(62,320) LYR,I,J,WELL,TOP(I,J,1),IRCH(I,J),MT
      WEL3 = WEL3 + WELL
160   CONTINUE
C
C                                                          RIVER
      LYR = 3
      RBOT = RIVALT(I,J) - DEPTH(IRCH(I,J))
      THK = (TOP(I,J,LYR) - TOP(I,J,LYR + 1)) / 2.0
      CTR = TOP(I,J,LYR) - THK
      M = RBOT - CTR
      IF (M .LT. 1.0) M = (RBOT - TOP(I,J,LYR + 1)) / 2.0
      IF (M .LT. 1.0) M - 1.0
      CRIV - (WID(IRCH(I,J)) * RCOND(I,J,LYR) * RATIO(I,J)) / M
      WRITE(61,310) LYR,I,J,RIVALT(I,J),CRIV,RBOT,IRCH(I,J),M,MT
C
```

```
      GO TO 220
170   CONTINUE
      IF (MT .NE. 4) GO TO 180
C
C                                                            TYPE 4
C
C                                                            RIVER
      LYR = 3
      RBOT = RIVALT(I,J) - DEPTH(IRCH(I,J))
      THK = (TOP(I,J,LYR) - TOP(I,J,LYR + 1)) / 2.0
      CTR = TOP(I,J,LYR) - THK
      M = RBOT - CTR
      IF (M .LT. 1.0) M = (RBOT - TOP(I,J,LYR + 1)) / 2.0
      IF (M .LT. 1.0) M = 1.0
      CRIV = (WID(IRCH(I,J)) * RCOND(I,J,LYR) * RATIO(I,J)) / M
C
      WRITE(61,310) LYR,I,J,RIVALT(I,J),CRIV,RBOT,IRCH(I,J),M,MT
C
      GO TO 220
180   CONTINUE
      IF (MT .NE. 5) GO TO 190
C
C                                                            TYPE 5
C
C                                                            DRAIN
      LYR = 3
      ELEV = TOP(I,J,1)
C     CDR = DRCOND(I,J,LYR) * RATIO(I,J) * 2640
      CDR = 0.0
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
      WELL = 2640.0 * 2640.0 * ET * RATIO(I,J)
      WELL = -1.0 * WELL
      WRITE(62,320) LYR,I,J,WELL,TOP(I,J,1),IRCH(I,J),MT
      WEL3 = WEL3 + WELL
C
      GO TO 220
190   CONTINUE
      IF (MT .NE. 6) GO TO 200
C
C                                                            TYPE 6
C
C                                                            DRAIN
      LYR = 1
      IR = 20
      ELEV = TOP(I,J,1)
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * HEIGHT(LYR)
      WRITE(60,300) LYR,I,J,ELEV,CDR,IR,MT
C
      GO TO 220
200   CONTINUE
      IF (MT .NE. 7) GO TO 210
```

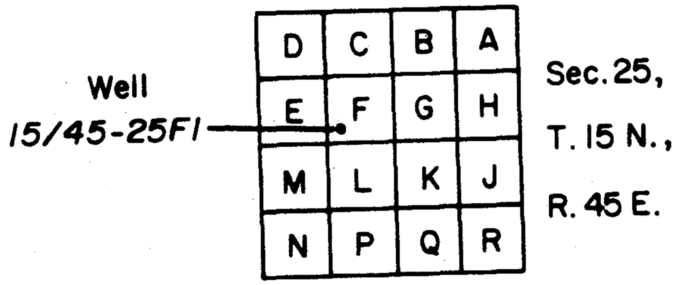
```
C                                                             TYPE 7
C
C                                                             DRAIN
      LYR = 1
      ELEV = TOP(I,J,LYR + 1) + 5.0
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * HEIGHT(LYR)
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C                                                             DRAIN
      LYR = 2
      ELEV = WACENT(I,J)
      IF (THKWA(I,J) .LT. 10.0) THKWA(I,J) = HEIGHT(LYR) * 2.0
      CDR = DRCOND(I,J,LYR) * RATIO(I,J) * (THKWA(I,J)/2.0)
      CDR = 0.0
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
C
C     CELL WIDTH IS 2640 FEET.  NOTE ONE-HALF CELL WIDTH
C     FOR LENGTH OF DRAIN FACE IN WANAPUM.
