Groundwater Modeling Report
West, Seep 2, and Seep 1 CKD Areas
Revision 0.0 – July 31, 2009
Little Traverse Bay CKD Release Site
Emmet County, Michigan

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1.0 Introduction

This groundwater modeling report has been prepared in support of the Removal Action Investigation/Remedial Investigation Report (RI report) (Barr, 2009) prepared on behalf of CMS Land Company and CMS Capital, LLC to document the removal action and investigation activities in accordance with the Administrative Order on Consent for Removal Action (AOC), Little Traverse Bay CKD Release Site (Docket No. VW-05-C-810, February 22, 2005).

This report discusses development of groundwater flow models for the Seep 1, Seep 2, and West Cement Kiln Dust (CKD) Areas which are part of the Little Traverse Bay (LTB) CKD Release Site. In this report, these areas are collectively referred to as the "Development". The locations of the Seep 1, Seep 2, and West CKD Areas are shown on Figure 1-1.

1.1 Site Location and Description

1.1.1 Location

The LTB CKD Release Site (the Site) is located along five miles of shoreline on Little Traverse Bay of Lake Michigan (Figure 1-1) and is approximately five miles west of the City of Petoskey in Resort Township, Emmet County, Michigan (Township 34N, Range 6W, Sections 2 through 10). The Seep 1, Seep 2, and West CKD Areas are located in Sections 8 and 9.

1.1.1.1 Seep 1 CKD Area Description

The Seep 1 CKD Area includes a covered stockpile of CKD and the undeveloped rocky beach area north of the pile as shown on Figure 1-2. The Seep 1 CKD Area is currently owned by Bay Harbor Golf Club, Inc. (which owns and operates a golf course on the Site), CMS Energy, and private property owners. Golf course fairway and rough areas and golf course drainage systems have been constructed over the CKD pile. The Seep 1 CKD Area is bounded by Lake Michigan on the north and by developed and undeveloped residential properties to the west, east, and south. An unnamed creek that discharges into Lake Michigan borders the Seep 1 CKD Area on the east. Additional information on the Seep 1 CKD Area is presented in the RI report (Barr, 2009).

1.1.1.2 Seep 2 CKD Area Description

The Seep 2 CKD Area includes a covered stockpile of CKD and the developed and undeveloped rocky beach area north of the pile as shown on Figure 1-2. The Seep 2 CKD Area also encompasses sub-areas identified as the Pine Court, Guard Rail, and Seep 2 Seep Areas which are locations of the

Interim Response (IR) collection drains. The area is currently owned by Bay Harbor Golf Club, Inc, CMS Energy, private property owners, and Bay Harbor Company. Golf course fairways and rough areas and golf course drainage systems have been constructed over the CKD pile. The Seep 2 CKD Area is bounded by Lake Michigan on the north, developed and undeveloped residential properties to the west, east, and south, and Coastal Ridge Drive and the Seep 1 CKD Area to the east. A wetland area is located to the southwest of the Seep 2 CKD Area. Additional information on the Seep 2 CKD Area is presented in the RI report (Barr, 2009).

1.1.1.3 West CKD Area Description

The West CKD Area includes a covered stockpile of CKD and the undeveloped rocky beach area north of the pile as shown on Figure 1-2. The West CKD Area is currently owned by Bay Harbor Golf Club, Inc and CMS Energy. A golf course fairway and rough areas and golf course drainage system have been constructed over the CKD pile. The West CKD Area is bounded by Lake Michigan and undeveloped residential lots on the north, developed and undeveloped residential properties to the west and south, and the golf course club house to the east. An unnamed creek flows from U.S. Highway 31 north through a constructed pond located south of the West CKD Area. The pond drains into Lake Michigan along the east side of the West CKD Area. Additional information on the West CKD Area is presented in the RI report (Barr, 2009)

1.2 Regional Geologic Setting

Available literature indicates that the native geology in the vicinity of the LTB CKD Release Site consists of thinly bedded (1 to 4 inches) to very thickly bedded (>3 feet) limestone or shale bedrock overlain by a mantle of weathered bedrock and/or unconsolidated deposits of varying thickness. The unconsolidated deposits are either glacial or lacustrine silty clay to sandy gravel sediment material (Richmond et al., 1984). Rocks of the Devonian-age Traverse Group (primarily limestone with some shale) make up the uppermost bedrock unit in the vicinity of the LTB CKD Release Site (Kesling et al., 1974 and Milstein, 1987). The Traverse Group is the uppermost unit of the Silurian-Devonian regional aquifer. A map of the extent of the Silurian-Devonian aquifer is shown in Olcott (1992).

Well logs for water wells outside of the Development obtained from a public database were used to prepare regional geologic cross sections. Locations of these cross sections are shown on Figure 1-3. As shown on Figures 1-4 through 1-9, the depth to bedrock varies considerably in the area to the south of the Development. Unconsolidated sand, gravel and clay overlie the bedrock. These cross sections also indicate that the bedrock consists mainly of limestone.

2.0 Model Objectives

There were two primary objectives for the Development groundwater modeling effort. These objectives were (1) to develop a tool to assist in the evaluation and understanding of the complex hydrogeologic setting of the Site, and (2) to provide a tool for evaluating interim response (IR) and final remedial options for the Development.

Secondary objectives were developed to guide the model selection and construction. For example, due to the heterogeneity of the aquifer system at the site, it was specified that:

1. The groundwater flow field produced by the model must fit as well as possible the available hydraulic head and other hydraulic data, including operational data from the existing interim remedial measures,

2. The model must be capable of simulating the unsaturated zone described in Sections 3.0 and 5.0 that develops seasonally beneath parts of the Development,

3. The model must be applicable in assessment of how changes in the water level in Lake Michigan might affect remedial elements, and

4. The model must provide the ability to simulate seasonal (winter and summer) conditions in the groundwater flow system (e.g., pumping from the Petoskey municipal wells)

In order to achieve these objectives, a regional-scale groundwater flow model and three local-scale groundwater flow models were constructed using publicly-available data along with Site-specific data collected as part of IR and RI activities (Barr, 2009).

3.0 Hydrogeologic Characterization

Extensive field investigations were conducted at the Development to characterize the hydrogeology. These investigations are documented in Sections 3.0 and 4.0 of the RI report (Barr, 2009). The field investigations included:

- In November/December 2004 a non-intrusive geophysical investigation was conducted to evaluate the locations and depths of CKD and identify bedrock features (e.g., topographic changes, potential fracture zones, and potential changes in the stratigraphic profile). The geophysical investigation included Electromagnetic Induction (EM), Direct Current Resistivity Imaging (DCR), Multi-channel Analysis of Surface Waves (MASW), and Seismic Refraction (Refraction).

- In fall 2004, geologic mapping of bedding planes and fractures was conducted.

- In 2005 and 2006 the first phase of intrusive investigations was conducted. The initial investigation locations were selected based on the geophysical investigation results. As the first phase of the intrusive site investigation proceeded, additional boring locations were selected. Soil borings were installed using the direct-push drilling method. Bedrock borings were advanced and monitoring wells were installed using the rotasonic drilling method. Borehole geophysical logging was conducted in bedrock borings. Aquifer testing via slug tests and small-scale packer pumping tests was completed.

- In 2007 a second phase of investigation activities was conducted. Investigation activities included surface geophysical surveys, soil and bedrock borings, aquifer testing via small-scale packer testing as well as short-duration pumping tests using existing monitoring wells, borehole geophysical logging, and monitoring well installation.

Primary objectives for the soil borings were to provide data for confirming/refining the extent of CKD and depth to bedrock, characterizing the CKD/unconsolidated material above the bedrock and to allow installation of temporary wells for performing slug tests (if saturated unconsolidated material was encountered). Objectives for the bedrock borings included obtaining additional information on the extent of CKD and depth to bedrock, obtaining samples for visual characterization of the bedrock beneath the Development, providing locations for borehole geophysical logging and aquifer testing, and construction of monitoring well nests.

3.1 Geology

Data collected during the intrusive site investigation activities were used along with results of the surface geophysical surveys and geologic mapping, and available public information to construct a conceptual geologic model of the Development.

Geologic mapping of exposed bedrock in the vicinity of the Development indicates that the Traverse Group in the vicinity is comprised primarily of limestone, with some shaley limestone or shale beds. As measured at outcrops in the vicinity of the Development, the bedding is generally horizontal to gently dipping (up to about 2 to 3 degrees). To the east of the Seep 1 CKD Area (Figure 1-1), the dips of limestone beds in an outcrop on the south side of Bay Harbor Lake were measured at up to 5 to 10 degrees to the northeast and southwest. These measurements indicate the presence of a subtle anticlinal structure with its fold axis trending northwest to southeast.

The geologic mapping also indicates that both horizontal to nearly horizontal fractures parallel to bedding planes and high angle fractures (dips of 70° or more) are present in the limestone bedrock (see Figure 4-9 of Barr, 2009). Two main strike azimuths were observed for the high angle fractures: approximately 300° and approximately 60°. Spacing of the high angle fractures is generally consistent between outcrops and ranges from approximately 1 to 2 feet. In addition, both horizontal/near horizontal and high angle fractures were identified in the acoustic televiewer logs from the bedrock borings at the Development. The average fracture density among all boreholes is 1.2 factures/foot (see Section 4.4.2, Table 4-2, and Figures 4-10a to 4-10i of Barr, 2009).

Several geologic cross sections through the Development are presented in the RI report (Barr, 2009). The stratigraphy beneath the Development consists of topsoil and unconsolidated sand, silt, gravel and/or CKD overlying bedrock. The bedrock consists mainly of limestone with some interbedded shaley limestone, shale or mudstone. There is also a locally significant unnamed shale layer referred to as the "marker shale." The marker shale underlies most of the Seep 2 CKD Area as well as portions of the Seep 1 and West CKD Areas. The topography of the bedrock surface is shown on Figures 3-2a to 3-2c. The estimated extent of the marker shale beneath the Development is shown on Figures 3-3a to 3-3c.

It is difficult to correlate the marker shale very far south of the Development due to the lack of detail in the regional logs. The only outcrop near US 31 where strikes and dips were measured was the quarry face near the entrance to the Bay Harbor commercial district (approximately a half-mile east of the Development).

3.2 Hydrology/Hydrogeology

3.2.1 Climate and Surface Hydrology

While the climate in the region surrounding the Development is moderated by the adjacent lake, annual temperatures range from as high as 99 degrees Fahrenheit (°F) to as low as -19 °F seasonally. The annual average maximum temperature is 53 °F and the annual average minimum is 36 °F based on 1952 to 1980 measurements recorded at the Petoskey, Michigan meteorological station (Michigan State Climatologist, 2005). The region receives between 27 and 35 inches of precipitation annually, based on National Oceanic and Atmospheric Administration (NOAA) records for the 30-year period 1970 to 2000, measured at Alpena, Houghton Lake, and Grand Rapids, Michigan (NOAA, 2005).

Based on historical records, the greatest amount of precipitation occurs from July through November. The lowest precipitation months are typically February and March. During December through early March the ground is generally frozen and, therefore, the majority of precipitation infiltration to groundwater must occur during the period April through November. Recharge to the water table aquifer/perched groundwater would be expected to vary based on slope, irrigation rates, soil type, cover, evapotranspiration, and precipitation. The published recharge rate in the general vicinity of the Development ranges from 4 inches/year to 14 inches/year (http://gwmap.rsgis.msu.edu/start.htm).

As discussed in Section 4.3.2.3 of the RI report (Barr, 2009), taking the average annual precipitation value of 31 in/yr minus the annual average ET (19.1 in/yr), minus the estimated regional runoff value (1.5 in/yr in the region) yields an estimate of 10.4 in/yr for recharge to the groundwater system, which is within the range of values estimated by the State of Michigan.

Inspection of the quadrangle topographic maps (USGS, 1983a; b; c) indicates that there is a surface water divide located approximately one-half mile south of the LTB CKD Release Site at an approximate elevation of 790 feet above mean sea level (ft. MSL). Surface water south of this divide flows generally south-southwest toward Walloon Lake, which has a surface elevation of approximately 680 ft. MSL. Surface water north of the divide flows generally north toward Lake Michigan, which has a surface elevation of approximately 578 ft. MSL.

There are two unnamed creeks in the vicinity of the Development [see Figures 3-5a and 3-5b of the RI report (Barr, 2009)]. The conceptual model, which is based in part on groundwater elevations measured at the Development, assumes that these creeks are generally surface expressions of the water table beneath the Development.

3.2.2 Hydrogeology

Gradient

The depth to groundwater across the LTB CKD Release Site is variable and the horizontal hydraulic gradient is typically oriented towards Little Traverse Bay. The horizontal hydraulic gradient steepens toward Little Traverse Bay, and ranges from approximately 0.04 to 0.07 feet/foot (average value of 0.06 feet/foot), based on groundwater elevations measured at the Site between 2005 and 2008. Groundwater elevations measured in monitoring wells at the Development are presented in the RI report (Barr, 2009).

Investigation results indicate that in some portions of the Development the CKD is saturated by groundwater while in other portions of the Development the water table is below the bottom of the CKD.

Groundwater occurs above the marker shale beneath the Seep 2 CKD Area. The piezometric surface of this groundwater is seasonally up to 30 or more feet above the piezometric surface below the marker shale as the water levels below the shale are depressed during the summer and fall. Comparison of Figures 4-20a (March 2007) and 4-17a (July 2006) of Barr (2009) show that the groundwater is not perched in the spring, but it is perched in the summer. In other words, the water above the marker shale in Seep 2 is seasonally perched.

During the RI field work, no aquifer tests were conducted within the shale. However, borehole geophysical logging (including flow logging) was conducted in boreholes that extended beneath the marker shale. In addition, long term water level monitoring showed differing responses above and below the shale to municipal well pumping.

Whether or not perched groundwater has developed in a given area, the directions of groundwater flow above and below the marker shale are likely different due to resistance to vertical flow through this unit.

Regional Discharge Zone

Little Traverse Bay is the regional discharge zone for groundwater in the vicinity of the Development. Groundwater discharge to lakes is typically observed to be concentrated in the near-shore zone (e.g., see McBride and Pfannkuch, 1975).

Effect of High Capacity Water Supply Wells

High capacity water supply wells have created localized sinks for groundwater and seasonally alter the groundwater flow patterns beneath much of the Development. The City of Petoskey operates three municipal water supply wells (Petoskey Well 3, Petoskey Well 4, and Petoskey Well 5) located near the southern boundary of the Development (Figure 3-4). Operation of these high capacity municipal water supply wells has produced the following conditions in the aquifer beneath the Development:

1. The Petoskey municipal wells near the Development cycle so frequently that they can be considered as operating at steady state over periods of days to weeks. Seasonally, the discharge varies markedly (see Section 5.3.1.5 for additional discussion).

2. The piezometric surface of the aquifer beneath the marker shale typically drops below the marker shale during the summer months resulting in seasonally unsaturated conditions beneath the marker shale.

3. During periods of high pumping from the nearby municipal water supply wells the horizontal groundwater flow direction beneath portions of the Seep 2 CKD and West CKD Areas is towards Petoskey Well 5.

4. Groundwater elevations measured in monitoring wells at the Development show both vertical downward gradients and vertical upward gradients. This variation is likely due to the superposition of the affects of local infiltration, regional flow/discharge, and the temporal variations in pumping of the nearby Petoskey municipal water supply wells.

Bedrock Flow Characterization (Heterogeneous Porous Medium)

Based on the available information, it is appropriate to approximate the groundwater flow system at the scale of the Development and the sub-areas (i.e., the Seep 1 CKD Area, the Seep 2 CKD Area, and the West CKD Area) by modeling the bedrock aquifer as a heterogeneous porous medium rather than explicitly modeling individual fractures/fracture zones. This is a critical aspect of the modeling, so it is repeated frequently in this report.

Quantitative methods for evaluating the flow of water through “porous media” are referred to as the continuum model in ASTM D5717-95e1 (ASTM, 2005). Most methods for developing hydrogeologic conceptual models are based on the continuum model. Geologic materials such as sand and gravel [where the void spaces (primary porosity) occur between the grains and are extensively

interconnected] are referred to as porous media. However, geologic units where water is transmitted through secondary porosity (e.g., bedding plane fractures and higher angle fractures) can also be evaluated using methods based on the continuum model if the fractures are dense enough and sufficiently interconnected and the scale of the site is sufficiently large with respect to the distance between fractures. The discrete flow model referred to in ASTM D5717-95e1 is used to evaluate flow through secondary porosity that does not meet these conditions (e.g., karst areas).

The following Site data support the interpretation that the bedrock aquifer can be modeled as a heterogeneous porous medium using methods based on the continuum model:

1. The results of the geologic mapping and surface and borehole geophysical work all indicate that the bedrock beneath the Development is densely fractured throughout the depths that have been investigated (Barr, 2009). The upper portion of the bedrock beneath the Development tends to be weathered and the affects of weathering diminish somewhat with depth. However, the fracture density in the bedrock does not decrease noticeably with depth (see Section 4.4.2 of Barr, 2009).

2. No visible indications of large-scale karst features were observed on or near the Development; however, the Development is located in a region known to have karst features (e.g., Olcott, 1992).

3. "Potential conduits" were identified and evaluated as part of the RI to determine if significant flow zones are present at the Site. See Section 4.6.4.5 of the RI report (Barr, 2009) for detailed discussion of this analysis. No significant flow zones or conduits were identified.

4. As shown on Figure 4-24 of the RI Report (Barr, 2009), hydraulic conductivity measurements from the Site are approximately log-normally distributed. ASTM Standard D5717-95e1 notes that "in porous-medium-equivalent settings, the distribution of hydraulic conductivity … tends to be approximately log-normal."

4.0 Modeling Software and Methods Selection

Software evaluation, the modeling software selected for this project, and specific modeling methods used with that software are discussed in this section. The finite element modeling software FEFLOW and the finite difference modeling software MODFLOW, were considered for the groundwater modeling of the Development portion of the Site.

4.1 Considerations for Modeling

Anisotropy

Groundwater flow systems in fractured rock are typically anisotropic in all three dimensions. Vertical anisotropy arises in settings like the bedrock at the Site due to predominance of bedding plane fractures creating a higher hydraulic conductivity parallel to the bedding than perpendicular to it. In addition, shale layers at the site create sub-horizontal layers with very high vertical anisotropy. Vertical anisotropy is detected using nested wells and readily simulated using either of the modeling software programs considered.

Anisotropy within hydrostratigraphic layers due to lower resistance to flow along the higher-angle fractures is not easily detected using hydraulic heads alone. This anisotropy can cause flow directions to differ significantly from the direction of hydraulic gradient and is readily simulated using most numerical methods.

Variable Saturation

Variable saturation occurs at depth in the aquifer system. A perched system has developed in areas of the site that varies in size depending on the rate of regional pumping. From a modeling perspective, this situation is exacerbated by the fact that the unsaturated zone must be simulated in a deeper model layer or layers. There are ways to address variable saturation with both of the modeling methods considered (see Section 4.2.2).

Site Configuration

Elongation of the site and many of the remedial elements parallel to the shoreline of Little Traverse Bay creates issues for any regional-extent flow model. The concentration of required model detail in the zone along Little Traverse Bay dictated either highly irregular model grids/meshes and/or telescopic mesh refinement (TMR; see Anderson and Woessner, 1992; p. 139-142). The Site

configuration could be addressed using either of the modeling software packages evaluated for this work.

Agency Preference

Regulatory agency reviewers of the groundwater modeling for the East CKD Area in the LTB CKD Release Site, which was done using the finite element modeling software FEFLOW [see Barr (2006)], indicated a preference for MODFLOW for the Development groundwater model.

4.2 Groundwater Flow Modeling

4.2.1 Modeling Software Selection

Given the aspects of the modeling problem, the applicability of the modeling codes to these types of problems, feedback from the U.S. EPA and Michigan Department of Environmental Quality (MDEQ) staff, and the experience of the modeling team, MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) developed by the United States Geological Survey (USGS) was selected as the groundwater modeling software. MODFLOW is widely used for groundwater modeling applications. This finite difference modeling software is most suited to modeling groundwater flow in porous media such as sand and gravel and bedrock aquifers in which groundwater flows through intergranular pore spaces rather than fractures. As noted above, saturated conditions occur in both portions of the CKD and other unconsolidated material and in the bedrock beneath the Development. As discussed below in Section 5.0, Site data indicate that, at the scale of the Development and the sub-areas, the bedrock aquifer can be simulated as an equivalent porous medium.

An extensive conduit flow system would have been the clearest reason to choose FEFLOW over MODFLOW. The Site data indicate that it was not necessary to use modeling software that can explicitly model flow in individual fractures.

MODFLOW-96 (Harbaugh and McDonald, 1996) was selected over newer versions of MODFLOW because newer packages that have been added since MODFLOW-96 was issued were not needed and because it was anticipated that the method for modeling dry cells that is available for MODFLOW-96 (and not in subsequent versions) would be needed.

4.2.2 Dry Cell Approximation

The standard MODFLOW method for handling of dry cells was not used for the automated calibration because in this method if the heads in model cells that contain observation points drop

below the layer bottom during a simulation, the cell is declared dry and the modeled value of the water level in that cell is not available. An automated calibration that includes one or more observations that depend upon the dry cell would fail because the sensitivity of that observation cannot be calculated. Resaturation based on surrounding heads typically leads to oscillation and poor model convergence. Further, simulation of the unsaturated zones that are observed beneath perched zones would likely have caused an upward propagation of dry cells throughout the parts of the model representing the perched zones.

Thus, two alternate approaches for approximating dry cells with MODFLOW-96 were tried:

1. The first alternate approach, referred to as "dry cell correction", was developed by Doherty (2001). This method addresses model cells where heads fall below the layer bottom by reducing layer thickness to a nominal value and reducing hydraulic conductivity to extremely small values. The reduction in hydraulic conductivity is to account for variable saturation. The reduction is not physically based, but it allows the application of MODFLOW to situations in which a rigorous assessment of the influence of unsaturated flow is not required or warranted.

2. The second alternate approach is based on the approach of Hill (1998) for modeling unconfined aquifers with confined layers of appropriate layer thickness. In this approach, as long as the model layer thicknesses are consistent with the saturated thickness of the aquifer layers the confined model will be a useful approximation of the unconfined system. In this approach, the aquifer system is modeled using confined (fixed transmissivity) layers rather than unconfined/convertible (variable transmissivity with varying saturated thickness) layers.

Preliminary "test" modeling indicated that the dry cell correction of Doherty (2001) could be used to simulate the creation of an unsaturated zone at depth (e.g. the condition observed beneath the marker shale) in a MODFLOW model. However, the dry cell correction method proved too non-linear to use in automated calibration of the highly parameterized models of the Development. The differences between measured and observed hydraulic heads (i.e., head residuals) were not being reduced to acceptable levels. Consequently, the decision was made to model the aquifer system using confined (fixed transmissivity) layers rather than unconfined/convertible (variable transmissivity with varying saturated thickness) layers.

Modeling unconfined aquifers as confined layers with appropriate layer thickness is a recommended approach for reducing model run times (Hill, 1998, p. 67). So long as the model layer thicknesses are consistent with the saturated thickness of the aquifer layers and there are no short-term transient effects that change the saturated thickness, the confined model is a useful approximation of the unconfined system.

While calibrating the TMRs, a two-step method suggested by Harbaugh et al. (2000, p. 5-18) was used. The confined model was initially calibrated using the ground surface as the top of layer 1. After the initial calibration, the thickness of layer 1 was modified as follows:

- If the simulated water level was below the bottom of the layer, a nominal thickness of 0.05 meters was used for layer 1.
- If the simulated water level was above the bottom of the layer but below the top, the top was reset to the simulated water level.
- If the simulated water level was above the top of the layer, no change was made to the layer thickness.

After the thickness of layer 1 was adjusted, the model was recalibrated. This allowed the confined models to simulate the saturated thickness of layer 1 as accurately as possible.

Using confined layers in MODFLOW, heads can drop below the bottom of a model cell and the saturated thickness and horizontal and vertical hydraulic conductivity are not reduced to reflect the affects of variable saturation. However, if the calibrated value of horizontal hydraulic conductivity that goes into the transmissivity calculation and the vertical hydraulic conductivity that goes into the leakage calculation are representative of variably-saturated material then the method is appropriate for the Development. As noted in Section 3.2.2, the Development has unconfined aquifer layers and unsaturated zones at depth.

Through the process of calibration, horizontal and vertical hydraulic conductivity parameter values were produced that simulate the distribution of saturated and unsaturated materials to an acceptable degree. This distribution is shown schematically in a vertical stack of model cells in Figure 4-1.

Perched hydraulic heads are defined as heads that are above the base of a layer in a position where, at some greater depth in the model, heads are below the base of a deeper model layer such as layers 1 and 2 in Figure 4-1. Perched heads may be within the layer such as for layer 1 in Figure 4-1, or above the top of the layer, indicating confined conditions, such as for layer 2 in Figure 4-1. Unsaturated cells are defined as cells in which the modeled heads are below the bottom of the layer, such as layers 3 and 4 in Figure 4-1. The water table is defined as the simulated hydraulic head in the highest model layer that has a hydraulic head above the base of the layer of interest and below which no heads are below the base of a deeper model layer. In other words, the model indicates continuous

saturation within the layers below the water table. Using this definition, it is possible for the "water table" to be above the top of the model. It would be more appropriate to refer to water levels above the top of the model as defining the piezometric surface, but this condition is rare in the Development modeling. The water table occurs in layer 5 in Figure 4-1.

In areas of the models where the layers are unsaturated, the modeling method we used does not explicitly account for the change in governing equation of flow, but the effective model parameters approximate the operation of a more rigorous approach. Examples are described in Sections 6.2.2 and 6.2.3. Near the interim response drains, which were the focus of the modeling initially, this assumption of confined layers is the most valid since there are no known unsaturated zones at depth and the model layer thicknesses approximate the saturated thicknesses.

4.2.3 Model Construction – Telescopic Mesh Refinement

The selected approach includes developing a regional-scale model and constructing separate local-scale models for the Seep 1, Seep 2, and West CKD Areas using telescopic mesh refinement (TMR) that have variable grid spacing (Anderson and Woessner, 1992; p. 139-142). As discussed below in Section 5.0, boundary heads for the TMR models were taken from the regional-scale model.

The TMR method was developed to address the problem of getting adequate discretization of site features while capturing the influence of relatively distant hydraulic boundaries. For example, the following quote from Anderson and Woessner (1992, p. 139), describes the process we used for setting boundary conditions for our TMR models.

> "The approach consists of designing a nested set of grids … so that the site grid, which has the finest nodal spacing, is embedded in a regional grid with coarser nodal spacing. The solution of the regional model is then used to define boundary conditions for the site model."

This report does not describe any scenarios involving further modifications of the remedial measures at the Development, however, any predictive simulations that involved significant changes in hydraulic stresses in any of the model domains would first be simulated in the regional model. This new regional model solution would be used to update the perimeter specified head boundary conditions of the TMR models. Then the changes in hydraulic stress would be simulated in the appropriate TMR model or models. Updating boundary conditions for a TMR model with a regional model during predictive simulations is described by Anderson and Woessner (1992, p. 139-142).

The model pre- and post-processing software Groundwater Vistas (ESI, 2004) was used for constructing the regional and local models and generating the MODFLOW input files.

4.3 Flow Model Calibration

Groundwater flow model calibration was completed using the automated inverse optimization program PEST (Watermark, 2005; Watermark, 2008a). PEST offers a number of methods for parameterizing (i.e., defining distributions of properties such as hydraulic conductivity, recharge, and storage) and calibrating numerical models. Based on the objective that the model must fit as well as possible the available hydraulic head and other hydraulic data, a spatial parameterization technique known as pilot points (Doherty, 2003) was used. In this project, the pilot points are sets of locations within the model at which the horizontal and vertical hydraulic conductivity are specified. The values from the pilot points are interpolated to non-pilot point nodes in the grid through kriging using the utility FAC2REAL (Watermark, 2008b) (see Appendix E). The resulting hydraulic conductivity arrays were used in both the 9/14/2006 and 1/02/2007 scenarios. In other words, the same hydraulic conductivity distribution was used for both scenarios. In addition, the same layer thickness array was used for both scenarios.

Pilot point parameterization can lead to very complex vertical and horizontal hydraulic conductivity fields with values that vary literally from cell to cell, in some cases by orders of magnitude. These heterogeneous hydraulic conductivity fields cause variations in maps of hydraulic head in plan view, changes in flow direction with depth in the model, and variations in plots of water levels in cross section that would not occur in more homogeneous conductivity fields. For example, these maps and cross sections may exhibit abrupt changes in hydraulic gradients and non-monotonic slopes on the water table. The variations in flow direction are caused by convergence of flow toward portions of the model with higher hydraulic conductivity.

If the value of horizontal and vertical hydraulic conductivity is to be estimated at many of the pilot points, this method can introduce hundreds of parameters to a model calibration. This gives the calibration process the ability to match observations from an extremely heterogeneous system. In order to constrain these parameter values and improve the stability of the calibration, a method known as regularization (Doherty, 2003; Watermark, 2005; Watermark, 2008a) was applied.

Regularization can take many forms but, in general, it supplies information to PEST about parameter values that are not otherwise constrained. This information is sometimes referred to as “soft knowledge” because it is not specific to any location. For example, the regularization information

may indicate the differences between each pair of pilot points should be zero regardless of what the values are. This would tend to reduce the introduction of heterogeneity into the hydraulic conductivity field and provide stability if the observations used in the calibration are not sensitive to some of the pilot point values. In this project, the regularization of values for the horizontal hydraulic conductivity of the pilot points consisted of specifying that unconstrained pilot point horizontal hydraulic conductivity values should equal the mean value from the Site data available at the time the models were constructed (3.03 ft/day or 0.924 m/day). For the regional model calibration, the regularization of values for the vertical hydraulic conductivity of the pilot points consisted of imposing a penalty if the value at each pilot point exceeded the horizontal hydraulic conductivity value. For the TMR models, the regularization of values for the vertical hydraulic conductivity of the pilot points consisted of specifying that unconstrained pilot point vertical hydraulic conductivity values should equal $1/10^{th}$ of the mean value from the available Site data (0.303 ft/day or 0.0924 m/day). Despite this specification of a preferred vertical anisotropy of $1/10^{th}$, the calibrated vertical anisotropy was much higher in some cases. This is considered appropriate given the observed predominance of horizontal fractures in the bedrock (see Figure 4-9 of Barr, 2009).

