UNIFIED GROUNDWATER FLOW MODEL OF THE RATHDRUM PRAIRIE - SPOKANE VALLEY AQUIFER SYSTEM

Prepared for

Water Quality Management Program
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and

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Introduction and Purpose

The first ever unified finite-difference regional groundwater flow model of the Rathdrum Prairie - Spokane Valley aquifer system has been developed. Although not suitable for highly resolved particle tracking and advective transport modeling, the model does function as a valuable tool in understanding the overall water balance of the aquifer system.

The primary purpose of this modeling exercise is to:

1. Review existing data from earlier modeling efforts and geotechnical work,
2. build a new and comprehensive mass-balance model of the entire system, and
3. estimate groundwater budgets in selected portions of the aquifer.

Funding for this project was shared between the Spokane County Water Quality Management Program and the Idaho Division of Environmental Quality.

Data Sources

This model is constructed on data gathered during years of work on the aquifer system in both Idaho and Washington. No new field data was collected in developing this flow model. However it does consider the comprehensive data generated in the delineation of wellhead capture zones for the City of Spokane and the Spokane Aquifer Joint Board (SAJB) by CH2M Hill (1998).

The results of recent groundwater flow modeling of the aquifer system were closely reviewed, including the work of Bolke and Vaccaro (1981), Painter (unpublished), Buchanan and Olness (1994), CH2M Hill (1998) and R&A Technical Consultants (1997). A recent mass balance calculation for recharge to the Rathdrum Prairie was also critically reviewed (Painter, 1991) and recent local scale groundwater modeling work in Idaho was also incorporated (Buchanan, 1999a; Buchanan, 1999b). The more recent reports listed above go to better defining the distribution of hydraulic conductivity of the aquifer media, but overall, the conceptual model of the aquifer still essentially remains the same.

Conceptual Model

The conceptual basis for the numerical groundwater flow model is one based on widespread contemporary agreement: the Rathdrum Prairie - Spokane Valley aquifer system is contained within a bedrock valley that is filled with considerably more permeable sands and gravels. Recharge is primarily from lake and river leakage and areally distributed precipitation in Idaho, while discharge from the system takes place mostly to the Spokane River and Little Spokane River in Washington.

The hydrostratigraphy is simply defined, recognizing that the main unconfined aquifer is contained within a framework of coarse-grained sediments that are the product of catastrophic glacial outburst processes during the Pleistocene Epoch. These thick sediments onlap or overly older crystalline rocks and lithified sediments that are orders of magnitude less permeable and porous (Breckenridge and Othburg, 1998: Joseph, 1990). Recent seismic reflection profiling work done as part of wellhead protection studies in Washington has resulted in a better understanding of the configuration of this buried bedrock surface that forms the base of the aquifer (CH2M Hill, 1997).

Recent work has added a more detailed understanding of the system in some selected areas. In northern Idaho, the contributions to the aquifer from the Chilco and Sage/Lewellen watersheds has been slightly modified (Graham, 1994). In the northern portion of the Hillyard Trough, the aquifer appears to have a deeper, confined component. In addition, the westernmost portion of the system (west of the City of Spokane and down river to Nine Mile) referred to as the "lower Spokane aquifer" is recharged through the Trinity Trough (CH2M Hill, 1997) and by groundwater contributions from the Hangman Creek watershed and the Columbia Plateau basalts (R&A Technical Consultants, 1997).

Model Code and Interface

This numerical simulation utilizes the finite-difference MODFLOW code (McDonald and Harbaugh, 1988), running under the Groundwater Vistas v. 2.06 graphical interface (Environmental Simulations, 1998). MODPATH interfaces with this code to allow advective particle-tracking (Pollack, 1989) though this module was not utilized in this study.

Model Grid

This single-layer model has 1,321 active cells defining the approximately 325 square mile surface area of the aquifer system. A uniform spacing of 2,640 feet (both rows and columns) is used, that is, each cell is a half-mile square. Such coarse resolution is acceptable in a model whose primary purpose is calculating a water budget; it would be inappropriate to use this model for any other purposes requiring a finer resolution grid without significant modification.

The model grid is oriented north-south, mostly parallel to township and range sections in Idaho and Washington. The model grid is shown in Figure 1, along with selected target nodes (symbols) used in the model calibration process.

Various model properties and boundary conditions are assigned to each active cell in the model grid. This provides the framework to describe large heterogeneities in the hydrogeology of the system throughout the model domain. The model calculates the head and mass balance for each active cell represented in the model domain.

