RECLAMATION

Managing Water in the West

Technical Series No. TS-YSS-19

Modeling Groundwater Hydrologic Impacts of the Potential Black Rock Reservoir

A component of
Yakima River Basin Water Storage Feasibility Study, Washington
Pacific Northwest Region

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

September 2007

Cover Photograph – View looking to the northwest, showing Horsethief Mountain in the area of the right (southern) dam abutment. Barrel Springs and a portion of Dry Creek drainage are in the foreground.

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Prepared for the Upper Columbia Area Office
by the

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September 2007

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Executive Summary

This report presents the results of a seepage analysis for the potential Black Rock reservoir. The Black Rock reservoir is one alternative being investigated as part of the Yakima River Basin Water Storage Feasibility Study (Storage Study) being conducted by the Bureau of Reclamation (Reclamation) in partnership with the Washington State Department of Ecology (Ecology). The Storage Study was authorized by Congress in 2003 to investigate the benefits of new storage in the Yakima River basin to threatened and endangered fish, irrigated agriculture, and municipal water supply; with emphasis on the feasibility of storage of Columbia River water in the potential Black Rock reservoir.

This analysis quantifies the expected reservoir seepage rate and determines the flow direction of seepage. Since the potential Black Rock dam could retain water up to about 600 feet deep, there is concern that hydrostatic pressure could result in a significant increase in aquifer head along the western boundary of the Hanford Reservation. The increased head condition could in turn cause migration of contaminants from the Hanford Reservation to the Columbia River. The modeling in this report describes the potential for reservoir seepage into underlying aquifers and the consequent impacts on aquifer head, groundwater flux, and groundwater discharge to creeks, drains, and springs in the vicinity of the reservoir. The modeling does not describe possible mitigation measures for reducing reservoir seepage and/or head conditions along the western boundary of the Hanford Reservation.

This investigation relies heavily on previous hydrogeologic studies of the Columbia Plateau by the U.S. Geological Survey (USGS), the Washington Department of Ecology (Ecology), and the Department of Energy (DOE) and its contractors at the Hanford Reservation. Some of the more important citations in this report include; USGS (1987, 1990, 1999, 2000b), Ecology (1994), Rockwell International (1979a, b), and Pacific Northwest National Laboratory (PNNL) (2004, 2006, 2007, 2007b). This investigation also incorporates the results of recent geologic drilling and aquifer testing by Reclamation at the Black Rock damsite.

Geologic drilling at the damsite revealed fractured and faulted basalts in an area of Horsethief Mountain that abuts the right side (south side) of the proposed dam. The fractures in this area are not expected to affect the stability or safety of the dam. However, extensive fracturing in this area of the damsite and in the Dry Creek drainage could cause water to flow in the subsurface, east toward the Hanford Reservation and south toward the Yakima River. The hydrologic impact of increased fracture permeability in Horsethief Mountain and Dry Creek drainage is an important consideration in this modeling investigation.

Black Rock Modeling Objectives

The Black Rock groundwater model, which was developed using the USGS MODFLOW software package (USGS, 1988), addresses six questions affecting the hydrologic feasibility (ability of reservoir to retain water) of the potential Black Rock reservoir:

1. How long would it take to fill the reservoir given the expected water availability and expected reservoir seepage rates?

2. What is the expected seepage rate from the reservoir during initial filling?

3. What is the expected seepage rate from the reservoir over time, once filled to capacity?

4. What impact would the full reservoir have on groundwater discharge to creeks, drains and springs, aquifer storage, and aquifer head conditions?

5. What impact would the reservoir have on groundwater flow and head conditions at the boundary of the Hanford Reservation?

6. What additional field testing would be most valuable in reducing uncertainty in model predictions of reservoir hydrologic impacts?

The model-based answers to these questions are described in detail in Chapter 9 of this report. A condensed version is included in the Executive Summary.

Black Rock Reservoir Site Description

The potential Black Rock dam and reservoir are located within the southwest portion of the Columbia Plateau, in an area known as the Yakima Fold Belt (Figure 1). The topography in this area consists of northwest-southeast trending ridges (anticlines) separated by broad, flat valleys (synclines) that were folded and faulted under north-south compression. The Black Rock dam and reservoir would be located in the Black Rock Valley between two of these anticlines; the Yakima Ridge to the north and Horsethief Mountain to the south.

The potential damsite is located at the east end of the Black Rock Valley where the Yakima Ridge anticline turns southeast and the Horsethief Mountain anticline extends northeastward from the Rattlesnake Hills. The area has been described as a “convergence zone” where these two structures appear to intersect in a north-trending cross structure. Recent aquifer testing indicates that much of the hydrogeologic complexity of the reservoir site is concentrated in this area.

Information about the hydrogeologic framework and geologic structure of Columbia Plateau and the Yakima Fold Belt is found in Chapter 3 of the report.

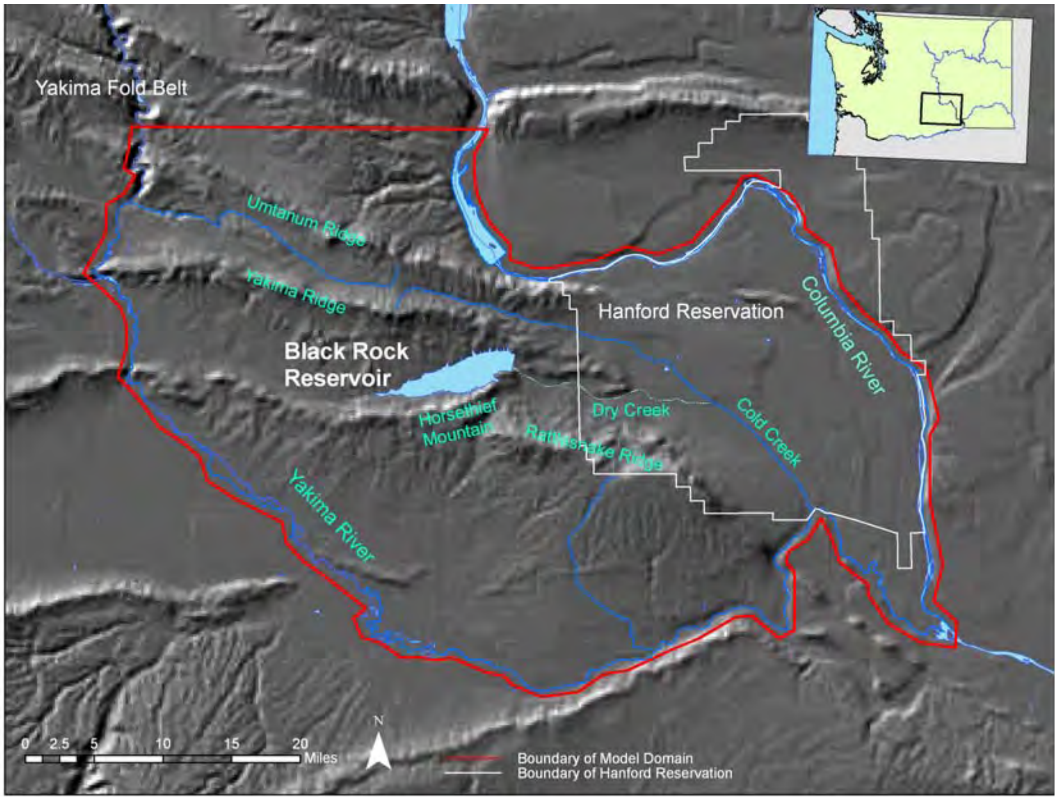

Figure 1: Overview of the Black Rock model domain.

Model Development and Calibration

The Black Rock model builds directly on U.S. Geological Survey (USGS) groundwater studies, including the Columbia Plateau regional groundwater model and the Yakima Basin sedimentary basin study (USGS, 1994, 2006b).

The Black Rock model domain, which is centered on the reservoir site, encloses an area of about 1,700 square miles (mi^2) and is bounded on the east by the Columbia River and on the south and west by the Yakima River (outlined in red in Figure 1). The model domain includes most of the Hanford Reservation (outlined in white in Figure 1). Five separate model layers are used to represent the Ringold and Ellensburg sediment formations, and the Saddle Mountains, Wanapum, and Grande Ronde basaltic units which underlie the model domain.

A steady-state, base-case Black Rock groundwater model representing current conditions at the site (without the reservoir) is used for calibration purposes and to provide a baseline for estimating future reservoir hydrologic impacts. A transient (time-dependent) model, which includes the reservoir, is used to describe early-time (years 0-5) and late-time (years 5-300) reservoir interactions with the surrounding aquifer system. The transient model results, which include total reservoir seepage as well as changes in aquifer head, groundwater flux, and aquifer storage, are all presented relative to the results of the base-case model.

The limited availability of aquifer test data for calibrating the base-case Black Rock model means that model calibration is largely dependent on the previous USGS calibration of the Columbia Plateau regional groundwater model. It also means that there is uncertainty in model parameter values, particularly with respect to the complex geologic structure that exists in the eastern portion of Horsethief Mountain. For this reason, the Black Rock model application is built around a sensitivity analysis involving variations in aquifer hydraulic conductivity (the ease with which water flows through geologic layers) and specific-storage parameters (the volume of groundwater an aquifer absorbs or expels per unit change in aquifer head). Six different variations in model parameterization produce a range of estimates for reservoir seepage and other hydrologic impacts that frame most of the uncertainty in the Black Rock model and provide sideboards for the most likely reservoir hydrologic outcomes.

For purposes of computational efficiency, two versions of the transient reservoir model were developed to address questions that involve early-time and late-time hydrologic impacts. One version of the model uses the MODFLOW Lake Package (LP) to represent the initial filling of the reservoir. The other uses the MODFLOW General Head Package (GHP) to represent the long-term effects of a full reservoir. The early-time LP version of the model represents reservoir interactions with the aquifer during the first 5 years, using reservoir elevations that reflect an average Columbia River water availability hydrograph. The late-time GHP version of the model represents reservoir interactions with the aquifer from year 5 through year 300, assuming a fixed reservoir stage of 1,775 feet (i.e., a full reservoir)[1]. The two model versions are otherwise identical and are based on the same (steady-state) model calibration.

For each transient model run, model output includes hydrographs showing time-dependent reservoir seepage rates. Model output also includes contour maps showing increases in aquifer head conditions over time, and tables showing increases in groundwater flow beneath Cold Creek at the boundary of the Hanford Reservation.

Reservoir Seepage Rates

Total reservoir seepage has two components; seepage that goes into aquifer storage and seepage that is subsequently discharged from the aquifer to creeks,

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[1] In an average water year, the reservoir stage is expected to fluctuate between 50 and 60 feet over the course of the irrigation season—a small fluctuation compared to total reservoir head, with comparatively little impact on seepage.

drains, and springs. Table 1 summarizes early-time and late-time model results with respect to the expected reservoir seepage and its two components. The minimum, maximum, and mean values in this table are the results of the model sensitivity analysis.

Table 1: Model-based estimates of total annual reservoir seepage rates.

Time since reservoir filling begins	Total annual reservoir seepage rate (acre-feet)[1]			Annual rate of increase in aquifer storage (acre-feet)			Annual rate of increase in discharge to creeks, drains and springs (acre-feet)		
	min	max	mean	min	Max	mean	min	max	mean
13 months (peak seepage)[2]	72,900 (101 cfs)	121,000 (168 cfs)	96,950 (135 cfs)	49,900 (69 cfs)	80,000 (111 cfs)	64,950 (90 cfs)	22,400 (31 cfs)	40,400 (56 cfs)	31,400 (44 cfs)
5 years[3]	32,100	54,300	44,900	2,400	14,700	8,600	25,600	51,100	36,300
25 years[3]	30,700	53,400	42,200	1,000	6,100	3,400	27,600	51,400	38,800
100 years[3]	29,900	53,200	41,300	200	2,900	1,300	28,500	51,500	40,000
300 years[3]	29,800 (41 cfs)	52,300 (73 cfs)	40,900 (57 cfs)	1 (0 cfs)	1,500 (2 cfs)	600 (1 cfs)	29,200 (41 cfs)	51,600 (72 cfs)	40,400 (56 cfs)

[1] Total annual reservoir seepage is generally not the exact sum of its two components in this table because the minimum, maximum, and mean values presented are from different model runs.

[2] These results are from early-time Lake Package model.

[3] These results are from late-time General Head Package model.

Based on the early-time LP version of the model and an average year of water availability from Priest Rapids Dam, it is estimated to take about 380 days to initially fill the reservoir to the 1,775-foot stage. Reservoir seepage is expected to peak at between 6,000 and 9,950 acre-feet per month (an annual rate of between 72,900 and 121,000 acre-feet per year) about 13 months after the reservoir begins filling and then decline rapidly over the next 4 years.

Based on the late-time GHP version of the model, 5 years after the reservoir is first filled, total reservoir seepage is expected to have declined to between 32,100 and 54,300 acre-feet per year. The decline continues, but more slowly in succeeding years. After 25 years, reservoir seepage is expected to be between 30,700 and 53,400 acre-feet per year, and after 100 years it is expected to be between 29,900 and 53,200 acre-feet per year. Eventually (after about 300 years) both aquifer storage and groundwater discharge to creeks, drains, and springs reach limiting values. When this happens, the reservoir has reached hydrologic equilibrium with respect to the aquifer and, assuming a full reservoir, total reservoir seepage is no longer changing with time. At equilibrium, total reservoir seepage is expected to range between 29,800 and 52,300 acre-feet per year.

Increase in Aquifer Head

Model results indicate that the effect of reservoir seepage on aquifer head conditions is greatest in the immediate area of the reservoir itself, but especially at the dam where the reservoir depth is greatest. The late-time GHP version of the model predicts that a full reservoir will ultimately increase aquifer head directly beneath the reservoir in model layers one, two, and three (sediments, Saddle Mountains, and Wanapum layers) by between 250 and 650 feet over that of base-case conditions. The effect of seepage on aquifer head diminishes rapidly, however, with distance from the reservoir. Five to ten miles from the reservoir, the head increase in layers two and three is generally less than 20 feet, and mostly south and northwest of the reservoir.

The increase in head in layer-one sediments is mainly the result of re-infiltration of reservoir seepage at the downstream end of the Dry Creek drainage to the east of the reservoir. The downstream re-infiltration is reservoir seepage that has daylighted at the upstream end of Dry Creek. Depending on the model run, the head in layer-one sediments in the Dry Creek drainage may increase by up to 250 feet as a result of re-infiltration (see for example Figure 2). Along Cold Creek, at the western boundary of the Hanford Reservation, head increases can range up to 60 feet. As these model results indicate, Dry Creek re-infiltration can also affect head conditions east of Cold Creek, inside the Hanford Reservation.

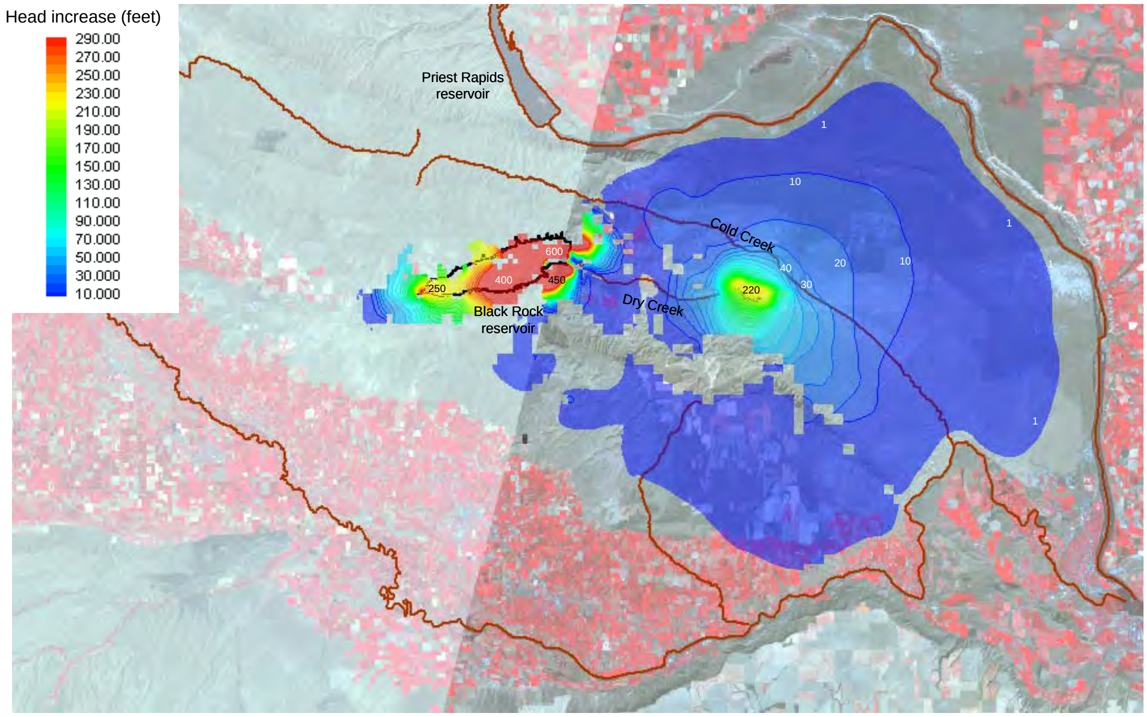

Figure 2: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 300 years.

Increase in Groundwater Flow beneath Cold Creek

East of the reservoir site the general direction of groundwater flow in the sediment layer is from west to east, toward the Hanford Reservation. Groundwater flow in this direction is expected to increase as a result of reservoir seepage and Dry Creek re-infiltration. Table 2 summarizes the Black Rock model results with respect to the estimated increase in groundwater flow in the sediment layer, beneath Cold Creek, at the boundary of the Hanford Reservation[2].

Table 2: Layer 1 Groundwater Flow Beneath Cold Creek

permeability 1 maximum storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	11	8,195			
10 years	14	9,959	3	1,765	22
100 years	22	15,885	11	7,690	94
300 years	31	22,701	20	14,507	177
steady-state	32	22,967	21	14,772	180
permeability 2 average storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	11	7,761			
10 years	17	12,239	6	4,478	58
100 years	32	23,158	21	15,397	198
300 years	41	29,494	30	21,733	280
steady-state	41	29,946	30	22,185	286
permeability 2 minimum storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	10	7,761			
10 years	26	19,182	16	11,722	147
100 years	39	27,994	28	20,534	260
300 years	41	29,645	30	21,883	282
steady-state	41	29,946	30	22,185	286

The base-case (without the reservoir) model estimate of groundwater flow beneath Cold Creek in layer-one sediments averages about 7,800 acre-feet per year [11 cubic feet per second (ft^3/s)]. West-to-east groundwater flow beneath Cold Creek is expected to gradually increase as a result of Dry Creek re-infiltration. Ten years after the reservoir is initially filled, groundwater flow beneath Cold Creek is expected to increase between 1,800 and 11,700 acre-feet per year. After 100 years, the increase is expected to be between 7,700 and 20,500 acre-feet per year, and after 300 years, the increase is in the range of 14,500 to 21,900 acre-feet per year over base-case flows. Only minor increases in groundwater flow beneath Cold Creek (less than 70 acre-feet per year) are expected in layers two and three (Saddle Mountains and Wanapum layers).

Water flowing down Dry Creek in excess of the infiltration capacity of Dry Creek sediments is expected to discharge on the surface into Cold Creek. Dry Creek

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[2] The geographic boundary of the Hanford Reservation is some distance to the west of Cold Creek (see Figure 1). However Cold Creek was the Hanford Reservation hydrologic boundary used in the PNNL Site-Wide Groundwater Model (SGM) (PNNL 2005b, 2006). In order to provide consistency with the PNNL model, Cold Creek is also used here as the western “hydrologic boundary” of the Hanford Reservation.

flow into Cold Creek is expected to increase between 9 and 22 ft^3/s as a result of increased Dry Creek flows.

A steady-state model that includes the reservoir was developed as a check on the 300-year transient model results. The steady-state model results are not significantly different from those of the 300-year transient model, indicating that the 300-year model is a good approximation of equilibrium conditions.

Additional Information Required

The seepage rates presented in this report have been calculated using the best available hydrologic data. Since no measured hydraulic conductivity data is available in the Dry Creek drainage, values from the U.S. Geological Survey's regional model were used and then adjusted until water levels predicted by the model matched measured water levels in local wells in the area.

The Dry Creek drainage contains unique and complex geologic features, including a large alluvial fan along the east flank of the Rattlesnake Hills, and the Barrel Springs thrust fault at the north end of the valley. These features could have hydraulic conductivities significantly different from those used in the model.

We believe that the seepage rates produced by this model are accurate based on the data we have available. However given the geologic complexity of the area at the damsite and the Dry Creek drainage, gathering new hydrologic data in the Dry Creek drainage could change the seepage rates that are presented in this report.

Additional multi-well aquifer testing aimed at characterizing hydraulic conductivities (and layering) within the Saddle Mountains Unit along the Dry Creek drainage is essential for reducing uncertainty in Black Rock model predictions of reservoir seepage and potential impacts on Hanford Reservation groundwater levels. Aquifer testing would involve additional geologic drilling, pump testing, and well monitoring in basalt layers and sedimentary interbeds within the Saddle Mountains Unit in this critical area.

The additional aquifer testing would also be useful in determining what and where specific mitigation measures would be most effective in controlling seepage rates. Mitigation measures could range from cutoff walls and grout curtains to drainage systems and pumping wells. Issues related to mitigation include but are not limited to, the seepage rate in the Dry Creek drainage, whether seepage water daylights on the surface or remains underground, what percentage of the seepage can be intercepted before reaching the Hanford boundary, and the potential uses for seepage water that is intercepted.

Contents

Page

Acknowledgments xiii
1.0 Background 1
2.0 Black Rock Groundwater Model Purpose and Scope 3
2.1 Purpose of Modeling 3
2.2 Scope of Model Development and Application 3
3.0 Hydrogeologic Framework of the Black Rock Model Area 7
3.1 Geologic Setting 8
3.2 Stratigraphy 8
3.3 Geologic Structure 14
3.4 Hydrogeology 14
3.5 Aquifer Recharge and Discharge 15
4.0 Black Rock Model Development 19
4.1 Principal Data Sources 19
4.2 Black Rock Model Domain 20
4.3 Model Layers 21
4.4 Hydrologic Properties of Model Layers 25
4.5 Black Rock Model Boundary Conditions 27
5.0 Steady-State Base-Case Model Development and Calibration 29
5.1 Base-Case Model Sensitivity Analysis 31
5.1.1 The *Permeability 1* Model 31
5.1.2 The *Permeability 2* Model 32
5.1.3 Conceptual Model Calibration Residuals 32
6.0 Transient Model Development 35
6.1 Early-Time and Late-Time Versions of the Transient Model 35
7.0 The LP (Early-Time) Model 37
7.1 The LP Model Sensitivity Analysis 38
7.1.1 Water Availability Hydrographs 38
7.1.2 Reservoir Stage and Time-to-Fill 39
7.1.3 Increase in Discharge to Creeks, Drains, and Springs 41
7.1.4 Increase in Aquifer Storage 41
7.1.5 Total Reservoir Seepage 42
7.2 Transition between LP and GHP models 43
8.0 The GHP (Late-Time) Model 47
8.1 The GHP Model Sensitivity Analysis 48
8.1.1 Increase in Discharge to Creeks, Drains, and Springs 49
8.1.2 Increase in Aquifer Storage 50
8.1.3 Total Reservoir Seepage 52
8.1.4 Maximum Likelihood Hydrographs 54
8.2 Increase in Aquifer Head 56
8.2.1 Dry Creek Re-Infiltration 56
8.2.2 Head Change Contour Maps 57
8.2.2.1 Permeability 1 Maximum Storage Model 59

8.2.2.2 Permeability 2 Average Storage Model 62
8.2.2.3 Permeability 2 Minimum Storage Model 66
8.2.3 Steady-State Reservoir Modeling 69
8.2.3.1 Steady-State Permeability 1, Maximum Storage Model...... 69
8.3 Groundwater Flow beneath Cold Creek 71
9.0 Model Based Responses to Six Initial Questions................................. 75
Glossary 81
References... 85

List of Tables

Table 4-1: Thickness properties of Black Rock model layers. 25
Table 4-2: Hydraulic conductivity values estimated from aquifer tests at the Black Rock Dam and Reservoir site. 26
Table 4-3: Horizontal and vertical hydraulic conductivities used in Black Rock model layers. 27
Table 4-4: Specific-yield /specific-storage estimates used in Black Rock model layers. 27
Table 5-1: Steady-state base-case model results. 33
Table 7-1: Summary of early-time LP model results.. 43
Table 8-1: Summary of late-time reservoir seepage results................................ 55
Table 8-2: Summary of layer 1 groundwater flow beneath Cold Creek. 73

List of Figures

Figure 3-1: Topographic features in the Black Rock model domain. 7
Figure 3-2: Stratigraphic chart for the Columbia Plateau (Modified from USGS, 1999). 9
Figure 3-3: Geologic map of bedrock units underlying Black Rock dam right abutment. 11
Figure 3-4: Surficial Geology of Black Rock model area. 13
Figure 3-5: Tectonic map of the Black Rock damsite. 17
Figure 4-1: Black Rock model area in relation to the USGS Columbia Plateau Model area. 20
Figure 4-2: Black Rock model grid cells. 21
Figure 4-3: Sediment layer (model layer 1) active grid cells.............................. 23
Figure 4-4: Saddle Mountains layer (model layer 2) active grid cells................ 23
Figure 4-5: Wanapum layer (model layer 3) active grid cells. 24
Figure 4-6: Five-layer Black Rock model cross-section..................................... 24
Figure 5-1: Layer 2 observation wells near the reservoir site............................. 30
Figure 5-2: Layer 3 observation wells near the reservoir site............................. 30
Figure 5-3: Modeled versus observed elevation heads in base-case conceptual models. 34

Figure 7-1: LP boundary conditions in layer 1 cells inside the reservoir boundary. 37
Figure 7-2: Monthly availability of water and monthly irrigation demand during an average water year (1967). 39
Figure 7-3: Nine year time series of net reservoir inflow for two LP conceptual models. 40
Figure 7-4: Reservoir stage hydrograph first nine years. 40
Figure 7-5: Increase in discharge to creeks, drains and springs during first nine years for two conceptual models 41
Figure 7-6: Increase in aquifer storage during first nine years for two conceptual models. 42
Figure 7-7: Total reservoir seepage during first nine years for two conceptual models. 43
Figure 7-8: MODFLOW LP and GHP results for the *permeability 1 average storage* model 44
Figure 7-9: MODFLOW LP and GHP results for the *permeability 2 average storage* model 45
Figure 8-1: Increase in discharge to creeks, drains, and springs over time due to reservoir seepage 49
Figure 8-2: Increase in aquifer storage over time, due to reservoir seepage (sediments, layer 1). 50
Figure 8-3: Increase in aquifer storage over time, due to reservoir seepage (Saddle Mountains, layer 2). 51
Figure 8-4: Increase in aquifer storage over time, due to reservoir seepage (Wanapum, layer 3). 51
Figure 8-5: Total increase in aquifer storage over time, due to reservoir seepage (layers 1, 2 and 3) 52
Figure 8-6: Total reservoir seepage over time. 53
Figure 8-7: Average annual hydrographs for all models. 55
Figure 8-8: Dry Creek re-infiltration area. 57
Figure 8-9: Time-dependent Dry Creek re-infiltration rates 58
Figure 8-10: Surface discharge from Dry Creek into Cold Creek. 58
Figure 8-11: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 10 years. 60
Figure 8-12: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 100 years. 60
Figure 8-13: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 300 years. 61
Figure 8-14: Layer 2 (Saddle Mountains) head increase, *permeability 1 maximum storage* model after 300 years. 61
Figure 8-15: Layer 3 (Wanapum) head increase, *permeability 1 maximum storage* model after 300 years. 62
Figure 8-16: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 10 years. 63
Figure 8-17: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 100 years. 64

Figure 8-18: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 300 years. 64
Figure 8-19: Layer 2 (Saddle Mountains) head increase, *permeability 2 average storage* model after 300 years. 65
Figure 8-20: Layer 3 (Wanapum) head increase, *permeability 2 average storage* model after 300 years. 65
Figure 8-21: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 10 years. 67
Figure 8-22: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 100 years. 67
Figure 8-23: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 300 years. 68
Figure 8-24: Layer 2 (Saddle Mountains) head increase, *permeability 2 minimum storage* model after 300 years. 68
Figure 8-25: Layer 3 (Wanapum) head increase, *permeability 2 minimum storage* model after 300 years. 69
Figure 8-26: Layer 1 (sediments) head increase, *permeability 1 maximum storage* steady-state model. 70
Figure 8-27: Layer 2 (Saddle Mountains) head increase, *permeability 1 maximum storage* steady-state model. 71
Figure 8-28: Base-case model heads and groundwater flow directions, layer 1. 72

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The authors wish to acknowledge the assistance of John Vacarro (USGS) in providing many of the MODFLOW input data sets used in the development of the Columbia Plateau regional aquifer system model, as well as providing hydrogeologic data from the ongoing Yakima Basin study. In addition, Paul Thorne (PNNL) provided hydrologic and stratigraphic data for the Hanford Site. All of these data were essential to this modeling investigation.

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1.0 Background

The Yakima River Basin Water Storage Feasibility Study (Storage Study) is an ongoing evaluation of alternatives for providing additional stored water for the benefit of fish, irrigation, and municipal water supply within the Yakima River basin. Congress has directed the Secretary of the Interior, acting through the Bureau of Reclamation (Reclamation), to conduct a feasibility study of options for additional water storage in the Yakima River basin. Sections 214 of the Act of February 20, 2003, (Public Law 108-7) contains this authorization and includes the provision "… with emphasis on the feasibility of storage of Columbia River water in the potential Black Rock Reservoir and the benefit of additional storage to endangered and threatened fish, irrigated agriculture, and municipal water supply." The Black Rock alternative includes building an off-channel storage reservoir in the Black Rock Valley about 6 miles south of Priest Rapids Dam, which is on the Columbia River. The reservoir would occupy about 13.67 square miles and have a storage capacity of about 1.46 million acre-feet when full. The Black Rock reservoir would be filled by pumping water from the Priest Rapids reservoir. The stored water would be conveyed to the lower Yakima Valley through a series of tunnels and canals (USBR, 2004c).

Groundwater investigations previously conducted by Reclamation include a Pacific Northwest National Laboratories (PNNL) assessment of the potential for increased mobility of contaminants beneath the Hanford Reservation as a result of increased groundwater levels due to reservoir seepage (PNNL, 2007).

To date, fourteen test holes have been drilled to investigate the geology and hydrogeology of the Black Rock damsite. Nine test holes were drilled by Reclamation, of these five were used to determine depth of sediments and the top elevation of basalts, and four were used for aquifer testing and water level observation (USBR, 2004b, 2004d and PNNL, 2004b, 2007b). Five test holes were drilled by Washington Infrastructure Services Inc. and used in the initial geotechnical investigation of the damsite (WIS, 2003). All but the four Reclamation observation wells were later backfilled and abandoned.

Given the current limited availability of hydrogeologic data from the site, any groundwater modeling effort aimed at predicting future reservoir seepage would necessarily have a significant amount of uncertainty associated with it. Nevertheless, model development under these conditions can still be extremely useful. Sensitivity analysis involving different conceptual models can provide a range of estimates for reservoir seepage and other reservoir hydrologic impacts. Equally important, Black Rock model results can be used to guide the process of future data acquisition at the reservoir site in order to reduce model uncertainty.

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2.0 Black Rock Groundwater Model Purpose and Scope

The following discussion of the development and application of the Black Rock groundwater model focuses mainly on answering five basic questions related to the hydrologic impacts of the reservoir. It also addresses the considerable uncertainty that exists in the answers to these questions.

2.1 Purpose of Modeling

The Black Rock model was developed in order to answer the following five questions regarding potential Black Rock reservoir hydrologic impacts and seepage conditions. A sixth question relates to the acquisition of additional aquifer test data in areas that are critical for reducing model uncertainty. The answer to this question is based largely on hydrologic insights and understanding gained from the current modeling effort.

1. How long would it take to fill Black Rock reservoir given the expected water availability and expected reservoir seepage rates?

2. What is the expected seepage rate from the Black Rock reservoir during initial filling?

3. What is the expected seepage rate from the reservoir over time, once filled to capacity?

4. What impact would the full reservoir have on groundwater discharge to creeks, drains and springs, aquifer storage, and aquifer head conditions?

5. What impact would the reservoir have on groundwater flow and head conditions at the boundary of the Hanford Reservation?

6. What additional field testing would be most valuable in reducing uncertainty in model predictions of reservoir hydrologic impacts?

2.2 Scope of Model Development and Application

The scope of the Black Rock model development and application is necessarily limited. However, the following modeling elements are considered essential to providing the most reliable answers possible to the six questions cited previously, in the time-frame and with the resources available.

- Application of a widely used and accepted groundwater modeling software package such as U.S. Geological Survey (USGS) MODFLOW.

- Representation of a heterogeneous, multi-layer aquifer system consistent with the generally understood hydrogeologic framework of the Columbia Plateau and the Yakima Fold Belt, and with previously developed groundwater models of the area.

- Development of a steady-state model of the aquifer system without the reservoir for calibration purposes, and a transient model with the reservoir, to represent reservoir/aquifer interactions through time.

- Specification of reservoir boundary conditions using either a time-dependent reservoir inflow rate or a time-dependent reservoir head condition.