C
      WELL = 2640.0 * 1320.0 * ET * RATIO(I,J)
      WELL = WELL * (-1.0)
      WRITE(62,320) LYR,I,J,WELL,THKWA(I,J),IRCH(I,J),MT
      WEL2 = WEL2 + WELL
C
      GO TO 220
210   CONTINUE
      IF (MT .NE. 8) GO TO 230
C                                                             TYPE 8
C
C                                                             DRAIN
      LYR = 3
      HTH = ((TOP(I,J,LYR) - RIVALT(I,J))/2.0)
      ELEV = RIVALT(I,J) + HTH
C     CDR = DRCOND(I,J,LYR) * RATIO(I,J) * PAIR * HTH * 2.0
      CDR = 0.0
      WRITE(60,300) LYR,I,J,ELEV,CDR,IRCH(I,J),MT
C
      WELL = 2640.0 * 2640.0 * ET * RATIO(I,J)
      WELL = -1.0 * WELL
      WRITE(62,320) LYR,I,J,WELL,TOP(I,J,1),IRCH(I,J),MT
      WEL3 = WEL3 + WELL
C                                                             RIVER
      LYR = 3
      RBOT = RIVALT(I,J) - DEPTH(IRCH(I,J))
      THK = (TOP(I,J,LYR) - TOP(I,J,LYR + 1)) / 2.0
      CTR = TOP(I,J,LYR) - THK
      M = RBOT - CTR
      IF (M .LT. 1.0) M = (RBOT - TOP(I,J,LYR + 1)) / 2.0
      IF (M .LT. 1.0) M = 1.0
      CRIV = (WID(IRCH(I,J)) * RCOND(I,J,LYR) * RATIO(I,J)) / M
      WRITE(61,310) LYR,I,J,RIVALT(I,J),CRIV,RBOT,IRCH(I,J),M,MT
```

```
      GO TO 220
C
220   CONTINUE
      GO TO 250
230   WRITE (67,240) LYR,I,J,MT
240   FORMAT ('  FOR LYR,ROW,COL',3I5,'   MT IS OUT OF RANGE',I5)
C
250   CONTINUE
C
      WRITE(100,290) WEL2,WEL3
C
260   FORMAT (55I2)
270   FORMAT (20F6.1 / 20F6.1 / 15F6.1)
280   FORMAT (F10.0)
290   FORMAT (' LYR 2 WELLS',F10.0,'  LYR 3 WELLS',F10.0,'  FOR DRAIN
     .SUBSTITUTION')
300   FORMAT (3I5,F10.0,E10.3,260X,10X,I10,10X,I5)
310   FORMAT (3I5,F10.0,E10.3,F10.0,260X,I10,F10.0,I5)
320   FORMAT (3I10,F10.0,260X,F10.0,2I5)
      STOP
      END
```

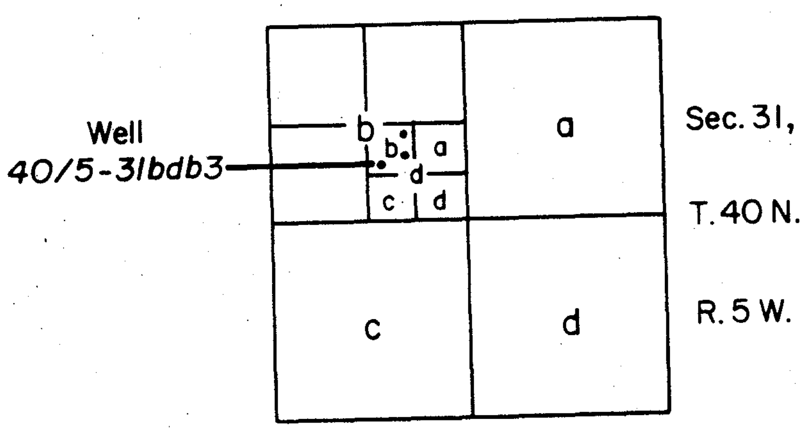
APPENDIX B

WELL NUMBERING SYSTEMS OF WASHINGTON AND IDAHO

Idaho and Washington identify wells based on the township and range system but divide the sections differently. Idaho wells are referenced to the Boise baseline and meridian while Washington wells are referenced to the Willamette baseline and meridian. Both states identify the township, range, and section of the well in question, 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 in order. The Washington well 15/45-25F1 and the Idaho well 40/5-31bdb3 are located on the following page.