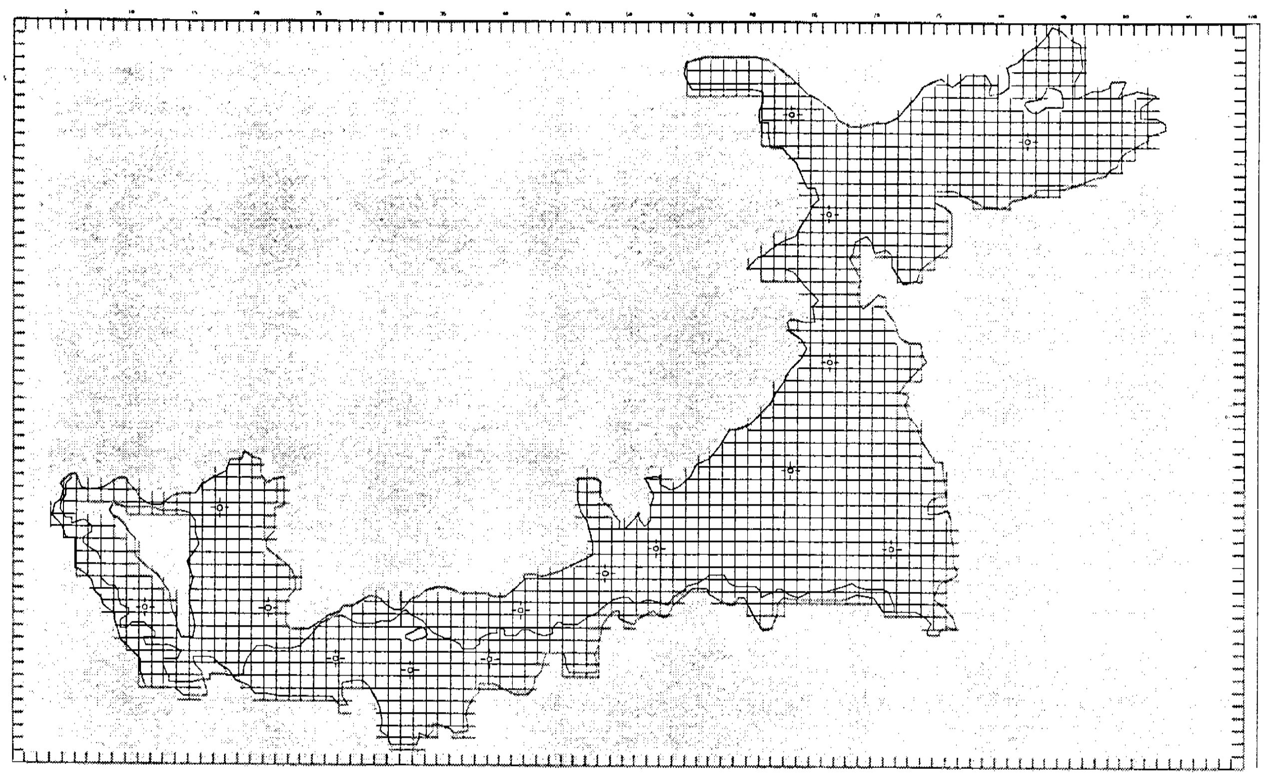

Figure 1. Diagram showing the finite-difference grid - active cells shown in white. Areas external to the active area are shown in gray. Tick mark along the model edge are 2,640 feet apart. Location of calibration targets (symbols) and the Spokane River course are also shown.

Temporal Definition

The model executes in a steady-state mode: to date there have been no transient simulations of the aquifer system. Although significant seasonal changes are observed in the head distribution in the aquifer, as well as river flows and pumping rates, too little information is known regionally to allow for transient modeling at this time.

Boundary Conditions

The aquifer system is bound upgradient by lakes and hillslopes around the periphery of the Rathdrum Prairie in Idaho, and downgradient by the Columbia River basalts and the Little Spokane River. Intermediate or lateral boundaries are defined geologically in the form of bedrock contacts, and hydrologically in the form of tributary lakes and contributing watersheds. Recent geologic mapping in Washington by Joseph (1990) and in Idaho by Breckenridge and Othburg (1998) was reviewed.

Known boundary conditions are simulated using constant head nodes that provide the appropriate inflow/outflow to and from the bounding sides of the subregion. Model data for inflows is from Painter's (1991) estimates and from Bolke and Vaccaro (1981) and coincide mostly with lakes adjacent to the aquifer and the Little Spokane River. Constant head cells are shown in Figure 2 as are river nodes corresponding to the position of the Spokane River.

Well Pumping

There is no comprehensive source of water usage statistics for large wells in the Rathdrum Prairie portion of the aquifer system. Consequently, water withdrawal through pumping wells was not included in this model.

