RECLAMATION
Managing Water in the West

Technical Series No. TS-YSS-25

Modeling Mitigation of Seepage from 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

December 2008

Cover Photograph – Dry Creek downstream of mitigation features (taken by Christensen, 2008).

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prepared by

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

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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.

Preface

The Congress 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. Section 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."

Reclamation initiated the Yakima River Basin Water Storage Feasibility Study (Storage Study) in May 2003. As guided by the authorization, the purpose of the Storage Study is to identify and examine the viability and acceptability of alternate projects by: (1) diversion of Columbia River water to a potential Black Rock reservoir for further water transfer to irrigation entities in the lower Yakima River basin as an exchange supply, thereby reducing irrigation demand on Yakima River water and improving Yakima Project stored water supplies; and (2) creation of additional water storage within the Yakima River basin. In considering the benefits to be achieved, study objectives are to modify Yakima Project flow management operations to improve the flow regime of the Yakima River system for fisheries, provide a more reliable supply for existing proratable water users, and provide water supply for future municipal demands.

State support for the Storage Study was provided in the 2003 Legislative session. The 2003 budget included appropriations for the Washington State Department of Ecology (Ecology) with the provision that the funds ". . . are provided solely for expenditure under a contract between the department of ecology and the United States Bureau of Reclamation for the development of plans, engineering, and financing reports and other preconstruction activities associated with the development of water storage projects in the Yakima river basin, consistent with the Yakima river basin water enhancement project, P.L. 103-434. The initial water storage feasibility study shall be for the Black Rock reservoir project." Since that initial legislation, the State of Washington has appropriated additional matching funds.

Storage Study alternatives were identified from previous studies by other entities and Reclamation, appraisal assessments by Reclamation in 2003 through 2006, and public input. Reclamation filed a Notice of Intent and Ecology filed a Determination of Significance to prepare a combined Planning Report and Environmental Impact Statement (PR/EIS) on December 29, 2006. A scoping process, including two public scoping meetings in January 2007 identified several concepts that were considered in the Draft PR/EIS (Reclamation, 2008). Those concepts were developed into "Joint" and "State" Alternatives.

The Joint Alternatives fell under the congressional authorization and the analyses were cost-shared by Reclamation and Ecology. The State Alternatives fell outside the congressional authorization, but within the authority of the state legislation, and were analyzed by Ecology only. Analysis of all alternatives was included in the Draft PR/EIS.

Some comments pointed out that Yakima River Basin issues were not being adequately addressed in the Draft PR/EIS. Given those comments and the narrow focus of the congressional authorization, the State of Washington has decided to not participate further in the joint NEPA/SEPA process. The State will continue the SEPA process to look at a broader range of solutions to water resource problems that are not limited to storage solutions. As a consequence, the State Alternatives have been deleted from the Final PR/EIS and will be addressed in a separate SEPA process.

This technical document and others explain the analyses performed to determine how well the alternatives meet the goals of the Storage Study and the impacts of the alternatives on the environment. These documents address such issues as hydrologic modeling, sediment modeling, temperature modeling, fish habitat modeling, and designs and costs. All technical documents were the basis for the Draft and Final Environmental Impact Statements and are available for review.

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Executive Summary

This report describes the development and results of a ground water model (henceforth referred to as the 'mitigation model') that examines the effectiveness of mitigation measures for reducing and intercepting reservoir seepage from the proposed Black Rock reservoir. An earlier model, the Black Rock seepage model (Reclamation, 2007b), was developed to simulate the hydrologic impacts of the proposed Black Rock dam and reservoir and predicted that the majority of seepage would migrate east of the reservoir into the Dry Creek drainage and eventually to the Hanford Site. This model, as was the earlier model, was calibrated to observed groundwater levels without any influence from the reservoir seepage.

There is widespread concern about the possibility of increased contaminant movement and higher groundwater levels on the Hanford Site due to the addition of seepage from Black Rock. Mitigation measures, such as a geomembrane blanket, cutoff walls, and interceptor wells have the potential to reduce reservoir seepage and/or intercept seepage water before it reaches the Hanford Site so that impacts are minimized. The mitigation model examines the effectiveness of specific measures for reducing the rate of reservoir seepage in the right abutment area of the dam and beneath the dam itself. The mitigation model also examines the potential for intercepting reservoir seepage that emerges in the Dry Creek drainage downstream from the dam.

Mitigation Model Objectives

The objectives of the mitigation model are:

- Refine the seepage model to provide better representation of the areas where most reservoir seepage occurs and where potential mitigation measures would be applied.

- Calibrate the steady-state mitigation model and verify that the resulting seepage estimates match, as closely as possible, the results of the earlier steady-state seepage model.

- Determine if the earlier Black Rock seepage model results represented the full range of seepage possibilities.

- Simulate potential mitigation measures and estimate their effectiveness in reducing reservoir seepage and/or intercepting seepage before it reaches the Hanford Site.

Model Domain and Development

The mitigation model domain is the same as the earlier seepage model and is bounded on the east by the Columbia River and on the south and west by the Yakima River (Figure ES-1).

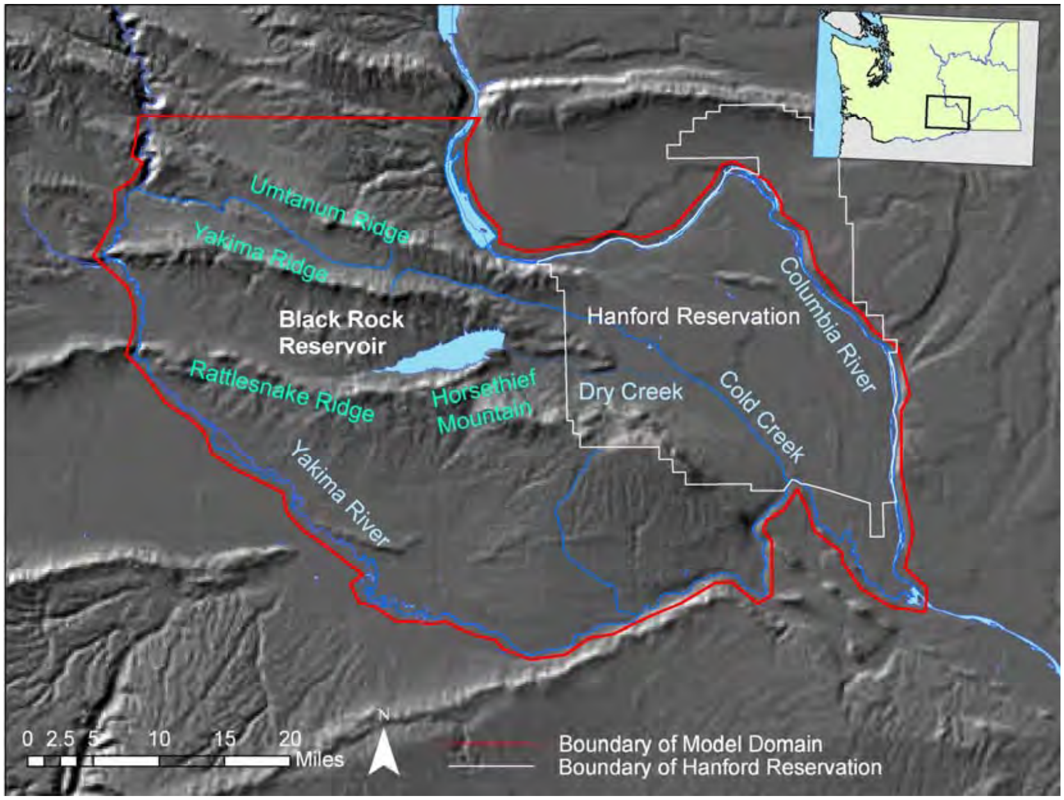

Figure ES-1: Modeled area bounded by the Columbia River to the east and the Yakima River to the south and west.

Like the seepage model, the mitigation model was calibrated without the reservoir present. Unlike the seepage model, the mitigation model was run in a steady-state mode only. All simulations of mitigation measures assume a full reservoir at equilibrium with the underlying aquifer. No attempt was made to simulate the time-dependent impacts of potential mitigation measures as the reservoir fills.

While the 2007 Black Rock seepage model was the basis for this mitigation model, certain refinements to model layering and calibration were made in order to meet the new modeling objectives. First, the horizontal grid spacing was reduced in the Dry Creek area to provide better resolution for comparatively small mitigation features that were to be represented in the model. The new grid mesh is 375 x 375 feet square in the dam area and the Dry Creek drainage, and gradually increases to 3,000 feet square in the out-lying areas. Second, the Saddle Mountain model layer (layer 2 in the seepage model) was split into two model

layers in order to provide greater vertical resolution in the layer that is most likely to be affected by installation of mitigation measures.
In the mitigation model, six model layers were used to represent Black Rock Valley hydrogeologic units: layer 1 represents the overburden sediments of the alluvium, Ringold and Ellensburg Formations, layers 2 and 3 represent the Saddle Mountains Basalt, layer 4 represents the Wanapum Basalt, and layers 5 and 6 represent the Grande Ronde Basalt.

Since seepage from the full reservoir (at equilibrium) is expected to completely saturate the Saddle Mountains Basalt, both upper and lower Saddle Mountains layers are represented in the model as confined aquifer layers. Additionally, since no new hydrogeologic data has become available since the seepage model was completed, the original distribution of hydraulic conductivity in the Saddle Mountains layer was assigned to cells in both upper and lower layers.

Model Calibration

The 2007 seepage model was calibrated to two conceptual models that varied in their distribution of hydraulic conductivity values in the Dry Creek valley. The results were labeled “Permeability 1” (resulting in a lower seepage estimate) and “Permeability 2” (resulting in a higher seepage estimate). Hydraulic conductivities from the “Permeability 2” seepage model were inserted in the mitigation model initially, and then modified slightly as part of a trial-and-error model calibration.

After calibration was achieved, the model was run with the reservoir full and the results were compared to the equilibrium results of the seepage model. The reservoir seepage rate calculated by the “Permeability 2” seepage model was 71.1 cubic feet per second (cfs) (Reclamation, 2007b). The reservoir seepage calculated by the calibrated mitigation model is 74.3 cfs. Like the seepage model, the mitigation model indicated that the majority of reservoir seepage would occur in the right abutment area of the dam, affecting head conditions in the sediments, the Saddle Mountains, and Wanapum Basalts underlying the reservoir.

To assess whether the seepage model results (the “Permeability 1” and “Permeability 2” models) captured the full range of possibilities with respect to reservoir seepage, a stochastic (Monte Carlo) simulation was performed using the calibrated mitigation model. In a Monte Carlo simulation, the model is run repeatedly with random parameter values that are uniformly distributed within a given range. For the case of the Black Rock mitigation model, hydraulic conductivities in the upper four layers in the Dry Creek drainage area were varied randomly.

The 95 percent confidence interval for stochastically generated seepage data ranged from 27.4 cfs to 75.1 cfs. The “Permeability 2” seepage estimate from the earlier Black Rock seepage model was 71.1 cfs, which approximates the upper bound of this 95 percent confidence interval. The results of the stochastic simulation verified that the “Permeability 2” hydraulic conductivity distribution did, in fact, produce a maximum estimate of reservoir seepage. This hydraulic conductivity distribution was therefore used in the mitigation model to assess the effectiveness of mitigation measures.

On the other hand, the “Permeability 1” seepage estimate from the earlier model was 41.2 cfs, which is similar to both the mean and median values of stochastically generated data. The Department of Energy at Hanford requested that Reclamation provide them an estimate of the “minimum seepage” predicted by modeling. In the absence of a calibrated model that produces seepage results comparable to those of the stochastic simulation at the lower bound of the 95 percent confidence interval, one was developed using the mitigation model. Hydraulic conductivity values which produced comparable results in the stochastic simulation were used as a starting point for trial-and-error calibration of a “minimum seepage” model. The calibrated “minimum seepage” model estimate of total reservoir seepage was 29.3 cfs.

Development and Modeling of Mitigation Measures

The mitigation measures selected for the modeling study were divided into two categories: those that reduce seepage from the reservoir and those that are designed to intercept the seepage water in the Dry Creek drainage before it reaches the Hanford Site. Prerequisites for the selected mitigation measures include mitigating seepage as close to the reservoir as possible and minimizing the operational costs of mitigation. The selected mitigation measures include:

- Replacement of overburden (sediment layer) under the dam with low permeability zone 1 core material and installation of a grout curtain along the dam alignment, across the valley and extending into the left (north) abutment.
- A geomembrane barrier on the right abutment blanketing an outcrop of Wanapum Basalt.
- Concrete cutoff walls in the right abutment and downstream of the reservoir in the Dry Creek valley.
- Pumping wells to intercept seepage below the Dry Creek cutoff wall

The location and hydraulic conductivity values assigned to these feature are shown in Figure ES-2. It is assumed in modeling that each of these mitigation measures is constructed without defects. The model does not account for risk or uncertainty due to imperfect construction or the engineering failure of a mitigation measure.

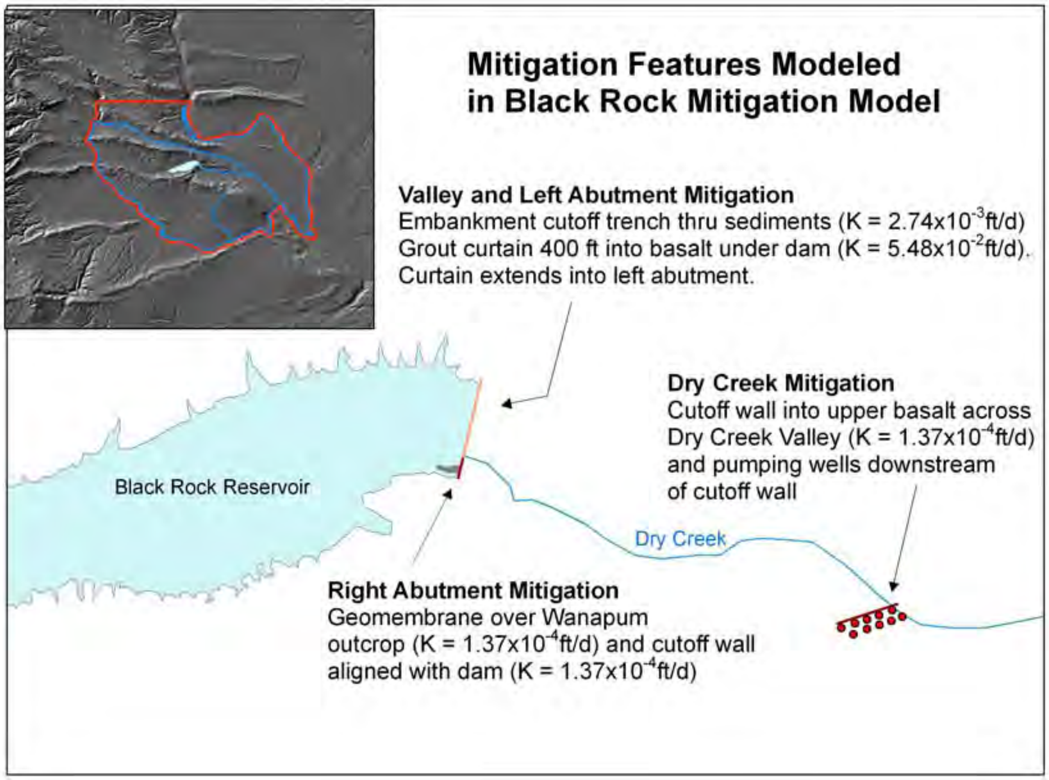

Figure ES-2: Map of mitigation features

In the absence of mitigation measures, the seepage model indicated that water would seep from the reservoir into underlying sediments and basalts. The majority of this seepage would then emerge on the surface in the Dry Creek drainage downstream of the dam. The water would then flow down Dry Creek drainage until it reached thick sediment layers near Cold Creek where it would re-infiltrate and continue flowing in the subsurface towards Hanford.