- Introduction of model boundary conditions to represent potential increases in groundwater discharge to creeks, drains, and springs in the vicinity of the reservoir.

- Introduction of model boundary conditions in the vicinity of the reservoir where groundwater discharge to creeks, drains, and springs may potentially re-infiltrate the aquifer.

- A model calibration process that combines previous Columbia Plateau regional-scale model calibration work with model sensitivity analysis in the area of the reservoir site.

- Development of model versions that reflect early-time and late-time reservoir interactions with the aquifer system.

- Development of different model parameterizations that produce a range of estimates for reservoir seepage and other hydrologic impacts, reflecting uncertainty in estimates of aquifer hydrologic properties.

The elements of the Black Rock model development are discussed in greater detail in the following chapters of this report, beginning with a discussion of the hydrogeologic framework in Chapter 3. Chapters 4 through 6 describe model development, including modeling software, data sources, the model domain, model layering, model and reservoir boundary conditions, steady-state and transient versions of the model, and model calibration.

Chapters 7 and 8 describe model application and discuss model results. Applications of the Black Rock model are intended to show the full range of possible hydrologic impacts of the reservoir, given the current level of uncertainty that exists with respect to aquifer parameterization. As such, the model applications are presented in the form of a sensitivity analysis, conducted mainly with respect to aquifer hydraulic conductivity and aquifer specific-storage parameters.

Model results are depicted in hydrographs showing early-time and late-time reservoir interactions with the aquifer system. Hydrographs show expected reservoir seepage rates; increases in discharge to creeks, drains and springs; and increases in aquifer storage. Model results also include contour maps showing expected increases in aquifer head conditions around the reservoir, over time. Data tables show changes in groundwater flux conditions along the western boundary of the Hanford Reservation.

Chapter 9 provides detailed model-based answers to the six questions affecting reservoir hydrologic feasibility.

3.0 Hydrogeologic Framework of the Black Rock Model Area

The potential Black Rock dam and reservoir are located within the southwest portion of the Columbia Plateau, in an area known as the Yakima Fold Belt (Figure 3-1). The topography of the Yakima Fold Belt consists of northwest-southeast trending ridges (anticlines) separated by broad, flat valleys (synclines) that were folded and faulted under north-south compression. It is between two of these anticlines, Yakima Ridge on the north and Horsethief Mountain on the south, that the Black Rock dam and reservoir would reside.

The area surrounding the Black Rock Dam and reservoir, extending from the Yakima River on the west and south to the Columbia River on the east, is hereafter referred to as the model domain. Surface elevations within the model domain range from less than 400 feet at the confluence of the Yakima and Columbia Rivers, to more than 3,800 feet at the top of the Umtanum Ridge.

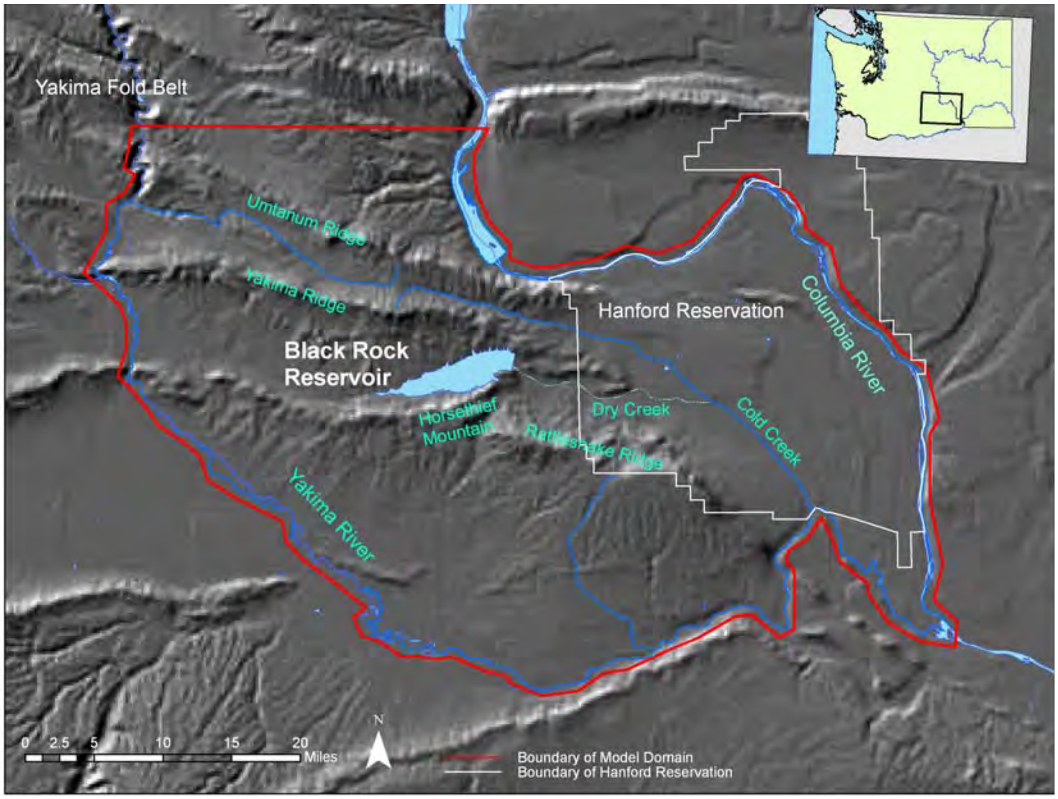

Figure 3-1: Topographic features in the Black Rock model domain.

3.1 Geologic Setting

Over 300 individual basaltic flows erupted from fissures in the eastern part of the Columbia Plateau during the Miocene Epoch (between 6 and 17 million years ago). Individual flows range in thickness from a few feet to more than 100 feet. The Columbia Plateau is the northern part of the Columbia River flood-basalt province and includes the thickest area of basaltic accumulation, on the order of 10,000 feet thick in the Pasco Basin. The flood basalts cover an area of over 63,000 mi^2 in the Pacific Northwest. Within the model domain, in the Yakima Fold Belt sub-province, the basalts overlie Tertiary continental sedimentary rocks. To the east of the fold belt, in the Palouse sub-province, the basalts are much thinner and overlie crystalline bedrock.

3.2 Stratigraphy

Rocks within the model domain are part of the Columbia River Basalt Group (CRBG) and consist of a series of lava flows with intercalated sediments. The basalts have been divided into separate formations based on their physical, geochemical, and paleomagnetic polarity differences. From oldest to youngest the basaltic formations include the Grande Ronde, Wanapum, and Saddle Mountains Basalt. Figure 3-2 is a generalized stratigraphic column that shows the relationship between the basaltic formations, interbedded sediments of the Ellensburg Formation, and the unconsolidated materials overlying the basalt.

The Grande Ronde Basalt is the deepest, most voluminous and areally extensive of the basaltic formations. Individual flows are often only distinguishable by their magnetic polarity (normal or reversed direction). The Grande Ronde is found mainly in the subsurface (from depths of >1,000 feet) and is only exposed at the surface where faulting along the anticlinal ridges (e.g. Umtanum ridge in the northern part of the model domain) has uncovered these rocks. The top of the Grande Ronde is generally defined by a zone of weathering or the presence of a sedimentary interbed (the Vantage sandstone).

The Wanapum Basalt overlies the Grande Ronde and is found throughout the model domain at depth. The uppermost member (Priest Rapids) is exposed in limited, but important outcrops on Horsethief Mountain near the south abutment of the dam (Figure 3-3). The exposures at the east end of Horsethief Mountain have been interpreted to be on the hanging wall of Horsethief Mountain fault (Bentley and Peterson, 2003). The Wanapum Basalt is probably continuous along the ridge to the west at shallow depth and connected to the Wanapum outcrops that are mapped higher on the hill slope. These outcrops are at elevation 1,570 feet and below; therefore, they would be in contact with the reservoir. The upper outcrops are interpreted to be located in the hinge area of the Horsethief Mountain anticline (Bentley and Peterson, 2003) where there may be stress fractures associated with the folding that could enhance horizontal and vertical hydraulic conductivity.

Geologic Framework								Hydrogeologic Framework	Model Layers
Basalt Stratigraphy							Sediment Stratigraphy	Unit	
Holocene to Miocene							Sediments (gaciofluvial, fluvial, lacustrine, eolian, and ash fall materials). Locally includes sediments of the Hanford, Palouse, Latah, Ringold and Ellensburg Formations.	Overburden sediments	Layer 1
Miocene	Upper Miocene	Columbia River Basalt Group	Saddle Mountains Basalt	Lower Monumental Member Ice Harbor Member Buford Member Elephant Mountain member Pomona Member Esquatzel Member Weissenfels Ridge Member Asotin member Wilbur Creek Member Umatilla Member			*Intercalated sediments of the Ellensburg Formation* —— Levey Interbed —— Rattlesnake Ridge Interbed —— Selah Interbed —— Cold Creek Interbed —— Mabton Interbed	Saddle Mountains Unit	Layer 2
	Middle Miocene		Wanapum Basalt	Priest Rapids Member Roza Member Frenchman Springs Member Eckler Mountain Member			—— Vantage Interbed	Wanapum unit	Layer 3
	Lower Miocene		Grande Ronde Basalt		Magnetostratigraphic units[1]	N_2 R_2		Grande Ronde Unit	Layer 4
						N_1 R_1			Layer 5

[1]Magnetostratigraphic units: N – normal polarity; R- reverse polarity; units numbered sequentially from oldest to youngest.

Figure 3-2: Stratigraphic chart for the Columbia Plateau (Modified from USGS, 1999).

The Wanapum Basalt is a very productive aquifer throughout the Columbia Plateau and is widely used for irrigation and municipal wells. To the west of the Black Rock reservoir site, in the Moxee valley, the Wanapum aquifer is partitioned by geologic structure, and portions of the aquifer have experienced water level declines due to irrigation pumping (Kirk and Mackie, 1993). The Mabton sedimentary interbed overlies the Wanapum Basalt and is a confining bed that separates the underlying Wanapum layer from the overlying Saddle Mountains layer.

The Saddle Mountains Basalt erupted during a period of decreased volcanism and increased folding. It exhibits increased development of sedimentary interbeds between flows and has a volume of less than 1 percent of the total volume of the CRBG, yet is the most chemically diverse of any of the basaltic formations in the group (Swanson and Wright, 1978). The thickness and extent of the Saddle Mountains Basalt also vary more than other basaltic units. Of the ten Saddle Mountains members identified throughout the Columbia Plateau, only half are found in the model domain and some cover only a small area. Basaltic exposures at the surface are principally those of the Saddle Mountains unit (Figure 3-4).

Three members of the Saddle Mountains Basalt, the Pomona, Esquatzel, and Umatilla, are found in the Black Rock valley and in the adjacent anticlinal ridges. The Elephant Mountain member, encountered in two test holes drilled within the Black Rock valley, is probably limited in aerial extent because it is confined by an ancient erosional channel that filled in this area. The Elephant Mountain flow is more extensive in the eastern part of the model domain. Outcrops of the Elephant Mountain flow are mapped along the Dry Creek valley, southeast of the damsite (Figure 3-3).

The interbedded sediments between basaltic flows are stratigraphically assigned to the Ellensburg Formation and are mainly found between flows of the Saddle Mountains Basalt. Towards the end of the volcanism period, there were longer intervals of time between subsequent flows for deposition to occur. The interbeds are relatively thin, compared to the thick sequence of basalts, and are generally fine-grained, weakly consolidated and have low permeability. However, in some areas the interbeds are coarse-grained and serve as aquifers. The interbed materials were derived chiefly from volcanic activity and erosion from the Cascade Range and from the anticlinal ridges.

The Ellensburg Formation comprises most of the unconsolidated sediments overlying the basalts in synclinal basins in the western part of the model domain. Basin-fill deposits also include alluvium, wind-blown silt (loess), alluvial fan deposits, and flood gravels. These deposits were recently mapped in the Yakima River Basin by the U.S. Geological Survey for a separate groundwater study (USGS, 2006b). Thickness of the basin-fill sediments varies from 0 (absent) to more than 500 feet.

The Ringold Formation overlies basalts in the eastern part of the model domain (Figure 3-4). The Ringold Formation consists of fluvial sediments derived from ancestral rivers that flowed into and through the Pasco Basin during the Pliocene Epoch. These deposits vary in texture, consolidation, and saturation. The mapped thickness of the Ringold sediments and overlying glaciofluvial deposits (informally called the Hanford formation) within the Hanford Reservation were obtained from Pacific Northwest National Laboratory (PNNL, 2006).

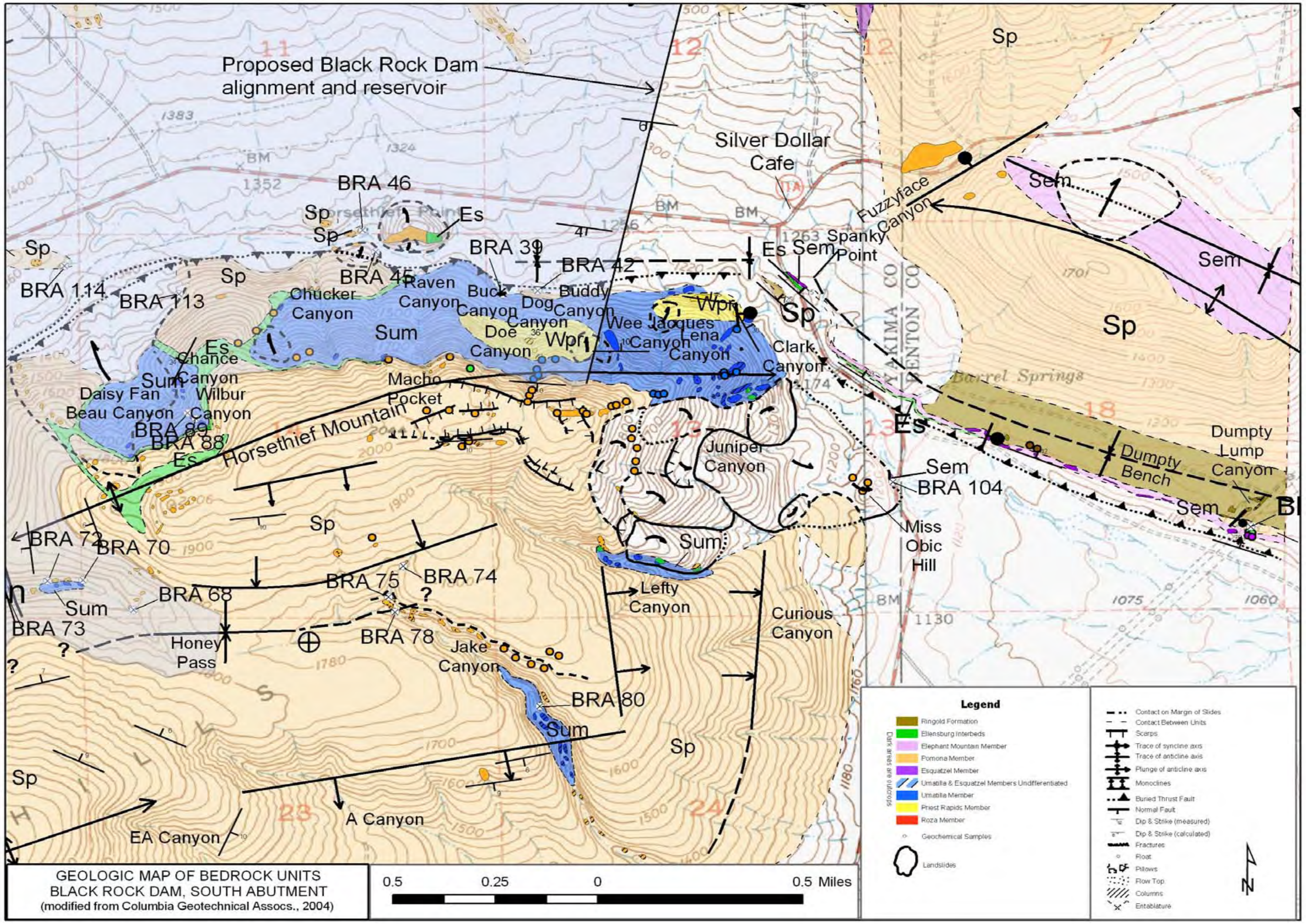

Figure 3-3: Geologic map of bedrock units underlying Black Rock dam right abutment.

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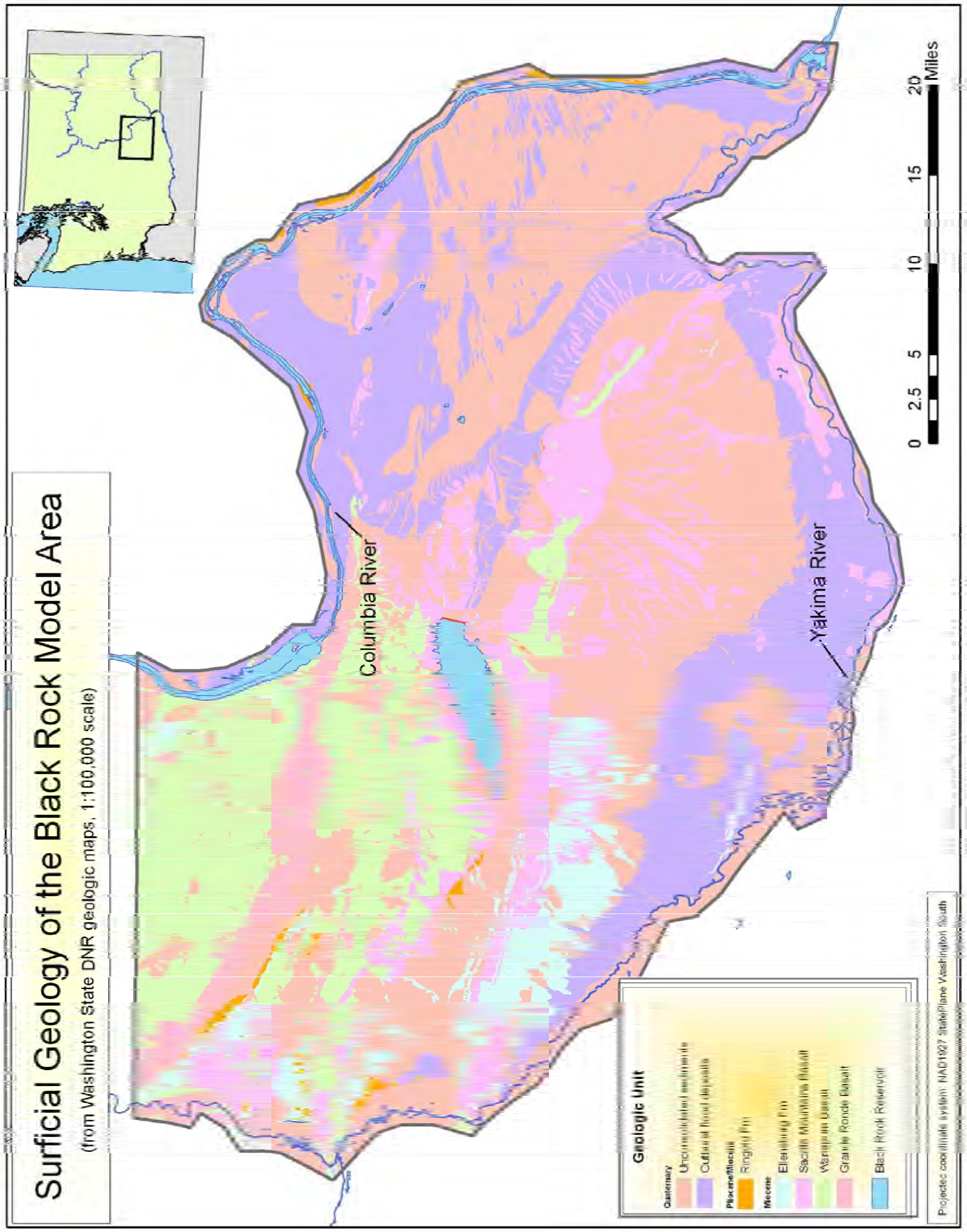

Figure 3-4: Surficial Geology of Black Rock model area.

3.3 Geologic Structure

The uplift of the Yakima Fold Belt started during the eruption and emplacement of the underlying basalts; most of the structural relief has developed in the last 10 million years and continues to the present. The anticlines are often complexly folded and faulted with en echelon thrust faults extending along the base of the northern limb. Most of the anticlines in the Yakima Fold Belt are asymmetric in shape with a steeply dipping north limb and a shallow dipping south limb. The folds are often segmented by cross-structures. To the west, the Hog Ranch anticline separates the Black Rock Valley to the east from the Moxee Valley to the west. In addition, large-scale deformation zones have displaced and deformed parts of the Yakima Fold Belt. For more detail on the structural geology of the region, refer to Reidel and others (2003), Bentley and Peterson (2003), and Campbell (1998).

The potential Black Rock damsite is located at the east end of the Black Rock Valley where the Yakima Ridge anticline turns southeast and Horsethief Mountain anticline extends northeastward from the Rattlesnake Hills. Bentley and Peterson (2003) described this as a “convergence zone” where the structures appear to intersect in a north-trending cross structure that they name the Cairn Hope Peak Axis (CHPA). Along the axis, the ridges change from simple, large amplitude folds to a diffuse series of smaller folds that may be more complexly faulted and folded. On their tectonic map (Figure 3-5) they show an east-west trending, south dipping thrust fault at the northern base of Horsethief Mountain and an intersecting northwest trending thrust fault that dips to the north. This fault, named the Barrel Springs fault, extends to the southeast from the damsite, along the Dry Creek Valley. It is uncertain whether the fault zone in the Dry Creek drainage represents a more intensely fractured, high permeability zone. There is anecdotal evidence however that historic “Barrel Springs”, mapped along the east side of the fault, stopped flowing when irrigation wells located on the west side of the fault began pumping from the Wanapum Basalt aquifer (personal communication Brett Lenz, Columbia Geotechnical Associates, 2004).

3.4 Hydrogeology

The occurrence and flow of groundwater within the Black Rock model domain are controlled primarily by the physical characteristics of the rock units, geometry and relationship between rock units, and geologic structure. The physical characteristics of the basaltic flows (density and texture, fractures, and internal structures) are important in determining their hydraulic properties. Internal structures found in the flows may influence both the ease of water movement and direction through the formation. Individual basaltic flows typically exhibit features that are formed from the emplacement and cooling of the flow. These features may include a vesicular flow top, dense flow interior, and vesicular or brecciated flow bottom. If the basalt flowed into a body of water or encountered saturated sediments, a pillow-shaped structure is formed and the space between the pillows is usually composed of palagonite (hydrated basaltic glass). The dense interior portions of the flows have predominately vertical cooling joints and exhibit a high level of anisotropy, with preferred vertical flow and very low lateral permeability. The combination of flow top with the adjacent flow bottom of the overlying flow is called an “interflow” and this zone generally has high lateral permeability. The basaltic flows and interflow zones are often laterally continuous for tens of miles.

The thickness and extent of flows and the occurrence or absence of fine-grained sedimentary interbeds also influence groundwater movement. At the distal ends of the basaltic flows or where erosion has interrupted the continuity of flows, interbedded sediments are able to co-mingle and may serve as a vertical conduit between previously separated flow systems. Often, the dense flow interiors and fine-grained interbeds serve as confining layers between the more permeable interflow zones.

Folding, faulting, and other large-scale geologic deformation can affect regional groundwater flow direction, influence hydraulic gradients, and create flow conduits or barriers. At least some of the faults in the model domain are proven hydraulic barriers. Others appear to be conductive and may connect deep basaltic formations with shallower formations and surface springs. Folding increases the occurrence of fractures on the anticlinal ridges and tends to enhance aquifer hydraulic conductivity.

3.5 Aquifer Recharge and Discharge

Local, intermediate, and regional scale groundwater flow systems within the model domain are recharged by various mechanisms. On a regional scale, basaltic units are recharged along the western margin of the Columbia Plateau where the basalts interfinger with pre-basaltic rocks and sediments at higher elevations in the Cascade Range. Intermediate and local flow systems are recharged through basalts that are exposed to precipitation at the ground surface on the anticlinal ridges, and through groundwater exchange with other basins and formations.

The lower arid portion of the Yakima River basin and the Hanford Reservation generally receives about 6 to 10 inches of precipitation annually. The ridges at higher elevations receive between 10 and 20 inches. In addition, crop irrigation on surficial sediments has increased recharge to the groundwater system of the Yakima Basin. Almost half of the applied irrigation water eventually returns to the surface via tile drains. Irrigation return flows to the lower Yakima River account for about 75 percent of the streamflow below the streamflow gaging station near Parker (USGS, 2006a).

Aquifer discharge occurs principally to major surface drainage systems (i.e. Yakima and Columbia Rivers) and through irrigation well pumping. Annual pumpage in the

Yakima River basin increased almost 270 percent from 1960 to 2000 (USGS, 2006a). About 430 ft^3/s were pumped in 2000, with 60 percent of the pumpage for irrigation and another 12 percent for municipal water supply.

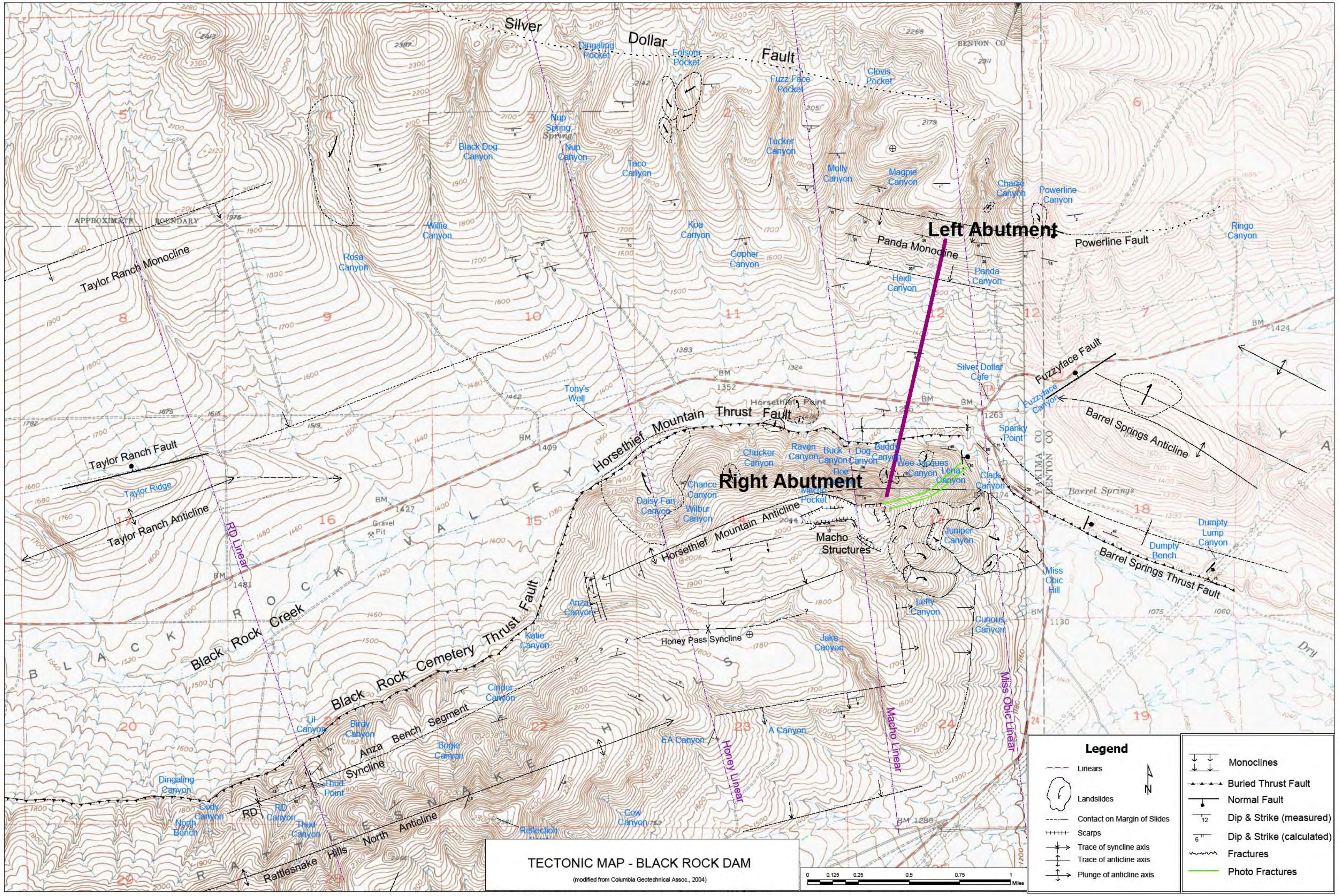

Figure 3-5: Tectonic map of the Black Rock damsite.

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4.0 Black Rock Model Development

The Black Rock model was developed using the well established USGS groundwater flow modeling software package MODFLOW 2000 (USGS, 2000). MODFLOW has been widely used for regional modeling problems for over 20 years and is widely regarded as a standard software package for groundwater flow modeling.

4.1 Principal Data Sources

The Black Rock model builds directly upon previous USGS modeling studies in the Columbia Plateau. Foremost among these is the USGS Columbia Plateau regional aquifer system modeling study (USGS, 1993; USGS, 1994; USGS, 2000b). The USGS Columbia Plateau aquifer model is a five-layer regional model of the groundwater flow system in the Columbia Plateau. Figure 3-2 shows the relationship between stratigraphic layers in the Columbia Plateau and modeled aquifer layers.

Aquifer properties, including thicknesses and hydraulic conductivities, of the Saddle Mountains layer (layer 2), Wanapum layer (layer 3), and Grande Ronde layers (layers 4 and 5) were imported directly from the Columbia Plateau regional aquifer model into the five-layer Black Rock model. Surficial aquifer recharge and discharge rates also came from the Columbia Plateau regional aquifer model.

The spatial distribution and hydrologic properties of the overburden sediment layer (layer 1 in the Black Rock model) were obtained from two other sources: USGS investigations of the hydrogeologic framework of sedimentary deposits in structural basins within the Yakima River Basin (USGS, 2006b); and assessments of surficial geologic processes and hydrogeologic conditions in the Pasco Basin (Rockwell International, 1979a, 1979b, 1980a).

Fault zone and fracture mapping described in the report, *Geologic Investigation of Black Rock Dam, Alternate Damsite, Yakima County, Washington* (Columbia Geotechnical Associates, 2004), were used as a guide in developing alternative conceptual models for permeability distributions in Saddle Mountains and Wanapum layers, in the vicinity of the damsite. The results of aquifer testing at the damsite by Reclamation (USBR, 2004d and PNNL, 2007b) were used to determine the appropriate range of permeability values for these conceptual models.

4.2 Black Rock Model Domain

The Black Rock model domain is a relatively small subset of the area represented in the USGS Columbia Plateau regional aquifer system model (Figure 4-1). The regional model grid covered an area of about 32,700 mi^2 with cells that were about 4 square miles. The Black Rock model focuses on a much smaller area within the regional grid, about 1,730 mi^2 centered approximately on the reservoir site, with grid cells that range between 0.08 and 0.32 mi^2.

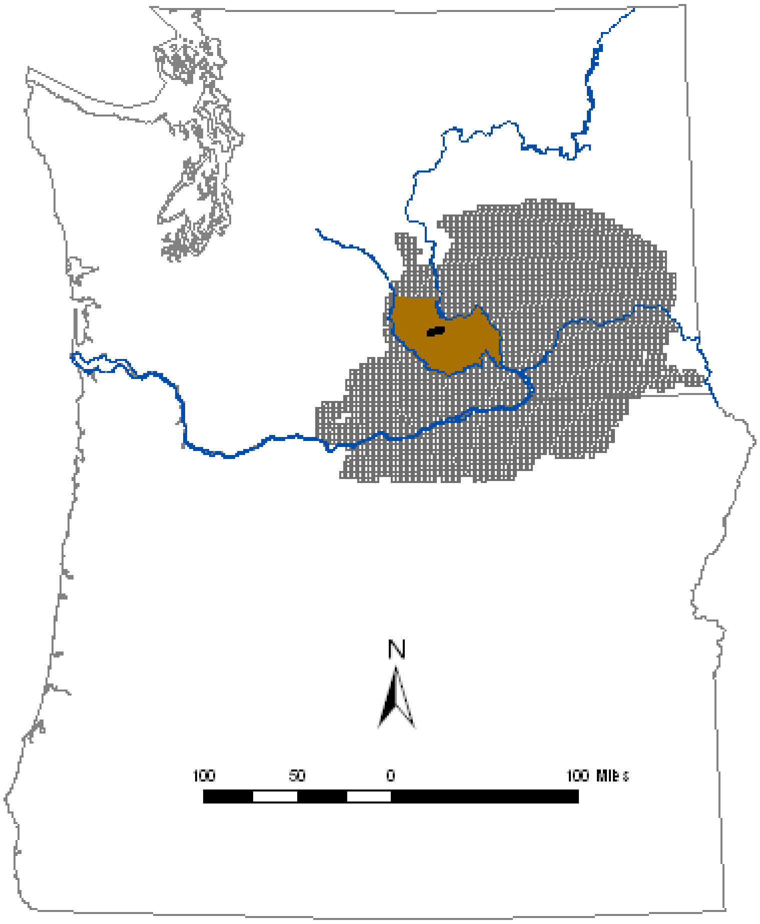

Figure 4-1: Black Rock model area in relation to the USGS Columbia Plateau Model area.