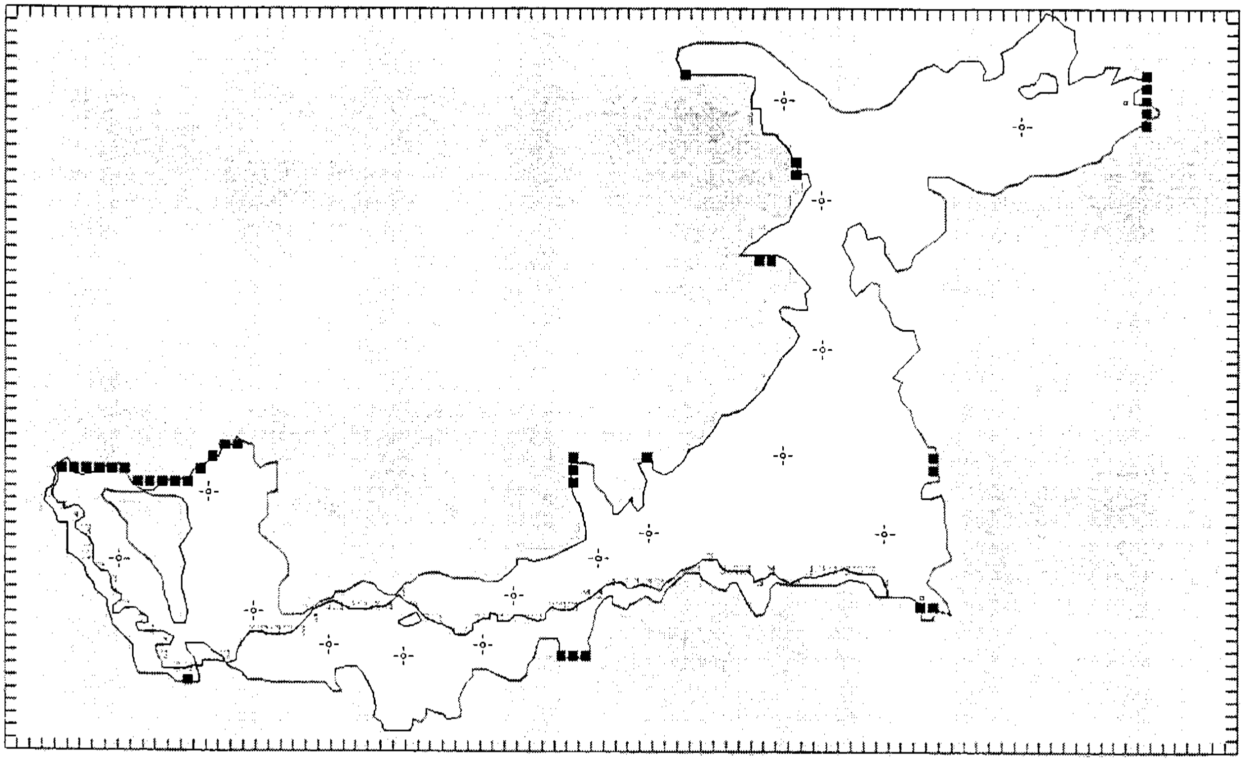

Figure 2. Map of model domain showing boundary conditions superimposed on the model grid. Dark cells are constant head nodes corresponding to peripheral lakes and the Little Spokane River. River nodes representing the Spokane River are shown in gray.

Groundwater/River Interaction

The Spokane River has long been known to both gain and lose water from and to the aquifer system (Broom, 1951). On-going studies are refining our understanding of this important relationship in the Spokane valley (Gearhart and Buchanan, in preparation).

In this numerical simulation of the aquifer system the relationship between the Spokane River and the aquifer is modeled using the "Rivers" module in MODFLOW. In each river node, the bed elevation, thickness and conductance and river stage are specified and the model determines whether the node is gaining or losing. A flux is also reported as either positive (losing) or negative (gaining) for each cell that corresponds to a river node. River nodes are shown in Figure 2.

Model Properties

Hydraulic Conductivity

Hydraulic conductivity estimates for the aquifer system are derived from previous modeling studies and are based both on field data as well as calibrated model values. Table 1 shows the range in hydraulic conductivity values used for this simulation. Note that vertical and horizontal hydraulic conductivity are identical for each zone (no anisotropy).

Figure 3 shows the distribution of zones within the model domain. It is clear that the values for hydraulic conductivity decrease, from east to west, through the model domain. This is consistent with a downstream fining of sediment deposited by the flood process that created the aquifer framework.

Table 1. Hydraulic conductivity zone codes and corresponding model values (ft/day).

Zone	Hydraulic Conductivity	Zone	Hydraulic Conductivity
1	50	13	4000
2	70	14	4500
3	90	15	6000
4	150	16	6500
5	170	17	7000
6	220	18	11000
7	1500	19	50000
8	1750	20	100000
9	2000	21	0
10	2500	22	0
11	3000	23	3
12	3500	24	1
		25	10

Notes: Zone 20 *not* used in the model.

Saturated Thickness

The aquifer thickness is complexly distributed, but minimum estimates can be made by utilizing work done in Washington using seismic reflection profiling by CH2M Hill (1998) for a wellhead protection study. A similar seismic line was surveyed along Scarcella Road near Twin Lakes on the Rathdrum Prairie. However, the depth to the base of the aquifer in much of the central part of the Rathdrum Prairie remains unknown.

Table 2 lists the bottom elevation zone codes and elevations in feet above mean sea level (ft MSL) of the bedrock base of the aquifer system and Figure 4 shows their distribution in the model.