The mitigation model indicates that a combination of the mitigation features installed at the dam site (the embankment cutoff trench, the grout curtain, cutoff wall, and the geomembrane) would reduce total maximum reservoir seepage by approximately 30 percent (from 74.3 to 51.9 cfs). However, most of the seepage (46.5 cfs) would bypass the mitigation features and daylight on the surface in the upper portion Dry Creek. A small percentage of the total reservoir seepage (about 5.4 cfs) would infiltrate into deeper basalts.

The mitigation model also indicates that a cutoff wall mitigation feature installed in the Dry Creek drainage down stream from the dam site would be an effective barrier to subsurface flow in the Dry Creek sediment layer (Figure ES-3). In addition to the cutoff wall, a low-head embankment in the Dry Creek drainage would block surface water flow before it could re-infiltrate into thick sediments near Cold Creek. The surface embankment in Dry Creek would serve as a collection point for seepage water which would then be diverted away from the site by a pipeline. The pipeline would be designed to convey all the surface flows away from behind the embankment to the Yakima River to the south.

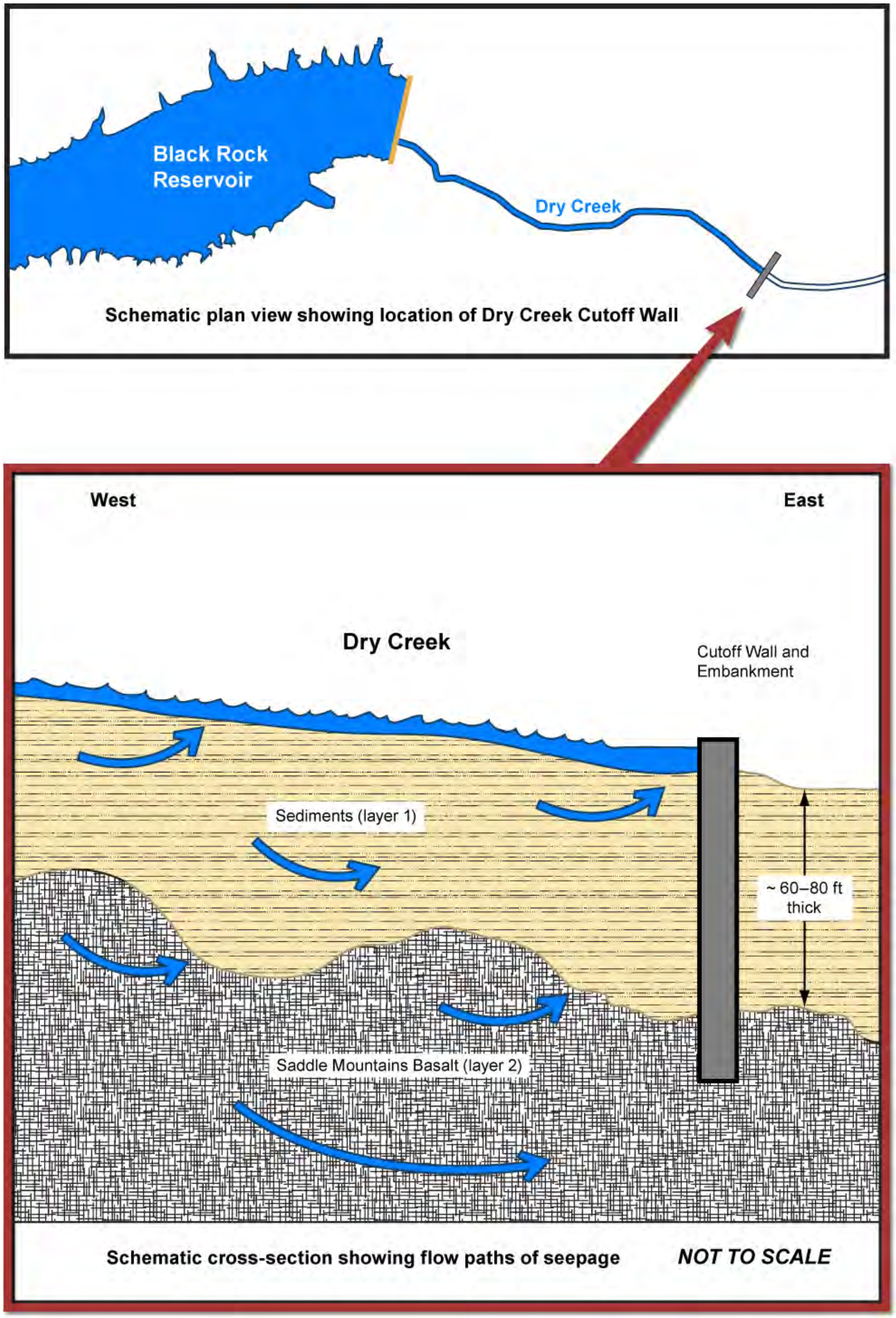

Figure ES-3: Illustration of embankment structure behavior. Above: plan view of structure. Below: cross section of structure.

The mitigation model indicated that by applying all of these mitigation features collectively, it is possible to reduce reservoir impacts to the Hanford Site (i.e., seepage-induced groundwater flow across Cold Creek) by about 99 percent.

Before developing final designs for mitigation features, additional hydrogeologic testing is recommended to better characterize properties of basalt layers beneath the dam site and the Dry Creek drainage. Additional geologic investigation would also help to refine understanding of key geologic structures that are an integral part of the current Black Rock conceptual model. The additional data would not only improve the Black Rock conceptual model, but also reduce the uncertainty associated with current model applications.

Acknowledgments

The authors of this report wish to acknowledge and express thanks to R.D. Schmidt for his assistance on this mitigation study. His work on the previous seepage study served as the basis for this study. In addition, his continued guidance and support throughout the mitigation model development and report writing was invaluable.

The authors also wish to acknowledge and thank Matt Ely (USGS), Vicky Freedman (PNNL), and Dib Goswami (Ecology) for their thorough and insightful reviews of the mitigation model results and initial draft of this report.

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. As noted in the Preface, 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 for the Yakima River basin, "… 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 14 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 pipelines (Reclamation, 2004b).

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 Site as a result of increased groundwater levels due to reservoir seepage (PNNL, 2008).

In response to the information presented in the 2008 PNNL report, Reclamation developed a groundwater model (the 2007 Black Rock seepage model) to simulate the hydrologic impacts of the proposed Black Rock dam and reservoir (Reclamation, 2007b). The model calculated two possible reservoir seepage rates and predicted that the majority of seepage would migrate east of the reservoir into the Dry Creek drainage and eventually to the Hanford Site.

There is concern about the possibility of increased contaminant movement and higher groundwater levels on the Hanford Site due to the addition of seepage from Black Rock. Mitigation measures, such as a geomembrane blanket, cutoff walls, and interceptor wells, have the potential to reduce reservoir seepage and/or intercept seepage water before it reaches the Hanford Site so that impacts are minimized.

This report describes the development and the results of the Black Rock mitigation model. The mitigation model examines the effectiveness of specific measures for reducing the rate of reservoir seepage in the right abutment area of the dam and beneath the dam itself. The mitigation model also examines the potential for intercepting reservoir seepage that emerges in the Dry Creek drainage downstream from the dam.

It was acknowledged in the earlier Black Rock seepage model report that there was a high level of uncertainty in seepage estimates due to the lack of hydrogeologic data, especially in the area of the Dry Creek drainage. Preliminary geologic mapping in this area indicates that a fault, or combination of intersecting faults, exist just east of the dam alignment (Bentley and Peterson, 2003). In other areas of the Yakima Fold Belt and the Columbia Plateau, faults often form hydrologic barriers to flow (USGS, 1994; PNNL, 2002). Possible truncation of the lateral flow path downstream of the dam could intercept the reservoir seepage before Dry Creek and route the flow in other directions. The available data supports the conceptual understanding that was simulated in these models (the 2007 seepage model and the current mitigation model), but additional field investigations could change the current understanding of the hydrogeologic conditions of the site, require modifications to the model, and alter the model results.

While the 2007 Black Rock seepage model was the basis for this mitigation model, certain refinements to model layering and calibration were made in order to meet the new modeling objectives. Nevertheless, since no new hydrogeologic data were obtained prior to the development of the mitigation model, the level of geologic uncertainty in this model has not been reduced from that of the earlier seepage model. However, the effectiveness of mitigation features proposed in this model for application at the Black Rock dam site has been demonstrated in numerous dam and hydrologic projects constructed by Reclamation (Reclamation, 1998). The seepage model is fully described in Reclamation (2007b); hence, the reader is directed to that report for background information and for a discussion of basic assumptions underlying both models.

1.1 Objectives and Scope of Mitigation Model

The objectives of the mitigation model are:

- Refine the seepage model to provide better representation of the areas where most reservoir seepage occurs and where potential mitigation measures would be applied (Section 2.0).

- Calibrate the steady-state mitigation model and verify that the resulting seepage estimates match, as closely as possible, the results of the earlier steady-state seepage model (Section 3.0).

- Determine if the earlier Black Rock seepage model results represented the full range of seepage possibilities (Section 4.0)

- Simulate potential mitigation measures and estimate their effectiveness in reducing reservoir seepage and/or intercepting seepage before it reaches the Hanford Site (Sections 5.0 and 6.0).

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2.0 Mitigation Model Development

Like the 2007 seepage model, the Black Rock mitigation model was developed using MODFLOW software (USGS, 2000). The mitigation model domain is the same as the earlier model. It is centered on the reservoir site and encloses an area of about 1,700 square miles. The model area is bounded on the east by the Columbia River and on the south and west by the Yakima River (Figure 2-1).

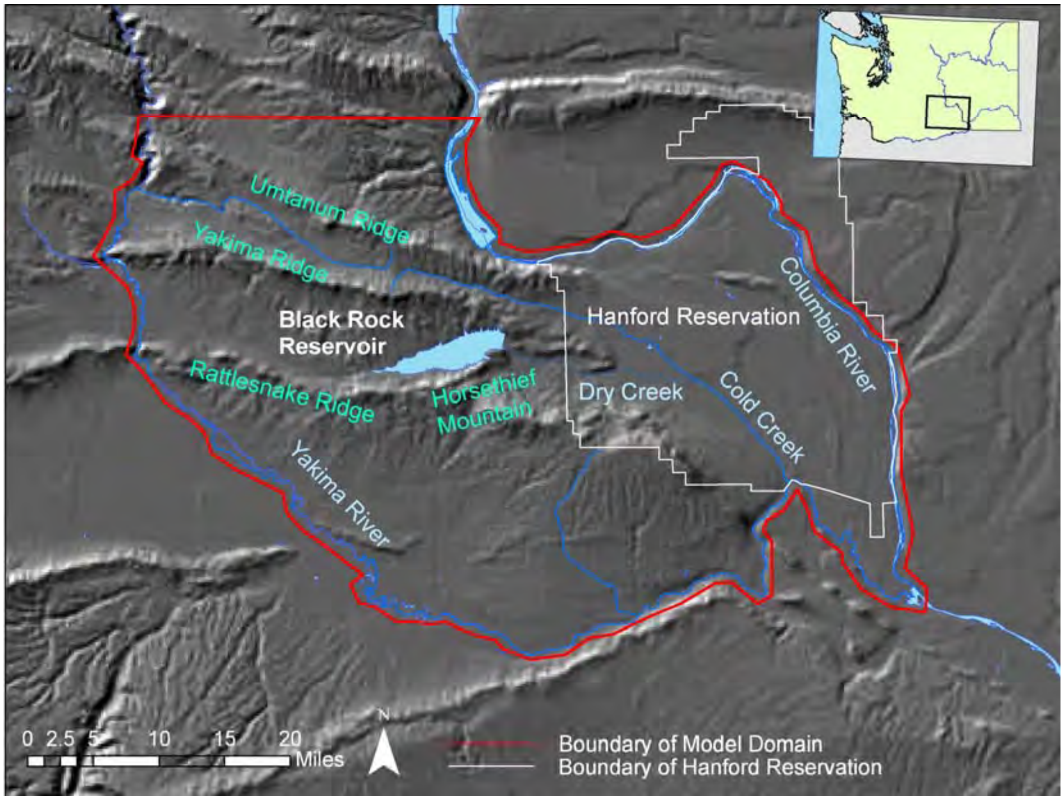

Figure 2-1: Modeled area bounded by the Columbia River to the east and the Yakima River to the south and west.

Unlike the earlier model, the mitigation model was run in a steady-state mode only. No attempt was made to simulate the time-dependent impacts of potential mitigation measures as the reservoir fills. All mitigation calculations assume a full reservoir.

Both the reservoir and the imposed mitigation measures are assumed to have equilibrated hydrologically with respect to the underlying aquifer system. In simple terms, this means that there is no additional change in aquifer storage. Prior to reaching equilibrium, a portion of the reservoir seepage goes into aquifer storage and raises aquifer head levels. At equilibrium, the available aquifer storage space is satisfied and the amount of seepage entering the aquifer system equals the amount that discharges from the aquifer system via springs, creeks and drains. The aquifer head conditions calculated by the mitigation model (with the reservoir present) are the result of steady-state reservoir seepage.

The mitigation model results are therefore indicative of the effectiveness of seepage mitigation features that have been in place for a comparatively long period of time. For perspective, the earlier seepage model indicated that it would take approximately 300 years for steady-state hydrologic conditions to develop once the reservoir filled, although seepage would reach 90 percent of the steady-state value within about 5 years.

The mitigation model represents a refinement of the earlier seepage model in two ways. First, the horizontal grid spacing was reduced in the Dry Creek area to provide better resolution for comparatively small mitigation features that were to be represented in the model. Second, the Saddle Mountain model layer (layer 2 in the seepage model) was split into two model layers in order to provide greater vertical resolution in the layer that was most likely to be influenced by mitigation measures.

