Final FRI/FS Report, Appendix H

This appendix describes the hydraulic analysis used in the preliminary design of the containment areas considered in the FFS. Calculations and computer simulations were performed to estimate the maximum expected groundwater flow out of the Alternative 2 reactor vessel system and the expected groundwater pumping rate needed to prevent hydraulic head buildup in the Alternative 3 containment area. In addition, computer simulations were used to evaluate the expected influence of Alternative 2 on the direction and magnitude of the vertical gradient across the Layer C aquitard underlying the Layer B aquifer. The data collected during the various phases of work comprising the RI were used in the calculations. Additional data (such as detailed lithology along the wall alignment) will be collected as part of final design of the selected containment alternative.

H.1 Modeling Objectives

H.1.1 Alternative 2

Alternative 2 consists of a surface low-permeability cap with a vertical slurry wall through the full extent of the Layer B aquifer around the boundary of Parcel G. At the northeast corner of the slurry wall, a zero valent iron (ZVI) treatment system will be installed consisting of a gravel-filled collection trench and ZVI reactor vessels inside the wall and a gravel-filled infiltration gallery located downgradient outside the wall (Figure 40). A valve in the pipe between the treatment vault and the infiltration gallery would prevent water from entering the containment area through the treatment system during periods of rising water levels outside the slurry wall. The surface cap, slurry wall, and basal aquitard (Layer C) would form low-permeability boundaries to the containment area. As part of the preliminary design of the ZVI reactor vessel system, the site groundwater flow model was used to evaluate these assumptions and to estimate the maximum expected groundwater flow rate out through the reactor vessel system. Furthermore, because the potential for downward transport of contaminants from the Layer B aquifer through the underlying Layer C aquitard is a potential issue, the model was used to evaluate the effect of Alternative 2 on vertical gradients.

H.1.2 Alternative 3

The Alternative 3 remedy consists of a surface low-permeability cap with a vertical slurry wall through the full extent of the Layer B aquifer around the entire boundary of Parcel G (Figure 41), with a groundwater extraction system within the containment area to provide hydraulic control. The objective of the groundwater extraction system would be to maintain an inward hydraulic gradient to prevent groundwater from flowing out of the containment area through the slurry wall or Layer C.

As with Alternative 2, the surface cap, slurry wall, and Layer C would form low-permeability boundaries to the containment area. As part of the preliminary design of the groundwater extraction system in the containment area, the site groundwater flow model was used to estimate the expected groundwater extraction rate required to provide hydraulic control.

The following sections describe the method used to estimate rainfall infiltration through the Parcel G cap, the groundwater flow model and its historical use at the site, the set up of the groundwater flow model to evaluate Alternatives 2 and 3, and the model results.

H.2 Estimate of Infiltration Through the Low-Permeability Cap

Rainfall infiltration through the low-permeability Parcel G cap was estimated to provide an input parameter for the groundwater flow model. Two methods were used to estimate the amount of rainfall infiltration into the containment area through the cap.

H.2.1 Mean monthly rainfall method

To estimate the maximum infiltration rate into the containment area, the mean wet season monthly rainfall for Parcel G was determined, the expected evaporation was determined and subtracted from the monthly rainfall total, and an estimated cap infiltration percentage was applied to the remainder. Since estimating runoff using the SCS curve number equation (see below) requires daily rainfall data, runoff was ignored. Table H-1 provides a summary of the data sources and calculations. The rainiest months are November, December, and January, with mean monthly rainfall totals of approximately 6 inches. Since runoff was ignored, a low cap infiltration (0.5 percent) was selected. Based on this method, the rate of infiltration through the cap (into the vadose zone) during the rainiest months of the year was estimated to be 0.07 gallons per minute (gpm).

H.2.2 Extreme rainfall event method

To estimate the maximum rainfall infiltration rate into the containment area, the volume of water falling on Parcel G during a very heavy 24-hour rain event was estimated, the volume of stormwater runoff during that event was estimated and subtracted, evaporation was estimated and subtracted, and the remainder was assumed to infiltrate through the Parcel G cap. A 24-hour storm total of 3 inches was assumed to fall on Parcel G. The total volume of water falling on the 4.2 acre Parcel G during the storm was calculated to be (0.25 feet) x (182,951 square feet) x (7.4805 gallons/cubic foot), or approximately 342,140 gallons of stormwater. The amount of runoff was calculated using the SCS curve number equation (Ecology, 2001):

$$Q = (P - 0.2S)^2/(P + 0.8S),\ Q = 0 \text{ if } P < 0.2S, \qquad (1)$$

Where Q = runoff depth over the area of interest (in),
P = precipitation depth (in),
S = potential maximum detention over the area due to infiltration, storage, etc. (in)
S = (1,000/CN) – 10, where CN = Western Washington runoff curve number (98 for paved surfaces).

Per the SCS equation, approximately 315,890 gallons of runoff would be generated from a 3 inch rainstorm, with approximately 26,250 gallons retained on site. If it is assumed that the entire thickness of the low-permeability cap is saturated (which it likely would not be since it sits on the vadose zone), the flow rate of the ponded water through the cap can be estimated by:

$$Q = kiA, \qquad (2)$$

Where Q = flow rate (cubic ft/min),
k = hydraulic conductivity (ft/min),
i = hydraulic gradient (ft/ft),
A = area of cap (square ft).

Assuming that the cap hydraulic conductivity is 1 x 10^{-7} ft/min (typical maximum hydraulic conductivity for designed low-permeability caps) and that the water is ponded in a 0.5-acre puddle, the flow rate of ponded water through the cap is estimated to be:

$$\begin{aligned} Q_{cap} &= (1 \text{ x } 10^{-7} \text{ ft/min}) \text{ x } (1 \text{ ft/ft}) \text{ x } (21{,}780 \text{ ft}^2) \text{ x } (7.4805 \text{ gal/ft}^3) \\ &= 0.0163 \text{ gpm out the bottom of the cap.} \end{aligned}$$

Based on the local measured evaporation rates (see Table H-1), the 26,250-gallon puddle (1.93 inches thick) would take less than 1 day to approximately 3 months to evaporate (depending on the time of year), compared to years to infiltrate the cap.

Based on these results, it is likely that rainfall infiltration through a well-maintained asphalt cap would be insignificant. For the sake of a conservative maximum flow estimate, a maximum rainfall infiltration rate of 0.07 gpm was selected for use in the model.

H.3 Groundwater Flow Model Description and Historical Use

The site groundwater flow model consists of a MODFLOW model developed by S.S. Papadopulos and Associates, Inc. (SSPA), as part of the corrective measures system (CMS) design (SSPA, 1993). The model uses the U.S. Geological Survey MODFLOW groundwater simulation code (McDonald and Harbaugh, 1988) to simulate hydrogeologic conditions and water-level gradients and the particle tracking code PATH3D (Zheng, 1989) to evaluate groundwater flow. Historically, the model was used to define target pumping rates for each recovery well and to evaluate the performance of the CMS with respect to capture of groundwater contaminants.