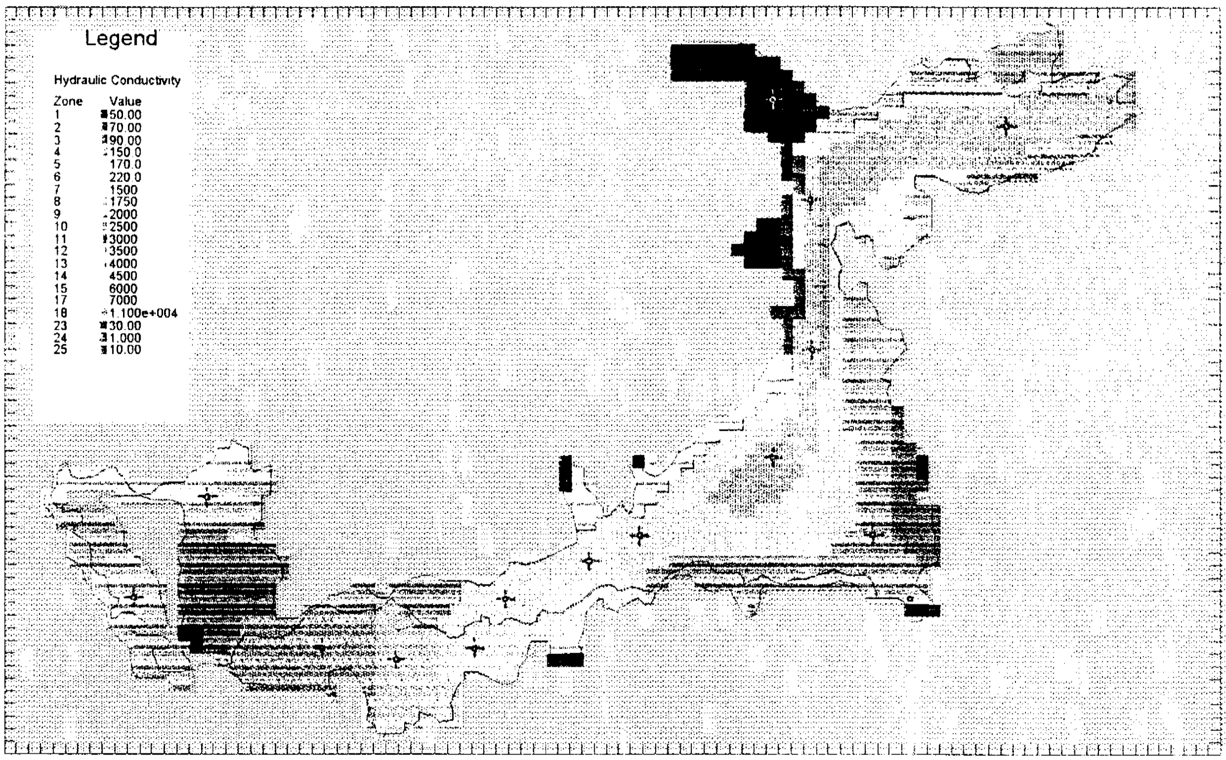

Figure 3. Map of model domain showing hydraulic conductivity zones in the final model. See Table 1 for range in values.

Table 2. Bottom elevation zone codes and corresponding elevation (ft MSL).

Zone	Elevation	Zone	Elevation
1	1400	11	1900
2	1450	12	1950
3	1500	13	2000
4	1550	14	2050
5	1600	15	2100
6	1650	16	2150
7	1700	17	2200
8	1750	18	2250
9	1800	19	2300
10	1850	20	2350

Porosity

The porosity is set to 20 percent (0.20) uniformly throughout the model domain. This parameter does not affect any of the mass balance computations.

Areal Recharge

Recharge due to rainfall is applied to the top surface of each active cell in the model, and is estimated to be 25 percent of rainfall volume. Input data (shown in Table 3) is derived from Olness and Buchanan (1994) and Painter (unpublished). Rainfall distribution in the model is shown in Figure 5.

Table 3. Recharge rates applied to upper surface of model.