In regularized inversion, PEST is trying to reduce the sum of squared, weighted differences between observations and regularization information and model output, and current parameter values. The sum of squared, weighted errors is called the objective function (Φ) and is defined in Equation 1.

$$\Phi = \Phi_m + \mu\Phi_r \qquad \text{Equation 1}$$

where:

Φ_m is the measurement objective function,

μ is the regularization weight factor, and

Φ_r is the regularization objective function.

Early in the calibration run, when the stabilizing effect of the regularization constraints are most needed, they are fairly rigidly enforced. Any values that change contrary to these constraints do so because there is a distinct advantage in terms of decreasing the measurement portion of the objective function. As the optimization progresses and the regularization weight factor decreases, parameters formerly constrained by the regularization constraints may likewise vary in favor of more modest

lowering of the measurement objective function, but those for which little advantage exists for change will still be bound by the constraints.

Finally, a calibration method designed for highly parameterized systems known as singular value decomposition assist (SVDA or SVD Assist; see Tonkin and Doherty, 2005) was applied. This method uses singular value decomposition to define super parameters that consist of linear combinations of each parameter in the base model. The linear combinations are defined by the eigenvectors associated with each singular value. The super parameters are ranked according to the relative magnitude of their corresponding singular value. Using SVDA can increase the stability of the inversion and dramatically reduce the number of model runs required for calibration.

4.4 Particle Tracking

The post-processing software MODPATH (Pollock, 1989; 1994) was used to compute groundwater flow paths for the groundwater flow simulations done with MODFLOW. MODPATH is a particle tracking post-processing package that was developed by the USGS to compute three-dimensional flow paths using output from steady-state or transient ground-water-flow simulations done using MODFLOW (Pollock, 1994).

MODPATH was not designed to handle situations in which the hydraulic head is below the bottom of the layer. However, the user can specify zones (i.e., groups of cells in which the heads are below the bottom of the cells) in the model at which MODPATH will terminate particle traces. With this approach, MODPATH can be used to evaluate flow paths in cells where hydraulic heads are above the bottom of the associated model layer.

5.0 Model Conceptualization and Construction

Hydrogeologic characterization of the Development is briefly described above in Section 3.0. Detailed discussion of the Site investigation is presented in the RI report (Barr, 2009). This section will discuss the conceptualization and construction of the three-dimensional groundwater flow models for the Development.

Groundwater modeling for the Development included the development of a regional-scale model that extends well beyond the boundary of the Development and one local-scale model for each of the sub-areas. Each of these models is a steady-state model consisting of two scenarios; one to represent late-summer conditions with high regional groundwater withdrawal and one to represent mid-winter conditions with low regional groundwater withdrawal. The regional-scale model was used to determine constant head boundary conditions for the local scale models and to evaluate regional-scale effects such as pumping from the Petoskey municipal wells near the Development.

5.1 Hydrogeologic Conceptual Model

A hydrogeologic conceptual model (referred to hereafter as "conceptual model") captures the understanding of how groundwater is transmitted beneath a specified area. The conceptual model for the Development formed the basis for selection of methods which can be used to evaluate remedial alternatives at the Development. An accurate conceptualization of the groundwater flow system is critical because this conceptualization is the basis for selecting the methods for evaluating remedial alternatives. The types of information used in the assessment and the mathematical basis of the tools used will differ depending on the findings of the conceptualization. This section describes the conceptual model for the Development.

The conceptual model was developed based on available regional information and Site-specific data produced during the Site remedial investigation. Special considerations to account for the type of bedrock and other conditions at the Site are described below. The data evaluated in forming the conceptual model are listed in Table 5-1, summarized above in Section 3.0 of this document, and presented fully in the RI Report (Barr, 2009). The following aspects of the groundwater flow system are included in the conceptual model:

- Boundary conditions – including Lake Michigan (Little Traverse Bay), water supply wells, streams, Lake Charlevoix, Walloon Lake, and other features (described in Section 5.3.1.3 below)

- Causes of perched groundwater (described in Section 4.6.1.3 of the RI report (Barr, 2009).

- Recharge to the aquifer system (described in Section 4.6.4.1 of the RI report (Barr, 2009).

- Aquifer porosity – causes, extent, and interconnection (described in Section 4.6.1.4 of the RI report (Barr, 2009).

- Aquifer anisotropy (described in Section 4.6.1.5 of the RI report (Barr, 2009).

- Aquifer heterogeneity (described in Section 4.6.1.6 of the RI report (Barr, 2009).

- Mechanisms of flow in the aquifer (described in Section 4.6.4 of the RI report (Barr, 2009).

One of the main objectives in the formulation of the conceptual model was to determine whether continuum modeling methods could be applied to this Site. Two circumstances under which continuum modeling methods cannot be applied to conduit flow systems are:

1. A system that is dominated by conduit flow because Site-specific knowledge of the orientation and interconnection of the conduits is required. This knowledge is gained primarily through tracer testing.

2. Systems in which Darcy's law is not applicable to flow in the conduits. This law, which allows rates and directions of flow to be inferred from hydraulic conductivity and hydraulic gradient measurements, is not applicable if flow in the conduits is turbulent, which is typically the case.

Differentiation between fractured-rock and karst aquifers can be difficult because the conduits that transmit the majority of water through the aquifer may be as small as a few millimeters in size (ASTM, 2005, p. 444). The goal in formulating this conceptual model was to determine whether such conduits could be identified, particularly in the vicinity of the existing and potential remedial elements because such conduits could influence the effectiveness of these remedial elements.

For a fractured-rock aquifer to be considered porous-medium-equivalent, "the observed vertical and horizontal fractures should be numerous, the distance between the fractures should be orders of

magnitude smaller than the size of the site under investigation, and the fractures should show appreciable interconnection" (ASTM, 2005, p. 442). The borehole logging provides a measure of the fracture density to the extent that these fractures intersect the vertical boreholes. Fracture density in outcrops was also mapped in the field.

Development of a conceptual model for the Site consisted of addressing the following issues. Findings are summarized in the list.

- **Where does the site fit in the spectrum from a fractured-rock aquifer to a karst aquifer?**
  Very few of the features found in karst terrains were detected at the Site. Although the bedrock consists primarily of limestone, development of tertiary porosity by solution enhancement of the abundant secondary porosity is apparently very limited. The Site is inferred to fall at or near the fractured-rock end of this spectrum.

- **What influence do individual fractures and conduits have on the flow system?**
  Potential conduits were identified, but few, if any are extensive enough to have been encountered in multiple boreholes, particularly in the vicinity of existing and proposed remedial elements. All of the potential conduits identified are low angle features (dips of 0-13 degrees) that are inferred to represent bedding plane partings. Therefore, groundwater flow in the bedrock is inferred to occur predominantly through the dense fracture system (i.e., flow is not dominated by isolated conduits).

- **Have conduits (tertiary porosity) developed within the bedrock to the extent that they must be explicitly accounted for in evaluating and designing remedial elements for the site?**
  None of the potential conduits identified were indicated by multiple lines of evidence. For example, what appears to be a conduit based on borehole geophysical logging also occurs in an interval that, when pumped, was surrounded by zones that did respond to the pumping. This suggests that interconnection of the water-transmitting fractures is sufficient that an equivalent porous medium approach is appropriate.

- **Can the site be modeled using an equivalent porous medium approximation?**

  The fracture density, packer testing results, fracture projection results, and log-normal hydraulic conductivity distribution of data from the Development all support the assumption of porous-medium-equivalence.

5.2 Model Conceptualization

In the vicinity of the Development, an upland area overlooks Little Traverse Bay. Available topographic information (e.g., USGS, 1983 a; b) indicates that the ground surface slopes relatively steeply northward (toward Little Traverse Bay) from a high of approximately 805 ft MSL (245 m MSL) down to the vicinity of U.S. Highway 31, which is at an elevation of approximately 680 ft MSL (207 m MSL). North of U.S. Highway 31, the maximum elevation of the top of the CKD pile in the Seep 1 CKD Area is approximately 660 ft MSL (201 m MSL); the maximum elevation of the top of the CKD pile in the Seep 2 CKD Area is approximately 709 ft MSL (216 m MSL); and the maximum elevation of the top of the CKD pile in the West CKD Area is approximately 634 ft MSL (193 m MSL). The topography slopes northward from the CKD piles down to Lake Michigan, which is at a mean elevation of 577.5 ft MSL (176.01 m MSL).

As discussed above in Section 3.0 and in the RI report (Barr, 2009, Section 4.4.2), inspection/ mapping of bedrock outcrop in the vicinity of the Development and borehole geophysical logging indicate that the limestone bedrock is fractured with fracture planes having both horizontal/near horizontal and high angle/near vertical dip angles. Generally, little difference in degree of fracturing could be discerned across a single outcrop although in some areas, outcrops were somewhat more broken than in other areas. Inspection/mapping of bedrock outcrops indicated that the high angle fracture spacing is generally approximately 1 to 2 feet. Bedrock fractures identified by geophysical logging in boreholes drilled in the Development exhibit fracture orientations consistent with those identified during bedrock outcrop mapping. In addition, fracture densities determined from the geophysical logging results are consistent with the fracture densities observed in outcrop. Thus, it is reasonable to assume that the outcrops in the vicinity of the Development are likely generally analogous to the subsurface bedrock with respect to fracturing.

Borehole geophysical logging also suggests that, at the scale of an individual borehole, groundwater movement is mainly through the horizontal/near horizontal fractures/fracture zones. As discussed above, for a fractured-rock aquifer to be considered porous-medium-equivalent for the purpose of modeling, the distance between fractures should be orders of magnitude less than the size of the site

under investigation and the fractures should show appreciable interconnection. While available information suggests that groundwater flow is mainly through fractures/fracture zones, the extent of the fracturing is such that groundwater flow at the scale of the Development and the sub-areas within it can be modeled using the equivalent porous medium approach.

High capacity water supply wells have created localized sinks for groundwater and seasonally alter the groundwater flow patterns beneath much of the Development. In the regional groundwater flow model, Little Traverse Bay (the regional groundwater discharge zone) is simulated with a constant head boundary condition.

Available information on groundwater elevations suggests that a groundwater divide is present to the south of the Development. South of this divide, groundwater flows toward Walloon Lake and north of the divide groundwater flows toward Lake Michigan. Walloon Lake was modeled with a lake stage of 685.76 ft MSL (see Table 5-3). This information was obtained from a digital elevation model (DEM from the USGS Seamless Data web resource; http://seamless.usgs.gov/index.php). Walloon Lake sits in a bedrock valley in which the lowest bedrock elevation is between approximately 500 and 550 ft MSL (approximately 152.4 to 167.6 m MSL) (Milstein, 1983). The surface elevation of Walloon Lake is above the elevations of both Lake Michigan to the north and Lake Charlevoix to the west-southwest. There is also a surface water divide between Walloon Lake and Lake Charlevoix. Thus, it is reasonable to consider Walloon Lake as an upgradient constant head boundary for the regional groundwater flow model. Lake Charlevoix was modeled with a lake stage of 580.77 ft MSL (see Table 5-3).

Walloon Lake has an outlet to Bear River. Groundwater discharges to the lake and the lake discharges to the river. The influence of the outlet at Bear River is to maintain the typical lake stage at the value used in the model. It is not necessary to explicitly model the Bear River to capture its influence on the aquifer system. In the 9/14/2006 scenario, the CHD cells representing Walloon Lake cause a net removal of water from the aquifer system at a rate of approximately 2,200 gallons per minute (gpm) or 4.9 cubic feet per second (cfs). In the 1/02/2007 scenario, the CHD cells representing Walloon Lake cause a net removal of water from the aquifer system at a rate of approximately 2,700 gpm or 6.0 cfs. This represents groundwater discharging from the aquifer system to the lake and from the lake to the river.

Lake Charlevoix is connected to Lake Michigan through channels and a small lake known as Round Lake. Discharge of water through the channels and Round Lake maintains the stage of Lake

Charlevoix at approximately the same stage as Lake Michigan. As with the outlet of Walloon Lake to Bear River, the outlet from Lake Charlevoix is not within the model domain, however, the influence of the outlet is captured using specified head cells. In the 9/14/2006 scenario, the CHD cells representing Lake Charlevoix cause a net removal of water from the aquifer system at a rate of approximately 2,300 gpm or 5.1 cfs. In the 1/02/2007 scenario, the CHD cells representing Walloon Lake cause a net removal of water from the aquifer system at a rate of approximately 2,350 gpm or 5.2 cfs.

Topographic maps prepared by the United States Geological Survey (USGS, 1983 a; b) show several small, perennial streams between Walloon Lake and Little Traverse Bay. As perennial streams, these water bodies would be expected to be surface expressions of the water table. Modeling of area streams is described below.

As noted above, recharge to the water table aquifer would be expected to vary based on soil type, cover, evapotranspiration and precipitation. Information obtained from the MDEQ's Groundwater Mapping Project website was used to define the recharge applied to the top of the regional model.

5.3 Model Construction Details

The model pre- and post-processing software Groundwater Vistas (ESI, 2004) was used for constructing the regional and local models and generating the MODFLOW input files. Construction details for the regional and local models are presented in the following subsections.

Local models for each sub-area of the Development were constructed with perimeter specified head boundary conditions based on the regional model using the TMR method as implemented in Groundwater Vistas. See Section 4.2.3 above for a discussion of how the TMR method was applied to the modeling described in this report.

5.3.1 Regional-Scale Model

Construction of the regional-scale model will be discussed in this section.

5.3.1.1 Model Domain and Grid

The regional groundwater flow model domain extends out to regional water bodies (Walloon Lake and Lake Charlevoix) because the boundary conditions for a smaller model domain could not be reliably assumed for the entire Silurian-Devonian Aquifer. The domain for the regional-scale model is shown on Figure 5-1.

The regional-scale model consists of eight layers. Model Layer 1 simulates the unconsolidated material above the bedrock in the model domain. Model Layers 2 through 6 have zones representing unconsolidated material and bedrock (see Appendix A). The bottom of the model was set at 244 ft MSL (74.4 m MSL), the elevation of the bottom of the open interval of Petoskey Well 5, which is the deepest of the three Petoskey Municipal Wells near the Development.

The rows of the regional model grid were rotated 30 degrees counterclockwise from due east to align with the predominant orientations of fractures in the bedrock in case horizontal anisotropy was needed to match the calibration data.

An irregular grid was designed, with grid cell dimensions ranging from approximately 900 feet (274 meters) in the far field to approximately 30 feet (9 meters) in the Development. The model domain was subdivided into 677,624 active cells. A plan view of the model grid is shown on Figure 5-2.

5.3.1.2 Model Layer Elevations

The top of the regional model was defined as the water table in the far field and ground surface in the Development. Because of its overall importance in the hydrogeology of the Development, Layer 3 of the model was designed to follow the marker shale through its known extent. Beyond the northern limit of the marker shale, the top of layer 3 was projected to the bottom of the existing interim leachate recovery system drains and from there lakeward at a low slope. This guaranteed that the drains would be simulated as penetrating two model layers. Layers 1 and 2 were given equal thickness. The deeper model layers were defined based on the available well screen locations and increase in thickness deeper in the model. The ranges of model layer elevations are shown in Table 5-2.

The upper six model layers and the top of Layer 7 project into Little Traverse Bay (see Figures 5-3 to 5-10). Likewise, Lake Charlevoix penetrates into Layer 7. Walloon Lake penetrates into Layer 4.

5.3.1.3 Boundary Conditions

MODFLOW boundary conditions and packages used in the model include Specified Head Cells, the Recharge Package, the River Package, and the Well Package. Regional model boundary conditions are shown by layer on Figures 5-3 through 5-10. Application of the boundary conditions is described below by type.

Specified Head Cells

As discussed above in Section 5.2, the conceptual model followed in constructing the regional groundwater flow model for the Development identifies Walloon Lake as an upgradient constant head boundary. Thus, Walloon Lake was used to define a portion of the eastern and southern boundaries of the regional-scale model domain as well as a constant head boundary through the central portion of the model domain. A portion of Lake Charlevoix forms a constant head boundary in the southwestern portion of the regional model domain (Figure 5-1). Model cells whose tops are above the bottom of Little Traverse Bay, Lake Charlevoix, and Walloon Lake were assigned heads using the time-variant specified-head package (CHD Package, Leake and Prudic, 1991) with the stages listed in Table 5-3. Variations in the stage of Little Traverse Bay were modeled explicitly. Lake Charlevoix and Walloon Lake were kept at uniform stages in all of the regional model runs as these features are in the far field and minor changes in lake stage would not be expected to have any significant affect on groundwater flow in the vicinity of the Development.

For the regional model, the River Package was not used to model the nearshore area of Little Traverse Bay (which was done for the TMR models, see Section 5.3.2.3.4 below), because this would only potentially affect heads on the TMR side boundaries (east and west edges), at locations that are removed from the areas of interest such as the interim leachate recovery system drains. In addition, the coarser discretization of the regional model does not allow as accurate a simulation of the shoreline as the TMR models. Therefore, the same methodology was not applied to the regional model.

The time-variant specified-head package (CHD Package, Leake and Prudic, 1991) was used to specify heads for model cells connected to the area lakes and for defining the boundary conditions around the perimeter of the TMR models. This package allows changes in heads from the regional model to be readily projected into the boundary conditions of the TMR models.

Although the CHD package was developed to support modeling of transient leakage from compressible, fine-grained materials, it provides a convenient way to indicate the location and head applied to specified heads cells in a steady-state model. It allows this information to be added through a single, list-based input file rather than in two arrays – the IBOUND array to indicate the cell type, and the initial heads array to indicate the head value. The lateral and upgradient boundary conditions for the TMR models were derived from the regional model by determining the hydraulic head at the location of the center of each cell on the perimeter of the TMR model in the regional

model hydraulic head solution (see Section 4.2.3 for a discussion of the TMR method). This data was then passed to MODFLOW for each TMR model through the CHD Package Input File.

Recharge Package

Recharge to the aquifer system was modeled using the Recharge Package (RCH Package, McDonald and Harbaugh, 1988). Initial values were set equal to values from the State database described above in Section 3.2.1. The MDEQ data provides recharge by section (1 square mile). Recharge data obtained from the MDEQ was modified so that a recharge value of 0 was applied over Lake Michigan, Walloon Lake, and Lake Charlevoix. During calibration, the recharge values were constrained within a range of 0.1 to 1.7 times the initial values. The initial recharge distribution used as input to MODFLOW is shown on Figure 5-11.

In the regional model, a parameter consisting of a scale factor applied to the entire recharge array for each scenario was optimized. This allowed the recharge values to vary from their estimated starting values if needed to provide a better match to observed heads but would keep the ratio between each of the estimates fixed. Results of this calibration are discussed in Section 6.0.

The steady-state recharge values represent an average for the period of time prior to each scenario. The 9/14/2006 scenario recharge values represent dry, late-summer conditions. The 1/02/2007 scenario recharge values represent conditions after a wetter fall had increased the rate of recharge to the aquifer. This is consistent with Site estimates of precipitation minus evapotranspiration shown, for example, on Figure 4-25a of Barr, 2009.

River Package

Area streams were simulated using the River Package (RIV Package, McDonald and Harbaugh, 1988). Heads were specified for each RIV cell using the elevations extracted along the stream courses from the DEM (USGS Seamless Data web resource) and topographic data for the Development.

Well Package for Simulating Drains

The interim response collection drains were simulated in the regional model using the Well Package (WEL Package, McDonald and Harbaugh, 1988) because this allows the observed discharge rates to be simulated explicitly during model calibration without the need for simultaneous calibration of drain conductance parameters to match the observed discharge.

The observed drain discharge was divided evenly among the cells that represent each drain. Since the purpose of the regional model is to set the boundary heads of the TMR models and the drains are not near the upgradient and side-gradient boundaries of the TMRs, simulation of the effects of variations in flux along the drains was not a goal for the regional model. The decision was made to not add drain conductance to the parameters that had to be calibrated for the regional model. This approach provided a straightforward way to simulate the influence of the drains on mass-balance in the regional model, and did not adversely affect calibration.

Well Package for Simulating Wells

Wells from the MDEQ's Wellogic database (http//:www.deq.state.mi.us/wellogic) that are located within the model domain had a completion interval or total depth indicated, and had pumping rates or pump capacity specified were included in the regional model. Figure 5-12 shows the locations of all the wells with pumping information in the regional model. The three Petoskey municipal wells near the Development are labeled on this figure. Figures 5-3 to 5-10 show the distribution of wells by layer.

The wells were assigned to specific model layers based on the information on the screen or open rock interval. For wells other than Petoskey Well 3, Petoskey Well 4, and Petoskey Well 5, if the pump capacity was specified and the pumping rate was not, the pumping rate used in the regional model was one-half of the pump capacity.

For Petoskey Wells 3 through 5, pumping rates were estimated based on 2006 pumping data. Daily average pumping rates in 2006 for Petoskey Wells 3, 4, and 5 are shown on Figures 5-13, 5-14, and 5-15, respectively. The wells are not pumped continuously. As described below in Section 5.3.1.5, data from two measurement events were used in the model calibration. The first event occurred in September 2006, the second in January 2007. The range of observed pumping rates in the two weeks prior to the first event and the corresponding two weeks of 2006 for the second event were used to assign bounds to the modeled pumping rates and these rates were treated as parameters in the model calibration. See Section 6.1.1 for more information.

The Petoskey wells are simulated as penetrating multiple layers in the regional model. The total pumping from each well was distributed among the layers penetrated by each well based on the fraction of the transmissivity represented by each layer as shown in Equation 2.

$$Q_i = Q \frac{K_i b_i}{\sum_{j=1}^{L} K_j b_j} \qquad \text{Equation 2}$$

where:

Q_i is the discharge applied to cell i representing a multi-layer well,

Q is the total discharge for the well,

K_i is the hydraulic conductivity applied to cell i,

b_i is the thickness of cell i, and

L is the total number of layers penetrated by a given well.

5.3.1.4 Material Properties

Hydraulic conductivity was parameterized in the regional model using interpolated values within zones that separate each layer into bedrock versus unconsolidated material (see Figures 5-16 to 5-22). Interpolation within each zone was done between points referred to as pilot points. With the exception of the zone under Little Traverse Bay, each of the pilot points were treated as parameters whose horizontal and vertical hydraulic conductivity were optimized during model calibration. Upper and lower bounds for horizontal hydraulic conductivities of the pilot points in the Regional and TMR models were set at or near the limits of estimated values based on all available data from the Development.

Because the zone under Little Traverse Bay has only one pilot point per layer, a uniform value equal to the mean value for the Development of 3.03 ft/day (0.924 m/day) was used for horizontal hydraulic conductivity and a uniform value of 0.303 ft/day (0.0924 m/day) was used for vertical hydraulic conductivity in this zone. These values were not adjusted during the model calibration because no information is available to constrain the values. Counting the 8 pilot points under Little Traverse Bay, the regional model has a total of 675 pilot points.

The hydraulic conductivities of the group of pilot points located within the known extent of the marker shale cause simulation of perching of water on the shale without explicitly including a zone to represent the shale. The use of pilot points in combination with zones prevents interpolation of

values between pilot points that occur in different zones. This typically leads to the creation of discontinuities in layer properties (horizontal and vertical hydraulic conductivity in this modeling) at the zone boundaries (for example, see Figure A-11 in Appendix A). This is appropriate if the zone boundary represents an abrupt material change such as the transition from unconsolidated material to bedrock. This would likely not be an appropriate approach for the marker shale in areas where its extent is unknown due to sparse data south of the Development, but in which it is not believed to have been truncated by erosion. There is not currently a way to incorporate the influence of a linear boundary such as the erosional edge of a bedrock unit into pilot point parameterization using PEST.

Where data were available, initial hydraulic conductivities were assigned to unconsolidated material and bedrock based on data from aquifer testing. Elsewhere, initial values were set equal to the mean value for the Development. The hydraulic conductivities in the x and y axial directions were tied together and allowed to vary independently of the hydraulic conductivity in the z axial direction. As discussed below, the hydraulic conductivity values were optimized using PEST (Watermark, 2005; 2008a).

The regularization of vertical hydraulic conductivity described in Section 4.3 did not impose a penalty if the vertical hydraulic conductivity was lower than the horizontal hydraulic conductivity, regardless of how large the difference became. This was considered an appropriate approach given the observed predominance of horizontal fractures in the bedrock (see Figure 4-9 of Barr, 2009). As described on p. 100 of Barr (2009), the measured anisotropy throughout the Bay Harbor Development was highly variable. The vertical conductivity of a model layer dominated by low conductivity units may be several orders of magnitude lower than the horizontal hydraulic conductivity (Zheng and Bennett, 1995, p. 238).

5.3.1.5 Selection of Calibration Data Sets

For calibration of the regional-scale model, groundwater elevations determined from well records were used for the portion of the model domain outside of the Development. These data were cross-validated by model layer. Cross-validation involved removing each observation in turn and gridding the remaining data using Surfer (Golden Software, Inc., 2002) and determining how different the interpolated value is at the location of the removed data point. The difference between the observed value and the interpolated value based on the cross-validation was removed from the target head value so that noise in the data set caused by errors in measurement, local heterogeneity, long-term changes in water level, and other causes did not interfere with the calibration process.

Groundwater elevations measured in monitoring wells in the Development were used for that portion of the model domain. Two sets of groundwater elevations measured in the monitoring wells at the Development were used in the calibration process. These measurement events were selected because they came at the ends of periods with relatively steady water levels in the monitoring wells and represent the extremes in regional pumping (e.g., see Figure 5-44). This allowed the use of steady-state rather than transient models for calibration. The first set of data is from September 14, 2006 (referred to as the 9/14/2006 data, 9/14/2006 scenario, or 9/14/2006 conditions in the remainder of this report) and represents groundwater conditions during periods of high pumping from the Petoskey municipal wells. The second set of data is from the period January 2-4, 2007 (referred to as the 1/02/2007 data, 1/02/2007 scenario, or 1/02/2007 conditions in the remainder of this report) and represents groundwater conditions during periods of low pumping from the Petoskey municipal wells. Groundwater elevation targets were assigned based on the elevation of the open interval of each well. Groundwater elevation targets used for the regional model calibration and locations of the calibration targets are shown in Appendix A.

The groundwater elevation data were also expressed as differences in water level within well nests and changes in elevation between the two scenarios.

Elevations used for the CHD cells representing Little Traverse Bay in these two scenarios are listed in Table 5-3.

5.3.2 Local-Scale Models

Three local-scale models, one for each sub-area of the Development, were constructed. The purpose of these local models was to provide the additional discretization needed near the existing drains. Construction of these models will be discussed in this section. Like the regional model, each of these models has eight layers.

Like the regional model, irregular grids were used for each of the TMR models to provide the level of discretization needed around the existing drains without making the models unmanageably large. Like the regional model, the rows of the grid for the Seep 1 TMR were rotated 30 degrees counterclockwise from due east to align the grid with the predominant orientations of fractures in the bedrock in case horizontal anisotropy was needed to match the calibration data. During the calibration process for the Seep 1 TMR, it was determined that grid rotation was not necessary, so the Seep 2 and West CKD TMR models were aligned so the rows were parallel to as many segments of

the existing drains as possible. The locations of the model domains for the local-scale models within the regional model domain are shown on Figure 5-23.

In general, the differences between the scenarios run with the local-scale models were the specified heads around the model perimeters (which were determined from the Regional Model and reflect the influence of changes in lake stage, recharge rates, and rates of regional groundwater withdrawal), recharge rates, and drain conductance.

5.3.2.1 Model Domain and Grid

5.3.2.1.1 Seep 1 CKD Area Model

The domain for the Seep 1 CKD Area local-scale model is shown on Figure 5-24. The regional model results were used to define the constant head boundaries along the southern, eastern, and western boundaries of the model as shown on Figures 5-25 to 5-28.

An irregular grid was designed with grid cell dimensions ranging from approximately 23 feet (7 meters) to 3 feet (1 meter) near the Seep 1 collection drain. The model domain was subdivided into 625,248 active cells. A plan view of the model grid is shown on Figure 5-24.

5.3.2.1.2 Seep 2 CKD Area Model

The domain for the Seep 2 CKD Area local-scale model is shown on Figure 5-30. The regional model results were used to define the constant head boundaries along the southern, eastern, and western boundaries of the model as shown on Figures 5-31 to 5-35.

An irregular grid was designed with grid cell dimensions ranging from approximately 5 feet (1.5 meters) near the Seep 2, Guard Rail, Pine Court, and Edge Drain collection drains to 65 feet (20 meters).

The model domain was subdivided into 590,040 active cells. A plan view of the model grid is shown on Figure 5-30.

5.3.2.1.3 West CKD Area Model

The domain for the West CKD Area local-scale model is shown on Figure 5-37. The regional model results were used to define the constant head boundaries along the southern, eastern, and western boundaries of the model as shown on Figures 5-38 to 5-42.

An irregular grid was designed with grid cell dimensions ranging from approximately 3 feet (1 meter) near the West CKD collection drain to 38 feet (12 meters). The model domain was subdivided into 394,240 active cells. A plan view of the model grid is shown on Figure 5-37.

5.3.2.2 Model Layer Elevations

As noted above, the local model TMRs were generated in Groundwater Vistas. As such, the initial model layer elevations were the same as in the regional model. Since the top elevations of the local models were defined as the water table, the elevations of the top of model layer 1 in each local model were modified during the calibration process.

5.3.2.3 Boundary Conditions

Locations of boundary conditions for the Seep 1 CKD Area local model are shown on Figures 5-25 through 5-29. Locations of boundary conditions for the Seep 2 CKD Area local model are shown on Figures 5-31 through 5-36. Locations of boundary conditions for the West CKD Area local model are shown on Figures 5-38 through 5-43.