The groundwater flow model was modified in 2003 to incorporate new data generated during the Parcel G source area investigations (IT Corporation, 2001). During these investigations, numerous borings were drilled across the site. Detailed soil sampling and logging resulted in fuller characterization of the shallow Layer B aquifer, including the thicknesses of the upper sand, the lower sand, and the intervening silt layer. While absent in some areas of Parcel G, the intermediate silt of Layer B was determined to be more continuous and thicker in most areas of Parcel G than was recognized at the time the original model was constructed. Based on these data, the flow model was modified to better represent the revised thicknesses and to explicitly represent the intermediate silt layer (Patterson Planning & Services, 2003). As in the original model, the transmissivity of the combined sand units in the revised model was based upon results of a pumping test using wells that penetrated the upper sand, the intermediate silt, and the lower sand. The hydraulic conductivity values used for the upper and lower sand units of Layer B were derived from the transmissivity and the thicknesses of the units. In addition to the change in the model layers, the model was also re-oriented to be consistent with a more accurate base map of the BSB and Hexcel facilities. The model was recalibrated using hydrologic and pumping data from the first four years of operation, 1993-1997.

H.4 Groundwater Flow Modeling of Alternatives 2 and 3

H.4.1 Groundwater Flow Model Set Up

The finite-difference grid for the groundwater flow model is shown in Figure H-1. The mean direction of groundwater flow is towards the northeast. The groundwater model is aligned so that the axes of the grid are aligned with the mean flow direction. The model is 2,550 feet wide divided into 80 rows, and 10,100 feet long divided into 70 columns. The BSB property is located in the core area of the model, where the grid spacing is 25 feet in both directions. The model is divided into 10 layers as summarized below.

Model Layer	Hydrostratigraphic Unit	Description
1	A	Alluvium
2	A	Alluvium
3	B	Aquifer
4	B	Silt zone
5	B	Aquifer
6	C	Confining unit
7	C	Confining unit
8	D	Aquifer
9	D	Aquifer
10	-	Regional artesian aquifer

The boundary conditions are shown in Figure H-2. The same types of boundary condition are applied for each model layer. The specified inflow along the upgradient boundary is distributed across the model layers according to their relative transmissivities. The specified head along the downgradient boundary is set at a constant value of 13.04 feet. No-flow boundary conditions are specified implicitly along the northwestern and southeastern edges of the model. These edges are conceived as streamlines parallel to the mean groundwater flow direction and are sufficiently distant from the site that they have no impact on groundwater flow at the BSB property.

Recharge is applied across the uppermost layer of the model. Recharge represents the infiltration of precipitation. The water table lies within the alluvial sediments of Unit A; the elevation of the water table is calculated during the solution, and the transmissivity of the upper model layers is adjusted to account for changes in the saturated thickness.

The bottommost layer of the model is assigned a uniform head of 37.0 feet. This water level represents the artesian conditions in the deep regional aquifer beneath the site; the water level was set based on calibration of the model.

H.4.2 Additional Modifications to the Groundwater Flow Model

The updated model from 2003 was used as the starting point for the current analysis. The following modifications were made to the updated 2003 model:

- Adaptation of the model to simulate transient flow on a monthly basis;
- Based on laboratory tests, adjustment of the hydraulic conductivity of Unit C (model layers 6 and 7) to better represent water level gradients between Units B and D; and
- Adjustment of the boundary head in the regional aquifer underlying Unit D to better represent water levels in Unit D.

Groundwater flow was simulated for a “representative” year. Simulations consisting of six annual cycles were used for all analyses. Groundwater levels stabilized to the annual cycle after a relatively brief period, between two and three years after the start of each simulation. A longer duration was used to ensure complete stabilization to a repeatable seasonal pattern. This is consistent with a long-term evaluation of groundwater flow for Alternatives 2 and 3. The model was adapted for the simulation of transient flow by subdividing each year into twelve month-long stress periods. Recharge rates and pumping rates were specified on a monthly basis.

The vertical hydraulic conductivity of the Unit C confining layer was adjusted to incorporate the results of recent tests. The values of five measurements of the vertical hydraulic conductivity ranged from 1.3×10^{-7} to 2.6×10^{-7} cm/sec. A value corresponding to the geometric mean (5.3×10^{-7} cm/sec) was specified for the current analyses.

The model has also been updated to include a revised estimate of the water level in the deep regional aquifer that underlies Unit D. A uniform water level of 37.0 feet has been specified to improve the match to the observed difference in water levels across Unit C.

The assigned properties for the model layers adjacent to the location of the proposed ZVI reactor vessel system are listed below.

Model Layer	Unit	Thickness (ft)	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)
1	A	5	2	0.01
2	A	5	20	0.1
3	B	2.1 – 12.9	51	0.26
4	B	0 – 8.7[a]	1	0.005
5	B	5.2 – 23.7	51	0.26
6	C	5	3	4.5×10^{-4}
7	C	5	3	4.5×10^{-4}
8	D	10	20	0.1
9	D	15	20	0.1
10	Regional aquifer	-	-	-

[a] Zero thickness is represented in the model by a layer thickness of one foot and hydraulic properties of the overlying unit.

With the exception of the layers representing Unit C, a uniform vertical anisotropy ratio (K_V/K_H) of 0.005 was retained from the previous model. The Unit C vertical hydraulic conductivity of 4.5×10^{-4} ft/day is equivalent to 5.3×10^{-7} cm/sec. The properties assigned for the deep regional aquifer (model layer 10) are not shown because they have no bearing on the model as the water levels are fixed in this layer.

H.4.3 Calibration of the transient model

A focused effort was made to calibrate the groundwater model to match observed water levels. The objective of the analysis was to retain the structure and parameters of the existing model to the extent possible while matching transient water levels observed at the site. To achieve this objective, only the recharge function is adjusted.

Recharge represents the amount of precipitation that infiltrates to the water table. Previous modeling conducted at the BSB and Hexcel properties demonstrated that the average annual recharge rate can be approximated as a fixed fraction of the total annual precipitation. For modeling of Alternatives 2 and 3, this approach was used to generate a representative record of monthly recharge rates from the monthly values of precipitation. The ratio between recharge and precipitation was treated as an adjustable fitting parameter. To simplify the analysis, it was assumed that the recharge to the water table was a constant fraction of the monthly precipitation.

The monthly rainfall at Parcel G from the beginning of 1993 to December 2004 is plotted in Figure H-3. To represent a monsoonal climate, a “representative” year was considered during which the annual precipitation occurs between November and March. For this study, a synthetic monthly precipitation record was used to represent long-term average seasonal changes in precipitation: the average monthly precipitation was specified according to the following distribution of the total annual precipitation.

Month	**Percentage of Annual Precipitation,** $\frac{P_{month}}{P_{annual}} \times 100$
October	0
November	14
December	23
January	23
February	22
March	18
April	0
May	0
June	0
July	0
August	0
September	0
Total	100

The total annual precipitation is plotted in Figure H-4. The total annual precipitation varied between 25 and 50 inches, with an average of about 39 inches over an 11-year period. The highest discharge from Parcel G corresponds to the period during which the rate of decline in the water levels within Parcel G is at a maximum. A typical hydrograph from a well within Parcel G is plotted in Figure H-5. The year of October 1, 1999, to September 30, 2000, was selected as the year most representative of high discharge from Parcel G, because the decline of water levels was sustained over the longest period. As shown in Figure H-5, the trend of water level patterns was very similar between years, indicating that the selection of a particular year for use is not critical. The total rainfall measured at the site for October 1, 1999, to September 30, 2000, was 49.3 inches, 11 inches above average.

The specified recharge rate for each month was calculated by multiplying the annual precipitation by the percentage of annual precipitation for that month and scaling that value by a factor that yielded the best match to the observed water levels:

$$I_{month} = P_{annual} \times \frac{P_{month}}{P_{annual}} \times \text{Recharge multiplier}$$

The following observation wells were examined to match the transient water level records:

- HY-1s and HY-1i;

- HY-11s and HY-11i;
- HYCP-3s and HYCP-3i; and
- Ls and Ld.