Zone	Recharge rate (ft/day)
1	0.0014
2	0.0015
3	0.0016
4	0.0023

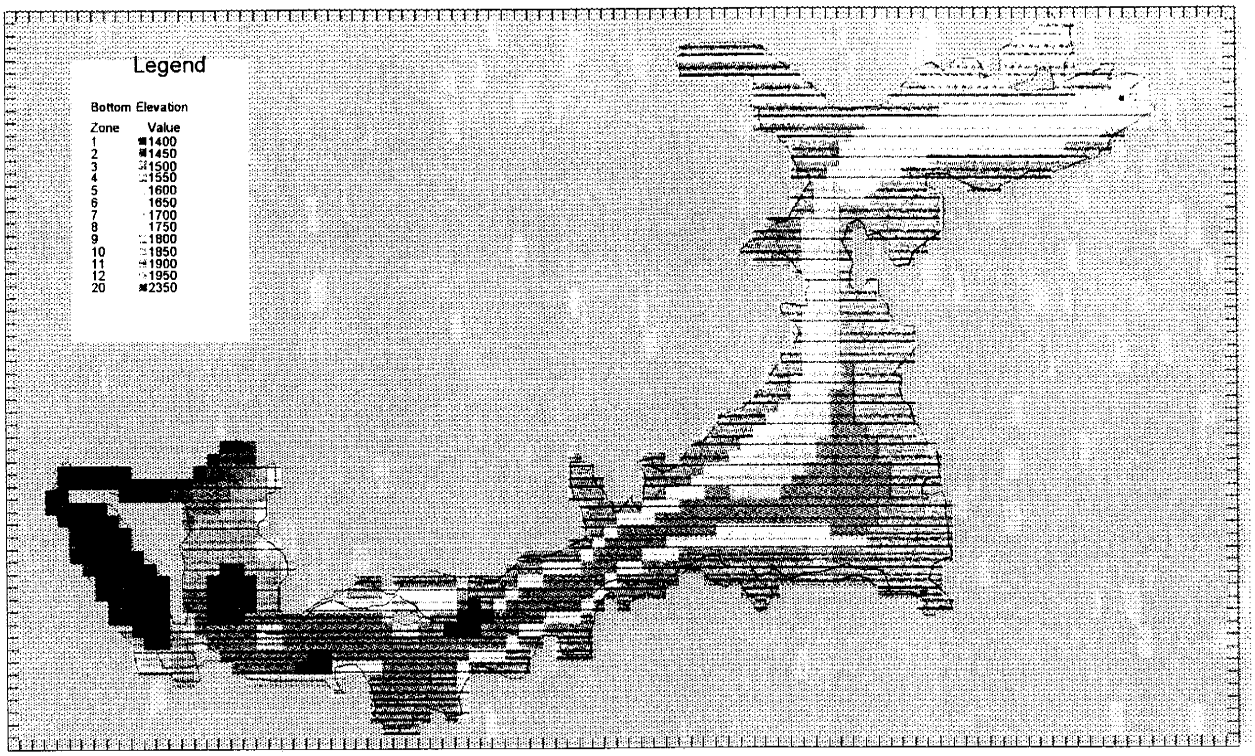

Figure 4. Map of model domain showing bottom elevation zone distribution. Refer to Table 2 for values, represented in 50 foot class intervals.

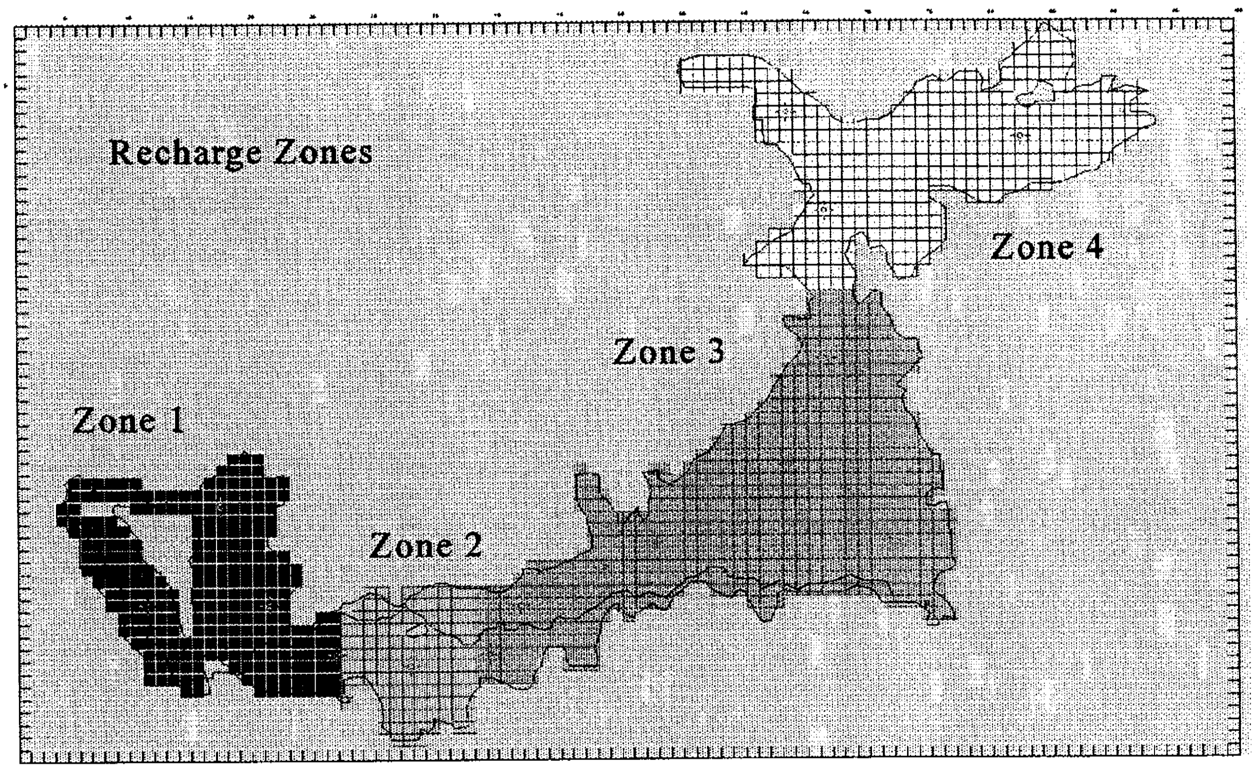

Figure 5. Map of model domain showing recharge zone distribution in the model. Refer to Table 3 for values. Recharge in this case is from areally distributed rainfall on top of the aquifer surface.

