Research Technical Completion Report

EVALUATION AND MODIFICATION OF THE PULLMAN-MOSCOW GROUND-WATER FLOW MODEL

by

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ABSTRACT

A ground-water flow model was cooperatively developed by the U.S. Geological Survey and the University of Idaho in the 1980's to predict the impact of future ground-water withdrawals on aquifer water levels in the Pullman-Moscow area. This three-dimensional model was transferred from the University of Idaho mainframe computer to personal computer compatible files. These original files are retained for time-averaged, history-match and predictive simulations.

The Pullman-Moscow ground-water flow model includes several assumptions which are difficult to support with the current level of information. Probably the greatest concern is the uncertainty of recharge and discharge to the deepest model layer in the Grande Ronde basalt. Most recharge to and discharge from this layer can not be directly measured. Evidence suggests, however, that discharge along the Snake River canyon has been overestimated. Over-estimation of this discharge would have adversely affected model calibration.

A five-layer revision of the model was developed that subdivided the aquifer in the Grande Ronde basalt into three layers. The revised model was not re-calibrated due to inadequate information on aquifer water levels and characteristics.

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BACKGROUND

Water-level declines in deep wells in the Pullman-Moscow area have raised concerns about future water supplies in the basin. Municipal and university pumping from the aquifer in the Grande Ronde basalt formation has been growing since the 1980's and demand is likely to continue to increase. The increased withdrawals from this aquifer have resulted in water-level declines in some of the production wells of nearly 20 feet since 1980.

Concern of the local communities has resulted in the formation of the Pullman-Moscow Water Resources Committee. The committee includes representatives of Washington State University; the University of Idaho; the cities of Pullman, Washington, and Moscow, Idaho; and Whitman County, Washington; and Latah County, Idaho. In 1992, the Committee passed a Ground Water Management Plan which outlines community measures for managing their ground-water resources. The Committee also contributes to research efforts to better understand the area's water resources. One of the research projects supported by the Committee was a ground-water flow model cooperatively developed by the University of Idaho and the U.S. Geological Survey (Smoot, 1987; Lum and others, 1990)

The ground-water flow model was developed with the dual purpose of 1) improving the understanding of the ground-water flow system, and 2) predicting impacts of future water use scenarios on ground-water levels (Lum and others, 1990). The reliability of model predictions depends upon the accuracy of the conceptual model and aquifer properties used in the numerical model. The continual evolution of ground-water flow model, using updated information, provides a process for better understanding the Pullman-Moscow aquifer system.

PURPOSE AND OBJECTIVES

The purpose of this study was to:

1) Convert the Pullman-Moscow ground-water flow model to a more readily usable form on a personal computer,

2) Understand and clearly convey uncertainties in the existing Pullman-Moscow ground-water flow model, and

3) Modify the model to represent the Grande Ronde Basalt with multiple layers.

The specific objectives of the project included:

1) Identify and test a personal computer version of the MODFLOW code (McDonald and Harbaugh, 1988) and ensure that the needs of the expanding Pullman-Moscow model can be met on a personal computer;

2) Transfer the Pullman-Moscow data sets from the University of Idaho mainframe computer to a personal computer system;

3) Modify data inputs of Lum and others (1990) to be compatible with the personal computer based code;

4) Organize, document, and store all data files on 3.5 inch floppy disks;

5) Qualitatively evaluate the conceptual and numerical model used by Lum and others (1990) to predict future water level trends;

6) Subdivide the Grande Ronde formation into multiple model layers on a geologic basis;

7) Simulate response of the aquifer to the history-match simulation of Lum and others (1990) and to a multi-layer representation of the Grande Ronde Basalt; and

8) Document all activities and results and provide recommendations for future research.

DESCRIPTION OF MODEL CONSTRUCTION

Introduction

This section provides a brief review of the ground-water flow model of the Pullman-Moscow area developed by Lum and others (1990). The basic features of the model are described, and changes needed to adapt to a personal computer version of MODFLOW.

Original Model Features

The Pullman-Moscow ground-water flow model, documented by Lum and others (1990) and Smoot and Ralston (1987), simulated ground-water flow in three layers in an area of about 750 square miles of western Idaho and eastern Washington (figure 1). The three layers, from top to bottom, represented the geologic units of the Palouse loess, the Wanapum basalt, and the Grande Ronde basalt. An idealized geologic cross-section is shown in figure 2.

The vast majority of ground-water recharge comes from precipitation on the rolling hills of the Palouse loess. A downward hydraulic gradient provides recharge to aquifers in the deeper Wanapum and Grande Ronde systems. Each of the model layers discharges as seepage to streams and rivers and along the face of the Snake River canyon near the southwest boundary of the model area. Approximate recharge and discharge features of each model layer are presented in the schematic of figure 3.

Initial estimates of aquifer horizontal and vertical hydraulic conductivity and storativity were calibrated by Lum and others (1990) in a trial and error process. The model was calibrated in an iterative process cycling between cross-section, time-averaged (steady-state), and history-match conditions. The time-averaged simulations were based on the 1974 to 1985 period and the history match on the period from 1890 to 1985. Calibrated aquifer properties were then used in predictive scenarios spanning the period from 1985 to 2005.

Model Code and Data Files

The work of Smoot and Ralston (1987), Lum and others (1990), and Brown (1991) were conducted with a mainframe version of the U.S. Geological Survey MODFLOW model (McDonald and Harbaugh, 1988). Subsequently, powerful personal computer versions of the code have become available. Simulation on personal computers is more convenient, efficient, economical, and transportable among researchers. Therefore, data sets have been converted to a form compatible with a personal computer version of MODFLOW, MODFLOW EM (Scientific Software Inc.).

Some manipulation and renaming of the input data files was necessary for compatibility with the selected personal computer based version of MODFLOW. File names and changes from the mainframe version are described in Appendices A and B. The implemented changes were required for operation of MODFLOW EM, but would not be necessary with some other personal computer versions of the model. The resulting three-layer data sets should be usable with any version of MODFLOW utilizing extended memory.