These wells were chosen as they are shallow and intermediate well pairs (upper and lower Unit B wells) located at or upgradient from Parcel G and sufficiently far removed from the HYR extraction wells such that they respond more to changes in recharge than to fluctuations in pumping rate.

Based on the results of a suite of simulations, the recharge multiplier of 0.15 yielded the closest match between the observed and calculated water levels. The match for HY-1s and HY-1i is shown in Figure H-6.

H.4.4 Alternative 2 Predictive Simulations

Following is a discussion of the predictive simulations for Alternative 2. For all simulations, it was assumed that Parcel G would be capped with a low-permeability cap. As discussed in Section H-2, the infiltration rate through the cap was conservatively assumed to be 0.07 gpm. The flow through the cap was represented as an equivalent steady recharge over the area of Parcel G.

The configuration of the ZVI reactor vessel system simulated in the model is shown in Figure H-7. The collection trench is located along the northern alignment of the slurry wall with the reactor vessels located inside the northeast corner of the slurry wall and the infiltration gallery located on the outside of the slurry wall and downgradient from the treatment vault.

For the simulation of both Alternative 2 and 3, the slurry wall was assumed to be 21 inches thick and to have a hydraulic conductivity of 1×10^{-7} cm/sec, based on information provided by DeWind One-pass Trenching.

In Alternative 2, the collection trench was treated as a high hydraulic conductivity zone with a MODFLOW DRAIN cell located at the inflow to the reactor vessels. The head at the DRAIN cell was set equal to the head in the infiltration gallery. The infiltration gallery was treated as a MODFLOW injection well with the flow rate in the injection well determined by the flow into the reactor vessel DRAIN cell. This representation does not introduce any artificial breaks in the slurry wall and results in one-way gravity flow from inside the wall to outside the wall. Because the DRAIN is linked to the infiltration gallery by both head and flow, the solution is iterative. Consequently, the model was run over several annual cycles while updating the head in the DRAIN cell and injection well rate until the head and flow converged between successive runs. The conductance in the DRAIN cell was set such that a head loss of approximately 0.1 feet occurred through the reactor vessel system.

Maximum Discharge Rate Through the ZVI Reactor Vessel System. The groundwater discharge through reactor vessel system is show in Figure H-8. The variations in the calculated discharge rates reflect the stratified nature of the soil as represented in the variable transmissivities, and the variable influence of the vertical components of flow (infiltration through the cap and flow upward through Unit C).

The critical design quantity is the maximum groundwater flow rate through the ZVI reactor vessel system. For a reactor vessel system with backflow control this is approximately 1.1 gpm, which occurs in July and August with slightly lower flow rates in September and October. There is minimal flow in November and no flow from December through April as water levels outside the wall are higher than water levels inside the wall.

Vertical Gradients Across Layer C. Tables and hydrographs in Appendix C (Tables C-5 through C-15 and accompanying hydrographs) compare Layer B and Layer D groundwater elevations measured between July 1992 and December 2004. Data are presented for Parcel G well clusters (HY-1, L, and HYCP-1) and for off-site well clusters (HY-11, G, H, B, C, HY-7, HY-8, and K). The hydrographs for the on-site and off-site well clusters show that under current corrective measures system (CMS) pumping conditions, there are occasional reversals of the typically upward gradients across Layer C. These reversals, when they occur, are generally short-lived and tend to happen at annual high water level peaks.

Because of the potential for downward transport of contaminants from the Layer B aquifer through the underlying Layer C aquitard if downward gradients were to occur for significant periods, the model was used to evaluate the effect of Alternative 2 on vertical gradients. Figure H-9 presents the simulated potentiometric heads at the HYCP-3i well location (situated within the containment cell) for the calibration simulation (current CMS pumping) and the Alternative 2 simulation. The results of these simulations indicate that, compared to current CMS pumping conditions, Alternative 2 will lower the highest potentiometric heads in Layer B inside the containment cell on the order of 1 to 2 feet. This suggests that Alternative 2 will reduce the potential for occasional reversals in gradient between Layers B and D.

It should be noted that the model is not currently capable of simulating variations in potentiometric heads in Layer D with the same degree of sensitivity as in Layer B. The similarity observed in Layers B and D of the period and magnitude of seasonal head changes suggests there is a significant hydraulic connection between these two layers in areas beyond the boundaries of Parcel G. However, the nature of discontinuities in Layer C that may hydraulically connect Layers B and D in areas beyond Parcel G is not sufficiently understood to incorporate in the model. The model is currently constructed assuming that Layer C is continuous. Therefore, although model simulations of the mean potentiometric head in Layer D reasonably match observations, the magnitude of the simulated seasonal head changes is attenuated in comparison to observations. Accordingly, model simulations of head in Layer D have not been directly compared to simulations of head in Layer B to evaluate the hydraulic gradients across Layer C.

H.4.5 Alternative 3 Predictive Simulations

This section presents a discussion of the predictive simulations for Alternative 3. For all simulations, it was assumed that Parcel G would be capped with a low-permeability cap. As discussed in Section H-2, the infiltration rate through the cap was assumed to be 0.07 gpm. The flow through the cap was represented as an equivalent steady recharge over the area of Parcel G.

For the Alternative 3 simulations, a slurry cutoff wall was placed completely around Parcel G. The slurry wall extended from the ground surface to the top of Unit C. Three extraction wells were located within Parcel G to ensure inward groundwater flow. In this scenario, there would be four components of flow within Parcel G: infiltration through the cap (recharge), flow through the cutoff wall (flow through the sides), flow across Unit C (flow through the base), and extraction by wells.

The results for this scenario are shown in Figure H-10. The following sign convention is adopted for Figure H-10:

- Infiltration through cap: recharge is positive;
- Flow through base: upward flow is positive;
- Flow through sides: flow across the wall into Parcel G is positive; and
- Extraction by wells is positive.

As shown in Figure H-10, there would be important seasonal fluctuations in the flow across the wall and across Unit C. Several pumping rates were evaluated to estimate the rate that could achieve the objective of complete containment throughout the year. The minimum cumulative pumping rate that achieves this objective is 0.6 gpm, or 0.2 gpm per well.