5.3.2.3.1 Constant Head Boundaries

The regional model results were used to define constant head boundaries along the eastern, southern, and western perimeters of the local model domains for both 9/14/2006 and 1/02/2007 groundwater flow conditions. A constant head boundary condition was also applied to those cells in each of the local model domains that are above the bottom of Lake Michigan from the position of the shoreline at low lake stage and north into Little Traverse Bay. For each of the calibration scenarios, an average lake stage value for the period prior to the synoptic water level measurement event was used. In the Seep 1 CKD Area model, the constant head for Lake Michigan is applied to cells in model layers 1 through 3. In the Seep 2 CKD Area and West CKD Area models, the constant head for Lake Michigan is applied to cells in model layers 1 through 4.

5.3.2.3.2 Existing Drains

The existing drains (including the IR drains referred to as WCKD, Pine Court, Guard Rail, Seep 2, and Seep 1, and the initial collection drain referred to as the Edge Drain) were simulated in layers 1 and 2 of the local models using the Drain Package (DRN Package, McDonald and Harbaugh, 1988). Drain conductance was adjusted during the calibration process in order to match the observed drain discharges. This differs from the regional model, where a well boundary condition was used to specify the discharge from the drains (see Section 5.3.1.3 for additional information).

5.3.2.3.3 Recharge

Recharge to the aquifer system was modeled using the Recharge Package (RCH Package, McDonald and Harbaugh, 1988). Initial values were set equal to values from the State Database described above in Section 3.2.1. The MDEQ data provides recharge by section (1 square mile). Recharge data obtained from the MDEQ for the northern portion of the model domain was modified so that a recharge value of 0 was applied over Lake Michigan. The recharge distribution used as input to the regional MODFLOW model is shown on Figure 5-11.

In the local models, recharge over the golf course (i.e., tee boxes, fairways, and greens) was allowed to vary independently from the MDEQ's zonation during the calibration process for the 9/14/2006 scenario when those golf course features would have been irrigated daily. For the 1/02/2007 scenario, the rates of recharge for the golf course features and surrounding areas were set the same because no irrigation of the golf course was occurring at that time.

Results of the model calibrations are discussed in Section 6.0.

5.3.2.3.4 Streams and Nearshore Portion of Little Traverse Bay

There are no streams within the model domains for the Seep 1 CKD Area and Seep 2 CKD Area local models. The streams on the east and west sides of the West CKD Area are simulated using the River Package (RIV Package, McDonald and Harbaugh, 1988). Heads were specified for each RIV cell using the elevations extracted along the stream course from the topographic data for the Development. Conductance of these cells was used as a calibration parameter.

RIV cells were also used to define the elevation of Little Traverse Bay in the zone between the highest and lowest lake stages. This was to allow addition of a conductance term to prevent heads in the model near the typical shoreline from being fixed at the lake stage and limit the amount of water that could be exchanged between the aquifer and these boundary cells if it was advantageous to the model calibration to do this.

5.3.2.3.5 Wells

There are no high capacity wells within the domains of the local models. The effects of pumping in the Petoskey municipal wells on the TMR domains are captured through the constant head boundary conditions along the perimeters of the local model domains defined by the regional model results (see Section 4.2.3 for more information).

5.3.2.4 Calibrated Recharge Values for the TMR Models in the Development

Two scenarios were modeled: 9/14/2006 during which the golf course would have been irrigated and 1/02/2007 during which the golf course would not have been irrigated. Based on the State of Michigan published estimates of recharge to the water table, recharge ranging from 0 over Little Traverse Bay to 8 inches/year was applied as starting values for the Development in the local models. As part of the calibration process for the regional model, a single multiplication factor was applied to the State-estimated recharge values in each scenario. The calibrated multiplication factors are 1.20 and 1.21 for the 9/14/2006 and 1/02/2007 scenarios, respectively.

No attempt was made to model the potentially higher recharge rates on the golf course features (tee boxes, fairways, and greens) in the regional model. However, in the local models, recharge greater than that in the regional model was allowed within the footprint of the golf course features for the 9/14/2006 scenarios. This was accomplished by including recharge over the golf course features in addition to recharge over the rest of the land surface as parameters in the model calibration process. Recharge zones and calibrated recharge parameters for each of the TMR models are shown on Figures 5-29, 5-36, and 5-43.

5.3.2.5 Material Properties

In each local model, the hydraulic conductivities in the x and y axial directions were tied together and allowed to vary independently of the hydraulic conductivity in the z axial direction. A continuously varying hydraulic conductivity field was used landward of Lake Michigan in each local model. This was accomplished by defining pilot points throughout each model domain. In the landward portion of each local model domain, initial hydraulic conductivities were assigned at the pilot points based on aquifer testing and other data collected during the Site investigation at the Development. As described in Section 5.3.1.4, upper and lower bounds for horizontal hydraulic conductivities of the pilot points in the TMR models were set at or near the limits of estimated values based on all available data from the Development. For the area beneath Little Traverse Bay, no data on hydraulic conductivity are available. Therefore, the hydraulic conductivity in the x and y axial directions were set equal to the mean hydraulic conductivity from the aquifer testing conducted in the Development. The hydraulic conductivity in the z axial direction beneath Lake Michigan was set at ten percent of the horizontal hydraulic conductivity.

As discussed below, the hydraulic conductivity values landward of Lake Michigan were optimized using PEST (Watermark, 2005; 2008a). The number of pilot points used in the local models was: Seep 1 CKD Area – 444 pilot points, Seep 2 CKD Area – 1322 pilot points, and West CKD Area –

544 pilot points. Pilot point locations are shown in Appendices A through D and are included in the Groundwater Vistas project files (Appendix E). Note that Groundwater Vistas allows properties such as hydraulic conductivity to be assigned by zones with a limited number of unique values or by a matrix in which each cell could potentially have a unique value. Groundwater Vistas allows hydraulic conductivity zones to be used while defining pilot point input files, but after the hydraulic conductivity fields have been calculated using pilot points, the project must be switched to assigning hydraulic conductivity by cell in order to display the hydraulic conductivity fields.

5.3.2.6 Selection of Calibration Data Sets

For calibration of the local models, groundwater elevations measured in monitoring wells in the Development and observed discharges from the collection drains were used as targets. As with the regional model, two sets of targets were used in the calibration of the local models: 9/14/2006 data representing groundwater conditions during periods of high pumping from the Petoskey municipal wells and 1/02/2007 data representing groundwater conditions during periods of low pumping from the Petoskey municipal wells. Groundwater elevation targets were assigned based on the elevation of the open interval of each monitoring well. The calibration targets used for each local model are shown in Appendices B through D.

An additional set of head observations was added to each of the TMR calibration data sets. These head observations were modeled heads from the regional model in areas near the perimeter of each TMR where no actual measurements are available. These sets act to keep the TMR model head solutions similar to the regional head solutions.

The perimeter head observations are located in active model cells (head calculated) not CHD cells (head specified). As described above, this subset of observations was added to keep the TMR models consistent with the data from the regional model. Each subset was compared individually with the calibration goals (see Section 6.2), so this subset did not “pad” the calibration statistics.

5.3.2.7 TMR Model Boundary Conditions

During calibration of the TMR models, the existing drains were simulated using the Drain Package. The drains were divided into reaches, along and parallel to the shoreline, based on changes in depth and/or slope of the trenches and drains. Drain conductance was made a parameter for each reach and was used to calibrate the overall discharge to the drain and discharge to specific drain reaches. In addition, a scaling factor was applied to the drain conductance values for the 1/02/2007 scenario compared with the 9/14/2006 scenario in the Seep 1 and West CKD TMR models. For the Seep 2 TMR model, which contains multiple drains, the Edge Drain and the Seep 2/Guard Rail drains had a

separate conductance parameter for each scenario. This allowed for matching of the drain discharge for both scenarios so the influence of the changes to remedial designs could be compared to the observed discharge. This scaling factor accounts for differences between the two scenarios, including water temperature and viscosity, differences in saturated thickness near the drains, and the degree of clogging of the drain backfill and collection pipe inlet slots.

Early modeling results indicated it would be difficult to match the drain discharges in both scenarios without allowing the drain conductance values to differ. The two scenarios were needed to evaluate the effects of the interim remedial drains under the observed range of hydraulic conditions, so it was very desirable to be able to match both drain discharges.

Conductance for a boundary condition in MODFLOW is defined as the hydraulic conductivity of the boundary material multiplied by the area of the boundary in contact with a model cell, divided by the thickness of the material (McDonald and Harbaugh, 1988, p. 6-4). Hydraulic conductivity is inversely proportional to viscosity, which is strongly dependent on water temperature. Seasonal groundwater temperature variations of at least 15 ^{o}C have been observed in some wells near the lake and beach drains (for example, see Figure 4-26c of Barr, 2009). The relative percent difference in water viscosity over this temperature range is 37 percent (Streeter and Wylie, 1979, Table C.1 lists the viscosity of water at 5 and 20 ^{o}C as 1.519×10^{-3} and 1.005×10^{-3} Pa·s, respectively).

Clogging of the drains likely would not be a seasonal factor (unless it was related to temperature-mediated biologic activity), but the drains do clog over time and the calibration scenarios are 3-1/2 months apart.

The top of Layer 3 was defined such that it coincided with the bottom of the collection trench fill of the existing drains. Layers 1 and 2 were defined to subdivide the interval penetrated by the trenches into two equal thicknesses. This allowed grouping of the drain conductance parameters of the layers.

6.0 Model Optimization and Results

The calibration methods applied to the regional and TMR models were described in general in Section 4.0. Details and calibration results for the specific models are presented in this section.

Flow model calibration is best constrained if multiple (distinct) hydrologic conditions are used in the model calibration (ASTM D 5981, Sec. 6.5.1), and if fluxes and heads are included as calibration targets (e.g., see Hill, 1998, p. 43). As described above in Section 5.0, all of the model calibrations include two steady-state scenarios that represent the range in the regional groundwater withdrawal observed. The TMR model calibrations included discharge to existing drains as observations and the Seep 1 TMR calibration included an estimated flux to Little Traverse Bay without the existing drain operating. Since one of the objectives of the TMRs is to be able to evaluate existing drain systems and potential additions/changes to the systems, inclusion of such flux observations, along with heads, in the vicinity of the existing drains makes the resulting calibrated models more accurate/robust in the area of predictive interest.

Prior information refers to independent estimates of model parameters that are included in the automated calibration. Pilot points were located in every model layer at the position of each well nest. For the locations where hydraulic conductivity estimates were available, these data were supplied as prior information to PEST.

6.1 Regional-Scale Model

Calibration with distributed hydraulic conductivity can lead to better matches between observations and model outputs (i.e., lower residuals). This was accomplished by establishing a very heterogeneous hydraulic conductivity field which is consistent with the conceptual model.

6.1.1 Petoskey Well Pumping Rates

As described Section 5.3.1.3, the total pumping rate of Petoskey Wells 3 through 5 and the simulated distribution of pumping by layer were determined during the regional model calibration. Calibrated pumping rates for each well in the two scenarios modeled are listed in Table 6-1.

6.1.2 Regional Recharge Rates

As described in Section 5.3.2.7, for each of the simulations a scaling factor was applied to the per-section recharge field estimated by the State. This was to allow the values to rise or fall by a small

factor if it allowed better calibration to the available data. The calibrated scaling factors for the 9/14/2006 and 1/02/2007 conditions were nearly identical and represent an increase over the State-estimated initial values of approximately 20 percent. Therefore, the regional model better matched the data when it simulated more recharge.

6.1.3 Area Streambed Conductances

Each of the area streams modeled with the River Package, shown in green in Figure 5-3, was assigned a separate conductance parameter in the Regional model calibration.

6.1.4 Hydraulic Conductivity Distributions

The distribution of calibrated pilot point horizontal hydraulic conductivity values is summarized on Figure 6-1a. The distribution of calibrated pilot point vertical hydraulic conductivity values is summarized on Figure 6-1b. Unsaturated cells in the 1/02/2007 scenario are differentiated from confined and unconfined cells in these histograms (see Section 4.2.2 for a description of cell types). The horizontal and vertical hydraulic conductivity fields are shown by layer in Appendix A. The heterogeneity of the model and the discontinuity in hydraulic conductivity across zone boundaries representing the unconsolidated material and bedrock are apparent on these figures.

6.1.5 Hydraulic Head Observations

Scatter plots for the observation data sets of the regional model are shown on Figures 6-2 to 6-7. Data falling on the diagonals of these plots represent an exact match between the observed and modeled values. Figure 6-2 shows the regional head values, which show a large range of differences (residuals) between the observed and modeled values. This is typical for such data. Acceptable residuals may differ by location in a particular model (ASTM D 5981 Sec. 5.2, Note 2). The plot shows no bias, which is a desirable outcome. The scatter plots of the head and head difference data from the Development wells show much smaller residuals, which is likely related to much smaller measurement error associated with these observations. The tight fit across the Development indicates that the regional model captures the heterogeneity of the Site and provides acceptable boundary heads for use in the construction of the TMR models.

Each of the hydraulic head observation data sets of the regional model calibration is also summarized in Table 6-2. The summary is in terms of the range of observed values, the square root of the mean squared error (RMS), and the ratio between the RMS error and the observed range of values. This ratio should be a small percentage (ASTM, 2002b). Ten percent or less was chosen as the goal for the

ratio of RMS/observed range. This goal was achieved in all cases, with the regional heads exhibiting the largest value as was anticipated.

6.2 TMR Models

None of the Petoskey municipal wells are located within the domains of the TMR models. The influence of these wells is imposed on the TMR models through the perimeter CHD boundary conditions (see Section 5.3.2.3).

As discussed above, the existing drains were simulated using the WEL package in the regional model and using the DRN package in the TMR models. In each TMR model, the drain discharges were essentially exactly matched.

Unlike the regional model, for which discretization of recharge was based on only the State database, a separate recharge zone was created to represent the tee boxes, fairways, and greens of the golf course for the 9/14/2006 scenarios of the TMR models. These zones represent the areas of golf course that would be irrigated during the golf season and that may experience a different recharge rate than non-irrigated areas. As described in Section 5.3.2.3.3, no difference in recharge rate was simulated in the 1/02/2007 scenario between the golf course and the surrounding area since the golf course would not have been irrigated at that time.

No regional head observations are located within the domains of the TMR models. As described in Section 5.3.2.6, heads from the calibrated regional model scenarios were included in the calibration data sets for the TMR models.

As described in Section 5.2.2.3.4, the MODFLOW RIV Package was used to model area streams and the nearshore zone of Little Traverse Bay in the TMR models. Only the West CKD model has streams within its model domain. Conductance of the cells representing the nearshore zone was used as a parameter in the calibration of the TMR models. Conductance of cells representing the two streams in the West CKD TMR model was used as two additional parameters in the calibration of that model.

Each of the TMR model calibration results are summarized in the following subsections.

6.2.1 Seep 1 TMR Model

Calibrated recharge parameters for the Seep 1 TMR model are summarized on Figure 5-29. The calibrated value for the golf course features is more than twice that for the portions of the model

domain not within the footprint of the golf course features for the 9/14/2006 scenario (21.6 in/yr versus 10 in/yr). The calibrated recharge value for the 1/02/2007 scenario is 12 in/yr.

The distribution of calibrated pilot point horizontal hydraulic conductivity values for the Seep 1 TMR model is summarized on Figure 6-8a. The distribution of calibrated pilot point vertical hydraulic conductivity values for the Seep 1 TMR model is summarized on Figure 6-8b. Unsaturated cells in the 1/02/2007 scenario are differentiated from confined and unconfined cells in these histograms (see Section 4.2.2 for a description of cell types). The influence of the regularization information is apparent on Figure 6-8a as the central peak includes the mean value from all available estimates, which was used as the preferred value in the regularization (see Section 4.3). The influence of the regularization information on the vertical hydraulic conductivity values is also apparent on Figure 6-8b as the central peak includes the mean value from all available estimates, which was used as the preferred value in the regularization. The horizontal and vertical hydraulic conductivity fields are shown by layer in Appendix B. The heterogeneity of the hydraulic conductivity field is apparent on these figures.

Scatter plots of observed and modeled hydraulic heads for the 9/14/2006 and 1/02/2007 data sets of the Seep 1 TMR model are shown on Figures 6-9 and 6-10, respectively. Data falling on the diagonal of these plots represent an exact match between the observed and modeled values. The hydraulic head scatter plots do not show excessive bias in the modeled head residuals. Each of the hydraulic head observation data sets of the Seep 1 TMR model calibration is summarized in Table 6-3. The calibration goals of an RMS/observed range of 10 percent or less were met in all cases except that of the difference between the two scenarios. This represents a sort of “double jeopardy” as each head data set was already considered. A combination of simulated heads in the 9/14/2006 simulation that were low compared to the associated observed value combined with simulated heads in the 1/02/2007 simulation that were high compared with the associated observed value could lead to a difference that is unusually large.

Contour maps of hydraulic heads from the calibrated models are shown by layer in Appendix B.

6.2.2 Seep 2 TMR Model

Calibrated recharge parameters for the Seep 2 TMR model are summarized on Figure 5-36. Like the Seep 1 TMR model, the value for recharge on the golf course features in the 9/14/2006 scenario is much higher than for the portions of the model domain not within the footprint of the golf course features. Portions of four sections, as defined by the State, are included in the Seep 2 TMR model.

Two of these are unconstrained by the State data because the majority of each section is under Little Traverse Bay. As with hydraulic conductivity, recharge was more highly parameterized in the TMR models than in the Regional Model. The recharge values for Sections 4/5, Section 8, and Section 9 were allowed to vary separately during model calibration of the TMR models. The calibrated recharge for off-of-the-golf course features ranges from 0.4 to 9.6 in/yr. The calibrated value for recharge beneath the golf course features in the 9/14/2006 scenario is 24.4 in/yr.

The distribution of calibrated pilot point horizontal hydraulic conductivity values for the Seep 2 TMR model is summarized on Figure 6-11a. The distribution of calibrated pilot point vertical hydraulic conductivity values for the Seep 2 TMR model is summarized on Figure 6-11b. Unsaturated cells in the 1/02/2007 scenario are differentiated from confined and unconfined cells in these histograms (see Section 4.2.2 for a description of cell types). The large number of pilot point conductivity values at the low end of the allowed range of values in the plots are the result of the confined model approximating the operation of a model that explicitly accounts for the reduction of hydraulic conductivity of unsaturated materials (see Section 4.2.2). Like the Seep 1 distribution, the central peak in Figure 6-11a shows the influence of the regularization information for horizontal hydraulic conductivity (see Section 4.3). Figure 6-11b shows a peak at the value used for regularization of vertical hydraulic conductivity and another peak at the lower bound for this parameter. The horizontal and vertical hydraulic conductivity fields are shown by layer in Appendix C. The heterogeneity of the hydraulic conductivity field is apparent on these figures.

Scatter plots of observed and modeled hydraulic head for the 9/14/2006 and 1/02/2007 data sets of the Seep 2 TMR model are shown on Figures 6-12 and 6-13, respectively. Data falling on the diagonal of these plots represent an exact match between the observed and modeled values. The hydraulic head scatter plots do not show excessive bias in the modeled head residuals. Each of the hydraulic head observation data sets of the Seep 2 TMR model calibration is summarized in Table 6-4. The calibration goals of an RMS/observed range of 10 percent or less were obtained in all cases.

Contour maps of hydraulic heads from the calibrated models are shown by layer in Appendix C.

6.2.3 West CKD TMR Model

Calibrated recharge parameters for the West CKD TMR model are summarized on Figure 5-43. Like the Seep 1 and Seep 2 TMR models, the value for recharge on the golf course features in the 9/14/2006 scenario is much higher than for the portions of the model domain not within the footprint

of the golf course features (16.6 in/yr and 0.43 in/yr, respectively). The calibrated recharge rate for the 1/02/2007 scenario was a uniform value of 9.6 in/yr. The off-of-the-golf course features recharge was not constrained by the State data because the majority of this section is under Little Traverse Bay.

The distribution of calibrated pilot point horizontal hydraulic conductivity values for the West CKD TMR model is summarized on Figure 6-14a. The distribution of calibrated pilot point vertical hydraulic conductivity values for the West CKD TMR model is summarized on Figure 6-14b. Unsaturated cells in the 1/02/2007 scenario are differentiated from confined and unconfined cells in these histograms (see Section 4.2.2 for a description of cell types). The large number of pilot point conductivity values at the low end of the allowed range of values in Figure 6-14b are the result of the confined model approximating the operation of a model that explicitly accounts for the reduction of hydraulic conductivity of unsaturated materials (see Section 4.2.2). Like the Seep 1 and Seep 2 TMR horizontal hydraulic conductivity distributions, the central peak in Figure 6-14a shows the influence of the regularization information (see Section 4.3). Like the Seep 2 TMR model, Figure 6-14b shows a peak at the value used for regularization of vertical hydraulic conductivity and another peak at the lower bound for this parameter. The value to the left of the peak representing the lower parameter bound on Figure 6-14b is based on a field measurement. The horizontal and vertical hydraulic conductivity fields are shown by layer in Appendix D. The heterogeneity of the hydraulic conductivity field is apparent on these figures.

Scatter plots of observed and modeled hydraulic heads for the 9/14/2006 and 1/02/2007 data sets of the West CKD TMR model are shown on Figures 6-15 and 6-16, respectively. Data falling on the diagonal of these plots represent an exact match between the observed and modeled values. The hydraulic head scatter plots do not show excessive bias in the modeled head residuals. Each of the hydraulic head observation data sets of the West CKD TMR model calibration is summarized in Table 6-5. The calibration goals of an RMS/observed range of 10 percent or less were obtained in all cases.

Contour maps of hydraulic heads from the calibrated models are shown by layer in Appendix D.

6.3 Sensitivity Analysis

A sensitivity analysis was performed on the regional groundwater flow model and each of the TMR models. This analysis was structured based on results of a discussion of the U.S. EPA comments on the East CKD Area groundwater flow model (see Appendix T of Barr, 2006) during a May 15, 2007

conference call between U.S. EPA contractors and Barr Engineering. During that conference call, U.S. EPA contractors requested that the East CKD Area groundwater model sensitivity analysis consist of multiplying the values of the six most sensitive parameters by the following factors: 0.2, 0.4, 0.6, 0.8, 1.2, 1.4, 1.6, 1.8, and 2.0. The East CKD model has 95 adjustable parameters.

As described in Section 4.3, the pilot point method of parameterizing horizontal and vertical hydraulic conductivity introduces a large number of parameters compared to the zone-based hydraulic conductivity parameterization method used for the East CKD Area groundwater model. For comparison with the 95 adjustable parameters of the East CKD model, the Development models have the following numbers of adjustable base parameters:

- The regional model: 1,349
- The Seep 1 CKD area model: 836
- The Seep 2 CKD area model: 2,242
- The West CKD area model: 808.

The SVDA approach identifies super parameters that are combinations of all of the base parameters in the model. The super parameters are defined through singular value decomposition of the matrix X^tQ_mX, where X is the Jacobian matrix of the sensitivities of each observation to each parameter and Q_m is the observation weight matrix (Tonkin and Doherty, 2005; Watermark Computing, 2005, Section 8.5). Singular values, like eigenvalues have associated vectors, which in this case define a linear combination of the base parameters associated with each super parameter.

Given the differences in the modeling approaches, it is more appropriate to deal with the most sensitive super parameters rather than the base parameters. Since there are so many adjustable parameters in the model calibrations, the influence of most of the parameters (particularly the pilot point hydraulic conductivities) is limited to a relatively small area near where the parameter is applied. Thus examining the sensitivity of all observations to the base parameters would tend to underestimate the model sensitivity to the parameters.

However, since the super parameters are combinations of all of the base parameters regardless of type, it is not possible to define a "reasonable range" over which to vary their values as is done for base parameters. When a single super parameter value is changed, all of the base parameters are changed to a certain extent (for example, see Table A-4 in Appendix A). Furthermore, an increase in

the value of a given super parameter may cause the value of a given base parameter to increase or decrease, depending on the relationship between the parameters established by the SVDA method.

The following approach was therefore used for the sensitivity analyses. The six most sensitive super parameters were identified based on the SVDA calibration results. An appropriate scaling factor for each super parameter was determined that produced the desired scaling factor of the base parameter that had the greatest change. This determination actually involved two super parameter scaling factors (one greater than one and one less than one) for each super parameter to produce the nine target base parameter scaling factors (i.e., 0.2, 0.4, 0.6, 0.8, 1.2, 1.4, 1.6, 1.8, and 2.0). Two super parameter scaling factors were used because, as described above, increasing the value of super parameter increases some base parameter values and decreases other base parameter values (for example, see Table A-4 in Appendix A).

The results of running the models used in the calibration for the increase and decrease of each super parameter were compared and the run that produced the larger change in the measurement objective function was used. As described in Section 4.3, the measurement objective function includes all of the observations to which model output is compared. Results of the sensitivity analysis are reported in terms of the observation groups that make up the measurement objective function for each model in Appendices A through D.

Details on the sensitivity analysis information presented in Appendices A through D are referred to here to help explain how the results of the analysis are presented. As described above, when any super parameter value is changed, all of the base parameter values that are not fixed will change. This is illustrated in Tables A-4, B-3, C-3, and D-3.

These tables list the following items:

- The parameter name.
- The type of transformation used by PEST (logarithmic or none). This item is also used to indicate if the parameter has a fixed value or if its value is tied to that of another parameter.
- The value from the calibrated model.
- The lower parameter bound allowed during calibration.
- The upper parameter bound allowed during calibration.

- The value of the parameter used in the sensitivity analysis run with the super parameter value that produces a maximum increase in a base parameter value of a factor of 2.

- The value of the parameter used in the sensitivity analysis run with the super parameter value that produces a minimum decrease in a base parameter value of a factor of 0.2.

In the case of the most sensitive super parameter in the regional model, the horizontal hydraulic conductivity of pilot point kpp100 had a calibrated value of 0.620191 m/day and ranged from 0.6205589 to 0.6193372 m/day during the sensitivity analysis (see the first line of Table A-4). In contrast, the value of parameter rchfac-1 (the recharge factor for the 1/02/2007 scenario) increased by a factor up to 2 and decreased by a factor as low as 0.2 during the sensitivity analysis (see p. 29/29 of Table A-4).

Likewise, the modeled outputs for the base parameter change factors of 2.0 and 0.2 for the most sensitive super parameter are listed on Tables A-5, B-4, C-4, and D-4. These tables list the following items:

- The observation name.

- The observation group to which the observation belongs. Observations of the same type are combined into groups for convenience in monitoring their contribution to the objective function. The observation groups that consist of hydraulic head observations were used in comparing the model results with the calibration goals in Tables 6-2 through 6-5. The observation groups for each model are described in Tables A-3, B-2, C-2, and D-2.

- The measured value.

- The modeled value from the calibrated model run.

- The residual (i.e., measured value - modeled value) from the calibrated model run.

- The weight applied to the observation. The contribution of each observation to the objective function is the defined by the formula (residual x weight)^2.

- The value from the sensitivity analysis run with the super parameter value that produces a maximum increase in a base parameter value of a factor of 2.

- The value from the sensitivity analysis run with the super parameter value that produces a minimum decrease in a base parameter value of a factor of 0.2.

The sensitivity analysis results are summarized by observation group in Tables A-6, B-5, C-5, and D-5. The observation groups for each model are described in Tables A-3, B-2, C-2, and D-2. The sum of squared, weighted residuals (also known as the sum or squared errors, SSE) of all of the observations in each group is listed for the calibrated model run and for each of the adjustments of the six most sensitive super parameters. Comparison of the SSE values for observation groups for a given sensitivity run with the value from the calibrated run indicates which types of observations are most sensitive to the given super parameter. For the TMR models, the observation group related to the drain discharge is typically most sensitive to the super parameter variations.

7.0 Evaluation of Current Conditions Using the Calibrated MODFLOW Models

Assumptions made in the modeling described in this report and limitations of the use of the models are summarized in this section. Simulated current conditions for the regional model and the three TMR models are also summarized in this section. Conditions evaluated include the estimated capture zones for the Petoskey municipal wells during the 9/14/2006 scenario and 1/02/2007 scenarios using the regional model, and evaluation of rates of groundwater flow through the aquifer system and delineation of capture zones for the interim leachate recovery system drains for the subareas using the two scenarios for each of the TMR models.

Modeled discharges to and from the various types of boundary cells for both scenarios in all of the Development MODFLOW models are summarized in Tables 7-1 through 7-4. Values are expressed in these tables in gpm and in cfs. Values have been rounded to two significant digits with the exception of recharge for the regional models, which are rounded to three significant digits.

Capture zones for the Petoskey municipal wells were delineated by tracking particles backward in time. The particles were released at ten vertical locations within each model layer penetrated by the municipal wells at each well location. This is a generally accepted approach to determining capture zones for pumping wells (e.g., Anderson and Woessner, 1992; EPA, 2008).

Capture zones of the drains were delineated in cross section by tracking particles released from specific locations along the traces of selected geologic cross sections from the RI report (Barr, 2009). The cross sections are roughly parallel to modeled flow lines. As described below, the method indicates where the model shows water flowing to the drains and where it does not. The approach has meaning regardless of whether or not the cross sections parallel flow lines. Because the cross sections are roughly parallel to the columns of the TMR models, particle starting locations are identified by the column in which they occur in the following discussion.

Based on the particle tracking, it was determined if any of the particles were predicted to be captured by any of the interim leachate recovery system drains. In determining the capture zones of the drains, we only consider the starting locations of the particles that were tracked because we know these are within the cross section. We did not consider the tracks themselves because, in a heterogeneous flow system, the particles typically do not stay within a given vertical section (see Section 4.3). If you

look at the particle starting points and identify the particle with the lowest release point that flows to a drain cell, the dividing streamline for the drain is located between the particle and the one below it. For example, the dividing streamline in Figure D-66 of Appendix D occurs between the lowest yellow particle track and the highest blue particle track. See Section D-1.4 of Appendix D for additional information.