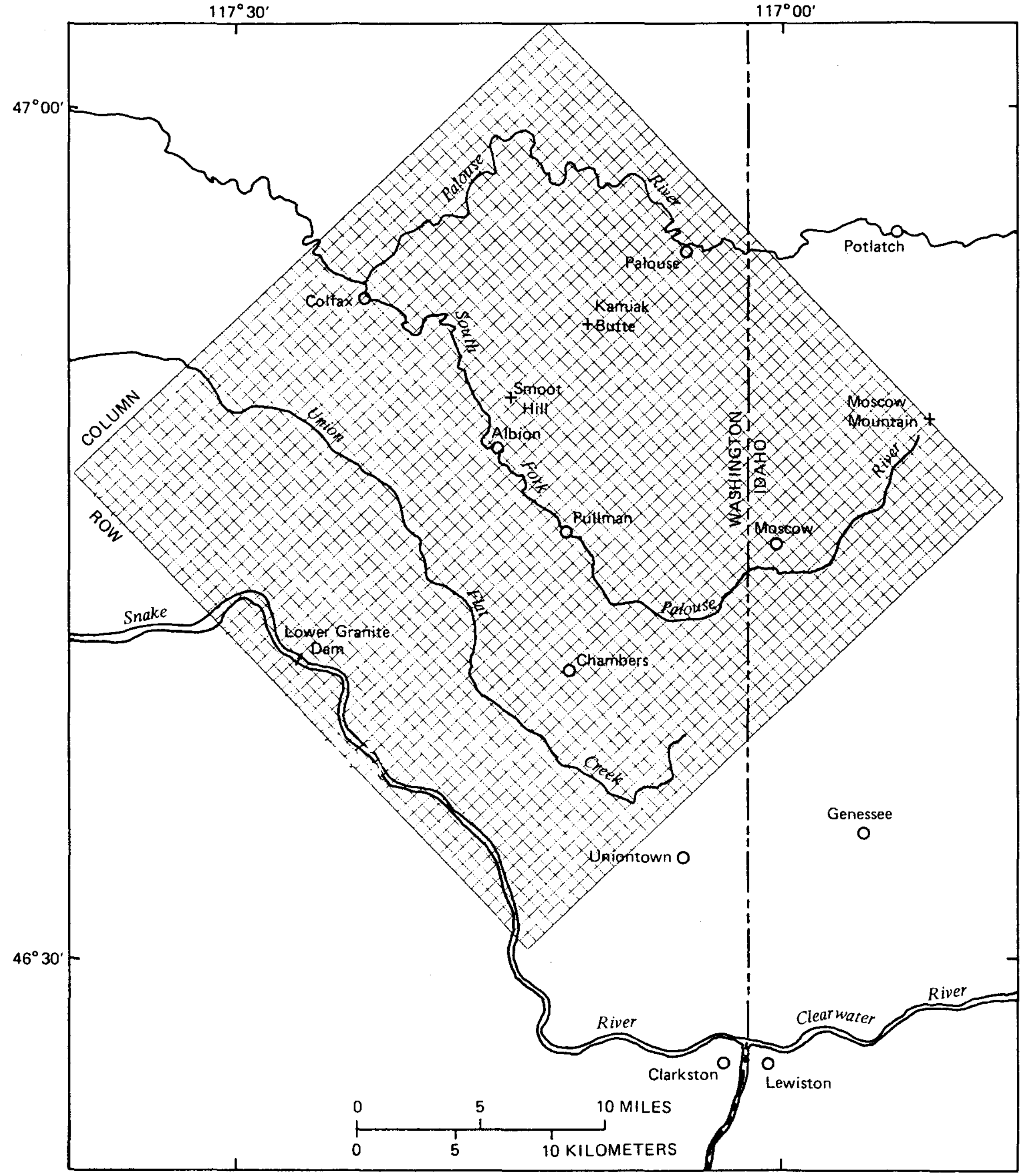

Figure 1. Map showing location and extent of model area (from Lum and others, 1990).

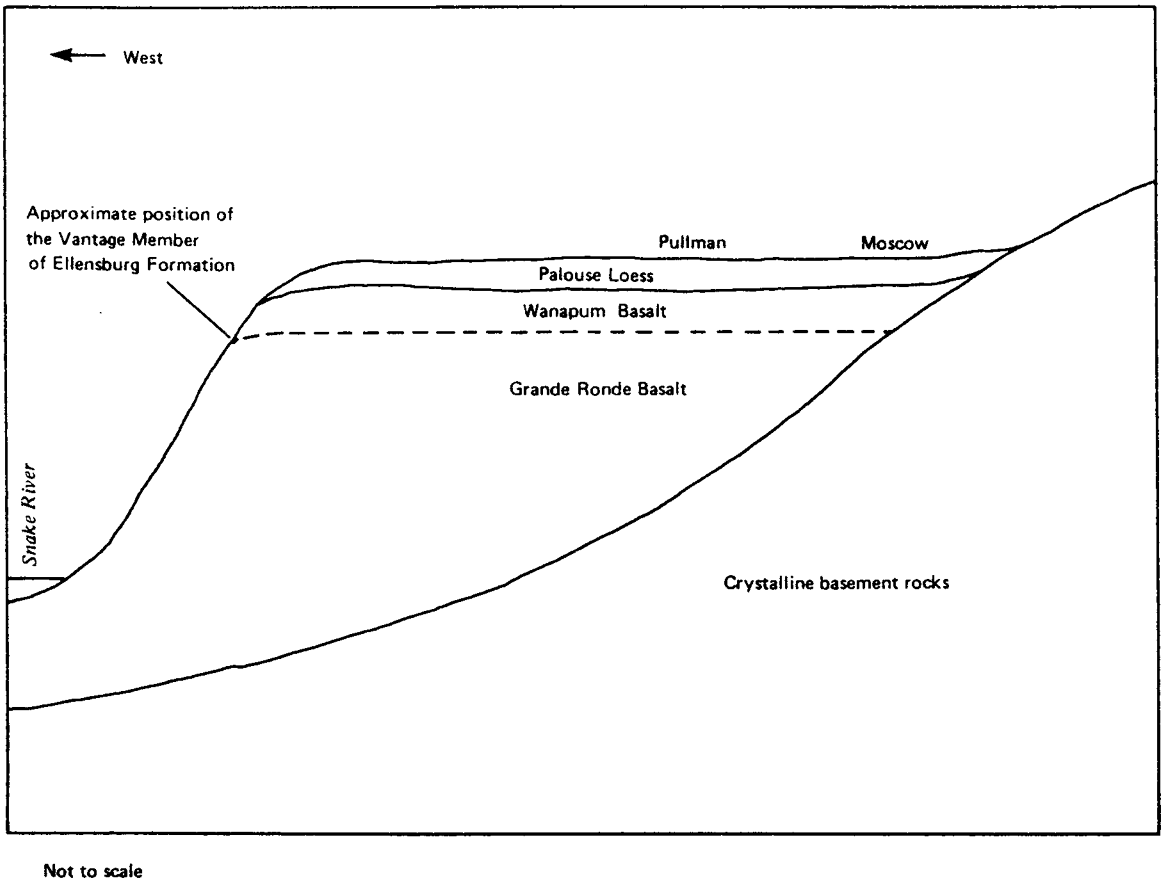

Figure 2. Idealized geologic cross section through the modeled area (from Lum and others, 1990).