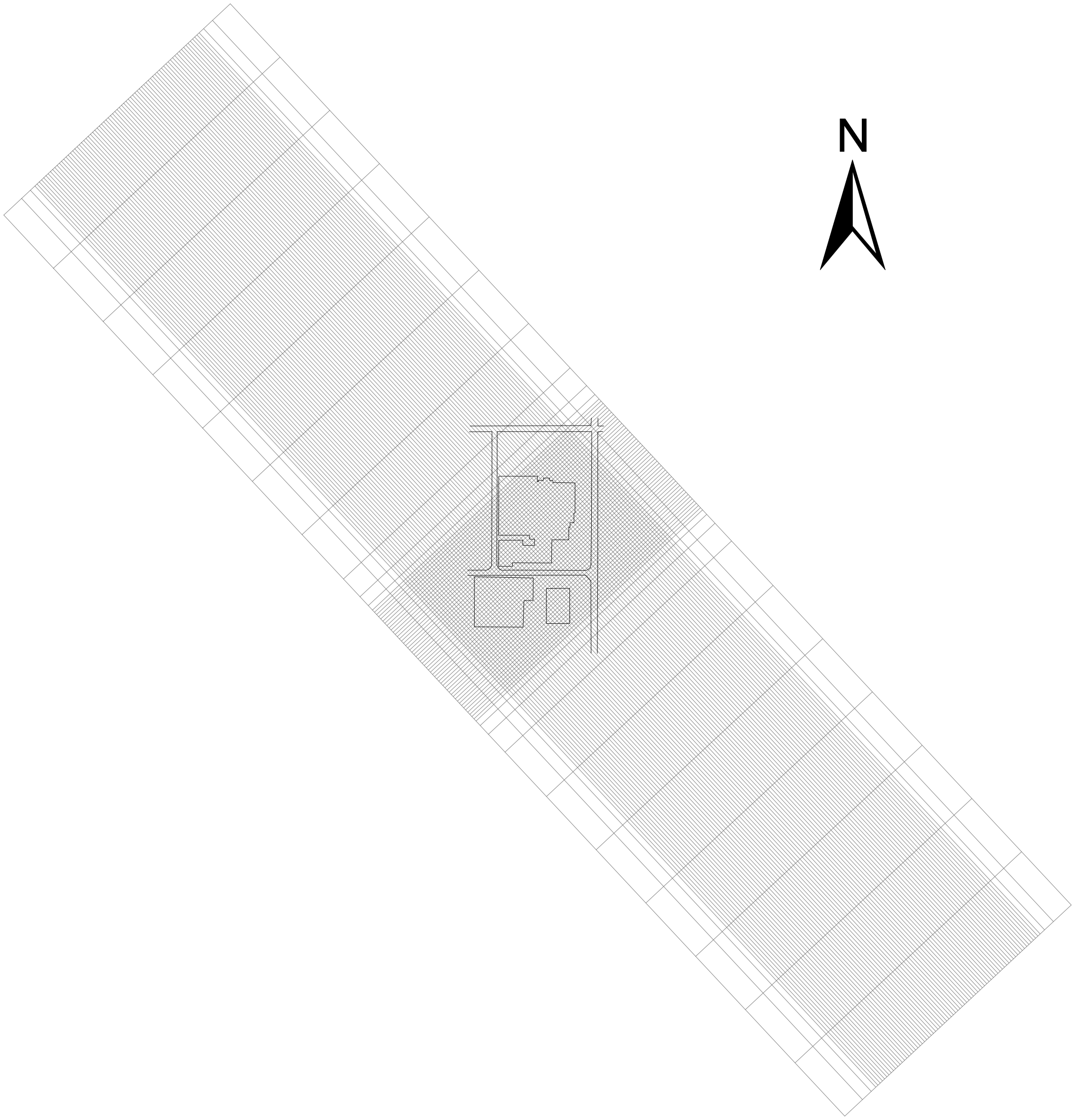

Figure H-1. Finite-difference grid for groundwater flow model

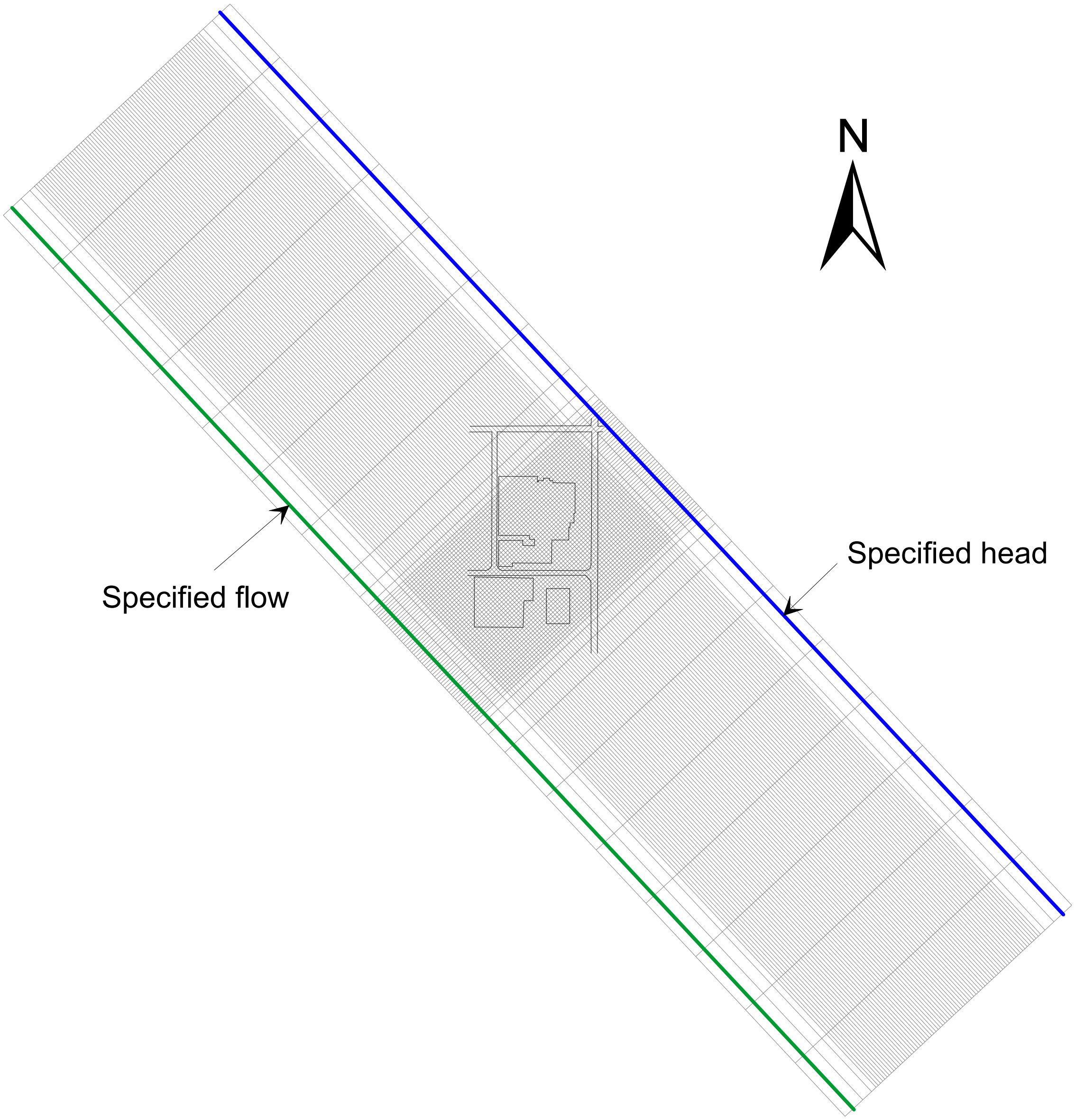

Figure H-2. Model boundary conditions