2.1 Horizontal Grid Spacing

The 2007 seepage model used a grid mesh that varied from 1,500 x 1,500 feet square in the immediate area of the reservoir to 3,000 x 3,000 feet square over most of the model domain. The mitigation model grid mesh was refined in order to discern the impacts of mitigation measures that are relatively small in size and to better define areas in the Dry Creek drainage where reservoir seepage would emerge on the surface. In addition, the large size of the cells in the seepage model did not allow for detailed matching of material types. The new, smaller grid size allowed for a better representation of the various hydrogeologic units in the sediment layer mapped by the Geological Survey (USGS, 2006; USGS, 2008). The new grid mesh is 375 x 375 feet square in the dam area and the Dry Creek drainage, and gradually increases to 3,000 feet square in the out-lying areas (Figure 2-2).

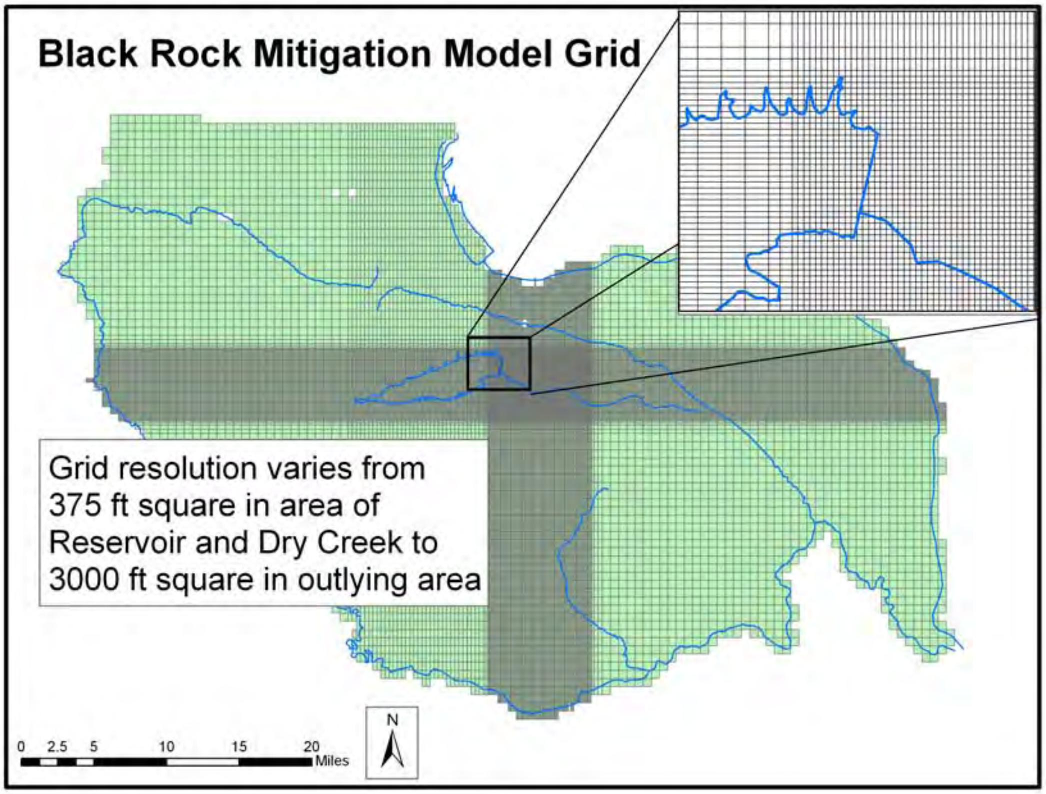

Figure 2-2: Mitigation model grid spacing.

The top and bottom elevations of the model layers were interpolated to fit the new grid mesh. Hydraulic conductivities and internal boundary conditions that were assigned to the model cells were redistributed to reflect the greater resolution of layer thicknesses and surface elevations. Figures 2-3 through 2-6 show the active model cells with the new distribution of internal boundary conditions.

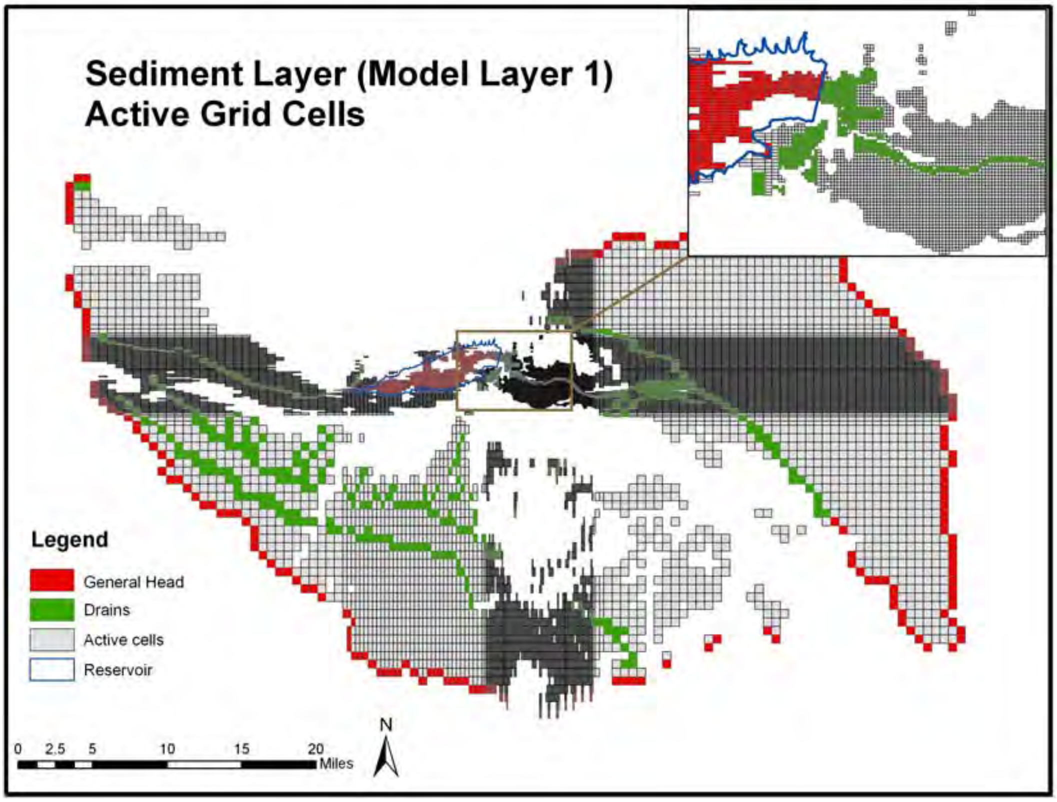

Figure 2-3: Layer 1 active model cells and internal boundary conditions.

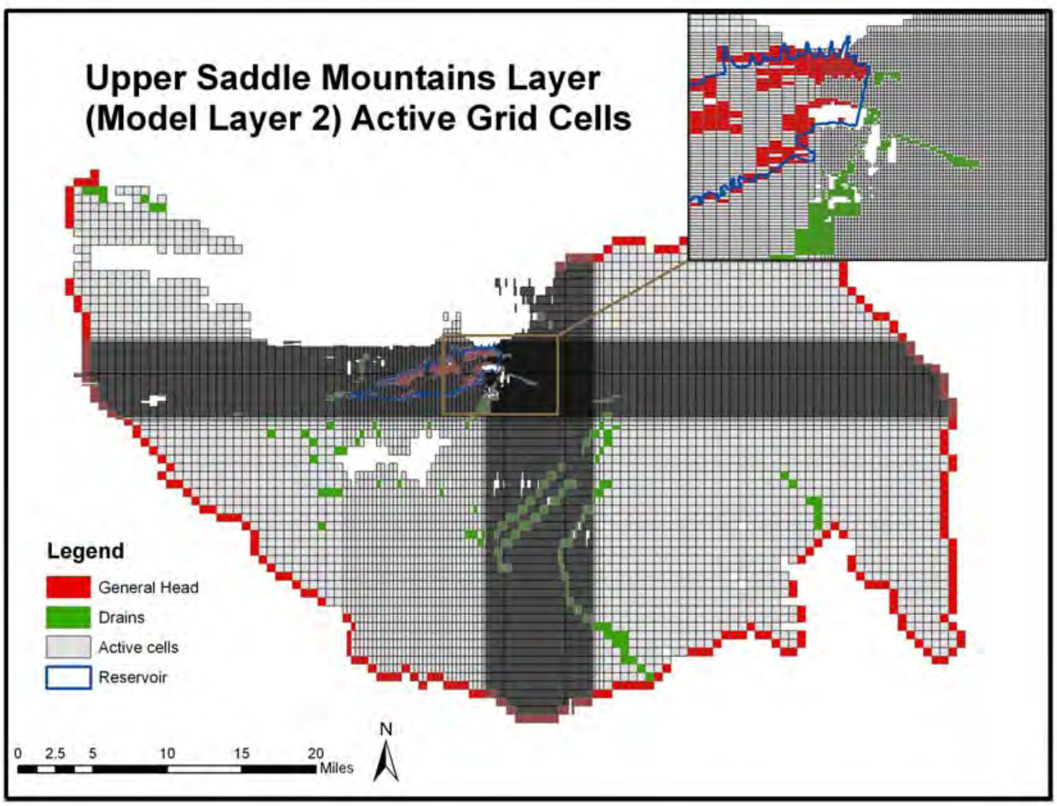

Figure 2-4: Layer 2 active model cells and internal boundary conditions.

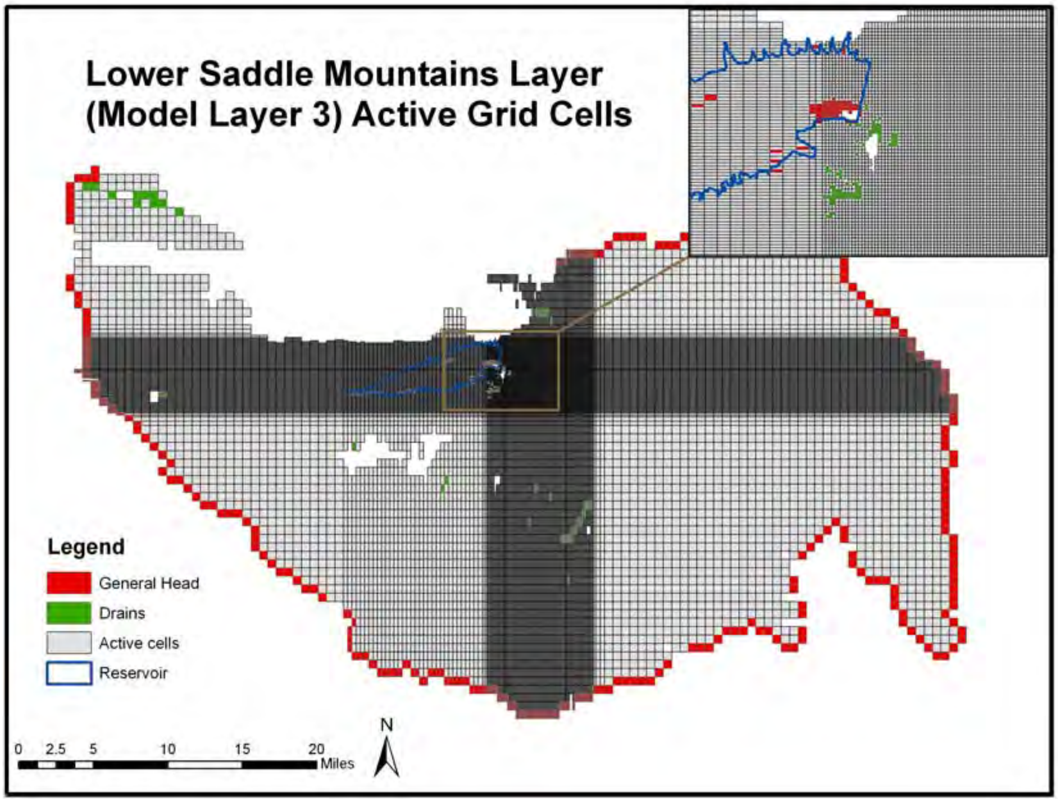

Figure 2-5: Layer 3 active model cells and internal boundary conditions.

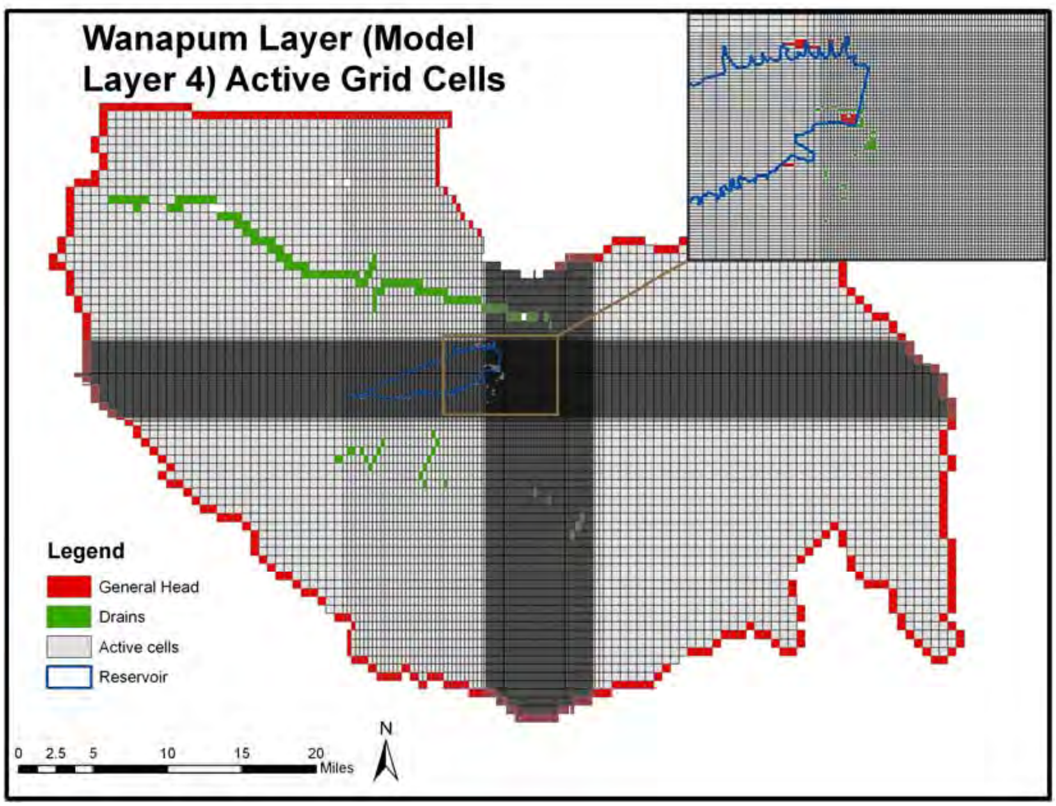

Figure 2-6: Layer 4 active model cells and internal boundary conditions.

2.2 Layering

Figure 2-7 is a stratigraphic column showing the geologic framework of the Black Rock Valley. Units in the Black Rock geologic framework are composed of multiple members and include both basalt formations and sedimentary layers.