Figure 4-2 shows the MODFLOW grid developed for the Black Rock model. The model grid is bounded on the east side by the Columbia River and on the south and west side by the Yakima River. On the north side it is bounded by an east-west line between the two rivers about 18 miles north of the reservoir site, just to the north of the Priest Rapids reservoir. No structural boundaries exist in this area between the Yakima and Columbia Rivers north of the reservoir. However the two uppermost model layers underlying the reservoir (the sediment layer and the Saddle Mountains layer) are absent over most of this area, and all along the northern model boundary. In the absence of the two uppermost layers, a general head boundary condition need be assigned only to the Wanapum and Grande Ronde model layers. Under these conditions, the northern model boundary is believed to be distant enough from the reservoir to have minimal influence on reservoir modeling results.

There are between 4,000 and 7,000 active cells in each of the five Black Rock model layers. Model cells are active within the model domain where geologic layers are present and inactive where they are absent. Most grid cells are 3,000 x 3,000 feet square. Cells in the immediate area of the reservoirs site are 1,500 x 1,500 feet square. MODFLOW uses a finite-difference numerical modeling approach to calculate a single average aquifer head and a single average groundwater flux for each grid cell.

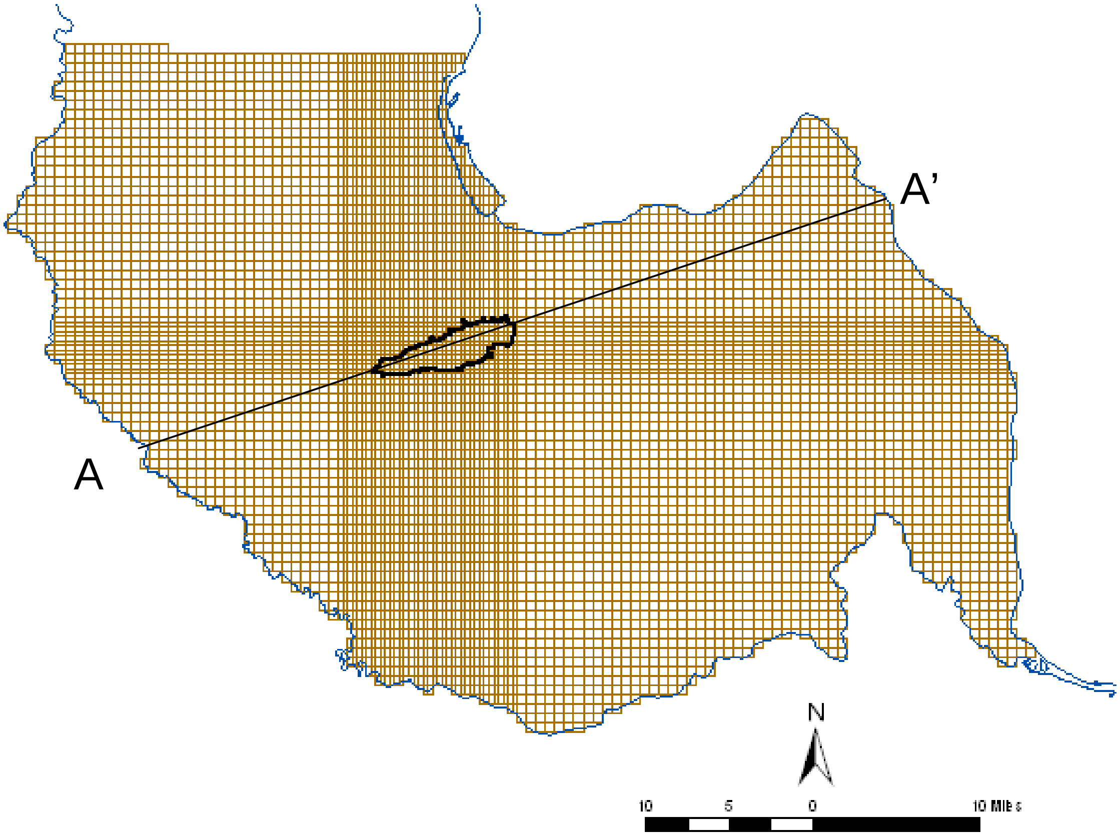

Figure 4-2: Black Rock model grid cells.

4.3 Model Layers

The association between Black Rock model layers and the regional stratigraphy of the Columbia Plateau is indicated in Figure 3-2. Model layer 1 consists of surficial units; loess, glacio-fluvial deposits, alluvium and alluvial fans, and unconsolidated sediments of the Ringold and Ellensburg Formations. Layer 1 sediments of the Ellensburg Formation are present in four Yakima River Valley structural basins, portions of which are located within the model domain (USGS, 2006b). In addition to these four structural basins, layer 1 sediments of the Ringold Formation are present in a portion of the Pasco Basin that includes the Hanford Reservation east of the reservoir site. Where the sediment layer is present, the top elevation of this layer is the land surface elevation, which is based on a 10-meter digital elevation model (DEM) of the model domain. Within the four structural basins, the bottom elevation of the sediment layer is assumed to be the top elevation of the basalt, as indicated in USGS report 2006-5116 (USGS, 2006b). Within the Pasco Basin (mainly the Hanford Reservation), the bottom elevation of the sediment layer is assumed to be the top elevation of the Elephant Mountain Basalt. Not all sediments in the model domain are saturated, and the sediment layer is modeled as an unconfined aquifer layer.

Model layer 2 consists of the Saddle Mountains Basalt and associated sedimentary interbeds. The upper portion includes the Elephant Mountain and Pomona Basalts along with overlying and underlying Rattlesnake Ridge and Selah interbeds. The lower portion includes the Esquatzel and Umatilla Basalts and the Cold Creek and Mabton interbeds. The Saddle Mountains layer is not present everywhere within the model domain. For the most part, the Elephant Mountain basaltic member is only present within the model area in the Pasco Basin. The Pomona Basalt is absent along portions of the Rattlesnake Hills and along much of the Yakima and Umtanum anticlinal ridges.

Model layer 3 consists of the Wanapum Basalts and associated sedimentary interbeds. Layer 3 consists mainly of the Priest Rapids, Roza, and Frenchman Springs basaltic members together with the Squaw Creek interbed. Layer 3 is present within most of the model domain including the Rattlesnake Hills and much of the Yakima and Umtanum ridges.

Figures 4-3 through 4-5 show the locations of active cells in Black Rock model layers 1, 2, and 3. Active cells are locations where these layers are present within the model domain. The figures also show the locations of head-dependent boundary conditions (including general head boundaries) used to represent hydrologic features that intersect each of the layers, including rivers, creeks, drains, springs, and the reservoir itself. Grande Ronde layers 4 and 5 are active everywhere within the model domain, and there are no internal boundary conditions in these layers. Black Rock model boundary conditions are described in more detail in a later chapter of the report.

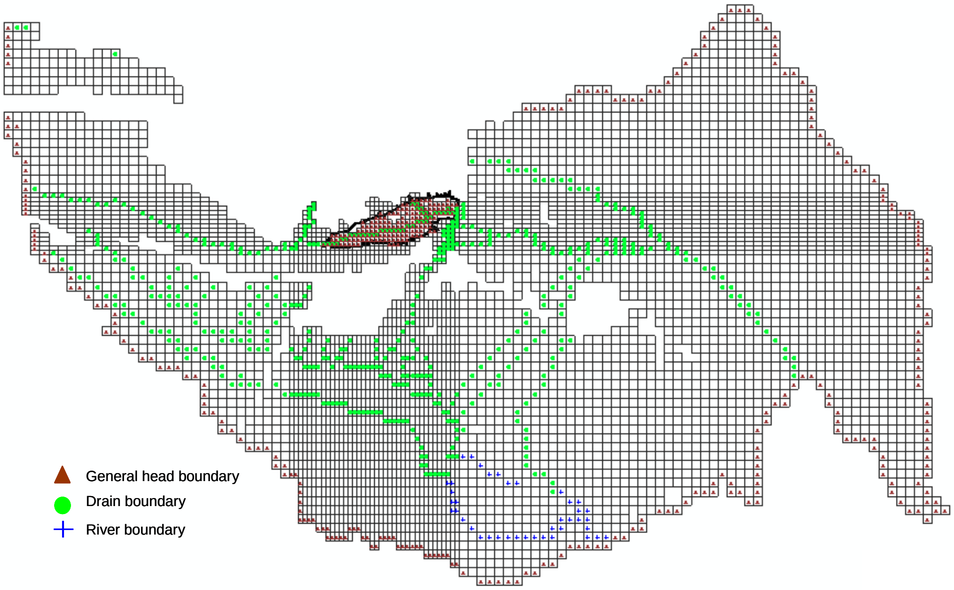

Figure 4-3: Sediment layer (model layer 1) active grid cells.

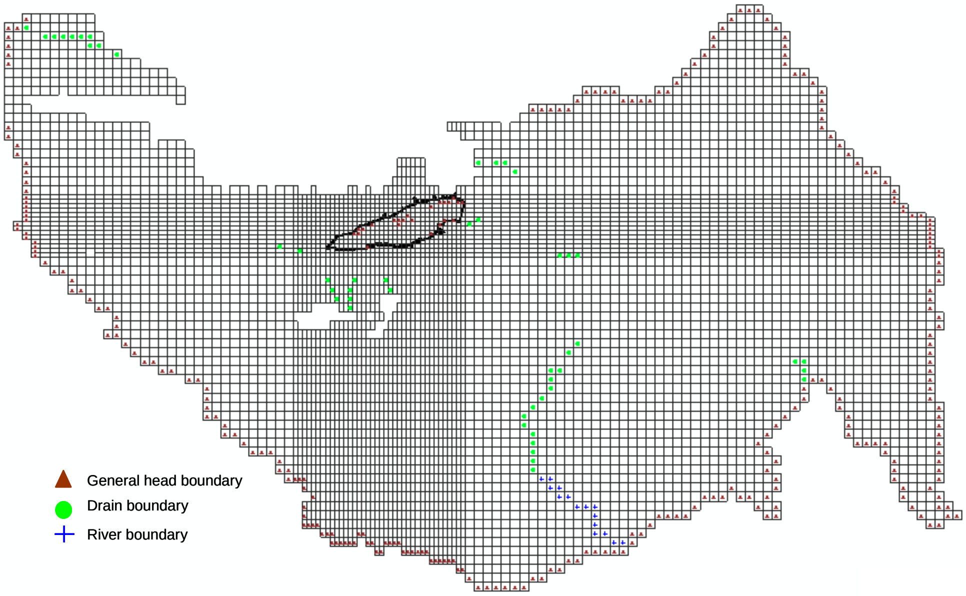

Figure 4-4: Saddle Mountains layer (model layer 2) active grid cells.

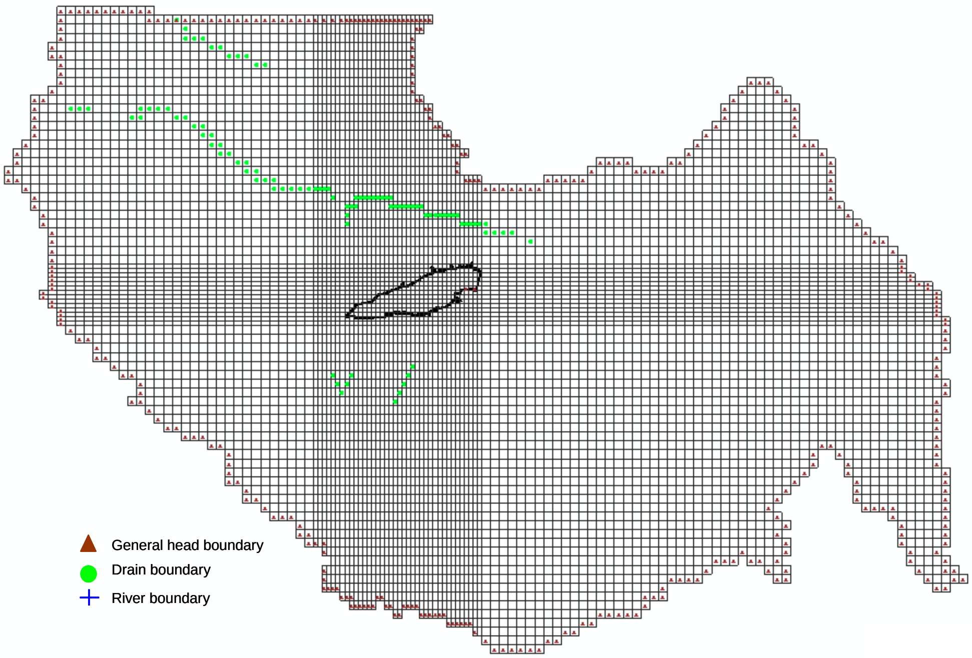

Figure 4-5: Wanapum layer (model layer 3) active grid cells.

Figure 4-6 is an east-west cross-section through the middle of the model grid running directly beneath the reservoir site (see Figure 4-2). The approximate boundaries of the reservoir and the approximate location of Cold Creek are noted along with layer thicknesses at the east end of the cross-section.

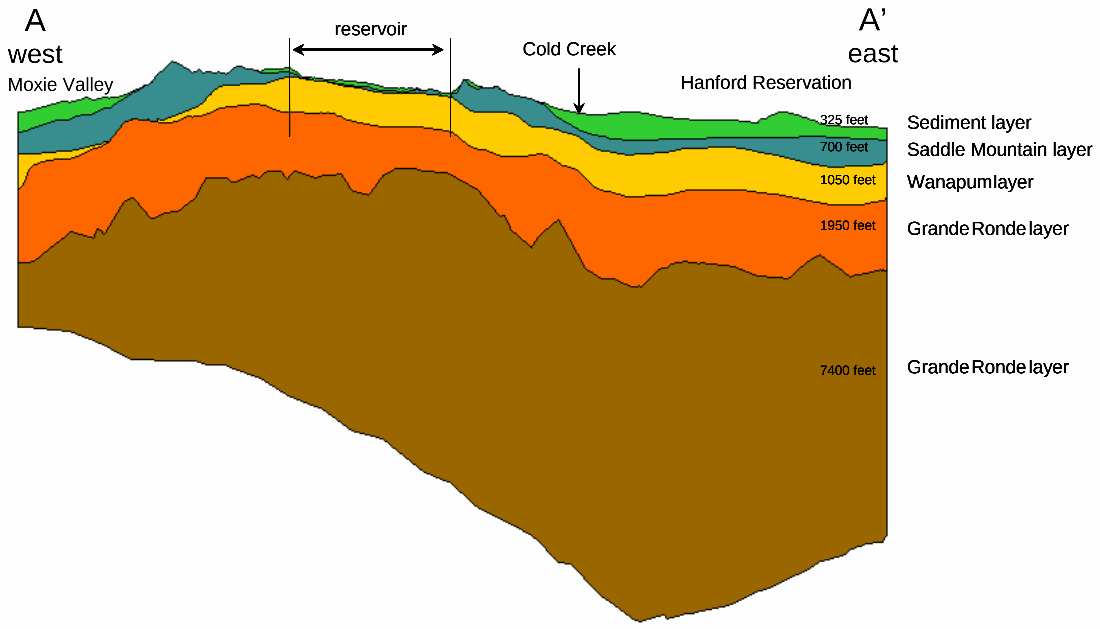

Figure 4-6: Five-layer Black Rock model cross-section.

The cross-section illustrates some of the variation in thickness that exists in model layers within the model domain. The sediment layer is comparatively thin beneath the reservoir and for some distance east and west of the reservoir. However, it is considerably thicker beneath Moxee Valley and beneath the Hanford Reservation. The Saddle Mountains layer is also comparatively thin beneath the reservoir, but becomes thicker immediately to the east and west of the reservoir. On the other hand, the Wanapum layer is thickest directly beneath the reservoir and to the east of the reservoir, but thins to the west. While the Grande Ronde layers are by far the thickest model layers, because of their depth they have little interaction with the reservoir.

In fact, the Grande Ronde layers 4 and 5 are included in the Black Rock model not because they are likely to be impacted by the reservoir, but simply because they were part of the original Columbia Plateau Regional groundwater model, and because that model was calibrated using five layers. Black Rock model results developed in this study pertain only to the three uppermost layers, the sediment, Saddle Mountains, and Wanapum layers. Table 4-1 summarizes some of the thickness properties of these three model layers.

Table 4-1: Thickness properties of Black Rock model layers.

	Sediments (layer 1) (feet)	**Saddle Mountains (layer 2) (feet)**	**Wanapum (layer 3) (feet)**
Minimum [1]	0	0	8
Maximum	1419	2271	1842
Average	266	461	759

[1] Layers are absent in certain areas of the model domain.

4.4 Hydrologic Properties of Model Layers

Hydraulic conductivities of model layers can be inferred from injection or pumping tests in drill holes, and from water level measurements and trends. Extensive aquifer testing was completed at the Hanford Reservation during the 1970's and 1980's and hydraulic properties were determined for various zones within the basalts (Rockwell International, 1979c; Rockwell International, 1980b). The testing revealed that hydraulic conductivity of the basaltic flow tops ranges from $1x10^{-11}$ to $1x10^{-4}$ ft/s. In the dense flow interiors, horizontal hydraulic conductivity ranges from $1x10^{-14}$ to $1x10^{-8}$ ft/s. Vertical hydraulic conductivity was estimated to be 1 to 3 times that of the horizontal conductivity of flow interiors, or between $1x10^{-14}$ to $3x10^{-8}$ ft/s. Ellensburg Formation interbeds were determined to have horizontal conductivities ranging from $1x10^{-11}$ to $1x10^{-5}$ ft/s.

Limited aquifer testing was also accomplished at the Black Rock site during field investigations between 2004 and 2006 (PNNL, 2004b and 2007b). The onsite tests provided estimates of hydraulic conductivity in the basin-fill sediments, basaltic units, Ellensburg Formation interbeds, and fault zone breccia that were encountered in the area of the right dam abutment (south abutment). Hydraulic conductivity estimates obtained from these tests are summarized in Table 4-2.

Horizontal and vertical hydraulic conductivities of sediment and basaltic layers were also estimated by the USGS as part of the Columbia Plateau Regional Groundwater Model development and calibration process (USGS, 1994).

To a large extent, the horizontal and vertical hydraulic conductivities used in the Black Rock model are taken directly from the calibrated Columbia Plateau Regional Groundwater Model. Some adjustments to USGS regional model hydraulic conductivities in the Saddle Mountains and Wanapum layers were made, mainly in the area of the damsite. The adjustments were done to reflect the range of hydraulic conductivity values in Table 4-2 and were made as part of a localized model sensitivity analysis that will be described in a later chapter. Table 4-3 shows the range of adjusted horizontal and vertical hydraulic conductivities used in the calibrated Black Rock model, which is within the range used in the USGS regional model.

Table 4-2: Hydraulic conductivity values estimated from aquifer tests at the Black Rock Dam and Reservoir site.

Formation Tested	**Drill Hole Tested[1]**	**Test in Vadose (V) or Groundwater Zone (GW)**	**Hydraulic Conductivity[2] (ft/sec)**
Quaternary Alluvium	DH-04-02	V	9.84x10^{-6}
Ringold Formation	DH-04-02	V	3.06 x10^{-5}
Rattlesnake Ridge Interbed	DH-04-02	V	9.26 x10^{-6}
Pomona Basalt –Flowtop	DH-04-02	V	4.63 x10^{-7}
Selah Interbed	DH-04-02	GW	3.11 x10^{-5}
Composite: Selah & Esquatzel Basalt	DH-04-02	GW	8.96 x10^{-5}
Mabton Interbed	DH-04-02	GW	3.47 x10^{-7}
Pomona Basalt	DH-05-1	V	5.32 x10^{-6} - 1.61 x10^{-5}
Esquatzel/Umatilla Basalt	DH-05-1	V	5.21 x10^{-6} - 2.40 x10^{-4}
Fault Zone Breccia	DH-05-1	GW	8.56 x10^{-6}
Pomona Basalt	DH-05-1	GW	3.70 x10^{-6} - 1.22 x10^{-4}
Esquatzel/Umatilla Basalt	DH-06-1	V	2.25 x10^{-5}
Fault Zone Breccia	DH-06-1	V	4.36 x10^{-5}
Fault Zone Breccia	DH-06-1	GW	4.86 x10^{-6}
Pomona Basalt	DH-06-1	GW	1.09 x10^{-4} 6.12 x10^{-4}

[1] DH-04-2 located in Black Rock valley, upstream of damsite; DH-05-1 and DH-06-1 located on lower south abutment of the dam.

[2] For details on testing methods and analysis, see PNNL, 2004b and 2007b.

Table 4-3: Horizontal and vertical hydraulic conductivities used in Black Rock model layers.

	Sediments (layer 1)		**Saddle Mountains (layer 2)**		**Wanapum (layer 3)**	
	Vertical hydraulic conductivity (ft/s)	**Horizontal hydraulic conductivity (ft/s)**	**Vertical hydraulic conductivity (ft/s)**	**Horizontal hydraulic conductivity (ft/s)**	**Vertical hydraulic conductivity (ft/s)**	**Horizontal hydraulic conductivity (ft/s)**
Minimum value	1.0x10^{-12}	2.0 x10^{-6}	1.95 x10^{-10}	5.0 x10^{-9}	1.0 x10^{-12}	1.0 x10^{-9}
Maximum value	1.0 x10^{-5}	2.31 x10^{-3}	1.0 x10^{-4}	2.89 x10^{-4}	2.89 x10^{-4}	8.0 x10^{-3}
Average value	1.18 x10^{-6}	5.83 x10^{-4}	1.28 x10^{-6}	1.21 x10^{-5}	2.07 x10^{-7}	1.07 x10^{-4}

Although the Columbia Plateau Regional groundwater model was not a transient model, several estimates of storage coefficients and specific-yields for basalts and sediments were included in model publications (USGS, 1994; USGS, 2000b). Estimates of specific-yields for sediments ranged from .03 to 0.2. Estimates of storage coefficients for Saddle Mountains and Wanapum Basalts ranged from 0.0025 to 0.032 and from 2.0x10^{-5} to 0.032, respectively.

Using these estimates and based on the distribution of layer thicknesses within the Black Rock model domain (Table 4-1), a range of values was produced (Table 4-4), reflecting likely minimum, maximum, and average values for specific-yield in the unconfined sediment layer, and specific-storage in the Saddle Mountains, Wanapum, and Grande Ronde layers.

Table 4-4: Specific-yield /specific-storage estimates used in Black Rock model layers.

Model layer	**Hydrogeologic Unit**	**Minimum estimate [1]**	**Maximum estimate [1]**	**Average of all estimates [1]**
1	fluvial and glaciofluvial sediments	.03	.2	.12
2	Saddle Mountains Basalt	3.0x10^{-6}	6. 0x10^{-5}	2. 0x10^{-5}
3	Wanapum Basalts	3. 0x10^{-8}	4. 0x10^{-5}	5. 0x10^{-7}
4-5	Grande Ronde Basalts	3. 0x10^{-10}	1. 0x10^{-6}	2. 0x10^{-7}

[1] layer 1 specific-yield units are dimensionless; layer 2-5 specific-storage units are ft^{-1}

4.5 Black Rock Model Boundary Conditions

Previously, Figures 4-3, 4-4, and 4-5 showed the locations of all MODFLOW cells in the Black Rock model with head-dependent boundary conditions. The outer boundaries of the model, including the Columbia River and Yakima River, are represented using the MODFLOW General-Head Package (GHP). The GHP Package is used instead of the MODFLOW River Package because the Black Rock model is not used to make predictions about river gains or losses. GHP head boundary conditions along the rivers, in the uppermost model layer, are the same as the river stage. In lower layers and along the line boundary north of the site, GHP head boundary conditions are the aquifer heads calculated by the Columbia Plateau regional groundwater model.

Head-dependent boundary conditions are also used to represent aquifer interactions with creeks, drains, and springs (and the reservoir itself) located inside the model boundary. With the exception of the reservoir, all of these head-dependent boundary conditions are surface elevations obtained from a 10-meter DEM.

In the absence of the reservoir, most creeks and drains inside the model domain (including Selah Creek, Cold Creek, and Dry Creek) (see Figure 3-1) are dry throughout most of the year. Almost all are represented in the model using the MODFLOW Drain Package. (A small portion of lower Cold Creek is a perennial stream and is represented by the MODFLOW River Package.) Groundwater can be discharged from the aquifer to MODFLOW drain cells, but drain cells cannot recharge the aquifer. Dry Creek, Selah Creek, and almost all of Cold Creek are represented using the MODFLOW Drain Package. Once the reservoir is introduced in the model, re-infiltration along a portion of the Dry Creek drainage is included via the MODFLOW Recharge Package. The process used to determine the Dry Creek re-infiltration rate is described in a later chapter of the report.

The conductances of all MODFLOW General Head, River, and Drain cells are set to large values, so as not to be a factor in limiting interaction with the aquifer. Aquifer interaction with head-dependent boundaries is limited only by the horizontal and vertical hydraulic conductivities of the model layers themselves.

Depending on which layers are exposed on the surface, MODFLOW drain cells may be present in model layers 1, 2, or 3 (see Figures 4-3, 4-4, and 4-5). For the most part, the head condition that is assigned to a MODFLOW drain cell is the surface elevation of the cell. However, some drain cells represent deeply incised creek beds that penetrate two model layers. If a creek is present only in the uppermost model layer, then the head condition of the drain cell is the top elevation of the uppermost model layer, based on the 10-meter DEM. However, if a creek is deeply incised and penetrates multiple layers, then a drain cell exists in both layers. The head condition of the drain cell in the underlying layer is the top elevation of that layer. The head condition of the drain cell in the overlying layer is the bottom elevation of that layer.

5.0 Steady-State Base-Case Model Development and Calibration

The steady-state Black Rock model, in the absence of the reservoir, is referred to as the base-case model. The steady-state, base-case Black Rock model is used to establish initial conditions for the transient Black Rock model. It is also used to calculate base-line aquifer heads, aquifer fluxes, and drain cell discharge rates (representing creeks, drains, and springs) for later comparison with transient model results.

As mentioned previously, the base-case Black Rock model calibration is built largely on the steady-state calibration conducted earlier by the USGS, as part of the Columbia Plateau regional groundwater model development (USGS, 1994). One drawback of adopting the USGS calibration stems from differences in the spatial resolution of the two models. The Columbia Plateau regional model grid cells are about 4.0 mi^2, the Black Rock model cells, on the other hand, are less than 0.32 mi^2.

As described previously, hydraulic conductivities within a square mile area of the Saddle Mountains layer can vary by up to four orders of magnitude (see Table 4-2). The most notable aquifer heterogeneities are associated with faulting and fracturing along the southern rim of the reservoir in the area of the right dam abutment, and at the intersection of the Horsethief Mountain and Barrel Springs thrust faults along the Dry Creek drainage (see Figure 3-4).

Currently 21 observation wells are located in the vicinity of the reservoir site, completed in the Saddle Mountains and Wanapum layers. Figures 5-1 and 5-2 show the locations of 10 Saddle Mountains layer (layer 2) observation wells, and 11 Wanapum layer (layer 3) observation wells. Most of these wells have been measured only once or twice in the past several years by the USGS or the Washington Department of Ecology. A few are recently drilled Reclamation wells that have continuous recorders installed in them.

The available observation well data in the vicinity of the reservoir is considered insufficient to produce a re-calibration of the Black Rock model that represents a unique model solution. Instead, two alternative calibrations were produced for Saddle Mountains layer and Wanapum layer hydraulic conductivities. The two alternative calibrations were created manually, and are based on two slightly different conceptual models of hydrogeologic conditions at the reservoir site. Based on the calibration results, the two conceptual models are assumed to represent more-or-less equally likely alternatives for base-case hydrogeologic conditions at the reservoir site.

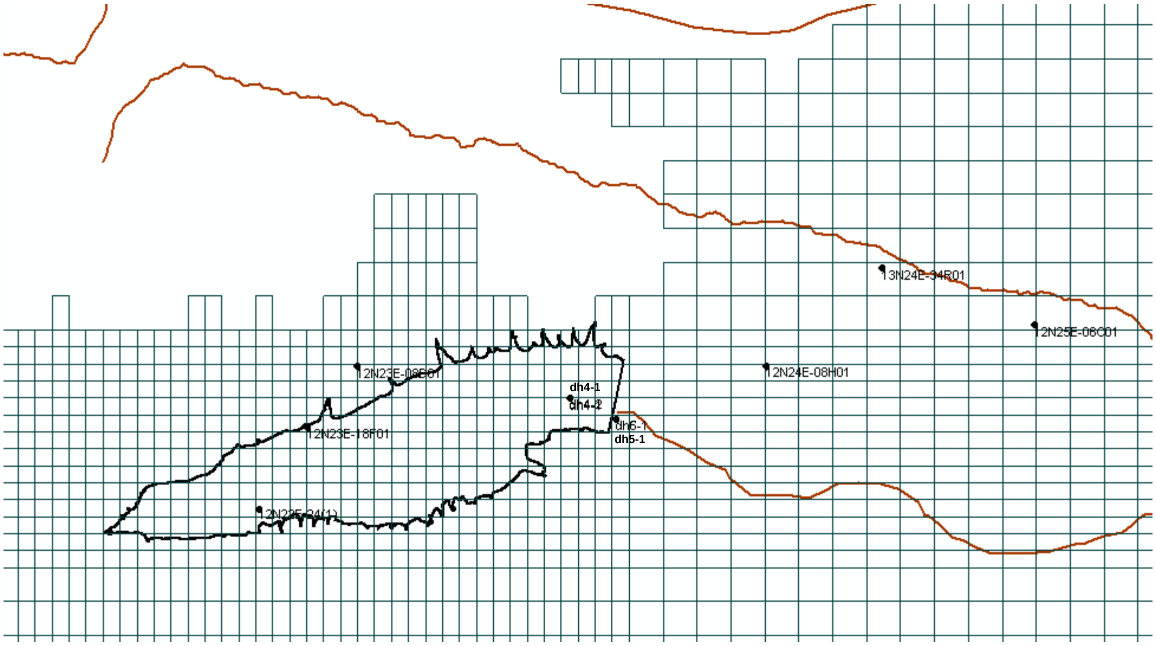

Figure 5-1: Layer 2 observation wells near the reservoir site.

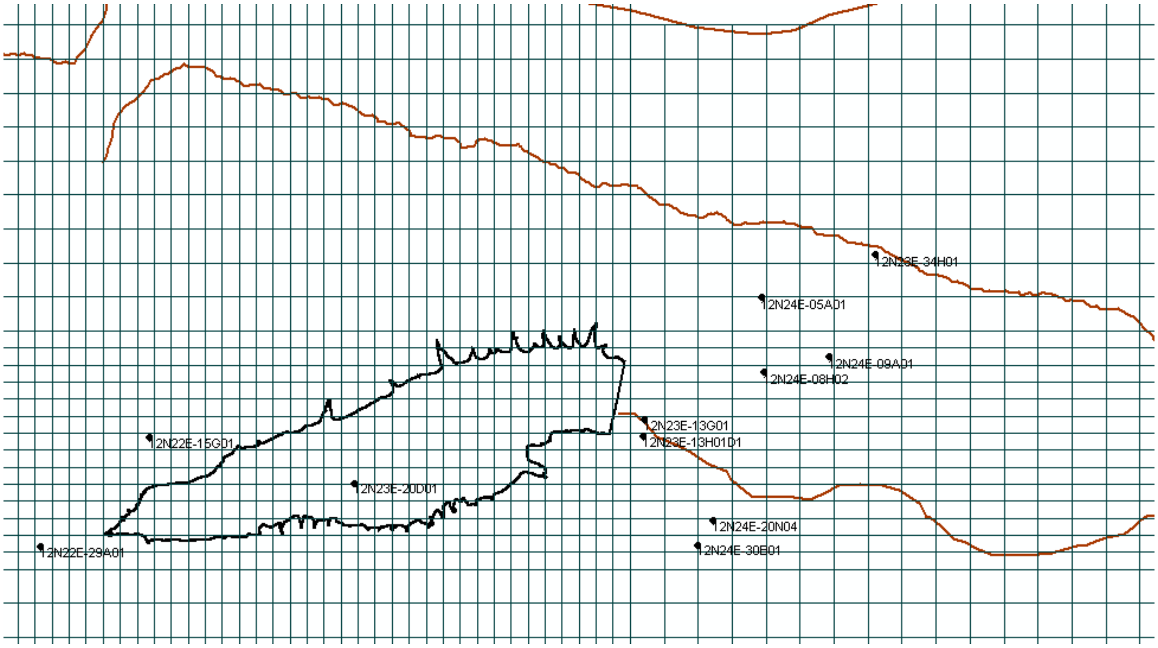

Figure 5-2: Layer 3 observation wells near the reservoir site.

5.1 Base-Case Model Sensitivity Analysis

The base-case model sensitivity analysis is an acknowledgment of the fact that given the hydrologic complexity of the site and the limited observation well data available, it is not possible to develop a unique Black Rock model solution. In this regard, the two alternative conceptual models represent more-or-less equally likely alternatives (based on their ability to match observation well data) for base-case hydrogeologic conditions at the reservoir site.

