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

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Submitted to

Pullman-Moscow Water Resources Committee

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ABSTRACT

Continued ground water level decline in the Grande Ronde Basalt near Pullman, Washington and Moscow, Idaho demonstrates a need for ground water management policies to be established; the Grande Ronde Basalt is the primary source of water in the region. Previous researchers have constructed a numerical ground water flow model to simulate future water level trends under various municipal pumping stress conditions.

The approximation of a ground water flow system with a numerical model incorporates many simplifications. Accuracy of the model results is dependent on model construction and the validity of the input values that characterize the system.

A sensitivity analysis is conducted on model responses to variations in: a) areal recharge to the ground water basin, b) seepage discharge from the face of the Snake River Canyon, and c) constant head versus constant flux boundary conditions.

Sensitivity studies demonstrate that simulated water levels in the Grande Ronde Basalt near Pullman and Moscow are relatively insensitive to changes in areal recharge, Snake River Canyon seepage, and model boundary conditions. This is believed to result from model construction and may not be conceptually correct.

Modifying the representation of the Grande Ronde Basalt with several model layers and simulating the Snake River Canyon seepage face with drains may enhance the confidence of using this ground water flow model as a management tool.

CHAPTER I

INTRODUCTION

Statement of the Problem

The Pullman-Moscow region of northern Idaho and southeastern Washington relies on ground water as the predominant source of water. The major users of ground water are the cities of Moscow, Idaho and Pullman, Washington, the University of Idaho, and Washington State University. Most ground water is pumped from basalt rocks and associated interbeds of the Grande Ronde Formation (Yakima Subgroup) of the Columbia River Basalt Group. Water levels in wells that penetrate the Grande Ronde have continued to decline slowly because of the increase in ground water pumping over the last several decades. Since 1975, the average annual pumpage of ground water has increased at a rate of about 1% a year and the associated rate of water level decline has been about 1¼ feet per year.

Local concern over the economic ramifications of continued water level decline led to a cooperative effort between the U.S. Geological Survey, the two cities, and the two universities to construct a ground water flow model of the region. Aided by the collection of new hydrogeologic data, a numerical finite difference model was created (Smoot, 1987; Lum and others, 1990). The model is based on the U.S. Geological Survey modular ground water flow program MODFLOW (McDonald and Harbaugh, 1988); the model can be used to simulate future trends in ground water level changes under various pumping scenarios.

The predictive capability of any model is dependent on the design characteristics of the model and the reliability of parameter values that are input to the model. Identification of individual parameters for which model results are sensitive is an important part of the modeling process. This report presents the results of sensitivity analyses of several parameters that are significant to the Pullman-Moscow model. Sequential procedures for simulating the model on the University of Idaho IBM 4381 computer are documented for the benefit of future researchers and operators of the model.

Purpose and Objectives

The purpose of this study is to gain a better understanding of the sensitivity and applicability of the Pullman-Moscow ground water flow model constructed by Lum and others (1990). The general objective is to perform a sensitivity analysis on several parameters that have a significant role in the conceptual model, in order to characterize to what degree they control the output of the numerical model.

Specific objectives include:

1) Adapt the Pullman-Moscow ground water flow model (Lum and others, 1990) so that it is operational on the University of Idaho IBM 4381 computer.

2) Document the sequential procedures that are necessary to run the model on the University of Idaho IBM 4381 computer.

3) Conduct an analysis of model responses to variations in areal recharge, seepage discharge from the face of the Snake River Canyon, and constant head versus constant flux boundary conditions.

4) Analyze the results of the sensitivity studies with respect to the applicability of the model for management purposes.

5) Recommend what future investigations are necessary to enhance the use of the numerical model as a tool in predicting ground water level trends in the Pullman-Moscow area.

Previous Investigations

Ground water investigations in the Pullman-Moscow region began with a hydrogeologic reconnaissance of the area by Russell (1897). DeMotte and Miles (1933) conducted a study of the Pullman artesian basin. Significant contributions were made by Foxworthy and Washburn (1963) and Walters and Glancy (1969) in defining the hydrogeology of the area. Investigations of the geology of the region were carried out by Foxworthy and Washburn (1963), Ross (1965), Lin (1967), Ringe (1968), Brown (1976), Barker (1979), and Cotton (1982). Swanson and others (1979) and Drost and Whiteman (1986) examined the structural geology and stratigraphy of the Columbia River Basalt Group. A reconnaissance geologic map of the Columbia River Basalt Group was provided by Swanson and others (1980). Hooper and Webster (1982) contributed a surficial geologic map of the Pullman-Moscow area. Information on local wells and water levels in the basin were provided by Ross (1965), Jones and Ross (1972), Crosthwaite (1975), Barker (1979), and Whiteman (1986). Ground water levels in the Columbia River Basalt and overlying materials were provided by Bauer and others (1985). Williams and Allman (1969) discussed the factors affecting infiltration and recharge in a loess covered basin. Bauer and Vaccaro (1987) documented a deep percolation model for estimating ground water recharge. Bauer and Vaccaro (1989) provided estimates of ground water recharge to the Columbia Plateau regional aquifer system for predevelopment and current land-use conditions. Bockius (1985) conducted a magnetic geophysical survey to delineate the extent of basalts in the Pullman-Moscow Basin. A magnetotelluric geophysical survey was done by Klein and others (1987) to provide data on basalt thicknesses in the Pullman-Moscow vicinity; the results were used as input into the numerical model constructed by Smoot (1987) and Lum and others (1990). Other ground water modeling investigations have been carried out by Jones and Ross (1972) and Barker (1979). Eyck and Warnick (1984) provided a detailed bibliography and summary of documents pertinent to the municipal water supply of the Pullman-Moscow area.

Smoot (1987) and Lum and others (1990) present the methods of field data collection, details of the numerical model construction and calibration, and an analysis of the results of several predictive simulations that were run under a variety of pumping scenarios. The research undertaken by this author is a continuation of the work initiated by Lum and others (1990).

Description of the Study Area

Location

The study area is located in northern Idaho and south-eastern Washington within the counties of Latah, Idaho and Whitman, Washington (fig. 1). The communities of Moscow and Pullman are situated about 8 miles apart and are separated by the state border. Moscow is the home of the University of Idaho and Washington State University is located in Pullman.

Physiography and Land Use

The Pullman-Moscow Basin consists of a thick sequence of volcanic rocks that is part of the Columbia River Basalt Group. The basalt is covered by a substantial layer of aeolian loess. The large soil-moisture storage capacity of the loess is sufficient to grow crops of wheat, lentils, and peas using dryland farming techniques.

The basin is bordered on the north, south, and east by a ring of low granitic mountains. The gentle rolling hills of the basin plateau are incised in the southwest corner of the study area by the Snake River Canyon. The plateau near the canyon is approximately 1500 feet above the river. The canyon wall is quite steep in places and is the site of numerous small springs and seeps.

Precipitation and Surface Water

Precipitation in the Pullman-Moscow Basin shows a trend of increasing from west to east. Average annual rainfall in

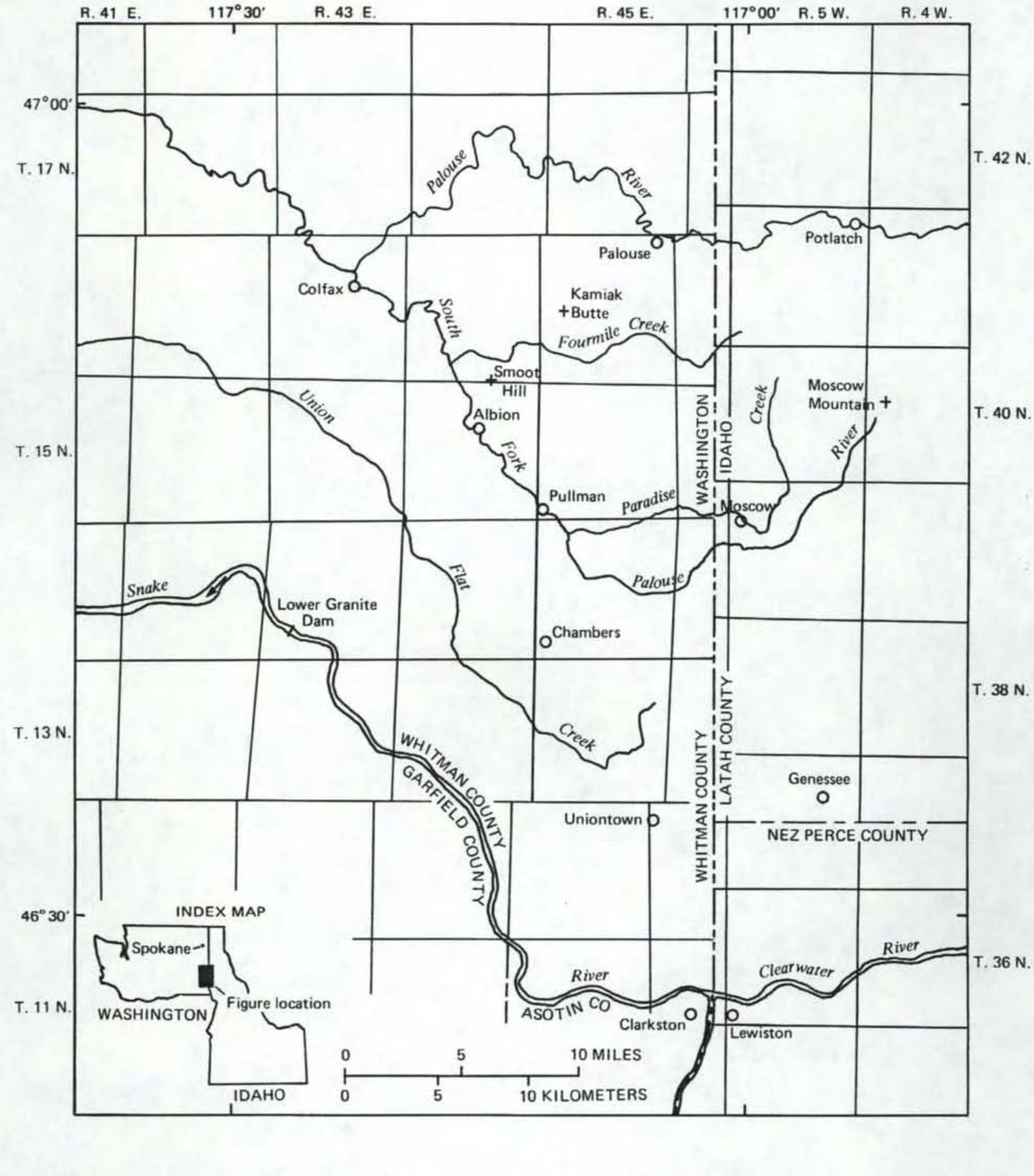


Figure 1. Location of the Pullman-Moscow area (Lum and others, 1990).

the Snake River Canyon can be as low as 15 inches per year, whereas in the higher hills east of Moscow, the precipitation is as much as 40 inches per year. Precipitation in Pullman is about 22 inches per year and in Moscow about 24 inches per year (NOAA, 1987a and 1987b). Most of the precipitation occurs during the winter months and is of low intensity. Precipitation and the resulting infiltration is the predominant mechanism for recharge to the ground water basin.

With the exception of the Snake River, streams within the study area are small. There are several perennial streams that flow from east to west in the region including Fourmile Creek, Paradise Creek, the South Fork of the Palouse River, and Union Flat Creek (fig. 1). The lower reaches of these streams have cut into the upper basalt flows. The Palouse River in the northern sector of the basin has a larger volume than these streams and incises deeper into the basalt. The only major body of surface water in the region is the Snake River. The Snake River Canyon may have a significant role in ground water discharge from the Pullman-Moscow Basin, because many of the water bearing zones in the basalt flows are exposed along the river canyon.

CHAPTER II

HYDROGEOLOGY

The hydrogeologic characteristics of the Pullman-Moscow Basin control the occurrence and movement of ground water in the region. A concise understanding and interpretation of the water-bearing properties of the geologic units and the recharge/discharge mechanisms within the basin are necessary to construct a reliable ground water flow model.

Geology and Water-Bearing Characteristics of Geologic Units

The geology of the Pullman-Moscow Basin consists of an aeolian loess, underlain by a thick sequence of basalts and then by crystalline basement rocks (fig. 2). The Pleistocene loess, which includes a well-developed silt-loam soil, varies in thickness from zero to several hundred feet.

The Miocene basalt flows in the region are grouped into the Wanapum and Grande Ronde Basalts, which are part of the Columbia River Basalt Group (Swanson and others, 1979). The Wanapum and Grande Ronde Basalts differ geochemically, and are separated by a siltstone/claystone interbed called the Vantage Member. Numerous other sedimentary interbeds occur within the basalt sequence, particularly near the margins of the Columbia Plateau. The Wanapum Basalt varies in thickness from zero to 250 feet and the Grande Ronde Basalt is over 3000 feet thick in the western margin of the study area (Klein and others, 1987). The combined thicknesses of the Wanapum and Grande

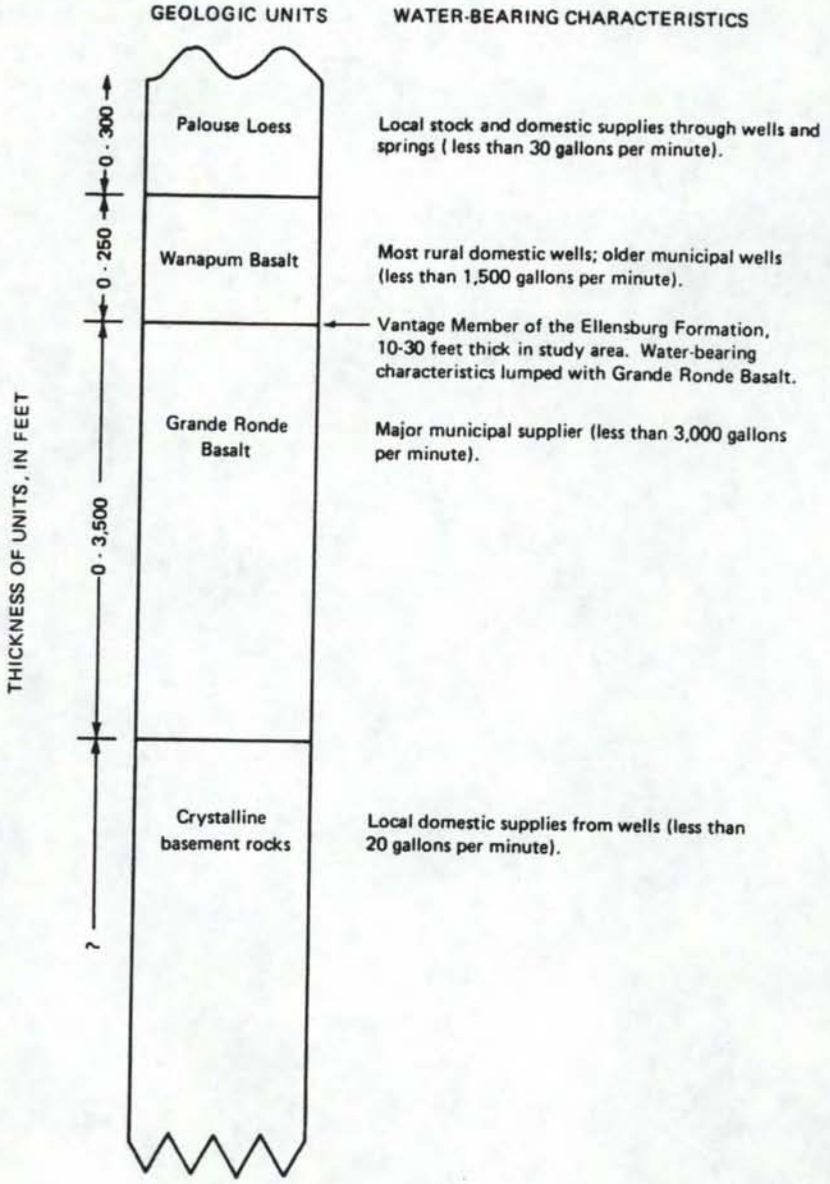


Figure 2. Stratigraphy and water-bearing characteristics of the geologic units in the Pullman-Moscow area (Lum and others, 1990).

Ronde Basalts are about 1300 feet near Moscow and 2000 feet near Pullman.

The crystalline basement rocks are primarily Cretaceous granites associated with the Idaho Batholith. Some basement rocks in the northern sector of the basin are metamorphic.

Although the loess, basalt, and crystalline rock units all yield water to wells, the major producing aquifers in the basin occur in the basalt (fig. 2). Shallow wells penetrating only the loess produce small quantities of water for domestic use and the watering of stock animals. Wells that penetrate the crystalline basement rocks along the eastern border of the basin also produce only a modest supply of water.

Most of the municipal water supply for the region is pumped from the fractured zones of the Grande Ronde Formation and its associated interbeds. In 1989, the average amount of water pumped from the Grande Ronde in the Pullman-Moscow area was nearly 7 million gallons per day. The two cities and the two universities maintain their own separate wells. Water levels in wells that penetrate the Grande Ronde continue to decline at a steady rate of about 1¼ feet annually.

The Wanapum Formation also contains several high yield zones, but the water quality near Moscow is not as good as the water being pumped from the Grande Ronde Basalt. Pumpage from the Wanapum has decreased substantially since the 1960's with the development of deep wells in the Grande Ronde Basalt; currently only about 3% of the municipal water comes from the Wanapum Basalt. The reduction in pumpage from the Wanapum has caused water levels to recover several tens of feet in wells that penetrate this formation near Moscow and Pullman.