In the 2007 Black Rock seepage model, five layers were used to represent the sediments and basalts. In the mitigation model, six model layers were used to represent these same hydrogeologic units: layer 1 represents the overburden sediments of the alluvium, Ringold and Ellensburg Formations, layers 2 and 3 represent the Saddle Mountains Basalt, layer 4 represents the Wanapum Basalt, and layers 5 and 6 represent the Grande Ronde Basalt. The Saddle Mountain layer was changed from a single layer in the seepage model to two layers in the mitigation model to allow for more accurate representation of the mitigation features.

The upper Saddle Mountains Basalt (including the Rattlesnake Ridge interbed and the Pomona Basalt member) is generally unsaturated and comprises about 35 percent of the total thickness of the Saddle Mountains unit. The lower Saddle Mountains Basalt (including the Selah interbed, the Esquatzel/Umatilla Basalt member and the Mabton interbed) is saturated and comprises the remaining 65 percent of the total unit thickness. For the most part, the two Saddle Mountains model layers mirror this proportional split (35 and 65 percent) in total thickness.

In the right dam abutment, a fault oriented parallel to the Black Rock Valley has thrust the Umatilla Basalt on top of the Pomona Basalt. In this area, the Umatilla Basalt is in model layer 2 (Saddle Mountains). It is unsaturated and overlies a fault zone of basalt breccia. Below the fault, the Rattlesnake Ridge interbed is a confining layer to the Pomona Basalt aquifer. The fault is simulated in the model as a zone of cells with lower horizontal hydraulic conductivity (Reclamation, 2007c).

Since seepage from the full reservoir (at equilibrium) is expected to fully saturate the Saddle Mountains Basalt, both upper and lower Saddle Mountains layers are represented in the model as confined aquifer layers. Additionally, since no new hydrogeologic data has become available since the seepage model was completed, the original distribution of hydraulic conductivity in the Saddle Mountains layer was assigned to cells in both upper and lower layers.

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 Layer 3
Miocene	Middle Miocene	Columbia River Basalt Group	Wanapum Basalt	Priest Rapids Member Roza Member Frenchman Springs Member Eckler Mountain Member	—— Vantage Interbed	Wanapum unit	Layer 4
Miocene	Lower Miocene	Columbia River Basalt Group	Grande Ronde Basalt	Magnetostratigraphic units[1]: N_2, R_2, N_1, R_1		Grande Ronde Unit	Layer 5 Layer 6

Figure 2-7: Stratigraphic column of Black Rock Valley (modified from USGS, 1999).

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3.0 Model Calibration

Hydrologic model calibration involves manipulating model parameter values (usually hydraulic conductivities) in order to match, as closely as possible, model results with observed data. Hydraulic conductivities in the Black Rock mitigation model were varied over a range of values obtained from published reports by the USGS (1994) and Department of Energy (DOE) (Rockwell, 1979) along with Reclamation field test results (Reclamation, 2004a; Reclamation, 2007c). Like the earlier seepage model, the mitigation model was calibrated without the reservoir.

The 2007 seepage model was calibrated with respect to two conceptual models that differed in their distributions of hydraulic conductivity values in the Dry Creek valley. The results were labeled “Permeability 1” (resulting in a lower seepage estimate) and “Permeability 2” (resulting in a higher seepage estimate). Initially, hydraulic conductivities from the “Permeability 2” seepage model were inserted in the mitigation model. Hydraulic conductivities from the seepage model Saddle Mountains layer (layer 2) were used in both upper and lower Saddle Mountains layers in the mitigation model (layers 2 and 3). Since there were some differences in grid size and layering, the hydraulic conductivities were modified during trial-and-error calibration of the mitigation model.

Model residuals are the differences between calculated and measured heads at observation wells. The average absolute value of residuals in the Black Rock mitigation model is 24 feet. The root mean square error (RMSE), which is the standard deviation of model residuals, is 27 feet. The RMSE is two percent of the total change in head over all of the measured water levels which is almost 1400 feet (less then 10% of the total change in head is considered to be a good calibration). Figure 3-1 is a plot of observed water levels versus simulated water levels. The regression line in this figure has an R^2 value exceeding 99, indicating that 99 percent of the observed variability in water levels is accounted for by the model.

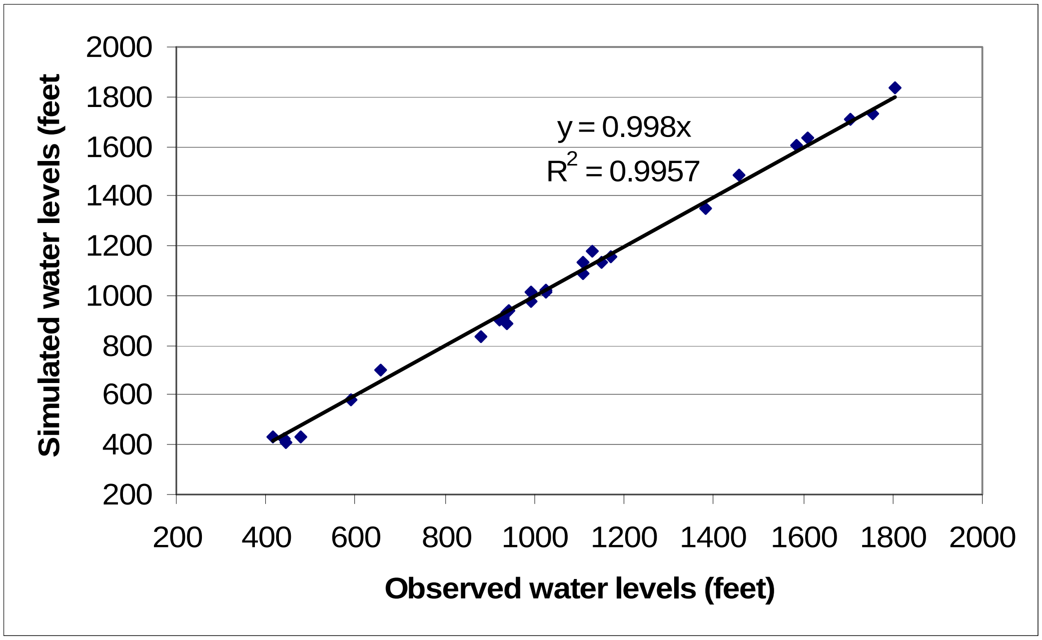

Figure 3-1: Simulated versus observed heads in calibrated mitigation model.

Calibration results are similar to those of the 2007 seepage model. However, there were 29 observation wells used in the mitigation model as opposed to 21 in the earlier model. Eight additional observation wells in lower Dry Creek drainage were added to insure model calibration in an area were cutoff wall mitigation features would be located. Figures 3-1 through 3-4 show all of the observation wells used in the mitigation model calibration. The wells are colored to show the residual value associated with each well. The range of observation well head conditions is close to 1,400 feet (from 1,803 feet to 414 feet, mean sea level (msl) elevation). The average absolute value of residual heads is about 2 percent of this total range in heads.

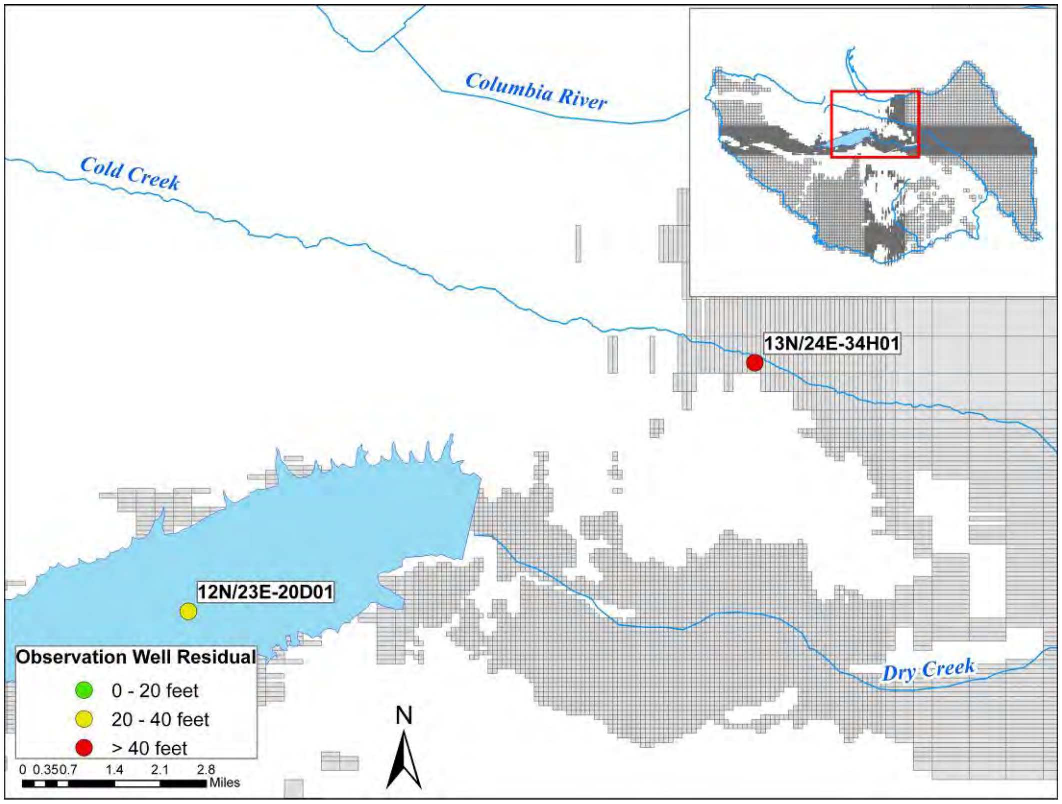

Figure 3-2: Map of observation wells and residuals for Layer 1 (sediments).

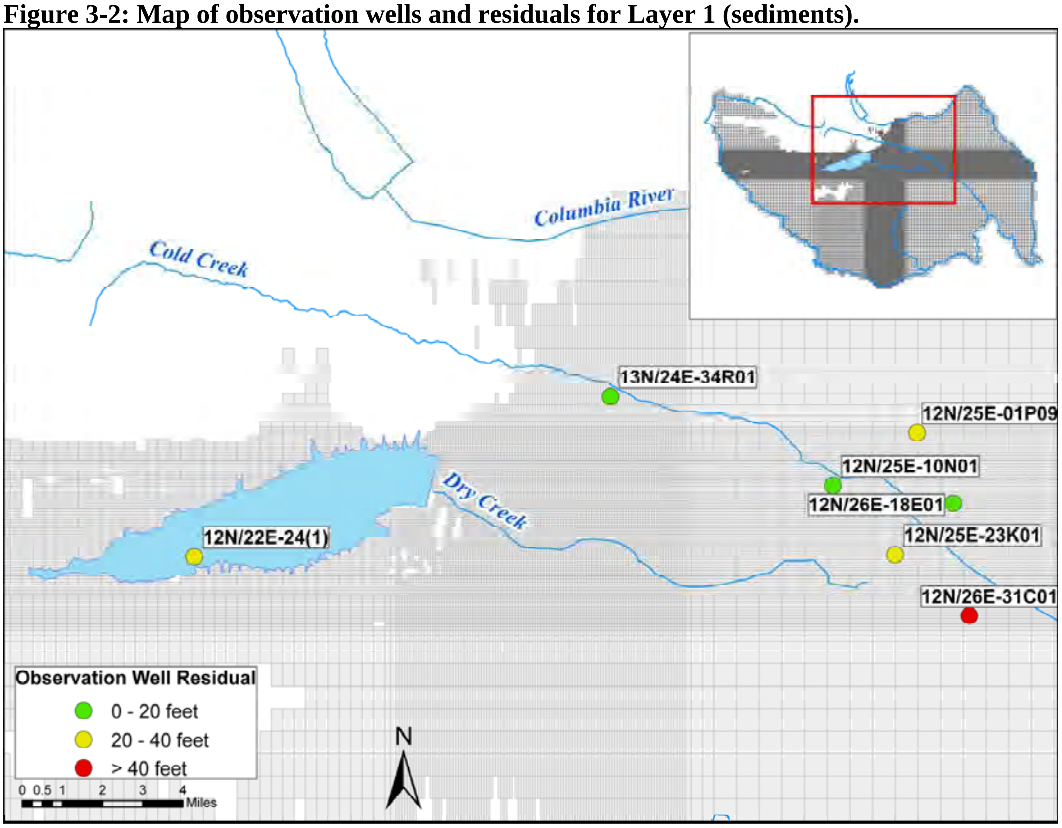

Figure 3-3: Map of observation wells and residuals for Layer 2 (Saddle Mountain Basalts).

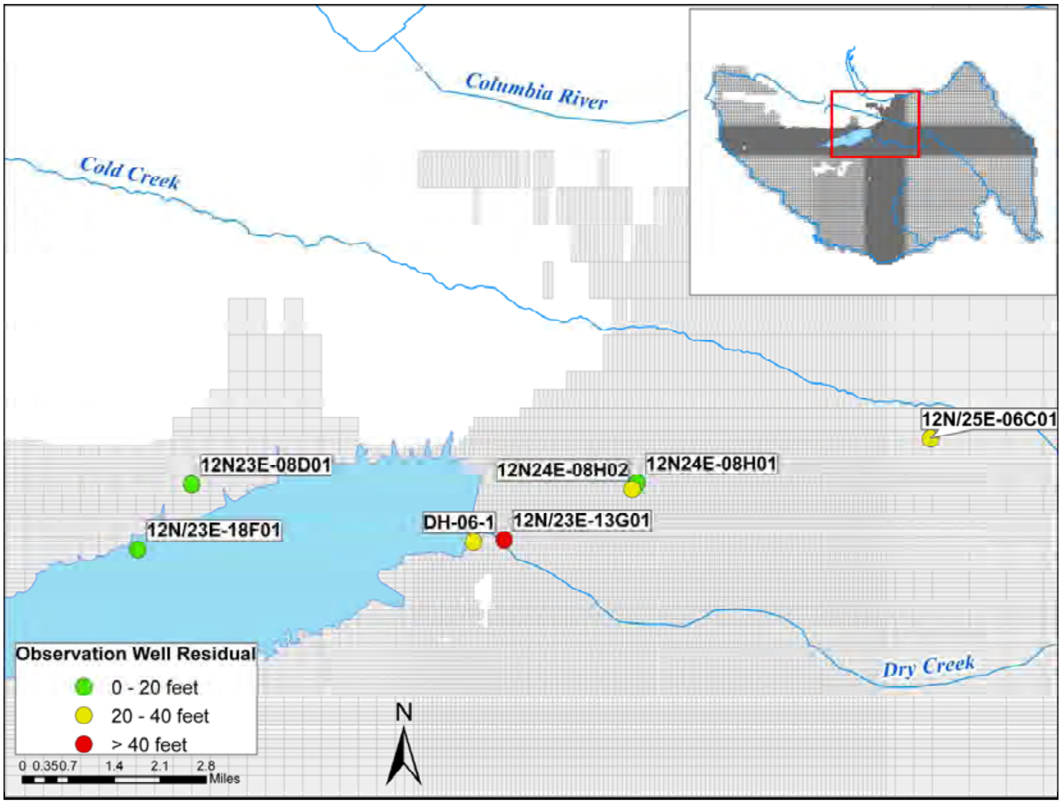

Figure 3-4: Map of observation wells and residuals for Layer 3 (Saddle Mountain Basalts).