The two conceptual models are based on recent investigations of geologic structure at the damsite, and differ mainly (but not entirely) in terms of postulated connectivity of permeable fractures in the area of the right dam abutment and in the Horsethief Mountain and Barrel Springs fault zones. They are referred to simply as the *permeability 1* model and the *permeability 2* model. The *permeability 1* model postulates a more restrictive hydrologic connection between the right abutment area and the faults zones, along with increased groundwater pumping. The *permeability 2* model postulates a much less restrictive fault zone connection extending from the right abutment to the southeast for about 6 miles along the Dry Creek drainage.

5.1.1 The *Permeability 1* Model

The premise of the *permeability 1* conceptual model is that groundwater pumping near the damsite combined with somewhat lower vertical hydraulic conductivities in the Saddle Mountains and Wanapum layers (layers 2 and 3) in the area of the right dam abutment (see Figure 3-4) are responsible for producing the head conditions in observation wells near the damsite.

Barrel Springs is located at the upper end of Dry Creek, less than 1,000 feet from the right dam abutment (see Figure 3-4). Groundwater flow emerges at this location from exposed Saddle Mountains Basalt. As mentioned previously, there is anecdotal evidence that flows from Barrel Springs have declined in recent years as a result of new irrigation pumping south of the spring.

The *permeability 1* model achieves a reasonable match between observed and modeled heads in observation wells 12N/23E-13G01, DH-04-1, DH-04-2, DH-05-1, and DH-06-1 in the area of the right dam abutment (see Figures 5-1 and 5-2) by assuming lower vertical hydraulic conductivities between Saddle Mountains and Wanapum layers in the area of the right abutment, combined with some additional groundwater pumping from the Saddle Mountains layer on irrigated lands about two miles south of Barrel Springs and the abutment.

5.1.2 The *Permeability 2* Model

The premise of the *permeability 2* conceptual model is that a more hydraulically conductive Barrel Springs fault zone is responsible for producing the distribution of head conditions observed in wells in the exposed Saddle Mountains and Wanapum basalts near the right dam abutment.

Fault and fracture lineament mapping suggests that the Dry Creek drainage is aligned with the Barrel Springs fault, indicating that a more hydraulically conductive fracture zone in the Saddle Mountains layer may extend for some distance beneath the creek bed.

The *permeability 2* model also achieves a reasonable match between observed and modeled heads in wells 12N/23E-13G01, DH-04-1, DH-04-2, DH-05-1, and DH-06-1 by assuming a higher vertical hydraulic conductivity between the Saddle Mountains and Wanapum layers in the area of the right abutment, combined with a higher horizontal hydraulic conductivity in the Saddle Mountains layer beneath the Dry Creek drainage. No new groundwater pumping is introduced in the permeability 2 conceptual model.

5.1.3 Conceptual Model Calibration Residuals

Model residuals are the differences between calculated and observed head conditions. Calibration residuals for the two base-case conceptual models, at the locations of the 21 observation wells (along with calculated and observed heads) are presented in Table 5-1. The root mean square error (RMSE) statistic in this table is the average absolute value of residuals. The RMSE for the *permeability 1* model is 32.1 feet, and the RMSE for the *permeability 2* model is 28.6 feet.

To put these results in perspective, the range in water level elevations in the 21 observation wells at the reservoir site is over 1,400 feet. The gradient in head in layer 2 (Saddle Mountains layer) between the west and east ends of the reservoir (about 9 miles) is about 700 feet, and the gradient in layer 3 (the Wanapum layer) is about 600 feet. Given the limitations of observation well data, including uncertainty about well depth and pumping history (some observation wells are unused irrigation wells), model heads that are within 30 feet of observed heads are considered to be in reasonably good agreement with observations.

Figure 5-3 is a plot of observed versus modeled heads for the two base-case conceptual models. The regression lines for both models have R^2 values that exceed 98 percent, indicating that in either case, 98 percent of the observed variability in heads is accounted for by the model. The only outlier in Figure 5-3 (and in Table 5-1) is well 12N/23E-13H01D1. The modeled elevation head in this relatively deep well is either 1,070 or 1,090 feet, and the observed elevation head is 940 feet. The observed head is intermediate between layer 3 and layer 4 heads at this location, suggesting that there is a localized, but highly permeable feature (most likely fractures) providing hydraulic communication between these two layers.

Table 5-1: Steady-state base-case model results.

Observation Well ID	Observations	Model Layer	Observed Elevation Head (ft)	Modeled Head Perm 1 (ft)	Residual Head Perm 1 (ft)	Modeled Head Perm 2 (ft)	Residual Head Perm 2 (ft)
12N/23E-18F01	25	2	1707	1748.0	41.0	1730.0	23.0
12N/22E-24(1)	1	2	1609	1657.0	48.0	1653.0	44.0
12N/24E-08H01	1	2	1171	1144.4	-26.6	1182.3	11.3
12N/23E-08D01	1	2	1754	1721.1	-32.9	1793.4	39.4
12N/25E-06C01	1	2	445	433.5	-11.5	437.7	-7.3
13N/24E-34R01	1	2	920	930.0	10.0	930.3	10.3
DH-04-1	daily	2	1150	1138.6	-11.4	1125.5	-24.5
DH-04-2	daily	2	1152	1138.7	-13.3	1125.8	-26.2
DH-05-1	daily	2	1025	1064.9	39.9	1071.1	46.1
DH-06-1	daily	2	1110	1066.0	-44.0	1071.7	-38.3
12N/23E-20D01	3	3	1458	1438.0	-20.0	1469.0	11.0
12N/23E-13G01	1	3	1130	1076.0	-54.0	1092.5	-37.5
12N/22E-29A01	1	3	1584	1565.0	-19.0	1606.0	22.0
12N/24E-20N04	3	3	932	895.8	-36.2	924.2	-7.8
12N/23E-13H01D1	2	3	940	1073.0	133.0	1090.3	150.3
12N/24E-08H02	1	3	1109	1046.9	-62.1	1079.3	-29.7
12N/24E-09A01	1	3	993	966.7	-26.3	967.2	-25.8
12N/24E-05A01	1	3	992	977.6	-14.4	972.9	-19.1
12N/23E-34H01	2	3	940	964.9	24.9	963.1	23.1
12N/24E-30B01	34	3	880	898.9	18.9	923.7	43.7
12N/22E-15G01	4	3	1803	1816.0	13.0	1787.0	-16.0
				[1]root mean square error =32.1 feet		[1]root mean square error =28.6 feet	

[1] statistics exclude well 12N/23E-13H01D1

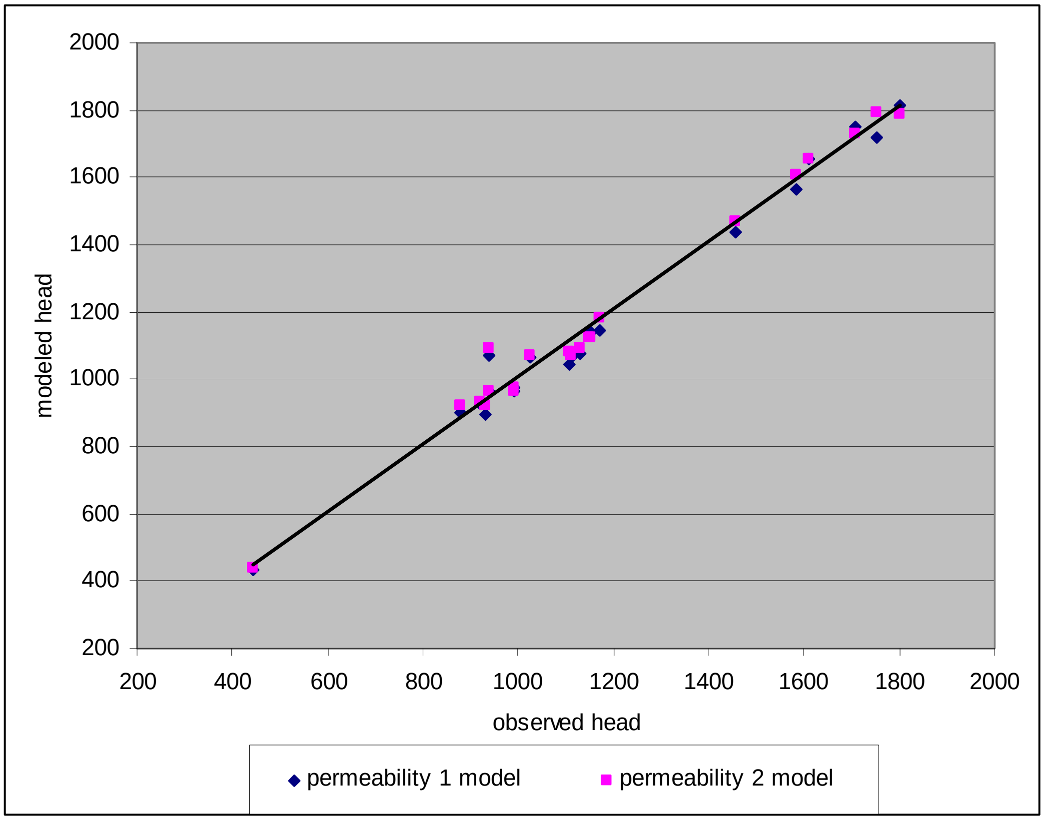

Figure 5-3: Modeled versus observed elevation heads in base-case conceptual models.

6.0 Transient Model Development

The transient Black Rock model includes all of the base-case model features in addition to a head-dependent boundary condition representing the reservoir. The head-dependent reservoir condition is represented either as a MODFLOW Lake Package (LP) boundary condition or as a MODFLOW General Head Package (GHP) boundary condition. The former is imposed using a reservoir water availability hydrograph.

All of the head-dependent boundary conditions for rivers, creeks, drains, and springs are present in both the steady-state base-case model and in the transient reservoir model (as steady-state conditions). The only new (transient) boundary condition introduced in the transient Black Rock model is the head-dependent LP or GHP boundary used to represent the Black Rock reservoir.

6.1 Early-Time and Late-Time Versions of the Transient Model

In order to answer as efficiently as possible, questions involving both the early-time and late-time hydrologic impacts of the reservoir, it was deemed expedient to develop two versions of the transient Black Rock model. One uses the MODFLOW LP boundary condition to represent the initial filling of the reservoir. The other uses the MODFLOW GHP boundary condition to represent the long term effects of a full reservoir. The two model versions are otherwise identical, and are based on the same (steady-state) base-case conceptual models.

The LP model is used to simulate early-time interactions between the reservoir and the aquifer. Changes in the reservoir head (stage) are calculated based on user input of a hydrograph that describes reservoir inflow and outflow rates over time. The LP model represents the reservoir as a head-dependent boundary condition; however, in each stress-period the reservoir head condition (the stage) is adjusted (using a Newton-Raphson iterative procedure) to account for the seepage that is expected to occur during that stress period. As a result, the LP model provides a more accurate estimate of reservoir interaction with the aquifer when the reservoir stage is changing very rapidly, as is the case during the initial filling of the reservoir (USGS, 2000a). The transient LP model is run for nine years, and the duration of each LP model stress period (and time step) is ten days.

The GHP model is used to make late-time estimates of reservoir seepage; to assess reservoir impacts on aquifer heads; to estimate discharge to creeks, drains, and springs; and to estimate groundwater flux conditions. The GHP model applies a reservoir head condition (stage) that is representative of a full reservoir (a 1,775-foot elevation head). The GHP model does not impose any constraints on availability of water to fill the reservoir, and the full reservoir head condition is established instantaneously in the first transient model stress period. As a consequence, the GHP model does not provide as accurate a measure of initial reservoir seepage as the LP model. As time progresses, however, the GHP boundary condition is characteristic of actual reservoir-aquifer interactions. The GHP model is run for 300 years, and the duration of stress periods (and time steps) varies from 10 days to 10 years.

The computational ease with which the GHP boundary condition can be applied in the model, and the robustness of the GHP Package compared to the LP Package within MODFLOW, make it a more desirable alternative for representing the reservoir, when it is appropriate.

7.0 The LP (Early-Time) Model

Figure 7-1 shows the distribution of LP boundary conditions inside the reservoir boundary. MODFLOW cells that have an LP boundary condition are inactive with respect to the aquifer, but active with respect to the reservoir. All LP boundary conditions are imposed on layer 1 (sediment layer) cells. This allows the reservoir to have a horizontal hydrologic connection with active layer 1 cells and a vertical connection with layer 2 cells. The LP reservoir cells are assigned a starting head of 1,286 feet, which is the land surface elevation of the lowest point inside the reservoir boundary.

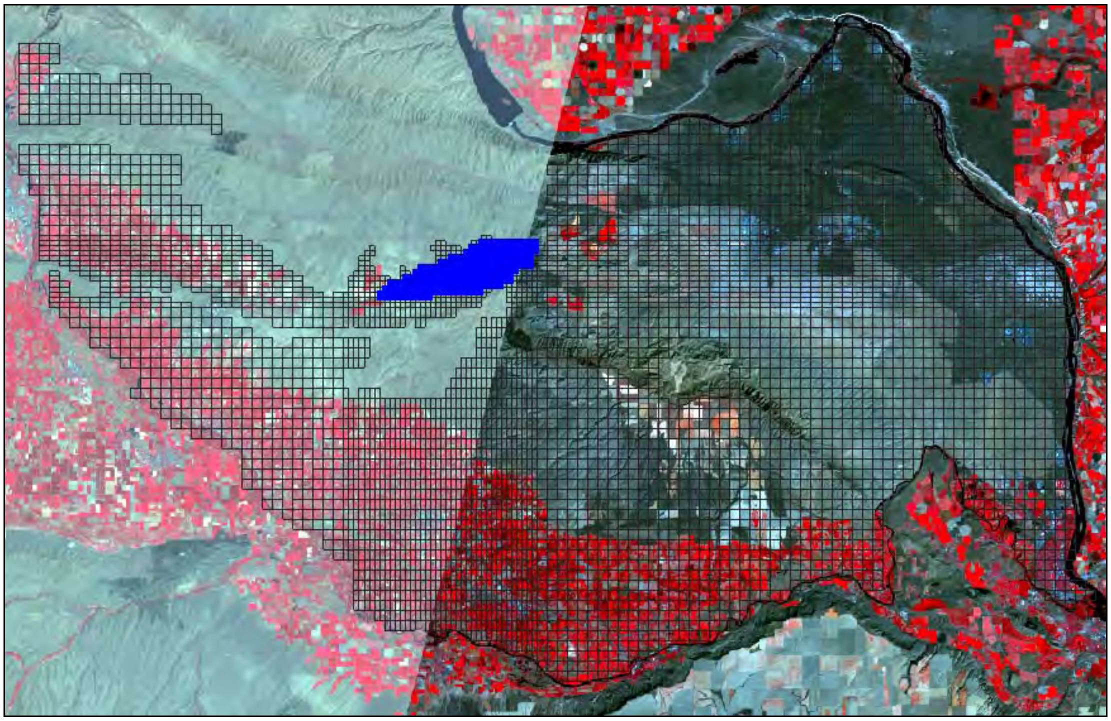

Figure 7-1: LP boundary conditions in layer 1 cells inside the reservoir boundary.

Since layer 1 reservoir cells are inactive (the reservoir is incised in layer 1), MODFLOW automatically sets the reservoir bottom elevation equal to the top of layer 2. To accommodate this, the top elevation of layer 2 directly beneath the reservoir is adjusted to represent the land surface elevation, based on the 10-m DEM. The adjustment enables MODFLOW to correctly calculate the volume and stage of the reservoir as it fills. Aquifer specific-storage beneath the reservoir is also adjusted to reflect the properties of both layers 1 and 2.

Lakebeds typically have a layer of sediment and organic matter that can slow the flow of water from the lake to the aquifer below. This resistance to flow is represented in the model by a leakance parameter [t^{-1}]. Since the layer one cells within the reservoir boundary were converted to inactive cells when the reservoir was defined, leakance was used as a substitute for the vertical hydraulic conductivity of the sediment layer. The leakance value used in the LP model is $1x10^{-7}$ sec^{-1}, which is the average vertical hydraulic conductivity of layer 1 beneath the reservoir divided by average layer 1 thickness.

7.1 The LP Model Sensitivity Analysis

As part of the model sensitivity analysis, two Black Rock model runs were made with the LP version of the model. The two runs use the hydraulic conductivity distributions of the *permeability 1* and *permeability 2* conceptual models and the average values for specific-storage listed in Table 4-4. The model runs are referred to as *permeability 1 average storage* and *permeability 2 average storage*, respectively. The two LP models are each run for nine years as the reservoir is initially filled. Net inflow rate to the reservoir is limited by the average monthly water availability and irrigation demand. No irrigation withdrawals are modeled until the reservoir has filled completely for the first time.

7.1.1 Water Availability Hydrographs

The availability of water to fill the Black Rock reservoir depends on the occurrence of Columbia River flows at the Priest Rapids Dam exceeding instream flow targets for endangered salmon (USBR, 2004d). Figure 7-2 shows the monthly water availability in excess of salmon flow targets during the year 1967, which was an average year (between the years 1943 and 1978)[3] for Columbia River flow at Priest Rapids Dam[4]. In the LP model, the maximum possible monthly reservoir inflow is the difference between the 1967 available flows, and the average monthly reservoir evaporation and irrigation demand.

The transient MODFLOW Lake Package does not recognize the existence of a maximum lake level, so depending on water availability, it is possible for the LP model to calculate a Black Rock reservoir stage that is greater than the maximum possible reservoir stage (i.e.1,775 feet). To get around this, after the reservoir has filled initially, modeled inflow rates are reduced as needed, in order not to exceed the 1,775-foot stage.

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[3] The date range used in the 2004 Preliminary Appraisal Assessment of Columbia River Water Availability for a Potential Black Rock Project study was 1929-1978, however the years from 1929-1943 were omitted because they were abnormally dry.

[4] This hydrograph is based on data from the 2004 Preliminary Appraisal Assessment of Columbia River Water Availability for a Potential Black Rock Project conducted by Reclamation (USBR, 2004a). Since that report was released, Washington Department of Ecology has implemented a rule that states no water can be taken from the Columbia River in July and August. This rule was not taken into account in this study.

Figure 7-3 shows the reduced monthly inflow rates needed to keep the reservoir stage from exceeding 1,775 feet, during the nine year *permeability 1 average storage* and *permeability 2 average storage* LP model runs. In both model runs, net inflow to the reservoir exceeds 200,000 acre-feet per month in eight of the first twelve months. Over the following eight years, however, net inflow exceeding 200,000 acre-feet per month occurs only four months of the year. After the first three years of operation, the net inflow rate needed to keep the reservoir stage from exceeding 1,775 feet is almost constant from year to year. The inflow rate accounts for about half the maximum annual water availability shown in Figure 7-2.

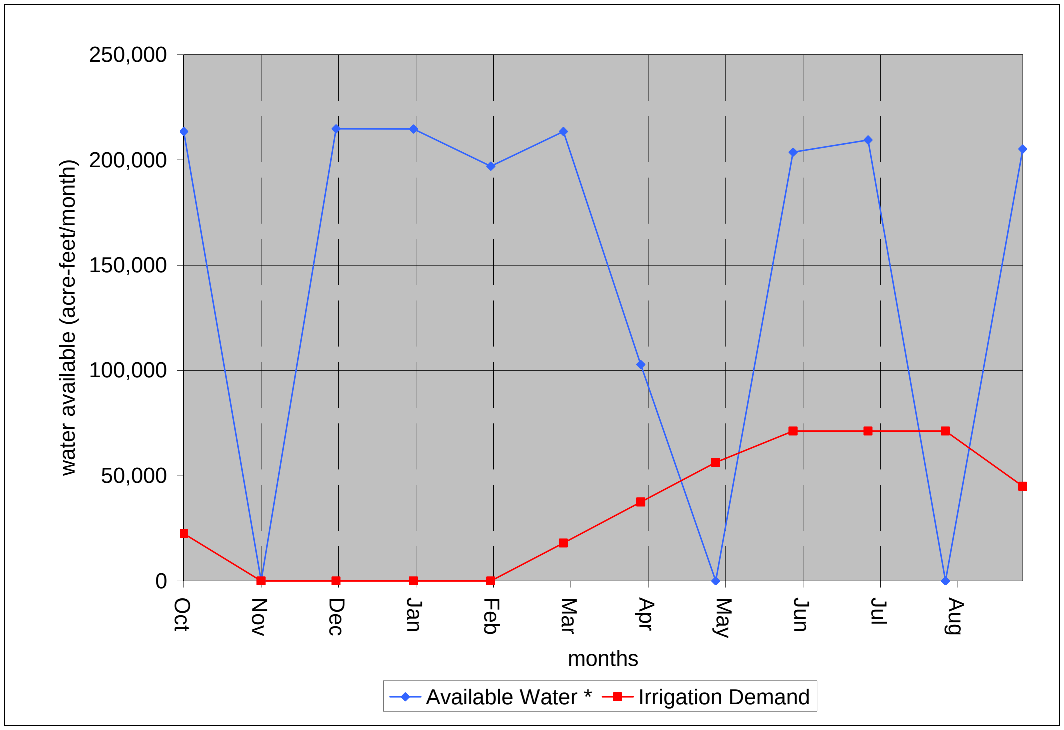

Figure 7-2: Monthly availability of water and monthly irrigation demand during an average water year (1967).

7.1.2 Reservoir Stage and Time-to-Fill

Figure 7-4 shows the monthly reservoir stage during the first nine years of reservoir operation, for the two LP model runs. The time required to fill the reservoir initially, is also annotated on this figure. Both runs required about 380 days to fill the reservoir initially. After the initial filling, the reservoir stage fluctuates between 1,750 and 1,775 feet, depending on monthly irrigation demand.

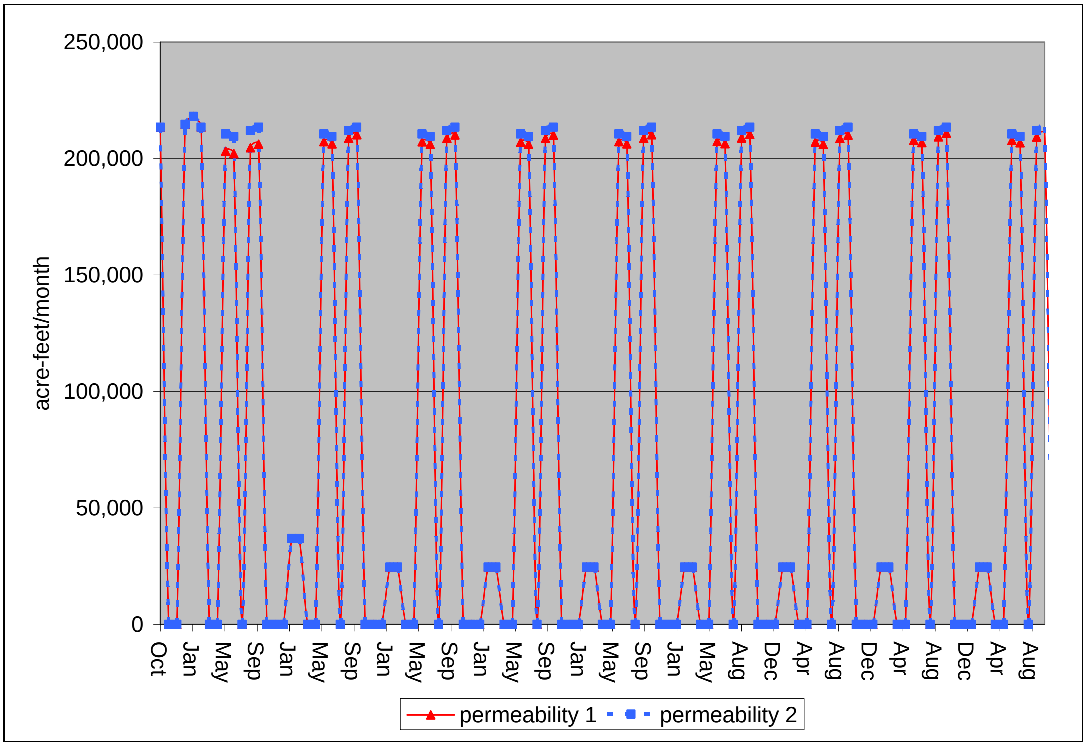

Figure 7-3: Nine year time series of net reservoir inflow for two LP conceptual models.

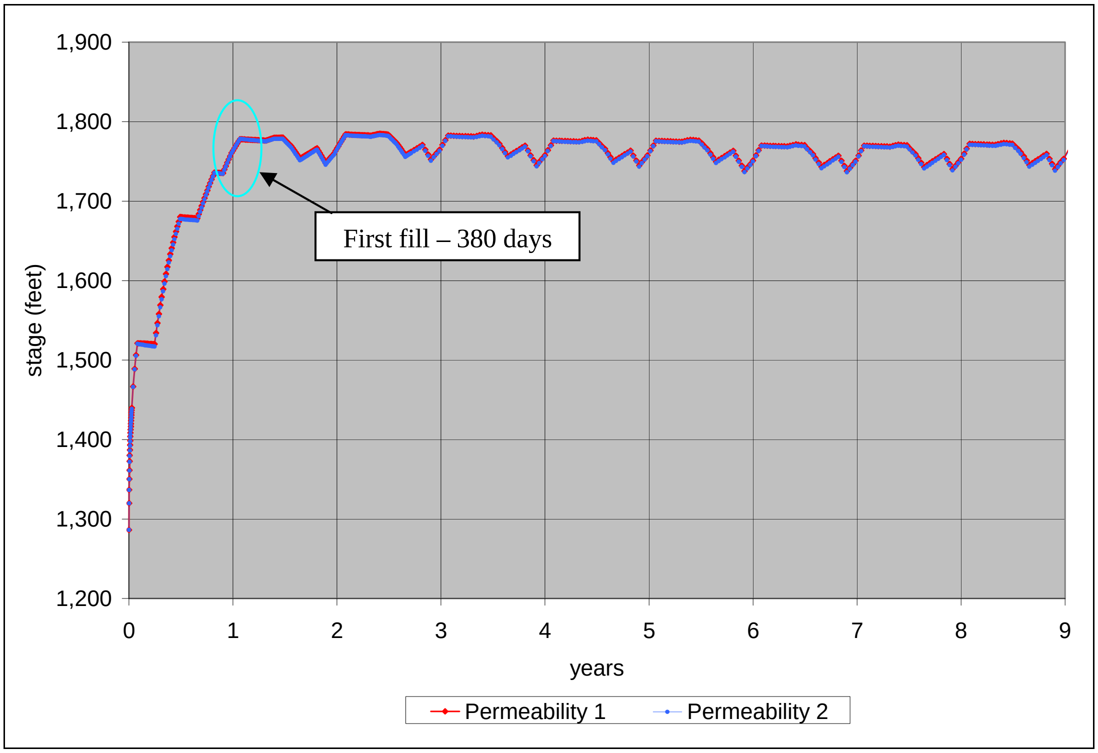

Figure 7-4: Reservoir stage hydrograph first nine years.

7.1.3 Increase in Discharge to Creeks, Drains, and Springs

Groundwater discharge to creeks, drains, and springs downstream of the reservoir increases as the reservoir fills. The *permeability 1 average storage* model predicts an increase of about 22,000 acre-feet per year after the first year, and about 27,000 acre-feet per year thereafter. The *permeability 2 average storage* model prediction is considerably higher; an increase of about 40,000 acre-feet per year after the first year, and 42,000 acre-feet per year in subsequent years (Figure 7-5).

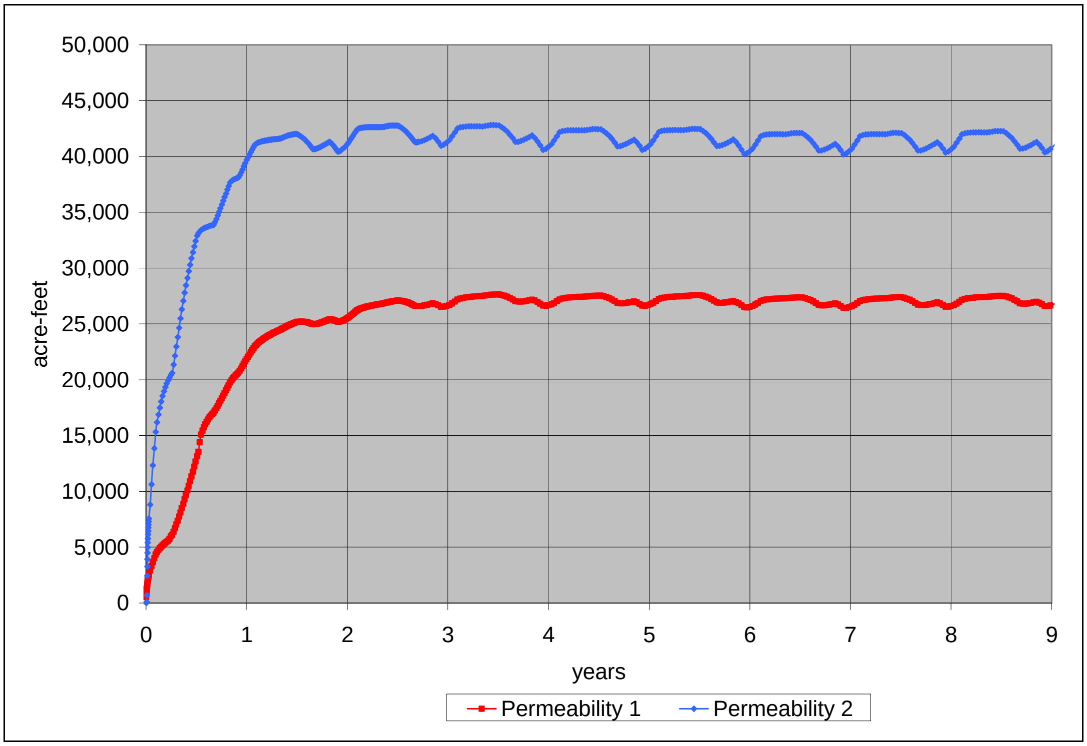

Figure 7-5: Increase in discharge to creeks, drains and springs during first nine years for two conceptual models.

7.1.4 Increase in Aquifer Storage

Aquifer storage also increases as the reservoir fills (Figure 7-6). The *permeability 1 average storage* model predicts a rate of increase in aquifer storage that peaks at 49,900 acre-feet per year after about 13 months and then declines. The storage rate fluctuates between 8,000 and 20,000 acre-feet per year after five years, and between 5,000 and 16,000 acre-feet after nine years. The *permeability 2 average storage* model predicts a peak aquifer storage rate of 80,000 acre-feet per year after about 13 months. The rate fluctuates between 8,000 and 22,000 acre-feet per year after five years, and between 5,000 and 21,000 acre-feet after nine years.

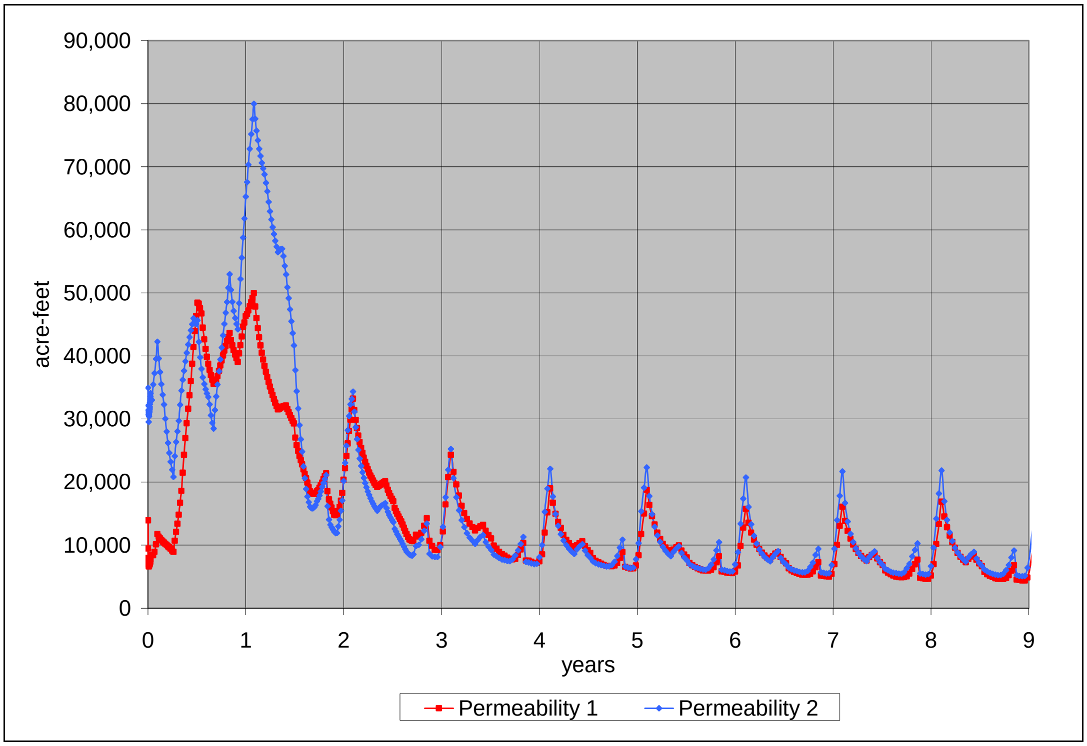

Figure 7-6: Increase in aquifer storage during first nine years for two conceptual models.