Lum and others (1990) define three hydrogeologic units based on the correlation of hydrologic properties with mappable geologic units. The hydrogeologic units are the Palouse Loess, the Wanapum Basalt, and the Grande Ronde Basalt. The Vantage Member is treated as part of the Grande Ronde. The perspective view in figure 3 shows a conceptual relation between the three units. The first two layers and much of the third are incised by the Snake River Canyon.

Recharge

The predominant mechanism for areal recharge to the ground water basin is from infiltration of precipitation through the surficial loess, which has a high water storage capacity. Water levels in shallow wells are responsive to the seasonal fluctuation in precipitation. Recharge occurs mainly during the fall, winter, and spring months. Infiltration of water below the root zone of crops and into the aquifer system has been calculated for two drainages in the Pullman-Moscow Basin using the deep percolation model described by Bauer and Vaccaro (1987). Details of this methodology are presented in chapter III.

Discharge and Ground Water Flow

A major ground water discharge zone for the study area appears to occur in the Snake River Canyon. Water level

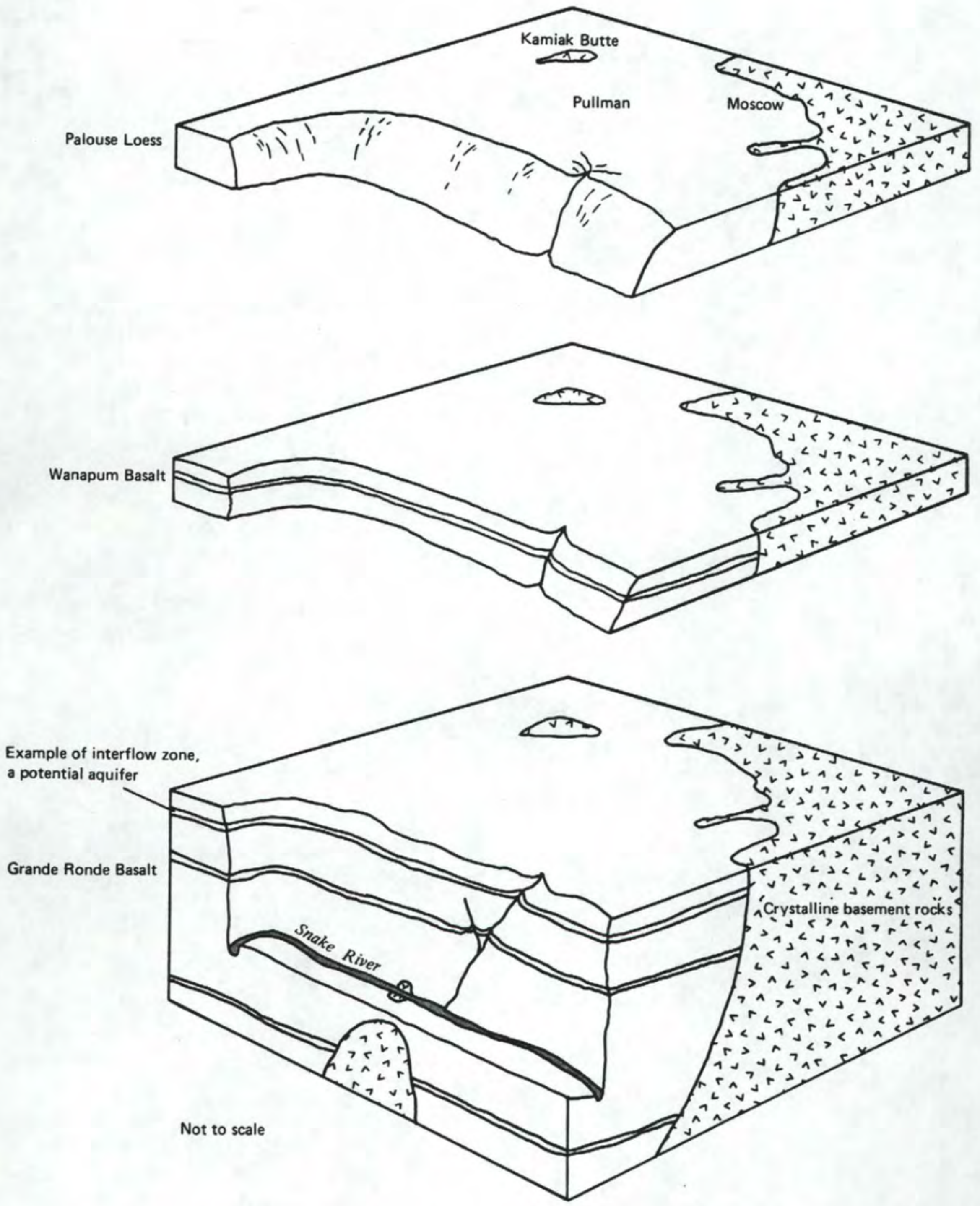


Figure 3. Three-dimensional perspective of the layered aquifer system (Lum and others, 1990).

contours indicate that ground water flows to the west, and may discharge as springs and seeps along the canyon face or discharge directly into the Snake River. Zones of higher hydraulic conductivity exist between basalt flows. Since many of the basalt flows have been incised by the Snake River, the principal means of discharge may be via seams at outcrop areas along the canyon wall. The rate of discharge directly into the river is unknown. Recent studies indicate that the rate of discharge from the canyon wall may be as high as 25 inches per year for the surface area of the canyon face (Maggi, oral commun., 1989). This flux was used as the initial input value into the numerical model constructed by Lum and others (1990), but was reduced to 10 inches per year during the model calibration process. Ground water discharge also occurs to small streams from local flow systems in the loess and Wanapum Basalt, particularly during the late summer and fall.

Conceptually, the withdrawal of water from the Grande Ronde Basalt by pumping and the resultant reduction of water in storage probably has affected the natural recharge and discharge rates. As water levels in wells decline, ground water flow to streams is reduced, and areal recharge may be enhanced.

CHAPTER III

PULLMAN-MOSCOW GROUND WATER FLOW MODEL

Introduction

A detailed discussion of the Pullman-Moscow model construction, calibration, and results from several predictive pumping scenarios is presented by Lum and others (1990). A review of the original documentation is recommended, since only a brief summary is included in this report.

A numerical ground water flow model constitutes a mathematical approximation of ground water movement in an aquifer system. The partial differential equations that describe ground water flow are discretized and represented in this numerical model as finite difference equations. Spatial discretization of hydrostratigraphic units is accomplished by superimposing a uniform model cell grid over the study area. Stratigraphic units are represented by layers of cells. Hydrogeologic properties of the system are simulated by assigning values for the model parameters to each cell. Model construction is achieved after an array is selected and all the available hydrogeologic data have been compiled and input to the model.

The numerical model constructed by Lum and others (1990), utilizes the modular ground water flow program MODFLOW, written by McDonald and Harbaugh (1988). One three-dimensional model and three two-dimensional cross-sectional models were constructed. A review only of the three-dimensional model is included in this report, since the cross-sectional models were used to aid construction of the three-dimensional model. The three-dimensional model was calibrated to simulate time-averaged conditions in the Pullman-Moscow area during 1974-85. Verification of the model was undertaken by simulating historical water level changes between 1890-1985. The calibrated model then was used to simulate future trends in ground water level changes under a variety of pumping scenarios.

Three-Dimensional Model Construction

Discretization of Hydrostratigraphic Units

A 55 by 55 uniform cell grid is used for each of three model layers. Each cell represents a one-quarter square mile parcel of the study area. The grid orientation coincides with the northwest trend of several rivers and streams in the region (fig. 4).

The Palouse Loess, the Wanapum Basalt, and the Grande Ronde Basalt are each represented in the model as individual layers. A spatial distribution of thicknesses is assigned to the model cells for both the Wanapum and Grande Ronde layers. The input values were determined from a magnetotelluric geophysical survey completed in the Pullman-Moscow vicinity by Klein and others (1987). The Palouse Loess is simulated in the model with a uniform thickness.

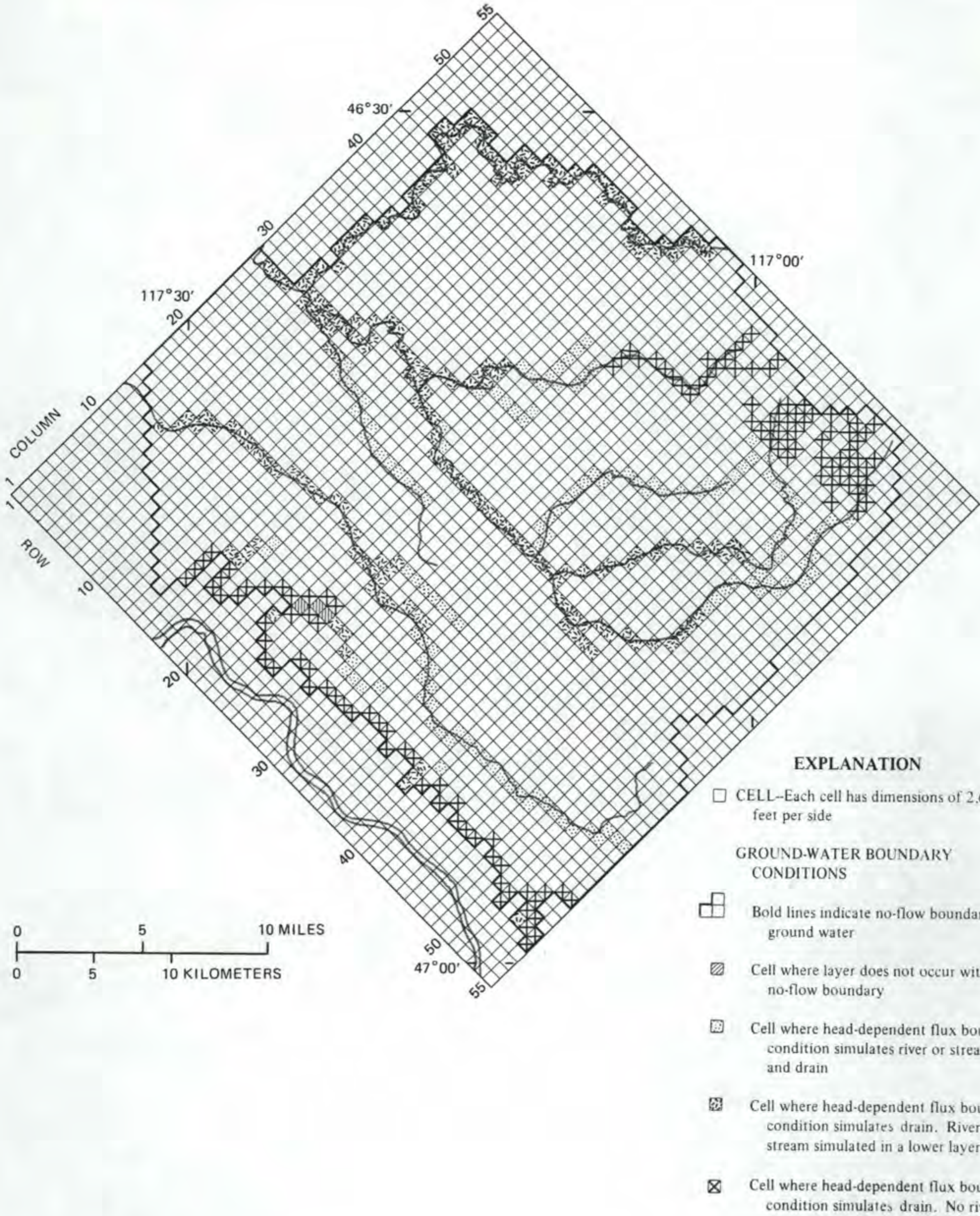
Figure 4. Location and orientation of the modeled area (Lum and others, 1990).

Boundary Conditions

The loess hydrostratigraphic unit is modeled with no-flow boundaries around its entire perimeter (fig. 5). This is justified because most of the boundaries are either formed by a topographic divide or by the Snake and Palouse Rivers. Ground water flow in the loess across the western boundary is probably insignificant because local flow systems are predominately controlled by the topography of the rolling hills. The bottom surface of the loess is hydraulically linked to the underlying basalt layers.

Both no-flow and constant-head boundaries are used to delineate the edges of the Wanapum and Grande Ronde layers (figs. 6 and 7). No-flow boundaries are simulated along the eastern perimeter where the basalt flows are in contact with the basement rocks and along the southwest edge near the Snake River. The Palouse River also is modeled as a no-flow boundary. This is warranted for the Wanapum unit because the majority of the layer has been truncated by the river. However, the Palouse River probably does not represent a regional discharge area, and underflow in the Grande Ronde layer may exist. Underflow in the Grande Ronde may be a potential source of water to municipal pumping wells; thus, modeling the Palouse River as a no-flow boundary may cause greater simulated water level declines resulting from pumpage. The effects of the no-flow boundary designation on drawdown from municipal pumping is believed to be minimal.

A no-flow boundary is placed on the bottom surface of



EXPLANATION

☐ CELL--Each cell has dimensions of 2,640 feet per side

GROUND-WATER BOUNDARY CONDITIONS

Bold lines indicate no-flow boundary to ground water

Cell where layer does not occur within no-flow boundary

Cell where head-dependent flux boundary condition simulates river or stream and drain

Cell where head-dependent flux boundary condition simulates drain. River or stream simulated in a lower layer

Cell where head-dependent flux boundary condition simulates drain. No river or stream simulated in any layer for this cell

Figure 5. Boundary conditions and cell characteristics for the loess hydrogeologic unit (Lum and others, 1990).

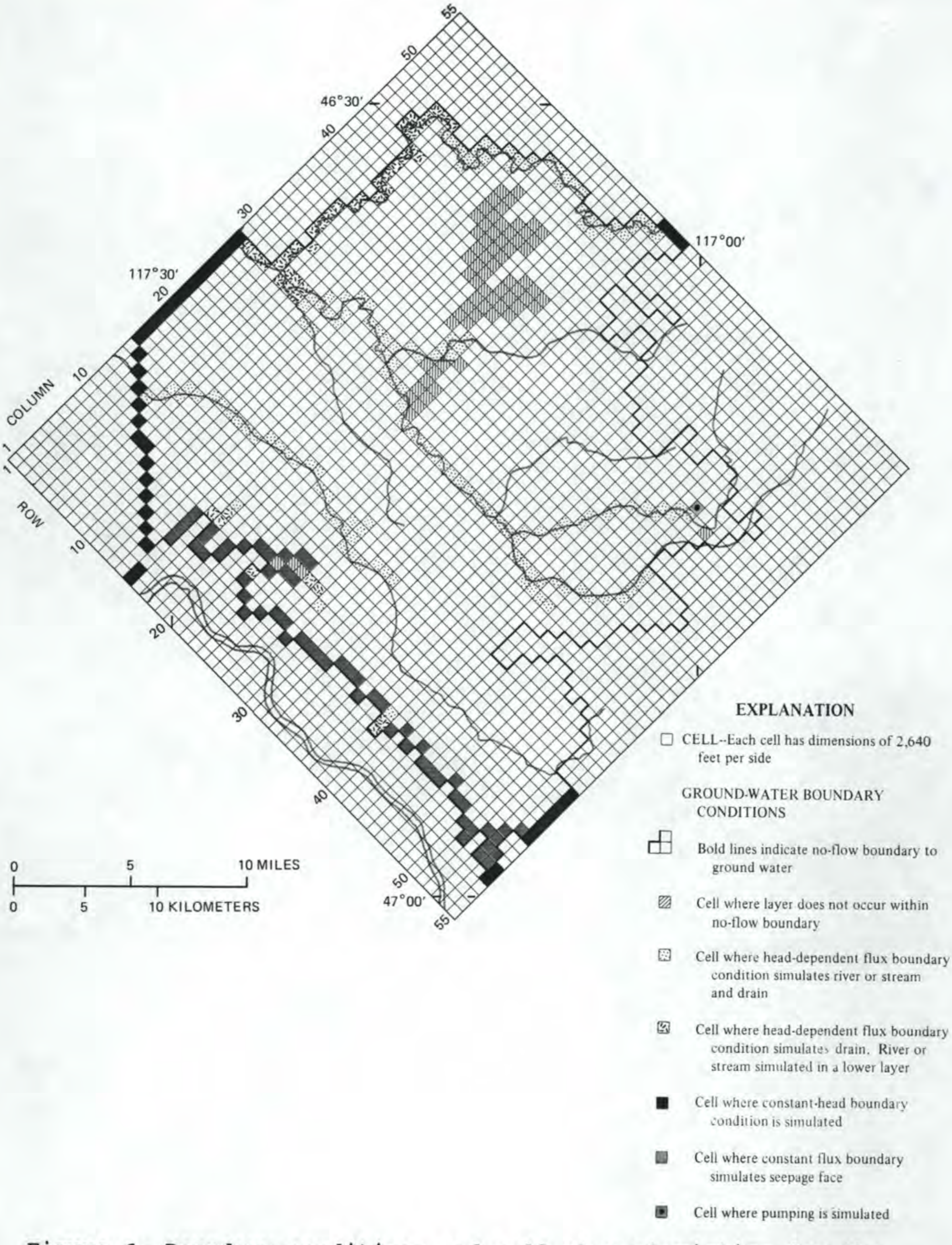


Figure 6. Boundary conditions and cell characteristics for the Wanapum hydrogeologic unit (Lum and others, 1990).