Many of the capture zones of the beach drains are estimated to extend to relatively great depths considering the discharge rates of these drains. This is believed to be due to their position near the shoreline of Little Traverse Bay, the regional groundwater discharge zone. As discussed in Section 3.2.2, discharge from aquifers to lakes tends to be concentrated near the shoreline of the lake. The drains act to capture water that would otherwise discharge to Little Traverse Bay, thus the depths of their capture zones tend to be increased by their position near the bay.

Simulated water level information is presented in the cross sections presented in this section. Perched hydraulic heads are defined as heads that are above the base of a layer in a position where, at some greater depth in the model, heads are below the base of a deeper model layer. Figure 4-1 illustrates this condition for a vertical stack of model cells. Perched conditions are simulated in layers 1 and 2 of this figure. Perched heads may be above the top of the layer, indicating confined conditions, such as for layer 2 in Figure 4-1, or within the layer such as for layer 1 in Figure 4-1. The water table is also shown for each scenario. The water table is defined as the simulated hydraulic head in the highest model layer that has a hydraulic head above the base of the layer of interest and below which no heads are below the base of a deeper model layer. In other words, the model indicates continuous saturation within the layers below the water table. The water table occurs in layer 5 in Figure 4-1.

Figures from the RI report that show water levels along the cross sections in July 2006 and March 2007 are discussed below for comparison with the modeled results. Note that these dates do not exactly correspond to the dates of the scenarios used in the modeling; however, they illustrate the effects of changes in the regional pumping regime on water levels.

7.1 Model Assumptions and Limitations

Assumptions behind the modeling are described throughout this report and summarized in the following list.

- The groundwater flow modeling is based on an assumption of porous-medium equivalence at the scale of the modeling (see Sections 3.2.2, 4.2, 5.1, and 5.2). The basis for this assumption is described in Section 5.1.

- Creeks and streams in the model domains are assumed to be surface expressions of the water table (see Section 3.2.1).

- The seasonal variations in the groundwater flow system can be captured using successive steady-state simulations. As described in Sections 3.2.2 and 5.3.1.5, two simulations were used to represent the extremes of the seasonal variation in groundwater withdrawal.

Limitations in applying the models are described in the following list.

- Since confined model layers were used, the modeling results are considered approximations in portions of the model where the modeled saturated thickness is markedly different from the observed saturated thickness and where the modeled heads are below the base of the modeled layers. See Section 4.2.2 of further discussion.

- If significant changes to hydraulic stresses are to be simulated, the changes must first be simulated using the Regional Model and the results of this model used to update the perimeter specified head boundary conditions of any TMR model that is affected by the changes in hydraulic stresses (see Section 4.2.3).

- The approach of using steady-state simulations to represent the seasonal variation in rate of groundwater withdrawal described in Section 5.3.1.5 would not be amenable to contaminant transport modeling. If transport were being modeled, a transient simulation with stress periods representing the seasonal stress fluctuations would be necessary to simulate the influence of seasonal gradient reversals on contaminant transport.

- Flow paths of particles passing into portions of the model where the modeled heads are below the bottom of the layer cannot be determined (see Section 4.4).

- The groundwater flow modeling does not account for the influence, if any, of fluid density on flow.

7.2 Flow Paths in the Groundwater Models

Directions of groundwater flow in plan view and cross section were evaluated to determine the interaction of the Petoskey municipal wells and IR drains with the aquifer system. These evaluations are described in this section.

7.2.1 Regional-Scale Model

The regional-scale model was used to delineate the capture zones for Petoskey Wells 3, 4, and 5 under 9/14/2006 and 1/02/2007 conditions. The estimated capture zones for the Petoskey municipal wells under 9/14/2006 conditions and 1/02/2007 conditions are shown on Figure 7-1.

7.2.2 Seep 1 CKD Area Model

The locations of the cross sections and the points along cross sections A-A' and C-C' are shown in plan view on Figure 7-2.

The column locations and model layers along Cross Section A-A' are shown on Figure 7-3. Note that layer 1 is very thin in this cross section, except near the drain, to represent desaturation of this layer as described in Section 4.2. The positions of the dividing streamlines (separating particle traces that end at the drain from those that end in Little Traverse Bay or in lateral boundaries of the TMR model) are shown for both scenarios on Figure 7-3. Figures 4-18a and 4-21a of the RI report (Barr, 2009) show water levels for July 2006 and March 2007 superimposed on the geology in Cross Section A-A' in the Seep 1 CKD Area. The observed conditions and the modeled conditions do not suggest any perching of water along this cross section. The observed gradients within the B1017 well nest indicate downward flow of groundwater which is consistent with the relatively deep modeled capture zones for the drain shown on Figure 7-3.

The column locations and model layers along Cross Section C-C' are shown on Figure 7-4. Note that layer 1 is very thin in this cross section, except near the drain, to represent desaturation of this layer as described in Section 4.2. The positions of the dividing streamlines (separating particle traces that end at the drain from those that end in Little Traverse Bay or in lateral boundaries of the TMR model) are shown for both scenarios on Figure 7-5. The shape of the dividing streamlines is related to the heterogeneity of the hydraulic conductivity field and the distribution of sources and sinks in the flow system (see Section 4.3). Figures 4-18b and 4-21b of Barr, 2009 show water levels for July 2006 and March 2007 superimposed on the geology in Cross section C-C' in the Seep 1 CKD Area. Both the observed conditions and modeled conditions suggest saturation above the marker shale

(layer 3 of the model) and a divide on the water table south of the pile. Note that the Seep 1 CKD Area TMR model does not extend as far south as the cross sections in the RI report.

7.2.3 Seep 2 CKD Area Model

Flow conditions were evaluated along two cross sections in the Seep 2 CKD Area: Cross Sections B-B' and D-D'. The starting locations for particle tracking along these cross sections are shown on Figure 7-6. These subareas are discussed separately in the following subsections.

Cross Section B-B' does not intersect any drains and none of the particles started in this cross section were captured by drains. Figure 7-7 shows modeled water levels and model layers along Cross Section B-B'. Layer 3 of the model is the marker shale. The modeled extent of perched groundwater (dashed lines in Figure 7-7) corresponds with the measured values. In other words, the model shows the expansion of the perched zone above the bedrock caused by the increased regional pumping in the summer and early fall.

Cross Section B-B' at Seep 2 illustrates the difficulty of depicting water levels associated with systems with variable saturation and the steep hydraulic gradients and non-monotonic slopes that are simulated for heterogeneous systems (see the discussion in Section 4.3 about heterogeneous flow fields). For example, see the sharp variation in hydraulic gradient that occurs between Columns 206 and 197 on Figure 7-7. There is an area of high hydraulic conductivity in layer 2 of the TMR model that causes this abrupt flattening of the gradient and drop of head toward the north (see the high hydraulic conductivity cells near Well W2122 on Figure C-2a of Appendix C).

This cross section cuts through an area of the domain which both the regional and TMR model indicate has no perched groundwater near where the cross section intersects the southern boundary of the TMR (see Figures 7-18 and 7-22). Consequently, the definition of the water table causes an exacerbation of the apparent gradient change in the 9/14/2006 scenario (see Section 7.0 for the functional definition of the water table). Where the heads drop abruptly in this scenario, there is also a transition from a water table to a perched zone for the 9/14/2006 scenario, but not for the 1/02/2007 scenario. The latter scenario shows much less offset of the water table because saturation is continuous with depth at that location.

Figures 4-17b and 4-20b of Barr (2009) show water levels for July 2006 and March 2007 superimposed on the geology in Cross Section B-B' in the Seep 2 CKD Area.

Both modeled scenarios indicate a perched water zone beneath the toe of the bluff along Cross Section D-D' (see Figure 7-8). Particle paths converge toward the near shore area of Little Traverse Bay, even in simulations without the drains operating. The edge drain acts as a weak sink in these simulations. In other words, it removes only a fraction of the amount of water passing through the cells from which the drain draws water. The drain does not create a local minimum in the hydraulic heads, so particles that are traced into the cells representing the edge drain continue on past this drain. Compared with the Seep 1 CKD Area, the capture zone of the beach drain intersects the water table closer to Little Traverse Bay (i.e., the capture zone does not extend far under the pile).

In general, particles in the columns toward the southern end of the cross section are being traced toward Petoskey Well 5 in the 9/14/2006 scenario and toward Little Traverse Bay or the eastern margin of the TMR model in the 1/02/2007 scenario. Particles from the middle of the cross section trace toward the eastern margin of the TMR model; and those particles starting near the northern end of the cross section that do not end at the drain trace to Little Traverse Bay. The drain capture zones in Cross Section D-D' for the 9/14/2006 and 1/02/2007 conditions are shown on Figures 7-9 and 7-10, respectively.

Figures 4-17c and 4-20c of Barr (2009) show water levels for July 2006 and March 2007 superimposed on the geology in Cross Section D-D' in the Seep 2 CKD Area. Water levels in both measurement events were below the marker shale, but the unsaturated zone was thicker in the July 2006 data set.

7.2.4 West CKD Area Model

The locations of the cross sections and the points along Cross Sections B-B' and C-C' in the West CKD Area are shown in plan view on Figure 7-11. The column locations and model layers along Cross Section B-B' are shown on Figure 7-12. Note that layer 1 is very thin in this cross section, except near the drain, to represent desaturation of this layer as described in Section 4.2.

No perched zones were simulated in either scenario in West CKD Area Cross Section B-B'. Cross sections showing the upper model layers, water tables in the two baseline scenarios, and the position of the dividing streamline (separating particle traces that end at the drain from those that end in Little Traverse Bay or in lateral boundaries of the TMR model) are shown on Figures 7-13 and 7-14.

The particle traces for the 9/14/2006 scenario show the influence of the higher regional pumping. From Column 151 north, the shallow groundwater flows toward the drain/bay. At some depth in each of the columns, however, the flow direction reverses and particles flow toward Well 5.

An additional scenario was run in which no discharge from the drains was simulated in order to investigate the cause of convergence of traces near the shoreline. The traces from the scenario without the drain removing water also show that shallow groundwater near Little Traverse Bay discharges toward the bay, but at depth, groundwater is flowing toward Petoskey Well 5.

The particle traces for the 1/02/2007 scenario show discharge toward Little Traverse Bay throughout the model. Unlike the Seep 1 and Seep 2 CKD Areas, particle traces in this scenario do not suggest concentrated discharge of groundwater from deep in the aquifer to the nearshore zone of Little Traverse Bay. This is apparently caused by the lower heterogeneity of the West CKD TMR model hydraulic conductivity field compared with the other models. This lower heterogeneity may have been caused by differences in the number of head observations used in the various TMR models. Data from 30 wells were used to calibrate the West CKD TMR model, whereas 66 wells were used in both the Seep 1 and Seep 2 TMR models. It may also be a reflection of the actual subsurface conditions – that the variability of hydraulic conductivity in the West CKD Area is lower than in the other two areas. The histogram of hydraulic conductivity for the West CKD area (Figures 6-14a and 6-14b) shows a smaller range of values and greater concentration at the mean value than the histograms for the other areas (see Figures 6-8a and 6-8b for the Seep 1 TMR model and Figures 6-11a and 6-11b for the Seep 2 model).

Figures 4-16a and 4-19a of Barr (2009) show water levels for July 2006 and March 2007 superimposed on the geology in Cross Section B-B' in the West CKD Area. The observed conditions show perched conditions in both scenarios at well W3120, however this well is beyond the model domain.

The column locations and model layers along Cross Section C-C' are shown on Figure 7-15. Note that layer 1 is very thin in this cross section, except near the drain, to represent desaturation of this layer as described in Section 4.2.

Cross sections showing the upper model layers, water tables in the two baseline scenarios, and the position of the dividing streamline (separating particle traces that end at the drain from those that end in Little Traverse Bay or in lateral boundaries of the TMR model) for West CKD area Cross Section C-C' are shown on Figures 7-16 and 7-17. The dividing streamline for the 9/14/2006 scenario extends under the northern portion of the pile (Figure 7-16). The dividing streamline for the 1/02/2007 scenario extends under the entire pile (Figure 7-17).

The particle traces for the 9/14/2006 scenario show the influence of the marker shale on flow directions above it and the higher regional pumping (see Section 4.3 for a discussion of the influence of heterogeneity on model output). For example, particles starting in layer 2 from Columns 240 and 237 track first toward the north, then track vertically down through layer 3, then flow toward Petoskey Well 5 (see Figures D-51 and D-52 in Appendix D). From Column 212 north to Column 174, the shallow groundwater flows toward the drain, whereas at some depth in each of the columns, the flow direction reverses and particles flow toward Petoskey Well 5 (see Figures D-58 through D-63 in Appendix D). North of the capture zone of the drain leakage is downward from Little Traverse Bay into the aquifer and toward Petoskey Well 5 (see Figures D-66 and D-67 in Appendix D). The traces without the drain also show that shallow groundwater very near Little Traverse Bay discharges toward the bay, but at depth groundwater is flowing toward Petoskey Well 5, and beneath Little Traverse Bay flow is from the bay to the aquifer.

The particle traces for the 1/02/2007 scenario show discharge toward Little Traverse Bay throughout the model. The particle traces in this profile are intermediate in character between those of West CKD Section B-B', which do not suggest concentrated discharge of groundwater from deep in the aquifer to the nearshore zone of Little Traverse Bay, and those of the Seep 1 and Seep 2 areas, which show a strong concentration of groundwater discharge from deep in the aquifer to the nearshore zone of Little Traverse Bay. For example, the traces in columns 222 through 209 in Scenario 1/02/2007 show a concentration of flow lines in the nearshore zone (see Figures D-73 through D-76 in Appendix D).

Water levels along West CKD Area Cross Section C-C' were not shown in the RI report.

7.3 Perched Groundwater

As described in Section 4.2, MODFLOW does not rigorously simulate unsaturated flow conditions. However, these conditions can be identified as cells in which the simulated head is below the bottom of the model cell as illustrated for layers 3 and 4 in Figure 4-1. Perched conditions in a MODFLOW solution were identified by finding model cells with simulated heads above the bottom of the cell that are underlain by cells with simulated heads below the bottom of the lower cell as illustrated for layers 1 and 2 in Figure 4-1. As would be expected, the modeled extent of perched groundwater varied with the rate of seasonal pumping. Model cells in the Development that are simulated to have perched groundwater for the 9/14/2006 scenario in the regional model are shown with orange fill in Figure 7-18. Areas with simulated perched groundwater are much smaller in the 1/02/2007 scenario from the regional model (Figure 7-19).

The extent of simulated perched groundwater in the Seep 1 TMR model is very limited in both scenarios and does not change markedly between the scenarios (see Figures 7-20 and 7-21). The extent of simulated perched groundwater in the Seep 2 TMR model is much greater in the 9/14/2006 scenario than the 1/02/2007 scenario (see Figures 7-22 and 7-23). The extent of simulated perched groundwater in the West CKD TMR model is very limited in the 9/14/2006 scenario (see Figure 7-24) and consists of only a few model cells in the 1/02/2007 scenario (see Figure 7-25).

7.4 Pine Court Subarea of the Seep 2 CKD Area Model

Capture zones for the Pine Court area were evaluated along Cross Sections A-A' and I-I'. These delineations are discussed separately because these drains were not operating during the two periods of time used for model calibration. Because of this, the conductance of the Drain Package cells representing the interim remedial drains in the Pine Court area could not be calibrated. These conductances were set to values similar to the other Seep 2 Area interim remedial drains. The Pine Court drains were simulated with control elevations at 576.0 ft MSL. Simulated drain discharges in gpm are as follows:

	Pine Court West	**Pine Court East**
9/14/2006	0.7	1.2
1/02/2007	0.9	1.0

Particle traces along Cross Section A-A' were started in the locations shown in plan view on Figure 7-26 and the columns shown in cross section on Figure 7-27. The two scenarios of the flow model calibration were used. The 1/02/2007 scenario has no perched water as defined in Section 7.3 (see Figure 7-27). The 9/14/2006 scenario has perched water at the upgradient (southern) boundary of the TMR model (see Figure 7-27). The regional pumping in this scenario is the likely cause of the simulation of greater perching relative to the 1/02/2007 scenario.

Compared to other interim remedial drains in the Development, the drain capture zone along Cross Section A-A' for the 1/02/2007 scenario is relatively shallow and does not extend under the pile (see Figure 7-28). However, this cross-section does not project through either interim remedial drain in the Pine Court area. In the 9/14/2006 scenario, the drains do not capture appreciable groundwater in this cross section.

In general, particles originating in layer 4 and below are being traced toward Petoskey Well 5 in the 9/14/2006 scenario and toward Little Traverse Bay or the western margin of the TMR model in the

1/02/2007 scenario. Particles originating in perched zones tend to stop where they are flowing toward underlying unsaturated layers. This represents downward seepage to the saturated zones below.

Particle traces along Cross Section I-I' were started in the locations shown in plan view on Figure 7-26 and the columns shown in cross section on Figure 7-29. The two scenarios of the flow model calibration were used. Both models have a perched water zone beneath the toe of the bluff (see Figure 7-29). In addition, the 9/14/2006 scenario has perched water beneath the pile and at the upgradient (southern) boundary of the TMR model. The regional pumping in this scenario is the likely cause of the simulation of greater perching relative to the 1/02/2007 scenario.

As with the results from the Seep 1 CKD Area, particle paths converge toward the nearshore area of Little Traverse Bay even in simulations without the drains operating. Compared to other drains, the capture zone of the Pine Court East Drain is relatively shallow and does not extend under the pile (see Figure 7-30 and 7-31).

In general, particles originating in layer 4 and below are being traced toward Petoskey Well 5 in the 9/14/2006 scenario and toward the lake or the eastern margin of the TMR model in the 1/02/2007 scenario. Particles originating in perched zones tend to stop where they are flowing toward underlying unsaturated layers. This represents downward seepage to the saturated zones below.

8.0 Summary and Conclusions

Groundwater flow directions and hydraulic gradients produced by the optimized groundwater flow models for the Development are consistent with available data. Furthermore, hydraulic conductivity values are consistent with the results of aquifer testing in the Development. This suggests that the conceptual hydrogeologic model on which the numerical model is based is appropriate for the Site. The optimized groundwater flow models also provide a tool for evaluating various components of potential remedial actions for the Development through linking of the regional and TMR models.

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Tables

Table 5-1

Types of Data used in Developing the Hydrogeologic Conceptual Model

Data Type	Aquifer System Characteristics	RI Section/Figure*
Field descriptions from drilling	• Lithology • Degree of fracturing and other secondary porosity (limited by drilling method) • Drilling properties – fluid loss, rate of bit advancement, etc. • Degree of saturation	Appendix 4-10
Geophysical Logs	• Shale content (gamma log) • Caliper log indicates rock strength (locations of open fractures or weak rock) • Changes in borehole fluid temperature, resistivity indicate flow in/out	Appendix 4-12
Water Level Monitoring (manual and automated)	• Aquifer response to stresses such as lake stage change, regional pumping, evapotranspiration, and recharge events • Hydraulic gradients within well nests indicate vertical hydraulic conductivity of interval separating screens • Perched zones versus regional flow systems • Water temperature trends (automated data sets only)	Section 4.6.1.7 Section 4.6.4
Borehole Flow Logging		Section 4.6.2
Ambient flow direction and normalized magnitude	Indicates flow direction, magnitude, locations of flow convergence or divergence	
Ambient flow differences between stations	Gaps in bar chart indicate inferred conduits) – indicates gaining/losing intervals	Figure 4-28a Figure 4-28c Figure 4-28e
Pumping flow differences between stations	Floating bar chart (in Seep 1, only one borehole pumped)	Figure 4-28b Figure 4-28d Figure 4-28f
Differences between differences pumping vs.	Shows where flow can be induced from in the borehole	Figure 4-29a Figure 4-29b

Table 5-1

Types of Data used in Developing the Hydrogeologic Conceptual Model

Data Type	Aquifer System Characteristics	RI Section/Figure*
ambient		Figure 4-29c
Response to borehole pumping	Hydraulic conductivity	Section 4.6.1.6 Section 4.6.2 Figures 4-22a to 4-22c
Packer test results	• Indication of hydraulic conductivity and other aquifer parameters • Details of response can indicate type of flow regime • Indicate hydraulic connection between packed interval and other intervals	Section 4.6.3.1 Figure 4-23a to 4-23c
Slug tests	Indication of hydraulic conductivity	Section 4.6.3.2 Figure 4-23a to 4-23c

***Refer to Barr, 2009 (RI Report - Revision 1.0, July 31, 2009)**

Table 5-2

Regional Model Layer Elevations

Top of Model Layer	Elevation Range (ft MSL; m MSL)
1	571.2 to 882.1; 174.1 to 268.9
2	538.9 to 825.4; 164.3 to 251.6
3	537.9 to 771.2; 163.9 to 235.1
4	527.9 to 761.2; 160.9 to 232.0
5	502.9 to 725.4; 153.3 to 221.1
6	481.2 to 703.7; 146.7 to 214.5
7	454.0 to 676.5; 138.4 to 206.2
8	381.2; 116.2
Bottom of Model Layer	
8	244.1; 74.4

Table 5-3

Lake Stages Used in the Modeling

Lake Stage	ft MSL	m MSL
Little Traverse Bay		
Low	576.00	175.565
High	581.50	177.241
9/14/2006	577.68	176.077
1/02/2007	577.40	175.990
Lake Charlevoix		
Average	580.77	177.020
Walloon Lake		
Average	685.76	209.020

Table 6-1

Regional Model Parameters Derived From Inverse Optimization

Parameter	Units	Calibrated Value	Description
RCHFAC-9	Unitless	1.20	Scale factor on State of MI Values for 9-14-2006 conditions
RCHFAC-1	Unitless	1.21	Scale factor on State of MI Values for 1-02-2007 conditions
Pumping Rates for Petoskey Municipal Wells in the 9/14/06 Simulation			
Well 3	gpm	715	Allowed range: 95 to 715
Well 4	gpm	755	Allowed range: 630 to 755
Well 5	gpm	420	Allowed range: 0.1 to 420
Pumping Rates for Petoskey Municipal Wells in the 1/02/07 Simulation			
Well 3	gpm	410	Allowed range: 245 to 410
Well 4	gpm	165	Allowed range: 165 to 350
Well 5	gpm	2.16	Allowed range: 0.1 to 190

Table 6-2

Regional Model Calibration Summary

Data set	Observed Range (m)	RMS Error (m)	RMS Error as % of Range
Regional heads	**120**	**9.6**	**8.0%**
9/14/2006 heads	**34**	**0.49**	**1.4%**
1/02/2007 heads	**31**	**0.44**	**1.4%**
Difference 9/14/2006 to 1/2/2007	**11**	**0.43**	**3.9%**
Nest differences 9/14/2006	**28**	**0.52**	**1.9%**
Nest differences 1/02/2007	**24**	**0.39**	**1.6%**

Table 6-3

Seep 1 TMR Model Calibration Summary

Data set	Observed Range (m)	RMS Error (m)	RMS Error as % of Range
9/14/2006 heads	**14.9**	**0.53**	**3.6%**
9/14/2006 perimeter heads	**19.4**	**1.00**	**5.2%**
1/02/2007 heads	**16.9**	**0.42**	**2.5%**
1/02/2007 perimeter heads	**19.4**	**0.93**	**4.8%**
Difference 9/14/2006 to 1/2/2007	**3.4**	**0.59**	**17.4%**
Nest differences 9/14/2006	**8.2**	**0.65**	**7.9%**
Nest differences 1/02/2007	**8.4**	**0.40**	**4.8%**

Table 6-4

Seep 2 TMR Model Calibration Summary

Data set	Observed Range (m)	RMS Error (m)	RMS Error as % of Range
9/14/2006 heads	**26.6**	**0.62**	**2.3%**
9/14/2006 perimeter heads	**34.7**	**2.4**	**6.9%**
1/02/2007 heads	**24.4**	**0.77**	**3.2%**
1/02/2007 perimeter heads	**30.7**	**1.9**	**6.2%**
Difference 9/14/2006 to 1/2/2007	**11.4**	**0.13**	**1.1%**
Nest differences 9/14/2006	**21.2**	**0.17**	**0.8%**
Nest differences 1/02/2007	**15**	**0.17**	**1.1%**

Table 6-5

West CKD TMR Model Calibration Summary

Data set	Observed Range (m)	RMS Error (m)	RMS Error as % of Range
9/14/2006 heads	**11.5**	**0.51**	**4.4%**
9/14/2006 perimeter heads	**17.7**	**0.24**	**1.4%**
1/02/2007 heads	**12.6**	**0.53**	**4.2%**
1/02/2007 perimeter heads	**14.9**	**0.42**	**2.8%**
Difference 9/14/2006 to 1/2/2007	**7.6**	**0.51**	**6.7%**
Nest differences 9/14/2006	**11.7**	**0.82**	**7.0%**
Nest differences 1/02/2007	**8.9**	**0.64**	**7.2%**

Table 7-1

Boundary Cell Discharge Summary, Regional MODFLOW Model

	Discharge (gpm)			Discharge (cfs)		
Boundary	**Inflow**	**Outflow**	**Net**	**Inflow**	**Outflow**	**Net**
9/14/2006 Scenario						
CHD	170	6900	-6700	0.37	15	-15
WEL	0	2600	-2600	0	5.7	-5.7
RIV	2200	3200	-930	5.0	7.1	-2.1
DRN	0	0	0	0	0	0
RCH	10200	0	10200	22.7	0	22.7
1/02/2007 Scenario						
CHD	10	8300	-8200	0.033	18	-18
WEL	0	900	-900	0	2.0	-2.0
RIV	2100	3400	-1200	4.8	7.5	-2.7
DRN	0	0	0	0	0	0
RCH	10400	0	10400	23.1	0	23.1

Values except recharge rounded to two significant digits.

Table 7-2

Boundary Cell Discharge Summary, Seep 1 CKD Area MODFLOW Model

	gpm			cfs		
Boundary	**Inflow**	**Outflow**	**Net**	**Inflow**	**Outflow**	**Net**
9/14/2006 Scenario						
CHD	880	860	19	2.0	1.9	0.041
WEL	0	0	0	0	0	0
RIV	0	26	-26	0	0.058	-0.058
DRN	0	14	-14	0	0.031	-0.031
RCH	22	0	22	0.048	0	0.048
1/02/2007 Scenario						
CHD	980	960	25	2.2	2.1	0.056
WEL	0	0	0	0	0	0
RIV	0	28	-28	0	0.062	-0.062
DRN	0	19	-19	0	0.042	-0.042
RCH	22	0	22	0.048	0	0.048

Values rounded to two significant digits.

Table 7-3

Boundary Cell Discharge Summary, Seep 2 CKD Area MODFLOW Model

	gpm			cfs		
Boundary	**Inflow**	**Outflow**	**Net**	**Inflow**	**Outflow**	**Net**
9/14/2006 Scenario						
CHD	590	550	37	1.3	1.2	0.081
WEL	0	0	0	0	0	0
RIV	2.8	33	-30	0.0063	0.073	-0.066
DRN	0	22	-22	0	0.050	-0.050
RCH	16	0	16	0.035	0	0.035
1/02/2007 Scenario						
CHD	480	420	67	1.1	0.93	0.15
WEL	0	0	0	0	0	0
RIV	1.2	47	-46	0.0027	0.10	-0.10
DRN	0	29	-29	0	0.064	-0.064
RCH	6.6	0	6.6	0.015	0	0.015

Values rounded to two significant digits.

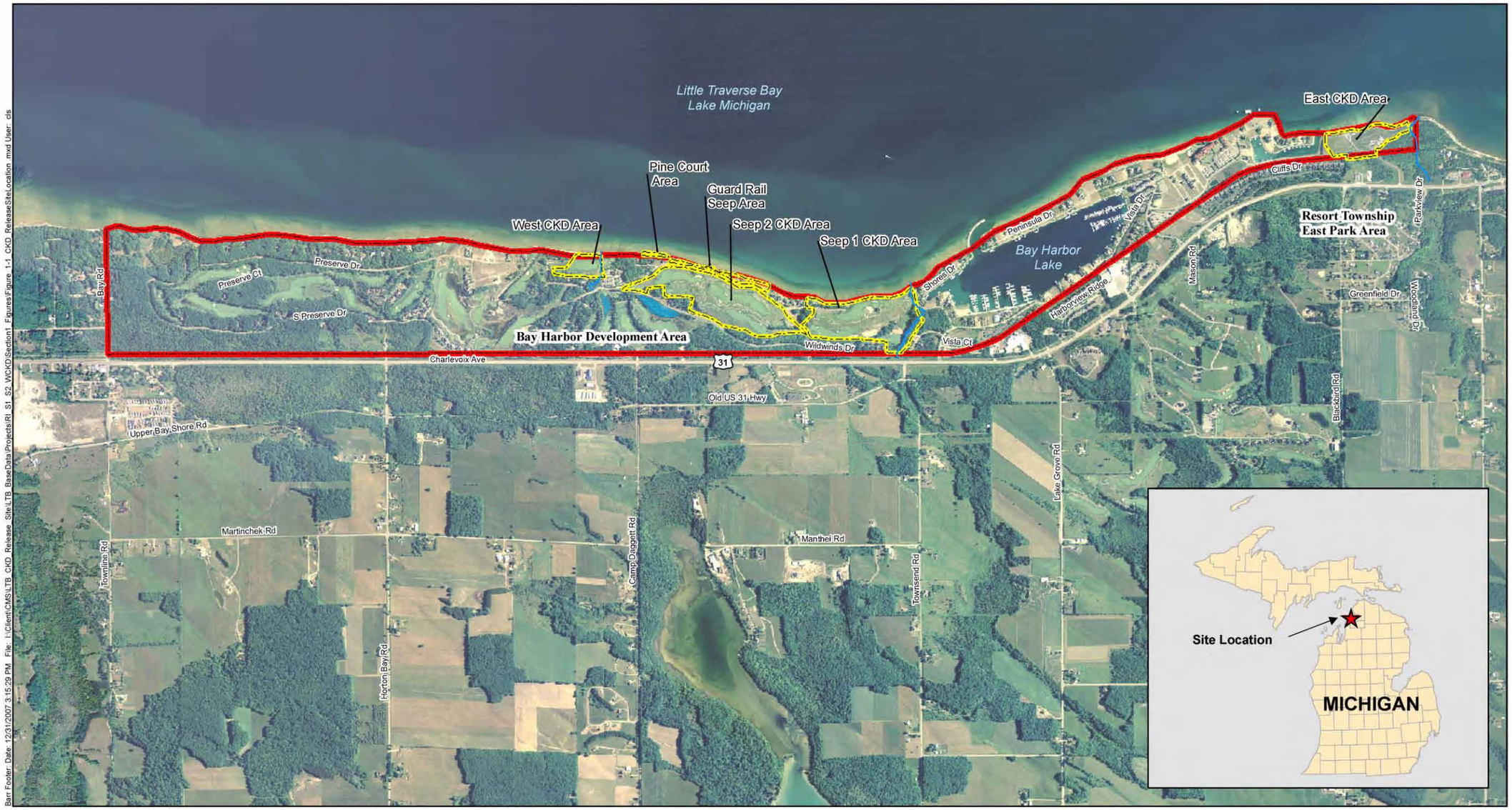
Table 7-4

Boundary Cell Discharge Summary, West CKD Area MODFLOW Model

	gpm			cfs		
Boundary	**Inflow**	**Outflow**	**Net**	**Inflow**	**Outflow**	**Net**
9/14/2006 Scenario						
CHD	42	35	7.0	0.093	0.077	0.016
WEL	0	0	0	0	0	0
RIV	3.3	8.2	-4.8	0.0074	0.018	-0.011
DRN	0	4.1	-4.1	0	0.0092	-0.0092
RCH	1.9	0	1.9	0.0043	0	0.0043
1/02/2007 Scenario						
CHD	88	70	18	0.20	0.16	0.040
WEL	0	0	0	0	0	0
RIV	2.3	19	-17	0.0051	0.043	-0.038
DRN	0	11	-11	0	0.024	-0.024
RCH	9.6	0	9.6	0.021	0	0.021

Values rounded to two significant digits.