7.1.5 Total Reservoir Seepage

Total reservoir seepage is the sum of the increase in groundwater discharge to creeks, drains, and springs, and the (net) increase in aquifer storage. The *permeability 1 average storage* model predicts increasing reservoir seepage for the first 13 months of reservoir operation, with a peak rate of about 72,900 acre-feet per year, followed by a gradual decline. Reservoir seepage fluctuates monthly after that, ranging between 32,000 and 47,000 acre-feet per year after five years, and between 31,000 and 44,000 acre-feet after nine years. The *permeability 2 average storage* model also predicts increasing reservoir seepage for the first 13 months, but with a peak rate of nearly 121,000 acre-feet per year, followed by a steep decline. After five years, this model predicts a seepage rate ranging between 47,000 and 66,000 acre-feet per year, and after nine years between 44,000 and 63,000 acre feet per year (Figure 7-7).

Table 7-1 summarizes early-time model results with respect to increases in discharge to creeks, drains, and springs; increases in aquifer storage; and total reservoir seepage. The results after 13 months are the peak values, and the results after five years are the averages for this year.

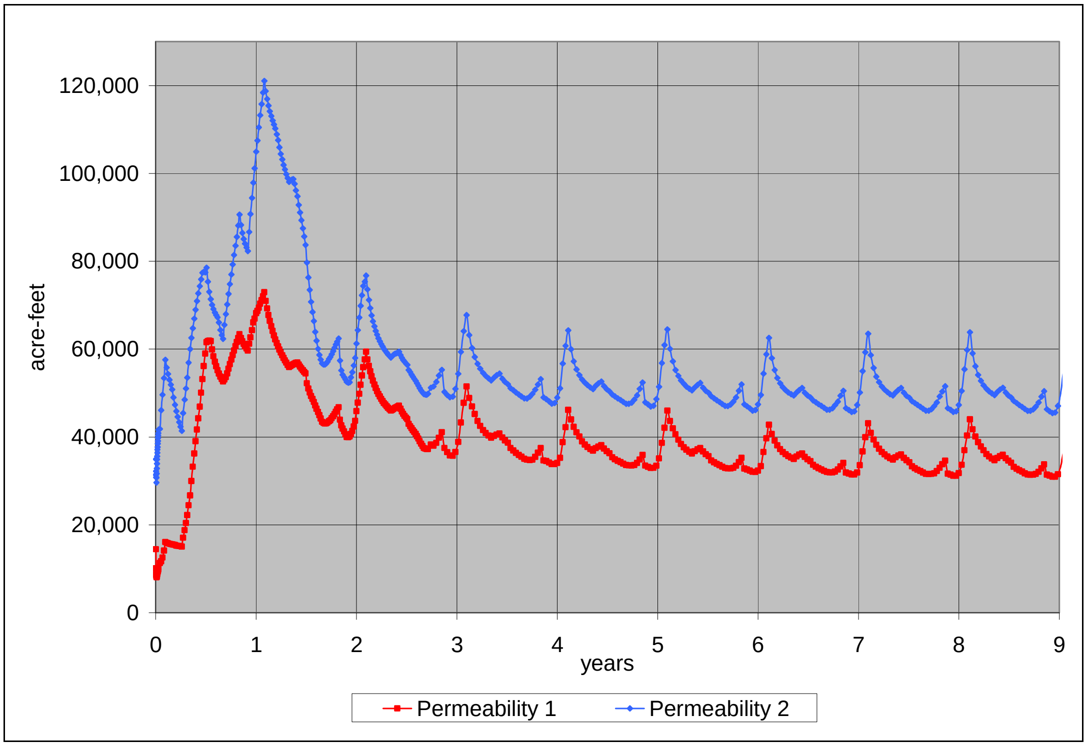

Figure 7-7: Total reservoir seepage during first nine years for two conceptual models.

Table 7-1: Summary of early-time LP model results.

	Annual rate of increase in discharge to creeks, drains, And springs (acre-feet)		**Annual rate of increase in aquifer storage (acre-feet)**		**Annual reservoir seepage rate (acre-feet)**	
Conceptual model	**after 13 months**	**after 5 years**	**peak (13 months)**	**after 5 years**	**peak (13 months)**	**after 5 years**
Permeability 1	22,400	27,200	49,900	8,900	72,900	36,100
Permeability 2	40,400	41,800	80,000	9,400	121,000	51,100

The difference between the two LP model runs in terms of increased discharge to creeks, drains, and springs; increased aquifer storage; and total reservoir seepage due entirely to differences in aquifer hydraulic conductivities, mainly in layer 2 (the Saddle Mountains layer) and mainly in the area of the right dam abutment and the Dry Creek drainage. As described previously, hydraulic conductivities in these areas are greater in the *permeability 2 average storage* model than in the *permeability 1 average storage* model.

7.2 Transition between LP and GHP models

The point at which the (more robust and easier to implement) MODFLOW GHP representation of the reservoir becomes an acceptable alternative to the (more accurate) MODFLOW LP representation can be estimated by plotting the first nine years of reservoir seepage predictions from both MODFLOW packages together on the same graph. Figures 7-8 and 7-9 compare the total reservoir seepage predictions of the two versions running the *permeability 1 average storage* model and the *permeability 2 average storage* model. In the *permeability 1 average storage* model, a reasonably good alignment between the LP predictions and GHP predictions of reservoir seepage (i.e. GHP model seepage matches LP model seepage) is apparent after about five years. In the *permeability 2 average storage* model, an alignment is apparent after about four years.

It is reasonable to expect that the GHP version of the Black Rock model would produce a good estimate of reservoir seepage in both cases, beginning about five years after the reservoir is first filled.

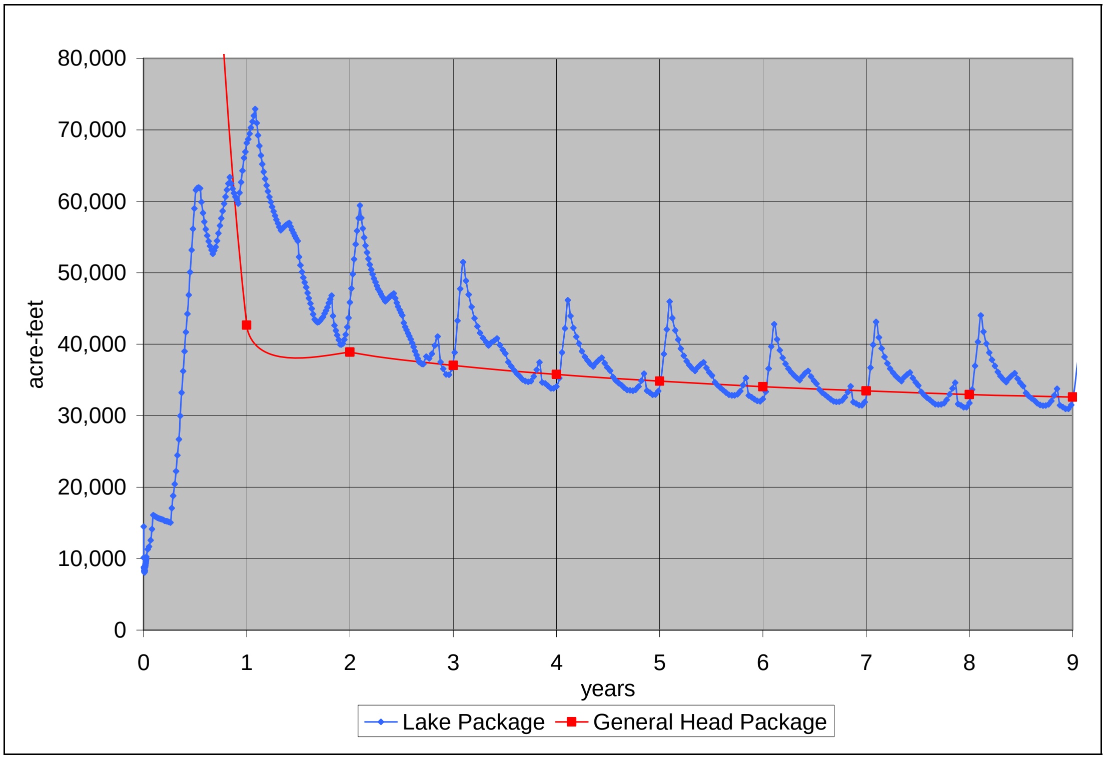

Figure 7-8: **MODFLOW LP and GHP results for the *permeability 1 average storage* model.**

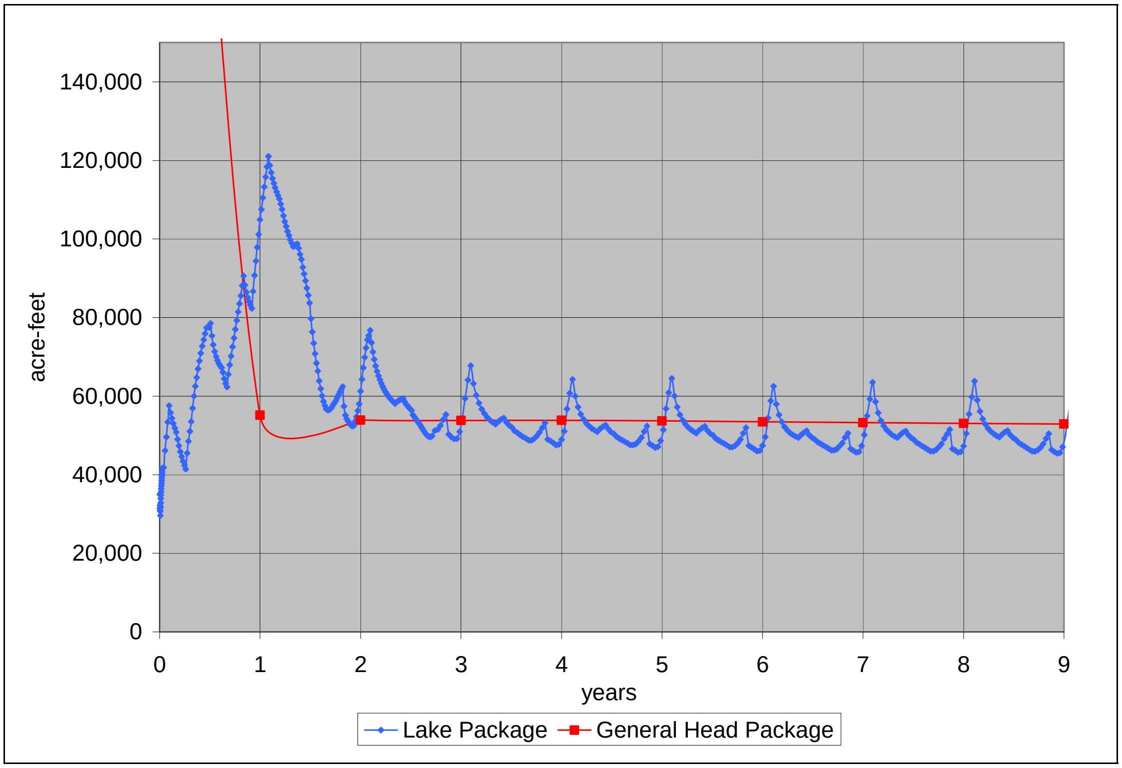

Figure 7-9: MODFLOW LP and GHP results for the *permeability 2 average storage* model.

8.0 The GHP (Late-Time) Model

The Black Rock GHP model is used to make late-time estimates of total reservoir seepage; increase in aquifer head; increase in discharge to creeks, drains, and springs; increase in aquifer storage; and changes in groundwater flux conditions. The GHP model uses 279 stress periods to represent the reservoir interaction with the aquifer during a roughly 300-year period. Stress periods in a MODFLOW simulation are discrete time periods within which model boundary conditions are fixed.

Time steps are also discrete time periods in a MODFLOW simulation. They are used to numerically approximate the time continuum in a transient model. In the Black Rock GHP model, time steps are made equivalent to stress periods. The initial model time-step/stress period is 10 days, however, as the aquifer equilibrates with respect to the new reservoir, the time step/stress period is gradually increased to 10 years. The GHP model calculates total reservoir seepage; aquifer heads; groundwater discharge rates to creeks, drains, and springs; aquifer storage; and groundwater flux after each time-step/stress period.

The layer-by-layer distribution of GHP reservoir boundary conditions is shown in Figures 4-3, 4-4, and 4-5. The GHP conditions are imposed on 174 reservoir cells, 152 in layer 1, 20 in layer 2, and 2 in layer 3. The GHP head condition (1775 feet) is representative of a full reservoir and is introduced in the second transient model stress period. (The first GHP model stress period is the steady-state base-case condition.) The conductance value for the GHP reservoir boundary is set to a very large value, so as not to be a limiting factor in reservoir interactions with the aquifer.

The GHP model represents a full reservoir, although in actuality the reservoir stage is expected to fluctuate between 50 and 60 feet over the course of an irrigation season. The fluctuation is small, however, compared to total reservoir head (see Figures 7-3 and 7-4). The objective of the Black Rock model is to estimate the maximum possible reservoir seepage conditions. This is done by assuming a full reservoir all the time. Including reservoir operations in the late-time GHP model would add another layer of complexity to the interpretation of model results that is not essential for addressing the basic modeling questions. (The influence of late-time reservoir operations could, however be addressed in the future in the GHP model.)

The steady-state base-case Black Rock model was developed with layer 1 represented as an unconfined aquifer layer. However, in the transient GHP model layer 1 is converted to a confined aquifer layer. The conversion helps with model convergence and enables previously dry layer 1 cells at the reservoir site to re-wet once the reservoir is introduced. Without rewetting of dry cells, MODFLOW will not assign new reservoir head conditions to dry layer 1 cells, and the model will underestimate seepage into layer 1. The minimum, maximum, and average specific-yield estimates given in Table 4-4 for layer 1 are converted to specific-storage estimates by dividing by layer thickness[5].

8.1 The GHP Model Sensitivity Analysis

The GHP model sensitivity analysis involves six different GHP model runs. The model runs use the hydraulic conductivity distributions of the *permeability 1* and *permeability 2* conceptual models together with three different specific-storage distributions (minimum, maximum, and average) from Table 4-4. The six GHP model runs are referred to as *permeability 1 minimum storage*, *permeability 1 average storage*, *permeability 1 maximum storage*, *permeability 2 minimum storage*, *permeability 2 average storage*, and *permeability 2 maximum storage*.

Predictive output from the six GHP models consists of hydrographs showing time-dependent increase in reservoir seepage, increase in groundwater discharge to creeks, drains, and springs in the vicinity of the reservoir, and increase in aquifer storage. All increases are relative to steady-state base-case model conditions that existed prior to introducing the reservoir.

For three of the six GHP model runs, predictive output also includes contour maps that show the time-dependent increase in aquifer head conditions in each of the model layers, and tables that show the increase in groundwater flux along Cold Creek, at the boundary of the Hanford Reservation. Again, all increases are with respect to base-case model conditions.

Based on previous LP model results (see Figures 7-11 and 7-12), GHP model results are applicable beginning about five years after the reservoir starts filling. All subsequent GHP model results are presented beginning in year five.

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[5] Input of aquifer layer storage properties in the MODFLOW LPF (Layer Properties Flow) package varies, depending on whether a layer is unconfined or confined. If a layer is unconfined, MODFLOW assumes that the storage parameter being input is specific yield (see glossary), which is independent of aquifer thickness (i.e. dimensionless). If a layer is confined, MODFLOW assumes that the storage parameter being input is specific-storage (see glossary), which is a per-unit-thickness storage property (i.e. units 1/length). Dividing specific-yield by layer thickness produces a specific-storage property that approximates the specific yield property of the unconfined sediment layer.

8.1.1 Increase in Discharge to Creeks, Drains, and Springs

The hydrographs in Figure 8-1 show the predicted increases in groundwater discharge to creeks, drains, and springs (MODFLOW drain cells) for each of the six GHP model runs, beginning five years after the reservoir is initially filled. Groundwater discharge to creeks, drains, and springs increases rapidly at first and then more slowly as the aquifer approaches a new equilibrium with respect to the reservoir. Depending on the model run, five years after the reservoir is first filled, discharge to creeks, drains, and springs has increased by between 25,900 and 51,100 acre feet per year due to reservoir seepage. Discharge continues to increase during the next 20 years, and after 25 years discharge has increased to between 27,600 and 51,400 acre-feet per year. The rate of increase slows considerably after this however, and after 100 years the increase in discharge is between 28,500 and 51,500 acre-feet per year. After 300 years it is between 29,200 and 51,600 acre-feet per year.

The increase in discharge to creeks, drains, and springs is much higher in the three *permeability 2* model runs than in the three *permeability 1* runs, due to higher layer 2 and layer 3 hydraulic conductivities in the area of the Dry Creek drainage and the right dam abutment. Depending on the run, between 75 and 100 percent of the increase in discharge to creeks, drains, and springs occurs either in the area of the right dam abutment or in the Dry Creek drainage. Most of the remaining increase occurs along the Cold Creek drainage.

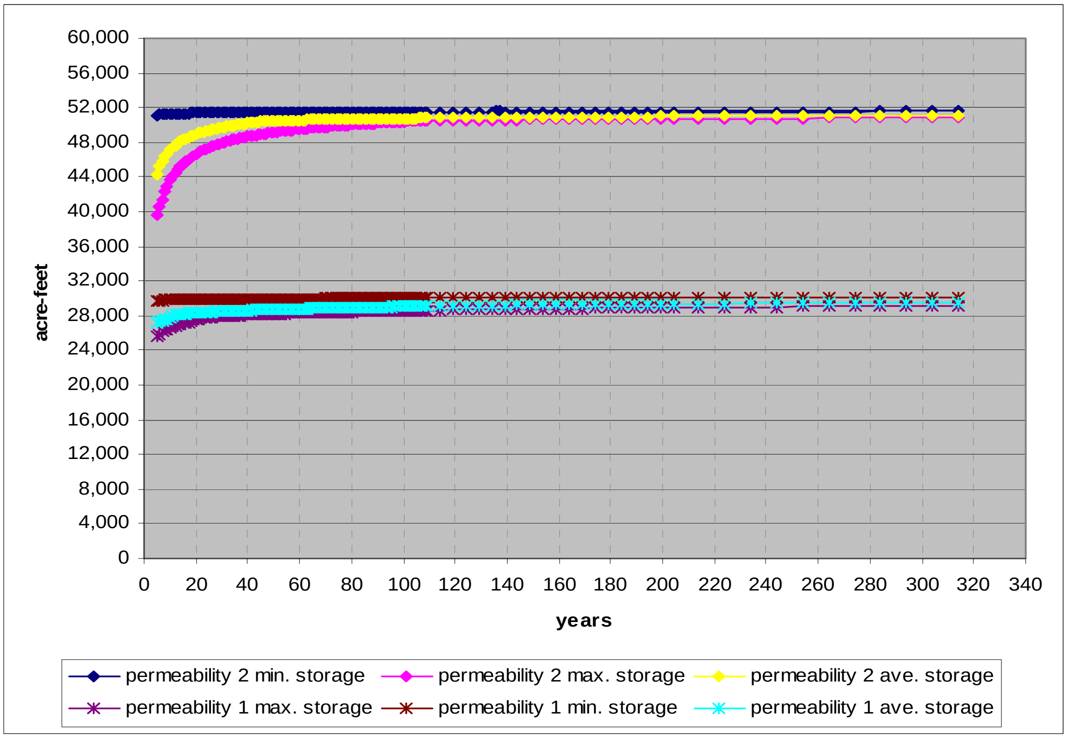

Figure 8-1: Increase in discharge to creeks, drains, and springs over time due to reservoir seepage.

8.1.2 Increase in Aquifer Storage

Figures 8-2, 8-3, and 8-4 show the net increase in aquifer storage in each of the model layers 1, 2, and 3, due to reservoir seepage. Each figure contains six hydrographs, one for each of the six GHP model runs. (Semi-log plots make it easier to distinguish between model runs.) The rate at which seepage goes into aquifer storage decreases with time after the reservoir is first filled and as the storage capacity of each aquifer layer is satisfied.

Because layer 1 sediments have a specific-storage value that is two to three orders of magnitude greater than that of layers 2 and 3, the greatest increase in aquifer storage occurs in this layer. Depending on the model run, between 60 and 80 percent of the increase in aquifer storage due to reservoir seepage is in layer 1 sediments.

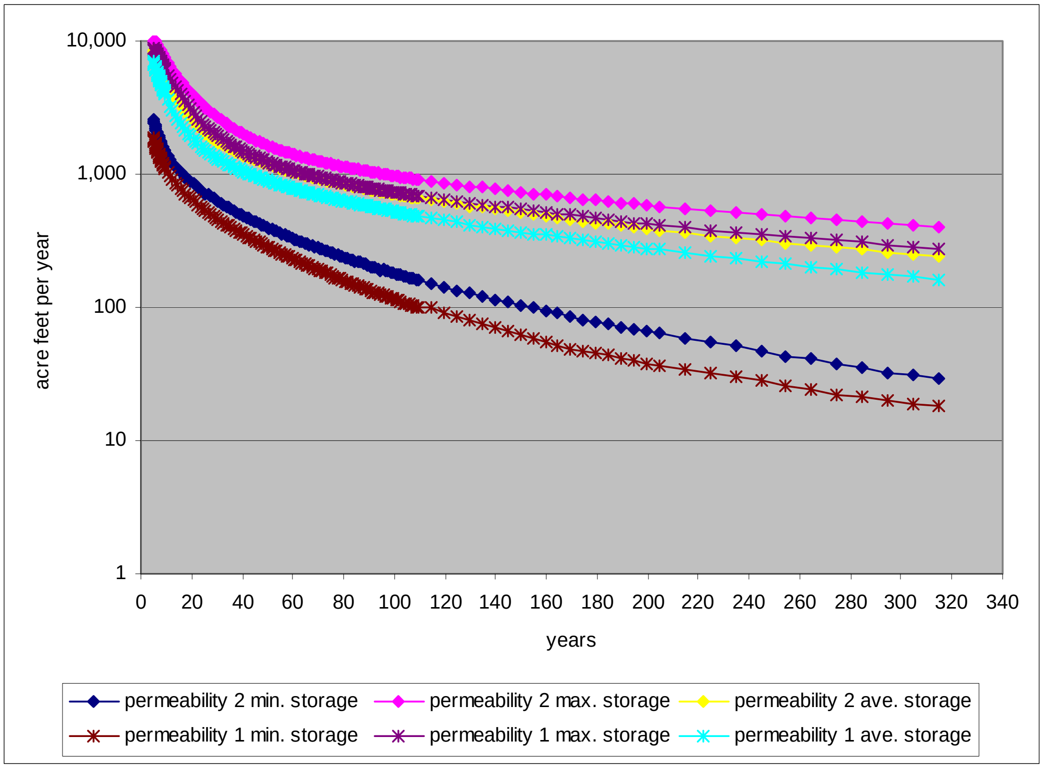

Figure 8-2: Increase in aquifer storage over time, due to reservoir seepage (sediments, layer 1).

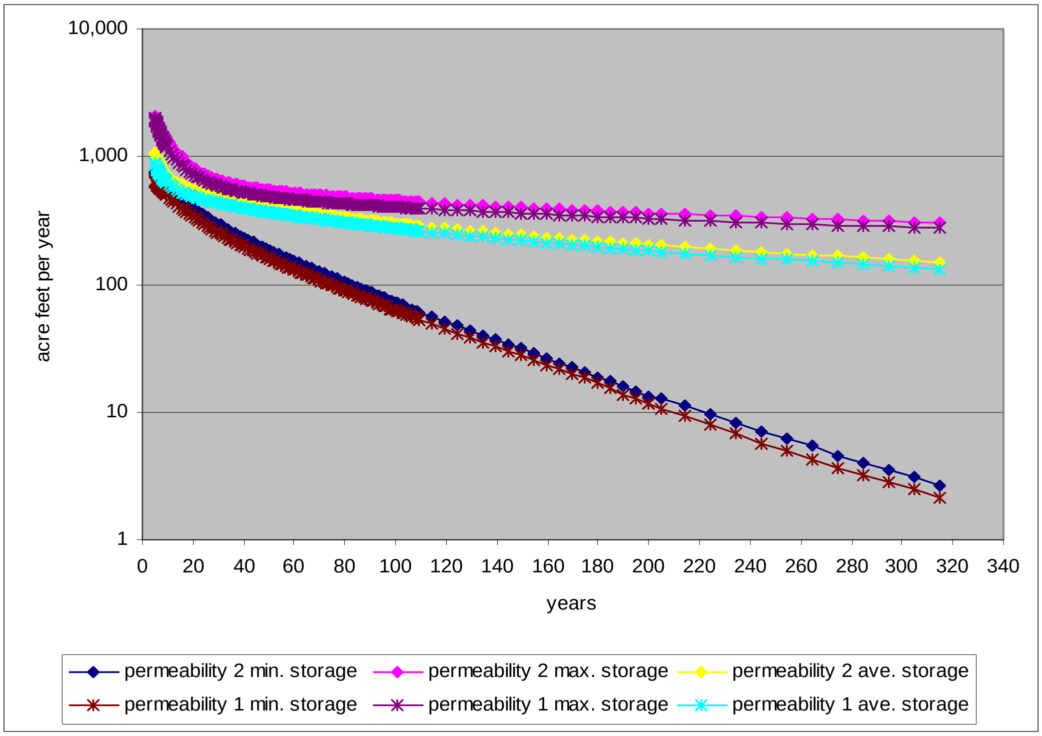

Figure 8-3: Increase in aquifer storage over time, due to reservoir seepage (Saddle Mountains, layer 2).

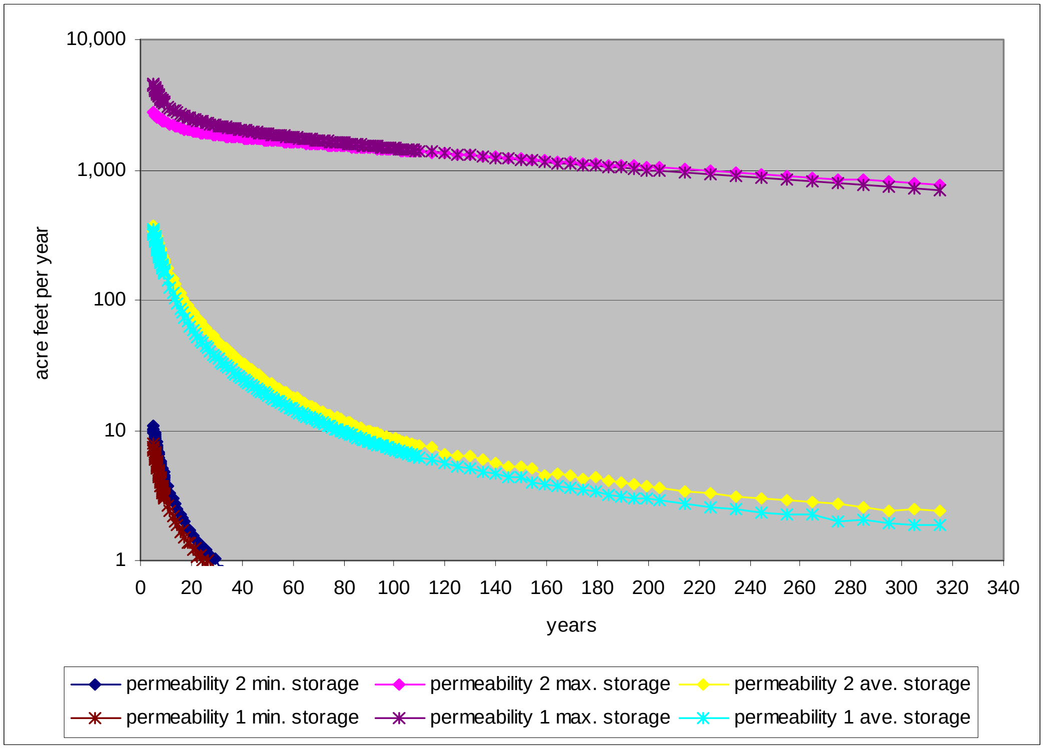

Figure 8-4: Increase in aquifer storage over time, due to reservoir seepage (Wanapum, layer 3).

The hydrographs in Figure 8-5 show the increase in aquifer storage over time in all three layers combined. Depending on the model run, five years after the reservoir is first filled, aquifer storage is increasing at the rate of between 2,400 and 14,700 acre feet per year due to reservoir seepage. The rate of increase in storage declines rapidly during the next 20 years. After 25 years aquifer storage is increasing at a rate of between 1,000 and 6,100 acre-feet per year. After 100 years the rate of increase is between 200 and 2,900 acre-feet per year, and after 300 years, it is between 1 and 1,500 acre-feet per year, indicating a near equilibrium condition with respect to the reservoir.

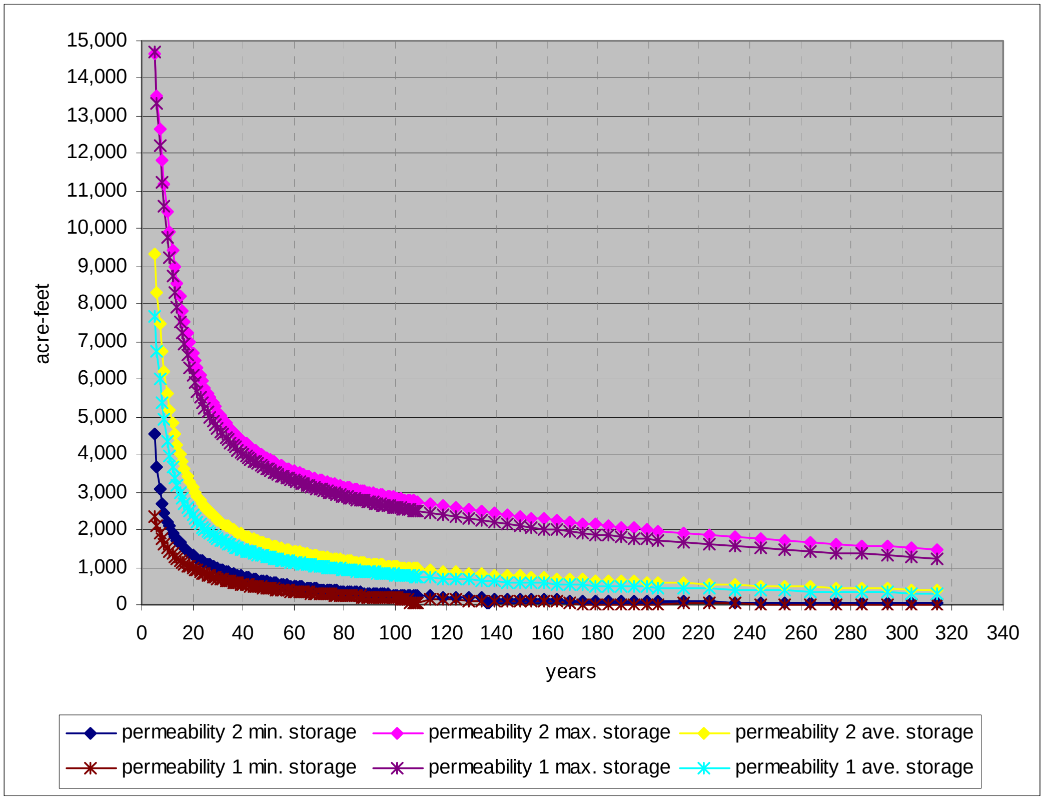

Figure 8-5: Total increase in aquifer storage over time, due to reservoir seepage (layers 1, 2 and 3).

8.1.3 Total Reservoir Seepage

Total reservoir seepage is the sum of the increase in discharge to all creeks, drains, and springs, and the increase in aquifer storage in layers 1, 2 and 3. The hydrographs in Figure 8-6 show the total reservoir seepage over time, for each of the six GHP model runs.

The three *permeability 2* model runs produce the highest reservoir seepage rates over time. Five years after the reservoir is first filled, total reservoir seepage for these three model runs ranges between 53,700 and 54,300 acre-feet per year. There is little change after 5 years, however. After 25 years, the seepage rate is between 52,100 and 53,400 acre-feet per year, and after 100 years, it is still between 51,800 and 53,200 acre-feet per year. Even after 300 years, seepage remains between 51,500 and 52,300 acre-feet per year. In the *permeability 2* model runs, the decline in reservoir seepage after the first five years is only about 3 percent of the five year rate, due mainly to the sustained high rate of discharge to creeks, drains, and springs, which dominates over the declining aquifer storage rate.

The models that produce the lowest reservoir seepage rates over time are the three *permeability 1* models. Five years after the reservoir is first filled, the total reservoir seepage rate for these three model runs ranges between 32,100 and 40,300 acre-feet per year. There is also considerable decline in total reservoir seepage after five years. After 25 years, reservoir seepage has declined to between 30,700 and 33,300 acre-feet per year, and after 100 years seepage is down to between 29,900 and 31,100 acre-feet per year. After 300 years, reservoir seepage remains between 29,800 and 31,100 acre-feet per year. In the *permeability 1* models, the decline in reservoir seepage that occurs after five years is 14 to 23 percent of the five-year rate. The greater rate of decline is due to the reduced discharge rate to creeks, drains, and springs, which is balanced by declining aquifer storage rate.