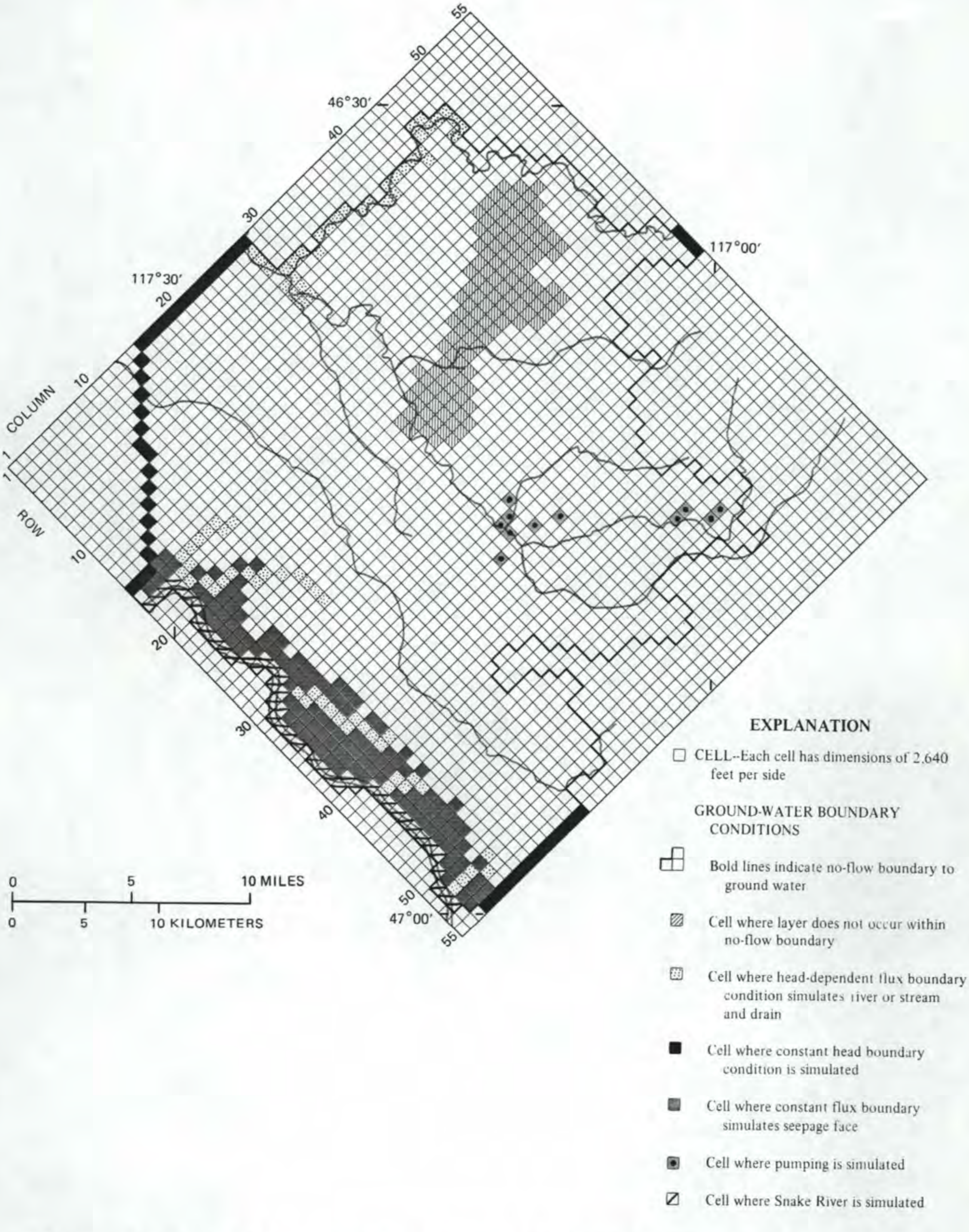


Figure 7. Boundary conditions and cell characteristics for the Grande Ronde hydrogeologic unit (Lum and others,1990).

basalt layers that are in direct contact with the basement rocks. The crystalline basement rocks have a much lower hydraulic conductivity than the overlying basalt flows.

Segments along the northwest, northeast, and southeast boundaries are designated as constant head (figs. 6 and 7). The head distribution along the boundaries is specified from existing water level information. The model calculates a flux into or out of each layer at the boundaries, based on the ground water gradient. For the time-averaged simulation used in calibrating the model, an overall flux of about 13 cfs enters the model through constant head boundaries. A total flux of approximately 19 cfs flows out of the model through constant head boundaries. Water level data collected in the region indicates that ground water flows into the basin along the northeast and southeast boundaries and out of the basin along the northwest boundary.

Areal Recharge

Input values for areal recharge to the model, as a result of precipitation, were calculated using the deep percolation method by Bauer and Vaccaro (1987). Recharge was calculated for the basins of the South Fork of the Palouse River and Union Flat Creek for both current land use practices and pre-development conditions. Outside of these two basins, recharge was estimated based on current farming practices and long-term average annual precipitation. Recharge is applied to the uppermost model layer, which generally is the loess. Input values change from cell to cell because of the spatial variation in recharge, but are fixed with time for the projected simulations. Recharge rates generally increase towards the east, coinciding with the increase in precipitation. The average recharge rate to the uppermost layer in the model, under current land use and farming practices, is about 3 inches per year applied over the entire surface area, or 136 cfs. An analysis of the time-averaged simulation water budget by Lum and others (1990) suggests that about 24% or 32 cfs of this recharge ultimately enters the Grande Ronde Basalt layer.

Discharge to Rivers, Drains, and Seepage Faces

River reaches are simulated in the model on a cell-by-cell basis (figs. 5-7). Rivers may either gain or lose water within the modeled area, depending on the head gradient between the river and the corresponding layer. Conceptually, most of the stream reaches in the study area are gaining. Cells that are transected by the Snake and Palouse Rivers and the perennial reaches of the smaller streams in the study area are simulated as rivers in the appropriate model layer. The model calculates a flux for the time-averaged simulation of about 40 cfs discharging from the ground water system into river reaches.

Drains are used to simulate discharge areas where springs or seeps exist. The discharged water may either evapotranspire or enter into a stream. A gradient dependent flux is calculated by the model based on the difference between the hydraulic head assigned to the drain and the hydraulic head for the corresponding model layer. If the head in the adjacent model layer falls below the head assigned to the drain, then the drain becomes inoperative. Drains are simulated in the model at locations where water bearing layers have been truncated by stream valleys or river canyons. With the exception of the Snake River Canyon, both intermittent as well as perennial stream reaches are simulated with drains. The model calculates a flux for the time-averaged simulation of about 42 cfs of ground water discharge into simulated drains located in the stream valleys, excluding the Snake River Canyon.

The seepage face of the Snake River Canyon represents a major discharge zone in the modeled area. Originally, it was simulated with drains; however, because of the great thickness of the Grande Ronde layer, drains did not represent the seepage face adequately. In many instances, the heads calculated for the Grande Ronde layer adjacent to the drains were below the bottom of the canyon. This made the drains inoperative. Consequently, the canyon wall is modeled by simulating constant flux conditions at each cell corresponding to a seepage area on the canyon face (figs. 6 and 7). The over-all flux was initially set at 25 inches/year for the surface area of the canyon wall, but was later lowered to 10 inches/year (35 cfs) during the calibration process. The flux spatially varies from cell to cell depending on the location and discharge of mappable seeps and springs. The flux is fixed with time for all transient simulations. Discharge from constant flux cells is incorporated in the Well Package of MODFLOW. Essentially, the constant flux cells are represented in the model as artificial pumping wells.

Hydraulic Properties of Model Layers

Actual values for the hydraulic properties of the model layers are the least known of all the descriptive information used in characterizing the model. A uniform horizontal hydraulic conductivity value of 2 feet/day initially was used for both basalt layers. This approximately is the median value identified for basalts from the Columbia Plateau (Lum and others, 1990). Aquifer tests near Moscow and Pullman indicate that the upper Grande Ronde Basalt has a horizontal hydraulic conductivity of at least one order of magnitude greater than the average of 2 feet/day (Lum and others, 1990). The initial input value for the vertical hydraulic conductivity in the basalt layers was set at 0.001 feet/day.

The input values for both vertical and horizontal hydraulic conductivities in the basalt layers were re-evaluated numerous times during the time-averaged calibration process. Input data were altered only within a range that was considered reasonable, based on existing literature. Final estimated values of horizontal hydraulic conductivity for the Wanapum Basalt spatially vary from 0.4 to 0.6 feet/day and for the Grande Ronde Basalt the range is from 0.4 to 12.0 feet/day. The range of estimated vertical hydraulic conductivity for the Wanapum is 0.0008 to 0.0012 feet/day and for the Grande Ronde the range is 0.0001 to 0.0025 feet/day.

A uniform storage coefficient of 0.001 is assumed for both basalt layers, which is considered to be a reasonable value for basalt aquifers.

The horizontal hydraulic conductivity of the loess is set at a uniform value of 5 feet/day and the vertical hydraulic conductivity is estimated to be 0.05 feet/day, based on a literature review and access to a limited amount of field data. However, recent studies from slug tests have indicated that the horizontal hydraulic conductivity of the loess may be as much as two orders of magnitude lower than the model input value of 5 feet/day (Keller, oral commun., 1990).

Three-Dimensional Model Calibration

The three-dimensional model was calibrated to replicate time-averaged conditions between 1974-85. The time-averaging technique has the advantage of allowing for the calibration of a model to a recent and more complete data set. Any transient conditions present are averaged over the time period so that they can be accounted for in the steady-state simulation. A trial-and-error method was used in calibrating the model to reproduce time-averaged conditions. The least known input data, such as the hydraulic coefficients and Snake River Canyon seepage, were altered until an approximate match was achieved between model output heads and recorded water levels in wells.

A verification process then was undertaken by simulating historical drawdown in the Pullman-Moscow area between 1890-1985. Recharge and pumping rates were simulated to change with time so that historical conditions were represented accurately. A reasonable correlation was achieved between simulated and observed water levels in Moscow and Pullman. The final heads in the history match simulation (1985) became the starting heads for the projected simulations.

Results of Projected Simulations

Six projected simulations are modeled and examined by Lum and others (1990) using various pumping schedules that are at or above the 1981-85 average withdrawal of 6.7 million gallons per day for all municipal (including university) wells combined. Three simulations are based on annual increases in pumpage of ½%, 1%, and 2%, starting with the 1981-85 rate. The other projections are characterized by stable pumping scenarios at the 1981-85 rate and at 125% and 200% of the 1981-85 rate. The time period projected is for 20 years from 1985 to 2005. The distribution of pumping remains consistent for all six simulations. The model projection results are shown in figure 8.

The model projects a decline in water levels followed by an asymptotic stabilization for the three scenarios with constant pumping rates. The degree of water level decline and the length of time necessary to reach recharge-discharge equilibrium are dependent upon the magnitude of the pumping

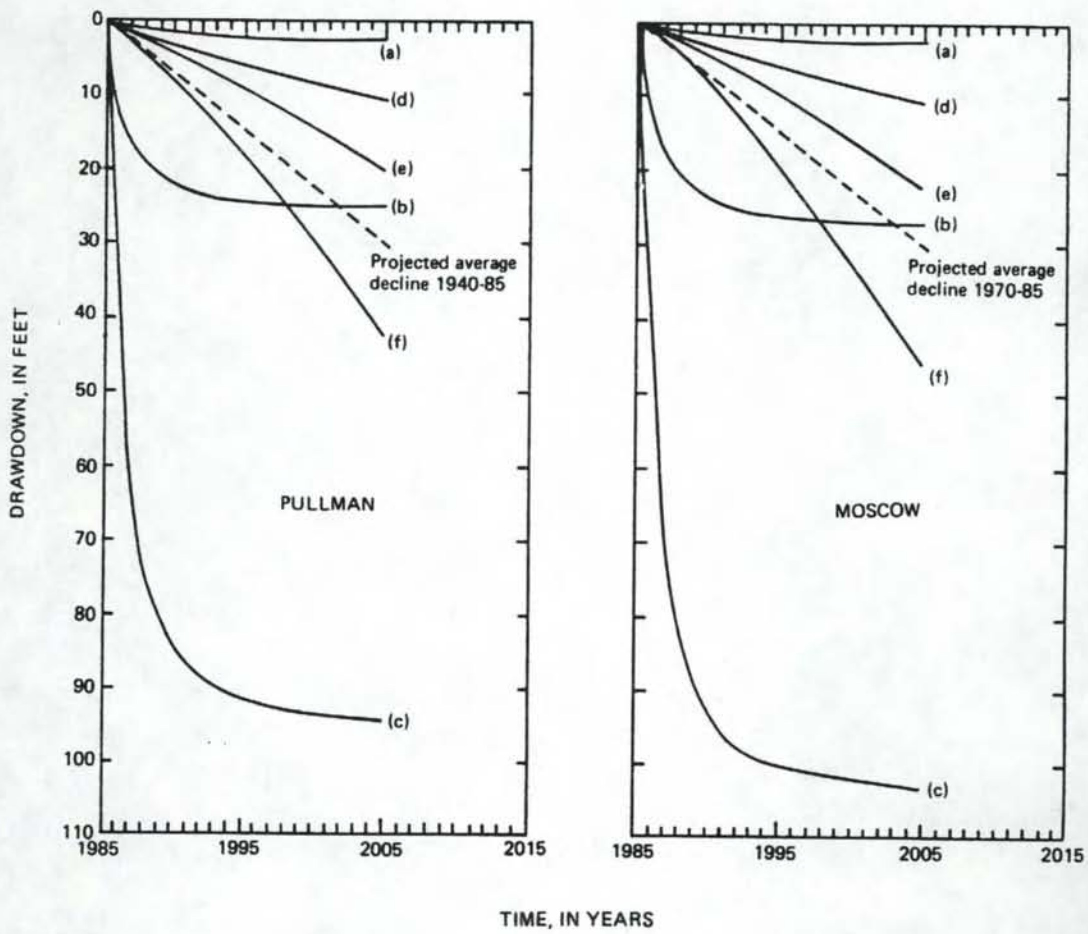


Figure 8. Simulated water levels at a constant pumpage rate equal to: (a) the 1981-85 average rate, (b) 125% of the 1981-85 average rate, and (c) 200% of the 1981-85 average rate; and at an annual pumpage rate increase from each preceding year of: (d) ½%, (e) 1%, and (f) 2%, starting with the 1981-85 average rate (Lum and others, 1990).

rate. The model suggests that drawdown will be minimal and water levels will stabilize in a few years if pumpage remains constant at the 1981-85 rate.

For the three projections with annual increases in pumpage, the rate of water level decline is proportional to the rate of pumpage increase. The simulations imply that water level decline will continue as long as withdrawal rates continue to increase, and that a recharge-discharge equilibrium will never be reached. The projection simulating a 1% annual increase in pumpage, which approximates the trend of actual pumping data between 1974-85, indicates that water levels will continue to decline at a rate of about 1 foot a year.

CHAPTER IV

METHODOLOGY OF THE SENSITIVITY ANALYSIS SIMULATIONS

Introduction

A ground water model incorporates many simplifications in its representation of a flow system. Thus, caution must be employed in its use as a management tool. Unquestioning faith in model results is an example of serious model misuse. The construction of a model should be viewed as an ongoing process where hydrogeologic information is updated in the model as it becomes available. Operation of the model provides insight into the need for and scope of future investigations.

A sensitivity analysis may be used to indicate how specific decisions in the construction and calibration of the model influence the model results. If the adjustment of a certain model parameter has a significant affect on simulated water levels, then one could hypothesize that this parameter is "sensitive". Changes in "sensitive" input parameters can dominate the model results.

The list of elements to consider in a sensitivity analysis includes input factors, which describe hydrogeologic properties, and model construction factors. Input factors include:

1) Hydraulic conductivity
2) Storativity
3) Ground water flux into rivers and streams
4) Discharge from seeps and springs
5) Areal recharge
6) Thickness of hydrostratigraphic units

The following model construction factors also could be considered in a sensitivity analysis:

1) Number of model layers
2) Size of model cells
3) Boundary conditions
4) Discretization of time

All of these factors are worthy of investigation to establish their degree of importance in controlling model output.

Three model parameters were selected for sensitivity analysis in this study: 1) areal recharge to the ground water basin, 2) seepage discharge from the face of the Snake River Canyon, and 3) constant head versus constant flux boundary conditions at the model perimeter. These parameters were selected for analysis for several reasons. Areal recharge and seepage discharge comprise a significant portion of the model water budget. However, very little hydrogeologic data have been collected in the field upon which to base estimation of areal recharge and seepage discharge. In addition, the values for both of these parameters are fixed with time during projected transient simulations. The assumption of using constant head conditions along some of the boundaries also is in question. These boundaries may have an impact on water level declines associated with pumping in Moscow and Pullman.

Systematic Approach and Considerations

Selection of Simulations

All sensitivity analysis simulations initially were run under time-averaged, steady-state conditions. Although trends were apparent with respect to how parameter variations affected the model output, the quantification of impacts from parameter variability required the simulation of transient conditions.

Projected transient conditions are modeled for a 20 year time period from 1985 to 2005. Ten stress periods are simulated, each lasting two years. The stress periods are characterized by an annual increase in municipal pumpage of 1%, starting with a five year average annual pumping rate calculated from 1981-85 records for each municipal well in the Pullman-Moscow area. This particular increase in annual pumpage was selected because it typifies the changes in actual pumping rates that have occurred over the past 15 years.

Model sensitivity is analyzed by comparing drawdown in the Grande Ronde layer from a simulation in which a parameter is adjusted, with drawdown in the Grande Ronde layer from a simulation where no variations are made. For ease of clarification, this latter simulation is referred to as the "base" simulation.

Starting Heads

Originally, all of the projected transient simulations used for sensitivity studies were run utilizing starting heads generated from the final stress period of the history match simulation. This worked adequately for the base simulation where no input parameters were varied. However, once parameter conditions were varied, the history match starting heads were no longer representative of an initial steady-state position in the projected transient simulations. Water levels not only were changing due to the effects of municipal pumping, but also because the model was equilibrating to the parameter variation. None of the projected simulations appeared to stabilize to the changes in parameter conditions even by the 10th and last stress period. In several of the simulations, a water level rise with time was noted at cells where municipal pumping occurs, rather than the head decline one would expect to see.