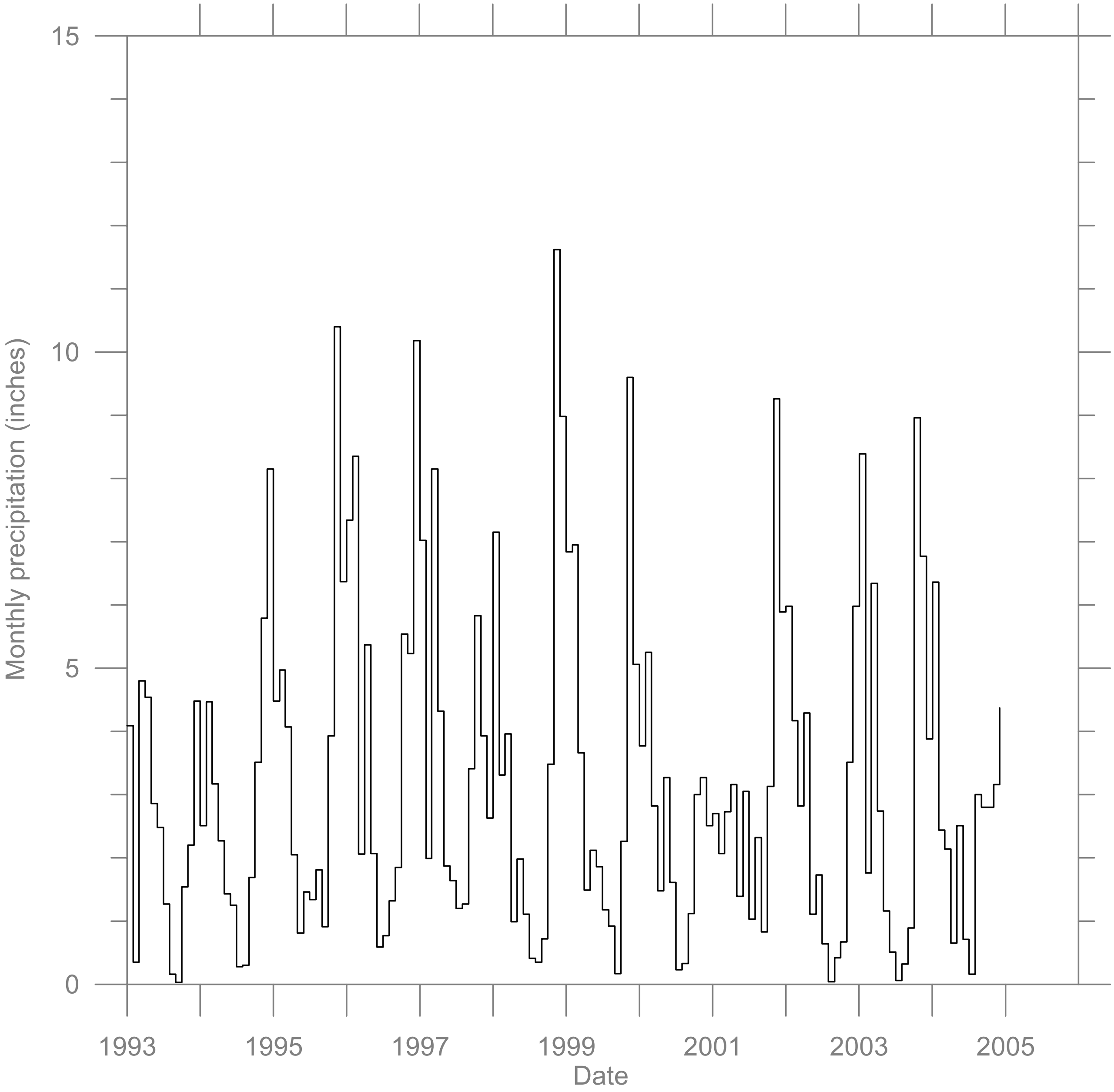

Figure H-3. Monthly precipitation record

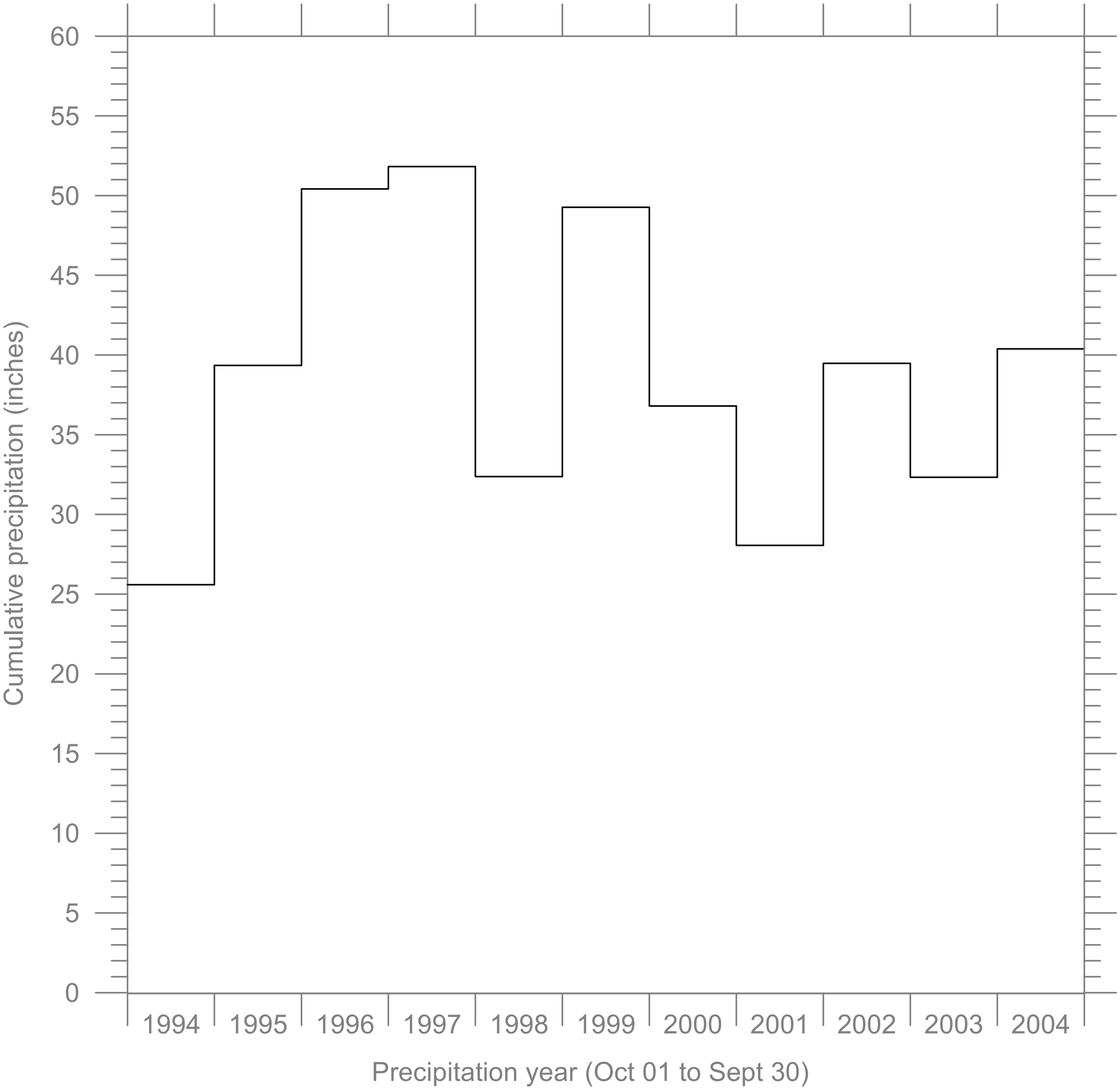

Figure H-4. Cumulative precipitation by water year (October 1 to September 30)