Additional recharge from hillslopes and small basins adjacent to the aquifer is applied to the appropriate cells in the model. Values are from Painter (1991) and Bolke and Vaccaro (1982).

Solver

The preconditioned conjugate-gradient solver (PCG2) was utilized in the iterative solution of the model.

Calibration

Calibration of the regional model was against measured heads in the aquifer system reported by Painter (written communication) and CH2M Hill (1998). Target nodes were defined at which calibration statistics could be calculated after each model run. A map showing the overall observed groundwater table surface in the entire aquifer is not presently available, and consequently, is not included in this report for comparison.

Initially model parameters were set to reflect estimated inflows (Painter, 1991) in the Rathdrum Prairie but this yielded too much water in the model, that is, too high a head distribution, particularly in the Rathdrum Prairie portion of the system. Hydraulic conductivity values were repeatedly changed near the "lake nodes" until calculated heads approached observed heads in the field. After calibration the output heads in the model closely matches those measured historically in the field within three feet. Table 4 shows the calibration statistics of the final simulation and Figure 6 shows observed versus predicted heads at the target nodes. For more information on these statistics, consult Anderson and Woessner (1992).

Table 4. Calibration statistics (in feet).

Residual Mean	-1.62
Residual Standard Deviation	9.62
Absolute Residual Mean	7.38
Head Range	490.0

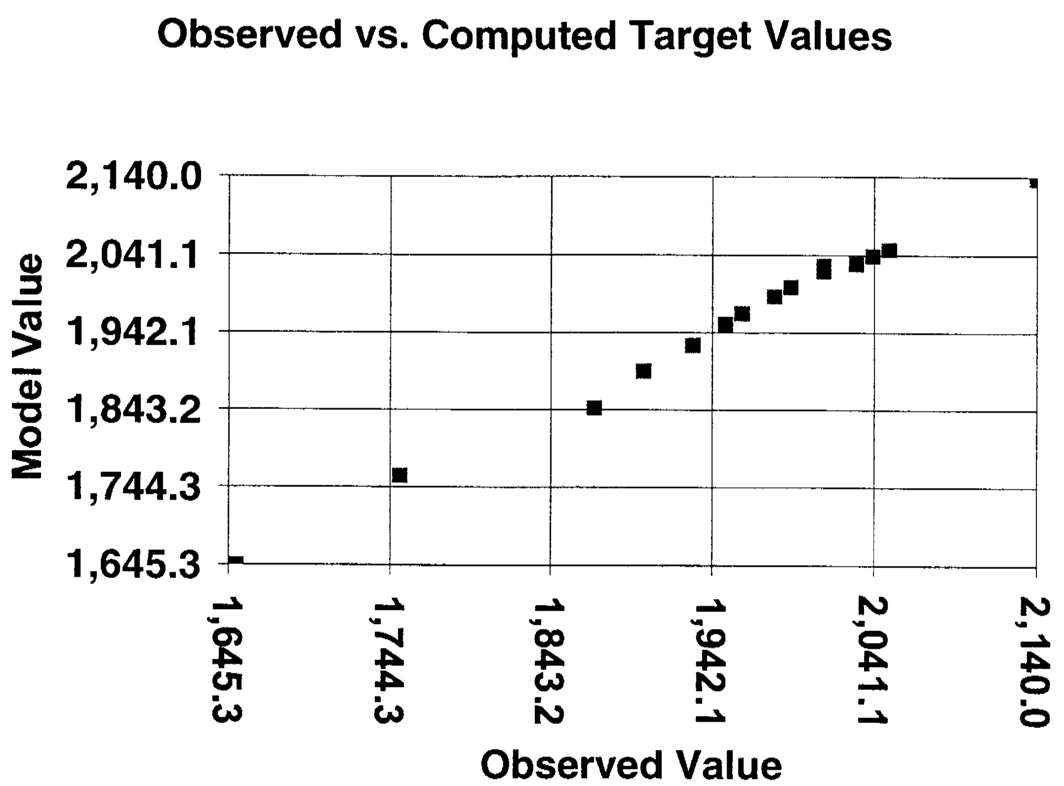

Figure 6. Observed versus calculated heads at target nodes in the final model. Values are in feet above mean sea level.

Results

The output head distribution for the final simulation is shown in Figure 7. It matches closely the results of all previous models and the measured distribution of water levels in the aquifer system, however, the final model by no means presents a unique solution. It was clear during the calibration process that a wide range of parameter values could give acceptable results with regards to matching the overall head distribution in the model domain. A flow vector map is also included as Figure 8, and generally shows the dominant groundwater flow direction in each cell of the model domain.

This model reveals, most interestingly, that the previously calculated recharge to the aquifer system in Idaho is significantly overestimated (Painter, 1991). Table 5 summarizes a comparison between the original estimates and those calculated by the final model after hydraulic conductivity was adjusted to provide a close match in heads as observed near those nodes.

Table 5. Prior Rathdrum Prairie recharge estimates and model predicted values.