Well Numbering System of Washington



Well Numbering System of Idaho

APPENDIX C

WELL DATA AND MASS WATER LEVEL MEASUREMENTS

WASHINGTON WELLS

LOCATION OF WELL	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FT MSL)	WELL DEPTH (FT)	DEPTH TO WATER BELOW LSD (FT)	WATER LEVEL ALTITUDE (FT MSL)	ALTITUDE OF CASED INTERVAL (FT MSL)	ALTITUDE OF OPEN INTERVAL (FT MSL)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
13/44-05C1	(34,10)	J. RYAN	2540	--	80. R	2460	--	--	W	--
13/44-11H1	(41,13)	J. DAVIS	2455	~130	11.18	2444	--	--	W	98
13/44-12P1	(42,13)	J. DAVIS	2440	70	7.29	2433	2425-2440	2370-2425	W	92
13/44-12P2	(42,13)	J. DAVIS	2505	165	61.59	2443	2487-2505	2340-2487	GR	1
13/45-01B1	(49,26)	R. HOOD	2740	--	20.47	2720	--	--	B	--
13/45-03M2	(46,21)	E. DRUFFEL	2618	100	18.85	2599	--	--	W	28
13/45-05D1	(42,18)	G. SENTER	2558	190	4.04	2554	2538-2558	2368-2538	W	0
13/45-10L1	(47,20)	P. KIRPIS	2663	137	78.47	2585	2613-2663	2526-2613	W	26
14/43-24M1	(27,10)	YOUNG	2430	165	78.94	2351	2290-2430	2265-2290	W	52
14/43-24M2	(27,11)	YOUNG	2420	~8	6.00	2414	--	--	U	--
14/43-24R1	(29,11)	H. WEGNER	2350	162	7.68	2342	2343-2350	2188-2343	W	86
14/43-25N1	(29, 9)	A. TOWNSEND	2480	250	37.65	2442	2460-2480	2230-2460	W	74
14/43-25N2	(29, 8)	A. TOWNSEND	2420	350	121.	2299	--	--	GR	3
14/44-01E1	(31,24)	R. HARLOW	2565	375	108.22	2457	--	--	GR	4
14/44-01J1	(32,25)	HENDRICKS	2660	200	0.00	2660	--	--	?U	--
14/44-01L1	(32,24)	B. BELL	2620	275	221.18	2399	--	--	W	75
14/44-01M3	(31,23)	195&WWPUL	2535	--	46.40	2489	--	--	W	--
14/44-02J1	(31,24)	R. HARLOW	2530	--	11.64	2518	--	--	?U	--
14/44-02M2	(30,22)	D. BLOOMFIELD	2498	102	34.26	2464	2468-2498	2396-2468	W	29
14/44-09J2	(30,19)	KIEFER	2485	286	210.	2275	2467-2485	2199-2167	?GR	-1
14/44-14P2	(33,19)	WSU DAIRY #2	2550	432	286. A	2264	2200-2550	2120-2200	GR	2
14/44-16F1	(30,17)	E. BROCH	2405	160	120.02	2285	--	--	?GR	-3
14/44-21R1	(33,15)	HATLEY	2340	150	13.41	2327	--	--	GR	0
14/44-23A1	(35,19)	R. WILBURN	2560	~90	40. R	2520	--	--	W	4
14/44-28A1	(33,15)	V. RUMLEY	2385	111	43.71	2341	--	--	W	66
14/44-31A1	(32,13)	BREWER	2460	--	3.72W	2456	--	--	W,U	--
14/44-34C1	(35,15)	N. HATLEY	2455	200	0.00	2455	2437-2455	2255-2437	W	83

LOCATION OF WELL	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FT MSL)	WELL DEPTH (FT)	DEPTH TO WATER BELOW LSD (FT)	WATER LEVEL ALTITUDE (FT MSL)	ALTITUDE OF CASED INTERVAL (FT MSL)	ALTITUDE OF OPEN INTERVAL (FT MSL)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