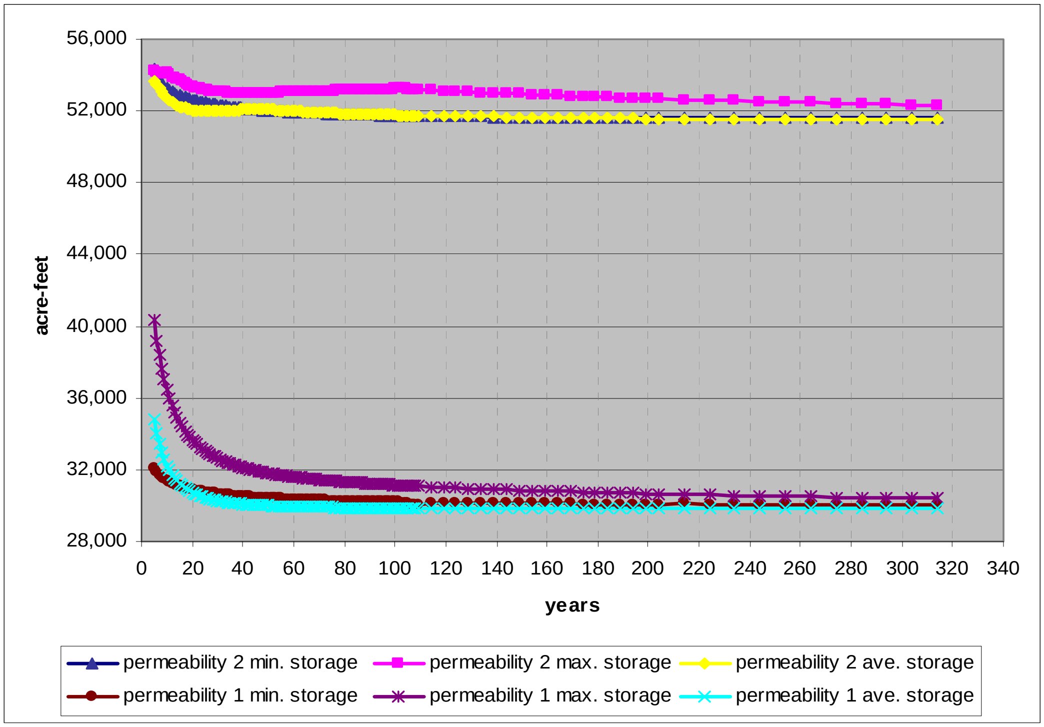

Figure 8-6: Total reservoir seepage over time.

The sometimes complex interaction between aquifer storage and discharge to creeks, drains, and springs is also evident in Figure 8-6. Notably, in the *permeability 2 average storage* and the *permeability 2 maximum storage* runs, the initially decreasing trend in reservoir seepage reverses itself and becomes an increasing trend. This happens after about 20 years in the case of the *permeability 2 average storage* model run, and after about 40 years in the case of the *permeability 2 maximum storage* run. The increasing trends reverse themselves again and become decreasing trends, after about 50 years in the *permeability 2 average storage* run, and after about 100 years in the *permeability 2 maximum storage* run. The reversal is due to two counteracting influences on total reservoir seepage, a decreasing rate of aquifer storage (see Figure 8-5), combined with an increasing rate of discharge to creeks, drains, and springs (see Figure 8-1).

8.1.4 Maximum Likelihood Hydrographs

If the error in model estimates of actual reservoir seepage is assumed to be a normally-distributed random-variable, then the maximum likelihood estimator of actual reservoir seepage, actual increase in aquifer storage, and actual increase in discharge to creeks, drains, and springs is the arithmetic mean value of these model results. (The assumption invokes a Bayesian approach to probability theory, see for example Leonard and Hsu, 1999.)

The hydrographs in Figure 8-7 show the mean annual increase in drain, creek, and spring discharge and in aquifer storage; and total reservoir seepage, based on GHP model results and beginning in year five. Table 8-1 provides summary statistics, including minimum, maximum, and mean values for annual rates of reservoir seepage; increase in aquifer storage; and increase in creek, drain and spring discharge after 5 years, 25 years, 100 years, and 300 years. Again all increases are relative to steady-state base-case model conditions that existed prior to introducing the reservoir.

In addition to the mean values in Table 8-1, confidence intervals (referred to as credence interval in Bayesian statistics) can also be calculated using the standard deviations of model results. Based on GHP model results, for any given year after year five, there is about a 95 percent probability that total reservoir seepage will be between 32,200 and 51,100 acre feet per year.

Although they can be calculated using model results, Bayesian confidence intervals should be interpreted with caution. The interval is subjective, in the sense that it is based on results of just six model runs assumed to represent the full range of possible reservoir outcomes. Additional aquifer test data incorporated into future model runs could significantly alter these statistics.

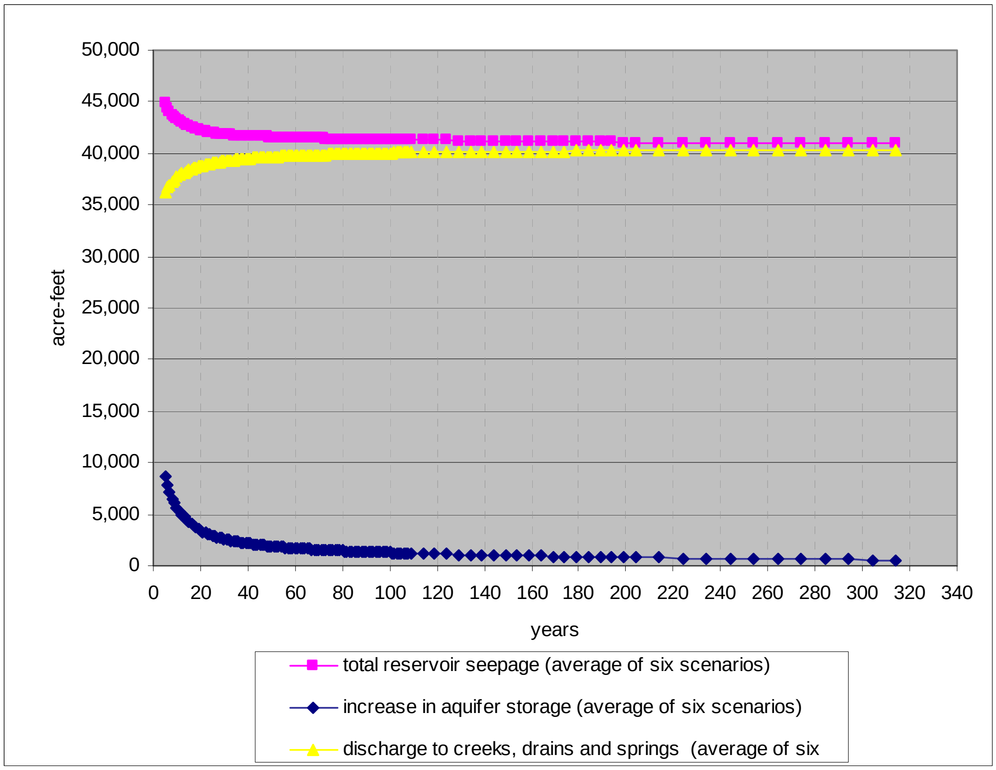

Figure 8-7: Average annual hydrographs for all models.

Table 8-1: Summary of late-time reservoir seepage results.

Time since reservoir filling begins	**Annual rate of increase in discharge to to creeks, drains and springs (acre-feet)**			**Annual rate of increase in aquifer storage (acre-feet)**			**Annual reservoir seepage rate (acre-feet)[1]**		
	min	max	mean	min	max	mean	min	max	mean
5 years	25,600	51,100	36,300	2,400	14,700	8,600	32,100	54,300	44,900
25 years	27,600	51,400	38,800	1,000	6,100	3,400	30,700	53,400	42,200
100 years	28,500	51,500	40,000	200	2,900	1,300	29,900	53,200	41,300
300 years	29,200	51,600	40,400	1	1,500	600	29,800	52,300	40,900

[1] Total reservoir seepage is generally not the exact sum of its two components in this table because the values presented are from different model runs.

Quantification of uncertainty in model parameters and model results using automated parameter estimation tools (such as PEST or UCODE) presupposes a high degree of confidence in a single underlying conceptual model. In the case of the Black Rock model, two alternative conceptual models were identified, incorporating significantly different fault zone properties and pumping conditions. Additional geologic drilling and aquifer testing in the area of the right dam abutment and the Dry Creek drainage are considered essential for building confidence in a single conceptual model, and a prerequisite for more rigorous quantification of uncertainty in Black Rock model results.

8.2 Increase in Aquifer Head

The GHP model is also used to describe the spatial distribution of increases in aquifer head conditions as a result of reservoir seepage. Increases in head are calculated by subtracting, on a cell-by-cell basis, transient model heads from steady-state base-case model heads. Head increases in the sediment and Saddle Mountains and Wanapum layers (layers 1-3) are calculated after 10 years, 100 years, and 300 years for three of the six GHP models; the *permeability 1 maximum storage* model, the *permeability 2 average storage* model, and the *permeability 2 minimum storage* model. The full range of increased head conditions produced by the six models is exhibited in these three runs.

8.2.1 Dry Creek Re-Infiltration

Aquifer head in the vicinity of the reservoir increases because of reservoir seepage. However, as previous hydrographs have shown, a large percentage of reservoir seepage (between 29,200 acre-feet per year and 51,600 acre-feet per year depending on the model run) is eventually discharged to creeks, drains, or springs.

Also, as noted earlier, between 75 and 100 percent of this increased discharge occurs in the area of the right dam abutment and in the Dry Creek drainage (see Figure 3-4). Because of the extremely thin sediment layer along most of the upstream portion of Dry Creek, groundwater that daylights in Dry Creek is likely to flow on the surface for several miles before reaching a fan-shaped area of much thicker alluvial sediments about three to four miles west of the confluence with Cold Creek. The sediment layer in this lower portion of Dry Creek is up to 480 feet thick and much of it is above the water table. At this point, it is expected that Dry Creek flows would spread out across the fan and much of it would re-infiltrate into the sediment layer. Figure 8-8 shows the locations of layer 1 model cell where re-infiltration of Dry Creek flows is likely to occur.

Model runs simulating Dry Creek re-infiltration are fairly conservative in assuming that no more than 75 percent of the upper Dry Creek discharge would potentially re-infiltrate in lower Dry Creek. It is assumed that 25 percent of the groundwater that daylights in upper Dry Creek would be lost to evaporation or for some other reason, before reaching the alluvial fan. (Pan evaporation rates in this area are 50 to 60 inches per year.)

Model runs simulating Dry Creek re-infiltration include MODFLOW drain cells in the re-infiltration area. The drain cells prevent head conditions in the sediment layer from exceeding the surface elevation and thereby limit the re-infiltration rate. Water flowing down Dry Creek in excess of the infiltration capacity of the fan sediments is assumed to discharge on the surface into Cold Creek.

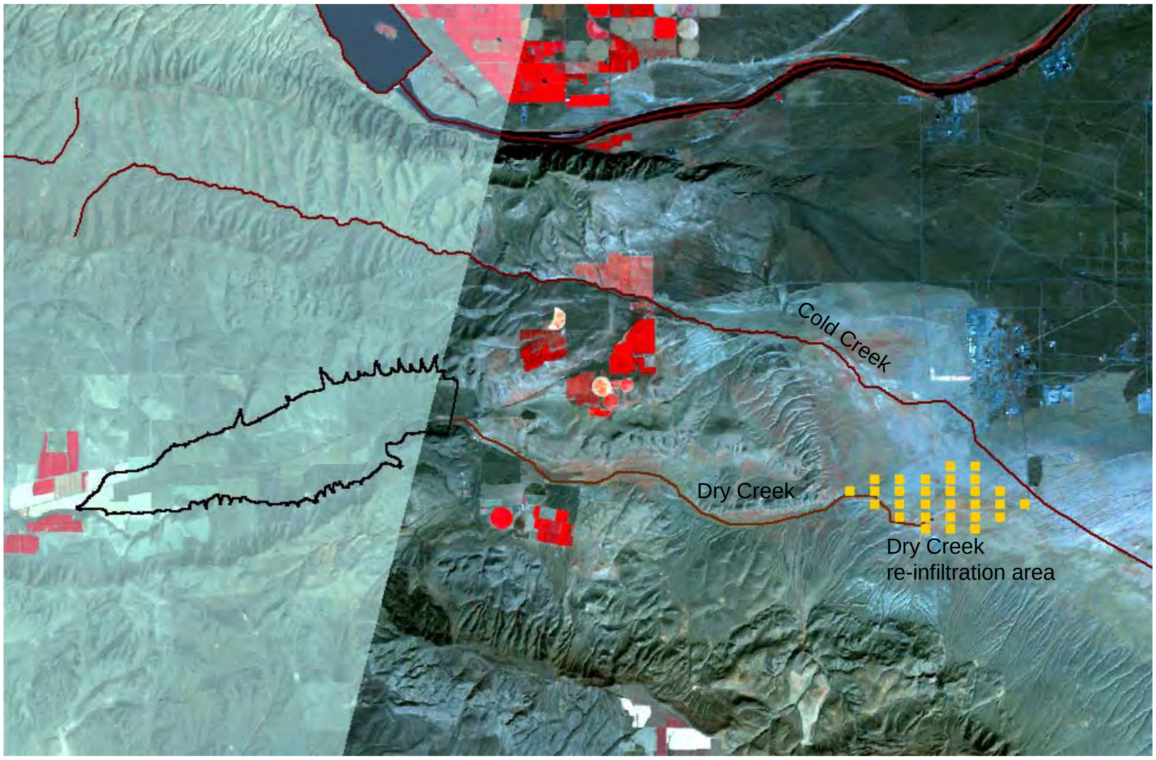

Figure 8-8: Dry Creek re-infiltration area.

Figure 8-9 shows the time-dependent re-infiltration rates used in the three GHP model runs. The re-infiltration rates (which are limited to 75 percent of the corresponding Dry Creek drain discharge rates) never exceed 31,000 acre-feet per year, and generally range between 15,000 and 22,500 acre-feet per year. Figure 8-9 also shows that within 20 years, re-infiltration in all three models is limited by the infiltration capacity of sediments (i.e. by drain cells).

Figure 8-10 shows the flow from Dry Creek into Cold Creek that exceeds the infiltration capacity of Dry Creek sediments. Dry Creek flow into Cold Creek increases steadily for about 50 years after the reservoir is introduced, and then levels off at between 9 and 22 ft^3/s.

8.2.2 Head Change Contour Maps

Head change contour maps developed for the three GHP model runs show the spatial distribution of increased aquifer head conditions in three model layers, as a result of reservoir seepage. Head change contour maps are developed for model layers 1, 2, and 3; after 10 years, 100 years, and 300 years.

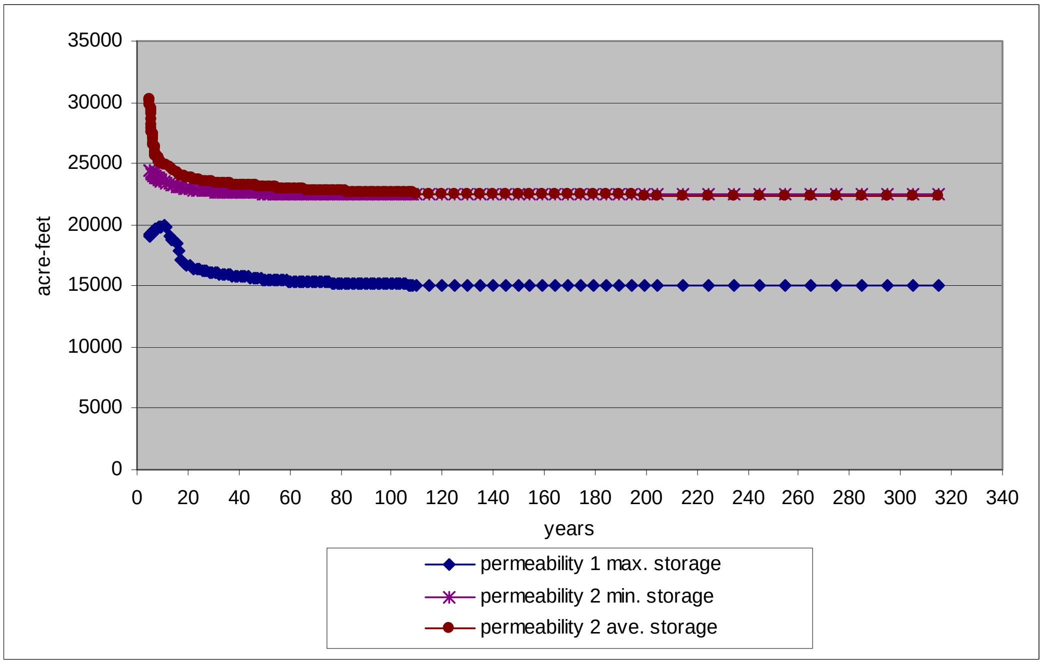

Figure 8-9: Time-dependent Dry Creek re-infiltration rates.

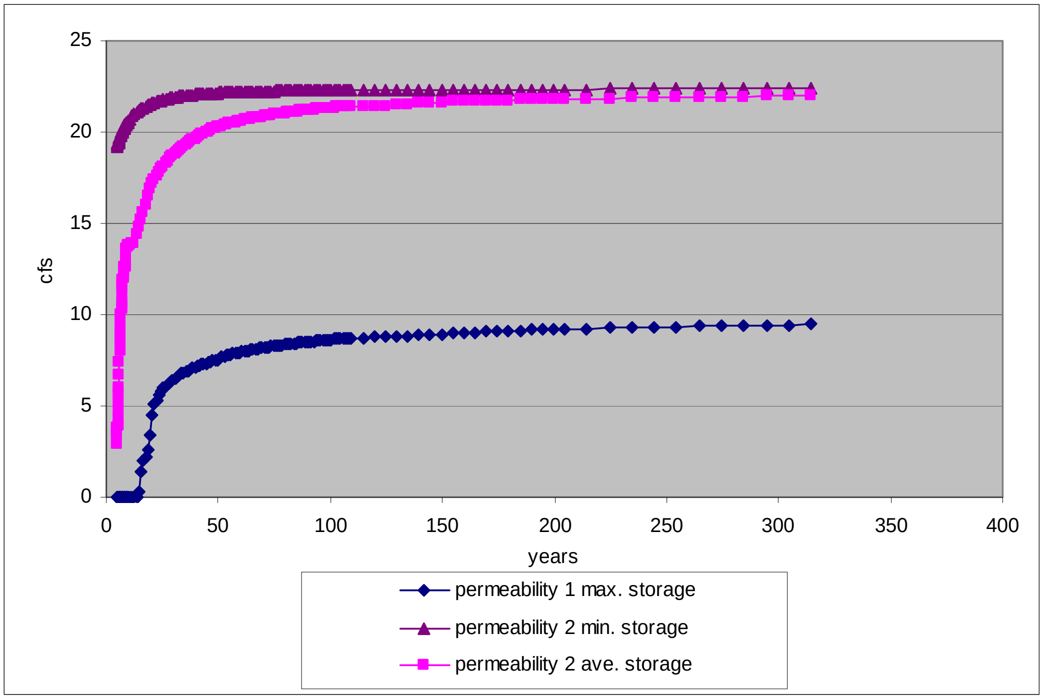

Figure 8-10: Surface discharge from Dry Creek into Cold Creek.

The contour maps are color-coded and labeled. For all maps, the contour range is from 1 foot to 300 feet, and the contour interval is 10 feet. The absence of a color contour indicates a head increase of less than 1 foot. Although there are locations directly beneath the reservoir itself where aquifer head increases by 600 feet or more, throughout most of the model area, head increases are less than 300 feet. In order to optimize the resolution of contour maps in these areas, the contour range is restricted to 300 feet. Areas where head increase exceeds 300 feet are labeled. To aid in spatial referencing, the contour maps also include a Landsat infrared background image.

8.2.2.1 *Permeability 1 Maximum Storage* Model

Figures 8-11 through 8-15 are produced by the *permeability 1 maximum storage* model run. The first three figures show the spatial distribution of increased head in layer 1 (the sediment layer) after 10 years, 100 years, and 300 years, as a consequence of reservoir seepage and re-infiltration at the downstream end of Dry Creek. Figures 8-14 and 8-15 show the increase in head in layers 2 and 3 (Saddle Mountains and Wanapum layers) after 300 years, as a consequence of reservoir seepage.

After 10 years, most of the impact on layer 1 head conditions is localized in the immediate vicinity of the reservoir (Figure 10-11). Re-infiltration at the lower end of Dry Creek has increased heads in this area by about 20 feet. Between 10 and 100 years there is a gradual increase in head on the periphery of the reservoir, mainly on the east and west ends, and a substantial increase in the re-infiltration area. After 100 years, the increase in head in the re-infiltration area ranges up to 180 feet (Figure 8-12). Along Cold Creek at the confluence with Dry Creek, layer 1 head has increased by about 10 feet.

Between 100 and 300 years, the impact of reservoir seepage on head conditions in layer 1 expands considerably, mainly due to re-infiltration at the lower end of Dry Creek. After 300 years head increases in the re-infiltration area range up to 220 feet, and along Cold Creek, layer 1 heads have increased by about 40 feet (Figure 8-13). The impact of reservoir seepage and re-infiltration on layer 1 also extends east of Cold Creek, with head increases of 10 feet or more up to 6 miles east of Cold Creek, and head increases of one foot or more extending across much of the area between Cold Creek and the Columbia River.

The impact of reservoir seepage on head conditions in the Saddle Mountains layer is concentrated at the reservoir site (Figure 8-14). After 300 years, the impacts on layer 2 extend 10 to 12 miles from the reservoir, mainly to the south and east. (The Saddle Mountains layer is largely absent north of the reservoir.) The increase in head throughout most of the area outside the reservoir is 10 feet or less. Within the reservoir the increase is 400 feet or more.

The impact of reservoir seepage on head conditions in the Wanapum layer is also concentrated at the reservoir site (Figure 8-15). After 300 years, the impacts on layer 3 extend 10 to 20 miles mainly to the south and northwest because the Wanapum layer is comparatively thin west of the reservoir. Again, most head increases in this layer outside of the reservoir are less than 10 feet.

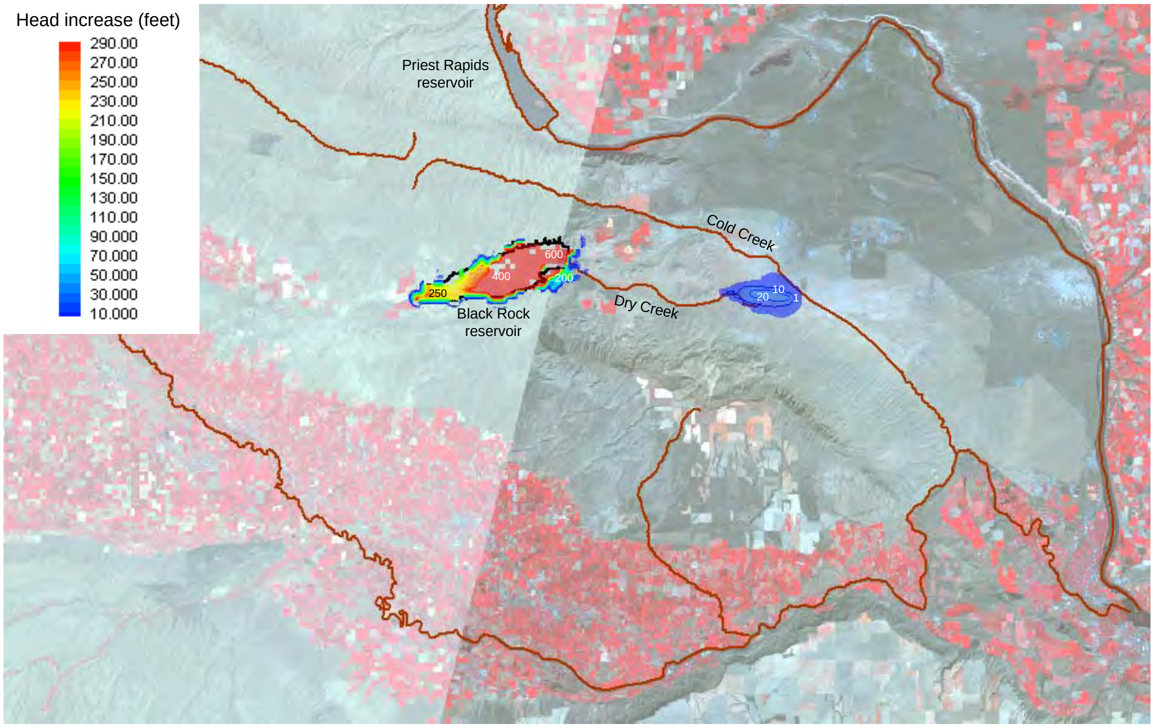

Figure 8-11: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 10 years.

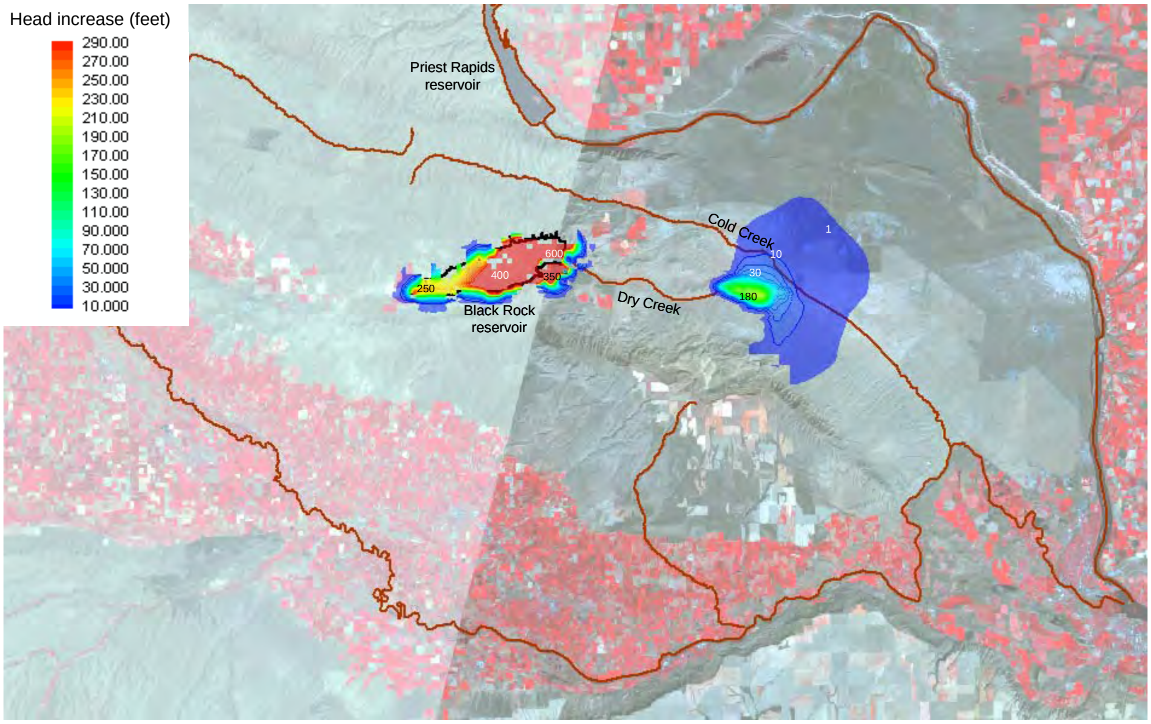

Figure 8-12: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 100 years.

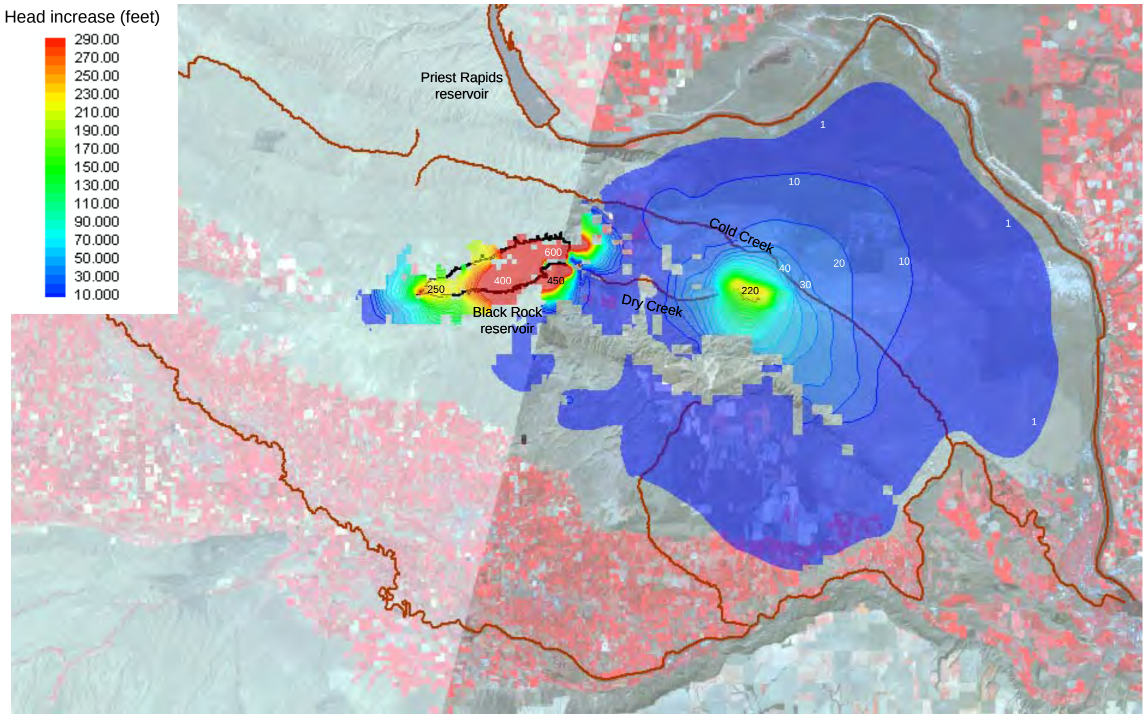

Figure 8-13: Layer 1 (sediments) head increase, *permeability 1 maximum storage* model after 300 years.

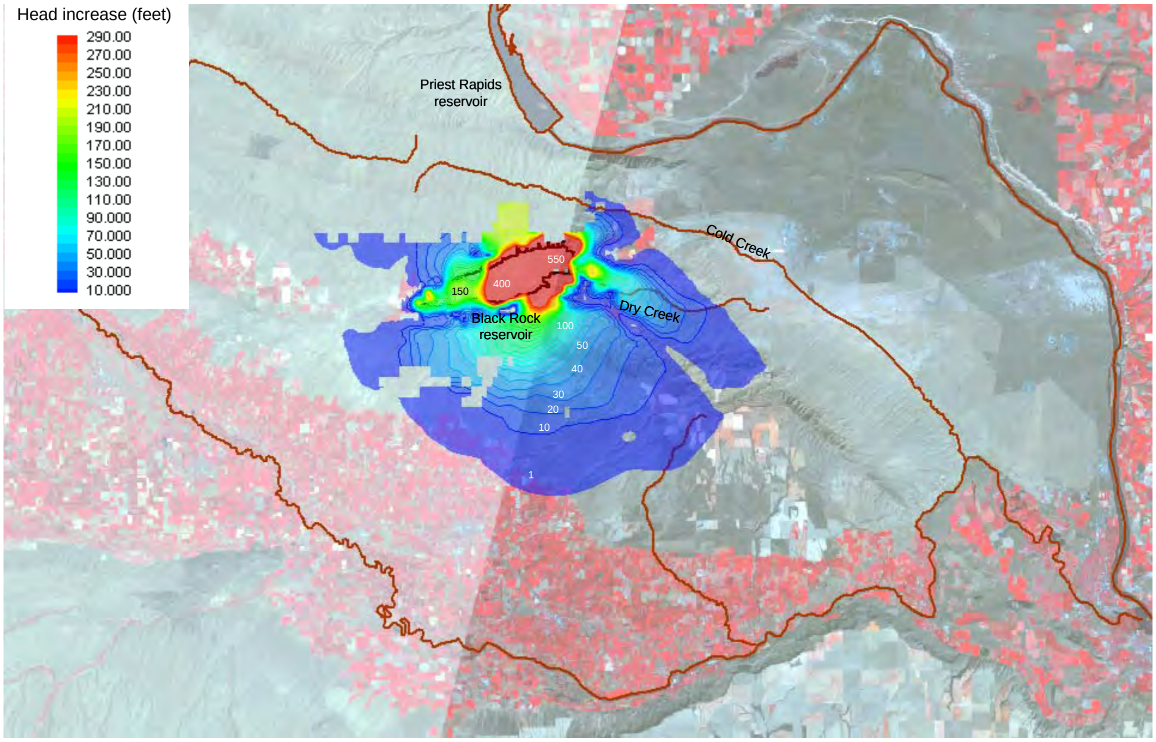

Figure 8-14: Layer 2 (Saddle Mountains) head increase, *permeability 1 maximum storage* model after 300 years.