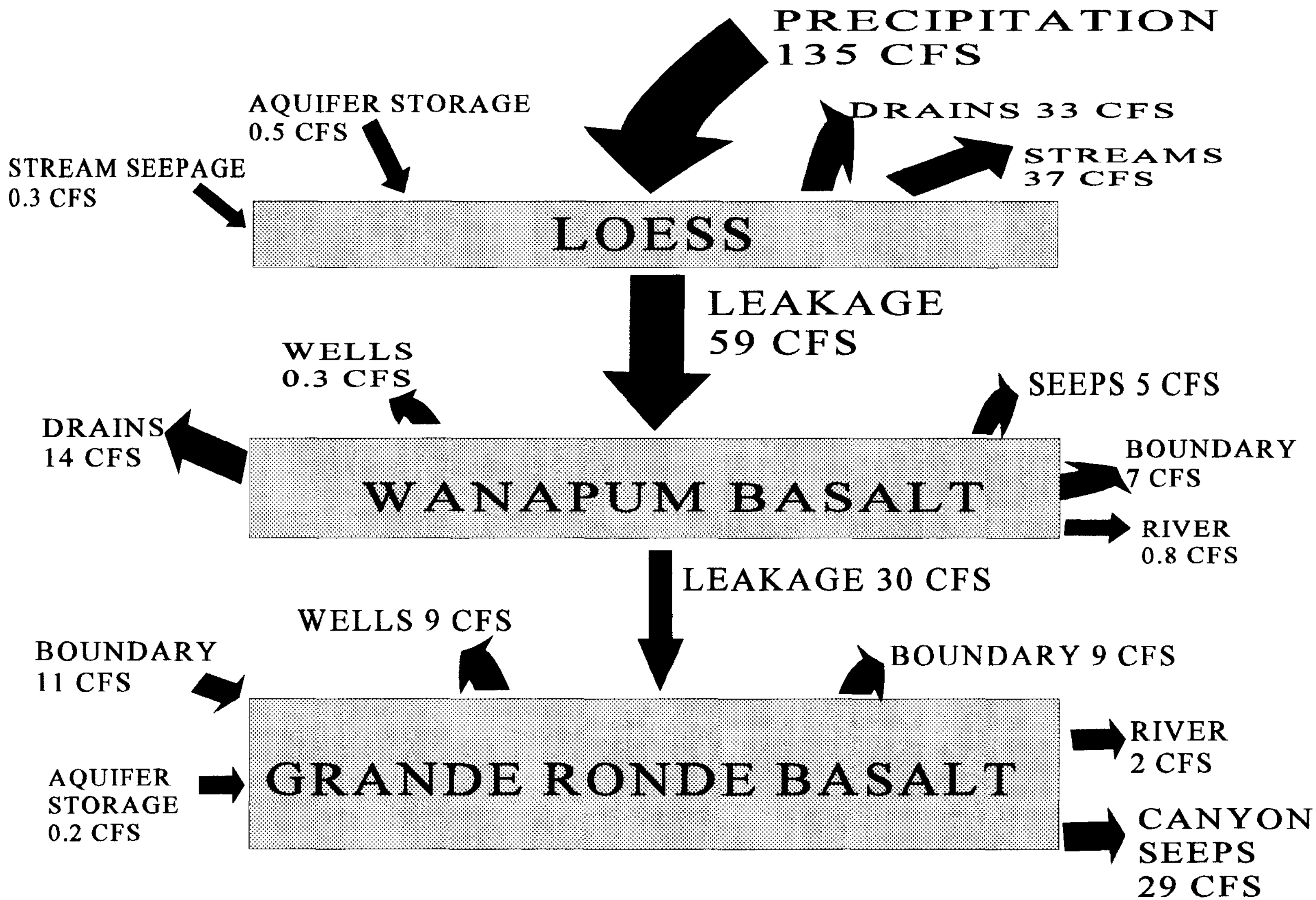

Figure 3. Schematic of recharge and discharge to each layer of the model by Lum and others (1990).

MODEL EVALUATION

Introduction

This section provides an evaluation of previous Pullman-Moscow ground-water modeling efforts. The evaluation includes a discussion of model construction, factors affecting model predictions, model assumptions and uncertainty, and model reliability. This discussion provides a basis for model refinements performed as part of this project.

Model Purpose and Construction

Ground-water flow models may be designed for investigation of the nature and properties of the flow system (investigative models), for the purpose of prediction of future water levels (predicative models), or both. The construction of a model is partially determined by the purpose for which the model is to be used. This section describes how model purpose relates to model construction.

Aquifer boundaries and the interaction with surface-water sources may be broadly classified as either 1) aquifer head dependent, or 2) independent of aquifer head. The head-dependent classification represents situations where a river and aquifer are hydraulically interconnected. Simulation of head-dependent flux requires an understanding and mathematical representation of the mechanisms controlling the interchange between surface water and ground water. In this case, the flux varies with aquifer water levels. In contrast, non-head dependent flux is pre-determined by the modeler and is independent of the simulated water level in the aquifer. An irrigation well is a typical example of this second group. Simulation of a flux which is independent of aquifer head requires that the magnitude of the flux be estimated or measured, but does not require knowledge or model representation of the mechanism. These distinctions are important because in some model applications, including the Pullman-Moscow basin, head-dependent boundaries may intentionally be altered and represented as a fixed flux to simplify simulation conditions or to decrease non-uniqueness problems in parameter identification (e.g. model calibration). This simplification is acceptable (and often desirable) in investigative models, but may lead to errors when applied in predictive simulations.

Non-predictive ground-water flow models may use a fixed-flux (non-head dependent) mechanism as a surrogate representation of aquifer recharge and discharge for situations where the flux indeed varies with aquifer head. Direct input of known values of flux between surface water and ground water avoids the complication of trying to match simulated surface water and ground water flux with measured values. Consequently, the procedure increases the efficiency of the effort and decreases the potential for non-uniqueness in estimation of aquifer properties. This distortion of the actual mechanisms controlling flow, however, may have a detrimental impact if applied in a predictive model. Because these artificial fixed flux situations do not respond to variations in aquifer stress, they may cause an exaggerated response to any simulated stress.

The predictive model used by Lum and others (1990) utilized a fixed flux representation of spring discharge from the wall of the Snake River canyon for the layer representing the Grande Ronde basalt. This representation aided model calibration and was carried over to the predictive model. This surrogate representation will exaggerate impacts of simulated stress, however, the magnitude of the impact is unknown.

Factors Affecting Prediction

It is important to understand the factors influencing model predictions to properly design a model and determine the model's reliability. The Pullman-Moscow model has been developed primarily to predict drawdown in the Grande Ronde aquifer from large production wells located in the cities of Pullman and Moscow. This section discusses the physical conditions and model properties which most strongly affect those predictions.

Brown (1991) conducted a sensitivity analysis of the model developed by Lum and others (1990). He examined the sensitivity of model predictions to the magnitude of areal recharge, seepage discharge from the face of the Snake River canyon, and certain boundary conditions. He concluded that model predictions are relatively insensitive to variations in any of these conditions, but also indicates that this may be misleading, and a result of model construction.