Figures



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Imagery: 2005 USDA-FSA-APFO NAIP

Approximate Site Boundary
CKD Investigation Area
Pond/Wetland

N

0 0.5 1 Miles

Figure 1-1

CKD RELEASE SITE LOCATION
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 12/31/2007 3:17:19 PM File: I:\Client\CMS\LTB_CKD_Release_Site\LTB_BaseData\Projects\RI_S1_S2_WCKD\Section1_Figures\Figure_1-2_SiteAreaLayout_WCKD_S2_S1.mxd User: cls

Imagery: April 2005

Approximate CKD Extent

Fairway

Green

Sand

Tee Boxes

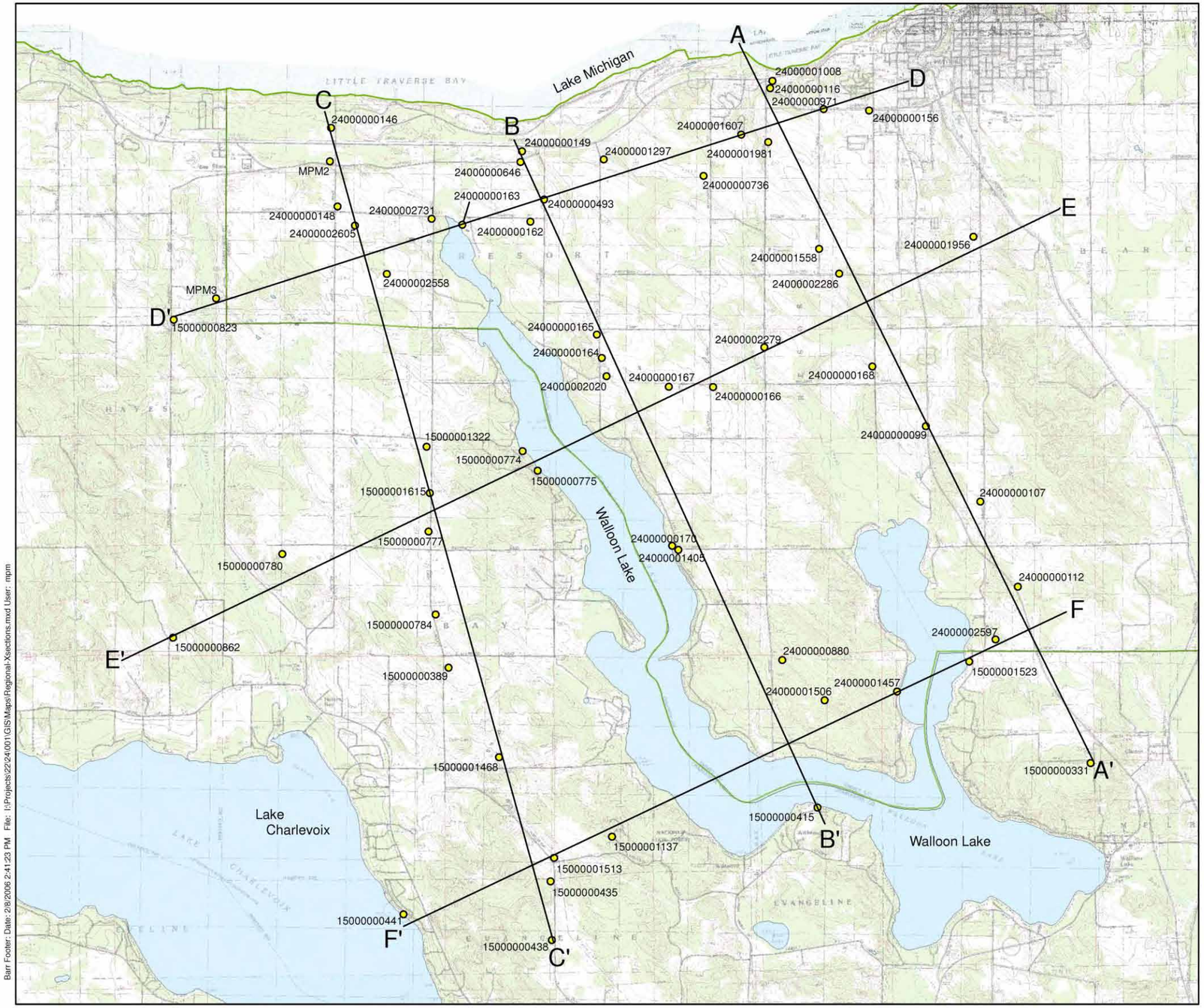
N

450 225 0 450 Feet

Figure 1-2

SITE AREA LAYOUT
WEST CKD, SEEP 2 CKD, and SEEP 1 CKD AREAS
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR



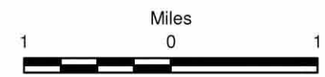


Figure 1-3

REGIONAL GEOLOGIC
CROSS SECTION LOCATIONS
Little Traverse Bay CDK Release Site
Emmet County, Michigan

BARR

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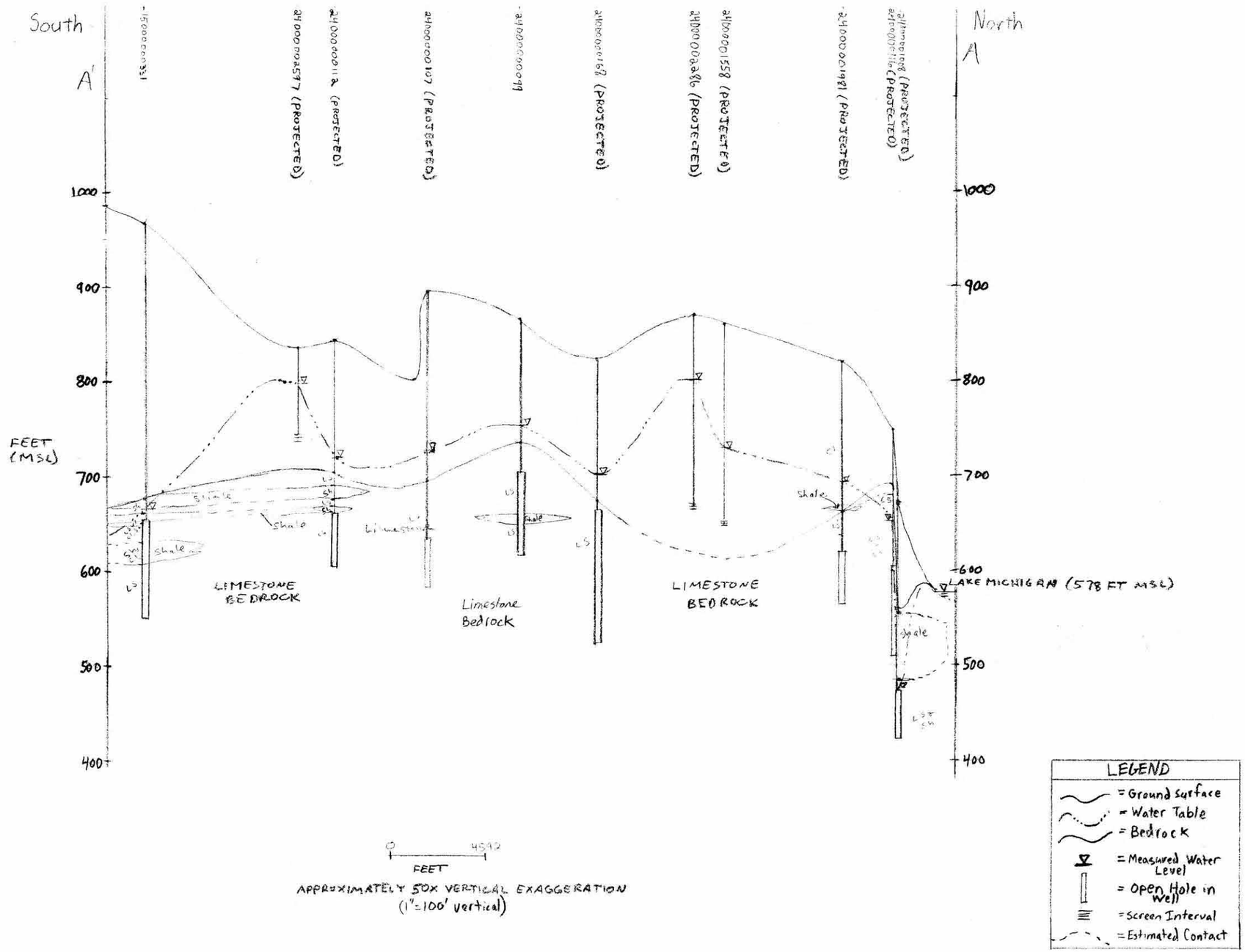
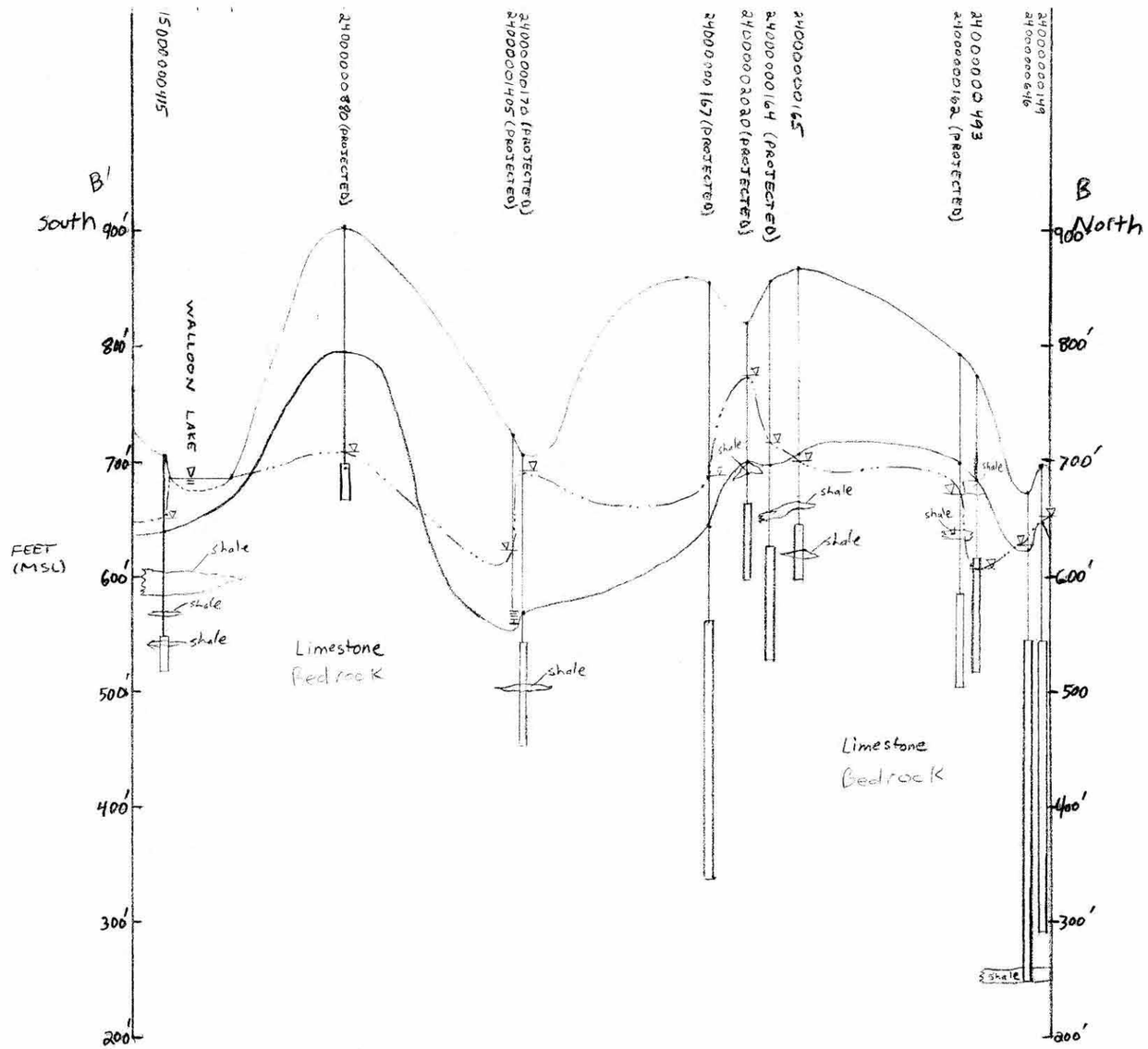
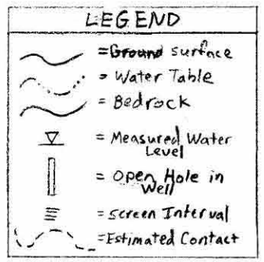


Figure 1-4
REGIONAL GEOLOGIC CROSS SECTION A-A'





0 4592
FEET
APPROXIMATELY 50X VERTICAL EXAGGERATION
(1" = 100' vertical)

Figure 1-5
REGIONAL GEOLOGIC CROSS SECTION B-B'

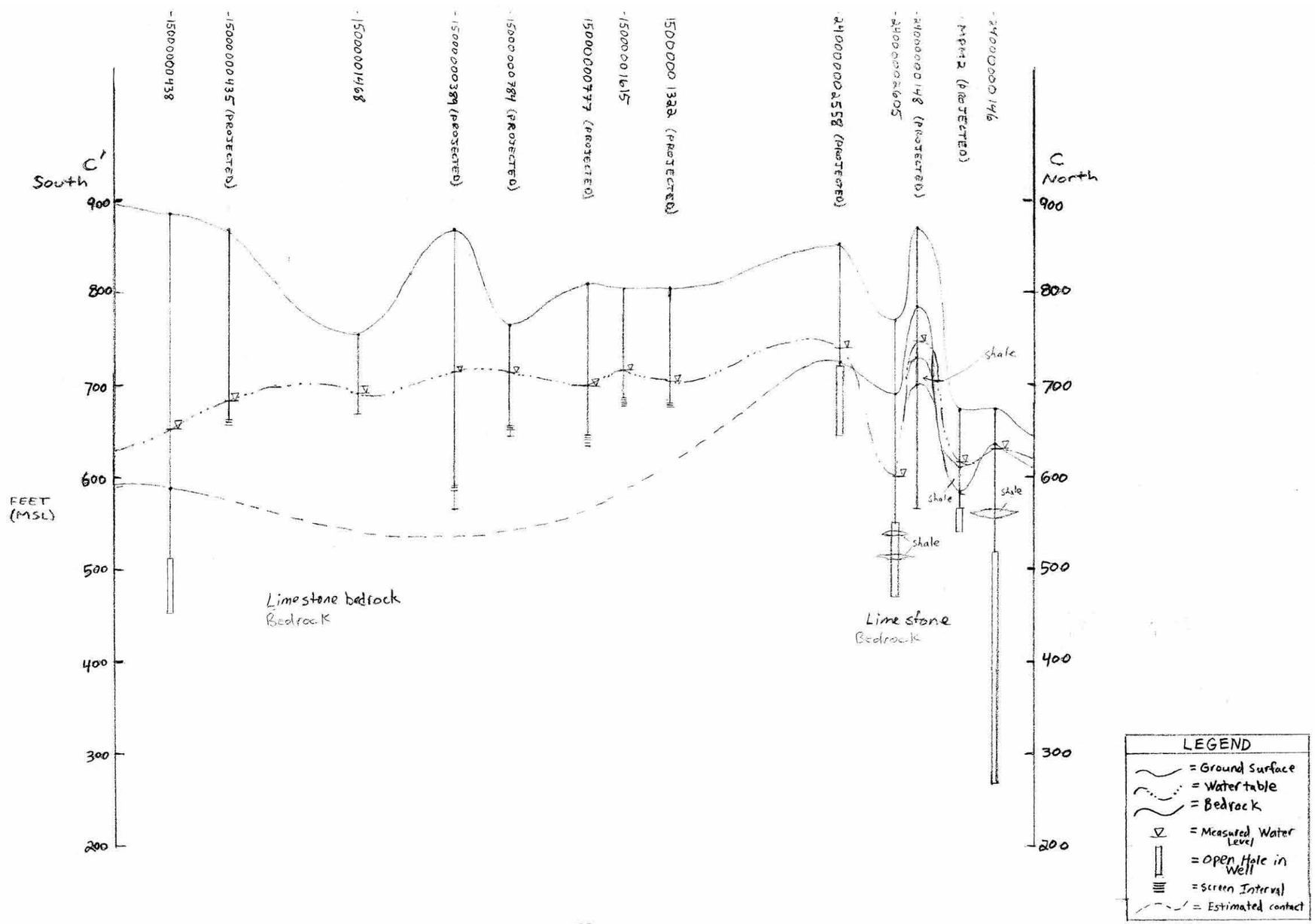


Figure 1-6
REGIONAL GEOLOGIC CROSS SECTION C-C'

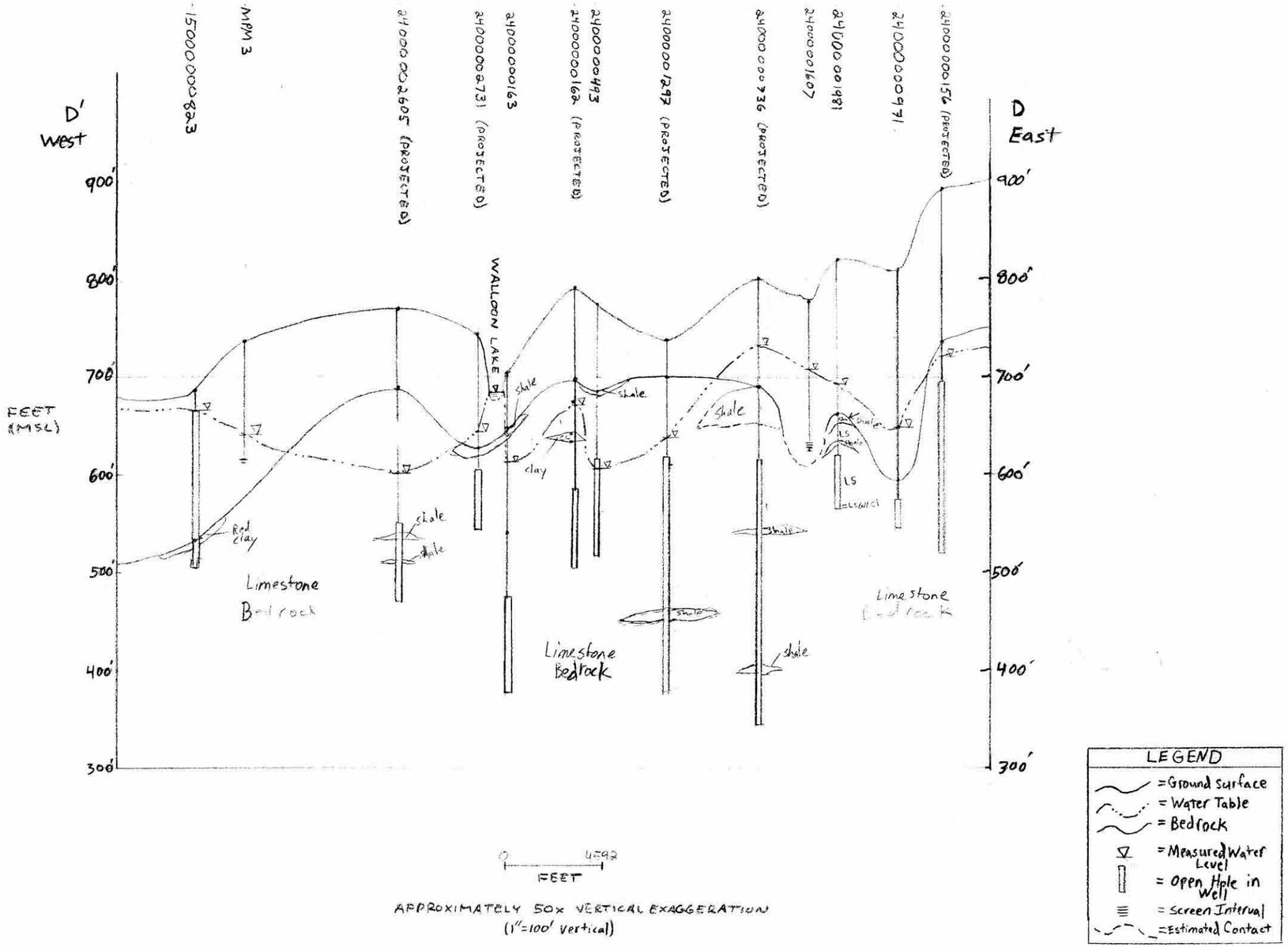


Figure 1-7
REGIONAL GEOLOGIC CROSS SECTION D-D'

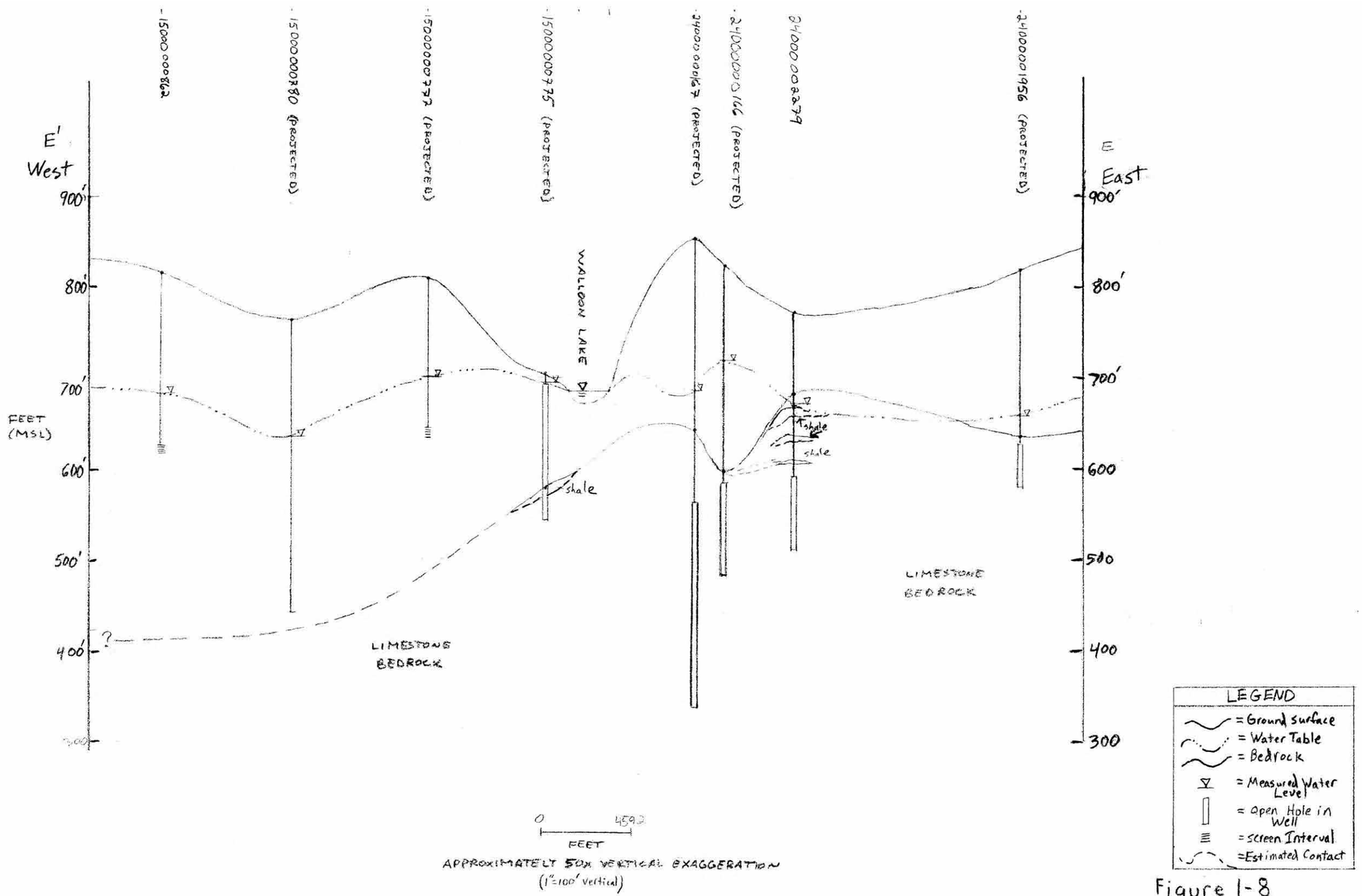
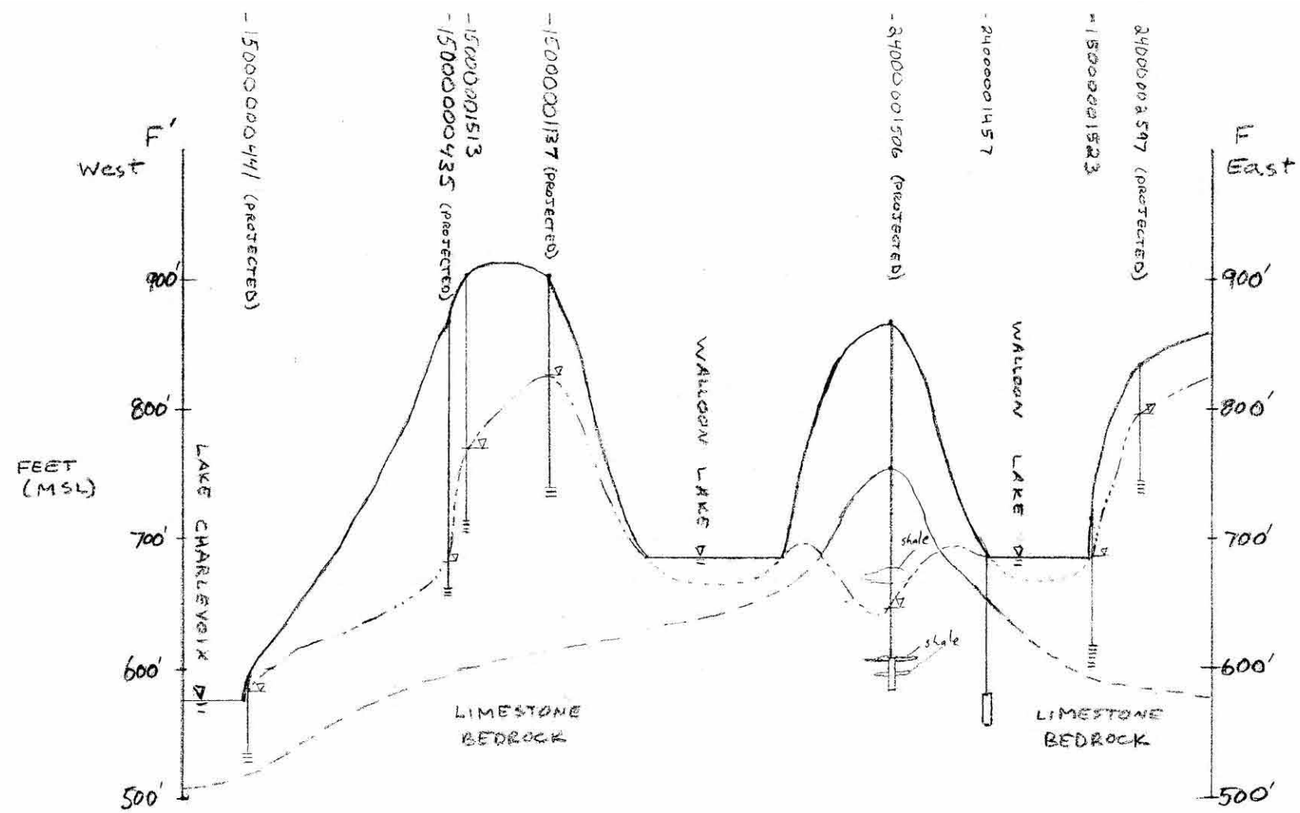