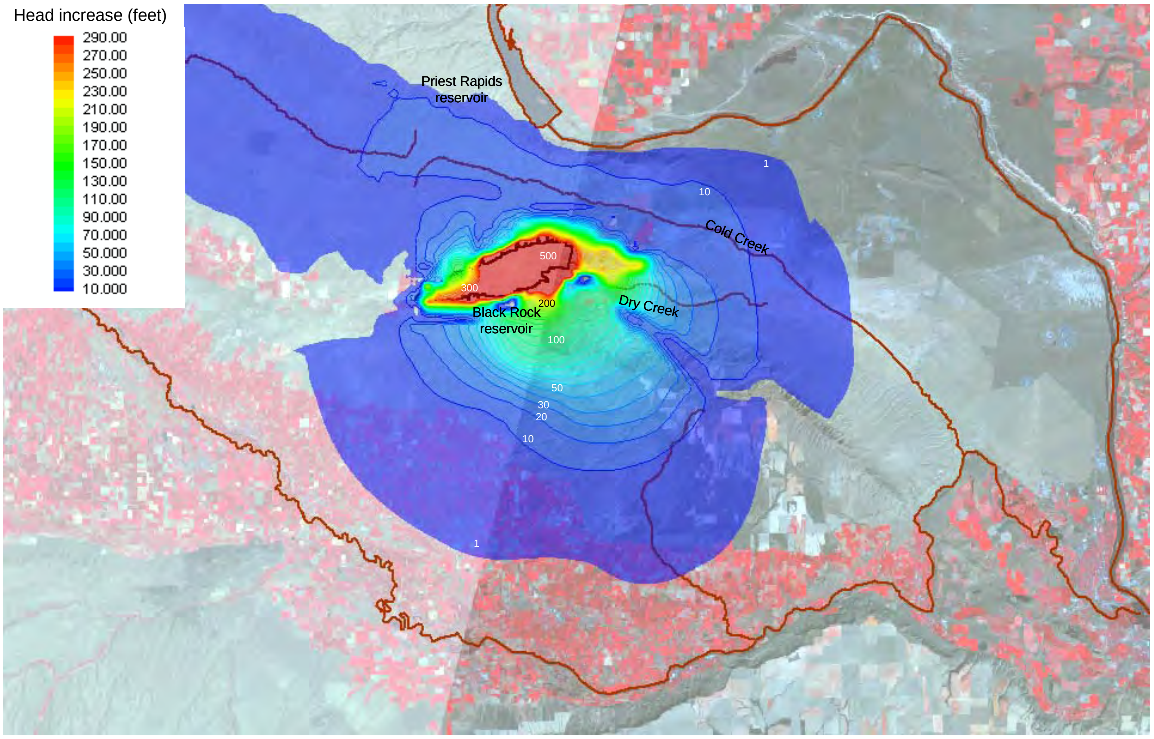

Figure 8-15: Layer 3 (Wanapum) head increase, *permeability 1 maximum storage* model after 300 years.

8.2.2.2 *Permeability 2 Average Storage* Model

Figures 8-16 through 8-20 are produced by the *permeability 2 average storage* model run. Again, the first three figures show the spatial distribution of increased head in layer 1 (the sediment layer) after 10 years, 100 years, and 300 years, as a consequence of reservoir seepage and re-infiltration at the downstream end of Dry Creek. Figures 8-19 and 8-20 show the increase in head in layers 2 and 3 (Saddle Mountains and Wanapum layers) after 300 years, as a consequence of reservoir seepage.

Once again, most of the impact on layer 1 head conditions during the first 10 years is localized in the immediate vicinity of the reservoir (Figure 8-16). Head increases in the re-infiltration area at the downstream end of Dry Creek range up to 80 feet after 10 years. The head increase is considerably greater than in the *permeability 1 maximum storage* model because the *permeability 2 average storage* model has a lower specific storage. Between 10 and 100 years, there is an increase in head on the periphery of the reservoir mainly on the east and west ends. After 100 years, the increase in head in the re-infiltration area ranges up to 250 feet (Figure 8-17), which means that the water table is at or near the land surface in this area, and some Dry Creek flows are discharging into Cold Creek. Along Cold Creek at the confluence with Dry Creek, layer 1 head has increased by about 30 feet.

Once again, between 100 and 300 years, the area of layer 1 impacted by reservoir seepage and re-infiltration expands considerably, mainly to the east of the reservoir. After 300 years, head increases in the re-infiltration area remain at around 250 feet (Figure 8-18). Along Cold Creek, layer 1 heads have increased by about 60 feet. Layer 1 head increases of 20 feet or more extend up to 5 miles east of Cold Creek and head increases of 10 feet or more extend up to 7 miles east of the creek. Again, head increases of one foot or more occur across nearly all of the area between Cold Creek and the Columbia River.

The impact of reservoir seepage on head conditions in the Saddle Mountains layer is, again, concentrated at the reservoir site (Figure 8-19). After 300 years, impacts of reservoir seepage in layer 2 extend 10 to 20 miles mainly to the south and east of the reservoir. The increase in head throughout most of the area outside the reservoir is 10 feet or less. Within the reservoir the increase is 400 feet or more.

The impact of reservoir seepage on head conditions in the Wanapum layer is also concentrated at the reservoir site (Figure 8-20). Impacts in layer 3 extend 10 to 20 miles mainly to the south and northwest. Again, most head increases are less than 10 feet.

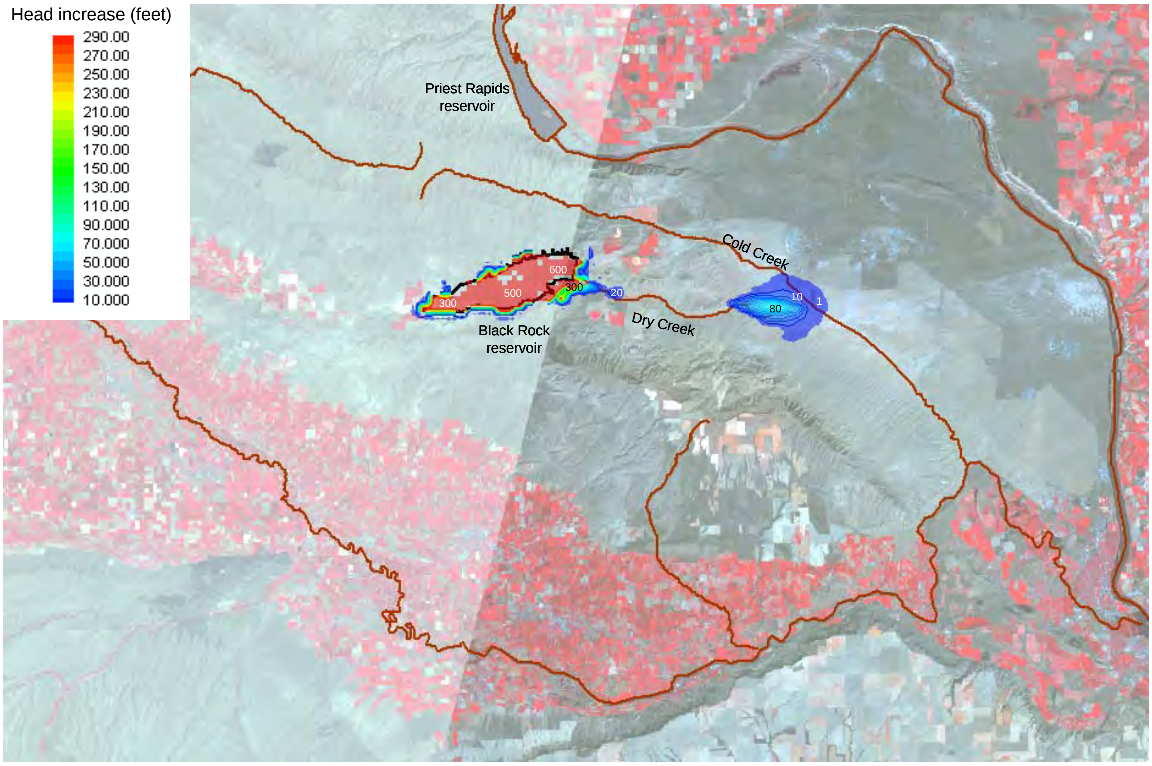

Figure 8-16: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 10 years.

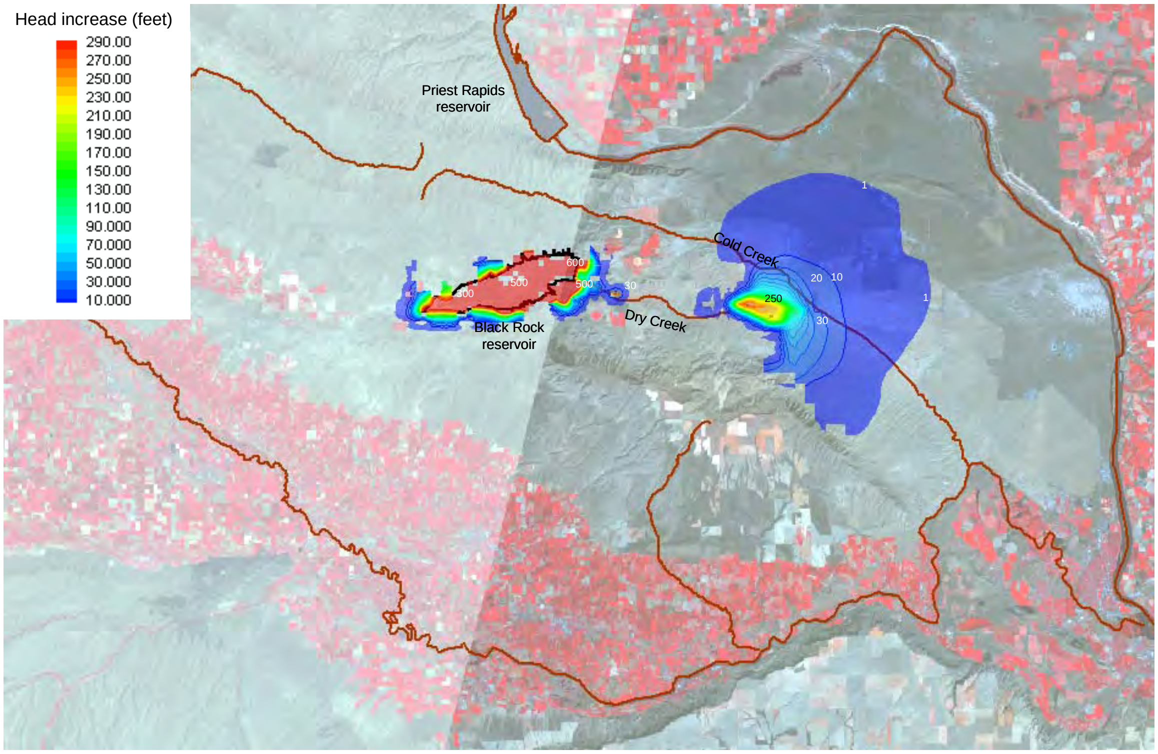

Figure 8-17: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 100 years.

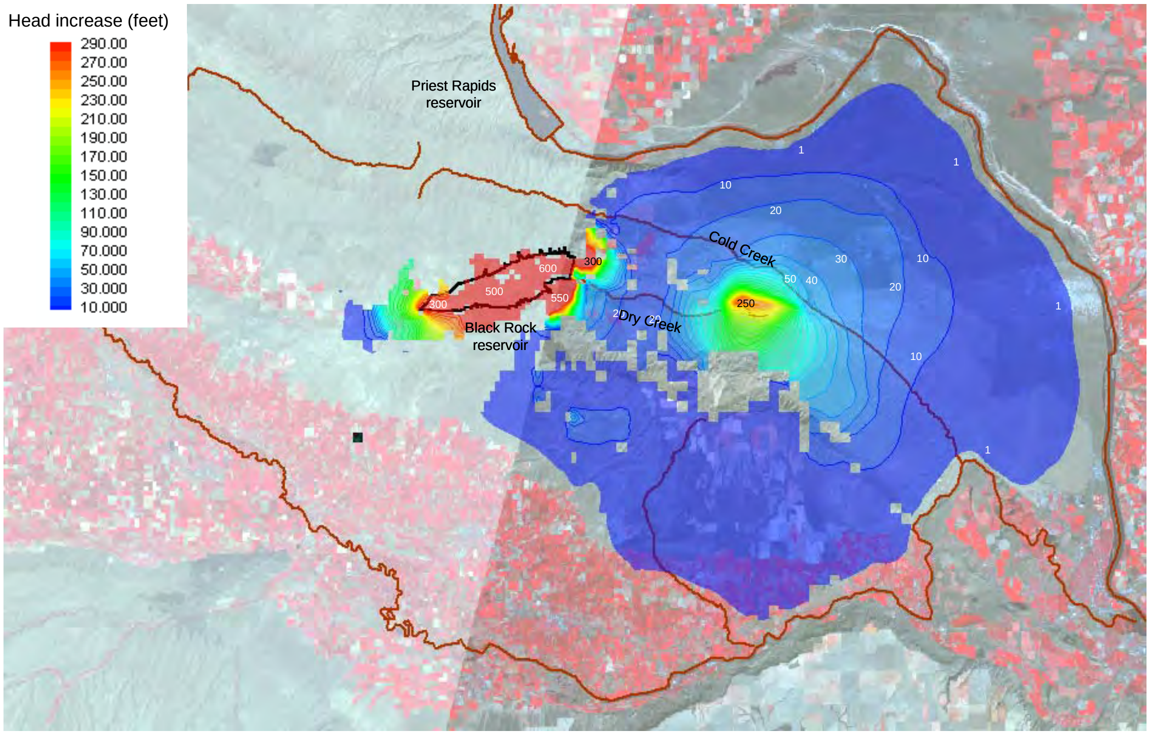

Figure 8-18: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 300 years.

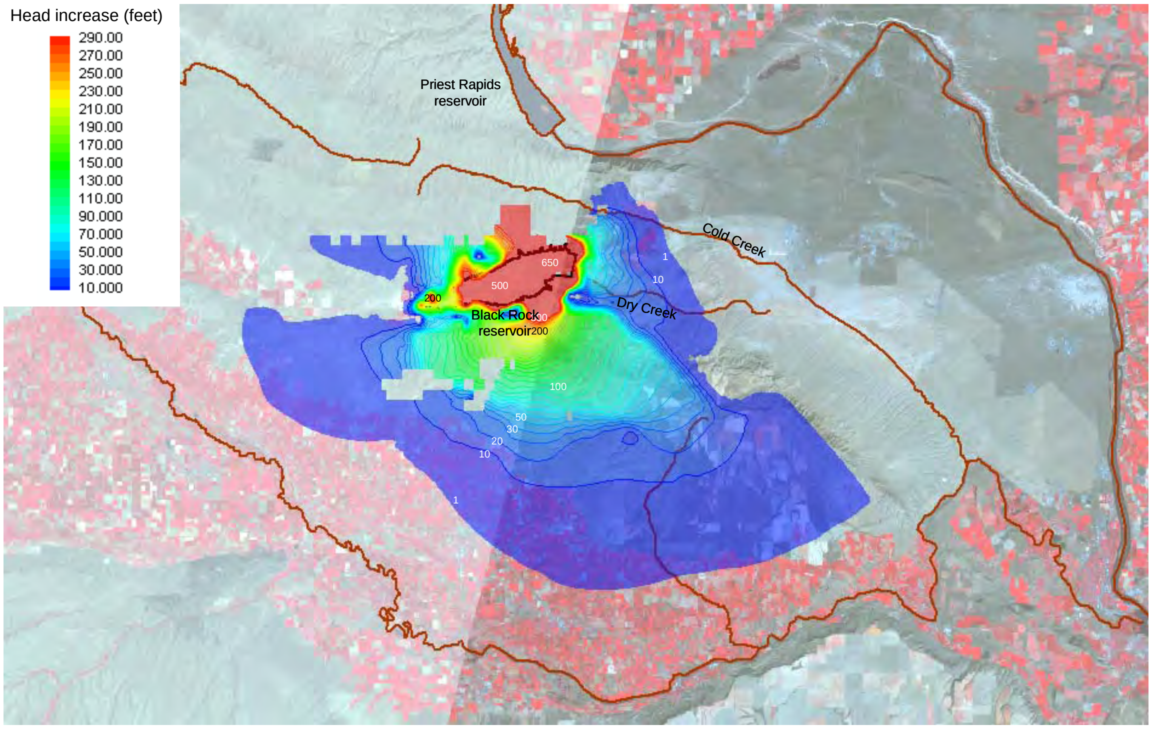

Figure 8-19: Layer 2 (Saddle Mountains) head increase, *permeability 2 average storage* model after 300 years.

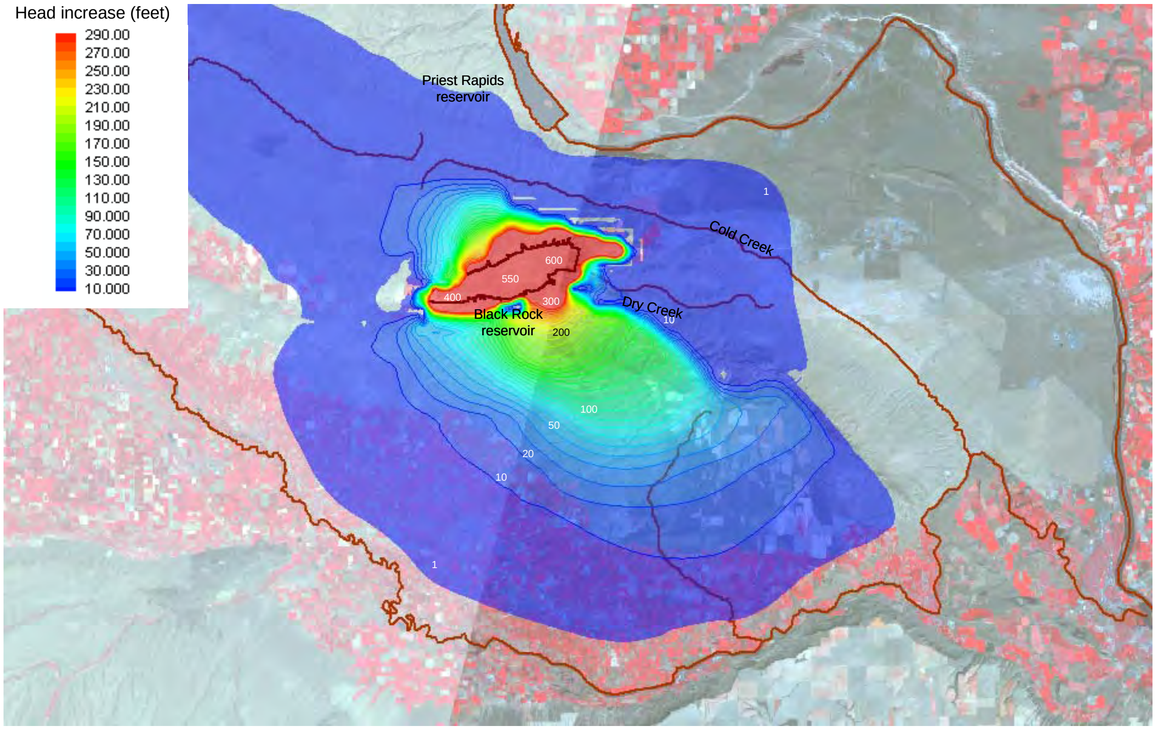

Figure 8-20: Layer 3 (Wanapum) head increase, *permeability 2 average storage* model after 300 years.

8.2.2.3 Permeability 2 Minimum Storage Model

Figures 8-21 through 8-25 show the results of the *permeability 2 minimum storage* model run, and again the first three figures show the increase in head in the layer 1 after 10 years, 100 years and 300 years. The next two figures show the increase in head in layers 2 and 3, respectively.

Once again, the head increase in layer 1 directly beneath the reservoir reaches a maximum within 10 years (Figure 8-21). However, because of higher permeability conditions in the Dry Creek drainage, the impact on head conditions is not quite as localized as in the two previous model runs. Head increases of up to 30 feet occur in about 3.5 miles of the Dry Creek drainage. After 10 years, head increases in the re-infiltration area at the downstream end of Dry Creek have reached their maximum of around 250 feet, and the impact of re-infiltration already extends across Cold Creek for about four miles. Along Cold Creek at the confluence with Dry Creek, layer 1 heads have increased by up to 20 feet.

Between 10 and 100 years, some increase in head occurs at the east and west end of the reservoir, but a much larger area east of Cold Creek is affected by re-infiltration. After 100 years, layer 1 heads have increased by up to 50 feet along Cold Creek (Figure 8-22). Head increases of 10 feet or more extend up to 6 miles east of Cold Creek, and head increases of one foot or more extend across much of the area between Cold Creek and the Columbia River.

Between 100 and 300 years, the area of layer 1 impacted by reservoir seepage and re-infiltration expands further, again mainly to the east of the reservoir. After 300 years, layer 1 heads along Cold Creek have increased by up to 70 feet (Figure 8-23). The impact of reservoir seepage on layer 1 also extends further to the east of Cold Creek, with head increases of 30 feet or more extending up to 4 miles east of the creek, and head increases of 20 feet or more extending up to 6 miles. Again, head increases of one foot or more extend across nearly all of the area between Cold Creek and the Columbia River.

Figure 8-24 and 8-25 show, as expected, that the impact of reservoir seepage on head conditions in the Saddle Mountains and Wanapum layers are concentrated at the reservoir site. The impact of the *permeability 2 minimum storage* model on layers 2 and 3 to the south, west and northeast of the reservoir, is only slightly more extensive than in the two previous model runs. To the east, increased head conditions in the Saddle Mountains layer occur at two locations along 12 miles of Cold Creek and range between 1 and 30 feet. Head increases in the Wanapum layer extend for about 22 miles along the creek and range between 1 and 5 feet.

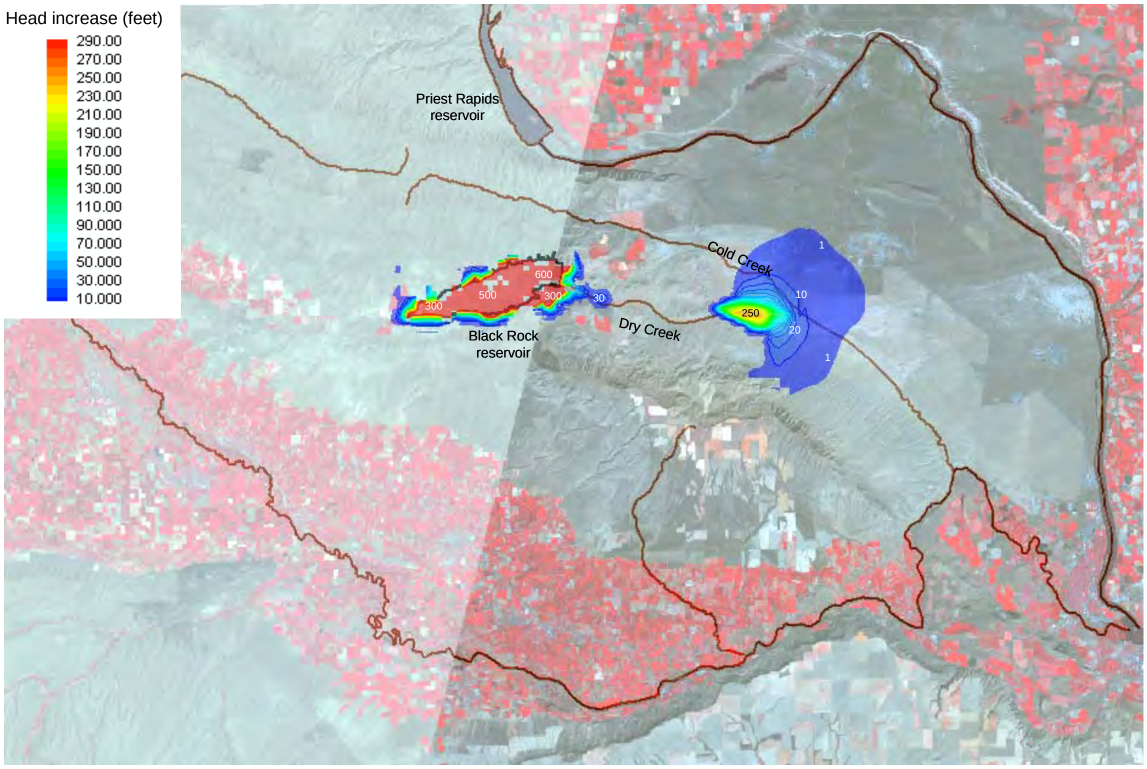

Figure 8-21: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 10 years.

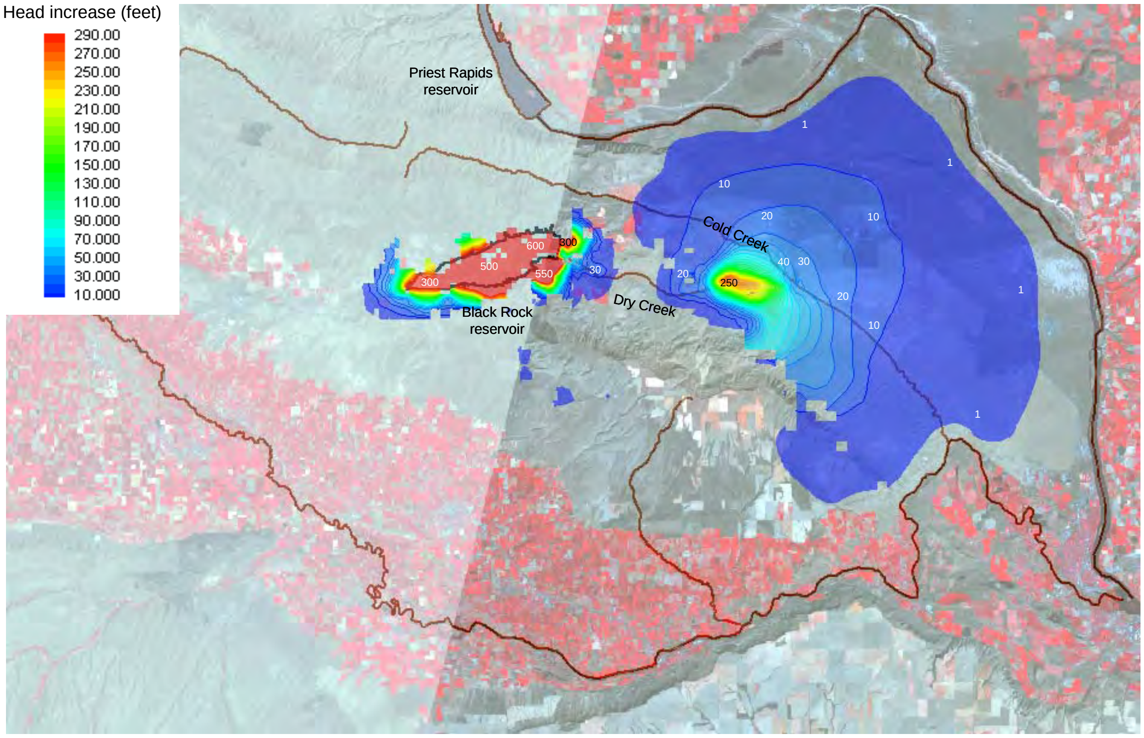

Figure 8-22: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 100 years.

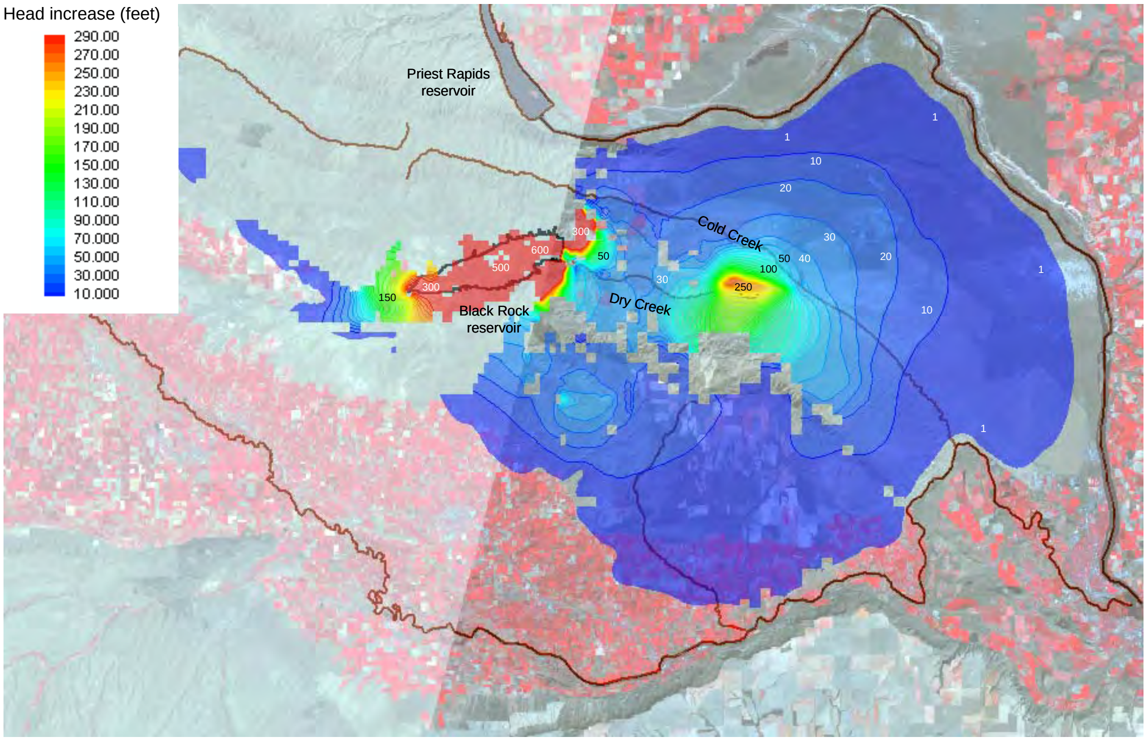

Figure 8-23: Layer 1 (sediments) head increase, *permeability 2 minimum storage* model after 300 years.

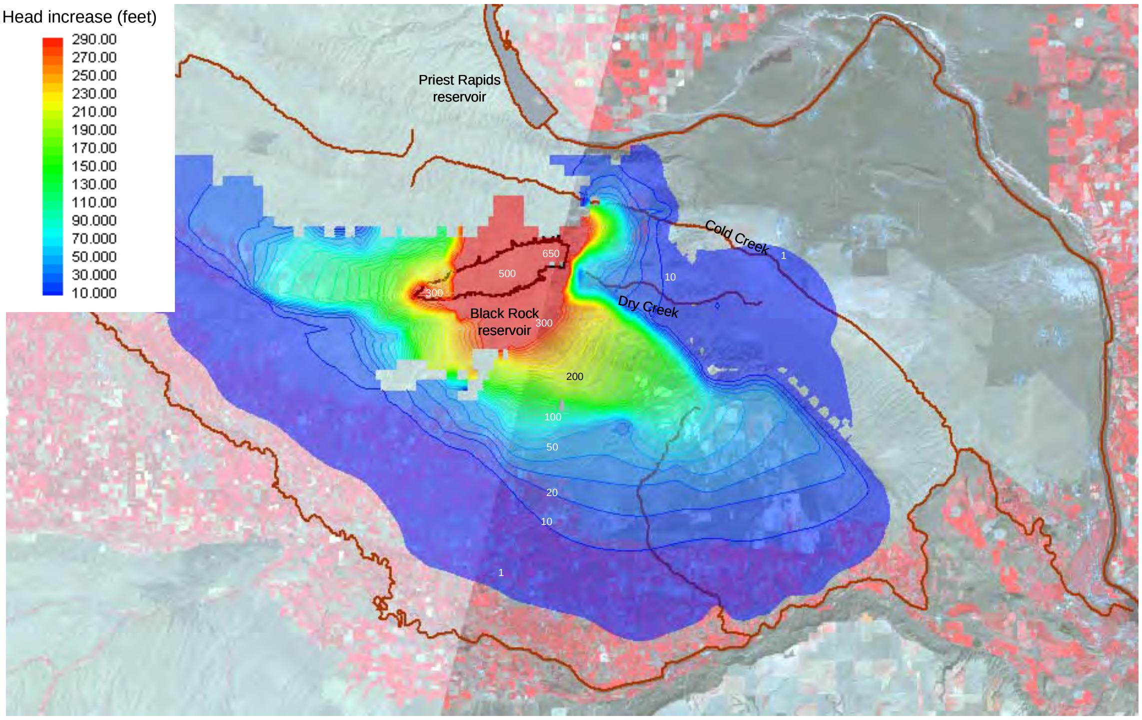

Figure 8-24: Layer 2 (Saddle Mountains) head increase, *permeability 2 minimum storage* model after 300 years.