The sensitivity analysis of Brown (1991) was not intended to be a comprehensive analysis of all model features and properties affecting prediction. The analysis did not include the full array of potentially significant characteristics, such as aquifer transmissivity and storativity, nor inter-aquifer leakance properties. Although Brown (1991) examined the sensitivity of the model to variations in canyon seepage, he did not evaluate the potentially more significant impact that uncertainty of canyon seepage may have on the calibration of aquifer properties.

There are multiple aquifer properties and conditions that control the magnitude of drawdown experienced by the production wells in Pullman and Moscow. These properties and conditions include:

1) The cumulative and individual discharge from production wells, primarily those completed in the Grande Ronde;

2) aquifer transmissivity and storativity, primarily of the layer representing the Grande Ronde basalt;

3) vertical hydraulic conductivity, primarily of units hydrologically separating the Grande Ronde from the aquifer in the Wanapum basalt (leakance);

4) the distance to and type of aquifer boundaries;

5) the existence and location of head-dependent aquifer recharge and discharge.

These conditions will predominantly control drawdown in the Grande Ronde basalt unless major stresses are imposed on the system resulting in conversion of aquifers from confined to unconfined, drying up of springs, or similar change in system operation.

Cumulative and individual discharge of the production wells completed in the Grande Ronde have a definite effect on the drawdown experienced. The long-term drawdown in the Grande Ronde aquifer will be proportional to the cumulative discharge of the production wells, provided that:

1) major discharge and recharge sources are not completely dried up,

2) confined aquifers do not become unconfined, and

3) no other significant changes in recharge or discharge are occurring in the basin.

Approximate proportionality was demonstrated by predictive simulations of Lum and others (1990, figure 26). Long-term drawdowns for the scenario representing a 100 percent increase in the 1981 to 1985 pumping rate (200% of base rate) were approximately four times greater than the drawdown determined for the scenario representing a 25 percent increase in pumping rate (125% of base rate), relative to the water levels simulated for continuation of the 100 percent scenario. Because of the demonstrated proportionality, it is likely that superposition principles may be legitimately applied to enhance understanding of system response to stresses.

Transmissivity and storativity of the Grande Ronde formation impact the short-term and long-term aquifer response. Transmissivity and storativity of overlying aquifers in the Wanapum basalt and loess also affect response of the Grande Ronde to pumping, but to a lesser degree.

The magnitude of recharge to the aquifer in the Grande Ronde basalt is strongly affected by vertical hydraulic conductivity and thickness of aquifers and confining layers, primarily those within or immediately above the Grande Ronde basalt. These properties that control vertical water movement are possibly the major controls on long-term drawdowns in the Grande Ronde basalt.

Aquifer boundaries will impact the long-term aquifer response to pumping near the cities of Pullman and Moscow. The importance of boundary conditions was investigated by Brown (1991). He found that boundary effects resulted in 2 to 6 feet of drawdown at Pullman and Moscow, or about 20% of the total drawdown. Brown (1991), however, described only the impact of boundaries which were originally specified as constant head by Lum and others (1990). The affect of all aquifer boundaries, including no-flow boundaries, on drawdown at Pullman and Moscow is probably greater than that implied by Brown (1991).

Aquifer interconnection with surface-water sources also affects drawdown. In the Pullman-Moscow model the surface-water interconnection with the aquifer in the Grande Ronde is limited to cells representing the Snake River, a portion of the Palouse river, and small streams incised into the wall of the Snake River canyon. The modeled interconnection of these surface-water sources stabilizes simulated aquifer water levels and reduces aquifer drawdowns. The significance of these surface water sources on simulated drawdowns near Pullman and Moscow is affected by the distance to the water bodies, and the estimated degree of interconnection with the aquifer (modeled as river conductance). There is relatively large uncertainty in the estimates of river conductance creating the potential for significant error. The generally large distance between the pumping centers and surface-water bodies (connected with the Grande Ronde) however, minimizes the impact on predicted drawdowns near Pullman and Moscow.

The above list of factors is composed of physical aquifer properties. An important distinction is that this list does not include aquifer recharge and discharge, except that associated with head-dependent sources and the production wells in the Grande Ronde. Recharge, discharge, and flow through the aquifer system provide the basis for calibrating aquifer properties, but otherwise do not impact drawdown. For example, a reduced vertical leakage rate between aquifer layers affects drawdown from the production wells because it implies a lesser hydraulic conductivity between the units. It is not the flow rates, but the aquifer properties that are of significance. This partially explains why Brown (1991) saw little sensitivity of aquifer response to changes in recharge and discharge. Those changes were not accompanied by recalibration of aquifer properties.

In summary, predictions of drawdown from the pumping wells in Pullman and Moscow are affected by the physical properties and boundaries of the aquifer system and the discharge rates of the production wells. Many of these properties are uncertain because of the limited number of wells penetrating the Grande Ronde basalt and the uncertainty of the magnitude of recharge and discharge of this unit.

Existing Model Assumptions and Uncertainties

Lum and others (1990) recognized that the developed model relied on several assumptions as compensation for lack of information about the real system. Those assumptions were applied in the development of the conceptual model and in the creation of input data representing aquifer recharge and discharge and aquifer properties. Subsequent evaluation of the assumptions coupled with new data provides the opportunity for model improvement.

The existing model of Lum and others (1990) incorporates the following assumptions and uncertainties:

1) Canyon Seepage.

Estimates of seepage along the Snake River Canyon are not based on measured values. Lum and others (1990) recognized the importance of this estimate and recommended further research. The unpublished research of Maggi (1993) and visual reconnaissance indicate that Lum and others (1990) may have overestimated canyon seepage. The overestimation is highly significant with respect to model reliability. It indicates that either the conceptual model is incorrect, or transmissivity of the Grande Ronde and leakance between the Wanapum and Grande Ronde are overestimated. Either case has a significant impact on the reliability of model predictions, and is likely to contribute to model underestimation of drawdown at Pullman and Moscow.

A second problem associated with canyon seepage was the inability to model the estimated seepage with head-dependent functions in the model (drains). The surrogate seepage mechanism was a fixed-flux discharge utilizing MODFLOW's well package. The simulated fixed flux discharge is not affected by future drawdown of the production wells in Pullman and Moscow, and therefore contributes to overestimation of long-term drawdown.

2) Snake River Interconnection With Aquifer

The hydraulic interconnection of the Snake River with the aquifer in the Grande Ronde is largely unknown. It is not possible to directly measure flow between the aquifer and river. Several wells near the river show rapid response to changes in the level of Lower Granite Reservoir, indicating a hydraulic connection. The uncertainty of the magnitude of this discharge source contributes to the uncertainty of model calibration of aquifer transmissivity and leakage parameters.

3) Surrogate Representation of Aquifer Boundaries.

