

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 mi² 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 mi² centered approximately on the reservoir site, with grid cells that range between 0.08 and 0.32 mi².

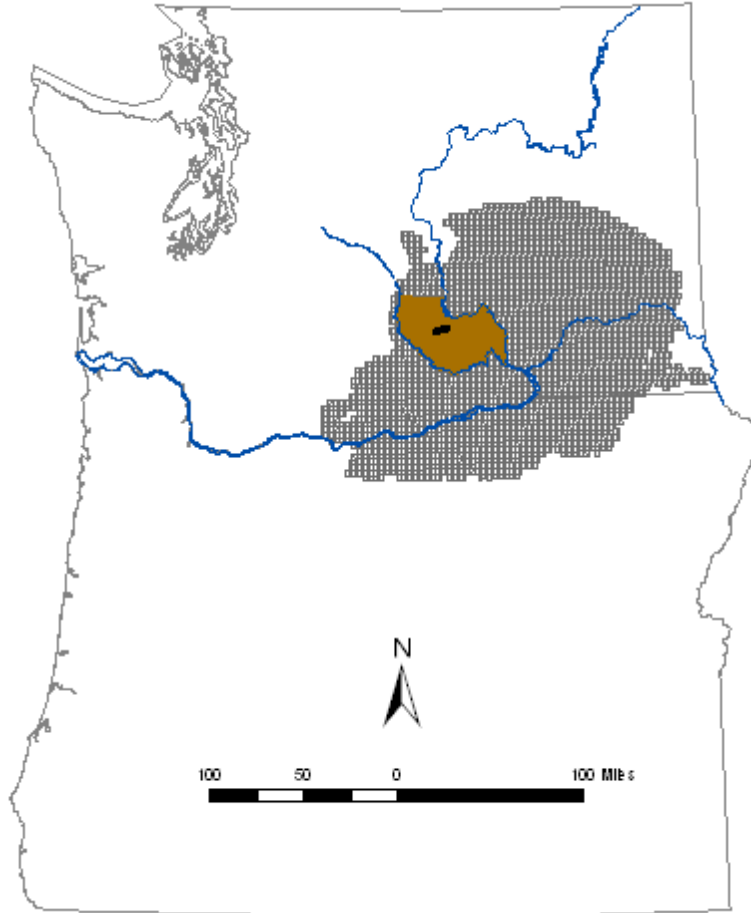


Figure 4-1: Black Rock model area in relation to the USGS Columbia Plateau Model area.

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 reservoir 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.