To correct this problem, the output heads generated from each steady-state simulation, under specified stress conditions, were used as the starting heads for the projected transient simulations governed by the same stress conditions. For example, in varying areal recharge, a steady-state simulation was run where water levels in the model were allowed to readjust to the new set of conditions exemplified by the change in recharge. The output heads generated from this steady-state simulation were used as the starting heads for the projected transient simulation under the same stress conditions of recharge.

In this way, all of the projected transient simulations, including the base run, were begun from an equilibrium or steady-state position. The changes that occurred in drawdown from one transient simulation to the next, thus could be attributed solely to the parameter variation, and an accurate representation of parameter sensitivity could be obtained.

Comparison of Model Results With Those of the Previous Study

The temporal and spatial distribution of water levels generated from the base simulation are comparable to the output of a projected run described by Lum and others (1990), despite that different starting heads are used in each simulation. The projected simulation by Lum and others uses starting heads generated from the final stress period (1985) of the history match simulation. Starting heads for the base simulation are generated from a time-averaged, steady-state simulation. Municipal pumpage is increased by one percent annually in both simulations. Negligible variations exist between the two simulations in predicted water levels in the Grande Ronde layer. The water levels are comparable simply because the starting heads generated from the final stress period (1985) of the history match simulation are similar to the starting heads generated from the time-averaged simulation (1974-85).

The projected simulations described by Lum and others (1990) are based on a modified version of the Pullman-Moscow model, whereas all simulations performed by this author are based on the documented version of the model. Variations between the two versions are minor. Simulated water levels in the Wanapum layer are slightly higher in the documented version of the model; thus, a slightly higher gradient exists between the Wanapum layer and the Grande Ronde layer. The higher gradient allows for a somewhat greater flux of recharge to enter the Grande Ronde layer in the documented version of the model (Lum, oral commun., 1990).

Bracketing Parameter Variation

Upper and lower limits of variation in areal recharge and seepage discharge from the face of the Snake River Canyon are selected to bracket the expected range of values for these factors. The upper limit of variation is 200% of the parameter value in the base simulation, and the lower limit is a 50% variation. Thus, the parameter values are doubled and halved in sensitivity simulations that are presented in this report. The determination of these percentage extremes is based on several factors. A large enough variation is established so that parameter sensitivities can be readily apparent. Model output results from initial sensitivity simulations, where areal recharge only was changed to 125% and 75% of the base simulation, did not show any significant variability. In addition, the simulated flux of ground water discharge to rivers, drains, and constant head boundaries and recharge from rivers and constant head boundaries to the ground water system become conceptually unreasonable beyond the 50% and 200% extremes. Simulations where areal recharge was reduced to 25% and 35% of the base simulation, generated unrealistically low values of ground water discharge to rivers and drains. Also, several river reaches became significant source areas of recharge to the ground water system, which is contradictory to the conceptual model.

Techniques of Parameter Variation in the Pullman-Moscow Model

Areal Recharge

Altering the spatial values for areal recharge in the model is a straightforward process. The array of values listed in the recharge file (RECHARGE 2) has units in inches per year, although the units specified in the computer program are in feet and days. Within the RECHARGE 2 file, there is a multiplication coefficient that converts all of the recharge values from inches per year to feet per day so that the units remain consistent with the rest of the program. Doubling or halving the multiplication coefficient adjusts the values for areal recharge in the array by 200% and 50% respectively.

Seepage Discharge from the Snake River Canyon Wall

Seepage from the face of the Snake River Canyon is simulated in the model with constant flux cells. The rationale behind this approach, instead of conventionally using drains, is discussed in chapter III. The flux for each cell corresponding to a seep or spring in the canyon is located in the WELL file. There are 222 active cells in the WELL file which represent Snake River Canyon seepage; 60 cells are in the Wanapum layer and 162 are in the Grande Ronde layer. All other seepage in the model is represented in the drains file (DRAINS DAT). The WELL file also contains values for cells where municipal pumping occurs and values for flow rates in constant flux boundary simulations.

Varying canyon seepage in the model is more complicated than altering areal recharge. The Pullman-Moscow model incorporates several Fortran programs besides MODFLOW; these programs generate extensive files that are necessary for the model to operate. One of these programs, entitled WFRDG, generates the RIVERS DAT and DRAINS DAT files and a file representing seepage from the Snake River Canyon wall. The canyon seepage file is called WELL SNAKE. Any leakage directly into the Snake River is specified in the RIVERS DAT file. When WFRDG is executed, the computer program accesses several data files to gather the necessary information to generate the RIVERS DAT, DRAINS DAT, and WELL SNAKE files. One of these data files, entitled DATA MISC, has a multiplication coefficient which converts canyon seepage from inches per year to the consistent model units of feet per day. Doubling or halving the multiplication coefficient adjusts the values for canyon seepage in the WELL SNAKE file by 200% and 50% respectively, once WFRDG is executed.

The WELL SNAKE file then is edited to include time-averaged municipal pumping data and fluxes for boundary cells when constant flux boundary conditions are simulated. The file is renamed WELL TA, for use in time-averaged simulations. The WELL file for a time-averaged simulation is obviously going to be different from the WELL file for a projected transient simulation because of the 1% annual increase in municipal pumpage included in the latter. The WELL file for projected simulations, named WELL PROJ, is generated by another Fortran program called PROJPUMP. This program accesses the WELL SNAKE file and the PUMP 8185 file. The PUMP 8185 file specifies the 5 year average annual pumping rate for each municipal well in the Pullman-Moscow area for the period 1981-85 and a multiplication factor for annual percentage increases in pumping rates. Once PROJPUMP is executed, the WELL PROJ file is generated and the variations in canyon seepage are reflected in the projected simulations. The file has to be edited further if constant flux boundary conditions are simulated instead of constant head.

Constant Flux Boundary Conditions

Boundary conditions are specified for the model in a file called IBOUND DAT. The IBOUND array differentiates whether a cell is active and variable (IBOUND > 0), whether it is a no-flow cell (IBOUND = 0), or whether it is a constant head cell (IBOUND < 0). To switch from constant head to constant flux boundary conditions, the constant head cells in the IBOUND array are changed to variable head cells, which allow heads to vary with time.

Both the time-averaged and projected WELL files are edited to include a constant flux for each boundary cell that is changed from constant head to constant flux conditions. The actual fluxes across the boundaries are not known. The main purpose of varying the boundary conditions is to test the relative sensitivity of areal recharge and canyon seepage under both sets of boundary situations. The boundary flow rates are fixed for all of the constant flux boundary simulations. Flux input values are generated from the time-averaged simulation described by Lum and others (1990). MODFLOW generates a flux value for each constant head cell in the model. These constant head flux values are input to the WELL file in the appropriate cells when constant flux boundary conditions are simulated. Once the WELL file is edited to include flow rates across constant flux boundary cells, the changes are reflected in the model output.

Water level data indicate that ground water flows out of the study area along the northwest boundary and into the study area along the northeast and southeast boundaries. The constant head fluxes generated from the time-averaged simulation by Lum and others (1990) were compared to the field data. Ground water flow directions into and out of the numerical model generally conform to the water level data. Table 1 lists the sum of constant head fluxes for each layer boundary in the time-averaged simulation. Fluxes that are marked with an asterisk signify that they do not conform to the conceptual model relative to ground water flow direction. However, only small ground water fluxes are believed to occur in areas where non-conforming values are present.

The sum of the constant head fluxes into and out of the model do not match those stated in chapter III in the volumetric water budget of the time-averaged simulation because the two budgets are summed differently by MODFLOW. According to McDonald and Harbaugh, "the cell-by-cell value at a cell for a given stress or flow component is the net flow for that

	LAYER	BOUNDARY LOCATION	FLUX (CFS)
	GRANDE RONDE	NORTHWEST	0.44 *
I	GRANDE RONDE	NORTHEAST	2.94
N	GRANDE RONDE	SOUTHEAST	7.49
	TOTAL WATER IN		10.87
	WANAPUM	NORTHWEST	6.57
O	WANAPUM	NORTHEAST	0.19 *
U	WANAPUM	SOUTHEAST	0.61 *
T	GRANDE RONDE	NORTHWEST	9.13
	GRANDE RONDE	SOUTHEAST	0.67 *
	TOTAL WATER OUT		17.17

Table 1. Summation of the constant head boundary fluxes for the time-averaged simulation calibrated by Lum and others (1990). Fluxes that are marked with an asterisk (*), signify that they do not conform to the conceptual model relative to flow direction.

component, which could possibly include two or more flows of the same type, some negative and some positive. Only the net flow for the cell is saved in the cell-by-cell disk file. In the overall budget calculations as performed in the model, on the other hand, positive and negative flows are assembled separately, so that a negative flow at the same cell would be added to the outflow term and a positive flow at the same cell would be added to the inflow term. Thus if inflow and outflow terms for the entire model are calculated by summing individual cell-by-cell values, they may differ from the corresponding terms as calculated by the model program in the overall budget." (1988, p.3-22).

CHAPTER V

PRESENTATION OF RESULTS FROM THE SENSITIVITY ANALYSIS SIMULATIONS

Introduction

The effects of parameter variation are examined in detail for eight projected simulations of the model. Additional transient simulations were run but are not presented in this report, because the eight runs summarize the findings of the sensitivity analysis.

Parameter adjusted simulations are initially modeled using time-averaged conditions to generate steady-state starting heads for input to the projected transient runs, as explained in chapter IV. The eight projected simulations that are analyzed in this report are listed in table 2. All of the

SENSITIVITY ANALYSIS SIMULATIONS			
RUN NUMBER	AREAL RECHARGE	CANYON SEEPAGE	BOUNDARY CONDITIONS
1	100%	100%	CONSTANT HEAD
2	200%	100%	CONSTANT HEAD
3	50%	100%	CONSTANT HEAD
4	100%	200%	CONSTANT HEAD
5	100%	50%	CONSTANT HEAD
6	100%	100%	CONSTANT FLUX
7	50%	100%	CONSTANT FLUX
8	100%	200%	CONSTANT FLUX

Table 2. Summary of the eight sensitivity analysis simulations evaluated in this report.

transient runs are simulated for 20 years (1985-2005) and assume a 1% annual increase in the municipal pumping rate.

Run 1 is the base simulation, as described in chapter IV. The percentages of subsequent parameter variations are relative to the base simulation. Areal recharge simulated in the base run is about 136 cfs (3 inches/year) assumed over the entire surface area of the model. Canyon seepage simulated in the base run is 34.6 cfs (10 inches/year) assumed over the surface area of the Snake River Canyon face.

Sensitivity studies are performed where areal recharge and canyon seepage are varied independently by 200% and 50% of the base simulation using constant head boundaries (Runs 2-5). Three simulations are performed using constant flux boundaries. One is analogous to the base simulation, only the boundary conditions are changed (Run 6). The remaining two simulations (Runs 7 and 8) are chosen based on their expected effect of increasing drawdown relative to the base simulation. This corresponds to a 50% decrease in areal recharge and a 200% increase in canyon seepage. For ease of comparison, the eight sensitivity analysis simulations are referred to in this report as the "base" simulation and Runs 2 through 8.

Constant flux boundary conditions were simulated in two additional runs with areal recharge doubled and canyon seepage halved. The results of these simulations are not presented in this report because their impacts on simulated water levels in the Grande Ronde layer near Moscow and Pullman are similar to the base run. The lowering of water levels (relative to the base simulation) caused by constant flux boundary conditions is compensated by rises in water levels related to increased areal recharge or reduced canyon seepage. Drawdown in the Grande Ronde layer near Moscow and Pullman, at the end of 20 years of pumping, was approximately the same as the base simulation in both instances.

Variations in areal recharge and canyon seepage were not simulated in the same model run. An accurate representation of model sensitivity to areal recharge and canyon seepage variations is obtained only when these parameters are changed independently of one another. In this way, the changes that occur in simulated water levels, relative to the base run, can be attributed entirely to the sensitivity of the model to variations of a single input parameter.

Drawdown Comparisons

Hydraulic head output is generated for all three model layers in the transient simulations; however, only simulated water levels in the Grande Ronde layer are analyzed in terms of comparing drawdown between the various simulations. This is because almost all of the ground water pumped from the Pullman-Moscow Basin comes from the Grande Ronde layer, the water-bearing unit of most concern.

Areal Recharge Variations

Simulated drawdown in municipal wells penetrating the Grande Ronde layer in Moscow and Pullman are compared for different recharge conditions. Figures 9 and 10 show drawdown curves for Moscow and Pullman when areal recharge is varied using both constant head and constant flux boundaries.

The amount of change from the base simulation in water levels is small for Runs 2, 3, and 6. At the end of 20 years of pumping, water levels vary from the base simulation only by two to four feet in both Moscow and Pullman. Doubling recharge results in less drawdown and simulating constant flux boundary conditions causes more drawdown to occur, relative to the base simulation.

Simulated drawdown in Moscow and Pullman is more significant in Run 7. Water levels are about nine feet lower than the base simulation in Moscow and Pullman after 20 years of pumping. Drawdown is more significant in this run because simulating constant flux boundaries with reduced areal recharge conditions has an additive effect in lowering water levels relative to the base simulation.

Very little drawdown occurs near the model perimeter in simulations when areal recharge is varied and constant head boundary conditions are assumed. An average drawdown of 0.3 feet is simulated near the northwest and southeast boundaries in Runs 2 and 3 at the end of 20 years of pumping. Near the northeast constant head boundary, an average drawdown of 1.7 feet is simulated in Runs 2 and 3 after 20 years of pumping.

Significant drawdown occurs at the boundaries when constant flux conditions are simulated. At the end of 20 years of pumping, an average drawdown of 9.8 feet is simulated

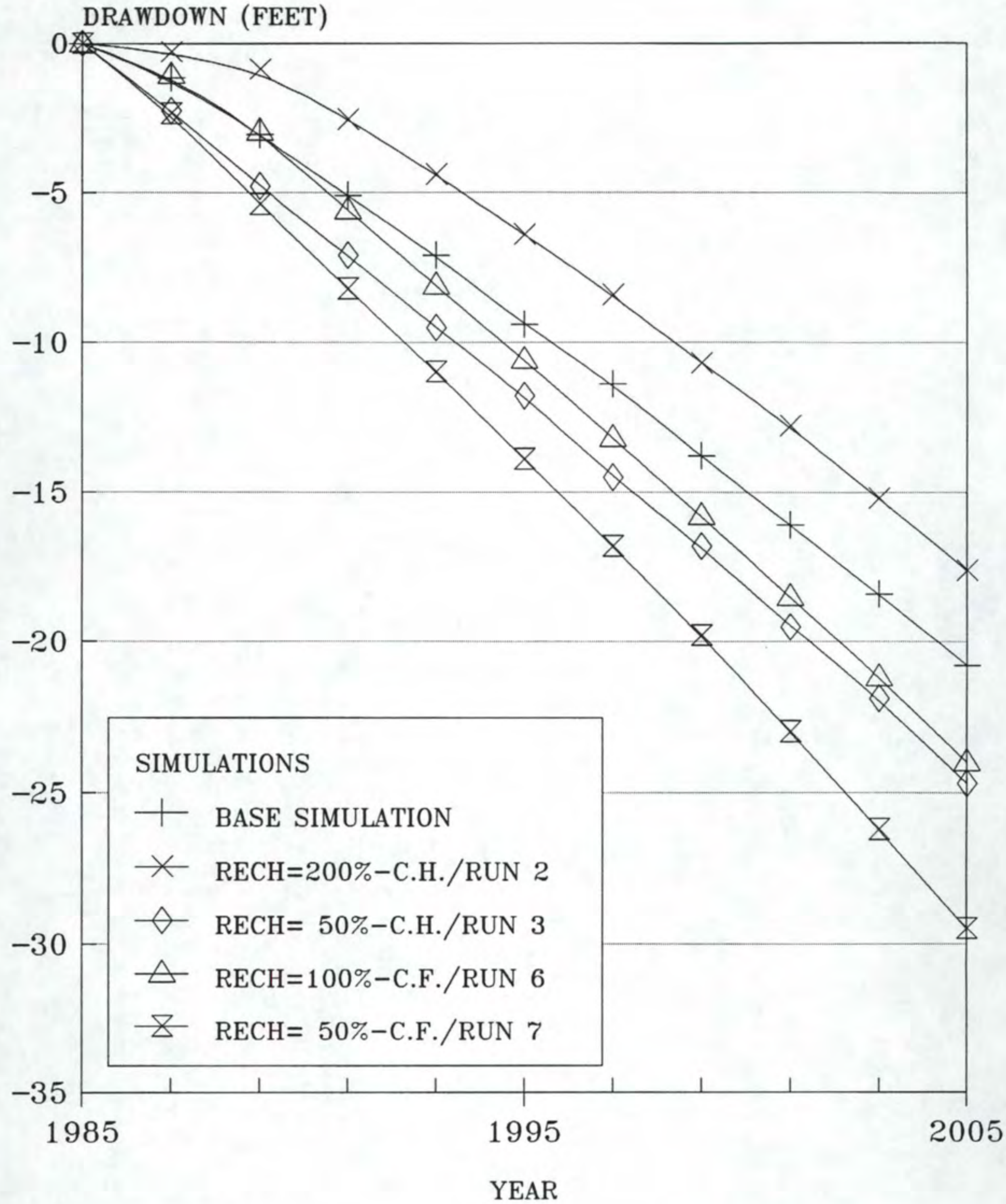


Figure 9. Simulated drawdown comparisons in the Moscow area (model cell-layer 3, row 43, column 39) varying areal recharge and boundary conditions.