Figure 1-8
REGIONAL GEOLOGIC CROSS SECTION E-E'



0 4597
FEET
APPROXIMATELY 50X VERTICAL EXAGGERATION
(1" = 100' vertical)

LEGEND
= Ground Surface
= Water Table
= Bedrock
= Measured Water Table
= Open Hole in Well
= Screen Interval
= Estimated Contact

Figure 1-9
REGIONAL GEOLOGIC CROSS SECTION F-F'

Imagery: April 2005

S1seismic_resistivityLineStations

S1_SeismicLineStations

50 25 0 50 100 150 200 250 300 350 400 450 Feet

Monitoring Well Location
Geoprobe Location
Rotosonic Boring Location
Pump Well Location
Hand Auger Location

Surface Topography (Contour Interval = 10 ft.)
Surface Topography (Contour Interval = 2 ft.)
Piezometer
Drain Line
Approximate CKD Extent
Storm Sewer
Edge Drain

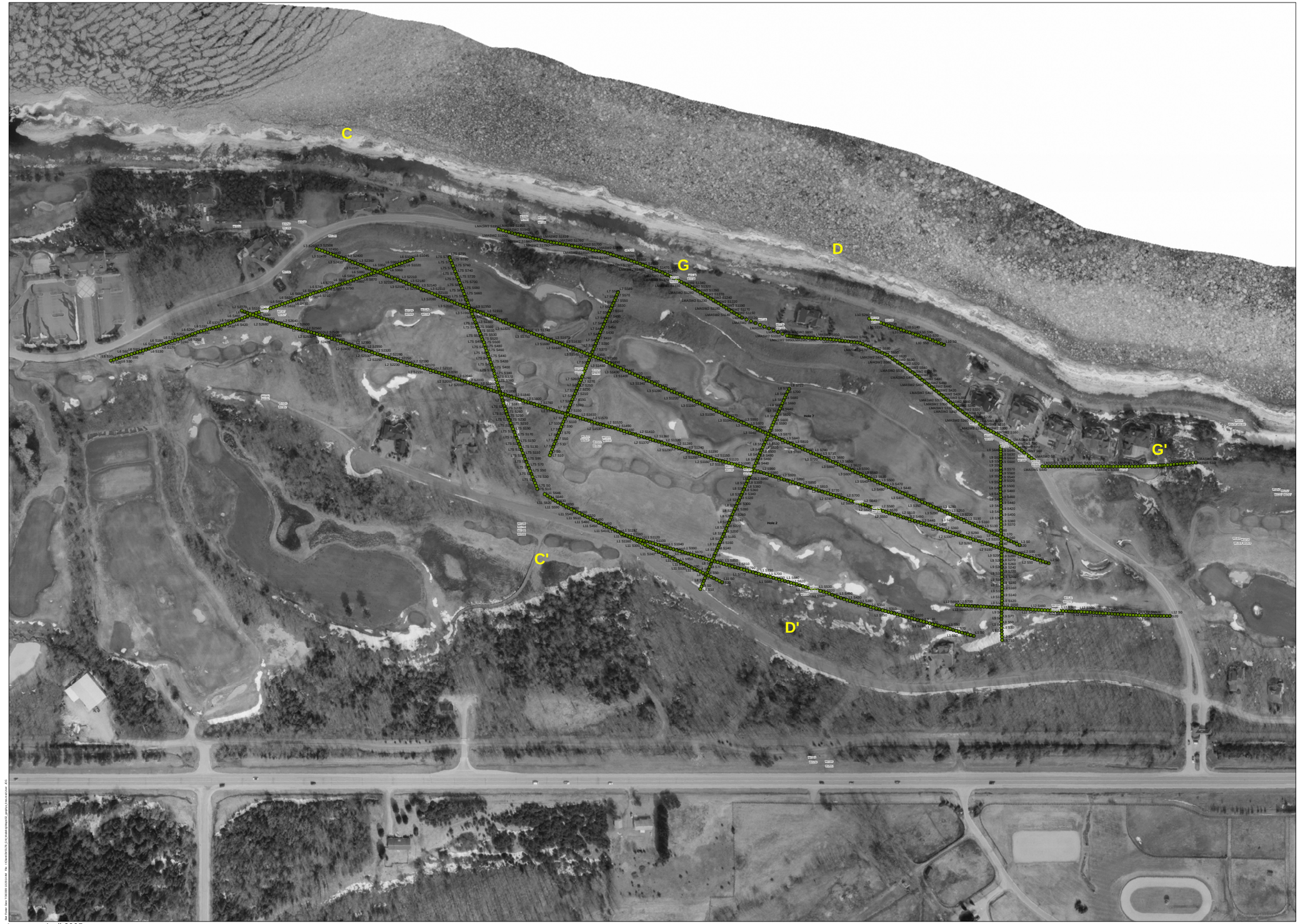
Fairway
Green
Sand
Tee Boxes

Cross Section Locations

Figure 3-1a

SEEP 1 CKD AREA
GEOPHYSICAL SURVEY LINES
Little Traverse Bay
CKD Release SIte
Emmet County, Michigan

BARR



Imagery: April 2005

80 40 0 80 160 240 320 400 Feet

S2 Seismic and Resistivity Line Stations

- Monitoring Well Location
- Geoprobe Location
- Rotosonic Boring Location
- Pump Well Location
- Hand Auger Location
- Preexisting Monitoring Well
- Surface Topography (Contour Interval = 10 ft.)
- Surface Topography (Contour Interval = 2 ft.)
- Piezometer
- East Drain Pine Court Piezometer (Field Located 7/25/06)
- Drain Line
- Approximate CKD Extent
- Storm Sewer
- Edge Drain
- Fairway
- Green
- Sand
- Tee Boxes
- Cross Section Locations

Figure 3-1b

SEEP 2 CKD AREA
GEOPHYSICAL SURVEY LINES
Little Traverse Bay
CKD Release SIte
Emmet County, Michigan

BARR

Imagery: April 2005

30 15 0 30 60 90
Feet

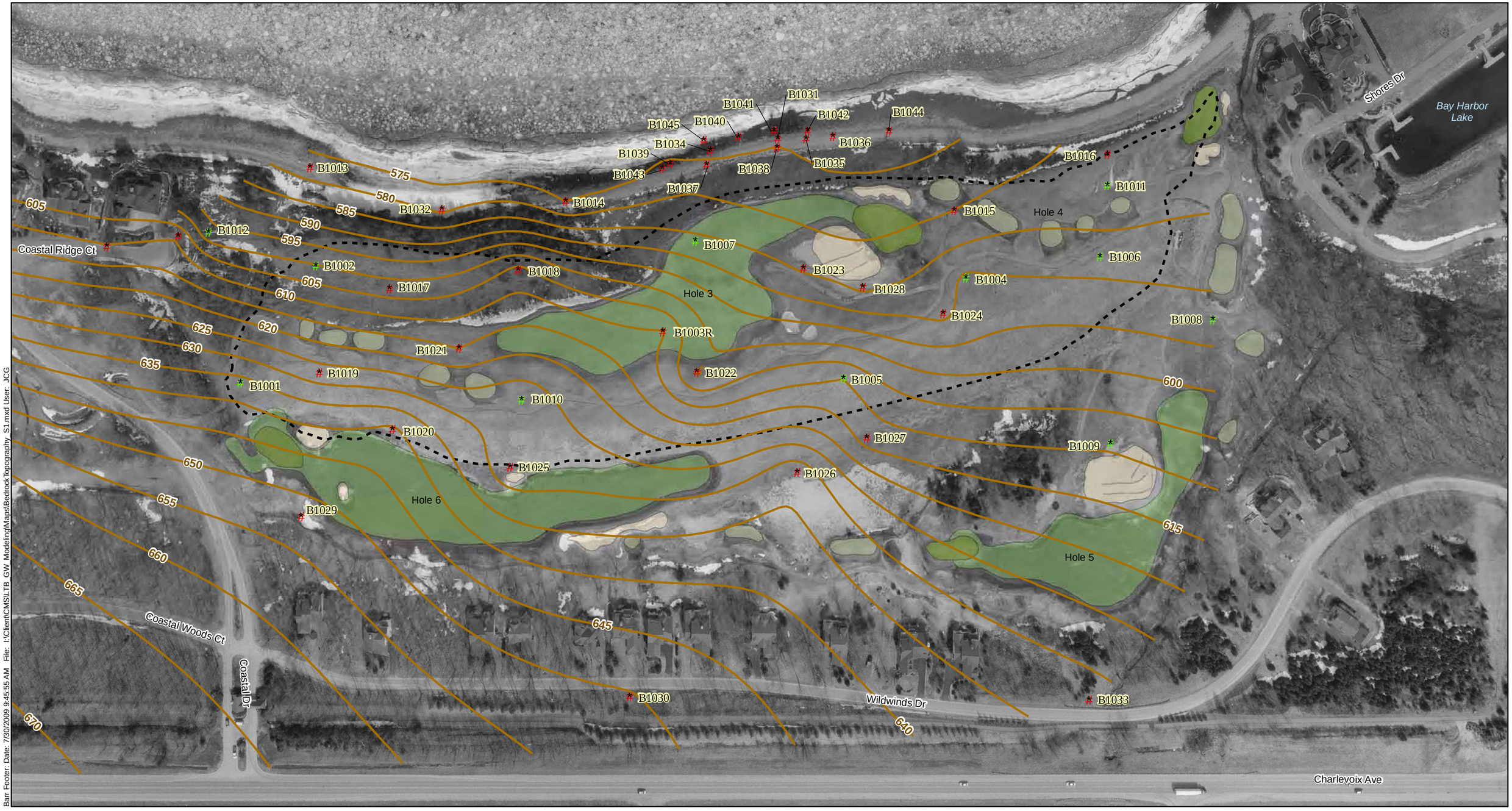
WCKD Seismic and Resistivity Line Stations

- Monitoring Well Location
- Geoprobe Location
- Rotosonic Boring Location
- Pump Well Location
- Hand Auger Location
- Surface Topography (Contour Interval = 10 ft.)
- Surface Topography (Contour Interval = 2 ft.)
- Piezometer
- Drain Line
- Approximate CKD Extent
- Cross Section Locations
- Fairway
- Green
- Sand
- Tee Boxes

Figure 3-1c

WEST CKD AREA
GEOPHYSICAL SURVEY LINES
Little Traverse Bay
CKD Release SIte
Emmet County, Michigan

BARR



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Imagery: April 2005

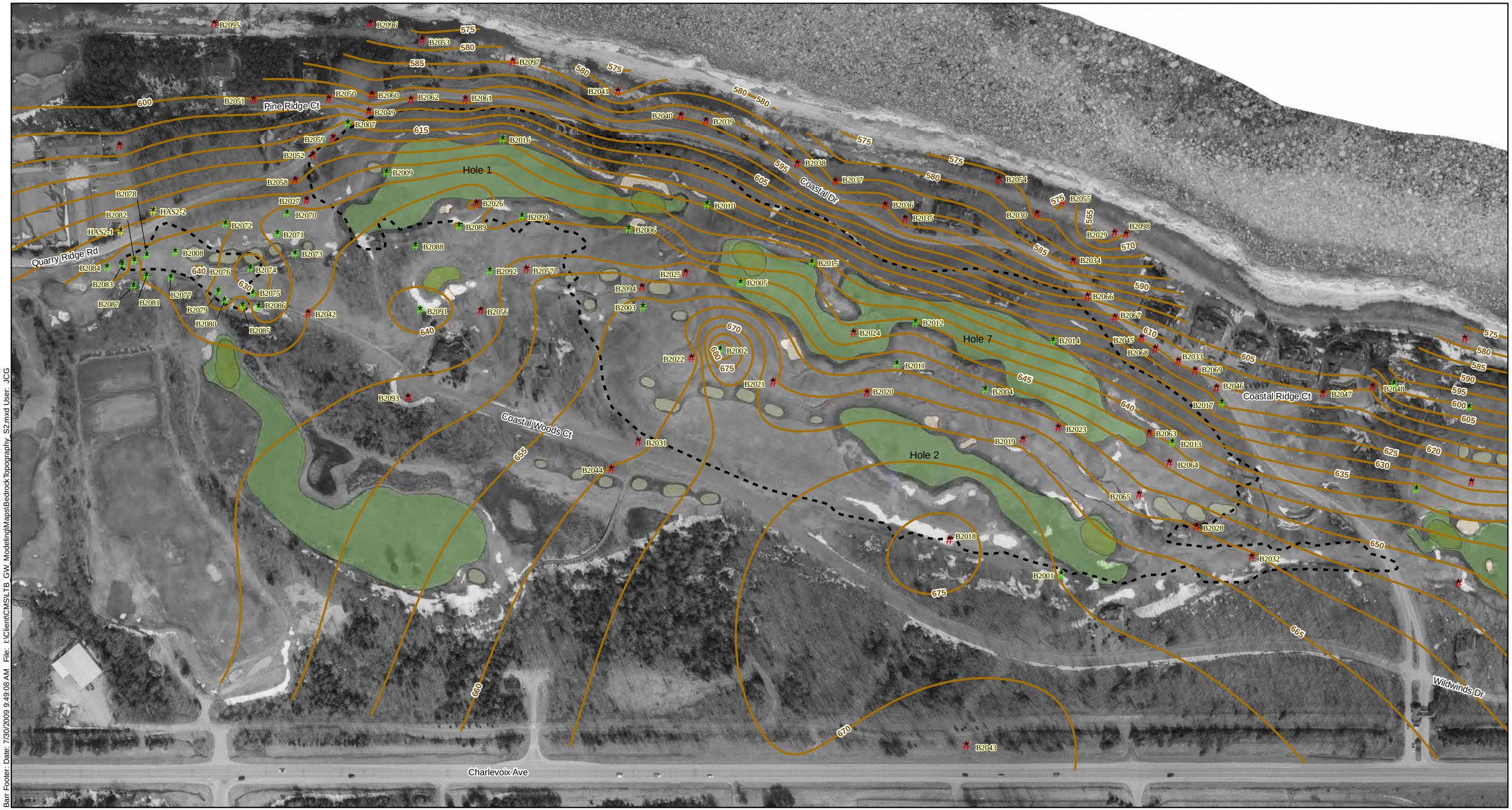
- Geoprobe Boring Location
- Rotosonic Boring Location
- Hand Auger Boring Location
- Bedrock Contour
- Approximate CKD Extent
- Fairway
- Green
- Sand
- Tee Boxes

175 87.5 0 175 Feet

Figure 3-2a

BEDROCK TOPOGRAPHY
SEEP 1 CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR



Imagery: April 2005

- Geoprobe Boring Location
- Rotosonic Boring Location
- Hand Auger Boring Location
- Bedrock Contour
- Approximate CKD Extent
- Fairway
- Green
- Sand
- Tee Boxes

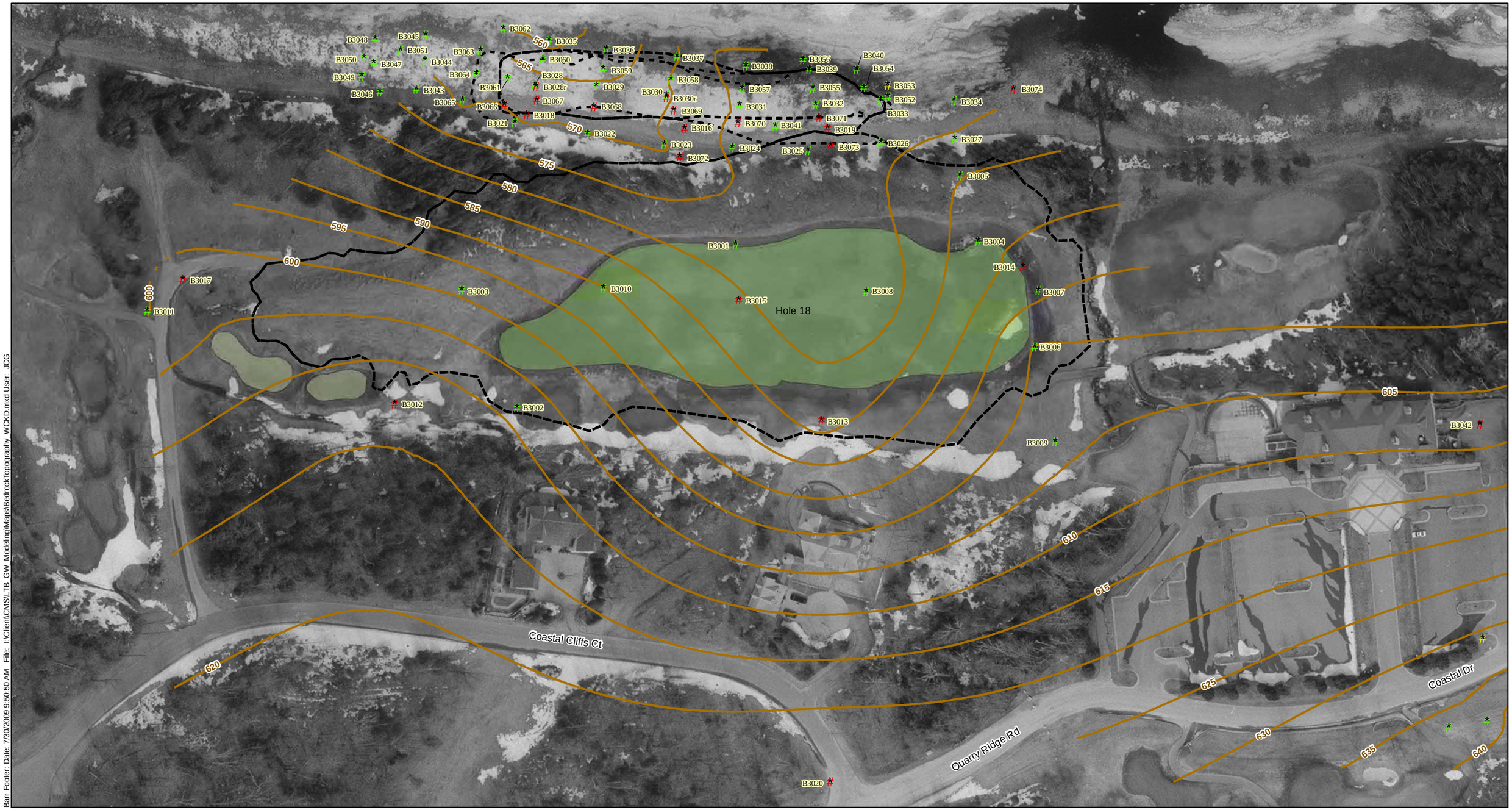
250 125 0 250 Feet

Figure 3-2b

BEDROCK TOPOGRAPHY
SEEP 2 CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 7/30/2009 9:49:08 AM File: I:\Client\CMS\LTB_GW_Modeling\Maps\BedrockTopography_S2.mxd User: JCG



Imagery: April 2005

Geoprobe Boring Location

Rotosonic Boring Location

Hand Auger Boring Location

Bedrock Contour

Approximate CKD Extent

Fairway

Green

Sand

Tee Boxes

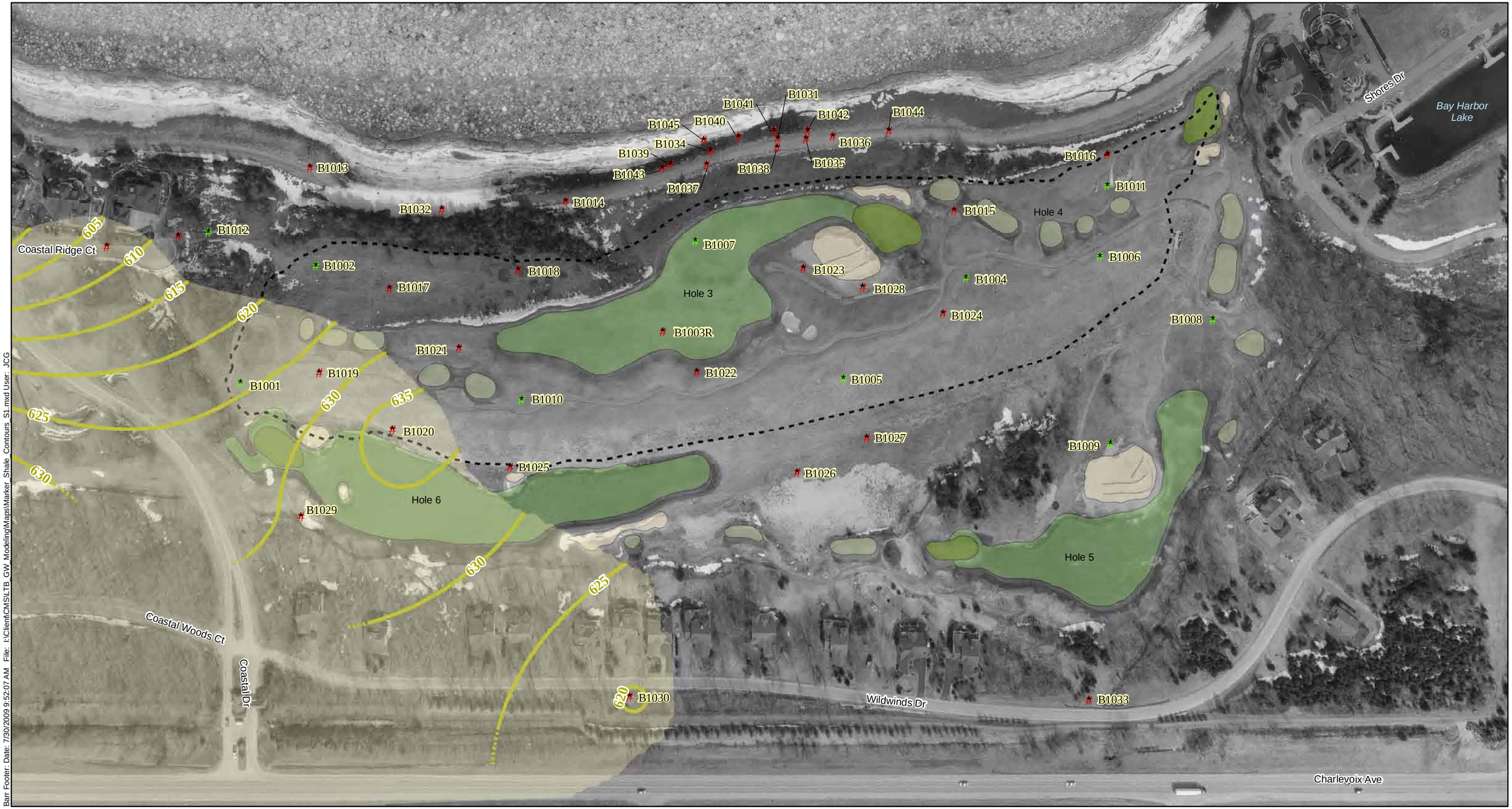
100 50 0 100 Feet

Figure 3-2c

BEDROCK TOPOGRAPHY
WEST CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 7/30/2009 9:50:50 AM File: I:\Client\CMS\LTB_GW_Modeling\Maps\BedrockTopography_WCKD.mxd User: JCG



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Imagery: April 2005

- Geoprobe Boring Location
- Rotosonic Boring Location
- Hand Auger Boring Location
- Approximate Shale Extent
- Shale Contour
- No Contour Data
- Approximate CKD Extent
- Fairway
- Green
- Sand
- Tee Boxes

175 87.5 0 175 Feet

Figure 3-3a

SHALE CONTOURS
SEEP 1 CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 7/30/2009 9:53:57 AM File: I:\Client\CMS\LTB_GW_Modeling\Maps\Marker_Shale_Contours_S2.mxd User: JCG

Imagery: April 2005

Geoprobe Boring Location
Rotosonic Boring Location
Hand Auger Boring Location

Shale Contour
No Contour Data
Approximate Shale Extent
Approximate CKD Extent

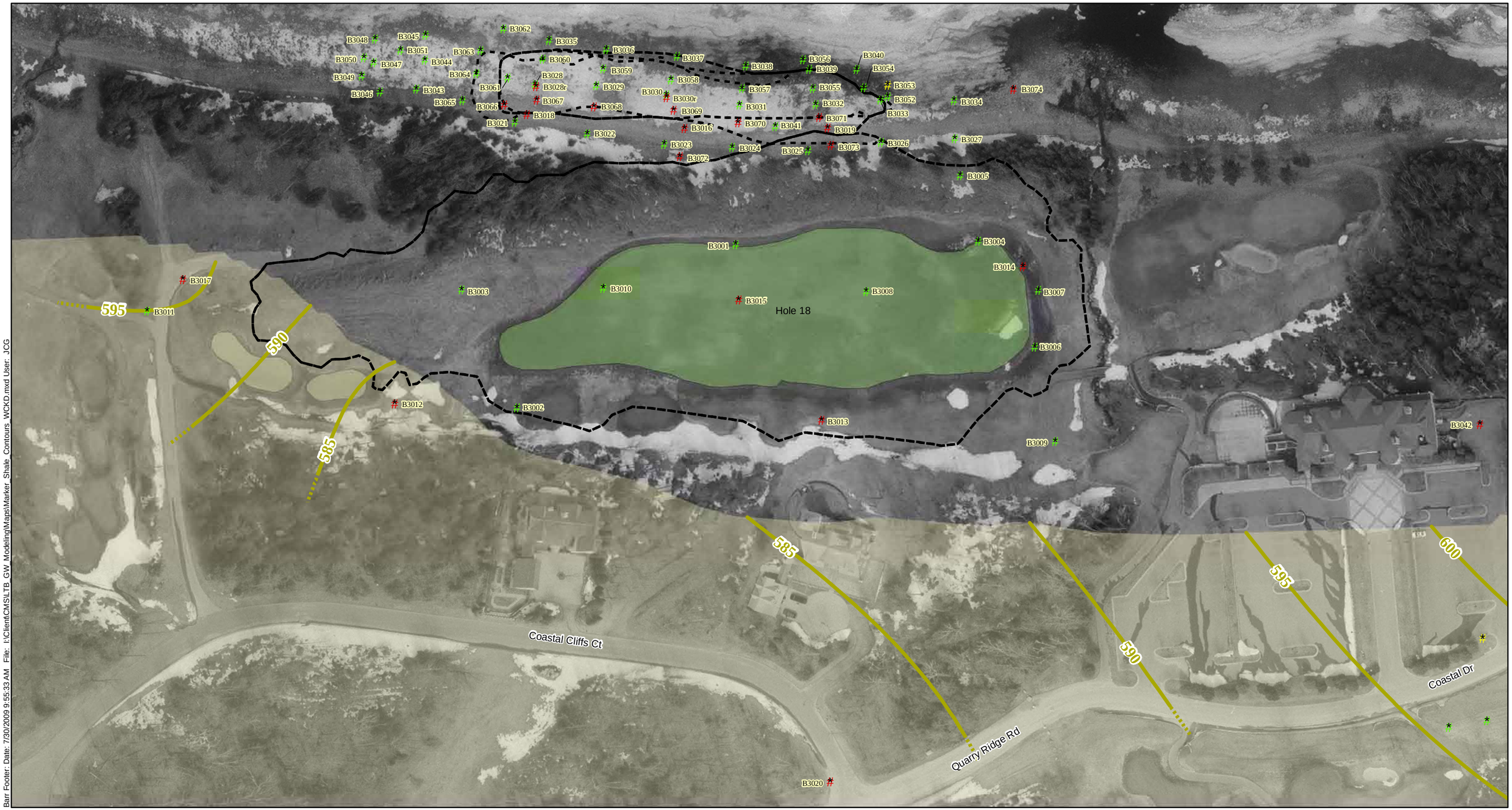
Fairway
Green
Sand
Tee Boxes

250 125 0 Feet

Figure 3-3b

SHALE CONTOURS
SEEP 2 CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR



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Imagery: April 2005

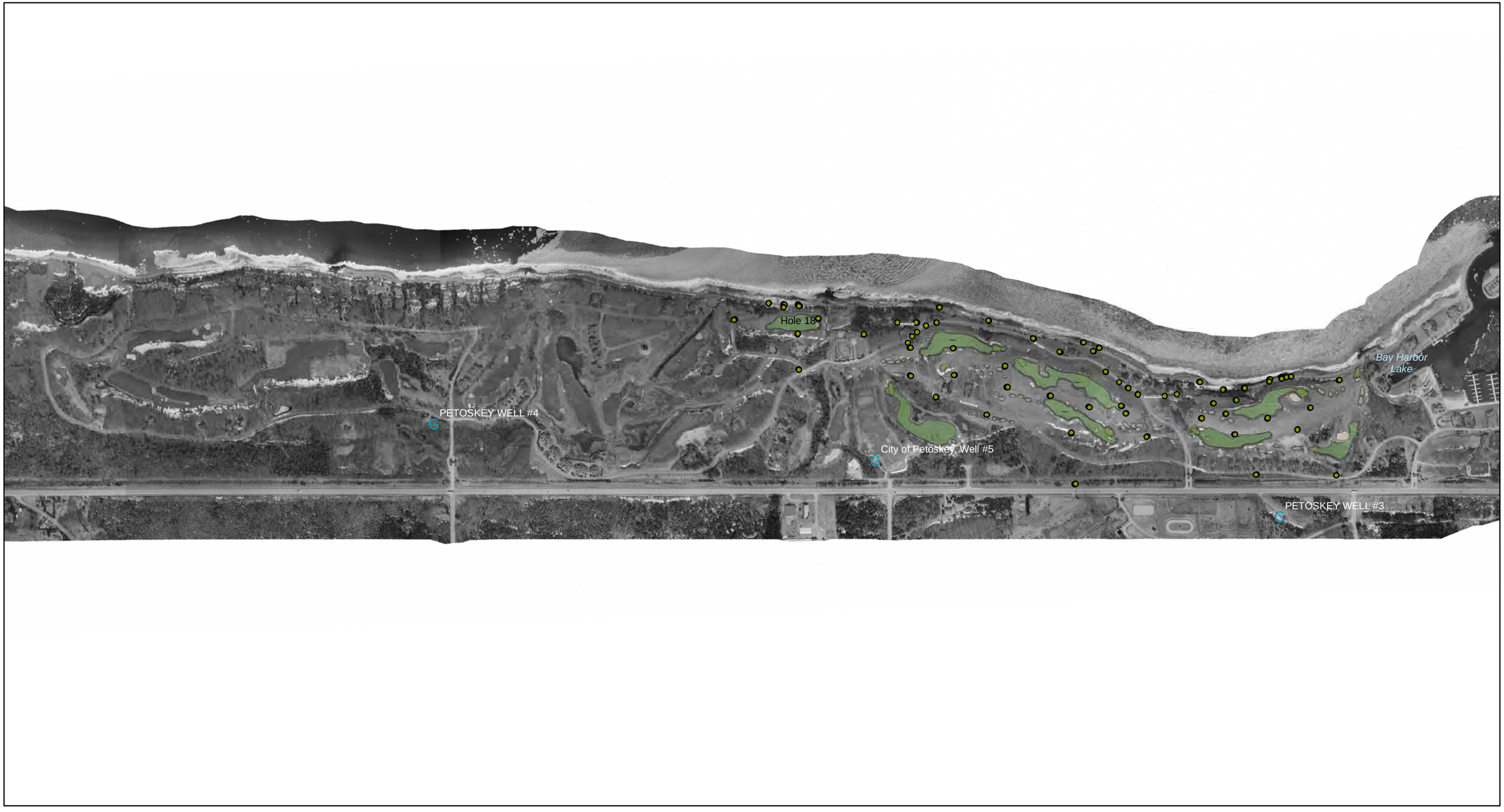
- Geoprobe Boring Location
- Rotosonic Boring Location
- Hand Auger Boring Location
- Shale Contour
- No Contour Data
- Approximate Shale Extent
- Approximate CKD Extent
- Fairway
- Green
- Sand
- Tee Boxes