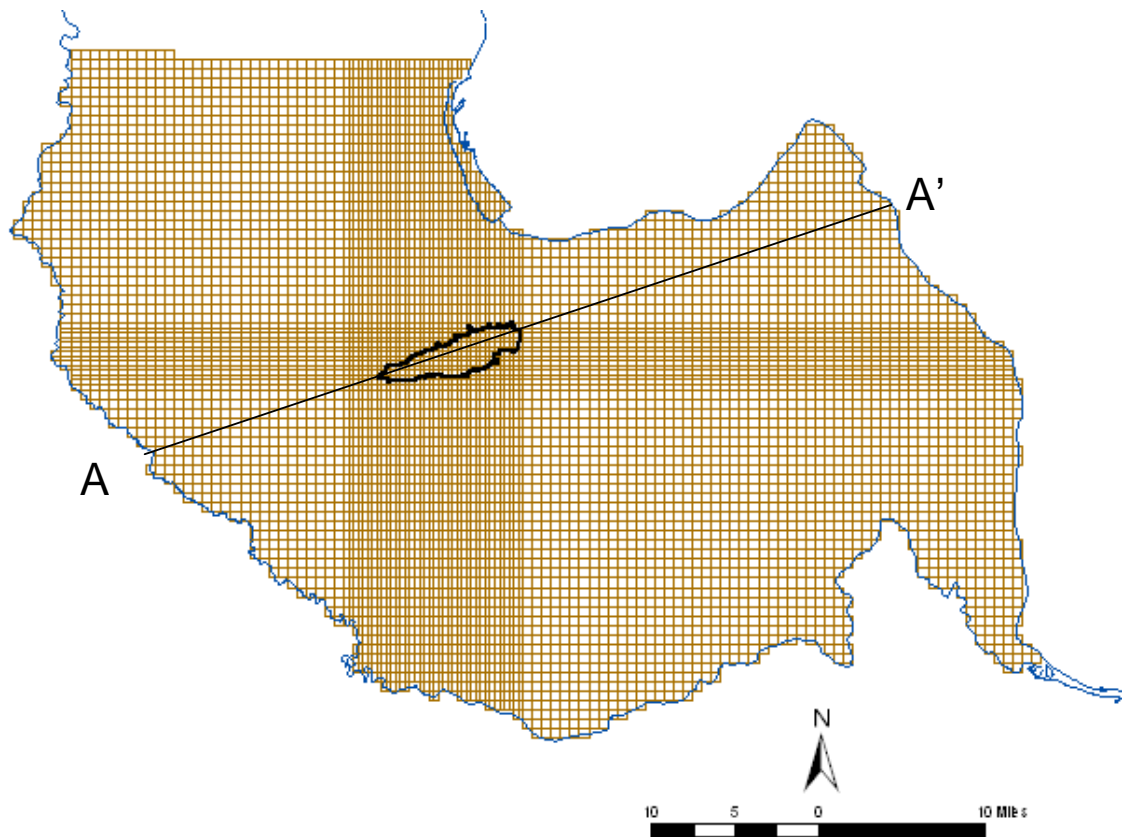


Figure 4-2: Black Rock model grid cells.

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.

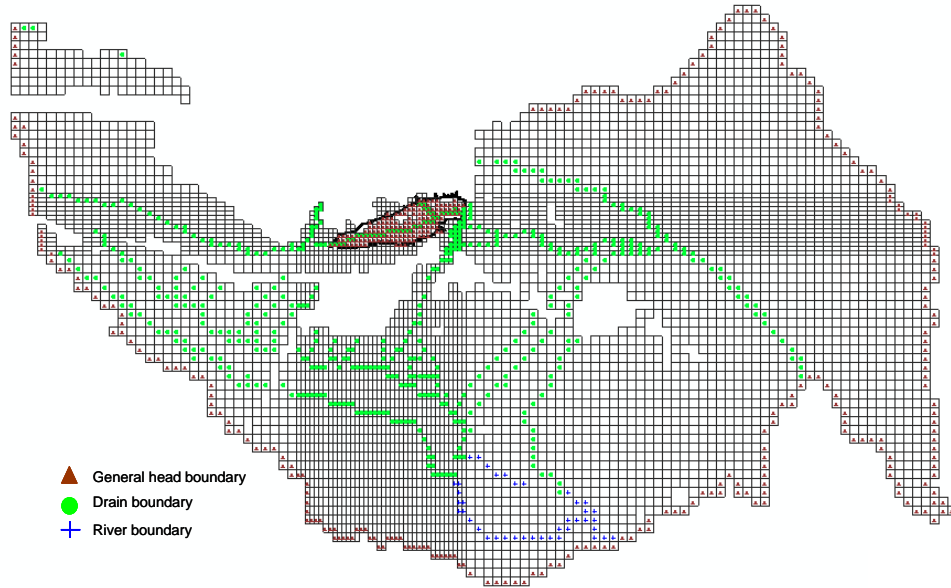


Figure 4-3: Sediment layer (model layer 1) active grid cells.