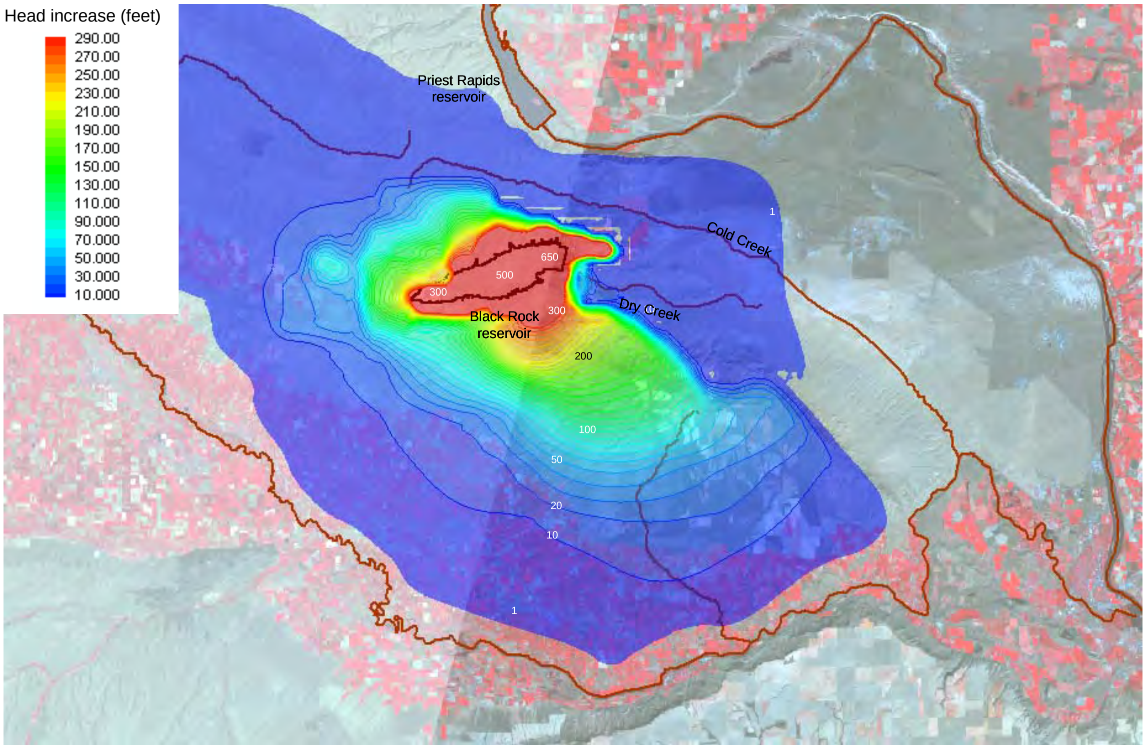

Figure 8-25: Layer 3 (Wanapum) head increase, *permeability 2 minimum storage* model after 300 years.

8.2.3 Steady-State Reservoir Modeling

In order to estimate an absolute maximum impact of the reservoir on aquifer head and flux conditions along Cold Creek, a steady-state version of the Black Rock model was developed incorporating the full reservoir and Dry Creek re-infiltration. The Dry Creek re-infiltration rate used in the steady-state reservoir model is the maximum rate observed at the end of the 300-year transient model. Re-infiltration rates of all three model runs are limited by the thickness of layer 1 sediments in the re-infiltration area, so re-infiltration rates are at their maximum possible values after 300 years.

8.2.3.1 Steady-State Permeability 1, Maximum Storage Model

The difference between steady-state model results and the 300-year transient model results is expected to be greatest for those model runs that assume *maximum specific-storage,* since these runs will require the longest time to reach steady state. If the steady-state version of *permeability 1, maximum storage* model is not appreciably different from the 300-year transient version of this model, then the transient models that assume average and minimum specific-storage values will not be appreciably different from steady state either.

Figure 8-26 shows the increase in layer 1 head conditions that result from a steady-state version of the *permeability 1 maximum storage* model. Comparison with Figure 8-13 reveals that most of the differences in head conditions between this run and the 300-year transient model run are south and west of the reservoir. There is very little difference between the two models along Cold Creek or to the east of Cold Creek.

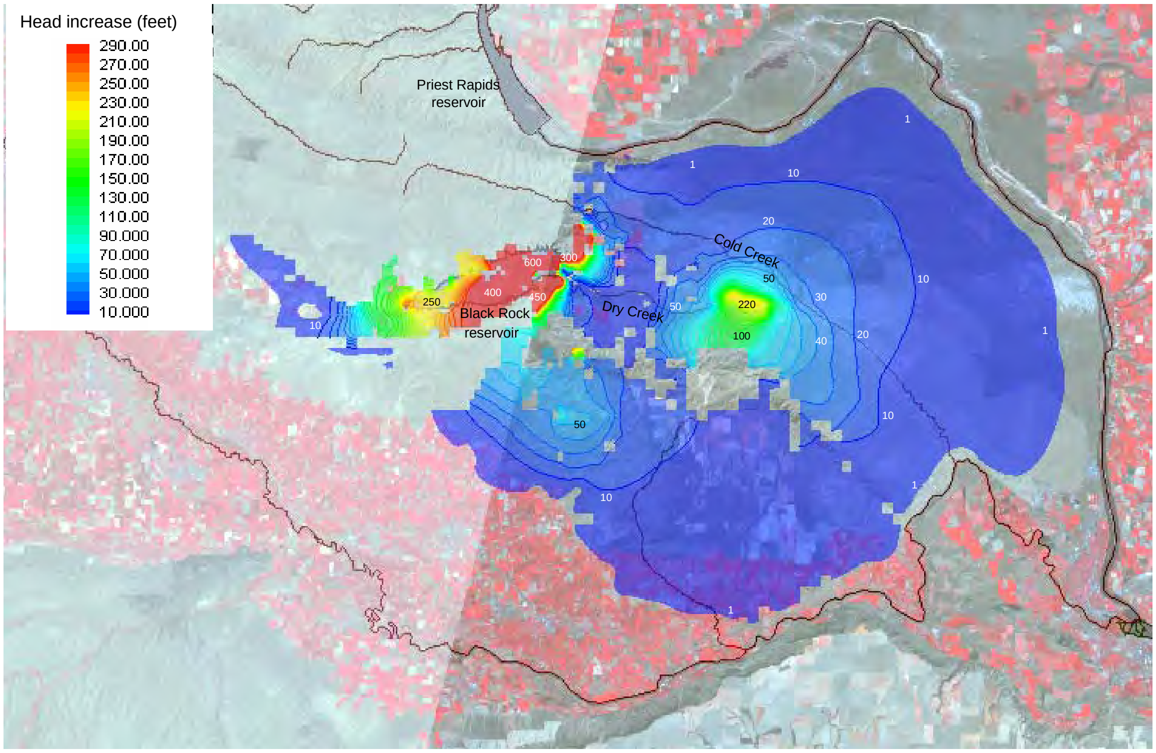

Figure 8-26: Layer 1 (sediments) head increase, *permeability 1 maximum storage* steady-state model.

Figure 8-27 shows the steady-state model results for layer 2. Comparison with Figure 8-14 indicates some additional increase in layer 2 head conditions after 300 years. Again, however, most of the increases are to the south and west of the reservoir where the Saddle Mountains layer is thickest.

These two figures demonstrate that there may be some additional increase in head conditions in layers 1 and 2 after 300 years, but because of the distribution and thickness of sediments and basaltic layers around the reservoir, most of these increases are likely to occur in the deeper basaltic layers, rather then in layer 1 sediments. The steady-state increase in groundwater flow beneath Cold Creek is described in the following chapter.

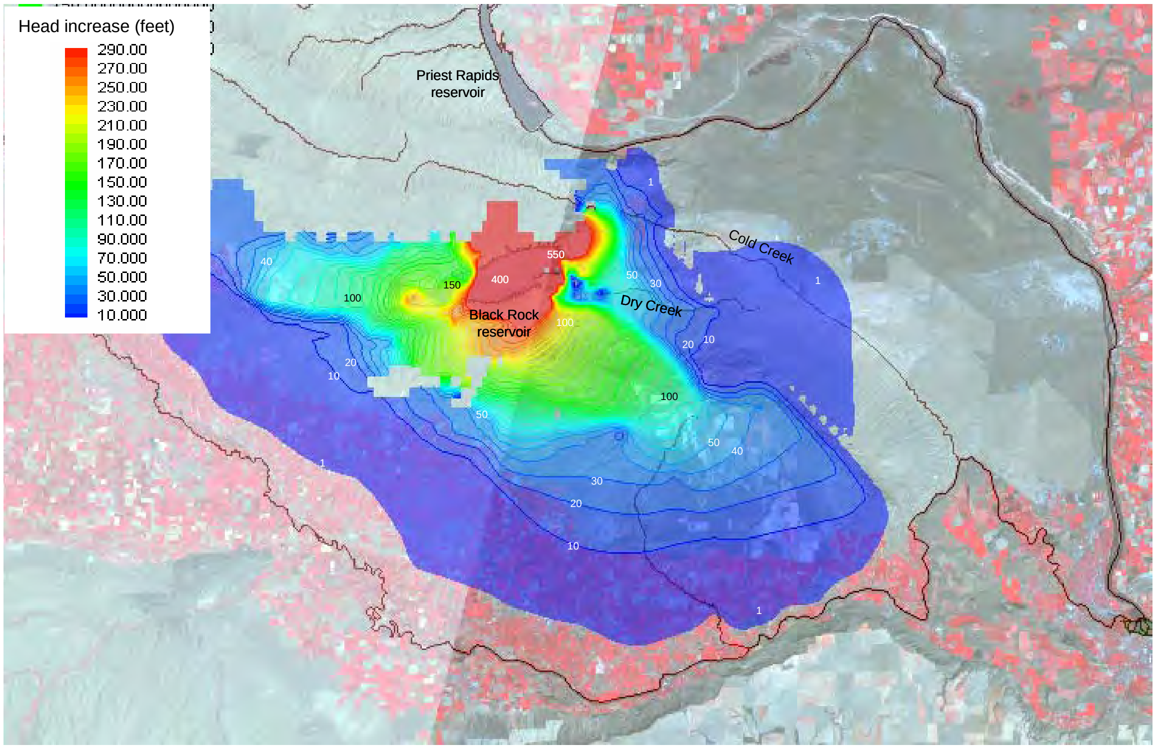

Figure 8-27: Layer 2 (Saddle Mountains) head increase, *permeability 1 maximum storage* steady-state model.

8.3 Groundwater Flow beneath Cold Creek

MODFLOW model results also include estimates of groundwater flux, i.e. the magnitude and direction of groundwater flow. In the Black Rock model, the groundwater flux conditions that are of greatest interest are those in the sediment layer in the vicinity of Cold Creek at the boundary of the Hanford Reservation[6,7].

Figure 8-28 is a contour map showing steady-state base-case head conditions and generalized flow directions in the sediment layer, in an area east of the reservoir that includes Cold Creek and the Hanford Reservation. The head contours in this figure show that the general direction of groundwater flow in the vicinity of Cold Creek is from west to east, toward the Columbia River.

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[6] The geographic boundary of the Hanford Reservation is some distance to the west of Cold Creek (see Figure 3-1). However Cold Creek was the Hanford Reservation hydrologic boundary used in the PNNL Site-Wide Groundwater Model (SGM) (PNNL 2005b, 2006). In order to provide consistency with the PNNL model, Cold Creek is also used here as the western “hydrologic boundary” of the Hanford Reservation.

[7] Black Rock model applications are deliberately limited to describing groundwater flux conditions at the boundary of the Hanford Reservation, recognizing that changes in head and flux in sediment layers within the reservation are more accurately represented by the multi-layer SGM model (PNNL 2005a).

Estimates of groundwater flow at locations along Cold Creek near the Umtanum Ridge, and along Dry Creek near the confluence with Cold Creek were made by PNNL for use as boundary conditions in the Hanford site-wide groundwater flow and transport model (PNNL, 2004a and 2005a). As described in the report, *Potential Impacts of Leakage from Black Rock Reservoir on the Hanford Unconfined Aquifer* (PNNL, 2007), the groundwater flux in sediments at Cold Creek and Dry Creek cell locations (Figure 8-28) were estimated to be 1,700 acre-feet per year and 365 acre-feet per year, respectively.

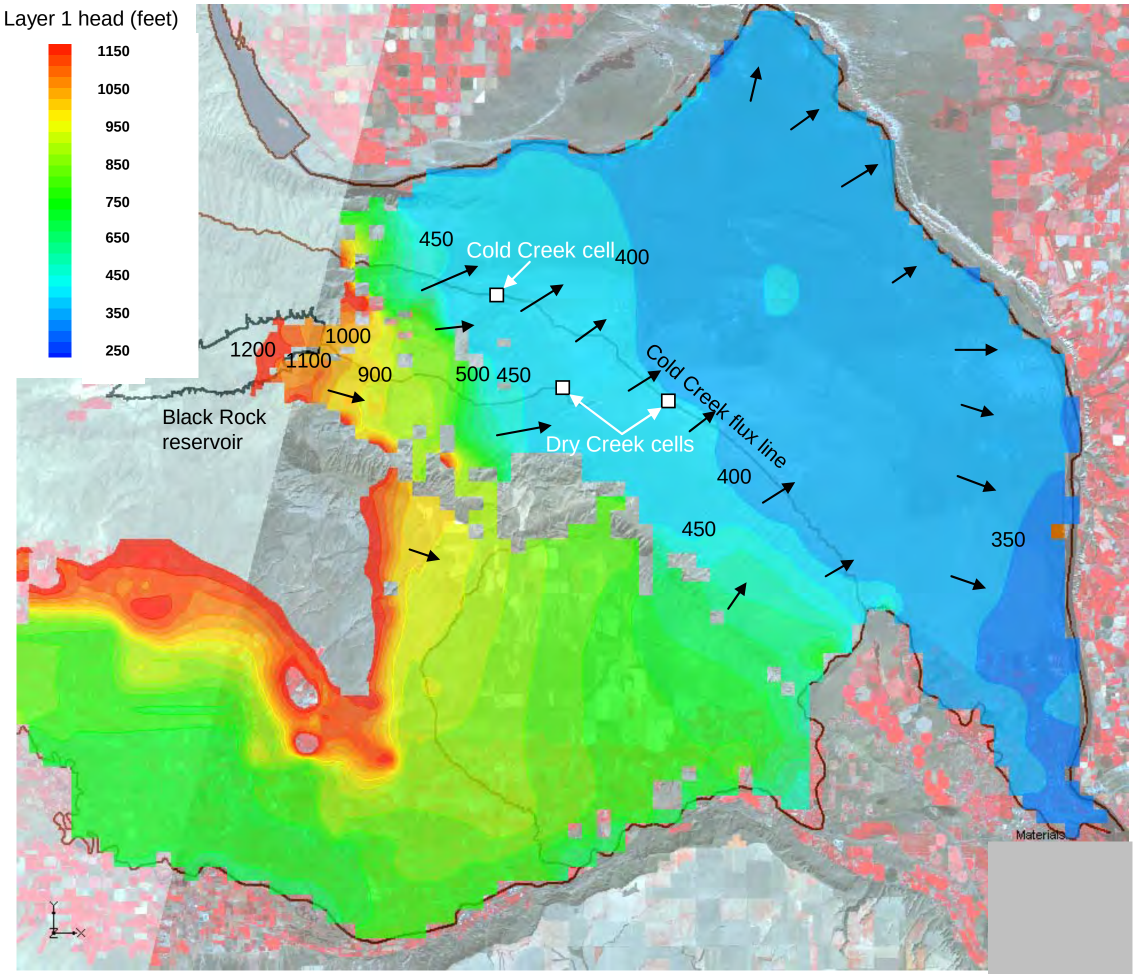

Figure 8-28: Base-case model heads and groundwater flow directions, layer 1.

The Black Rock base-case model estimates of groundwater flow along Cold Creek are comparable to the PNNL estimates. The base-case model estimate of flow in the sediment layer at the Cold Creek cell location was 1,400 acre-feet per year, and the estimate of flow at the two Dry Creek cell locations was 435 acre-feet per year (based on the *permeability 2* conceptual model).

The Black Rock GHP model was also used to calculate groundwater flow at these two cell locations, after 300 years of reservoir operation. Based on results of the *permeability 2 minimum storage* conceptual model, after 300 years, west-to-east groundwater flow at the Cold Creek cell location increased from 1,400 to 1,760 acre-feet per year, and groundwater flow at the Dry Creek cell locations increased from 435 to 3,310 acre feet per year.

Black Rock model results also indicate however, that west-to-east groundwater flow in the sediment layer could be expected to increase all along Cold Creek, as a result of reservoir seepage and re-infiltration in the Dry Creek drainage. Table 8-2 summarizes the Cold Creek groundwater flow results for three conceptual models. Total flow, increase in flow, and percentage increase in flow over base case conditions along the entire length of Cold Creek, are presented after 10 years, 100 years, 300 years, and at steady-state. Base-case model estimates of groundwater flow along the length of Cold Creek vary depending on the model, but average about 7,800 acre-feet per year.

Table 8-2: Summary of layer 1 groundwater flow beneath Cold Creek.

permeability 1 maximum storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	11	8,195			
10 years	14	9,959	3	1,765	22
100 years	22	15,885	11	7,690	94
300 years	31	22,701	20	14,507	177
steady-state	32	22,967	21	14,772	180
permeability 2 average storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	11	7,761			
10 years	17	12,239	6	4,478	58
100 years	32	23,158	21	15,397	198
300 years	41	29,494	30	21,733	280
steady-state	41	29,946	30	22,185	286
permeability 2 minimum storage					
	total flow cfs	**total flow af/year**	**flow increase cfs**	**flow increase af/year**	**Percent increase in flow over base case**
base case	10	7,761			
10 years	26	19,182	16	11,722	147
100 years	39	27,994	28	20,534	260
300 years	41	29,645	30	21,883	282
steady-state	41	29,946	30	22,185	286

Of the three conceptual models, the *permeability 1 maximum storage* model predicts the smallest increase in groundwater flow beneath Cold Creek, relative to base case conditions. The increase in groundwater flow beneath Cold Creek occurs more slowly in this model because of its high specific-storage values. After 300 years, groundwater flow along the entire length of Cold Creek is expected to increase to 22,701 acre-feet per year, a 14,507 acre-foot increase over the base-case flow rate. The steady-state groundwater flow rate of 22,967 acre-feet per year is only about 1 ft^3/s greater than the 300-year transient model result.

The *permeability 2 average storage* model predicts a larger increase in groundwater flow beneath Cold Creek. The flow rate also increases more rapidly in this model because specific-storage values are lower. After 300 years groundwater flow beneath Cold Creek is expected to increase to 29,494 acre-feet per year, a 21,733 acre-foot increase over the base-case rate. The steady-state flow rate of 22,946 acre-feet per year is less than 1 ft^3/s greater than the 300-year result

The *permeability 2 minimum storage* model predicts an increase in groundwater flow beneath Cold Creek that matches the *permeability 2 average storage* model at steady state; however because this model assumes the lowest specific-storage values, the flow rate increases even more rapidly then before. Once again, the difference in flow between the 300-year result and the steady-state result is negligible.

In the Saddle Mountains and Wanapum layers, all three models predict very small increases in west-to-east groundwater flow beneath Cold Creek, ranging from just 20 to 70 acre-feet per year, after 300 years.

9.0 Model Based Responses to Six Initial Questions

Although the model builds directly on the fully-calibrated USGS Columbia Plateau Regional Groundwater Model, the hydrogeologic complexity of the Black Rock site, the limited hydrologic data for characterizing this complexity, and the time constraints on model development mean that the first five questions posed earlier can only be answered within a fairly broad range of possible outcomes.

The first two questions are addressed using results of the (early-time) LP version of the Black Rock model. The next three questions are addressed using results of the (late-time) GHP version of the model. The last question is answered based on knowledge gained during development and application of the model

1. How long will it take to fill Black Rock reservoir initially, given the expected water availability and expected reservoir seepage rates?

Based on monthly water availability at the Priest Rapids Dam Reservoir during an average water year (i.e. 1967), the LP model estimates that it will take approximately 380 days to initially fill the reservoir to the1,775-foot stage, assuming no reservoir withdrawals for irrigation during the first year.

2. What is the expected seepage rate from the Black Rock reservoir during initial filling?

Reservoir seepage is expected to increase from month to month as the reservoir initially fills. Based on two model runs that assume different hydraulic conductivity distributions but the same average value for specific-storage, the LP version of the model predicts that seepage would range between 1,160 and 4,390 acre-feet per month (14,100 and 53,400 acre-feet per year) after the first month of reservoir operation. After six months, the seepage rate could be expected to increase to between 4,850 and 6,370 acre-feet per month (58,980 and 77,480 acre-feet per year), and at the end of the first year, reservoir seepage rate is expected to range between 5,600 and 8,630 acre feet per month (68,200 and 105,000 acre-feet per year). The reservoir seepage losses are expected to peak at 13 months between 6,000 and 9,950 acre-feet per month (72,933 and 121,043 acre-feet per year). Cumulative seepage losses during the first 13 months of reservoir operation are expected to be between 45,700 and 77,900 acre-feet.

3. What is the expected seepage rate from the reservoir over time, once filled to capacity?

The GHP version of the model predicts a range of reservoir seepage rates based on six model runs that assume two different hydraulic conductivity distributions, and three different estimates of specific-storage. Seepage estimates are bounded by the *permeability 1 minimum storage* model, which produces the minimum estimate of seepage; and the *permeability 2 maximum storage* model, which produces the maximum estimate.

After the first few years of operation, the GHP version of the Black Rock model predicts that reservoir seepage rate would begin decreasing. After 5 years seepage is expected to range between 32,100 and 54,300 acre-feet per year, the most likely seepage rate is 44,900 acre-feet per year. After 25 years, seepage is expected to range between 30,700 and 53,400 acre-feet per year, and the most likely rate is 42,200 acre-feet per year. After 100 years, the range is 29,900 and 53,200 acre-feet per year, and the most likely rate is 41,300 acre-feet per year. Finally, after 300 years reservoir seepage approximates a steady-state rate that ranges between 29,800 and 52,300 acre-feet per year. The most likely rate, based on model results, is 40,900 acre-feet per year.

4. What impact will the full reservoir have on groundwater discharge to creeks, drains, and springs, aquifer storage, and aquifer head conditions?

The range of estimates for discharge to creeks, drains, and springs is bounded by results of the *permeability 1 maximum storage* model, which produces the minimum estimate of discharge; and the *permeability 2 minimum storage* model, which produces the maximum estimate.

Groundwater discharge to creeks, drains, and springs in the vicinity of a full reservoir is expected to gradually increase from year to year. After 5 years, the GHP version of the Black Rock model predicts the discharge rate will increase by between 25,600 and 51,100 acre-feet per year and the most likely increase in discharge is 36,300 acre-feet per year. After 25 years, the increase in discharge is expected to range between 27,600 and 51,400 acre-feet per year and the most likely increase is 38,800 acre-feet per year. After 100 years, the increase is expected to be between 29,000 and 51,500 acre-feet per year and the most likely increase is 40,000 acre-feet per year. After 300 years, the increase in discharge to creeks, drains, and springs over base-case conditions is expected to be between 29,500 and 51,600 acre-feet per year. The most likely increase after 300 years is 40,400 acre-feet per year, which approximates the steady-state discharge rate.

The range of estimates for the increase in aquifer storage is bounded by the results of the *permeability 1 minimum storage* model, which produces the minimum estimate of increased storage; and the *permeability 1 maximum storage* model, which produces the maximum estimate.

The rate of increase in aquifer storage is expected to peak within a year or two after the reservoir is first filled, and then decline from year to year after that. After 5 years, the GHP model predicts that aquifer storage will be increasing at the rate of between 2,400 and 14,700 acre-feet per year, and the most likely rate of increase in aquifer storage is 8,600 acre-feet per year. After 25 years, the rate of increase is expected to be between 1,000 and 6,500 acre-feet per year and the most likely rate is 3,400 acre-feet per year. After 100 years the increase ranges between 200 and 2,900 acre feet per year and the most likely rate is 1,300 acre-feet per year. After 300 years the rate of increase in aquifer storage is reduced to between 1 and 1,500 acre feet per year and the most likely rate is 600 acre-feet per year, indicating a near steady-state condition.

Ultimately, a full reservoir will increase aquifer heads directly beneath the reservoir in layers 1, 2 and 3 (sediments, and the Saddle Mountains and Wanapum layers) by between 250 and 650 feet over base-case conditions. The greatest increases are expected to occur at the east end of the reservoir, where reservoir depth is greatest.

Away from the reservoir, increased aquifer heads that are a direct result of reservoir seepage are expected mainly in layers 2 and 3, and mainly south and northwest of the reservoir. For the most part, head increases in layer 1 are not a direct result of reservoir seepage but rather the result of re-infiltration in the Dry Creek drainage, and are spread out mainly to the east of the reservoir.

5. What impact will the reservoir have on groundwater flow and head conditions at the boundary of the Hanford Reservation (along Cold Creek)?

The GHP model predicts that the west-to-east flow of groundwater in the sediment layer, beneath Cold Creek into the Hanford Reservation could be expected to increase as a result of reservoir seepage. The increased groundwater flow results from increased surface flow in the Dry Creek drainage, which re-infiltrates the sediment layer near the confluence of Dry Creek and Cold Creek drainages.

The base-case model estimate of west-to-east groundwater flow beneath Cold Creek in the sediment layer is about 7,800 acre feet per year. As a result of re-infiltration, the GHP model estimates that groundwater flow beneath Cold Creek, along its entire length, could ultimately (after 300 years) increase to between 22,700 and 29,500 acre-feet per year, an increase of between 14,500 and 21,700 acre-feet per year over base-case conditions. Most of the increased flow beneath Cold Creek would be near the confluence with Dry Creek. The GHP model predicts little increase in groundwater flow beneath Cold Creek in the Saddle Mountains and Wanapum layers.

Head increases at the center of the re-infiltration area (along Dry Creek, west of Cold Creek) could ultimately be expected to range between 220 feet and 250 feet.

The impact of re-infiltration on head conditions in layer 1 could also be expected to extend across the entire area between Cold Creek, and the Columbia River.

The smallest impact on head conditions at the boundary of the Hanford Reservation is predicted by the *permeability 1 maximum storage* model. In this model, head in the sediment layer along the 21-mile length of Cold Creek would ultimately increase between 1 and 40 feet. The impact of the *permeability 2 average storage* model at the Hanford boundary is somewhat greater. Under this scenario the increase in head along the length of Cold Creek ranges between 1 and 60 feet. The greatest impact is predicted by the *permeability 2 minimum storage* model. In this model the increase in head along the length of Cold Creek would ultimately range between 1 and 90 feet.

6. What additional field testing would be most valuable in reducing uncertainty in model predictions of reservoir hydrologic impacts?

Groundwater model development is, fundamentally, a rigorous investigative process in which numerical modeling tools are used to build a coherent hydrologic picture from contrasting elements of hydrogeology, groundwater mechanics, aquifer testing, and observation. The model development process itself invariably results in new hydrologic insights and understanding that can serve as a guide to the acquisition of other important hydrologic data.

Modeling, together with geologic drilling and aquifer testing at the reservoir site provide indications that much of the hydrogeologic complexity of site (i.e. heterogeneity in aquifer properties including hydraulic conductivity and specific-storage) is concentrated near the right dam abutment and in the Dry Creek drainage.

While high hydraulic conductivity zones within the Saddle Mountains and Wanapum Basalts are mainly concentrated in flow tops, horizontal and vertical hydraulic conductivities can also be affected by subsequent folding and faulting of these basaltic layers. The hydrogeologic complexity of the right abutment area and the Dry Creek drainage is mainly the result of this complex geologic structure.

Multi-well aquifer testing involving cross borehole packer tests is standard practice for characterizing the directional components of hydraulic conductivity in heterogeneous fault and fracture zone settings (Committee on Fracture Characterization and Fluid Flow, 1996). Additional multi-well testing aimed at characterizing hydraulic conductivity (and layering) within Saddle Mountains Basalts at the east end of the reservoir site and along Dry Creek drainage could reduce uncertainty in Black Rock model predications of reservoir seepage and potential impacts on Hanford Reservation groundwater levels.

The seepage rates presented in this report have been calculated using the best available hydrologic data. Since no measured hydraulic conductivity data is available in the Dry Creek drainage, values from the U.S. Geological Survey's regional model were used and then adjusted until water levels predicted by the model matched measured water levels in local wells in the area.

We believe that the seepage rates produced by this model are accurate based on the data we have available. However given the geologic complexity of the area at the damsite and the Dry Creek drainage, gathering new hydrologic data in the Dry Creek drainage could change the seepage rates that are presented in this report.

Glossary

Alluvium – Clay, silt, sand, gravel, or similar remnant material that has been deposited by running water.

Alluvial fan – A cone-shaped alluvial deposit made by a stream where it issues from a mountain upon a plain or by a tributary stream at its junction with the main stream.

Anadromous fish habitat – River or stream environment suitable for fish who return from the ocean to spawn.

Anisotropy – Property of an aquifer system with physical and hydrologic properties that vary directionally.

Anticline – A geologic fold that is convex upward and whose core contains stratigraphically older rocks.

Aquifer – Subsurface formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield usable quantities of water to wells and springs.

Aquifer flux – The directional volumetric flow or discharge of groundwater per unit length, within an aquifer.

Aquifer recharge/discharge – The process by which groundwater enters or leaves an aquifer.

Aquifer system – The hydrologic interaction and relationship between multiple aquifer layers.

Aquifer test – The process of applying a hydraulic stress to an aquifer in order to determine hydrologic properties. Aquifer testing generally involves extracting or injecting water and measuring the resulting change in aquifer head.

Base-case model – Initial model run representing current aquifer conditions from which all subsequent model runs are compared.

Boundary conditions – Spatially defined constraints imposed on the MODFLOW groundwater flow equation at the locations of aquifer boundaries such as rivers, drains, and wells.

Calibration – The process by which modeling parameters such as aquifer hydraulic conductivity and specific-storage are estimated, based on observations of aquifer head and aquifer flux.

Columbia River Basalt Group – A series of Miocene-age lava flows with interbedded sediments that underlie the Columbia Plateau and model study area.

Confined aquifer – An aquifer in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations.

Fracture zone – A zone of bedrock that exhibits increased fracturing, often due to folding or faulting.

Glaciofluvial deposits – Deposits produced by meltwater streams flowing from melting glacier ice.

Grande Ronde Basalt – Oldest, most voluminous, and areally extensive formation of basalt in the Columbia River Basalt Group in the Black Rock area.

Groundwater – Subsurface water that resides in saturated pore spaces of a rock formation.

Ground-water modeling – Computer-based process of calculation by which numerical methods are used to represent and describe the subsurface movement of groundwater.

Head (hydraulic) – A specific measurement of water pressure or total energy per unit weight, above a datum elevation.

Heterogeneous – A non-uniform aquifer condition in structure or composition.

Hydraulic conductivity – A material (and fluid) property that describes the ease with which water can move through connected pore spaces or fractures in a geologic formation.

Hydraulic connection – The capacity for water to move between discrete locations within an aquifer system.

Hydraulic gradient – The change in hydraulic head between two or more points in an aquifer.

Hydrogeology – Science that deals with subsurface water and the related geologic aspects of surface water.

Hydrograph – A graph showing stage, flow, velocity, or other characteristics of water with respect to time.

Hydrologic model – A computer-based process of calculation by which numerical methods are used to represent and describe surface water or groundwater systems and their interactions.

Hydrologic test – A test conducted to determine aquifer hydraulic properties including hydraulic conductivity and specific-storage.

Hydrology – The science that deals with the properties, distribution, and circulation of water on and below the earth's surface, and in the atmosphere.

Infiltration – The movement of surface water through soil or porous rock.

Leakance parameter – A MODFLOW modeling parameter describing the rate at which water will move between a surface water body, such as a stream or lake, and the underlying aquifer.

Loess – Wind-blown silt.

Model domain – The modeling area of interest, bounded by model boundary conditions.

Model cells – Discretized aquifer volumes used to numerically approximate the solution to the governing groundwater flow equation of the MODFLOW model. The collection of model cells within the model domain is the model grid.

Model layer(s) - Model representation of aquifer layers.

Model run – A single model application incorporating a unique set of model parameter values representing aquifer hydraulic conductivity and specific-storage values.

Permeability – A hydrologic property that describes the rate at which groundwater can move through an aquifer. Permeability may be extrinsic or intrinsic. Intrinsic permeability is a property of the aquifer medium alone. Extrinsic permeability is a property of the medium and the fluid and is used (in this report) interchangeably with hydraulic conductivity.

Overburden – A general geologic term that includes all of the unconsolidated sediments that overlie a bedrock formation.

Reservoir seepage – The subsurface infiltration of reservoir water occurring beneath and along the sides of the reservoir. Reservoir seepage is the sum of the increase in ground-water discharge to creeks, drains, and springs, and the increase in groundwater storage in all model layers.

Reservoir stage - The elevation of water in a reservoir relative to a datum.

Saddle Mountains Basalt – The youngest basaltic formation of the Columbia River Basalt Group.

Spatial resolution – A model characteristic determined by the size and distribution of cells in the MODFLOW model grid.

Spatial distribution – The distribution of parameters with respect to space.

Specific storage – The amount of water that a given aquifer volume will expel when a unit change in hydraulic head is applied to it, while it remains fully saturated. Specific-storage is a property of confined aquifers.

Specific yield – A ratio representing the volumetric fraction of total bulk volume that an aquifer will yield when all the water is allowed to drain out of it under the force of gravity. Specific yield is a property of unconfined aquifers.

Steady-state model – A model of an aquifer system in equilibrium (or in balance) with respect to groundwater inflow and outflow; i.e. an aquifer model in which groundwater head and flux conditions are unchanging in time.

Stratigraphy – Classifying rock and geologic materials into separate formations based on their physical, geochemical, and paleomagnetic polarity differences and in geologic age from oldest to youngest.

Stress period – A MODFLOW model time period within which all aquifer stresses are fixed.

Syncline – A geologic fold in which the strata dip inwards from both sides toward the axis, concave in shape.

Time step – The basic discretization of time in a transient or time-dependent MODFLOW model.

Transient model (time-dependent) – A model of an aquifer system that is not in equilibrium with respect to groundwater inflow and outflow. Also an aquifer model in which groundwater head and flux conditions are changing with time.

Wanapum Basalt – Basaltic formation of the Columbia River Basalt Group that overlies the Grande Ronde Basalt and underlies the Saddle Mountains Basalt.

Yakima Fold Belt – The southwest portion of the Columbia Plateau that is characterized by folded topography.

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