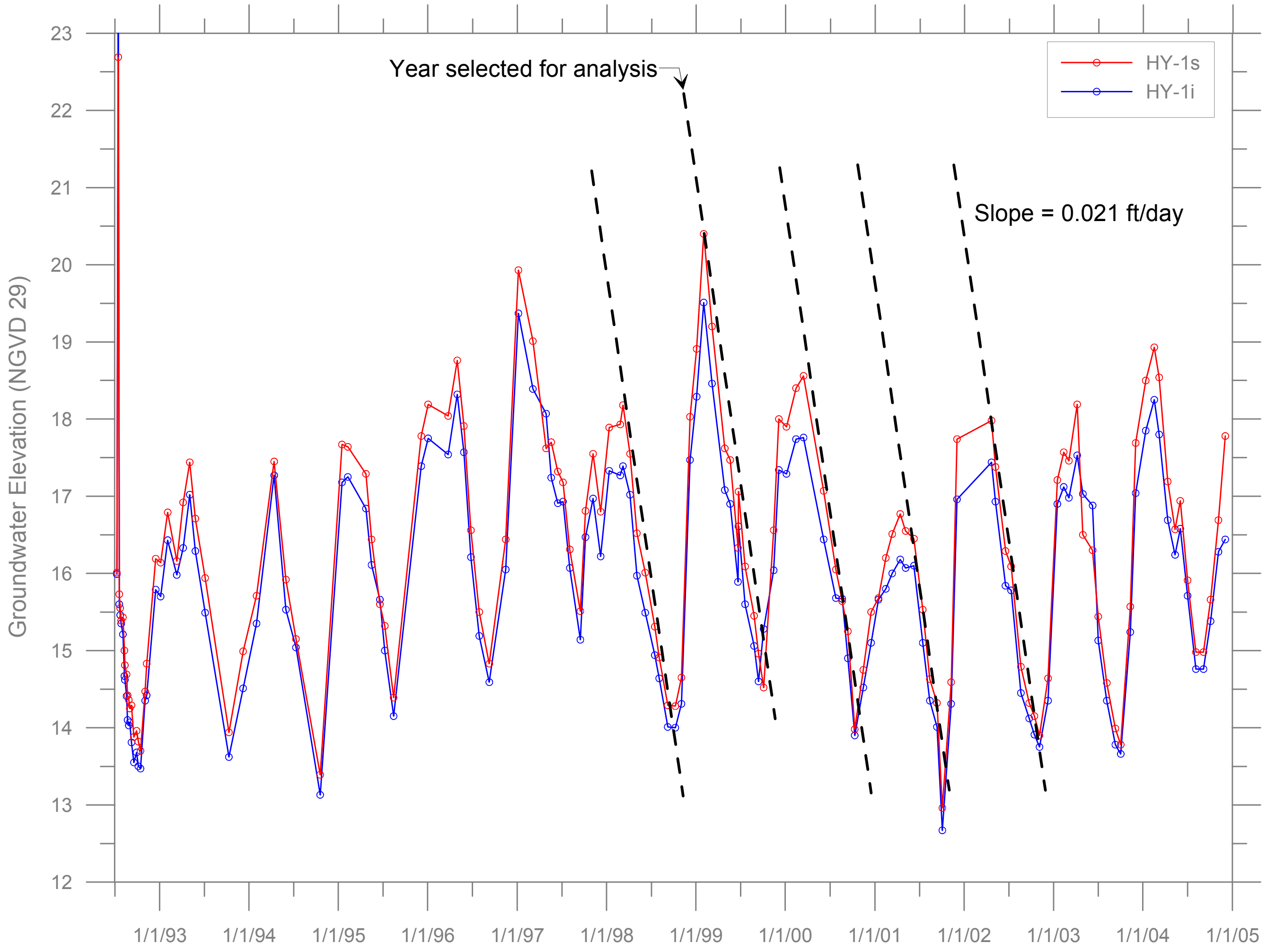

Figure H-5. Hydrograph for wells HY-1s and HY-1i

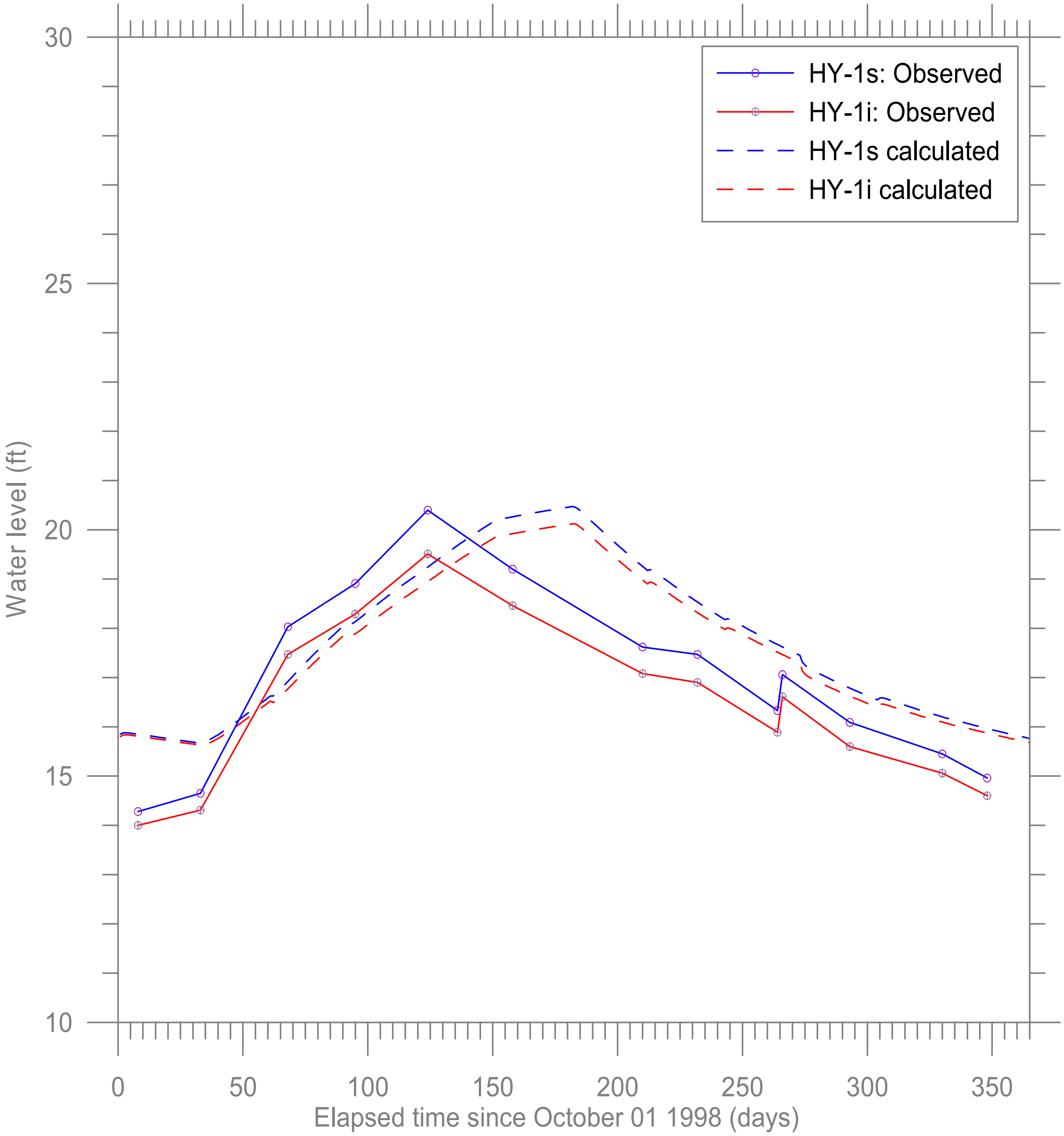

Figure H-6. Comparison between observed and calculated water levels for wells HY-1s and HY-1i