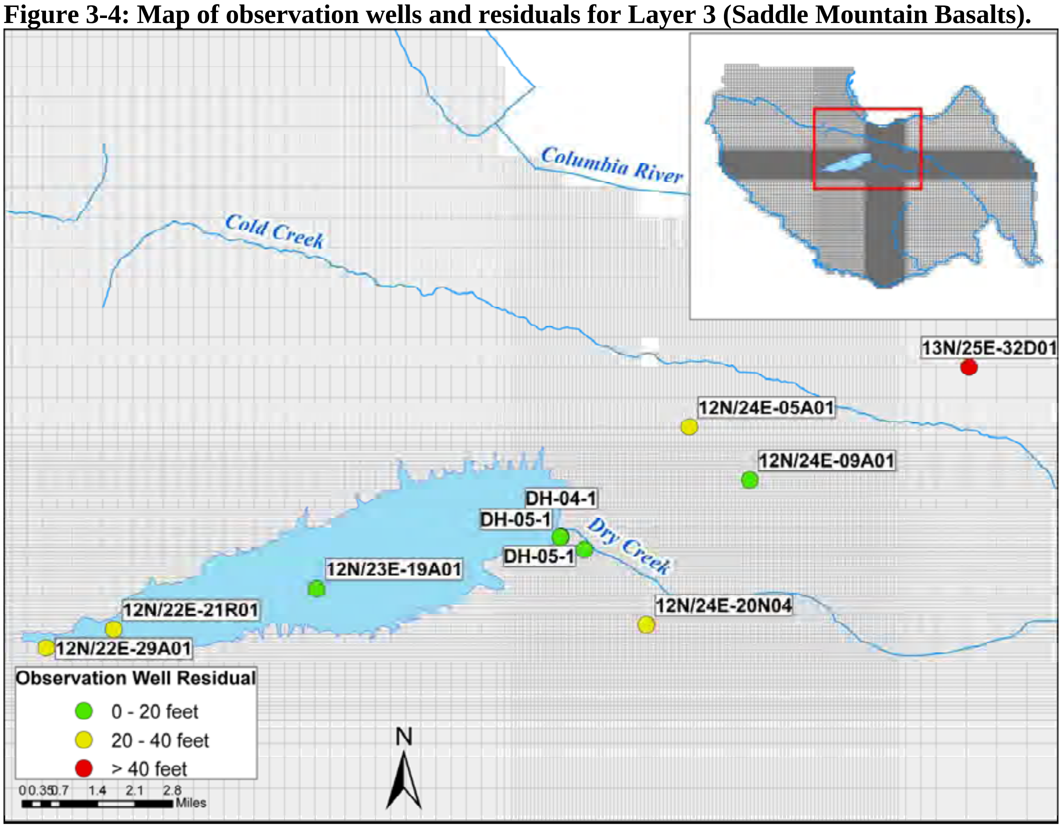

Figure 3-5: Map of observation wells and residuals for Layer 4 (Wanapum Basalts).

3.1 Sensitivity Analysis

"The purpose of a sensitivity analysis is to quantify the uncertainties in the calibrated model caused by uncertainties in the estimates of aquifer parameters, stresses, and boundary conditions" (Anderson and Woessner, 1992). In this case, a sensitivity analysis is conducted in order to show the impact that uncertainty with respect to hydraulic conductivity and drain conductance has on observation well residuals. These parameters are increased and decreased by a specific amount and the change in observation well residuals is reported (Table 3-1). The hydraulic conductivity parameters are changed by a factor of 2 and the drain conductances are changed by a factor of 10.

Table 3-1: Results of sensitivity analysis.

Model Input Parameter	Observation well residuals (reported in RMSE, feet)
Horizontal Hydraulic Conductivity	
Increase by factor of 2	258.76
Decrease by factor of 2	299.65
Vertical Hydraulic Conductivity	
Increase by factor of 2	49.28
Decrease by factor of 2	51.93
Drain Conductance (w/o reservoir)	
Increase by factor of 10	27.2
Decrease by factor of 10	34.34

Recall the RMSE of the calibrated model residuals was 27 feet. Observation well residuals increase very rapidly with changes in horizontal conductivity but less so with changes in vertical conductivity. Changes in drain conductance also have little impact on residuals. This sensitivity analysis indicates that accuracy in horizontal hydraulic conductivity values is the most important to obtaining a well calibrated model, while the drain conductance values are much less important.

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4.0 Stochastic Analysis of Dry Creek Valley

The earlier seepage model report (Reclamation, 2007b) acknowledged that given the hydrologic complexity of the site and the limited observation well data available, there was uncertainty associated with the conceptual model

To assess whether the seepage model results (the "Permeability 1" and "Permeability 2" models) captured the full range of possibilities with respect to reservoir seepage, a stochastic (Monte Carlo) simulation was performed using the calibrated mitigation model with a full reservoir. In a Monte Carlo simulation, the model is run repeatedly with random parameter values that are uniformly distributed within a given range. For the case of the Black Rock mitigation model, hydraulic conductivities in the upper four layers were randomly varied within the range shown in Table 4-1. These values were gathered from published reports as footnoted in the table.

Table 4-1: Hydraulic conductivity ranges used in stochastic model runs (the vertical hydraulic conductivities are 2 to 6 orders of magnitude less than the horizontal values from literature).

			Minimum value	Maximum value	Average value
Sediments (Layer 1)	**Alluvium**	Kh (ft/d)	4.32E+01[1]	2.00E+02[2]	1.21E+02
		Kv (ft/d)	4.32E-02	2.00E+00	1.02E+00
	Touchet Beds	Kh (ft/d)	4.30E-02[1]	1.73E+00[1]	8.86E-01
		Kv (ft/d)	4.30E-05	1.73E-02	8.66E-03
	Loess	Kh (ft/d)	1.73E+00[1]	8.64E+00[1]	5.18E+00
		Kv (ft/d)	1.73E-03	8.64E-02	4.41E-02
Saddle Mountains (Layers 2 & 3)	**Basalts**	Kh (ft/d)	1.73E+00[1]	2.50E+01[2]	1.29E+01
		Kv (ft/d)	1.73E-05	2.50E-01	1.25E-01
	Fault Breccia	Kh (ft/d)	4.20E-01[3]	4.49E+00[1]	2.46E+00
		Kv (ft/d)	4.20E-05	4.49E-02	2.25E-02
Wanapum (Layer 4)	**Basalts**	Kh (ft/d)	8.64E-02[1]	6.91E+02[2]	3.46E+02
		Kv (ft/d)	8.64E-08	6.91E-01	3.46E-01

1 – USGS, 1994; 2 – Reclamation, 2007b; 3 – Reclamation, 2007c

Figures 4-1 through 4-3 show the zones within which random variations in hydraulic conductivity were made. Note that the zones were located only in the Dry Creek area where little is known about the distribution of hydraulic conductivity. The zones are associated with changes in sediment and Saddle

Mountain layer geologic materials, as it is recognized that material changes often correspond to changes in hydraulic conductivity.

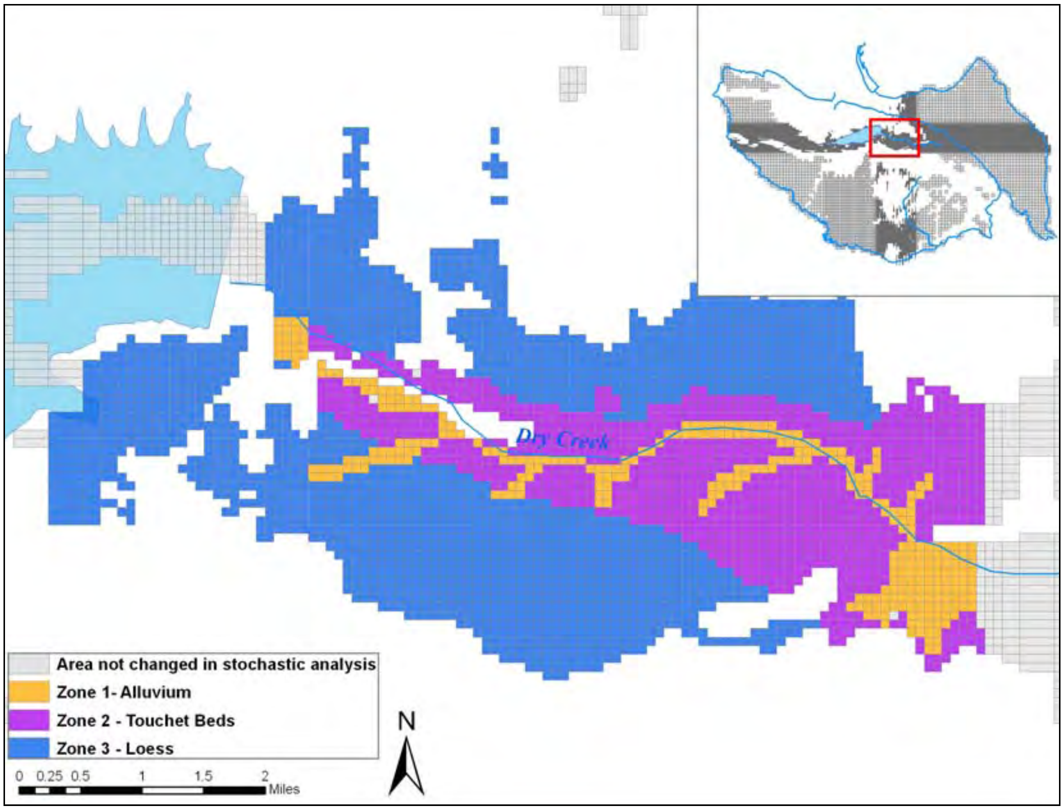

Figure 4-1: Map of Layer 1 stochastic model zones.

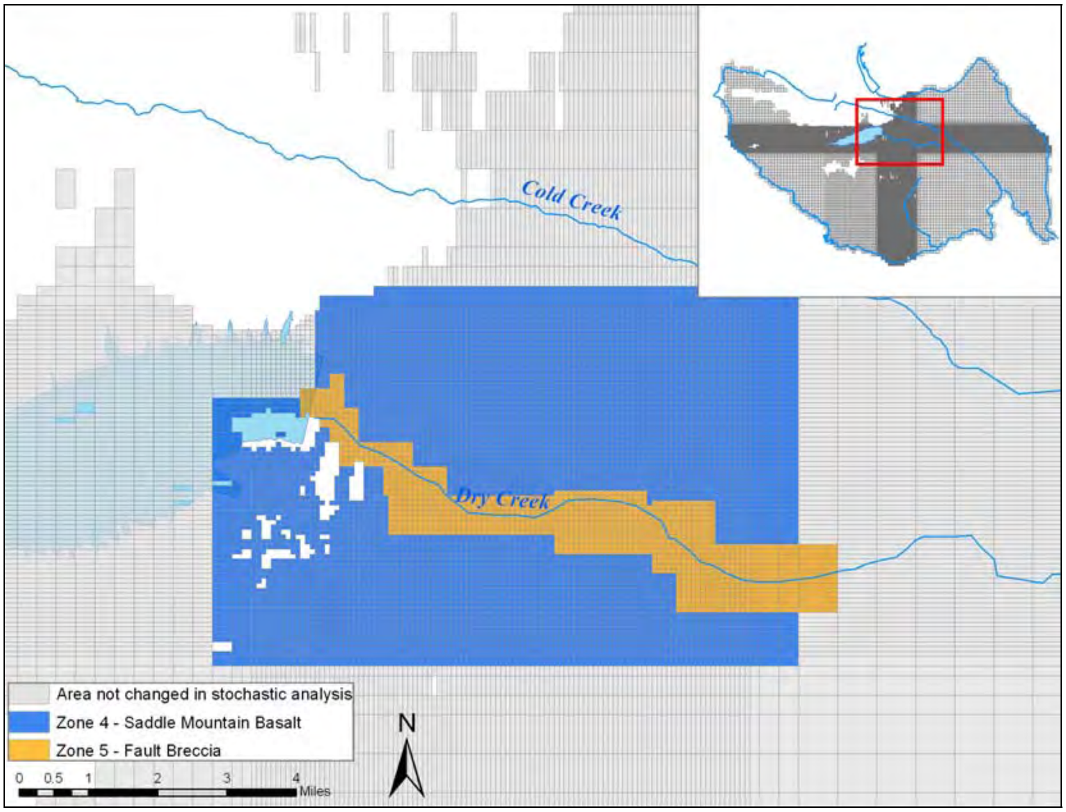

Figure 4-2: Map of Layer 2 stochastic model zones.

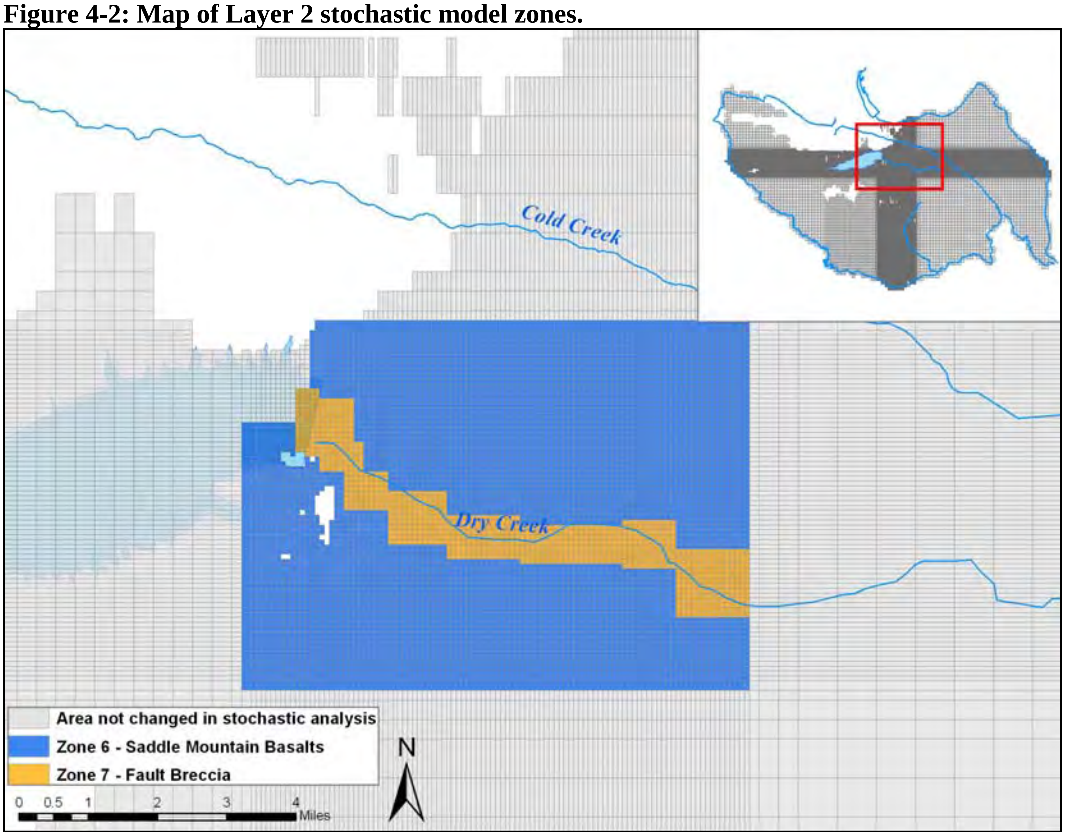

Figure 4-3: Map of Layer 3 stochastic model zones.