Surrogate aquifer boundaries are sometimes established to keep model areas to a workable scale. These boundaries do not necessarily portray a realistic representation of the real system. The Pullman-Moscow model has utilized surrogate boundaries as follows:

a) A no-flow boundary was simulated beneath the Snake River. The basalts are continuous beneath the river and no physical boundary exists. This assumption was applied to create a model of workable dimensions, but may result in overestimation of drawdown in the aquifer in the Grande Ronde, depending upon the duration of the time period being simulated.

b) A fixed-head boundary on the west edge of the study area was introduced to limit the model extent. This artificial boundary will result in underestimation of predicted drawdowns. Brown (1991) determined that this boundary condition impacts twenty-year predictions of drawdown by several feet.

c) An artificial no-flow boundary was simulated along the Palouse River on the north edge of the study area. This boundary will result in overestimation of drawdown in long-term predictions. The magnitude of the error is dependent on the time period of the prediction. The effects on the 20-year predictions of Lum and others (1990) were not evaluated.

4) Model Layering.

The Grande Ronde formation is simulated as a single layer. The potential flaw of a single-layer concept was recognized by Lum and others (1990) as a possible reason that canyon seepage could not be adequately simulated and as a potential source of discrepancy between simulated and measured water levels in production wells in the Grande Ronde.

5) Limited Calibration Information.

The calibration of aquifer transmissivity, storativity, and leakage parameters is based on knowledge of aquifer recharge and discharge, and spatial and temporal changes in aquifer water level. Uncertainties in recharge and discharge have been previously discussed. Areal distribution of aquifer water levels is also largely unknown because of the sparse network of wells completed in the Grande Ronde. Model calibration was based on changes in only a few wells that penetrate into the Grande Ronde. There is still little or no improvement in the level of knowledge of water levels in the Grande Ronde outside of the production wells of the cities of Pullman and Moscow and the universities.

Model Reliability

A numerical ground-water model is never a perfect representation of the real system. Our concepts of the mechanisms governing flow in the aquifer are always flawed to some degree, and our estimation of aquifer parameters, recharge and discharge are only approximate. The intention of model calibration is to use the more certain knowledge of some aquifer conditions, commonly recharge, discharge, and water levels, to refine estimates of properties known with less certainty, such as aquifer storativity and transmissivity. The model represents the best estimate of the system characteristics at a point in time, and should evolve as more information becomes available.

Concerns exist about the predictive accuracy of the Pullman-Moscow ground-water flow model. The greatest concern probably results from possible overestimation of aquifer discharge to the Snake River Canyon. Seepage along the canyon wall represents the primary simulated discharge source from the Grande Ronde (figure 3). If this discharge component has been overestimated, then calibrated aquifer properties or flow system concepts are also in error. The result may be an underestimation of the long-term drawdown in Pullman and Moscow.

Lack of information on the properties of the aquifer in the Grande Ronde basalt has required previous investigators to make numerous assumptions and simplifications. These assumptions and simplifications impact the accuracy of model predictions. Some errors introduced by assumptions may be partially offsetting, but the degree to which this occurs is unknown. More information on water levels and flow in the Grande Ronde basalt is needed to improve accuracy of predictions.

MODEL LAYER REFINEMENT

Introduction

This section provides a description of model refinements made in an effort to improve the predictive capability of the Pullman-Moscow ground-water flow model. The refinements focus on representing the Grande Ronde basalt as three layers in the numerical model.

Background

The Pullman-Moscow area is underlain by three basic geologic layers: The surficial loess deposits, the Wanapum Basalt, and the Grande Ronde Basalt. The Wanapum and Grande Ronde basalts are, themselves, composed of numerous individual basalt flows. It is not known what impact these layered flows have on vertical and lateral ground-water flow through the system. The three-layer model by Lum and others (1990) accounted for potential impedance to vertical ground-water flow between the major geologic layers (e.g. loess, Wanapum Basalt, and Grande Ronde Basalt), but did not account for vertical flow within these units. The model assumed that no vertical head gradient existed within the three individual units. This is equivalent to the assumption of an infinite vertical hydraulic conductivity within each layer. Lum and others (1990, p. 27) made this assumption because:

> "First, a mappable logical division (a 'marker' bed or single basalt flow) could not be found in the Grande Ronde Basalt; second, data indicate that in the Pullman and Moscow area the

basalt probably acts as one hydrologic unit."

Some problems, however, resulted from the use of a three-layer model.

Probably the most significant problem was the inability to properly simulate the springs and seeps along the Snake River canyon in the Grande Ronde Basalt. Ideally, springs should be simulated as aquifer head-dependent discharges which dry-up, or become non-functional when the aquifer water level drops below the elevation of the springs (drain package). This was not possible in the model developed by Lum and others (1990, p. 37) because:

> "The great thickness of the Grande Ronde geohydrologic unit did not allow gradient-dependent fluxes to be represented adequately, because in some cases the model calculated head for those cells was below the bottom of the canyon and the drains were inoperative."

Consequently, constant flux (wells) was used as a surrogate for drains in the model. Lum and others (1990) also noted that representation of the Grande Ronde as a single layer made it difficult to compare model results with field data. Presumably, the authors were referring to comparing water levels in wells completed at different depths in the Grande Ronde.

The previously mentioned inadequacies of the three-layer model stimulated interest in modifying the model to include multiple layers in the Grande Ronde. Unfortunately, few additional data have been collected which provide information on vertical variations in the hydraulic characteristics of the Grande Ronde.

Subdivision of the Grande Ronde into multiple model layers was done on the basis of general geologic knowledge.

Sublayering of the Grande Ronde formation in the ground-water model does not necessarily produce a ground-water flow model of improved reliability. This exploratory exercise does not utilize new information on the properties of the aquifers, recharge and discharge characteristics, nor aquifer head. The uncertainty in the calibration is perhaps increased due to the increase in the number of parameters calibrated. Increasing the complexity of the model does not, by itself, increase the reliability of the model.

The 5-layer model was developed in 2 stages to ensure that the impacts of individual changes were understood prior to compounding the effects by including multiple changes. The first stage was to develop a 5-layer model that would duplicate the results of the 3-layer model of Lum and others (1990). This resulted in what is described as the "equivalent 5-layer model" in which canyon seepage is still treated as a fixed flux. The second stage involved the conversion from a fixed-flux representation of canyon seepage to a variable flux, dependent on aquifer head. This step included 2 variations: a) elimination of all seepage from the Grande Ronde to the Snake River canyon (5-layer reduced seepage model), and b) adjusting drain conductance values to nearly match the estimated canyon seepage used by Lum and others (1990) (5-layer model with head-dependent canyon seepage). The first of these variations demonstrates the potential affect of uncertainty in the conceptual model on simulation results. The second simulation produces a model which can be used in subsequent investigations if a multi-layer representation of the Grande Ronde is desired.