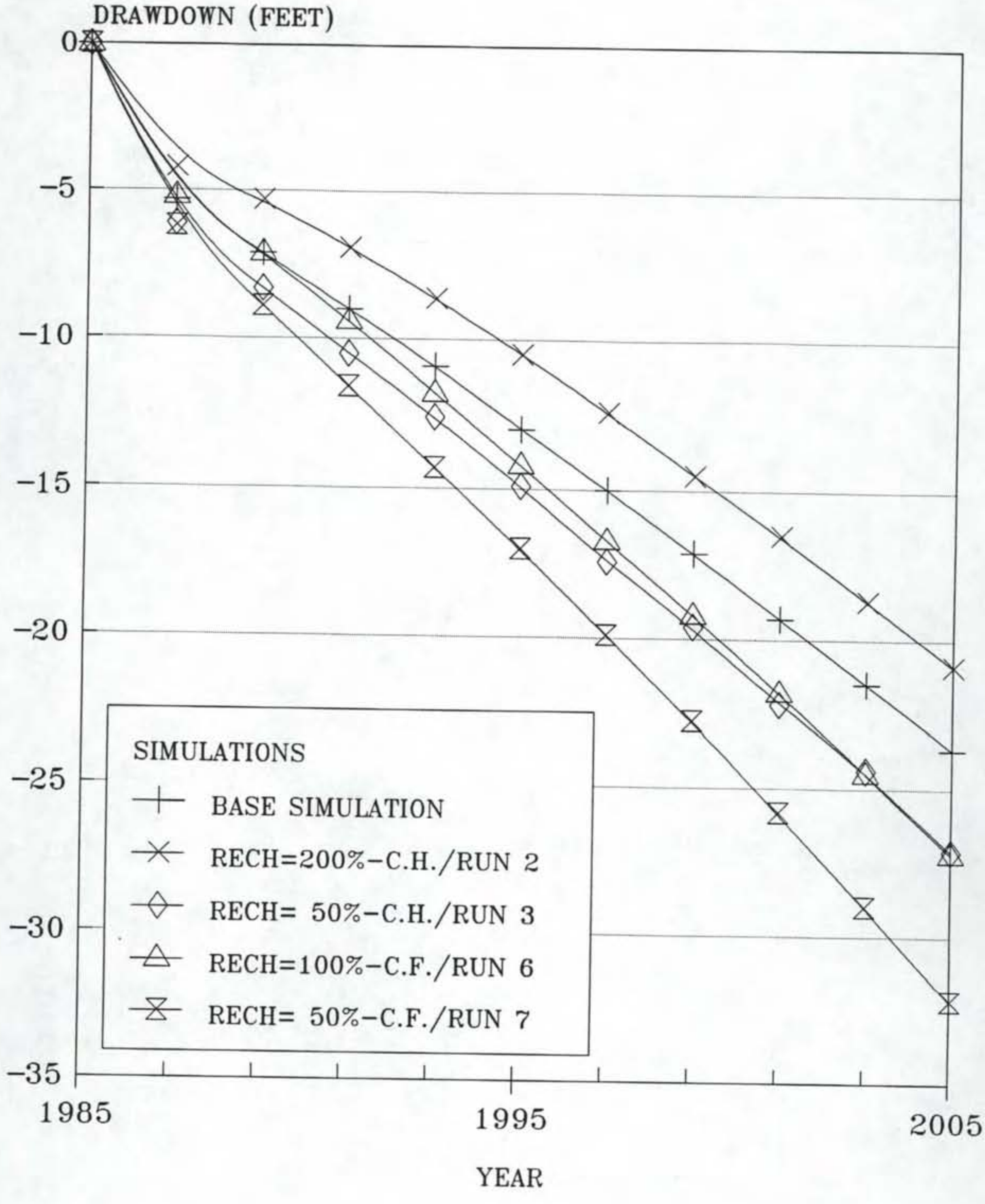


Figure 10. Simulated drawdown comparisons in the Pullman area (model cell-layer 3, row 34, column 27) varying areal recharge and boundary conditions.

in Runs 6 through 8 at the northwest and southeast boundaries. An average drawdown of 18.9 feet is simulated in Runs 6 through 8 at the northeast constant flux boundary after 20 years of pumping. The variable head boundary cells are affected by the cone of depression created by pumping in Moscow and Pullman. This implies that simulation of the model with constant head boundary conditions may impact water level declines associated with municipal pumping. An infinite source of water becomes available to the model as the cone of depression reaches the constant head boundaries, thus causing less simulated drawdown to occur than expected.

Canyon Seepage Variations

Drawdown in Moscow and Pullman in simulations when canyon seepage is varied (figs. 11 and 12) follows a similar trend to drawdown in simulations when areal recharge is varied. After 20 years of pumping, water levels vary from the base simulation in Moscow and Pullman by 1½ to three feet in Runs 4, 5, and 6. By decreasing canyon seepage, less drawdown occurs relative to the base simulation. When constant flux boundary conditions are modeled, more drawdown occurs compared to the base simulation.

Simulated drawdown in Moscow and Pullman is more significant in Run 8. Water levels are about eight feet lower than the base simulation in Moscow and Pullman after 20 years of pumping. Drawdown is more significant in this run because simulating constant flux boundaries with increased canyon

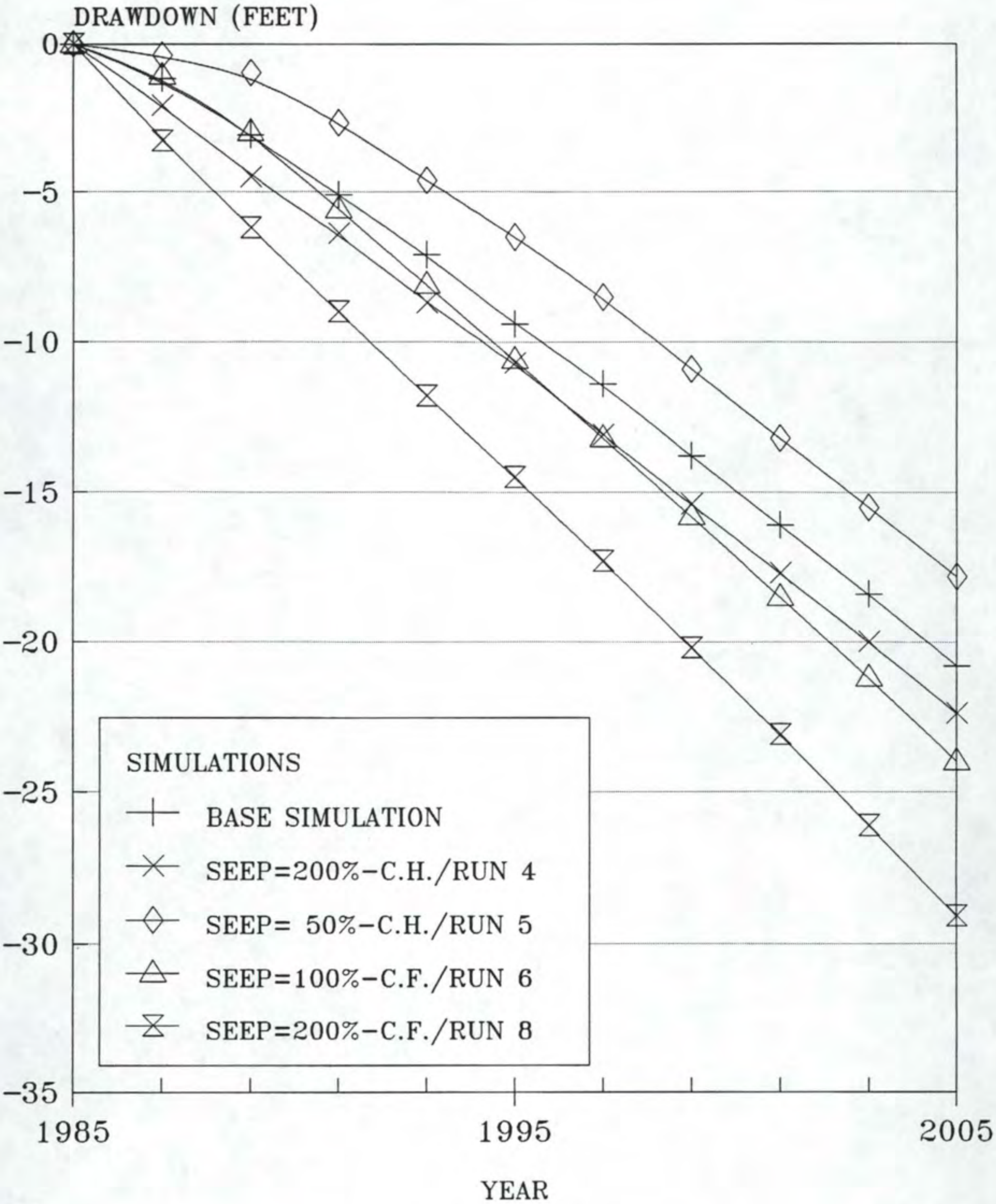


Figure 11. Simulated drawdown comparisons in the Moscow area (model cell-layer 3, row 43, column 39) varying seepage from the face of the Snake River Canyon and boundary conditions.

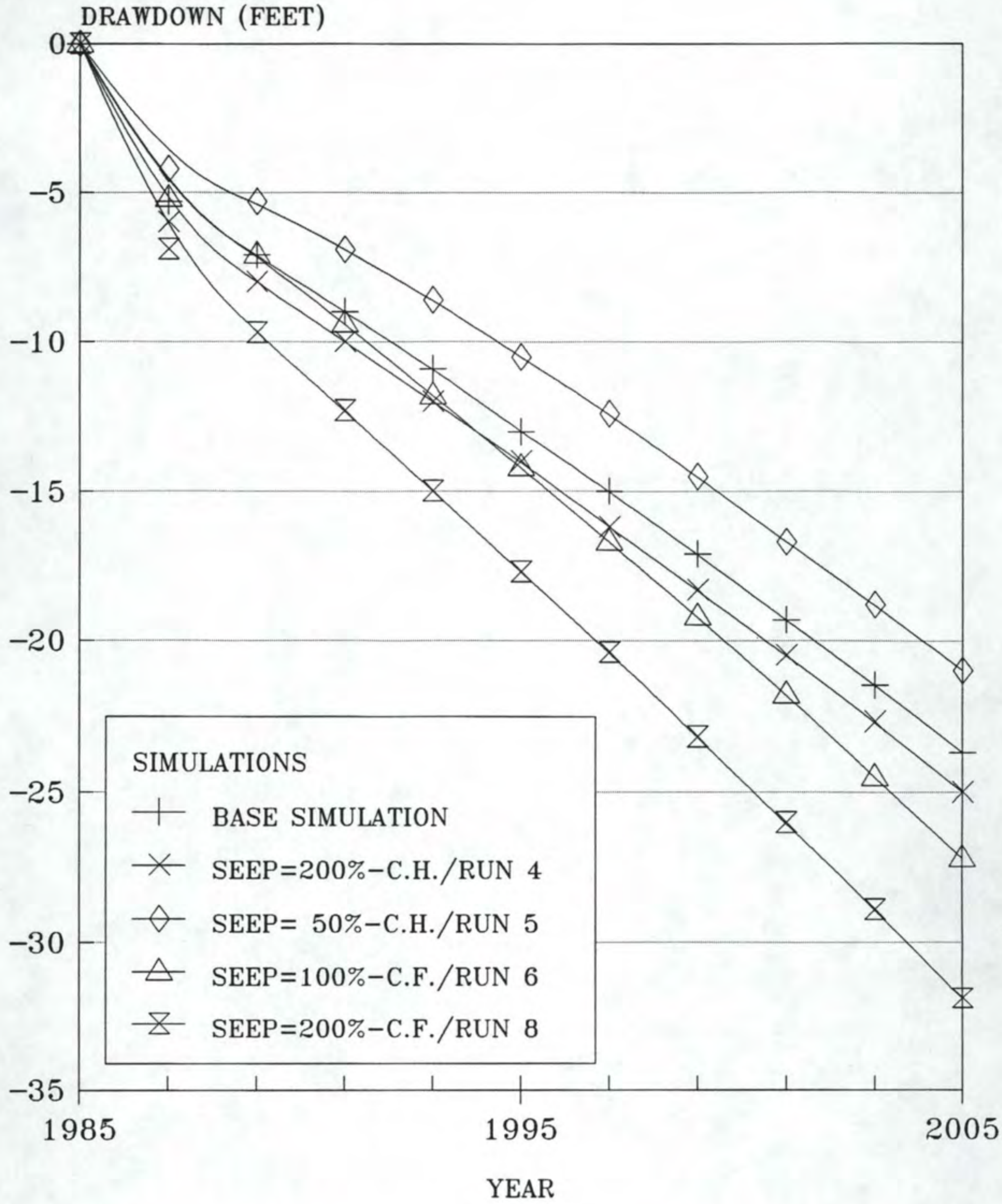


Figure 12. Simulated drawdown comparisons in the Pullman area (model cell-layer 3, row 34, column 27) varying seepage from the face of the Snake River Canyon and boundary conditions.

seepage conditions has an additive effect in lowering water levels relative to the base simulation.

Drawdown is negligible near the model boundaries in simulations when canyon seepage is varied and constant head conditions are modeled. Drawdown at the boundaries in simulations assuming constant flux boundary conditions is greater, for the reasons explained in the previous section.

Water Budget Comparisons

Areal Recharge Variations

The effects on model output from varying areal recharge conditions also are evaluated by examining the overall water budgets of the projected simulations. A comparison of these water budgets is presented in table 3.

The flux of water into the model is predominantly from areal recharge and constant head or constant flux boundaries. This is balanced by the flux of water leaving the model through constant head or constant flux boundaries, pumping wells, rivers, drains, and Snake River Canyon seepage. The percent discrepancies between water in and water out of the model are negligible for all of the simulations. The drain flux in every simulation encompasses drains along the stream reaches that truncate the loess and Wanapum layers. The river flux leaving the model represents the discharge of ground water mainly from the loess and Wanapum layers to stream reaches. Ground water flowing directly into the Snake River discharges from the Grande Ronde layer, but the flow represents an insignificant portion of the total river flux discharging from the ground water system. The small amount of water that recharges the ground water system from rivers, infiltrates entirely into the loess and Wanapum layers. Of the 34.6 cfs of water that leaves the model through seepage faces in the Snake River Canyon (specified in the WELL file), 29.1 cfs of the seepage is coming from the Grande Ronde layer.

The model compensates a decrease in areal recharge mainly by decreasing discharge to rivers and drains in the loess and Wanapum layers. Thus, the percentage change in water levels

		FLUX (CFS)				
		CONSTANT HEAD BOUNDARIES			CONST.FLUX BOUNDARIES	
WATER BUDGET TERM		RECH 100% BASE	RECH 200% RUN2	RECH 50% RUN3	RECH 100% RUN6	RECH 50% RUN7
IN	CONSTANT HEAD OR FLUX	13.2	7.9	16.8	10.9	10.9
IN	AREAL RECHARGE	135.8	272.1	67.9	136.0	68.0
IN	RIVERS	0.3	0.0	1.8	0.3	2.4
IN	DECREASE IN STORAGE	0.4	0.3	0.7	0.6	1.1
IN	TOTAL IN	149.7	280.3	87.2	147.8	82.4
OUT	CONSTANT HEAD OR FLUX	19.1	25.4	15.5	17.4	17.4
OUT	CANYON SEEPAGE (WELL)	34.6	34.6	34.6	34.6	34.6
OUT	AVERAGE PUMPAGE	11.0	11.0	11.0	11.0	11.0
OUT	DRAINS	45.8	123.7	14.1	45.7	10.9
OUT	RIVERS	39.7	85.9	12.4	39.4	8.7
OUT	TOTAL OUT	150.2	280.6	87.6	148.1	82.6
	PERCENT DISCREPANCY	0.33	0.11	0.46	0.20	0.24

Table 3. Water budgets of the projected simulations used in the analysis of areal recharge variations.

in the Grande Ronde layer is much less than the associated change in areal recharge. Water entering and leaving the model through constant head boundaries increases and decreases, respectively. A decrease in areal recharge results in a small increase in water removed from storage and in water entering the ground water system from rivers. An increase in areal recharge has the opposite effects.

Ground water flow to rivers and drains decreases when constant flux boundary conditions are simulated. In addition, an increase in the amount of water removed from aquifer storage is noted. A slight increase in the amount of water recharging the ground water system from rivers also is apparent. The totals of the water budgets are lower in constant flux boundary simulations than in constant head boundary simulations under the same areal recharge conditions. The above phenomena occur in part to compensate for the predominantly lower and fixed flow rates specified for the constant flux boundaries relative to the flux values generated for the constant head boundaries.

Doubling or halving the total areal recharge to the uppermost layer in the model does not increase or decrease the recharge to the Grande Ronde layer by the same percentage. Table 4 shows a comparison of total areal recharge and the proportion of the total recharge which infiltrates into the Grande Ronde layer for several simulations.

Large variations in the total areal recharge are reflected by small changes in simulated infiltration to the Grande

Ronde layer; river and drain fluxes are the main compensators for variations in areal recharge. Since all of the drain flux and most of the river flux discharges from the loess and Wanapum layers, only a small amount of additional infiltration reaches the Grande Ronde layer when the total areal recharge is doubled. Similarly, very little decrease in recharge to the Grande Ronde layer occurs when the total areal recharge to the uppermost layer is halved.