14/45-01F1	(39,33)	PUL. TEST	2470	982	213.61	2256	2270-2470	1488-2270	GR	35
14/45-03H3	(38,31)	WWP	2460	259	198.94	2261	2282-2460	2201-2282	GR	7
14/45-03P1	(38,29)	S. JORSTAD	2460	--	19.65	2440	--	--	W	--
14/45-04D1	(35,29)	WSU #6	2535	702	266.5 A	2268	2143-2535	1833-2143	GR	17
14/45-04N1	(36,28)	WSU	2390	95	>95.	--	--	--	W	100
14/45-05D1	(33,27)	PULLMAN #1	2342	164	67.22	2275	2308-2342	2178-2308	GR	5
14/45-05D3	(33,27)	PULLMAN #3	2340	167	69.37	2271	2300-2340	2173-2300	GR	5
14/45-05F1	(34,27)	WSU #1(OBS)	2364	145	92.87	2271	2304-2364	2219-2304	GR	3
14/45-05F4	(34,28)	WSU #4	2364	275	95.00A	2269	--	--	GR	7
14/45-06D4	(32,26)	H. WOO	2515	220	168.21	2347	2475-2515	2295-2475	W	107
14/45-07E1	(34,24)	H. COLE	2530	82	33.21	2497	2522-2530	2448-2522	W	30
14/45-08E1	(35,25)	PULLMAN #5	2447	712	175.45	2271	--	--	GR	21
14/45-08J4	(36,26)	J. ASKINS	2420	223	147.65	2272	--	--	GR	4
14/45-09E1	(37,27)	M. WISE	2415	67	9.05W	2406	2395-2415	2348-2395	W	71
14/45-09E2	(37,27)	H. NEIL	2420	240	142.97	2277	2398-2420	2180-2398	GR	4
14/45-10P1	(39,28)	H. STRATTON	2540	--	31.45	2509	--	--	W	--
14/45-15B1	(40,28)	G. LEONARD	2610	213	147.62	2462	2515-2610	2397-2515	W	57
14/45-16E1	(38,26)	W. STRATTON	2400	110	DRY	--	2360-2400	2290-2360	W	100
14/45-16G1	(39,26)	WSU SPILLMAN	2480	400	215. A	2265	2448-2480	2080-2448	GR	9
14/45-16R1	(40,26)	G. WISE	2418	195	142.87	2275	2243-2418	2223-2243	GR	4
14/45-19G1	(37,22)	J. BENSCOTER	2575	198	13.50	2562	--	--	W	70
14/45-20A1	(39,24)	JACOBSON	2550	--	37.77	2512	--	--	W	--
14/45-21H2	(41,25)	SEARS	2440	--	166.86	2273	--	--	GR	--
14/45-22P2	(42,25)	A. FAIRBANKS	2464	250	185.67	2278	2444-2464	2214-2444	GR	14
14/45-23A1	(43,28)	R. DRUFFEL	2480	--	0.00	2480	--	--	U	--
14/45-23R1	(44,28)	R. MEYER	2520	80	38.74	2481	2474-2520	2440-2474	W	42
14/45-24F1	(44,29)	--	2505	--	13.96	2491	--	--	W	--
14/45-26J2	(45,26)	WEBER FARM	2545	223	42.99	2502	2483-2545	2318-2483	W	120
14/45-26J1	(45,26)	WEBER FARM	2545	--	9.34	2536	--	--	?U	--
14/45-36Q2	(48,26)	J. WHITMAN	2680	127?	4.44	2676	2623-2680	2553-2623	W	0

LOCATION OF WELL	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FT MSL)	WELL DEPTH (FT)	DEPTH TO WATER BELOW LSD (FT)	WATER LEVEL ALTITUDE (FT MSL)	ALTITUDE OF CASED INTERVAL (FT MSL)	ALTITUDE OF OPEN INTERVAL (FT MSL)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
14/46-07N1	(43,32)	J. BRADEN	2570	100	16.41	2554	--	--	W	27