Geologic Basis

The best geologic basis for selection of layers within the Grande Ronde was determined to be reversals in magnetic polarity that exist within the formation. The uppermost part of the Grande Ronde exposed at the Snake River canyon has a reversed magnetic polarity and is identified as magnetic reversal 2. A normal polarity is observed at intermediate depths in the Grande Ronde, and is referred to as magnetic normal 1. Reversed polarity is again found near the bottom of the Snake River canyon. It is estimated that at the Snake River canyon, the uppermost unit (magnetic reversal 2) is composed of 6 to 10 basalt flows and is 500 to 900 feet in thickness. The intermediate layer (magnetic normal 1) contains approximately 10 basalt flows and is about 800 feet thick. The lowest apparent unit is magnetic reversal 1 and is perhaps 600 feet in thickness and contains about 10 basalt flows (Hooper and others, 1985).

Equivalent Five-Layer Model

A five-layer model was developed that duplicated the results of the 3-layer history-match model of Lum and others (1990). Input data sets of the 3-layer model were altered to include a total of 5 layers. Model layers representing the loess and Wanapum Basalt were not changed. The Grande Ronde, however, was altered from a single model layer to include 3 layers. Development of this model was accomplished by:

1. Uniformly proportioning transmissivity among all three layers in the Grande Ronde. The total transmissivity of the Grande Ronde is therefore unchanged from that calibrated by Lum and others (1990). Transmissivity was proportioned equally among the layers because little information is available to warrant non-uniform distribution, and the model layers represent units of approximately equal thickness.
2. The storativity of each of the three layers representing the Grande Ronde was assumed to be equal to 1/3 the storativity estimated for the Grande Ronde by Lum and others (1990). The 3-layer model of Lum and others (1990) used a Grande Ronde storativity equal to a constant value of 0.001. The 5-layer model, therefore used storativity values of 0.000333 for each of the three layers within the Grande Ronde.
3. The vertical leakance between layers in the Grande Ronde was set to an arbitrarily high value of 0.1 (in units of 1/days). This value was determined to be sufficiently large to cause the entire thickness of the Grande Ronde formation to respond as a single aquifer.

No changes were necessary in any other input data. For this simulation, springs were represented as a constant-flux discharge (wells) as in the 3-layer model by Lum and others (1990). Boundary conditions and all recharge and discharge was unaltered from the 3-

layer model. Wells and drains in the Grande Ronde were all represented as occurring in layer 3, uppermost in the Grande Ronde. Vertical hydraulic conductivity within the Grande Ronde was sufficiently large that all three layers acted as a single layer.

Simulation results of the five-layer model closely matched those of the 3-layer history match simulation. The maximum head deviation between the two simulations was less than one foot at any node. The mass balance was satisfactory and is presented in Appendix C. Closure criteria was reduced by an order of magnitude (from 0.1 to 0.01) in the 5-layer simulation to achieve a satisfactory water balance of -0.27% discrepancy. Input files to the 5-layer simulation are saved on 3.5 inch diskette, on file with the Idaho Water Institute. File names are also listed in Appendix B.

Five-Layer Reduced Seepage Model

Actual seepage from the Grande Ronde layers in the Snake River canyon has not been accurately determined. This simulation was conducted to examine changes in aquifer water levels that would result from the extreme case in which no regional discharge from the Grande Ronde occurs as seepage in the Snake River canyon. Excessive differences in aquifer head between this scenario and the 3-layer history-match simulation would indicate that major adjustments in aquifer parameters would be required to calibrate to this conceptual model. The simulation was conducted using the

"Equivalent 5-layer Model", except that all seepage from the Grande Ronde layers to the Snake River canyon was eliminated. This amounted to an elimination of approximately 29 cfs of discharge from the Grande Ronde relative to the 3-layer history-match simulation. Simulation results indicate that aquifer head in the Grande Ronde increased dramatically over that resulting from the history-match simulation of Lum and others (1990). Head values at specific nodes increased by as much as 730 feet, with differences of over 100 feet common. The simulation produced head values 56 feet higher than those from the 3-layer history-match simulation at the node representing Pullman (row 34, column 27). At a node representing Moscow (row 43, column 39), the simulated head was 45 feet higher at the end of the history-match simulation relative to the simulation of Lum and others (1990).

The dramatic and unrealistic increases in head indicates an incompatibility between the conceptual model and aquifer properties used in this case. The following alternative scenarios are possible:

1) Canyon seepage from the Grande Ronde is significant, and perhaps as large as the values suggested by Lum and others (1990).

2) Canyon seepage is not as large as estimated by Lum, but the impacts of this error are offset by underestimation of the discharge directly into the Snake River.

3) Ground-water flow in the Grande Ronde to the Snake River canyon is impeded by low permeability materials somewhere

between the canyon and the cities of Pullman and Moscow.

It is not possible to determine which of these alternatives most closely represents the real system with our current level of knowledge.

Five-Layer, Head-Dependent Seepage Model

This version of the Pullman-Moscow model is intended to serve as a starting point for future work involving a multi-layer representation of the Grande Ronde. Use of the 5-layer model for predictions is discouraged, however, until additional data collection can support calibration.

All changes specified for the "equivalent 5-layer model" were applied to this version, with the additional change that canyon seepage from the Grande Ronde (model layers 3, 4, and 5) was simulated as a head-dependent discharge. This change was implemented by removing all Grande Ronde fixed-flux discharge along the canyon (MODFLOW's well package) and re-activating drains that had been left inactive (conductance of 0) in the 3-layer model. Layers were assigned to each drain based on elevations tabulated in the original input data set. Drains that were indicated as being within the Grande Ronde, and with elevations greater than 1800 feet above sea level were assigned to layer 3. Those with elevations between 1100 and 1800 feet were assigned layer 4, and those below 1100 feet elevation were included in layer 5. Since little information is available on either the location or discharge of individual springs or seeps, no attempt at a refinement was made.

Hydraulic conductance of the drains, coupled with aquifer head and drain elevation, controls the amount of discharge from the individual drain. Hydraulic conductance was adjusted to achieve a total canyon discharge from the Grande Ronde that is comparable to that used in the original 3-layer history-match model. Again, no attempt was made to calibrate discharge of specific drains due to lack of field measured values. Vertical hydraulic conductivity (model leakance) was also left at an arbitrarily large value for layers within the Grande Ronde.

Simulation results indicate that the 5-layer model with head-dependent canyon discharge will reproduce approximately the same large-scale results as the original 3-layer history-match model. Canyon discharge (simulated as drains) from the Grande Ronde in the 5-layer model was within 0.5 percent of the corresponding well discharge of the 3-layer model, indicating an acceptable overall duplication of discharge. Simulated aquifer head varied between the simulations on a local scale along the Snake River canyon. Over most of the modeled area, however, simulated aquifer water levels exhibited little change. At some nodes near the Snake River canyon, the two sets of simulated heads differed by as much as 118 feet. Near Pullman and Moscow, the differences were less than 5 feet.