	FLUX (CFS)		
SIMULATION	**TOTAL AREAL RECHARGE**	**RECHARGE TO GRANDE RONDE**	**PERCENT OF TOTAL RECH.**
RECHARGE = 100% CONSTANT HEAD BASE SIMULATION	**136**	**40**	**29%**
RECHARGE = 200% CONSTANT HEAD RUN 2	**272**	**49**	**18%**
RECHARGE = 50% CONSTANT HEAD RUN 3	**68**	**34**	**50%**
RECHARGE = 100% CONSTANT FLUX RUN 6	**136**	**40**	**29%**
RECHARGE = 50% CONSTANT FLUX RUN 7	**68**	**39**	**57%**

Table 4. Comparison of the total areal recharge for several simulations and the proportion of recharge which infiltrates into the Grande Ronde layer.

A discrepancy exists in the values of recharge to the Grande Ronde layer for the base simulation (40 cfs) and the time-averaged simulation described by Lum and others (32 cfs). The fact that the base simulation is transient and the time-averaged simulation is steady-state is not the cause of the variability in Grande Ronde recharge between the two simulations. Model results reported by Lum and others (1990) are based on a modified version of the Pullman-Moscow model, whereas all simulations performed by this author are based on the documented version of the model. Although variations between the two model versions are slight, the modifications are believed to affect the amount of recharge entering the Grande Ronde layer. Simulated water levels in the Wanapum layer are higher in the documented version of the model than in the modified version; thus a higher vertical gradient exists between the Wanapum layer and the Grande Ronde layer. The higher gradient allows for a greater flux of areal recharge to enter the Grande Ronde in the documented version of the model (Lum, oral commun., 1990).

Canyon Seepage Variations

The effects on model output by varying seepage discharge from the Snake River Canyon face are evaluated by examining the overall water budgets of the projected simulations. A comparison of these water budgets is presented in table 5.

Variations in canyon seepage are accommodated in the model by changes in flux across cells that are simulated with rivers, drains, and constant head boundary conditions. The model compensates an increase in canyon seepage mainly by decreasing discharge to rivers and drains in the loess and Wanapum layers. In addition, water entering and leaving the model through constant head boundaries increases and decreases, respectively. Also, a slight increase in the flux of water entering the model from rivers and an increase in water removed from aquifer storage occurs when canyon seepage is increased. A decrease in canyon seepage has the opposite effects on model output.

		FLUX (CFS)				
		CONSTANT HEAD BOUNDARIES			CONST.FLUX BOUNDARIES	
	WATER BUDGET TERM	SEEP 100% BASE	SEEP 200% RUN4	SEEP 50% RUN5	SEEP 100% RUN6	SEEP 50% RUN8
IN	CONSTANT HEAD OR FLUX	13.2	27.4	8.3	10.9	10.9
	AREAL RECHARGE	135.8	135.8	135.8	136.0	136.0
	RIVERS	0.3	0.8	0.3	0.3	2.5
	DECREASE IN STORAGE	0.4	0.6	0.3	0.6	0.9
	TOTAL IN	149.7	164.6	144.7	147.8	150.3
OUT	CONSTANT HEAD OR FLUX	19.1	12.5	24.4	17.4	17.4
	CANYON SEEPAGE (WELL)	34.6	69.1	17.3	34.6	69.1
	AVERAGE PUMPAGE	11.0	11.0	11.0	11.0	11.0
	DRAINS	45.8	41.0	48.4	45.7	32.2
	RIVERS	39.7	31.7	43.6	39.4	20.8
	TOTAL OUT	150.2	165.3	144.7	148.1	150.5
	PERCENT DISCREPANCY	0.33	0.43	0.05	0.20	0.18

Table 5. Water budgets of the projected simulations used in the analysis of varying seepage from the face of the Snake River Canyon.

Simulated Streamflow Comparisons

Simulated areal recharge variations are further analyzed by examining the discharge of ground water into rivers and streams for several simulations. A comparison of simulated flow into streams and measured stream discharges during baseflow conditions is presented in table 6.

	FLOW RATE (CFS)			
	MEASURED STREAM DISCHARGE OCT. 1984	SIMULATED AVERAGE NET FLOW CONSTANT HEAD SIMULATIONS		
RIVER REACH		BASE SIMULATION	RECH=200% RUN 2	RECH=50% RUN 3
SNAKE	---	40.9	46.6	39.3
S.F.PALOUSE	17.0	17.1	41.0	5.9
PALOUSE	---	10.1	23.3	3.5
UNION FLAT	4.7	21.8	53.4	4.7
PARADISE	4.0	3.7	11.6	0.7
FOURMILE	---	6.6	23.6	2.1
MISSOURI FLAT	0.5	6.4	15.0	0.2
SPRING FLAT	0.4	4.8	11.8	0.9

Table 6. Simulated discharge into rivers and streams for several simulations and measured stream discharge for the same reaches.

Simulated flows represent the net sum of discharge from the ground water system to the river reach and to drains that are located immediately adjacent to the river reach. Fluxes to rivers and drains obtained from the final stress period of a simulation are used to determine simulated streamflows. Although variations in fluxes exist between the first stress period and the last, the average discrepancy in fluxes for any simulation is only about 3%. Water losses due to evapotranspiration in the drainages are not accounted for; thus, simulated net flow to streams may be too high. Streamflow measurements taken for the same reaches in October of 1984 are listed for comparison. During the fall months prior to the rainy season, ground water discharge is probably the only source of streamflow for the river reaches other than the Snake River and Paradise Creek. A year-round snowpack, irrigation return flow, and summer precipitation contribute to streamflow in the headwaters of the Snake River. The measured streamflow on Paradise Creek includes ungauged sewage plant effluent.

Simulated streamflows in Run 2 (recharge=200%) are much greater than measured streamflows, indicating that this amount of simulated areal recharge is conceptually unreasonable as the model presently functions. However, if the face of the Snake River Canyon was simulated with operative drains rather than constant flux cells, more of the increased recharge would infiltrate into the Grande Ronde layer and less of the increased areal recharge would discharge from the loess and Wanapum layers into rivers and drains. Thus, simulated streamflow would be more reasonable. Simulated ground water discharge from the Grande Ronde layer to river reaches only occurs for the Snake River and a small portion of the Palouse River.

Modeled streamflows in the base simulation are comparable to measured streamflows for the South Fork of the Palouse River and Paradise Creek. Simulated streamflows in the base run are too high for Union Flat Creek, Missouri Flat Creek, and Spring Flat Creek. In contrast, modeled streamflows in Run 3 (recharge=50%) are comparable to measured streamflows for these three creeks. Simulated streamflows in Run 3 are too low for the South Fork of the Palouse River and perhaps Paradise Creek. However, if the ungauged sewage effluent was subtracted from the listed measured stream discharge for Paradise Creek, then the simulated streamflow in Run 3 might be comparable to the actual streamflow.

Thus, in terms of model calibration, specifying an input value for areal recharge at 50% of the base simulation is just as viable as designating areal recharge at 100%.

Modeled streamflows in constant flux simulations are not listed because the results are similar to the constant head simulations that are shown. Model calculated streamflows in simulations when canyon seepage is varied are not tabulated either. The simulated streamflows in canyon seepage runs are bracketed by the higher and lower modeled streamflows in the areal recharge simulations.

Flux Comparisons at Constant Head Boundaries

Actual ground water flow rates across boundaries that are modeled as constant head are not known. Water level data near the boundaries indicate that water leaves the study area along the northwest boundary and enters the study area along the northeast and southeast boundaries.

Fluxes generated in the final stress period of the constant head simulations are examined for their consistency in replicating conceptual ground water flow directions at the boundaries of the model. Flux variations between the first and last stress periods are not significant.

Simulated flow directions in the Wanapum layer across the northeast and southeast boundaries are contradictive to conceptual flow directions in all of the constant head simulations, but the magnitudes of the simulated fluxes are not significant. Only small ground water fluxes are believed to occur in areas where non-conforming values are present. Simulated flow direction in the Wanapum layer at the northwest boundary is consistent with the conceptual flow direction in all of the simulations.

In all simulations assuming constant head boundary conditions, the calculated flow directions in the Grande Ronde layer for several individual boundary cells are opposite of ground water flow directions indicated by water level data near the boundaries. However, the net sum of simulated fluxes of all cells at any one boundary usually generates an average simulated flow direction that is the same as the conceptual flow direction. Doubling canyon seepage or halving areal recharge appear to be the threshold points where net simulated flow directions in the Grande Ronde layer at constant head boundaries become contradictory with flow directions indicated by water level data.

In summary, inconsistencies are present between simulated and conceptual flow directions at two of the boundaries in the Wanapum layer (Runs 1-5) and at several individual boundary cells in the Grande Ronde layer (Runs 1-5). Although the degree of inconsistencies is not large, this indicates that these constant head boundary conditions do not accurately portray the basin characteristics along its perimeter and probably control model output to some extent.

CHAPTER VI

EVALUATION OF RESULTS FROM THE SENSITIVITY ANALYSIS SIMULATIONS

Areal Recharge Variations

Decreasing the amount of simulated areal recharge to the Pullman-Moscow model induces more drawdown to occur throughout the model in a projected simulation where municipal pumpage is increased by 1% annually. Conversely, less drawdown occurs when the amount of areal recharge is increased. However, the water level changes are not proportional to the percentage adjustments in the recharge rate. In constant head boundary simulations when areal recharge is doubled or halved, drawdown in the Grande Ronde Basalt near Moscow and Pullman varies from the base simulation only by two to four feet at the end of 20 years of pumping. Negligible variation in drawdown is evident at the model boundaries when they are simulated with constant head conditions. No major changes in water levels are generated for other regions of the Grande Ronde layer when constant head boundary conditions are assumed.

Significant changes in simulated areal recharge to the model only have a subtle affect on water levels in the Grande Ronde layer because the variation in recharge is accommodated mostly in the loess and Wanapum layers. Variations in areal recharge are balanced in the model predominantly by changes in discharge to rivers and drains, and ground water flow rates across constant head boundaries. All of the water discharging through drains flows from the loess and Wanapum layers. Most of the water discharging to rivers also flows from the loess and Wanapum. The discharge of ground water from the Grande Ronde layer directly into the Snake River represents an insignificant portion of the total river flux in all simulations. Thus, if areal recharge is increased, most of the additional water leaves the model before it reaches the Grande Ronde layer. Conversely, when areal recharge is reduced, less water discharges from the loess and Wanapum layers to rivers and drains, and recharge to the Grande Ronde layer diminishes only slightly. Small fluctuations in simulated infiltration into the Grande Ronde layer, when areal recharge is varied, are a result of changes in flux across constant head boundaries.

Doubling simulated areal recharge values generates unreasonably high fluxes to rivers and drains in the loess and Wanapum layers, yet there is no change in flow from the major discharge zone along the Snake River Canyon wall. This occurs because Snake River Canyon seepage is simulated with constant flux cells and is fixed with time in the model.

The insensitivity of water levels in the Grande Ronde layer to areal recharge variations is a function of model construction. This conclusion does not imply that areal recharge is an insignificant parameter in the conceptual model.

Canyon Seepage Variations

The effects on model output when canyon seepage is varied parallel those effects depicted in variations of areal recharge, except that the influences on model results are opposite. Decreasing the amount of simulated seepage from the face of the Snake River Canyon induces less drawdown to occur throughout the model. More drawdown occurs in the model when canyon seepage is increased. Significant specified variations in canyon seepage flux cause only minor changes in hydraulic head in the Grande Ronde layer near Moscow and Pullman. Drawdown in wells that penetrate the Grande Ronde layer in Moscow and Pullman change by a maximum of three feet at the end of 20 years of simulated pumping when canyon seepage is varied under constant head boundary conditions. Conceptually, this could be substantiated because of the considerable distance between the pumping centers and the canyon face. However, the insensitivity of canyon seepage variations on water levels in the Grande Ronde layer probably is a function of model construction to a great degree. Variations in canyon seepage are accommodated in the model by changes in discharge to rivers and drains in the loess and Wanapum layers, and fluxes across constant head boundary cells. Negligible variations in water levels occur near the boundaries when constant head conditions are assumed.

The Snake River Canyon seepage face was originally simulated in the Pullman-Moscow model with drains, but the drains did not represent the seepage face adequately. Many of the drains became inoperative because the heads calculated for the Grande Ronde cells adjacent to the drains were below the specified drain elevation. Much of this problem could be eliminated by representing the Grande Ronde Basalt with at least three layers, rather than as a single thick layer. The MODFLOW program calculates water levels at the center of the single layer. In most cases, the model generated water levels do not correlate with the field data. Representation of the Grande Ronde Basalt with multiple layers would refine the values between actual water levels and simulated water levels to a more correlative degree. Drain operation in a multiple Grande Ronde layer model may prove to be more effective.

Constant Flux Boundary Simulations

Additional drawdown is present throughout the model when constant flux boundary conditions are simulated. Water levels in Moscow and Pullman are two to six feet lower after 20 years of pumping than in constant head boundary simulations under the same conditions of areal recharge and canyon seepage. This implies that the cone of depression from municipal pumping extends to the present location of the model boundaries. Thus, constant head boundary conditions control the model output to a certain extent. The influence of the constant head boundaries is not considerable in view of the fact that the changes in water levels in Moscow and Pullman vary only by two to six feet after 20 years of pumping.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Simulated water levels in the Grande Ronde layer near Moscow and Pullman are relatively insensitive to changes in areal recharge to the ground water basin and seepage discharge from the face of the Snake River Canyon. This is believed to result from model construction and may not be conceptually correct.

The Snake River Canyon seepage face is a major discharge area for the Pullman-Moscow Basin, yet discharge from the seepage face is fixed in the ground water model. If the seepage face was simulated with drains, rather than with constant flux cells, discharge could vary with time. This is a more realistic approximation of the conceptual model. In addition, a numerical model with drains representing Snake River Canyon seepage probably would be much more sensitive to changes in areal recharge. Variations in recharge would partially be reflected in the model by changes in discharge from Grande Ronde layer drains in the Snake River Canyon.

Additional drawdown occurs throughout the model when constant head boundaries are changed and simulated with constant flux conditions instead. This implies that the cone of depression from municipal pumping in Moscow and Pullman extends to the current model boundary locations. This probably does not represent a significant model design error because the amount of additional drawdown is small.

Caution must be exercised in utilizing the Pullman-Moscow numerical model as a tool for developing ground water management policies in the region. The representation of the Grande Ronde Basalt as a single layer in the model has created several inherent inaccuracies in the depiction of the ground water flow system. The simulation of the Snake River Canyon seepage face with constant flux cells does not accurately portray the discharge mechanisms. Water level insensitivities in the Grande Ronde layer to areal recharge and canyon seepage variations suggest that the numerical model may not closely approximate the conceptual model.

Specific conclusions are listed below:

1) A maximum of four feet of water level change from the base simulation is present in Grande Ronde layer cells near Moscow and Pullman at the end of 20 years of simulated pumping (1% annual increase) when areal recharge is doubled or halved.

2) A maximum of three feet of water level change from the base simulation is present in Grande Ronde layer cells near Moscow and Pullman at the end of 20 years of simulated pumping (1% annual increase) when seepage discharge from the face of the Snake River Canyon is doubled or halved.

3) Two to six feet of additional drawdown is simulated in Grande Ronde layer cells near Moscow and Pullman at the end of 20 years of pumping (1% annual increase) when constant flux boundaries are assumed rather than constant head. The amount of additional drawdown is dependent on the specified flux at

the boundaries.

4) Variations in areal recharge and Snake River Canyon seepage mainly are accommodated in the model by changes in discharge to rivers and drains and fluxes across constant head boundaries.

5) All of the discharge to drains, and most of the discharge to rivers, is from the loess and Wanapum layers.

6) Large variations in the areal recharge rate to the uppermost layer (predominantly the loess) are reflected by small changes in the recharge rate and ground water levels in the Grande Ronde layer.

7) Simulated ground water discharge to streams becomes conceptually unreasonable when areal recharge is doubled.

8) Simulated flow directions across constant head boundaries begin to contradict conceptual ground water flow directions when canyon seepage is doubled or areal recharge is halved.

Recommendations

The construction and refinement of the Pullman-Moscow ground water flow model is a continual process in which additional hydrogeologic information is input to the model as it becomes known. The limitations of the current model identified in this report provide a scope of study for future investigations. The suggested revisions of representing the Grande Ronde Basalt with several layers and simulating the Snake River Canyon seepage face with drains may enhance the confidence of using this model as a management tool.

Other recommendations for model refinement include:

1) Place the constant head boundaries further from the pumping centers so they have less influence on drawdown in the model when pumping in Moscow and Pullman is simulated.

2) Test the model more extensively using constant flux boundary conditions. The amount of additional drawdown simulated in the model when constant flux conditions are assumed is dependent on the magnitude of the specified boundary fluxes. Boundary fluxes should be varied to determine their effects on the sensitivity of changes in water levels throughout the model.

3) Test the model sensitivity to variations in the input values of the hydraulic properties.

4) Simulate the Grande Ronde layer adjacent to the Palouse River with a constant head or constant flux boundary. A no-flow boundary does not accurately characterize this portion of the model since underflow in the Grande Ronde layer probably is occurring.

5) Initiate field investigations of the recharge rate to the surficial loess by installing lysimeters in strategic locations in the basin.

6) Examine the mechanisms and rate of discharge from the seepage faces in the Snake River Canyon.

The Pullman-Moscow area relies exclusively on ground water for its municipal water needs. The importance of conserving and wisely utilizing this precious resource cannot be over-emphasized. As continued growth and development add further strain on the ground water system, management policies will need to be established that will enhance the use of this resource as a supply of fresh water well into the next century.

Programs in water conservation awareness should be initiated for the benefit of enlightening the public sector to the need for prudent water use. The practice of using treated sewage effluent for the purpose of lawn irrigation should be expanded. The withdrawal of water from the Wanapum Basalt, for needs where water quality is not of great concern, would help relieve the burden of withdrawal from the Grande Ronde Basalt. Enhancement of infiltration and reduction in overland flow during periods of rapid snowmelt and intense precipitation could be achieved through the construction of minor barriers in the valley bottoms of the Palouse hills to impede runoff.