Watershed	Recharge (Painter) in cfs	Calculated inflow rate in new model in cfs
Blanchard	62.2	3
Chilco	40.6	4
Hauser Lake	8.2	2.5
Hayden Lake	37.8	27
Spirit Lake	22.3	13
Twin Lakes	25.0	6
Lake Cd'A	*	35
Spokane River	230.0	120
Lake Pend Oreille	50.0	61
Rainfall	250.0	125

* Painter (1991) included Lake Cd'A leakage with his Spokane River value.

The final model yields an aquifer throughflow at the state line of about 390 cubic feet per second (cfs). This figure agrees very well with that of Bolke and Vaccaro's (1981) value of 487 cfs, Buchanan and Olness' (1994) 320 cfs and that of CH2M Hill (1998) of 380 cfs at the state line.

Conclusions

This modeling exercise was an attempt to reconcile vastly different water budgets for the Washington and Idaho portions of the Spokane Valley - Rathdrum Prairie aquifer system. This report, as well as all recent groundwater flow modeling of the system, consistently arrives at the conclusion that the groundwater flux at the state line is approximately half that of earlier estimates made during the process of sole source designation (Buchanan, 1995).

Additional work can be suggested to better understand the overall mass-balance of the system:

1. The thickness of the aquifer in the southern Rathdrum Prairie remains unknown. Two additional seismic reflection survey lines in this area would be desirable. Suggested transects would include one along the north-south state highway 41 and the east-west oriented Hayden or Lancaster Roads. A recent M.S. thesis from the University of Idaho has just been received and may help in this regard (Adema, 1999).

2. Estimated contributions to the periphery of the aquifer system need to be refined. Water budget calculations for lake and watershed contributions to groundwater in the main aquifer need to be critically reviewed. Often, when lake water budgets are calculated, the imbalance or residual in the estimates are usually attributed to groundwater inflow/outflow since this is not measured directly. A close examination of water well logs coupled with periodic water level measurements, careful field estimation of hydraulic conductivity, and knowledge of the geometry

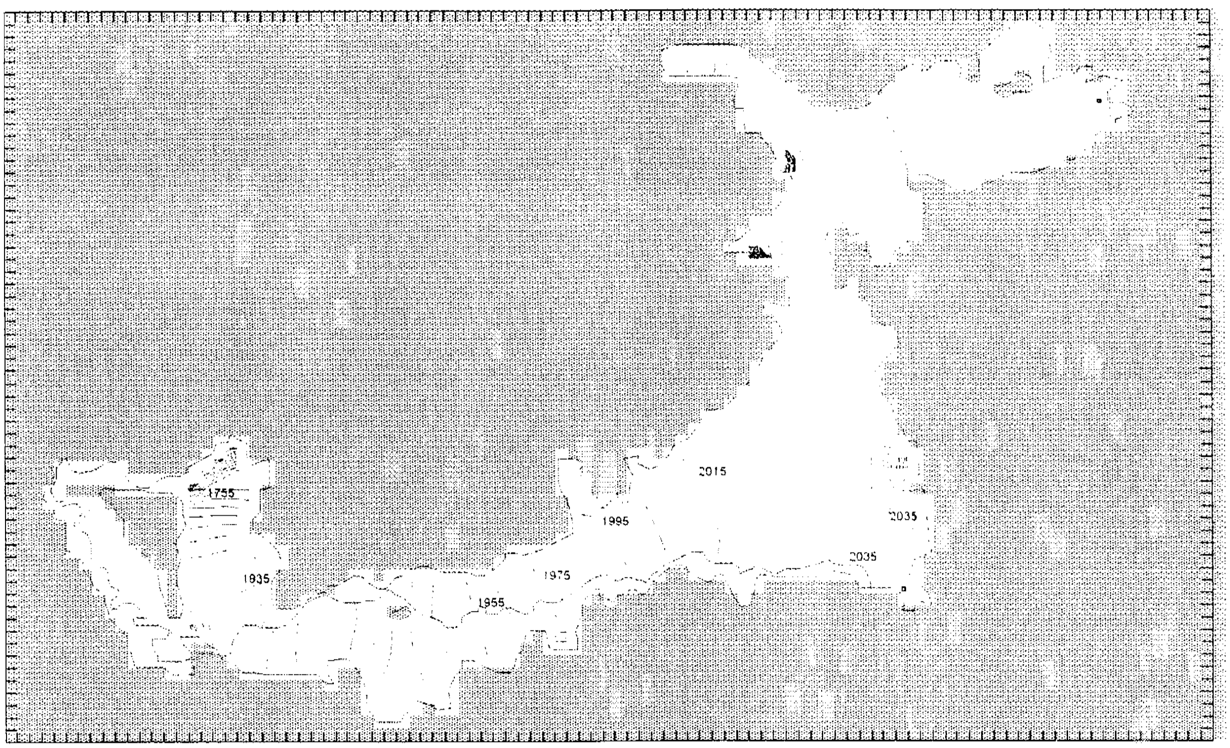

Figure 7. Map showing the calculated head distribution in the final model. Head values for the unconfined groundwater surface range about 490 feet from the northern Rathdrum Prairie to the Little Spokane River. Contour interval is 10 feet.