SUGGESTED DIRECTIONS FOR FUTURE INVESTIGATIONS

The following list of suggestions is intended to help focus future investigations on the specific properties and conditions that most strongly affect drawdown in the Grande Ronde and attempt to minimize the uncertainty in our knowledge of those factors.

1) In this model, as in many others, our computer and conceptual sophistication has exceeded our knowledge of properties of the real system. Excessively complicated models will often not increase the predictive accuracy, and may actually be less reliable. Future simulations should concentrate on improving knowledge of the system and not complexity of the model. It is recommended that the 3-layer model continue to be used and improved, rather than the 5-layer representation.

2) Concentrate efforts on those properties and conditions that are most important in affecting drawdown in the Grande Ronde. These include:

   a) vertical hydraulic conductivity between the Grande Ronde and Wanapum basalts,

   b) connection of the Grande Ronde basalt to surface water sources including any discharge from the wall of the Snake River canyon,

   c) transmissivity and storativity of the Grande Ronde Basalt, and

   d) lateral boundaries of the aquifer in the Grande Ronde.

Analytical aquifer testing techniques may provide valuable insights into the above properties.

3) Continue efforts to quantify system recharge and discharge. This information is normally our best base for calibrating the unknown aquifer properties identified in item #2. Relating physical and chemical characteristics of springs to those of specific aquifers may be helpful, as well as quantify and locating discharge points.

4) Continue to collect information on rates of water use and drawdown in municipal and university wells.

5) Improve the information on the areal distribution of water levels in the Grande Ronde. The potential for a low-permeability barrier between the cities of Pullman and Moscow and the Snake River canyon should also be investigated.

6) Apply superposition to further investigate sensitivity of model predictions to aquifer properties of vertical leakance, transmissivity, and storativity.

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APPENDIX A: INPUT FILE CONVERSION

Some data files from the mainframe version of the Pullman-Moscow model were not directly transferrable to MODFLOW-EM (Scientific Software Inc.), the selected personal computer version of MODFLOW. Input data sets for the time-averaged, history match, and predictive simulations were converted to the personal computer system. The following changes were implemented in mainframe data files for compatibility with the personal computer system. The names of the input data files are provided in Appendix B.

1) BASIC files (.BAS)
Unit numbers corresponding to specific input files are assigned in the BASIC file. The file numbers were changed for consistency with the code:

Data Set	Mainframe Unit	PC Unit Number
BASIC	20	11
WELL	80	12
DRAIN	61	13
RIVER	62	14
EVAPOTRANSPIRATION	00	00
GENERAL HEAD	00	00
RECHARGE	00	00
SIP	64	18
SSOR	00	00
OUTPUT CONTROL	65	22

In addition, values of zero were required to be entered in the IUNIT array in positions 13 and 14.

2) Boundary and Initial Head arrays
The mainframe version (and other personal computer versions) of MODFLOW allowed input of the boundary array (IBOUND) and starting head array (Shead) from a separate input file. MODFLOW EM only accepts starting head data in the BASIC file. Input starting head data from the Pullman-Moscow model were merged into the BASIC file for use with this version of MODFLOW. The data sets are all still of a manageable size for most computers and text editors.

3) BLOCK CENTERED FLOW files (.BCF)
MODFLOW EM does not allow entry of arrays of aquifer

properties (transmissivity and vertical leakance) from individual files as was done with the mainframe version. Transmissivity and vertical leakance were therefore integrated into the BLOCK CENTERED FLOW files for use with MODFLOW EM.

The above changes were implemented in the time-averaged, history-match, and predictive data sets. MODFLOW EM was run with each of the data sets and results were compared with printed outputs of mainframe runs conducted by Brown (1991). Some small differences in mass balance and resulting head distributions were determined. Table A2 compares mass balance results from the mainframe and MODFLOW EM simulations. Table A3 compares simulated heads at three model nodes approximately representing a location on the Snake River canyon, and the cities of Pullman and Moscow.

TABLE A1. MASS BALANCE COMPARISON:
MAINFRAME SIMULATIONS TO MODFLOW EM

TIME-AVERAGED SIMULATION

	MAINFRAME VERSION	MODFLOW EM
Cumulative volumes (cubic feet)		
Inflows:		
storage	0.0	0.0
constant head	0.11173E7	0.11228E7
wells	9429.0	9429.0
drains	0.0	0.0
recharge	0.11730E8	0.11731E8
river leakage	23735.0	28836.0
TOTAL IN	0.12886E8	0.12893E8
Outflows:		
storage	0.0	0.0
constant head	0.16535E7	0.16549E7
wells	0.37976E7	0.37976E7
drains	0.39984E7	0.39923E7
recharge	0.0	0.0
river leakage	0.34622E7	0.34574E7
TOTAL OUT	0.12912E8	0.12902E8

HISTORY MATCH SIMULATION

	MAINFRAME VERSION	MODFLOW EM
Cumulative volumes (cubic feet)		
Inflows:		
storage	0.39696E10	0.39755E10
constant head	0.34935E11	0.34984E11
wells	0.0	0.0
drains	0.0	0.0
recharge	0.45890E12	0.45895E12
river leakage	0.10875E10	0.10877E10
TOTAL IN	0.49890E12	0.49900E12
Outflows:		
storage	0.14123E10	0.14144E10
constant head	0.61103E11	0.61195E11
wells	0.11953E12	0.11953E12
drains	0.18115E12	0.18114E12
recharge	0.0	0.0
river leakage	0.13655E12	0.13654E12
TOTAL OUT	0.49975E12	0.49982E12

PREDICTIVE SIMULATION (1%/yr increase)

	MAINFRAME VERSION	MODFLOW EM
Inflows:		
storage	0.25525E9	0.37607E9
constant head	0.83524E10	0.83454E10
wells	0.0	0.0
drains	0.0	0.0
recharge	0.85632E11	0.85640E11
river leakage	0.22041E9	0.22054E9
TOTAL IN	0.94460E11	0.94582E11
Outflows:		
storage	30104.0	0.37862E8
constant head	0.12024E11	0.12025E11
wells	0.28733E11	0.28733E11
drains	0.28862E11	0.28923E11
recharge	0.0	0.0
river leakage	0.25016E11	0.25037E11
TOTAL OUT	0.94635E11	0.94755E11

Differences in the mass balances between the mainframe simulations and those using MODFLOW EM can be at least partially explained from known differences in input data sets. The balance compares reasonably well for the time-averaged and history match simulations. Differences may be the result of numerical error, rounding, and minor differences in input data sets. The predictive simulations, however, show a notable difference in the volume of water released or consumed by aquifer storage. This is most likely the result of the use of different starting heads in the two simulations. The MODFLOW EM simulation used starting heads which were output from the history-match simulations, as was done by Lum and others (1990). The predictive simulation from the mainframe was the result of work by Brown (1991) and used starting heads from a steady-state simulation.