Most importantly, an ongoing effort of communication, cooperation, and the sharing of ideas should be maintained between the four main users of the Pullman-Moscow aquifer.

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APPENDIX A

DOCUMENTATION OF PROCEDURES FOR OPERATING THE PULLMAN-MOSCOW GROUND WATER FLOW MODEL ON THE UNIVERSITY OF IDAHO IBM 4381 COMPUTER

The purpose of this appendix is to assist operators of the Pullman-Moscow ground water flow model in executing projected transient simulations using operator specified stress conditions. The CMS Users Guide, published by Computer Services at the University of Idaho, should be referenced to answer questions specific to the operation of the IBM 4381 computer. The MODFLOW documentation (McDonald and Harbaugh, 1988) should be reviewed to gain familiarity with data file organization and the MODFLOW Fortran code.

The Pullman-Moscow ground water flow model operates by executing various batch files called EXEC files. The EXEC files contain definition statements that open pertinent input data files and identify by name and unit number the files that will be generated by the Fortran program. The last definition statement in an EXEC file loads and executes the compiled Fortran code called a TEXT file. The model incorporates several Fortran programs besides MODFLOW; these additional programs generate some of the input data files accessed by MODFLOW and also process model output. All of the EXEC files are described in Appendix B.

The user identification name for the model is PMGWB. The password to gain access to the account can be obtained from the Idaho Water Resources Research Institute located on campus. The account contains 20 cylinders or approximately nine megabytes of permanent A-disk space. After the operator logs onto the account, the memory size of the virtual machine must be increased from 512K to four megabytes to accommodate the large memory requirements needed to run the model. This can be performed by typing the command DEF STOR 4M, followed by the command IPL ELCMS to restore the Conversational Monitoring System (CMS) back to the virtual machine. However, if any changes are made to the Fortran source code, the storage capacity must be temporarily redefined before the program is compiled. The compiler does not operate with a specified storage capacity greater than two megabytes.

Many of the model files have been packed to reduce the tremendous amount of storage space required by the files. Packed files can be identified in the file list (FLIST) by the presence of a full block record length of 1024 characters. Packed files must be unpacked before they can be used in a model operation or examined on the computer screen. Thus, before executing an EXEC file, the operator should make certain that all of the accessed files in the EXEC file are unpacked. The Fortran source file does not have to be unpacked, since only the TEXT file is read once the program has been compiled. A file can be unpacked in FLIST by typing the command COPY / (UNPACK next to the filename. A file can be packed in the same manner by typing the command COPY / (PACK. The current amount of available disk space on this account only will accommodate the storage of model output from one or two more projected simulations, unless additional room is made by erasing the output files from this author's study, or by expanding the account size. Printout (LISTING) files are large and can be erased after a hardcopy has been printed. Additional disk space can be temporarily defined for use during a single work session, but will automatically be deleted at the end of the session when the user logs off the computer terminal.

A model operation is executed by entering the filename of the appropriate EXEC file. For example, the command to execute the EXEC file for projected transient simulations (PROJ EXEC) is PROJ. Simulated water level and drawdown output are saved under the filenames HDOUT PROJ and DDOUT PROJ, respectively. These files are written in machine code; however, the output processor Fortran programs HYDROPR1, HYDROPR2, and HYDROPR3 access the machine code files and generate selected water level and/or drawdown files (BDRAWOUT PROJ, DRAWOUT PROJ, and HYDROUT PROJ) that are saved in a readable form. All model output files (BDRAWOUT PROJ, DDOUT PROJ, DRAWOUT PROJ, HDOUT PROJ, HYDROUT PROJ, and PROJOUT LISTING) must be renamed before the EXEC file is executed again, or the output files will be overwritten. This can be accomplished with the RENAME command (i.e. RENAME HDOUT PROJ HDOUT PROJ1).

A review of the PROJ EXEC file will help clarify the operation procedures for executing projected transient simulations of the Pullman-Moscow model. The file contents are listed below:

```
FI * CLEAR
FI  5 DISK BAS PROJ A (PERM LRECL 80 RECFM F
FI  6 DISK PROJOUT LISTING A (PERM LRECL 133 RECFM F
FI 80 DISK WELL PROJ A (PERM LRECL 40 RECFM F
FI 66 DISK VCONT DAT A (PERM LRECL 120 RECFM F
FI 20 DISK BCF HM A (PERM LRECL 80 RECFM F
FI 61 DISK DRAINS DAT A (PERM LRECL 80 RECFM F
FI 62 DISK RIVERS DAT A (PERM LRECL 80 RECFM F
FI 63 DISK RECHARGE 2 A (PERM LRECL 80 RECFM F
FI 64 DISK SIP DAT A (PERM LRECL 80 RECFM F
FI 65 DISK OCL PROJ A (PERM LRECL 80 RECFM F
FI 14 DISK IBOUND DAT A (PERM LRECL 110 RECFM F
FI 11 DISK TRANS2 DAT A (PERM LRECL 120 RECFM F
FI 12 DISK TRANS3 DAT A (PERM LRECL 120 RECFM F
FI 29 DISK HDOUT TA A4 (PERM LRECL 12108 RECFM V
FI 30 DISK HDOUT PROJ A4 (PERM LRECL 12112 RECFM V
FI 31 DISK DDOUT PROJ A4 (PERM LRECL 12112 RECFM V
EXEC FORTG MODFLOW
 * * * END OF FILE * * *
```

FI stands for file definition. The unit number that follows is translated to a Fortran data definition name recognized by the Fortran program. FI * CLEAR clears all previous file definition statements. DISK fn ft fm refers to the filename, filetype, and filemode stored on disk. PERM retains the current definition until it is explicitly cleared or changed with another FI statement. LRECL followed by a number is the logical record length of the records in the file. RECFM followed by a letter is the record format of the file, either fixed or variable. FORTG loads and executes the MODFLOW TEXT file.

Input for the Basic Package (BAS PROJ) is read from unit number 5. This package handles the administrative tasks of the model and should not have to be edited unless the model is modified (i.e. more model layers, stress periods, etc.). The assignment of unit numbers for starting heads (29) and boundary conditions (14) are handled in the basic package; however, the actual values are listed in the IBOUND DAT and HDOUT TA files.

The PROJOUT LISTING file is a model output file which lists the results of the simulation as specified in the Output Control file (OCL PROJ). The OCL PROJ file often is changed to meet the specific needs of a particular simulation. Head and drawdown output values can be saved on disk and/or printed in the LISTING file by setting the appropriate flags in the OCL PROJ file. A wide variety of combinations can be specified for individual stress periods or model layers. Flags to print the overall volumetric budget and to print or save cell-by-cell flow terms are located in the OCL PROJ file. The PROJOUT LISTING file should be renamed after it has been generated so that it will not be overwritten by execution of other projected simulations.

The WELL PROJ file lists: 1) fluxes for cells where municipal pumping occurs, 2) constant fluxes specified as seepage discharge in the Snake River Canyon, and 3) constant fluxes specified at the model perimeter if constant flux boundary conditions are simulated. If any of these values or situations change, the WELL PROJ file must be appropriately edited to reflect the changes. For information on how to edit the WELL PROJ file, refer to the sub-headings <u>Seepage Discharge from the Snake River Canyon Wall</u> and <u>Constant Flux Boundary Conditions</u> in Chapter IV of this thesis.

The VCONT DAT file lists the values for vertical conductance from the Palouse Loess layer to the Wanapum layer and from the Wanapum layer to the Grande Ronde layer. Unless vertical hydraulic conductivity values are modified in the model or the number of model layers is changed, this file does not have to be edited. The VCONT DAT file is generated by executing the PRE EXEC file.

The Block Centered Flow Package (BCF HM) specifies steady-state conditions, cell-by-cell flow terms, the anisotropy ratio, layer type, row width, column width, storage coefficient, and the uniform model transmissivity value in the

Palouse Loess. In addition, the unit numbers and format codes for VCONT DAT, TRANS2 DAT, and TRANS3 DAT are designated. Model transmissivity values in the Wanapum (TRANS2) and Grande Ronde (TRANS3) layers are not uniform and thus are listed in separate files. The BCF HM file does not have to be edited unless any one of the above model characteristics is changed. If transmissivity values in the Wanapum or Grande Ronde layers are modified, the TRANS2 DAT and TRANS3 DAT files will have to be edited. Both of these files are generated by executing the PRE EXEC file.

The Drain (DRAINS DAT) and River (RIVERS DAT) files also are generated by executing the PRE EXEC file. The RIVERS DAT file contains information on the location of a river reach, the head in the river, the riverbed hydraulic conductance, and the elevation of the bottom of the riverbed. This file does not have to be edited, unless any one of these characteristics is modified. The DRAINS DAT file contains information on the location of a drain, the elevation of the drain, and the hydraulic conductance of the interface between the aquifer and the drain. If the Snake River Canyon seepage face is simulated with drains instead of constant flux cells, this file will have to be edited to include the changes.

The RECHARGE 2 file specifies areal recharge fluxes to the uppermost model layer (generally the loess) on a cell-by-cell basis, based on current land use and farming practices and annual rainfall data. If the fluxes are changed, this file will have to be edited. For information on how to modify the RECHARGE 2 file, refer to the sub-heading <u>Areal Recharge</u> in Chapter IV of this thesis.

The Strongly Implicit Procedure Package (SIP DAT) solves the linear equations which approximate ground water flow in the Pullman-Moscow model. The equations are solved simultaneously by iteration. This file does not need to be modified unless another solver package is selected.

The Ibound array (IBOUND DAT) differentiates whether a cell is active and variable, whether it is a no-flow cell, or whether it is a constant head cell. There are two IBOUND DAT files in the Pullman-Moscow model. IBOUND0 DAT is the Ibound array for constant head boundary simulations. IBOUND1 DAT is the Ibound array for constant flux boundary simulations. In either type of simulation, the Ibound array has to be renamed IBOUND DAT before the simulation can be executed.

Starting heads are read on unit number 29 of the model. Depending on the simulation being run, the starting heads may vary. Starting heads used in projected simulations documented by Lum and others (1990) were generated from the final stress period of the history match simulation (HDOUT HM). Starting heads used in projected simulations documented in this thesis were generated from time-averaged simulations (HDOUT TA). The starting head filename has to be changed in the PROJ EXEC file when different starting heads are used in a particular simulation. If model characteristics that would affect starting heads are modified, a steady-state simulation initially should be run to generate starting heads for the projected transient simulation.

As mentioned above, HDOUT PROJ and DDOUT PROJ are model output files that record simulated head and drawdown values in machine code. These files should be renamed after they have been generated so that they will not be overwritten by execution of other projected simulations. If head and/or drawdown values are flagged in the OCL PROJ file to not be saved on disk, then the file definition statement(s) for HDOUT PROJ and/or DDOUT PROJ should be removed from the PROJ EXEC file before the simulation is executed.

APPENDIX B

DESCRIPTION OF THE PULLMAN-MOSCOW GROUND WATER FLOW MODEL FILES

This appendix includes descriptions of all the Pullman-Moscow ground water flow model files that are stored on the University of Idaho IBM 4381 computer. The user identification name is PMGWB. Printout files of the executed model simulations, called LISTING files, could not all be stored on the account because the files use an immense amount of disk space. However, the LISTING files can be re-generated simply by executing the various simulations. Hard copies of the LISTING files for time-averaged and projected simulations were printed before the files were erased. Water level and drawdown data for each simulation are stored in separate files; the LISTING files are repetitious of this information. Flux terms for rivers, drains, and constant head cells and volumetric water budgets are stored in the LISTING files. These data were edited from the LISTING files of the projected simulations before the files were erased, and stored on disk under the filename PROJ FLUX.

BAS HM - This is the basic file for the history match simulation. The basic package handles the administrative tasks of the model. A thorough description of the basic package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 4-1).

BAS PROJ - This is the basic file for projected transient simulations.

BAS TA - This is the basic file for time-averaged, steady-state simulations.

BASFMT SS - This is the basic file for a formatted steady-state simulation which solves the system in pre-development conditions.

BCF HM - This is the block centered flow file for the history match and projected simulations. The block centered flow package computes the conductance components of the finite-difference equation which determine flow between adjacent cells. A complete description of the block centered flow package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 5-1).

BCF SS - This is the block centered flow file for a formatted steady-state simulation which solves the system in pre-development conditions.

BCF TA - This is the block centered flow file for time-averaged, steady-state simulations.

BDRAWDOUT PROJ0 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the base simulation. This file, as well as all BDRAWOUT PROJ data files, are generated by the Fortran program HYDROPR1.

BDRAWOUT PROJ1 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2).

BDRAWOUT PROJ2 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3).

BDRAWOUT PROJ3 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant flux projected simulation when no variations are made to areal recharge or canyon seepage (Run 6).

BDRAWOUT PROJ4 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4).

BDRAWOUT PROJ5 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

BDRAWOUT PROJ8 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7).

BDRAWOUT PROJ9 - This data file lists simulated drawdown in selected Grande Ronde cells near the model boundaries in the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8).

DATA INT - This data file contains information on stream type, reach name, and reach length. It is accessed by the Fortran program WFRDG to generate the RIVERS DAT, DRAINS DAT, and WELL SNAKE files.

DATA MISC - This data file contains information on stream width and depth and a discharge rate from the seepage face of the Snake River Canyon. It is accessed by the Fortran program WFRDG to generate the RIVERS DAT, DRAINS DAT, and WELL SNAKE files.

DATA REAL - This data file contains information on the altitude of the tops and bottoms of the model layers. It is accessed by the Fortran program WFRDG to generate the RIVERS DAT, DRAINS DAT, and WELL SNAKE files.

DDOUT PROJ0 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the base simulation. This file, as well as all DDOUT PROJ binary data files, are accessed by the Fortran programs HYDROPR1, HYDROPR2, and HYDROPR3, which write drawdown and head for specified cells in a readable form.

DDOUT PROJ1 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2).

DDOUT PROJ2 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3).

DDOUT PROJ3 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant flux projected simulation when no variations are made to recharge or canyon seepage (Run 6).

DDOUT PROJ4 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4).

DDOUT PROJ5 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

DDOUT PROJ8 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7).

DDOUT PROJ9 - This binary data file, written in computer code, lists simulated drawdown for every cell during each stress period in the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8).

DICTNARY DAT - This data file lists this appendix.

DRAINS DAT - This is the drain file for all of the simulations. The drain package simulates the effects of seepage faces in stream valleys other than the Snake River Canyon. This file is generated by the Fortran program WFRDG under the name OUT DRN. The file is edited to include the maximum number of drain cells active at one time and repeat codes for multiple stress periods in transient simulations. The file is renamed DRAINS DAT. A complete description of the drain package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 9-1).

DRAWOUT PROJ0 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the base simulation. This file, as well as all DRAWOUT PROJ data files, are generated by the Fortran program HYDROPR2.

DRAWOUT PROJ1 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2).

DRAWOUT PROJ2 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3).

DRAWOUT PROJ3 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when no variations are made to areal recharge or canyon seepage (Run 6).

DRAWOUT PROJ4 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4).

DRAWOUT PROJ5 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

DRAWOUT PROJ8 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7).

DRAWOUT PROJ9 - This data file lists drawdown in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8).

GRKH DAT - This data file lists the horizontal hydraulic conductivities of cells in the Grande Ronde layer. The file is generated by the Fortran program KVKH3D, and is accessed by the Fortran programs MULT, VCONT, and WFRDG.

GRKV DAT - This data file lists the vertical hydraulic conductivities of cells in the Grande Ronde layer. The file is generated by the Fortran program KVKH3D, and is accessed by the Fortran programs VCONT and WFRDG.

HDINFMT SS - This formatted data file lists the starting heads for each model cell in a steady-state simulation which solves the system in pre-development conditions.

HDOUT HM - This binary file lists the output heads for the final stress period of the history match simulation. This file is used for the starting heads of all of the time-averaged simulations and for the projected simulations modeled by Lum and others (1990).

HDOUT PROJ0 - This binary data file lists simulated water levels for every cell during each stress period in the base simulation. This file, as well as all HDOUT PROJ binary data files, are accessed by the Fortran programs HYDROPR2 and HYDROPR3, which write water levels for specified cells in a readable form.

HDOUT PROJ1 - This binary data file lists simulated water levels for every cell during each stress period in the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2).

HDOUT PROJ2 - This binary data file lists simulated water levels for every cell during each stress period in the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3).

HDOUT PROJ3 - This binary data file lists simulated water levels for every cell during each stress period in the constant flux projected simulation when no variations are made to areal recharge or canyon seepage (Run 6).

HDOUT PROJ4 - This binary data file lists simulated water levels for every cell during each stress period in the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4).

HDOUT PROJ5 - This binary data file lists simulated water levels for every cell during each stress period in the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

HDOUT PROJ8 - This binary data file lists simulated water levels for every cell during each stress period in the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7).

HDOUT PROJ9 - This binary data file lists simulated water levels for every cell during each stress period in the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8).

HDOUT TA0 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when no parameter variations are made. The water levels in this file are used as the starting heads in the base simulation. This file, as well as all HDOUT TA binary data files, are accessed by the Fortran program HYDROTA which writes water levels for specified cells in a readable form.

HDOUT TA1 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when areal recharge equals 200% and constant head boundaries are specified. The water levels in this file are used as the starting heads in Run 2.

HDOUT TA2 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when areal recharge equals 50% and constant head boundaries are specified. The water levels in this file are used as the starting heads in Run 3.

HDOUT TA3 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when boundary conditions are changed to constant flux. The water levels in this file are used as the starting heads in Run 6.