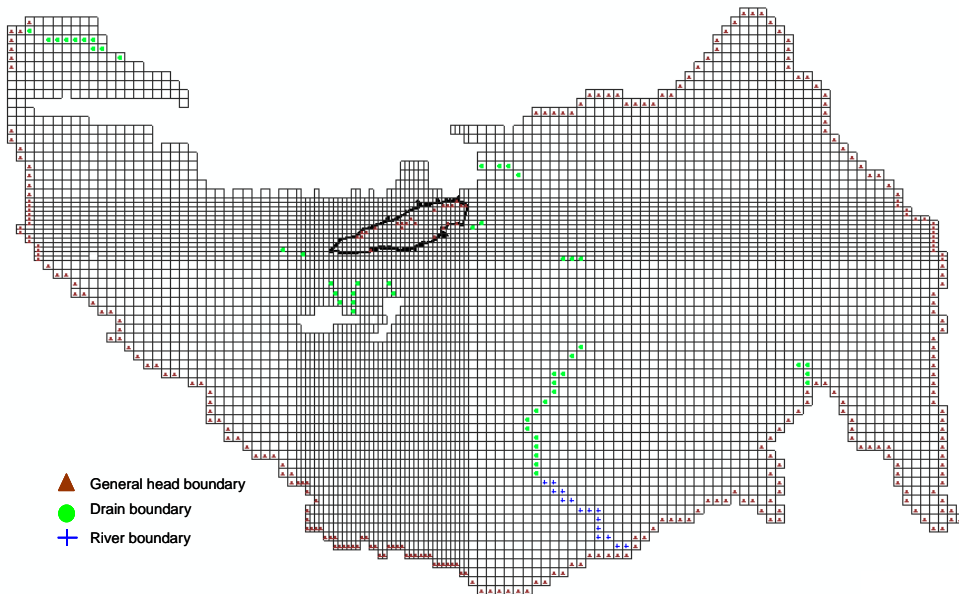


Figure 4-4: Saddle Mountains layer (model layer 2) active grid cells.

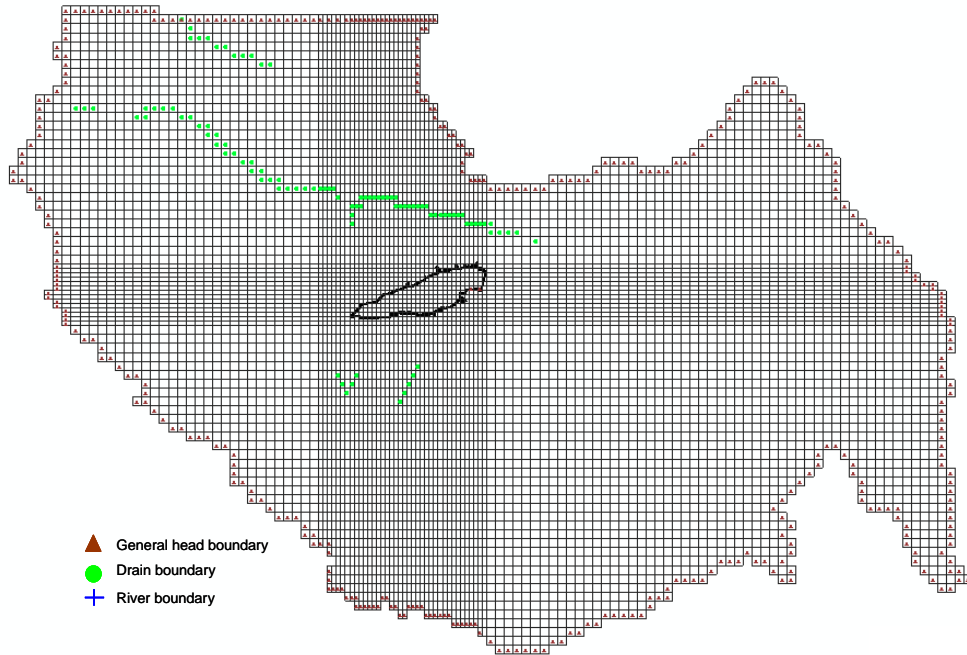


Figure 4-5: Wanapum layer (model layer 3) active grid cells.

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.