A comparison was also made of simulated head values at the end of the simulation period for the time-averaged, history-match, and predictive simulations (Table A3). The comparison was made at nodes which represent the cities of Pullman (3,34,27) and Moscow (3,43,39), and at a node near the Snake River canyon (3,29,8). The results compare favorably for the history-match and predictive simulations. The time-averaged MODFLOW EM simulation however converged to a slightly different head distribution than the documented mainframe simulation. The reason for the difference is not known, but future runs of the time-averaged data should be done with caution.

TABLE A2. SIMULATED HEAD COMPARISON: MAINFRAME TO MODFLOW EM

Time-Averaged Simulation

			Simulated Head (end of simulation)	
Layer	Row	Column	Mainframe	MODFLOW EM
3	29	8	1498	1498
3	34	27	2245	2244
3	43	39	2277	2276

History-Match Simulation

			Simulated Head (end of simulation)	
Layer	Row	Column	Mainframe	MODFLOW EM
3	29	8	1499	1499
3	34	27	2241	2241
3	43	39	2277	2277

Predictive Simulation

			Simulated Head (end of simulation)	
Layer	Row	Column	Mainframe	MODFLOW EM
3	29	8	1492	1492
3	34	27	2220	2220
3	43	39	2255	2255

APPENDIX B: MODFLOW EM INPUT FILES

The following is a list of files used in the time-averaged, history match and predictive simulations that as nearly as possible duplicate the work of Lum and others (1990):

Table B1. Data Set Names.

MODFLOW PACKAGE	Time-Averaged	History-Match	Predictive
BASIC	TIMEAVG.BAS	HISTMAT.BAS	PROJ.BAS
BLOCK CENTERED	TIMEAVG.BCF	HISTMAT.BCF	PROJ.BCF
WELL	TIMEAVG.WEL	HISTMAT.WEL	PROJ.WEL
DRAIN	TIMEAVG.DRN	HISTMAT.DRN	PROJ.DRA
RIVER	TIMEAVG.RIV	HISTMAT.RIV	PROJ.RIV
RECHARGE	TIMEAVG.RCH	HISTMAT.RCH	PROJ.RCH
SIP	TIMEAVG.SIP	HISTMAT.SIP	PROJ.SIP
OUTPUT CONTROL	TIMEAVG.OPC	HISTMAT.OPC	PROJ.OPC

The data files for the predictive simulation represent the simulation of a 1 percent increase in pumping scenario.

Input data files used in the five-layer models are as follows:

Table B2. 5-Layer Model File Names

MODFLOW PACKAGE	Equiv. 5-Layer	No Canyon Seepage	Including Drains
BASIC	EQUIV5.BAS	NOSEEP.BAS	LAY5.BAS
BLOCK CENTERED	EQUIV5.BCF	NOSEEP.BCF	LAY5.BCF
WELL	EQUIV5.WEL	NOSEEP.WEL	LAY5.WEL
DRAIN	EQUIV5.DRN	NOSEEP.DRN	LAY5.DRA
RIVER	EQUIV5.RIV	NOSEEP.RIV	LAY5.RIV
RECHARGE	EQUIV5.RCH	NOSEEP.RCH	LAY5.RCH
SIP	EQUIV5.SIP	NOSEEP.SIP	LAY5.SIP
OUTPUT CONTROL	EQUIV5.OPC	NOSEEP.OPC	LAY5.OPC

APPENDIX C: FIVE-LAYER MODEL DESCRIPTION

The five-layer model includes identical layers for the loess and Wanapum basalt as the previous three-layer model, but the Grande Ronde basalt is represented by three layers instead of the single layer used by Lum and others (1990). The layers in the Grande Ronde were assigned based on a rough knowledge of magnetic reversals for different basalt flows within the Grande Ronde. The second magnetic reversal forms the uppermost Grande Ronde model layer. This layer is simulated as existing in the Grande Ronde above an elevation of 1800 feet above sea level. The resulting thickness varies from 500 to 900 feet. The middle Grande Ronde layer (model layer 4) is normal polarity and is modeled between elevations of 1100 to 1800 feet above sea level, giving this layer a constant thickness of 700 feet. Model layer 5 is the lowest layer in the model and represents the first magnetic reversal. It is represented in the model as the portion of the aquifer below 1100 feet elevation.

Subdividing the Grande Ronde into three layers requires multiple changes in the ground-water flow model. Those changes are documented below for each of the MODFLOW input packages.

BASIC PACKAGE (.BAS)

1. The number of model layers (NLAY) is changed from 3 to 5.

2. Two additional boundary arrays (IBOUND) are added with the same configuration as the single Grande Ronde representation used by Lum and others (1990).

3. The starting head arrays (Shead) for the two additional layers is provided and is made identical to the Grande Ronde starting head array used by Lum and others (1990).

BLOCK CENTERED FILE (.BCF)

1. The layer designation (LAYCON) for all layers is set to confined.

2. The vertical leakance (Vcont) between Grande Ronde model layers is set to an arbitrarily large value of 0.1. This will result in simulation results very similar to the model of Lum and others (1990).

3. Storativity (Sf1) is evenly proportioned for all Grande Ronde layers at a value of 0.000333. This results in a total Grande Ronde storativity equal to that used by Lum and others (1990) of 0.001.

4. Transmissivity of individual Grande Ronde layers is established such that the total transmissivity of the Grande Ronde is unchanged at all locations from that used by Lum and others (1990). The transmissivity was uniformly distributed among the three Grande Ronde layers. Proportioning based on thickness cannot be done with confidence since vertical variations of hydraulic conductivity are expected, but unknown.

RIVER PACKAGE (.RIV)

Nodes previously designated as river reaches remained so. The layer of individual river reaches was altered, however, when the river bottom elevation indicated the river bed was in the lower two layers of the Grande Ronde. River bottom elevations above 1800 feet and designated as layer 3 remained in layer 3. River bottom elevations between 1100 and 1800 feet were assigned as layer 4. River bottom elevations less than 1100 feet were assigned to layer 5. This resulted in 59 river reaches (nodes) in layer 5, 20 reaches in layer 4, and 45 reaches in layer 3. Layers 1 and 2 were unchanged.

WELL PACKAGE (.WEL)

The only change in the well package was the assignment of the layer from which the well is withdrawing water. This is not a trivial task, however, since the well term is used to represent not only pumping wells, but also springs and seeps; and several thousand wells may be represented. The layer for all wells withdrawals was assigned as follows.

1. Wells in layers 1 and 2, the loess and Wanapum basalt, were unchanged.

2. Wells representing pumping in the cities of Pullman and Moscow

were assigned to layer based on completion of the wells relative to depth of the model layers.

3. Wells in the Grande Ronde along the canyon were:
   a) left in layer 3 for the "equivalent 5-layer model",
   b) made inactive for the 5-layer model with no canyon discharge from the Grande Ronde, and
   c) made inactive for the 5-layer model simulating canyon discharge from the Grande Ronde with head-dependent drains.