HDOUT TA4 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when canyon seepage equals 200% and constant head boundaries are specified. The water levels in this file are used as the starting heads in Run 4.

HDOUT TA5 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when canyon seepage equals 50% and constant head boundaries are specified. The water levels in this file are used as the starting heads in Run 5.

HDOUT TA8 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when areal recharge equals 50% and constant flux boundaries are specified. The water levels in this file are used as the starting heads in Run 7.

HDOUT TA9 - This binary data file lists simulated water levels for every cell in the time-averaged simulation when canyon seepage equals 200% and constant flux boundaries are specified. The water levels in this file are used as the starting heads in Run 8.

HM EXEC - This batch file accesses pertinent data and program files, executes the history match simulation, and assigns unit numbers to the files being generated. The water levels of only the final stress period are saved.

HMSAVE EXEC - This batch file accesses pertinent data and program files, executes the history match simulation, and assigns unit numbers to the files being generated. The water levels of every stress period are saved, so that a simulated hydrograph can be created from the output.

HYDROHM EXEC - This batch file accesses HDOUT HM, executes the Fortran program HYDROHM, and assigns a unit number to the generated file HYDROUT HM.

HYDROHM FORTRAN - This Fortran program writes water levels for selected cells during every stress period of the history match simulation in a readable form.

HYDROHM TEXT - This text file is the compiled executable code for the HYDROHM FORTRAN source file.

HYDROPR1 EXEC - This batch file accesses DDOUT PROJ files, executes the Fortran program HYDROPR1, and assigns unit numbers to the generated files BDRAWOUT PROJ.

HYDROPR1 FORTRAN - This Fortran program writes drawdown values for selected Grande Ronde cells near the model boundaries for every stress period of a projected simulation in a readable form.

HYDROPR1 TEXT - This text file is the compiled executable code for the HYDROPR1 FORTRAN source file.

HYDROPR2 EXEC - This batch file accesses DDOUT PROJ and HDOUT PROJ files, executes the Fortran program HYDROPR2, and assigns unit numbers to the generated files DRAWOUT PROJ and HYDROUT PROJ. DRAWOUT PROJ and HYDROUT PROJ have to be generated independently and the EXEC file has to be edited so the accessed and generated file names coincide with each other.

HYDROPR2 FORTRAN - This Fortran program writes either drawdown or water levels (depends on which is specified in the EXEC file) in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman for every stress period of a projected simulation in a readable form.

HYDROPR2 TEXT - This text file is the compiled executable code for the HYDROPR2 FORTRAN source file.

HYDROPR3 EXEC - This batch file accesses either DDOUT PROJ or HDOUT PROJ files, executes the Fortran program HYDROPR3, and assigns unit numbers to the files being generated. The readable drawdown and head files have to be generated independently. None of the generated files have been stored on disk because of their immense size.

HYDROPR3 FORTRAN - This Fortran program writes either drawdown or water levels (depends on which is specified in the EXEC file) in every model cell for each stress period of a projected simulation in a readable form. The file can be viewed on the computer screen, but cannot be printed because the file format is too wide.

HYDROPR3 TEXT - This text file is the compiled executable code for the HYDROPR3 FORTRAN source file.

HYDROTA EXEC - This batch file accesses HDOUT TA files, executes the Fortran program HYDROTA, and assigns unit numbers to the generated files HYDROUT TA.

HYDROTA FORTRAN - This Fortran program writes water levels for selected Grande Ronde cells in a time-averaged simulation in a readable form.

HYDROTA TEXT - This text file is the compiled executable code for the HYDROTA FORTRAN source file.

HYDROUT HM - This data file lists selected water levels for every stress period in the history match simulation. The file is generated by the Fortran program HYDROHM.

HYDROUT PROJ0 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the base simulation. This file, as well as all HYDROUT PROJ data files, are generated by the Fortran program HYDROPR2.

HYDROUT PROJ1 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2).

HYDROUT PROJ2 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3).

HYDROUT PROJ3 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when no variations are made to areal recharge or canyon seepage (Run 6).

HYDROUT PROJ4 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4).

HYDROUT PROJ5 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

HYDROUT PROJ8 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7).

HYDROUT PROJ9 - This data file lists water levels in selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8).

HYDROUT TA0 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when no parameter variations are made. This file, as well as all HYDROUT TA files, are generated by the Fortran program HYDROTA.

HYDROUT TA1 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when areal recharge equals 200% and constant head boundaries are specified.

HYDROUT TA2 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when areal recharge equals 50% and constant head boundaries are specified.

HYDROUT TA3 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when boundary conditions are changed to constant flux.

HYDROUT TA4 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when canyon seepage equals 200% and constant head boundaries are specified.

HYDROUT TA5 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when canyon seepage equals 50% and constant head boundaries are specified.

HYDROUT TA8 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when areal recharge equals 50% and constant flux boundaries are specified.

HYDROUT TA9 - This data file lists water levels for selected Grande Ronde cells that simulate municipal pumping in the cities of Moscow and Pullman in a time-averaged simulation when canyon seepage equals 200% and constant flux boundaries are specified.

IBOUND0 DAT - This is the IBOUND array for constant head boundary simulations. The IBOUND array contains a code for each cell which indicates whether the cell is variable, no-flow, or constant head. A thorough description of the IBOUND array can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 4-2).

IBOUND1 DAT - This is the IBOUND array for constant flux boundary simulations.

KHL2ZONE DAT - This data file specifies the zonation of the horizontal hydraulic conductivity in the Wanapum layer. It is accessed by the Fortran program KVKH3D to generate the data file WANKH.

KHL3ZONE DAT - This data file specifies the zonation of the horizontal hydraulic conductivity in the Grande Ronde layer. It is accessed by the Fortran program KVKH3D to generate the data file GRKH.

KVGRZONE DAT - This data file specifies the zonation of the vertical hydraulic conductivity in the Grande Ronde layer. It is accessed by the Fortran program KVKH3D to generate the data file GRKV.

KVKH DAT - This data file specifies the horizontal and vertical hydraulic conductivities of the Wanapum and Grande Ronde layers for each zone. It is accessed by the Fortran program KVKH3D to generate the data files WANKH, WANKV, GRKH, and GRKV.

KVKH3D FORTRAN - This Fortran program accesses the zonation files (KHL2ZONE, KHL3ZONE, KVWAZONE, and KVGRZONE) and the zone value file (KVKH) of the hydraulic conductivities in the Wanapum and Grande Ronde layers. The program generates the data files WANKH, WANKV, GRKH, and GRKV. The batch file which executes this Fortran program is PRE EXEC.

KVKH3D TEXT - This text file is the compiled executable code for the KVKH3D FORTRAN source file.

KVWAZONE DAT - This data file specifies the zonation of the vertical hydraulic conductivity in the Wanapum layer. It is accessed by the Fortran program KVKH3D to generate the data file WANKV.

MODEL DAT - This data file lists appendix A, which documents the procedures for operating the Pullman-Moscow ground water flow model on the University of Idaho IBM 4381 computer.

MODFLOW FORTRAN - This Fortran program is the U.S. Geological Survey modular ground water flow program (McDonald and Harbaugh, 1988) from which the Pullman-Moscow model is based.

MODFLOW TEXT - This text file is the compiled executable code for the MODFLOW FORTRAN source file.

MULT FORTRAN - This Fortran program multiplies layer thicknesses (THKWA and THKGR) by horizontal hydraulic conductivities (WANKH and GRKH) to generate transmissivities (TRANS2 and TRANS3) for the basalt layers. The batch file which executes this Fortran program is PRE EXEC.

MULT TEXT - This text file is the compiled executable code for the MULT FORTRAN source file.

OCL HM - This is the output control file for the history match simulation. Output control specifies whether or not heads, drawdown, and cell-by-cell flow terms will be saved and/or printed. A description of the output control options is presented in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 4-14). This output control file specifies to save and print heads only for the final stress period of the history match simulation.

OCL PROJ - This is the output control file for the projected simulations which specifies to save both drawdown and heads for every stress period.

OCL SS - This is the output control file for the steady-state simulation which solves the system in pre-development conditions.

OCL TA - This is the output control file for the time-averaged simulations.

OCLSAVE HM - This is the output control file for the history match simulation which specifies to save heads for every stress period so that a simulated hydrograph can be created.

PRE EXEC - This batch file accesses numerous pertinent data files, executes several Fortran programs including KVKH3D, MULT, VCONT, and WFRDG, and assigns unit numbers to the files being generated.

PROJ EXEC - This batch file accesses numerous pertinent data files, executes the projected simulations, and assigns unit numbers to the files being generated.

PROJ FLUX0 - This data file is an edited version of the print out (LISTING) file for the base simulation. It includes flux terms in the final stress period for river, drain, and constant head cells and a cumulative water budget for the entire model.

PROJ FLUX1 - This data file is an edited version of the print out (LISTING) file for the constant head projected simulation when areal recharge equals 200% of the base simulation (Run 2). It includes flux terms in the final stress period for river, drain, and constant head cells and a cumulative water budget for the entire model.

PROJ FLUX2 - This data file is an edited version of the print out (LISTING) file for the constant head projected simulation when areal recharge equals 50% of the base simulation (Run 3). It includes flux terms in the final stress period for river, drain, and constant head cells and a cumulative water budget for the entire model.

PROJ FLUX3 - This data file is an edited version of the print out (LISTING) file for the constant flux projected simulation when areal recharge and canyon seepage are not varied (Run 6). It includes flux terms in the final stress period for river and drain cells and a cumulative water budget for the entire model.

PROJ FLUX4 - This data file is an edited version of the print out (LISTING) file for the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4). It includes flux terms in the final stress period for river, drain, and constant head cells and a cumulative water budget for the entire model.

PROJ FLUX5 - This data file is an edited version of the print out (LISTING) file for the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5).

It includes flux terms in the final stress period for river, drain, and constant head cells and a cumulative water budget for the entire model.

PROJ FLUX8 - This data file is an edited version of the print out (LISTING) file for the constant flux projected simulation when areal recharge equals 50% of the base simulation (Run 7). It includes flux terms in the final stress period for river and drain cells and a cumulative water budget for the entire model.

PROJ FLUX9 - This data file is an edited version of the print out (LISTING) file for the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8). It includes flux terms in the final stress period for river and drain cells and a cumulative water budget for the entire model.

PROJ SUM - This data file lists a summary of simulated municipal pumping in Moscow and Pullman. The summary includes annual discharge from each cell simulated by pumping, a multiplication factor for an annual percentage increase in pumping, and a total pumpage flux for each stress period. The file is generated by the Fortran program PROJPUMP.

PROJPUMP EXEC - This batch file accesses the WELL SNAKE and PUMP 8185 files, executes the Fortran program PROJPUMP, and assigns unit numbers to the generated files WELL PROJ AND PROJ SUM.

PROJPUMP FORTRAN - This Fortran program combines the discharge from the seepage face of the Snake River Canyon (WELL SNAKE) with annual municipal pumpage in Moscow and Pullman at the average rate between 1981-85 (PUMP 8185). Well fluxes for each stress period are generated (WELL PROJ), depending on the specified annual rate of pumpage increase. The discharge represented by WELL SNAKE remains constant and is used in each stress period.

PROJPUMP TEXT - This text file is the compiled executable code for the PROJPUMP FORTRAN source file.

PUMP HIST - This data file lists a history of well pumpage in Moscow and Pullman from 1890 to 1985. The information is used to create the well file for the history match simulation.

PUMP 8185 - This data file specifies the 5 year average annual pumping rate for each cell simulated by municipal pumping in Moscow and Pullman and a multiplication factor for annual percentage increases in pumping rates. It is accessed by the Fortran program PROJPUMP to generate a well file for projected simulations.

RECHARGE 1 - This is the recharge file for pre-development conditions. It is used in a formatted steady-state simulation, which solves the system in pre-development conditions, and in the history match simulation. A thorough description of the recharge package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 7-1).

RECHARGE 2 - This is the recharge file for current land use and farming conditions. It is used in time-averaged and projected simulations.

RIVERS DAT - This is the river file for all of the simulations. The river package simulates discharge to and from streams and rivers. This file is generated by the Fortran program WFRDG under the name of OUT RIV. The file is edited to include the maximum number of river cells active at one time and repeat codes for multiple stress periods in transient simulations. The file is renamed RIVERS DAT. A complete description of the river package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 6-1).

SIP DAT - This file is the strongly implicit procedure package, which is the method used in the Pullman-Moscow model for solving the linear equations which describe the flow system. The equations are solved simultaneously by iteration. A discussion of the SIP package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 12-1).

SSFMT EXEC - This batch file accesses numerous pertinent data files, executes the pre-development, steady-state simulation, and assigns unit numbers to the files being generated.

TA EXEC - This batch file accesses numerous pertinent data files, executes the time-averaged simulations, and assigns unit numbers to the files being generated.

THKGR DAT - This data file lists the thicknesses of the Grande Ronde layer. It is accessed by the Fortran program MULT, which generates transmissivity values for the Grande Ronde.

THKWA DAT - This data file lists the thicknesses of the Wanapum layer. It is accessed by the Fortran program MULT, which generates transmissivity values for the Wanapum.

TRANS2 DAT - This data file specifies the transmissivities of the Wanapum layer. The file is generated by the Fortran program MULT.

TRANS3 DAT - This data file specifies the transmissivities of the Grande Ronde layer. The file is generated by the Fortran program MULT.

VCONT DAT - This data file lists the vertical conductance from the Palouse Loess to the Wanapum and from the Wanapum to the Grande Ronde. The file is generated by the Fortran program VCONT.

VCONT FORTRAN - This Fortran program calculates the vertical conductance from the Palouse Loess to the Wanapum and from the Wanapum to the Grande Ronde. A discussion of vertical conductance formulation can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 5-11). The batch file which executes this Fortran program is PRE EXEC.

VCONT TEXT - This text file is the compiled executable code for the VCONT FORTRAN source file.

WACENT DAT - This data file specifies the center elevation for each cell in the Wanapum layer. It is used in the generation of the RIVERS DAT AND DRAINS DAT files by the Fortran program WFRDG.

WANKH DAT - This data file lists the horizontal hydraulic conductivities of cells in the Wanapum layer. The file is generated by the Fortran program KVKH3D, and is accessed by the Fortran programs MULT, VCONT, and WFRDG.

WANKV DAT - This data file lists the vertical hydraulic conductivities of cells in the Wanapum layer. The file is generated by the Fortran program KVKH3D, and is accessed by the Fortran programs MULT, VCONT, and WFRDG.

WELL HM - This is the well file for the history match simulation. In addition to listing fluxes for cells where municipal pumping is simulated, this well file specifies a flux for cells that simulate seepage discharge from the face of the Snake River Canyon (WELL SNAKE). A discussion of the WELL package can be found in the MODFLOW documentation (McDonald and Harbaugh, 1988, p. 8-1).

WELL PROJ012 - This is the well file for the constant head projected simulations including the base simulation and the two simulations when areal recharge is varied (Runs 2 and 3). In addition to listing fluxes for cells where municipal pumping is simulated, this well file specifies a flux for cells that simulate seepage discharge from the face of the Snake River Canyon (WELL SNAKE).

WELL PROJ38 - This is the well file for the constant flux projected simulations when no other parameter variations are made (Run 6) and when areal recharge equals 50% of the base simulation (Run 7). The flux rates to and from constant flux boundary cells in these simulations are specified in this well file. In addition, municipal pumpage and canyon seepage fluxes are included.

WELL PROJ4 - This is the well file for the constant head projected simulation when canyon seepage equals 200% of the base simulation (Run 4). Both municipal pumpage and canyon seepage (WELL SNAKE) are specified in this well file.

WELL PROJ5 - This is the well file for the constant head projected simulation when canyon seepage equals 50% of the base simulation (Run 5). Both municipal pumpage and canyon seepage (WELL SNAKE) are specified in this well file.

WELL PROJ9 - This is the well file for the constant flux projected simulation when canyon seepage equals 200% of the base simulation (Run 8). The flux rates to and from constant flux boundary cells are specified in this well file. In addition, municipal pumpage and canyon seepage fluxes are included.

WELL SNAKE - This well file specifies the fluxes from cells that simulate seepage discharge from the face of the Snake River Canyon. The file is generated by the Fortran program WFRDG.

WELL SS - This is the well file for the formatted steady-state simulation which solves the system in pre-development conditions. Both municipal pumpage and canyon seepage fluxes are specified in this file.

WELL TA - This is the generic well file for time-averaged simulations. The contents of the file vary depending on the parameter attributes that are simulated. Both municipal pumpage and canyon seepage fluxes are specified. When constant flux boundary conditions are simulated, those flux rates are also included in this file.

WELLSUM RD - This data file summarizes the total flux from cells in the Wanapum and Grande layers that simulate seepage from the face of the Snake River Canyon. The flux summary applies to the base simulation and all of the other projected simulations when canyon seepage is not varied. The file is generated by the Fortran program WFRDG.

WELLSUM RD4 - This data file summarizes the total flux from cells in the Wanapum and Grande layers that simulate seepage from the face of the Snake River Canyon. The flux summary applies to the projected simulations when canyon seepage equals 200% of the base simulation. The file is generated by the Fortran program WFRDG.

WELLSUM RD5 - This data file summarizes the total flux from cells in the Wanapum and Grande layers that simulate seepage from the face of the Snake River Canyon. The flux summary applies to the projected simulation when canyon seepage equals 50% of the base simulation. The file is generated by the

Fortran program WFRDG.

WFRDG FORTRAN - This Fortran program generates the RIVERS DAT, DRAINS DAT, and WELL SNAKE files. The batch file which executes the program is PRE EXEC.

WFRDG TEXT - This text file is the compiled executable code for the WFRDG FORTRAN source file.