100 50 0 100 Feet

Figure 3-3c

SHALE CONTOURS
WEST CKD AREA
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR



Imagery: April 2005

Fairway
Green
Sand
Tee Boxes

G Petoskey Municipal Wells
Monitoring Wells

250 0 250 250 500 750 1,000 1,250
Feet

Figure 3-4

LOCATIONS OF PETOSKEY
WELLS 3, 4, AND 5
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 7/30/2009 9:57:16 AM File: I:\Client\CMS\LTB_GW_Modeling\Maps\Petoskey_muni_wells_Locations.mxd User: JCG

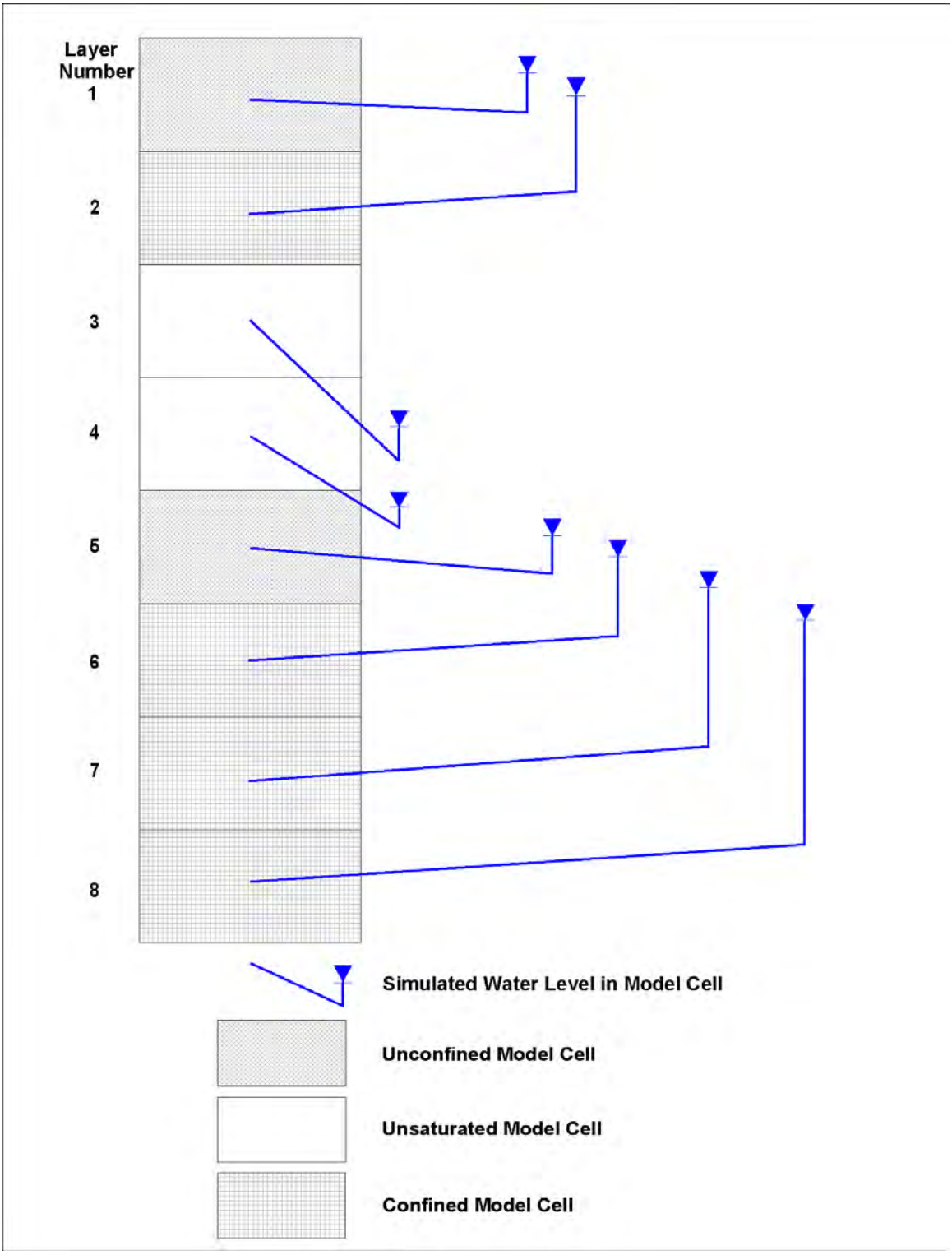


Figure 4-1

Schematic Showing Cell Types Based on Simulated Water Level

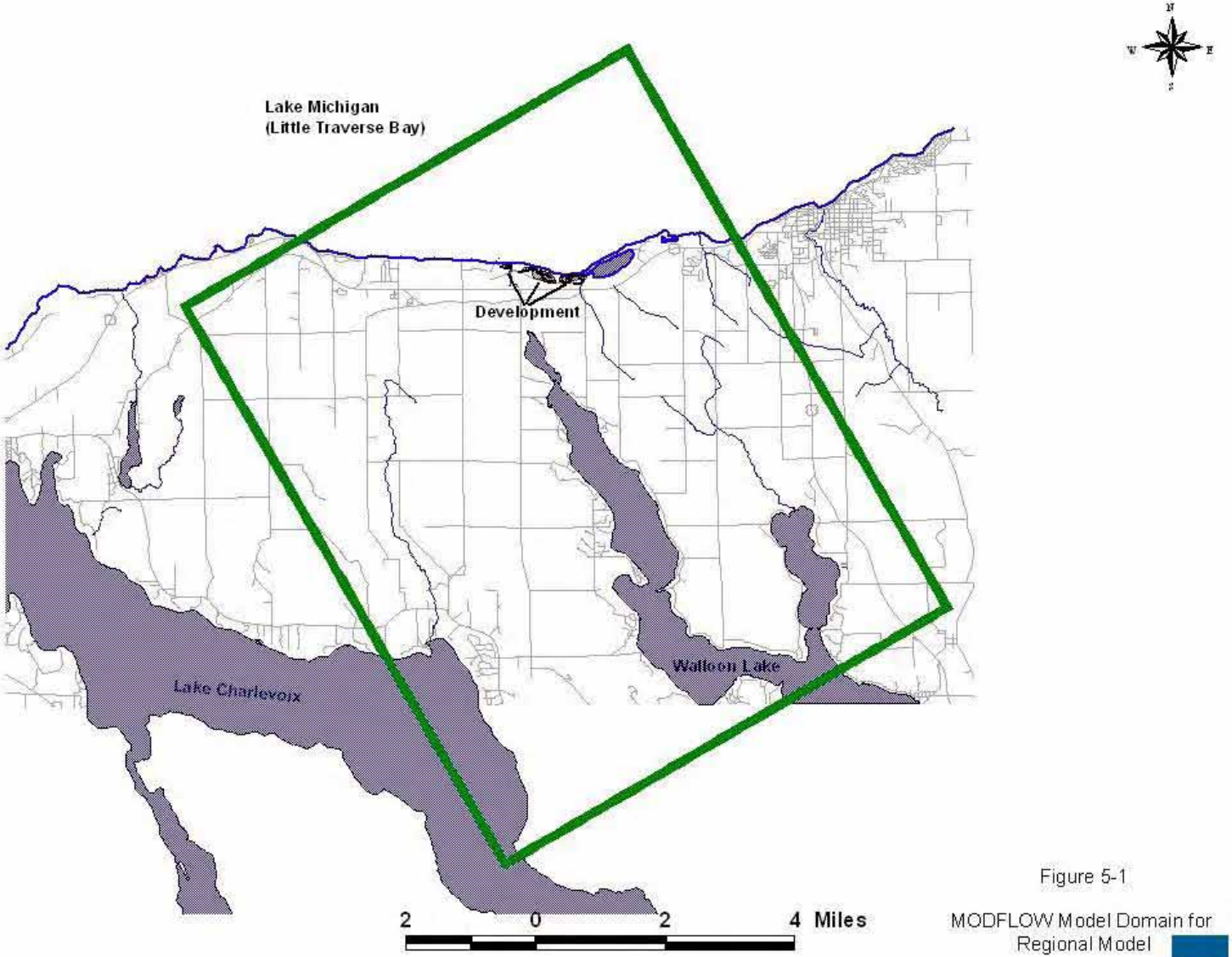


Figure 5-1

MODFLOW Model Domain for Regional Model

BARR

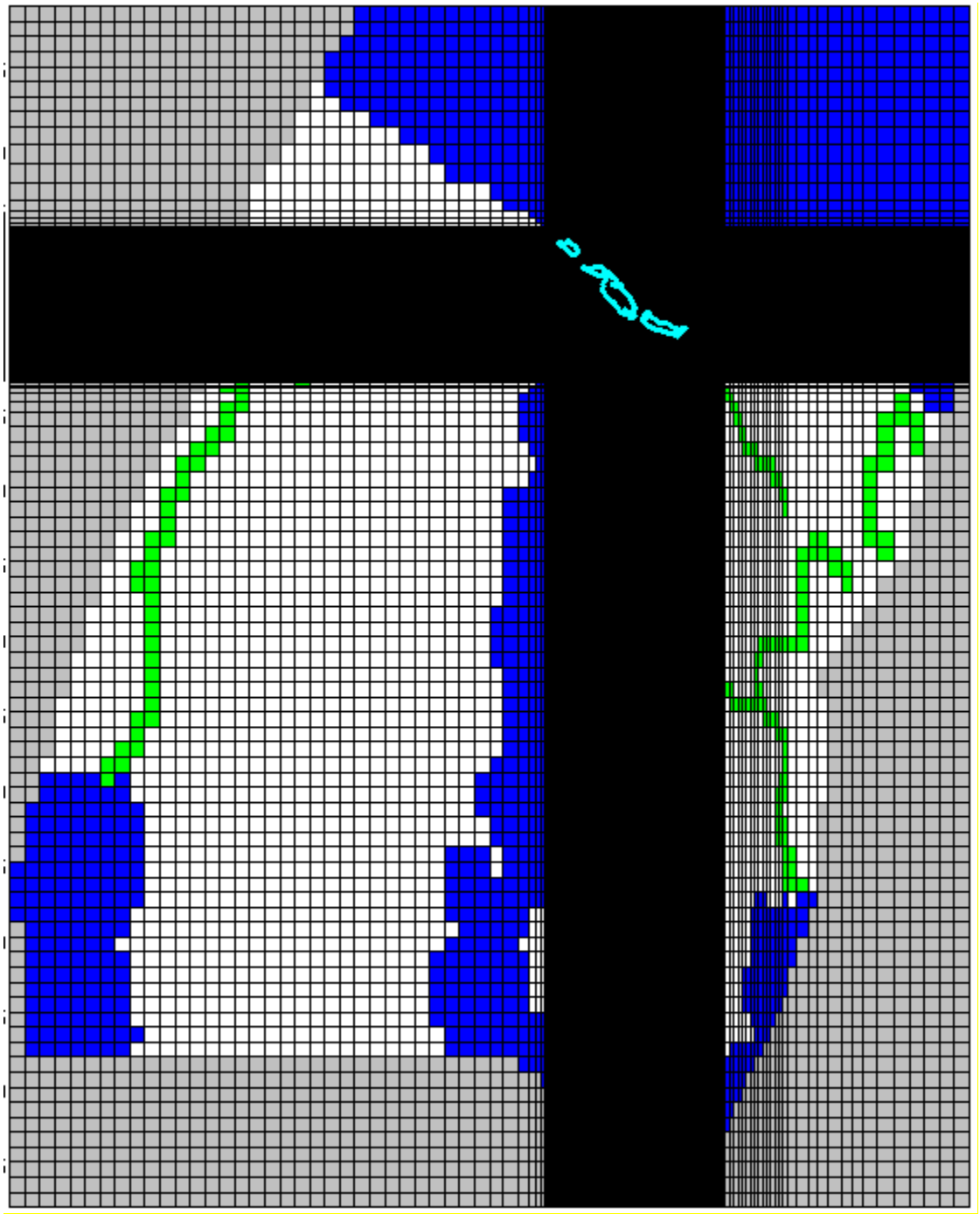


Figure 5-2

MODFLOW Model Grid for the Regional Model

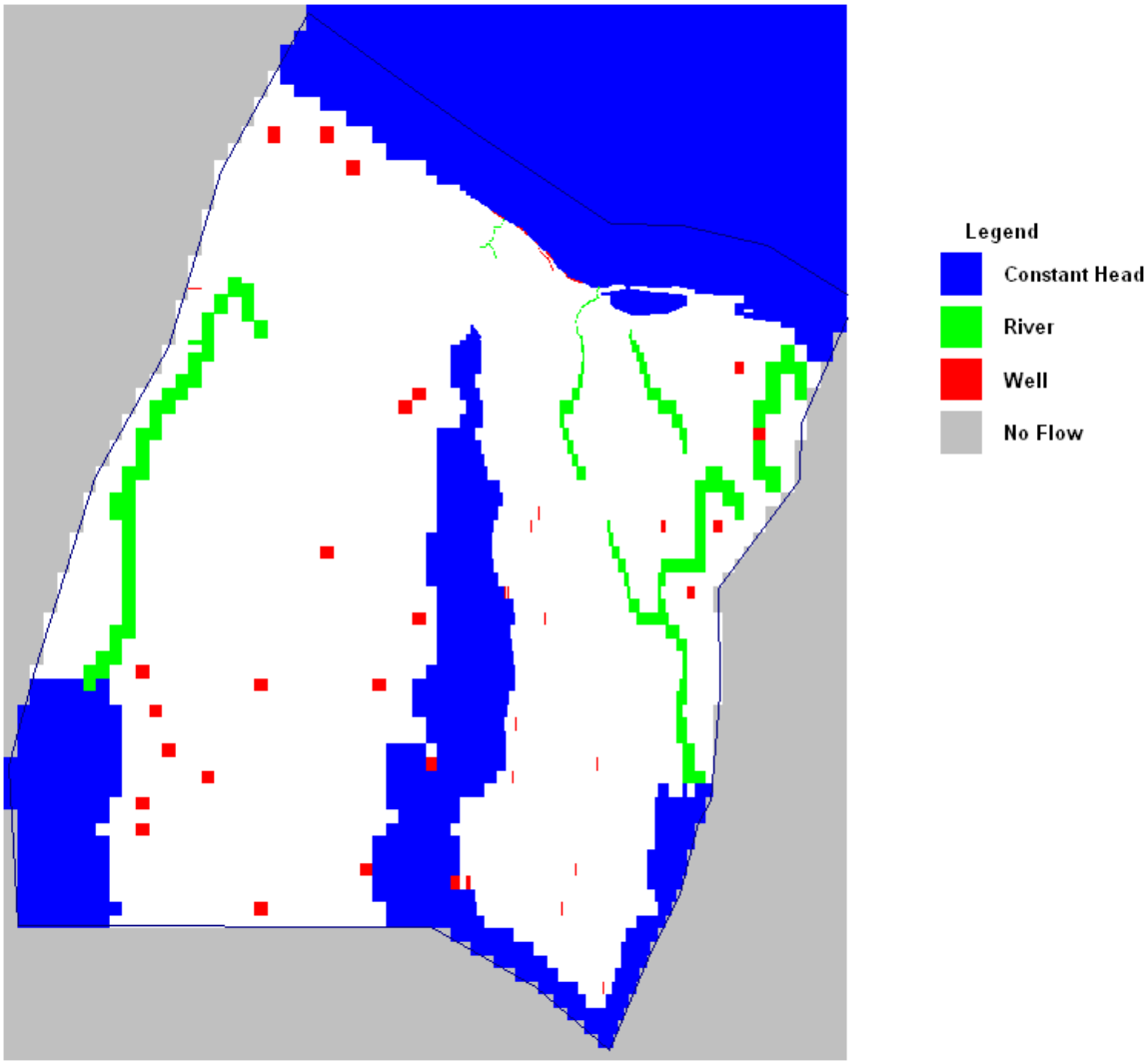


Figure 5-3

Layer 1 Boundary Conditions for the Regional Model

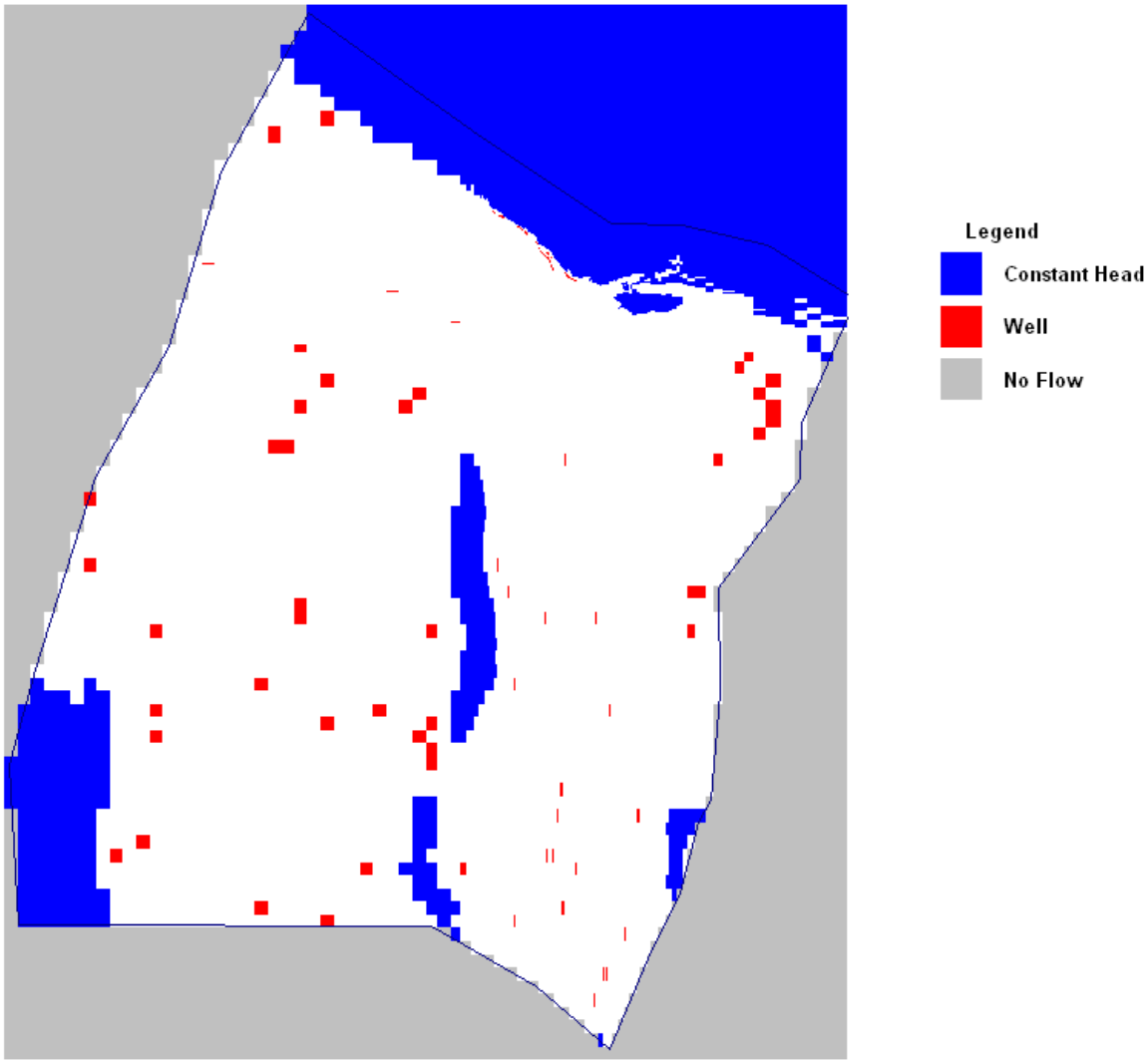


Figure 5-4

Layer 2 Boundary Conditions for the Regional Model

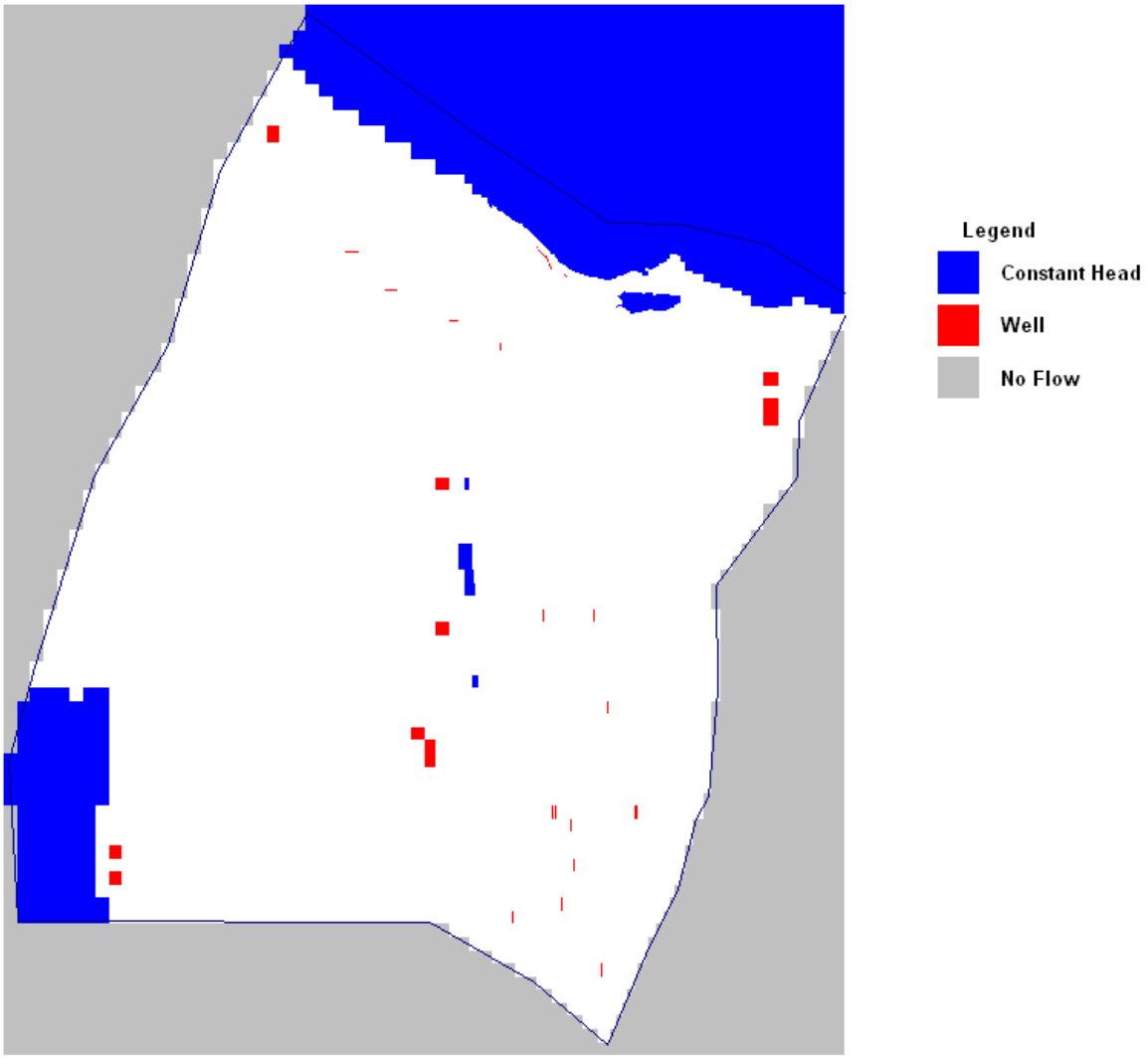