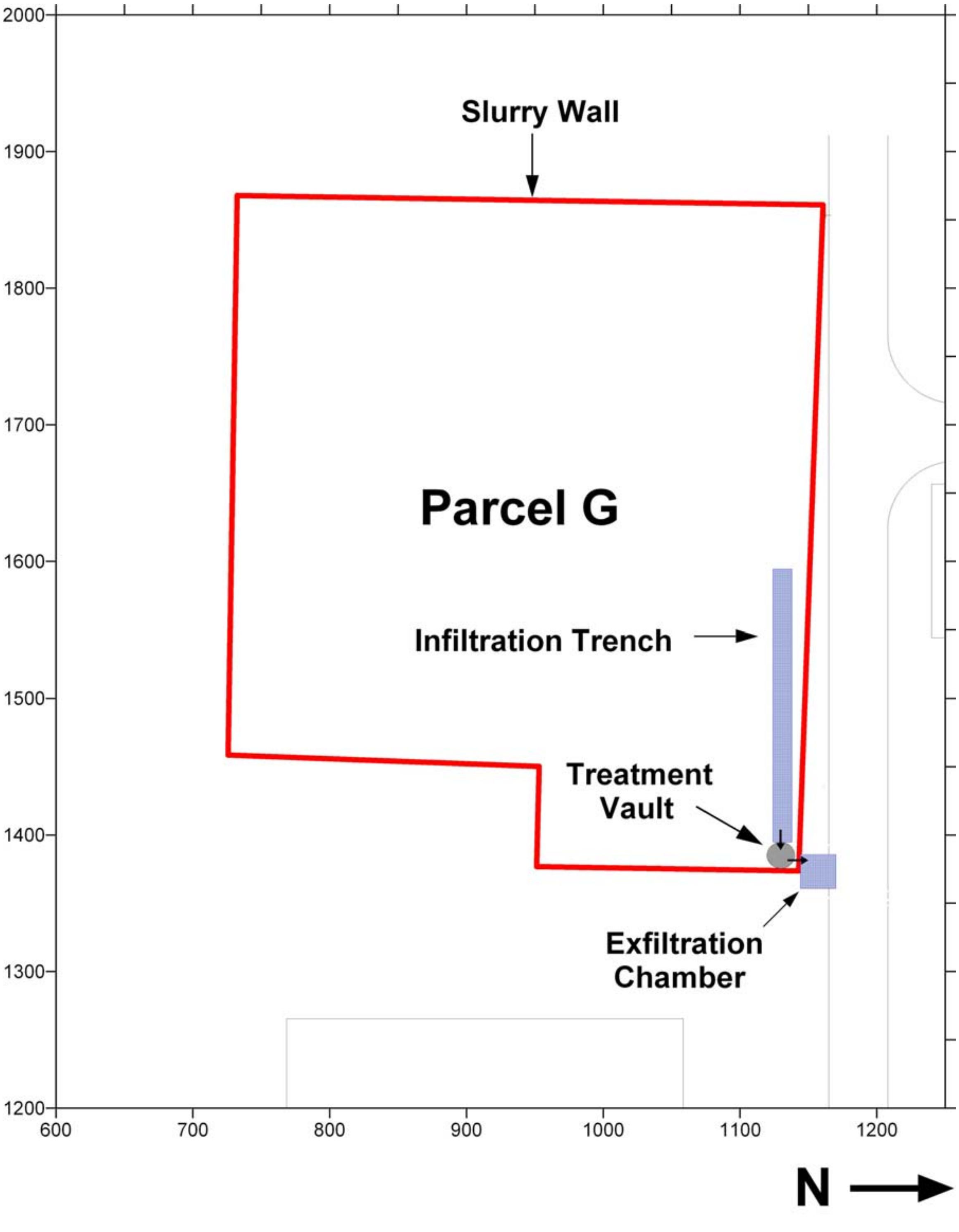

Figure H-7. Location of slurry wall and ZVI treatment vault system

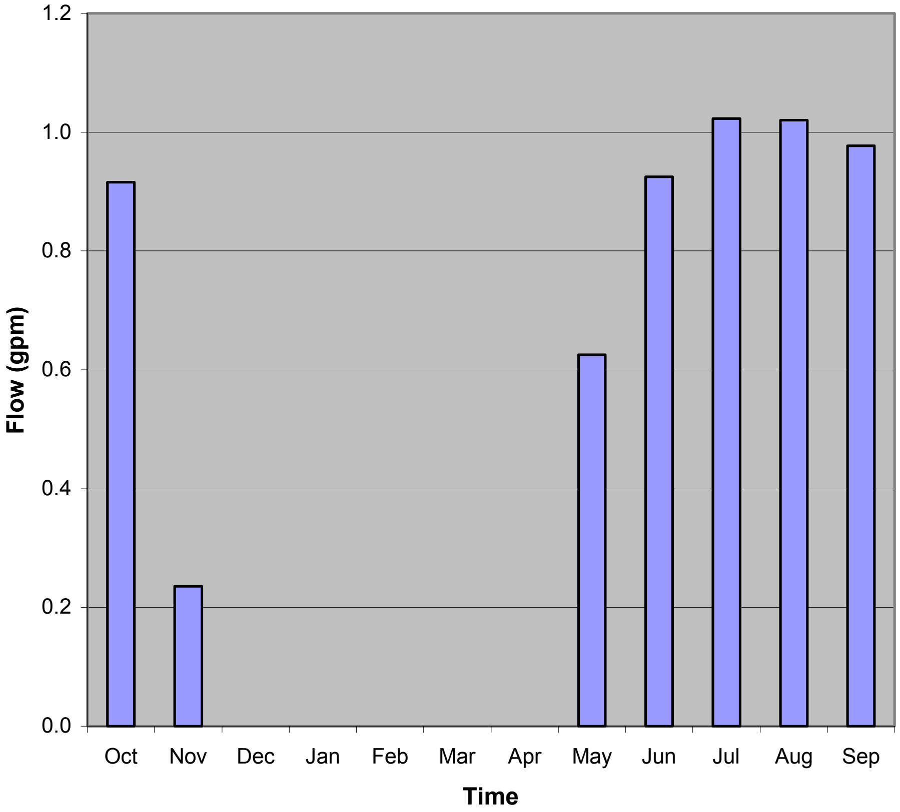

Figure H-8. Calculated flows through the ZVI treatment system

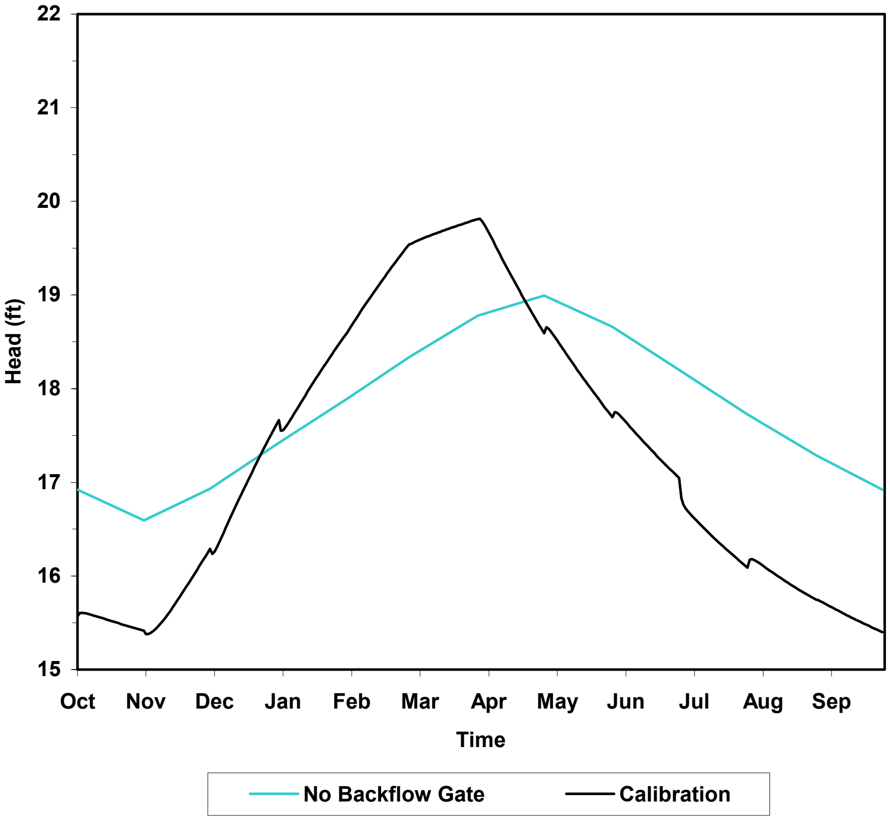

Figure H-9. Calculated water levels at HYCP-3i

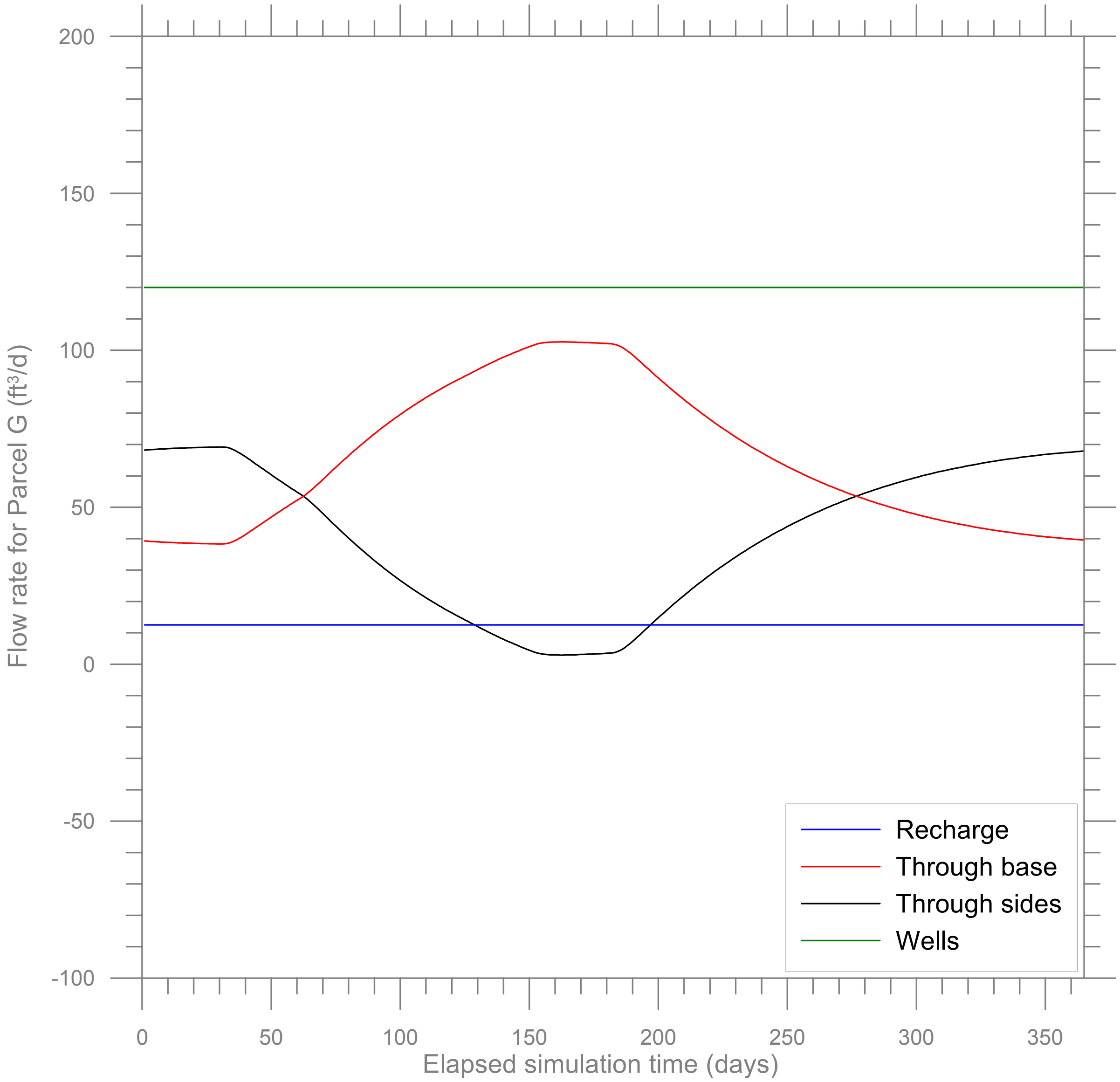

Figure H-10. Calculated flows across full containment slurry wall

Table H-1

Estimated Flow Into Containment Area Through The Surface Asphalt Cap
BSB Property, Kent, Washington

Month	Mean Rainfall (in.)	Estimated Pan Evaporation Rates (in.)	Calculated Evaporation Rates (in.)	Rainfall Minus Evaporation (in.)	Potential Water Available for Infiltration (gal)	Cap Infiltration Rate (gpm) Based on Estimated Cap Leakage		
						0.5%	1%	5%
January	5.71	0.61	1.2	4.51	514,354	0.06	0.12	0.58
February	4.10	0.71	1.6	3.39	386,621	0.05	0.10	0.48
March	3.73	1.58	2.3	2.15	245,202	0.03	0.05	0.27
April	2.53	2.46	3.2	0.07	7,983	0.00	0.00	0.01
May	1.68	3.97	5.1	-2.29	0	0	0	0
June	1.44	4.63	5.8	-3.19	0	0	0	0
July	0.76	5.61	7.0	-4.85	0	0	0	0
August	1.11	4.97	5.5	-3.86	0	0	0	0
September	1.74	2.92	3.5	-1.18	0	0	0	0
October	3.51	1.28	2.0	2.23	254,326	0.03	0.06	0.28
November	6.03	0.61	1.2	5.42	618,137	0.07	0.14	0.72
December	5.82	0.61	1.0	5.21	594,187	0.07	0.13	0.67
Annual	38.16	29.96	39.4	23.0				

NOTE: 1. Mean monthly rainfall (1948-2004) from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?waseat.

2. Pan evaporation rates from the NOAA Western Regional Climate Center (http://www.wrcc.dri.edu/htmlfiles/westevap.final, 11/13/04); the WRCC adjusted the pan evaporation rates (determined by pan measurements in Puyallup, WA, between 1931 and 1995) by a factor of 0.7 to 0.8 to account for pan effects. Pan measurements were not available for January and December; the lowest pan measurement available (November) was used for January and December.

3. Calculated evaporation rates (from NOAA WRCC website referenced above) were determined by the WRCC using Seattle-Tacoma meteorological data and the Penman Equation.

4. The lower of two evaporation rates was used to calculate potential rainfall available for cap infiltration.

5. Runoff was ignored since daily rainfall data would be required for analysis by the SCS curve number equation.

6. Containment area = 4.2 acres = 182,951 square feet.