14/46-07N3	(43,32)	J. BRADEN	2570	353	306.62	2263	2505-2570	2217-2505	GR	6
14/46-19F1	(45,30)	L. BROWN	2485	180	11.52W	2473	--	--	GR	3
15/43-08B1	(10,18)	KINCAID	~2100	--	157.49	1943	--	--	GR	--
15/43-16J1	(14,17)	J. GHILCHRIST	~2100	138	97.82	2002	--	--	GR	-1
15/43-18H1	(11,15)	R. MILLER	2270	160	75.93	2194	2180-2270	2110-2180	W	-3
15/43-18R1	(11,14)	M. MILLER	2140	~130	80. R	2060	--	--	W	20
15/43-21A1	(15,17)	--	~2230	~30	24.33	2206	--	--	U	--
15/44-01G1	(23,33)	A. CLARK	2380	157	18.56	2371	2340-2380	2213-2340	W	0
15/44-01N1	(23,32)	G. CLARK	2450	73	0.85	2449	2415-2450	2377-2415	W	0
15/44-11F1	(23,30)	V. BIDDLE	2435	140	0.	2435	--	--	W	0
15/44-11F2	(23,30)	V. BIDDLE	2430	225	FLOWING	2430	--	--	B	--
15/44-15G2	(23,27)	ALBION #1	2390	290	180. R	2210	--	--	GR	600
15/44-15G3	(23,27)	ALBION #2	2400	--	112.	2288	--	--	GR	--
15/44-21D1	(22,24)	M. MCCROSKEY	2355	177	125.44	2230	2335-2355	2178-2335	?W,U	95
15/44-24D1	(26,28)	J. MORRISON	2380	35	7.92	2372	--	--	U	--
15/44-24E1	(26,28)	J. MORRISON	2375	135	120.19	2255	--	--	W	100
15/44-24F1	(27,29)	J. MORRISON	2390	165	21.50	2378	--	--	W	125
15/44-26L1	(27,25)	M. HARLOW	2390	160	120.97	2269	2370-2390	2230-2370	GR	0
15/44-35E1	(28,24)	V. MICHAELSON	2412	300	130.15	2282	2373-2412	2112-2373	GR	11
15/44-35F1	(28,25)	V. MICHAELSON	2435	96	14.86	2420	--	--	W	36
15/45-06E	(23,34)	A. CLARK	2480	--	76.77	2403	--	--	W	--
15/45-07Q1	(26,33)	G. LAWSON	2525	150?	48.30	2477	--	--	W	37
15/45-08L1	(27,34)	H. ROSSEBO	2480	124	22.05	2458	2440-2480	2360-2440	W	39
15/45-08M2	(27,34)	R. HOWELL	2495	290	>210.	<2285	2440-2495	2205-2440	GR	3
15/45-10M1	(30,36)	R. GILLESPE	2510	~200	180. R	2330	--	--	W	113
15/45-16B1	(29,35)	R. WHITMORE	2500	200	21.62	2478	--	--	W	113
15/45-16K1	(30,34)	R. WHITMORE	2520	--	18.70	2501	--	--	W	--
15/45-19E2	(28,30)	G. LAWSON	2445	110	18.95	2426	--	--	W	63

LOCATION OF WELL	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FT MSL)	WELL DEPTH (FT)	DEPTH TO WATER BELOW LSD (FT)	WATER LEVEL ALTITUDE (FT MSL)	ALTITUDE OF CASED INTERVAL (FT MSL)	ALTITUDE OF OPEN INTERVAL (FT MSL)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
15/45-20H2	(30,32)	D. PORT	2530	~130	30.56	2500	--	--	W	50
15/45-24C1	(35,38)	--	2540	350	60.	2480	--	--	GR	15
15/45-25A2	(37,37)	M. BOYD	2650	215	114.10	2536	--	--	W	63
15/45-25Q1	(38,36)	L. BOYD	2609	264	50. R	2559	2544-2609	2345-2544	W	107
15/45-30G4	(30,29)	USDA AG EXP	2520	371	249.40	2271	--	--	GR	10