It was necessary to determine the number of model runs that would sufficiently sample the range of hydraulic conductivities and, ultimately, capture the full distribution of possible outcomes. This was done by developing a cumulative frequency distribution plot (Figure 4-4) for consecutively larger subsets of the total number of model runs (i.e., first, a plot of the first 50 runs, then a plot of the first 100 runs, etc.). The plot is constructed using the cumulative frequency distribution versus the difference from the mean of the drain returns. As more runs are added to the plot, the distinctive S-shaped curves begin to deviate less from one another. When the curves are almost identical, enough runs have been made to sufficiently sample the input data.

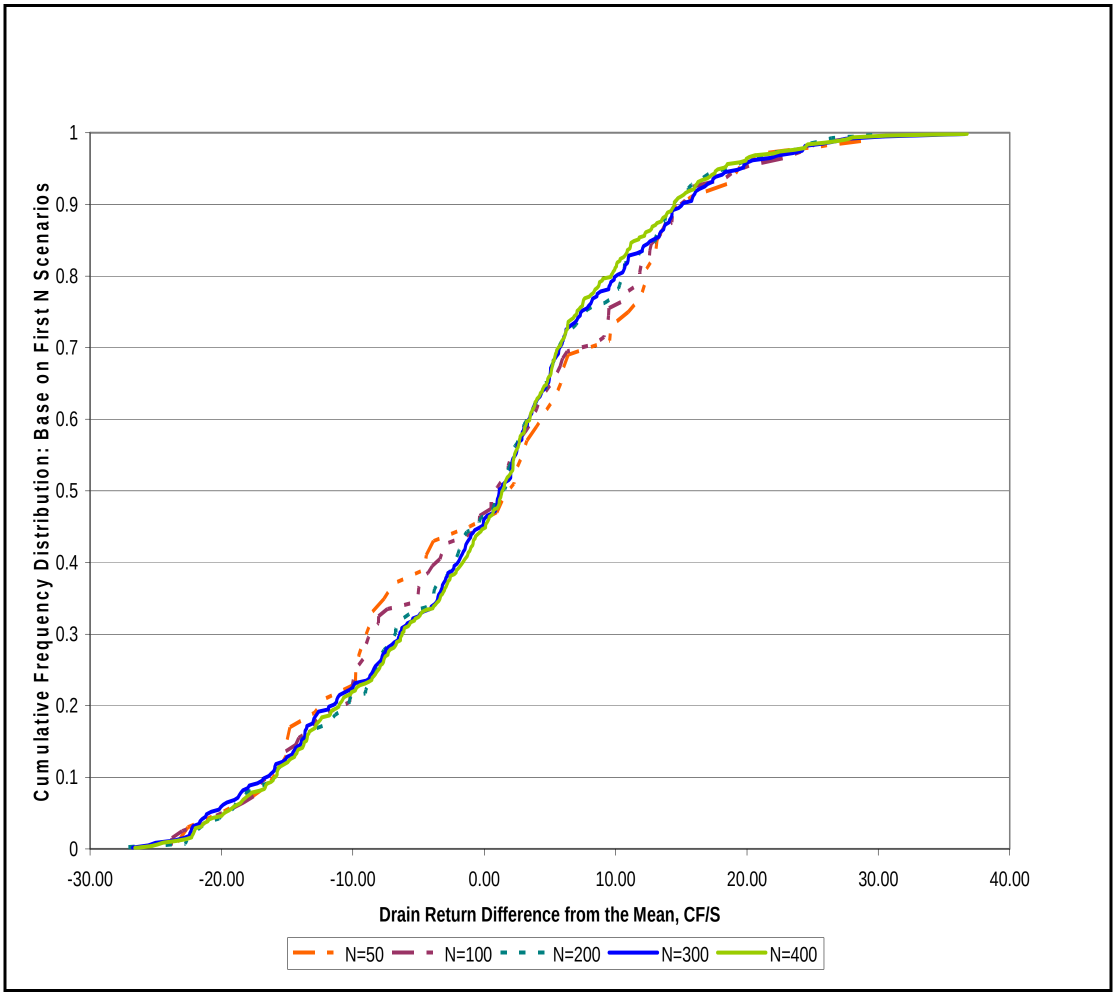

Figure 4-4: Cumulative frequency distribution plot, where N is the number of Monte Carlo simulations.

It can be seen from Figure 4-4 that when the number of model runs, N, is equal to 50, 100 and 200 there are many deviations from the S-shaped curve. As the number of runs increases, the S-shape smoothes out and the curves deviate less and less from one another. The difference between 300 and 400 runs is small enough that 400 runs were determined to be sufficient for this simulation.

Figure 4-5 shows the distribution of flows into Dry Creek resulting from stochastic simulations; flows into Dry Creek are a very large portion of total reservoir seepage. The mean value of the stochastic data is 48.3 cubic feet per second (cfs) and the standard deviation is 11.6 cfs. The median value is 49.6 cfs. The skewed nature of the distribution stems from the fact that seepage has an absolute lower bound of zero.

Data constrained by this type of boundary is generally fit to a Gamma distribution. A procedure used to calculate confidence intervals for data with this distribution is described by Krishnamoorthy and others (2008). Using this procedure, the 95 percent confidence interval for stochastically generated seepage data is estimated to range from 27.4 cfs to 75.1 cfs. The "Permeability 2" seepage estimate from the earlier seepage model was 71.1 cfs, which is close to the upper bound of this 95 percent confidence interval. The results of the stochastic simulation verify that the "Permeability 2" seepage value is, in fact, a reasonable approximation of the maximum possible reservoir seepage, and therefore it was the hydraulic conductivity distribution used in the mitigation model to assess mitigation measures.

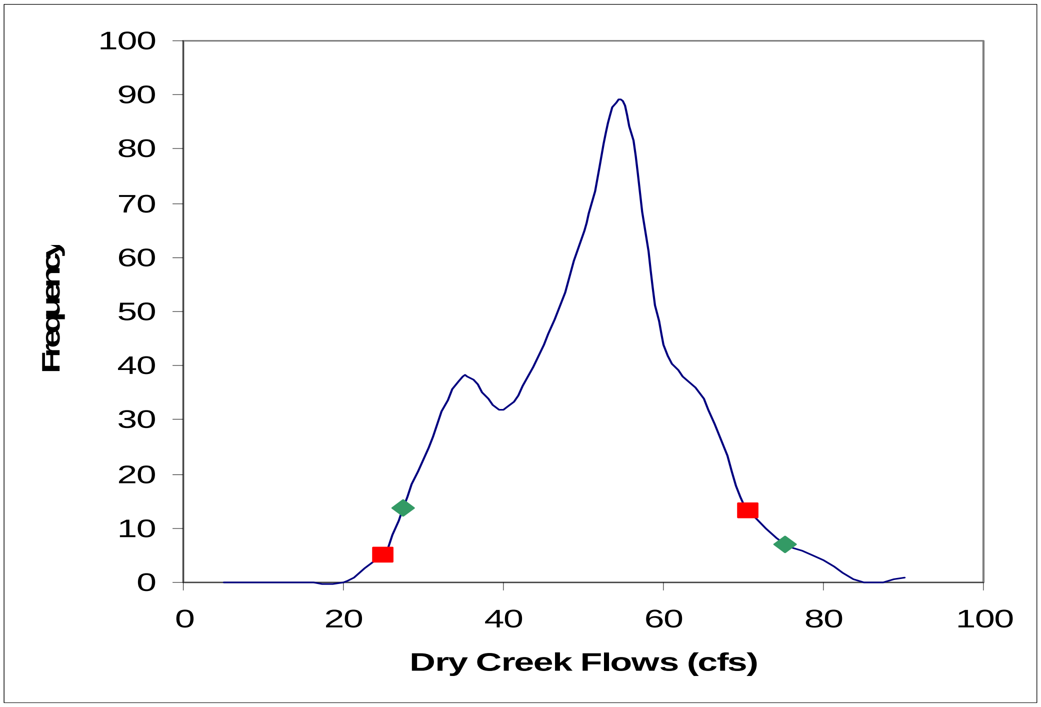

Figure 4-5: Histogram of Dry creek seepage rates based on results of stochastic simulations. Red squares indicate where the calibrated maximum and minimum Dry Creek flows fall; green diamonds indicate the 95 percent confidence interval.

On the other hand, the "Permeability 1" seepage estimate from the earlier seepage model was 41.2 cfs, which is lower than the mean and median but much greater than the lower bound of the 95 % confidence interval.

The Department of Energy at Hanford requested that Reclamation provide them an estimate of the "minimum seepage" predicted by the modeling. In the absence of a calibrated model that produces seepage results comparable to those of the stochastic simulation at the lower bound of the 95 percent confidence interval, one was developed using the mitigation model. Hydraulic conductivity values which produced comparable results in the stochastic simulation were used as a starting point for calibration. (Section 3 discussed the calibration process for the mitigation model; the same process was used for the minimum seepage case model.) The root mean square error (RMSE) for the resulting calibrated minimum seepage model was 37 feet.

The calibrated minimum seepage model estimate of total reservoir seepage was 29.3 cfs. Of this, 24.9 cfs (85 percent) emerges in the Dry Creek drainage downstream of the dam. The remaining 4.4 cfs stays in the deeper basalt layers and disperses radially from the reservoir. As in the earlier seepage model, it is assumed that the seepage that emerges in the Dry Creek drainage flows on the surface down the creek bed and has some loss (assumed to be 25 percent) to evaporation. In the absence of mitigation measures, the remaining flow re-infiltrates thicker sediments near Cold Creek. In the minimum seepage case, this means the increase in flow (above current baseline flow conditions) beneath Cold Creek towards the Hanford Site is about 18.4 cfs (13,184 acre-feet per year).

Table 4-2 summarizes seepage results from the various models discussed in this report. The reservoir seepage rate calculated by the "Permeability 2" seepage model was 71.1 cfs (Reclamation, 2007b). The total reservoir seepage calculated by the calibrated mitigation model is 74.3 cfs. The percentage difference between the two models is about 3 percent.

Table 4-2: Relationship between models discussed in this report

Model	Base Model Used	Total Seepage[3] (cfs)	Seepage to Dry Creek[3] (cfs)	Comments
Permeability 1	Seepage Model[1]	41.2	40.8	
Permeability 2	Seepage Model[1]	71.1	70.6	Used this model to develop mitigation model
Minimum Seepage Model	Mitigation Model[2]	29.3	24.9	Developed for DOE use
Mitigation Model	Mitigation Model[2]	74.3	69.6	Applied the mitigation features to this model

1 – Reclamation, 2007b, 2 – Developed for this study, 3- without mitigation features

5.0 Development of Mitigation Measures

Consultations with a team of technical experts working on the Yakima Basin Water Storage Feasibility Study, including the Pacific Northwest Regional Geologist and the lead embankment dam design engineer, provided information about the constructability of various mitigation measures at the Black Rock site (Reclamation, 2007a; Reclamation, 1998). The mitigation measures were divided into two categories: those that reduce seepage from the reservoir and those that are designed to intercept the seepage water before it reaches the Hanford Site.

From a list of possible mitigation measures, four were considered to have the greatest likelihood of success in reducing both reservoir seepage and hydrologic impacts on the Hanford Site. Key requirements of selected mitigation measures include preventing or intercepting reservoir seepage as close to the reservoir as possible and minimizing operational costs of mitigation (such as by pumping wells). The selected mitigation measures include:

- Replacement of overburden (sediment layer) under the dam with zone 1 core material and installation of a grout curtain along the dam alignment, across the valley and extending into the left (north) abutment. Although these features were part of the initial dam design, they were modeled as mitigation measures since they weren't included in the original seepage model. A grout curtain is constructed by injecting neat cement or other suitable grouting materials into joints and fractures in the underlying foundation rock, creating an impervious barrier beneath the dam.

- A geomembrane barrier on the right abutment blanketing the outcrop of Wanapum Basalt. A geomembrane barrier is an overlayment of various low permeability materials usually Polyethylene or Polyvinyl Chloride bonded together to create an impervious barrier. The geomembrane blanket can be extended to cover a fractured rock outcrop or other highly pervious portion of the reservoir bottom in order to prevent infiltration into the underlying aquifer.

- Concrete cutoff walls in the right abutment and downstream of the reservoir in the Dry Creek valley. A cutoff wall is generally constructed to replace a pervious zone in the shallow foundation or to increase the seepage path within the foundation. It was assumed for this study that one cutoff wall, extending to a depth of 400 feet, would be constructed in the right abutment of the dam and another, extending through the sediment layer into the top of the basalt bedrock, would be constructed in the Dry Creek valley. In both cases, the native materials would be excavated and replaced with concrete or other impervious materials.

- Pumping wells to intercept seepage below the Dry Creek cutoff wall. This mitigation measure was not modeled due to the effectiveness of other mitigation features, as described later in this report.

The location of the mitigation features are shown in Figure 5-1 and the hydraulic conductivity values assigned to each feature are given in Table 5-1. It is assumed in modeling that each of these mitigation measures is constructed without defects. The model does not account for risk or uncertainty due to imperfect construction or the engineering failure of a mitigation measure.