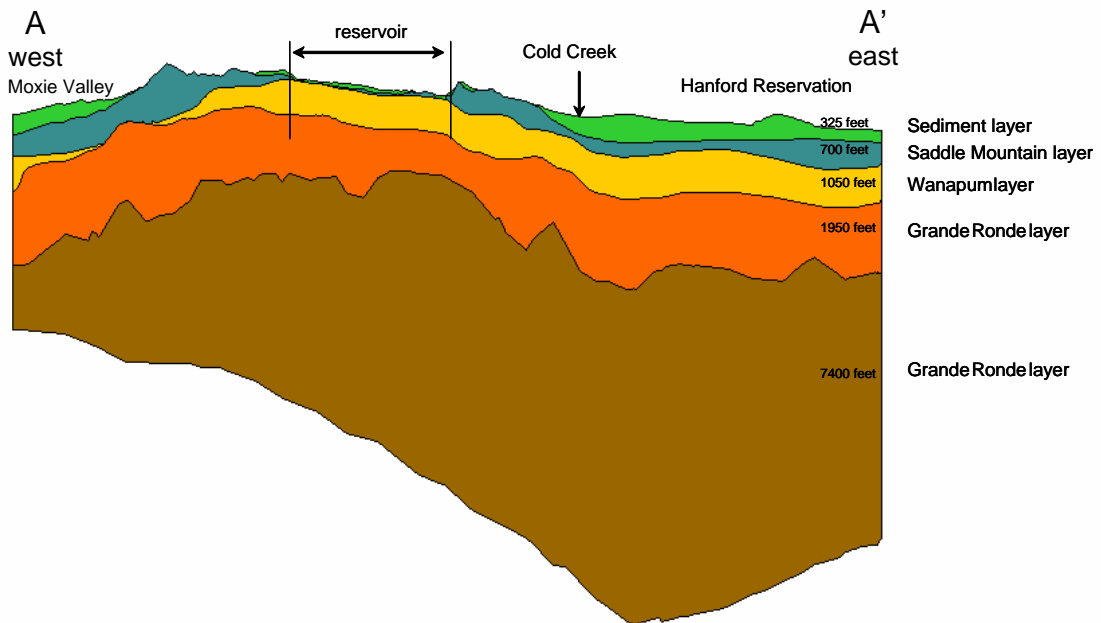


Figure 4-6: Five-layer Black Rock model cross-section.

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

¹Layers 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 1×10^{-11} to 1×10^{-4} ft/s. In the dense flow interiors, horizontal hydraulic conductivity ranges from 1×10^{-14} to 1×10^{-8} ft/s. Vertical hydraulic conductivity was estimated to be 1 to 3 times that of the horizontal conductivity of flow interiors, or between 1×10^{-14} to 3×10^{-8} ft/s. Ellensburg Formation interbeds were determined to have horizontal conductivities ranging from 1×10^{-11} to 1×10^{-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	9.84×10^{-6}
Ringold Formation	DH-04-02	V	3.06×10^{-5}
Rattlesnake Ridge Interbed	DH-04-02	V	9.26×10^{-6}
Pomona Basalt –Flowtop	DH-04-02	V	4.63×10^{-7}
Selah Interbed	DH-04-02	GW	3.11×10^{-5}
Composite: Selah & Esquatzel Basalt	DH-04-02	GW	8.96×10^{-5}
Mabton Interbed	DH-04-02	GW	3.47×10^{-7}
Pomona Basalt	DH-05-1	V	5.32×10^{-6} - 1.61×10^{-5}
Esquatzel/Umatilla Basalt	DH-05-1	V	5.21×10^{-6} - 2.40×10^{-4}
Fault Zone Breccia	DH-05-1	GW	8.56×10^{-6}
Pomona Basalt	DH-05-1	GW	3.70×10^{-6} - 1.22×10^{-4}
Esquatzel/Umatilla Basalt	DH-06-1	V	2.25×10^{-5}
Fault Zone Breccia	DH-06-1	V	4.36×10^{-5}
Fault Zone Breccia	DH-06-1	GW	4.86×10^{-6}
Pomona Basalt	DH-06-1	GW	1.09×10^{-4} 6.12×10^{-4}

¹DH-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.

²For 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	1.0×10^{-12}	2.0×10^{-6}	1.95×10^{-10}	5.0×10^{-9}	1.0×10^{-12}	1.0×10^{-9}
Maximum value	1.0×10^{-5}	2.31×10^{-3}	1.0×10^{-4}	2.89×10^{-4}	2.89×10^{-4}	8.0×10^{-3}
Average value	1.18×10^{-6}	5.83×10^{-4}	1.28×10^{-6}	1.21×10^{-5}	2.07×10^{-7}	1.07×10^{-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 2.0×10^{-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	3.0×10^{-6}	6.0×10^{-5}	2.0×10^{-5}
3	Wanapum Basalts	3.0×10^{-8}	4.0×10^{-5}	5.0×10^{-7}
4-5	Grande Ronde Basalts	3.0×10^{-10}	1.0×10^{-6}	2.0×10^{-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.