15/45-32C2	(32,29)	PULLMAN #6	2430	518	152.10	2278	2196-2430	1912-2196	GR	17
15/45-32N2	(33,28)	PULLMAN #4	2356	954	73.22	2283	1957-2356	1402-1957	GR	35
15/45-34L2	(36,31)	WSU WHITLAOW#5	2510	396	238. A	2272	2210-2510	2114-2210	GR	9
15/45-35F1	(37,33)	MOS-PUL AIRPT	2531	172	7.00	2524	--	--	W	126
15/46-06L1	(33,43)	T. QUIST	2620	--	29.20	2591	--	--	W	--
15/46-06P2	(33,42)	S. FLEENOR	2625	100	53.02	2572	--	--	W	31
15/46-08L1	(35,43)	F. FLEENOR	~2700	280	13.99	2686	--	--	B	--
15/46-20N1	(38,39)	H. NELSON	2570	--	5.87	2563	--	--	U	--
16/43-25D1	(10,27)	NELSON	2140	20	17. R	2123	--	--	U	--
16/44-29F1	(14,30)	R. COCKING	2135	~500	400. R	1735?	--	--	GR	22
16/45-10A2	(21,47)	F. ELLS	2630	50	11.52	2620	--	--	W	-30
16/45-15P1	(23,44)	M. KUEHNER	2495	100	7.99W	2487	--	--	U?,W	--
16/45-22K1	(24,43)	E. RUPP	2470	165	42.02	2428	2442-2470	2305-2442	W	102
16/45-27Q3	(26,41)	L. THOMPSON	2460	--	12.98	2447	--	--	W	--
16/45-28H1	(24,41)	J. REDFIELD	2450	--	95.02	2355	--	--	W	--
16/45-29J1	(23,39)	D. HARLOW	2430	--	56.75	2373	--	--	W	--

IDAHO WELLS

LOCATION OF WELL	MODEL CELL LOCATION	WELL OWNER	ALTITUDE OF LAND SURFACE (FT MSL)	WELL DEPTH (FT)	DEPTH TO WATER BELOW LSD (FT)	WATER LEVEL ALTITUDE (FT MSL)	ALTITUDE OF CASED INTERVAL (FT MSL)	ALTITUDE OF OPEN INTERVAL (FT MSL)	FMT YLD WTR	PERCENT OF FORMATION THAT WELL PENETRATES
39/05-07DAD2	(45,40)	MOSCOW #2	2568	320	49.	2511	--	--	W	157
39/05-07DAD3	(45,40)	MOSCOW #3	2568	261	58.	2502	--	--	W	124
39/05-07	(43,39)	MOSCOW #8	2620	1458	367.	2253	--	--	GR	113
39/05-7CBB1	(43,39)	UI #3	2567	1336	294.65	2272	--	--	GR	106
39/05-08BDB	(45,41)	MOSCOW #6	~2600	1308	334. R	2266	--	--	GR	78
39/05-16DDB	(49,41)	D. GENTRY	2620	?55	37.00	2583	--	--	W,U?	-6
39/05-30AA	(48,36)	D. SINCLAIR	2620	--	3.00	2617	--	--	U	--
39/06-12	(43,38)	MOSCOW #9	2538	1252	287.	2251	--	--	GR	93
39/06-12DAA1	(43,38)	UI #4	2554	747	284.66	2255	--	--	GR	47
40/05-30CA	(40,43)	F. WARD	2638	--	125.38	2513	--	--	W	--
40/05-31DB	(41,42)	K. ROGERS	2635	--	30. R	2605	--	--	W,U?	--
40/06-19CB	(36,43)	C. LADWIG	2770	258	12.17	2758	--	--	W,U?	0
40/06-25DA	(39,42)	D. CLARK	2680	--	27.74	2652	--	--	W	--
40/06-36AD	(40,41)	A. CARSON	2610	135	0.00	2610+	--	--	W	40

R-----REPORTED
W-----WINTER MEASUREMENT
+-----FLOWING AT THIS ALTITUDE
A-----AIRLINE MEASUREMENT
N-----APPROXIMATE

U-----UNCONSOLIDATED
W-----WANAPUM FORMATION
GR----GRANDE RONDE FORMATION
B-----BASEMENT (GRANITE)