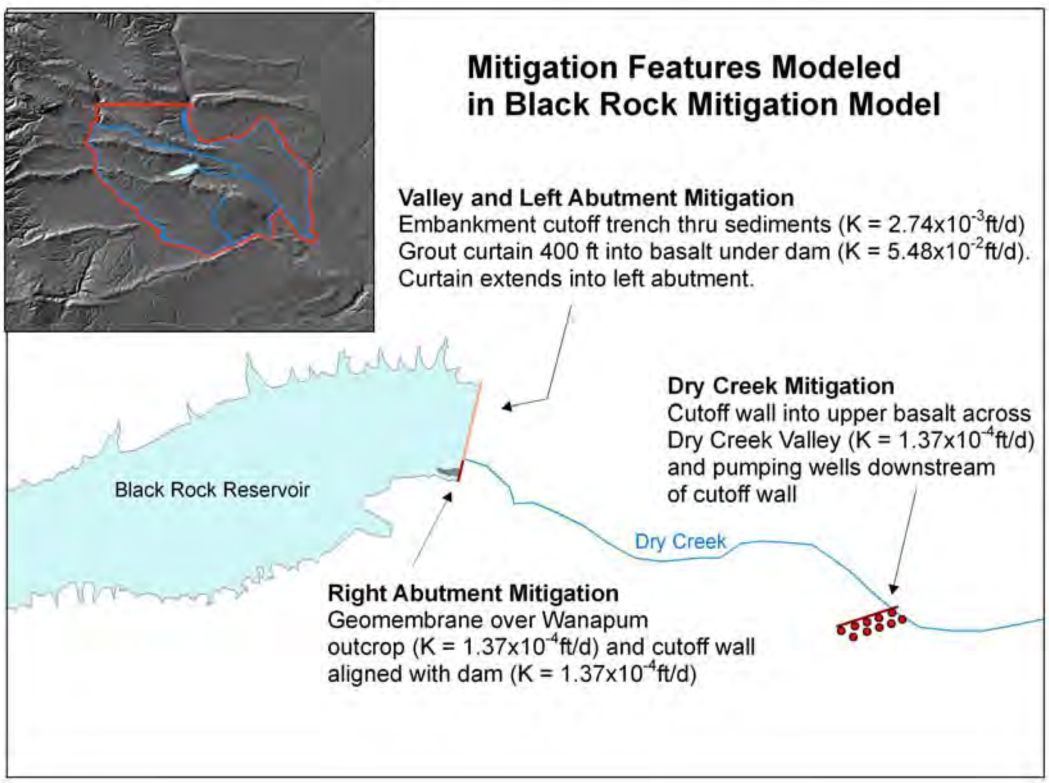

Figure 5-1: Map of mitigation features.

Table 5-1: Hydraulic conductivity values for the mitigation features.

Valley and Left Abutment Mitigation	**Hydraulic conductivity (ft/d)[1]**	**Feature thickness (ft)**
Embankment cutoff trench thru sediments	2.74E-03	10
Grout curtain 400 ft into basalt under dam	5.48E-02	variable
Right Abutment Mitigation		
Geomembrane over Wanapum outcrop	1.37E-04	0.17
Cutoff wall aligned with dam (400 ft deep)	1.37E-04	10
Dry Creek Mitigation		
Cutoff wall through the sediments into the basalt	1.37E-04	10

1 – Engemoen (personal communication, January 11, 2008)

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6.0 Modeling Mitigation Features

As noted, all mitigation model runs were made with a full reservoir and assuming steady-state hydrologic conditions with respect to reservoir seepage. Figure 5-1 shows the location of the five mitigation features that were inserted into the calibrated model: replacement of sediment layer with low permeability zone 1 core material, a grout curtain beneath the dam, a geomembrane covering the Wanapum outcrop near the right abutment of the dam, a cutoff wall in the right abutment of the dam, and a cutoff wall in the Dry Creek valley.

As part of dam construction, the sediment layer (layer 1) beneath the dam would be removed and replaced by zone 1 core material. This is represented in the model by a change in the horizontal and vertical hydraulic conductivity of layer 1 cells beneath the dam. The horizontal hydraulic conductivity of zone 1 core material is modeled at 2.74×10^{-3} feet per day.

A grout curtain would also be constructed in the basalt layers beneath the dam to a depth of 400 feet. Since basalt layer thickness beneath the dam varies, the grout curtain would extend completely through some layers and partially into others. The layers that would be partially penetrated by the grout curtain were assigned a weighted average hydraulic conductivity based on the depth of penetration. In some areas the hydraulic conductivity of the existing basalt is lower than the grout material that would be used to fill the fractures and openings in the rock. In those areas, the basalt hydraulic conductivity was not changed in the model. In other areas, the modeled value for basalt hydraulic conductivity was slightly higher than the grout material and those values were reduced in the model to 5.48×10^{-2} feet per day in order to represent the grout curtain.

The geomembrane was represented in the model by reducing the conductance of the general head (GH) boundaries, which represents the head induced by the reservoir over the Wanapum outcrop, to the hydraulic conductivity of the geomembrane (Table 5-1). Reducing the conductance value of the GH boundary reduces the rate that water will flow into the cell due to the overlying reservoir without altering the rate that water will flow through the cell. The reduced conductance is based on an assumed geomembrane thickness of two inches.

The cutoff walls in the right abutment area and in the Dry Creek drainage were both represented in the model by reducing the horizontal and vertical hydraulic conductivity of those cells containing cutoff wall material (Table 5-1). The cutoff wall in the right abutment extends 400 feet into the basalt. The modeled cutoff wall in the Dry Creek drainage extends only through the sediments (layer 1) into the basalt (about 60-100 feet), since the majority of flow is in the sediments or on the surface in Dry Creek at that distance from the dam. The location of the Dry

Creek cutoff wall (approximately 6.6 miles downstream of the dam) was chosen to take advantage of a constriction in the valley caused by outcrops of Saddle Mountains Basalt (USGS, 2008).

7.0 Model Results and Discussion

Results from the Black Rock seepage model indicated that water would seep from the reservoir into underlying sediments and basalts. Based on Black Rock valley field investigations, the sediments and upper Saddle Mountain basalts are dry prior to the addition of seepage from the Black Rock reservoir. The seepage would eventually saturate the sediments and a large portion of the seepage would emerge on the surface in the Dry Creek drainage downstream of the dam. The water would then flow down Dry Creek drainage until it reached thick sediment layers near Cold Creek where it would re-infiltrate and continue flowing in the subsurface towards Hanford (Figure 7-1).

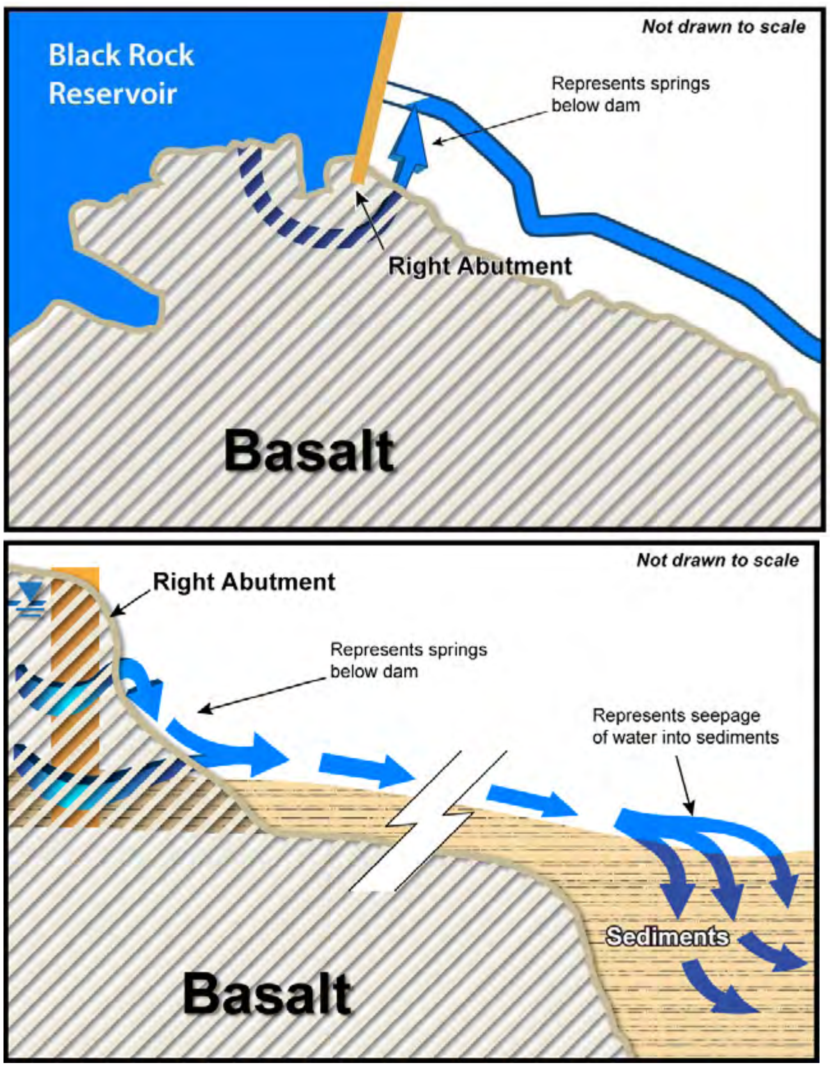

Figure 7-1: Illustration of seepage behavior. Above: plan view of seepage bypassing right abutment. Below: cross section of seepage flowing down Dry Creek and re-infiltrating into thick sediments.

As shown in Figure 7-2 (which is a copy of Figure 8-18 from the seepage report, Reclamation, 2007b), re-infiltration of the Dry Creek surface flow would increase the head in the sediments at Cold Creek by about 50 feet.

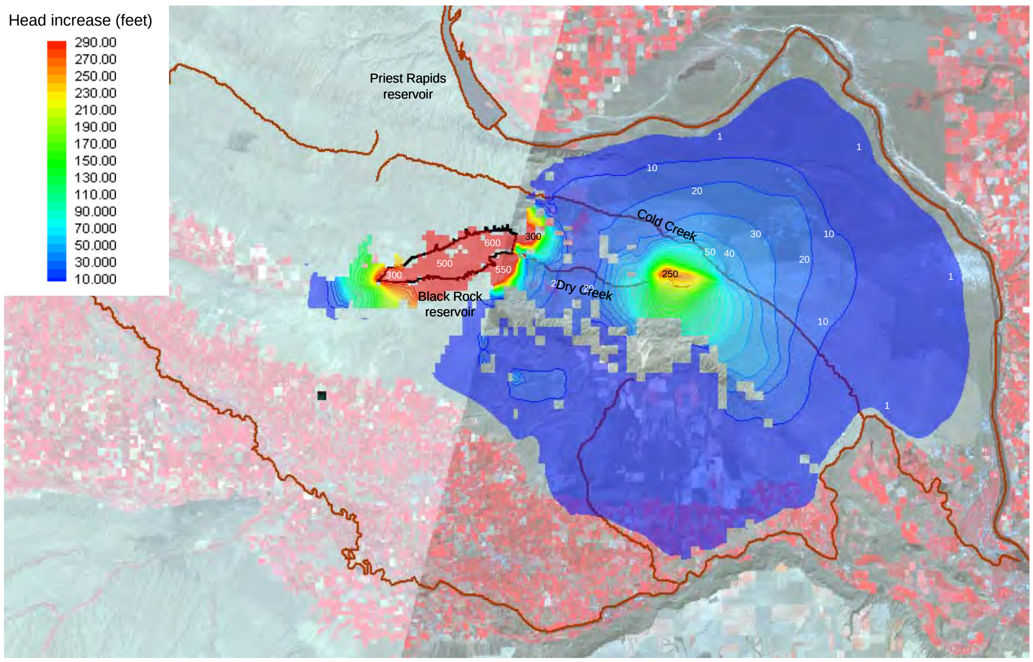

Figure 7-2: Layer 1 (sediments) head increase, *permeability 2 average storage* model after 300 years (from Figure 8-18, Reclamation, 2007b).

However, without the re-infiltration, the sediments on the Hanford Site would experience significantly less head change, as shown in Figure 7-3. The seepage and mitigation models indicate that if there were no re-infiltration of the surface flow from Dry Creek, the increase in head at the Cold Creek boundary would be less than one foot. This result showed the importance of a barrier to the *surface* flow in the Dry Creek drainage to prevent the eventual re-infiltration of seepage upgradient of Cold Creek.

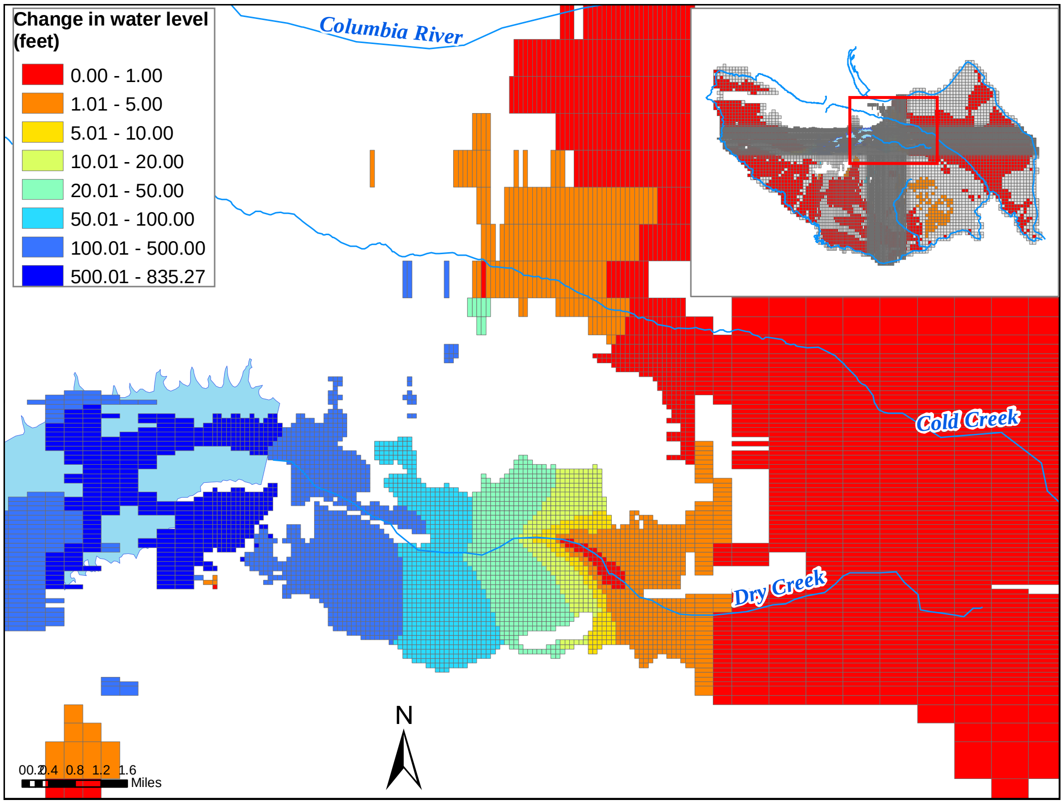

Figure 7-3: Change in water level in layer 1 (sediments) if there were no re-infiltration of surface seepage in lower Dry Creek.

While reservoir seepage also had an impact on head conditions in the lower Saddle Mountain and Wanapum Basalts, that deeper seepage is not expected to influence head conditions in the sediments at the Hanford Site (Reclamation, 2007b). The mitigation model reproduced these same hydrologic outcomes prior to including any mitigation features.

The mitigation model shows that the total seepage from the reservoir could be reduced by replacing the sediments under the dam with zone 1 core material, installing a grout curtain under the dam, installing a geomembrane liner over the Wanapum outcrop, and constructing a cutoff wall beneath the right dam abutment. The model indicates that a combination of these mitigation measures would reduce total maximum reservoir seepage by approximately 30 percent (from 74.3 to 51.9 cfs). However, most of the seepage (from 69.6 to 46.5 cfs) would bypass these mitigation features and daylight downstream of Black Rock dam. A small amount of the total reservoir seepage (about 5.4 cfs) would continue deeper into the basalts but would have no measurable impact on head conditions in sediments beneath the Hanford Site.