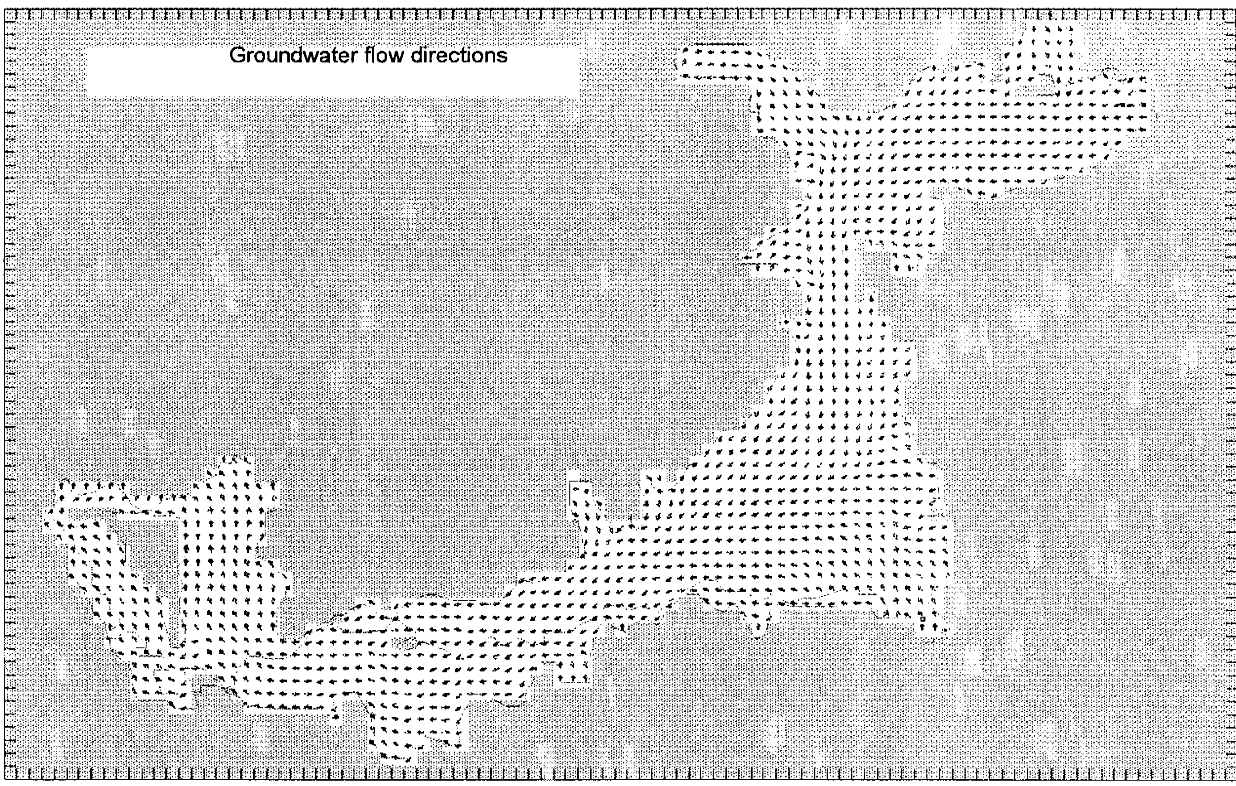

Figure 8. Flow vector map showing dominant groundwater flow direction in each cell.

of the aquifer interface can provide input to a solution of Darcy's equation with regard to groundwater leakage from select portions of the Prairie and to the aquifer system.

3. There is no central location for well production data from the Rathdrum Prairie aquifer. A comprehensive reporting on water pumping rates by domestic, commercial, municipal and agricultural users would be beneficial to better calculate usage statistics.

4. The linkage between the Spokane River and the aquifer system can be better modeled using the new "streams" module of MODFLOW, or by using another flow model. Better leakance coefficients for the Spokane River are required, as well as precise definition of inflection points between gaining and losing reaches, as well as fluxes into and from the aquifer.

5. More detailed definition of boundary conditions in the northern part of the Rathdrum Prairie aquifer. Precise watershed boundaries need to be delineated as well as physical continuity with the main aquifer body, especially in the Blanchard and Hoodoo valleys. Small scale hydrogeologic studies, such as that performed around the Chilco channel area by Graham (1994), could more precisely define the aquifer boundary.

6. A transient flow model needs to be developed for the aquifer system. There are large seasonal changes in head throughout the system, as well as pumping rates and river flows.

7. Estimation of recharge to the aquifer system by direct precipitation needs to be refined. At present it is usually assumed that about 20 percent of precipitation falling on the surface of the aquifer actually contributes to recharge. In addition, the recharge due to irrigation return and septic effluent, needs better quantification.

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APPENDIX: Attached Files (on disk)

vista3.gwv	(Groundwater Vistas file)
svrpmod.bas	(MODFLOW basic)
svrpmod.bcf	(MODFLOW block-centered flow)
svrpmod.oc	(MODFLOW output control)
svrpmod.rch	(MODFLOW recharge)
svrpmod.riv	(MODFLOW river)
svrpmod.pcg	(MODFLOW solver)