The mitigation model also shows that a cutoff wall installed in the Dry Creek drainage would be an effective barrier to flow within the sediment layer east of the Black Rock dam site (Figure 7-4). Figures 7-5 and 7-6 show the change in groundwater level in layers 1 and 2, respectively, after the cutoff wall is installed.

The groundwater level increases upstream and decreases downstream of the cutoff wall. Increased head conditions indicate that more groundwater will emerge on the surface up-gradient of the cutoff wall. To capture the emerging water along with the water flowing down Dry Creek, a low-head embankment structure would be constructed on top of the cutoff wall. This structure would block surface water flow before it could re-infiltrate into thick sediments near Cold Creek. This water would be conveyed away from behind the embankment by a pipeline designed for the total capacity of the surface flows and emerging groundwater in Dry Creek.

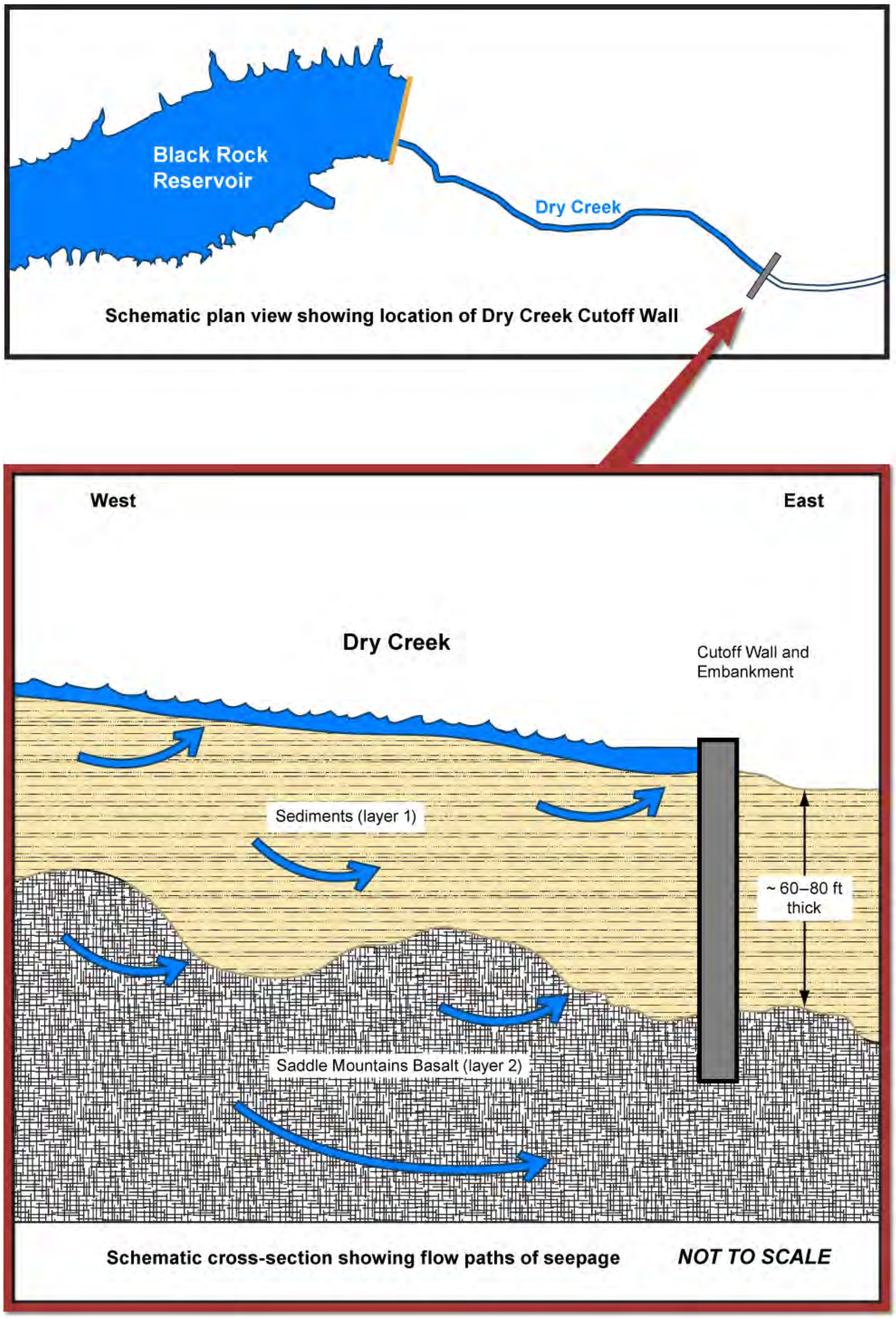

Figure 7-4: Illustration of embankment structure behavior. Above: plan view of structure. Below: cross section of structure.

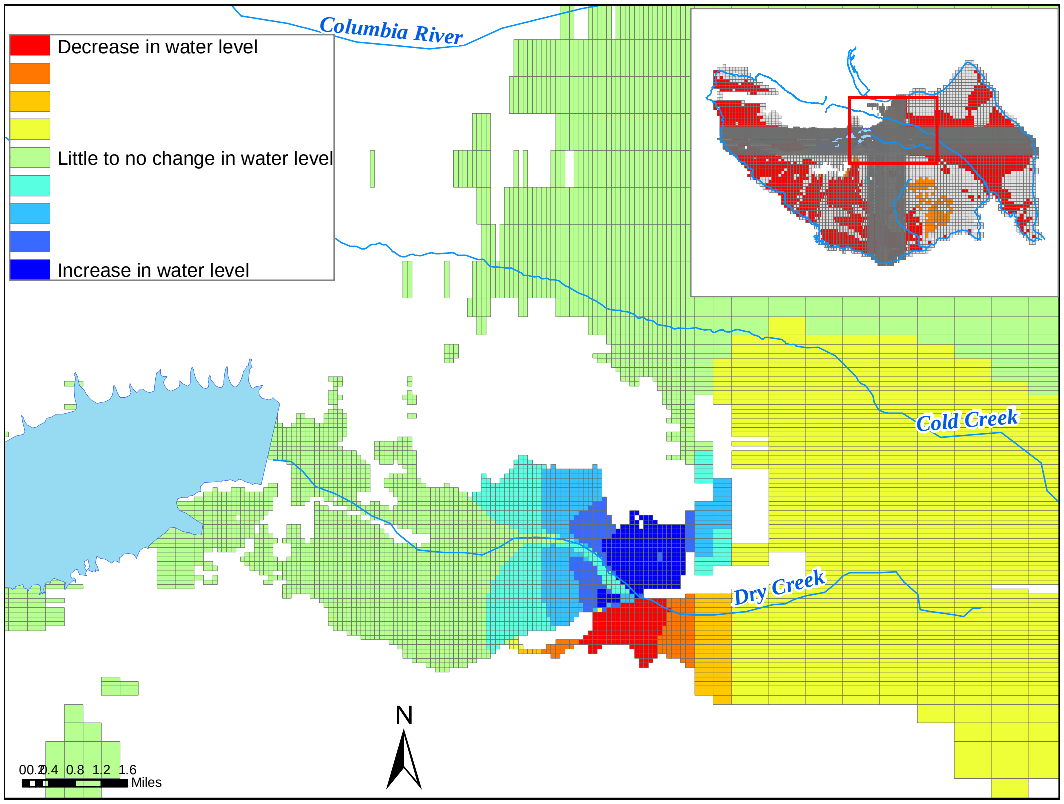

Figure 7-5: Change in water levels after Dry Creek cutoff wall is installed (Layer 1).

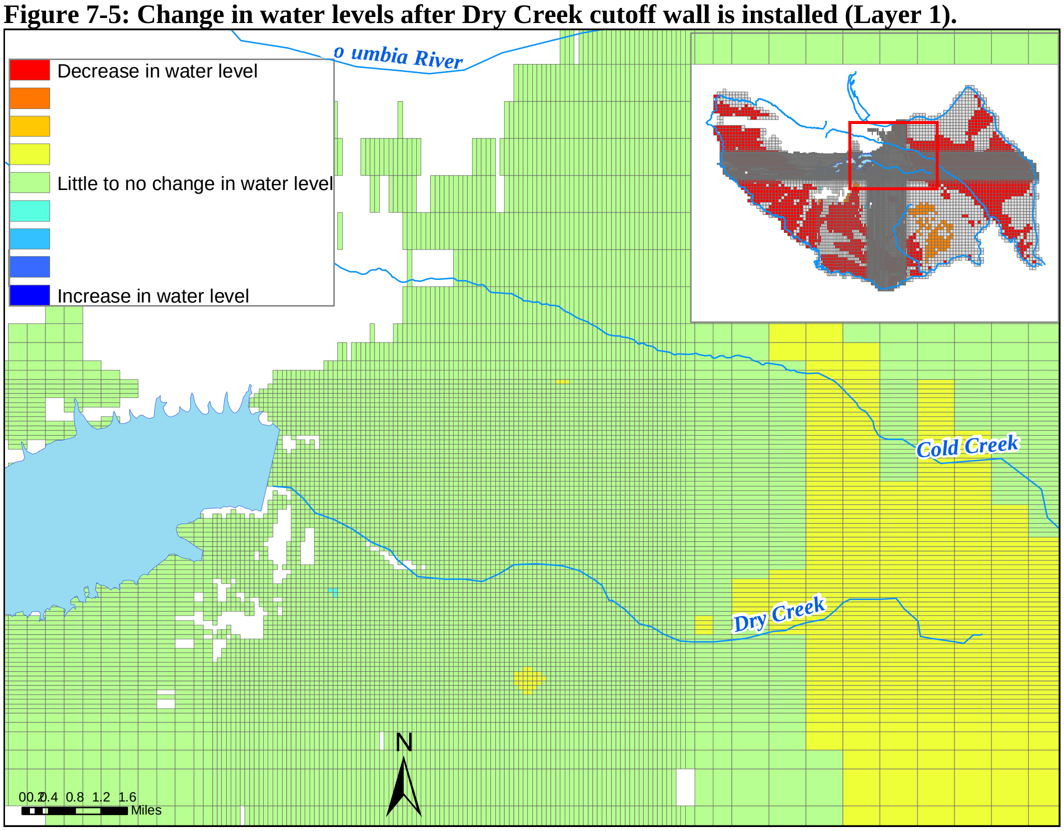

Figure 7-6: Change in water levels after Dry Creek cutoff wall is installed (Layer 2).

The mitigation model indicates that total reservoir seepage *across the Cold Creek boundary* could be reduced by 99 percent by employing all of the above mitigation measures. The remaining seepage is in the deeper Saddle Mountains and Wanapum Basalts and has little impact on the Hanford Site.

Pumping wells to intercept the deeper basalt seepage in the Dry Creek valley have been proposed as an additional mitigation measure. They were ultimately not modeled in these mitigation runs, but could be considered a backup measure and to provide a factor of safety in case the seepage quantities in the basalts are greater than expected from the model results.

Since modeling the maximum seepage case indicates that mitigation features would either prevent or recapture almost all of the reservoir seepage, it was not deemed necessary to also model the minimum seepage case with mitigation features.

In characterizing the effectiveness of mitigation measures based on model results, it is important to recognize the underlying assumptions: that the model represents a reasonable approximation of the geology and geologic structure and that all mitigation features are installed with the same specifications and hydrologic properties as their model representations. Since the complex geology or installation of mitigation features may be different from what has been modeled, there is potential for Black Rock reservoir seepage to be larger than what is estimated by the model.

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8.0 Conclusions

The Black Rock mitigation model is based on the earlier Black Rock seepage model developed by Reclamation (2007b). The grid mesh and layering of this model were refined in order to address questions about the effectiveness of potential reservoir seepage mitigation measures.

A stochastic Monte Carlo simulation using the mitigation model demonstrated that the earlier “Permeability 2” seepage model results are representative of maximum possible reservoir seepage. The “Permeability 1” seepage model results are significantly greater than the minimum 95% confidence interval.

Like the seepage model, the mitigation model showed that a large portion of reservoir seepage will occur in the right abutment area of the dam, affecting head conditions in the sediments, the Saddle Mountains, and Wanapum Basalts underlying the reservoir. The majority of reservoir seepage will emerge on the surface downstream of the dam and flow on the surface down the Dry Creek drainage. As in the seepage model, if this water is not collected or contained and removed in some manner, the water will re-infiltrate sediments near Cold Creek and cause a significant rise in groundwater levels beneath the Hanford Site.

Mitigation features were introduced in a version of the mitigation model that is based on the earlier “Permeability 2” seepage model. Mitigation features aimed at preventing reservoir seepage include replacing the sediments under the dam with zone 1 core material, a grout curtain beneath the dam, a cutoff wall in the right abutment, and a geomembrane blanket over a Wanapum outcrop in the right abutment. Collectively these features reduced total reservoir seepage by about 30 percent (22.4 cfs). From these mitigation measures alone, seepage into Dry Creek would be reduced to 46.5 cfs.

The key to reducing flow across the Cold Creek boundary, and thus reducing groundwater flows into the Hanford Site, are mitigation measures aimed at capturing seepage in the Dry Creek drainage. Mitigation measures in the Dry Creek drainage include a cutoff wall and a low-head embankment structure. For the purposes of this model, it was assumed that the water contained by the embankment structure would be conveyed away to the Yakima River by a pipeline. The pipeline would be designed to continuously remove the water from the site.

The mitigation model indicated that by applying these mitigation features collectively, it is possible to reduce reservoir seepage impacts to the Hanford Site (i.e., *seepage-induced groundwater flow across Cold Creek*) by 99 percent.

Models contain many types of uncertainty resulting from the necessary simplification of a complex natural system of geologic units and structure, from hydrologic parameter variation across the model domain, and from assumptions made about how an engineered mitigation feature would be built and its effectiveness. In a large model domain with few measured data points, even a good model calibration can contain a large degree of uncertainty. In this mitigation model, the sensitivity analysis indicated the importance of the horizontal hydraulic conductivity values in calibrating to observation well data. The Monte Carlo simulation indicated the range of flows that could be expected from different conductivity distributions and from using higher and lower conductivity values than those used to calibrate the model. These exercises help to understand the uncertainty, but don’t necessarily reduce it. Predictive flow quantities resulting from the model are based on the current conceptual understanding and simulation of the site and should be regarded as a guide rather than exact quantities or locations of seepage flow.

Before final designs are initiated on the mitigation features, additional geologic investigations are recommended to determine locations and properties of geologic structures. Additional hydrogeologic testing is also recommended to better characterize the variation of hydraulic properties in the reservoir and Dry Creek areas.

Glossary

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

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.

Groundwater 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.

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.

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.

Neat cement – Portland Cement mixed with water only

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.

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.

Stochastic – A modeling method where the model is run repeatedly with random parameter values that are distributed within a given range.

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.

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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