Figure 5-5

Layer 3 Boundary Conditions for the Regional Model

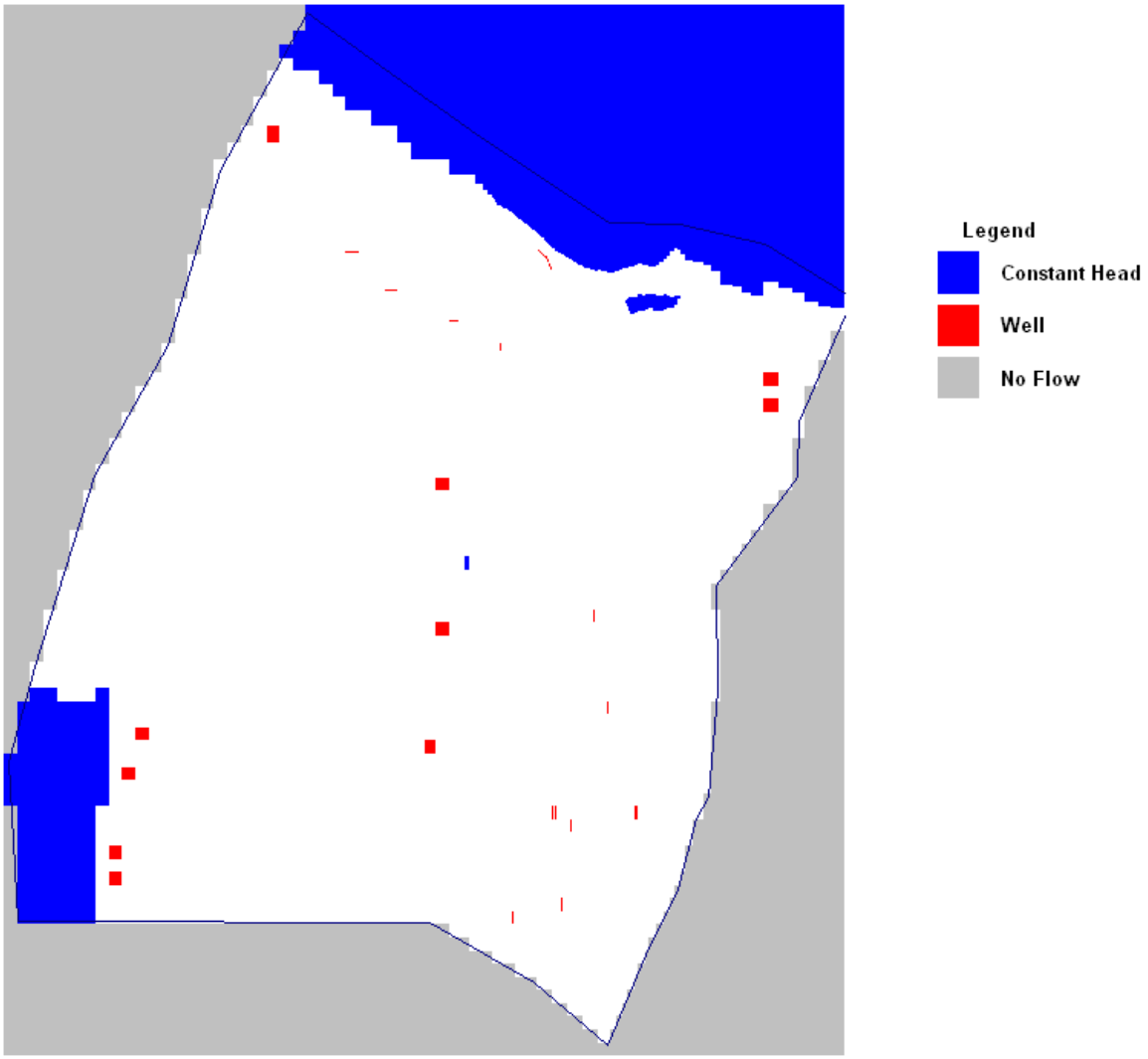


Figure 5-6

Layer 4 Boundary Conditions for the Regional Model

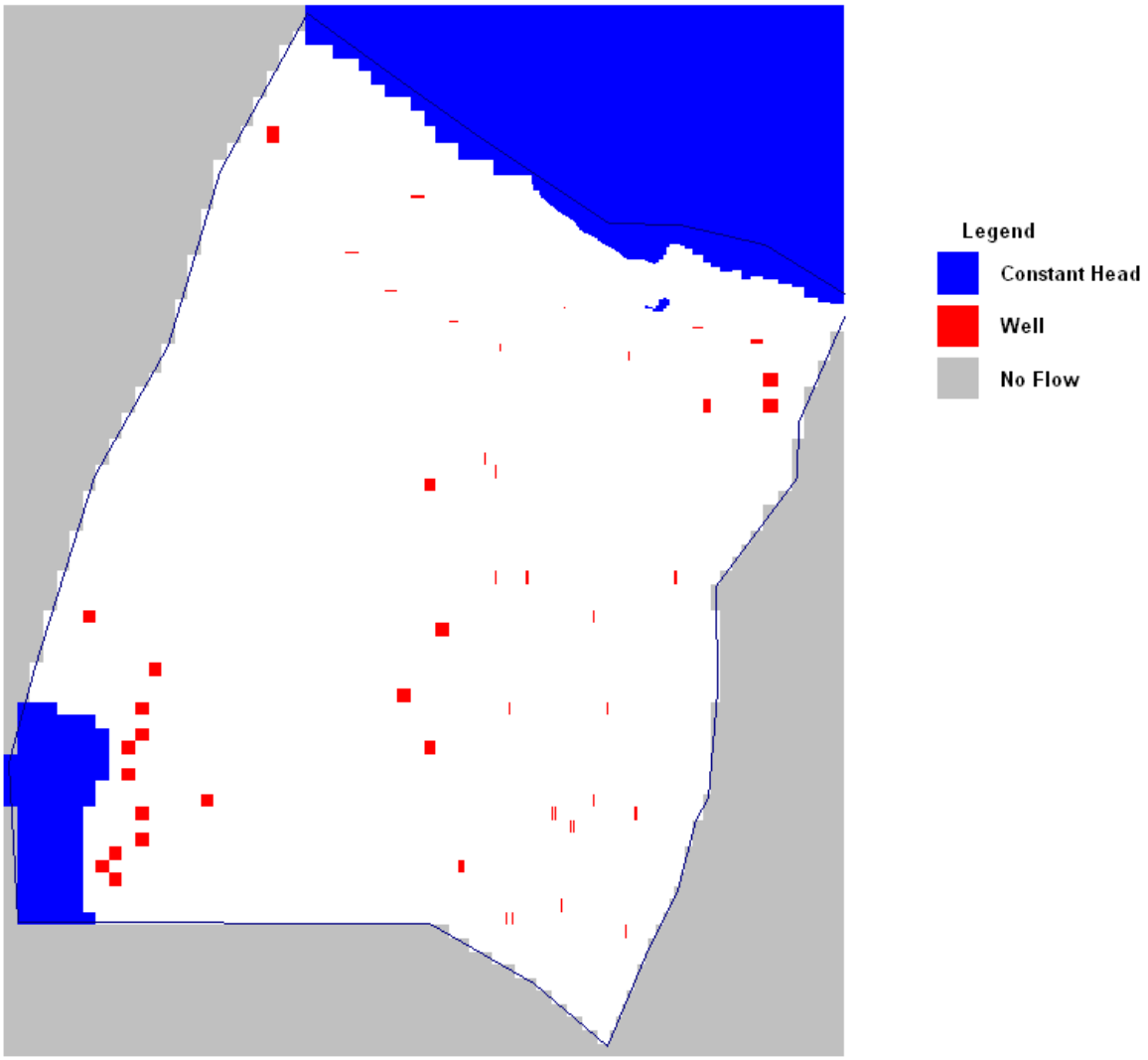


Figure 5-7

Layer 5 Boundary Conditions for the Regional Model

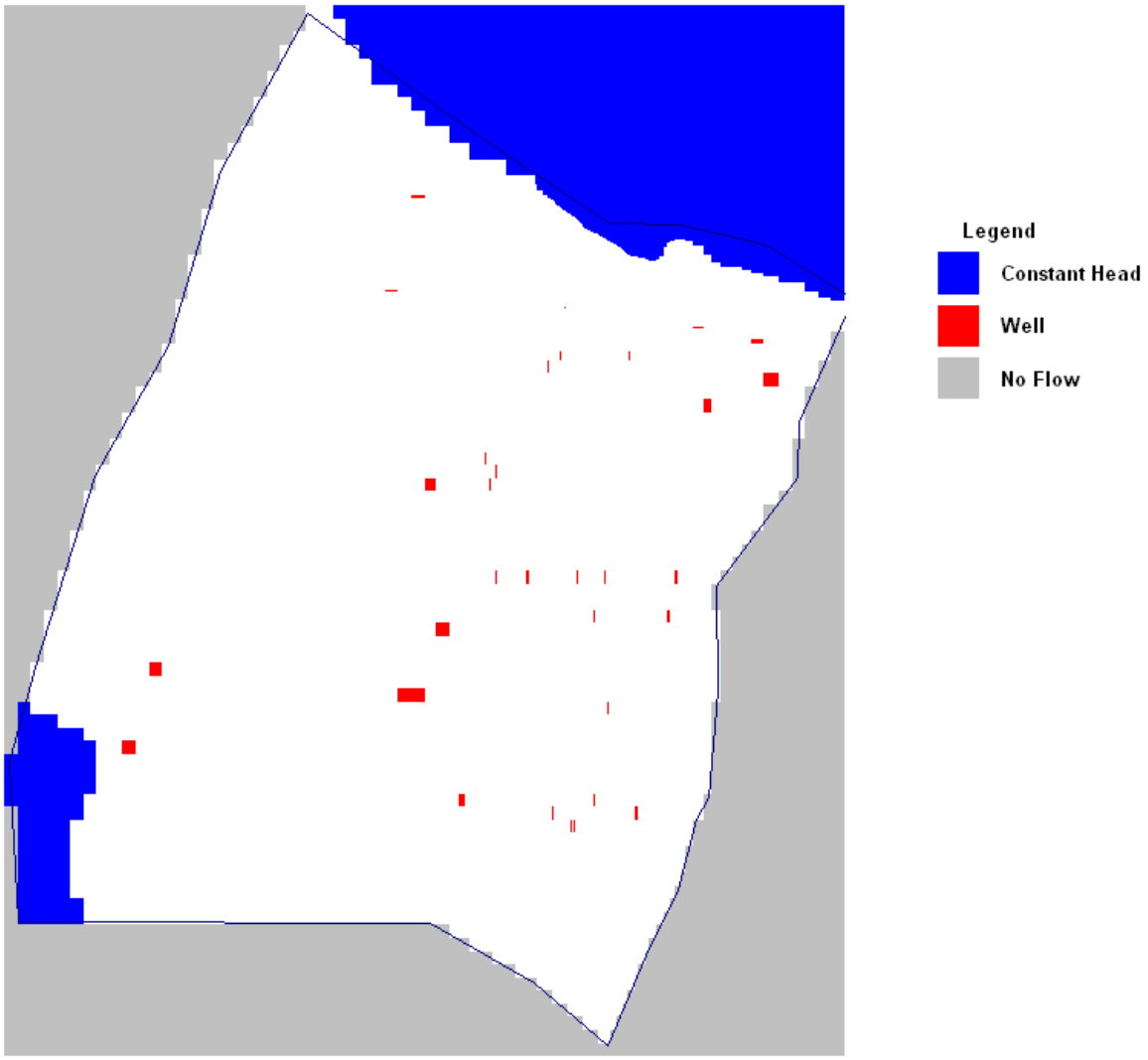


Figure 5-8

Layer 6 Boundary Conditions for the Regional Model

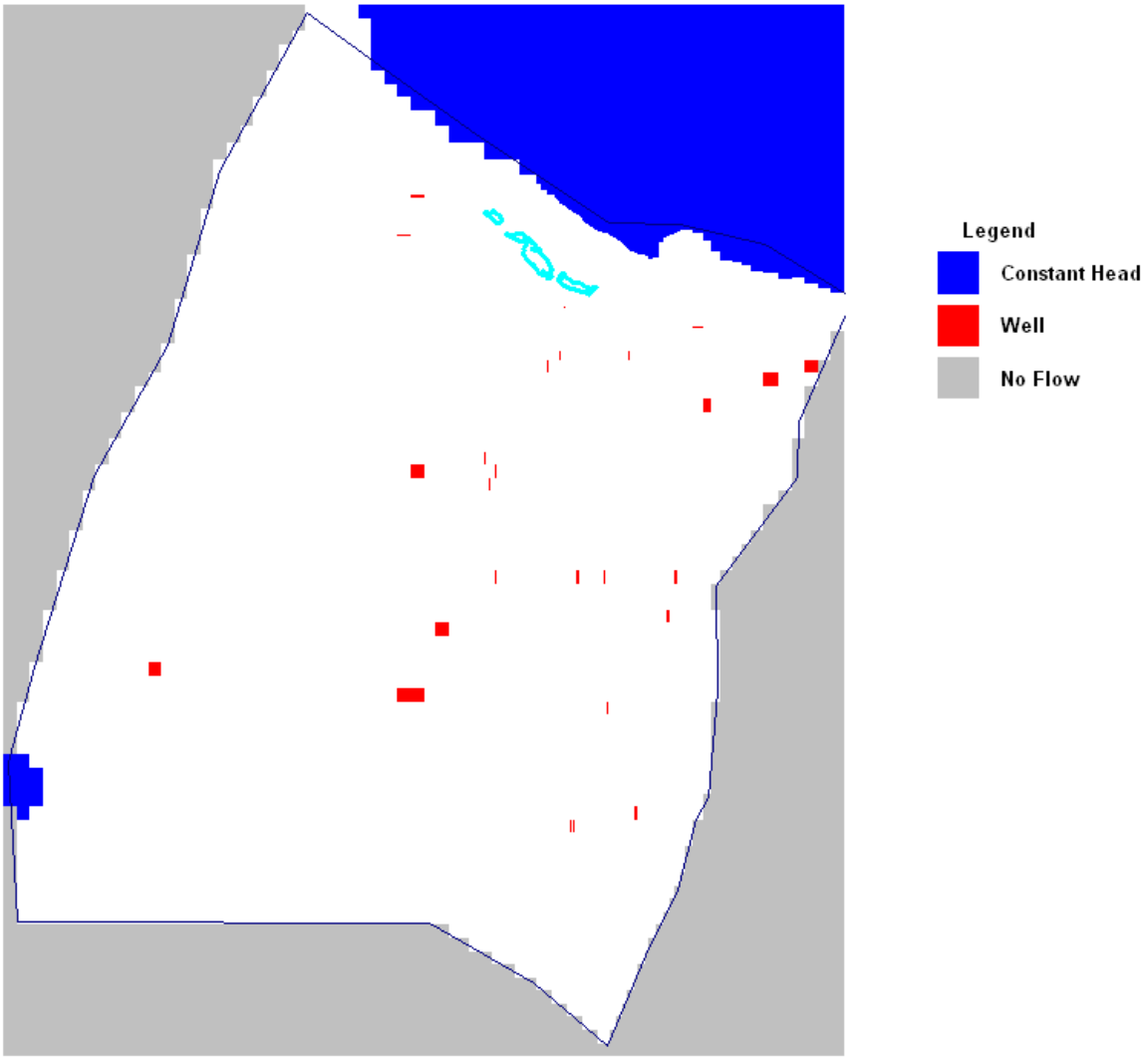


Figure 5-9

Layer 7 Boundary Conditions for the Regional Model

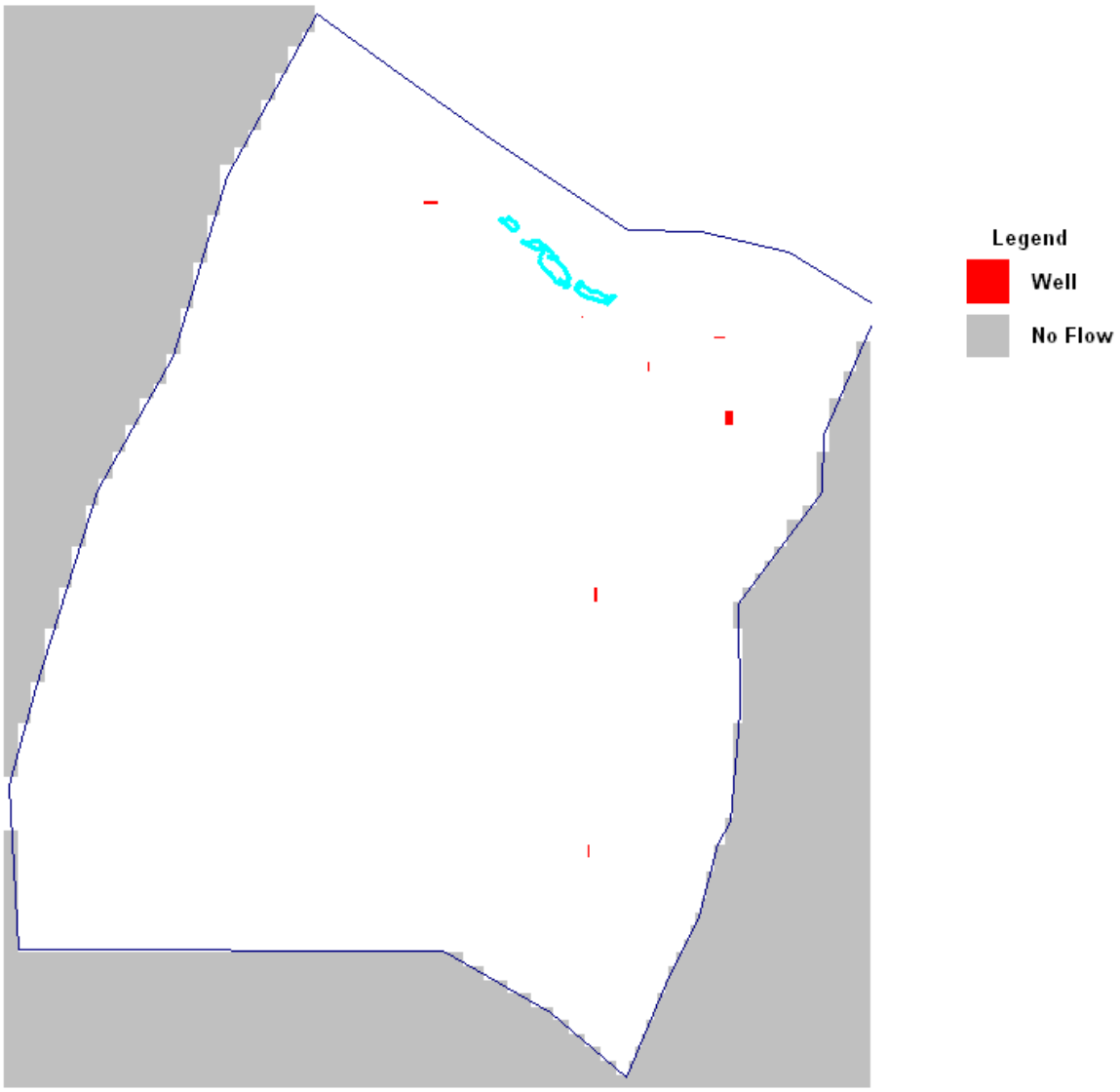


Figure 5-10

Layer 8 Boundary Conditions for the Regional Model

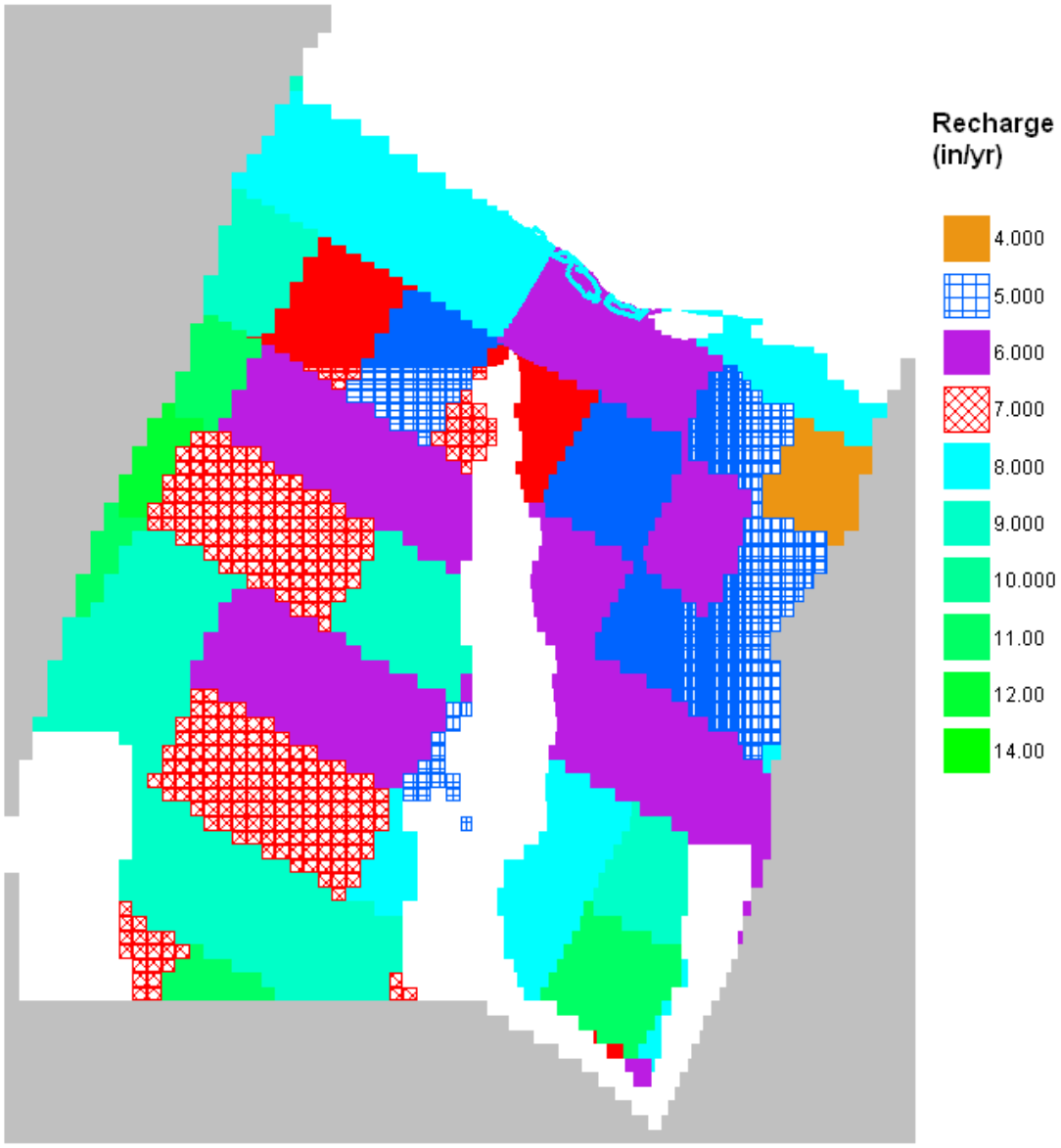


Figure 5-11

Initial Recharge Distribution for the Regional Model

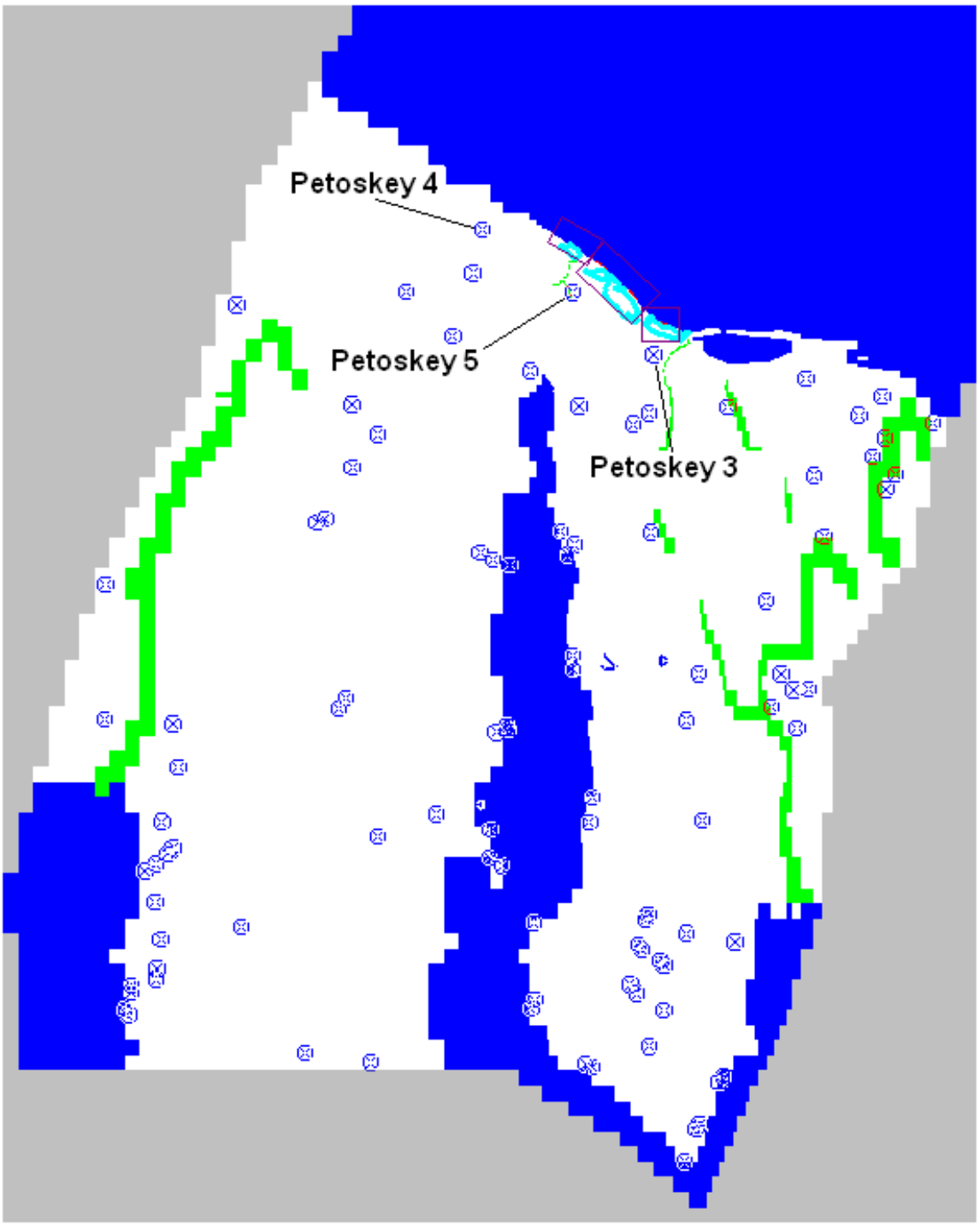


Figure 5-12

State Database Well Locations Within Regional Model Domain

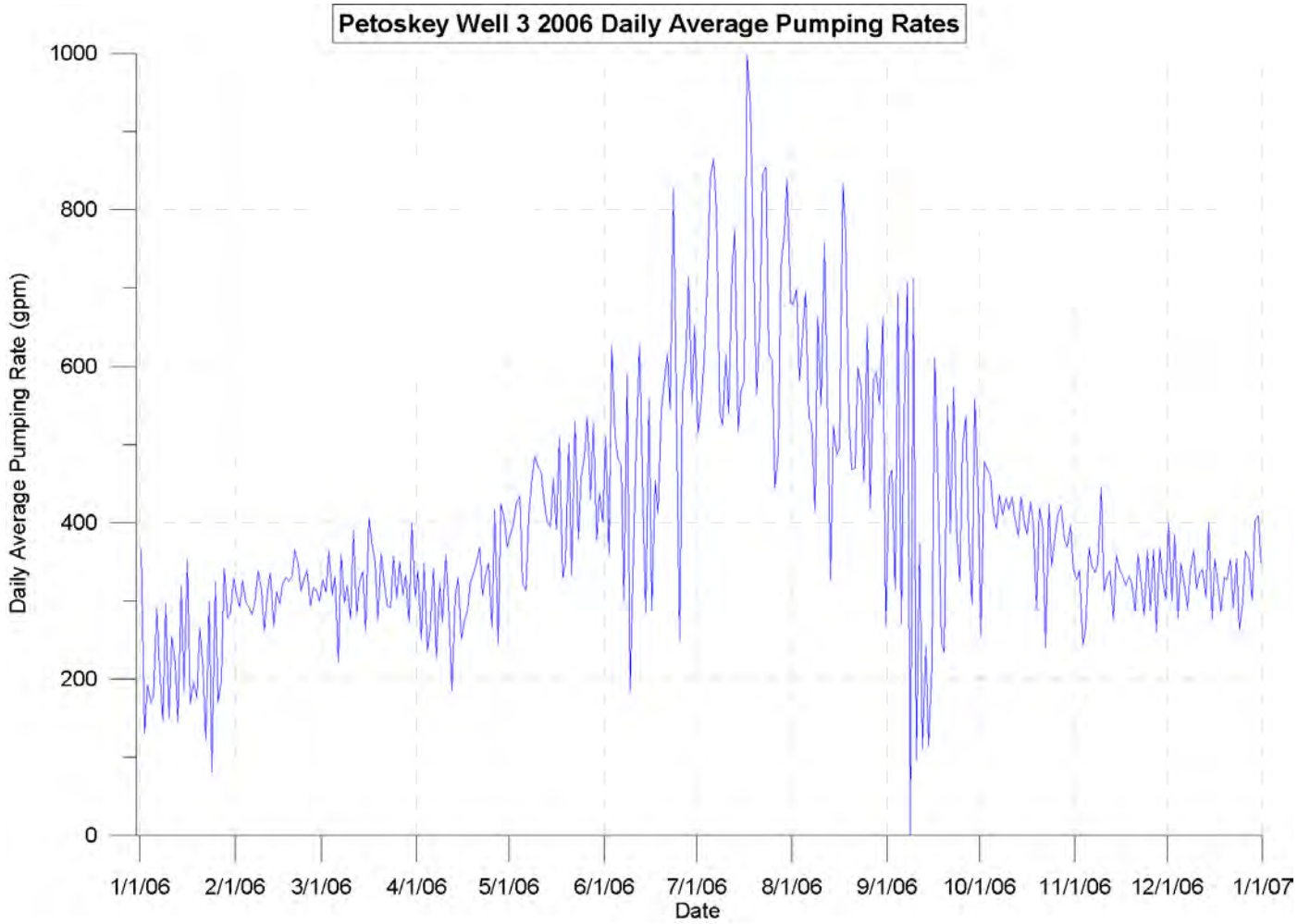


Figure 5-13

Petoskey Well 3 Daily Average Pumping Rates for 2006

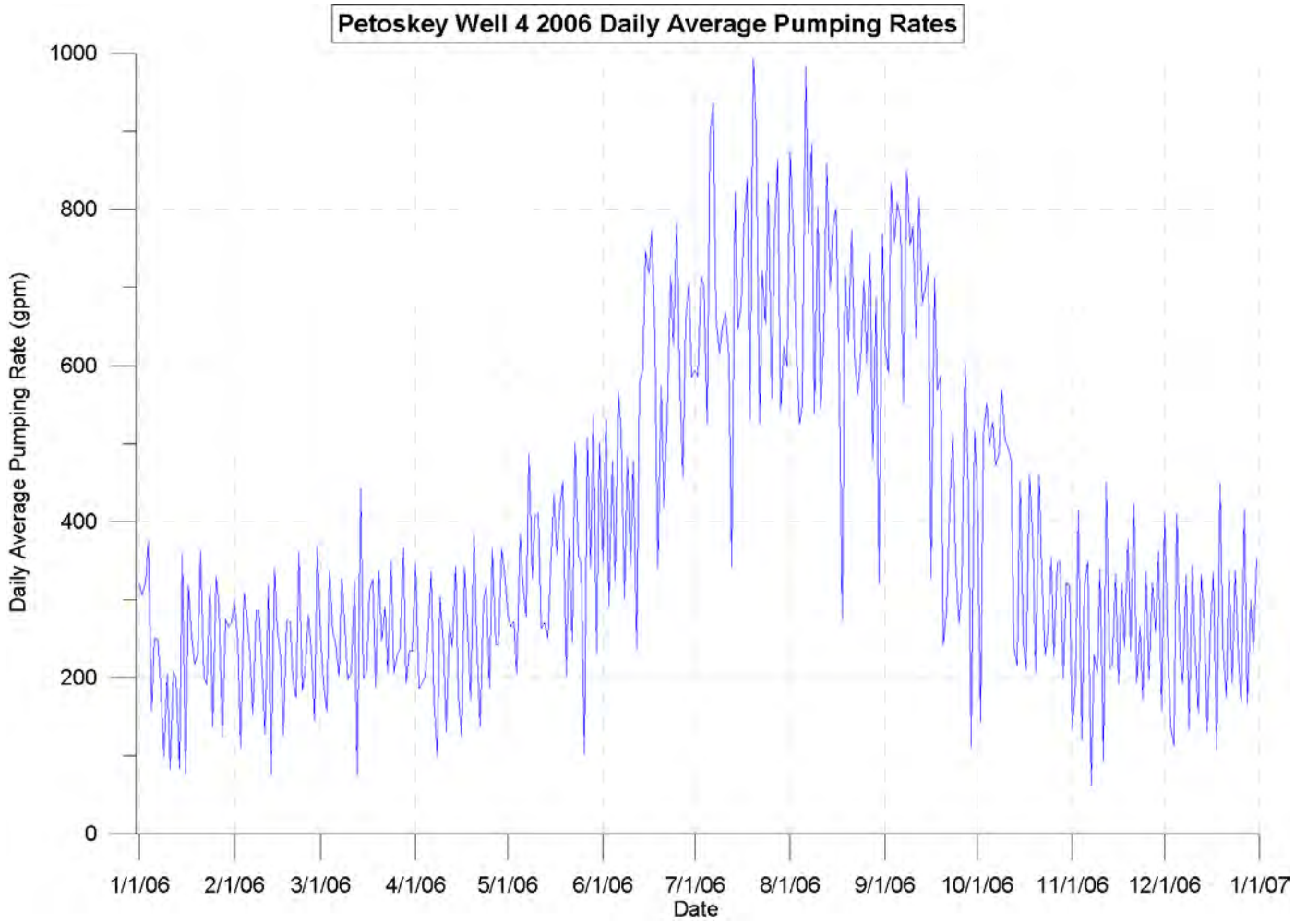


Figure 5-14

Petoskey Well 4 Daily Average Pumping Rates for 2006

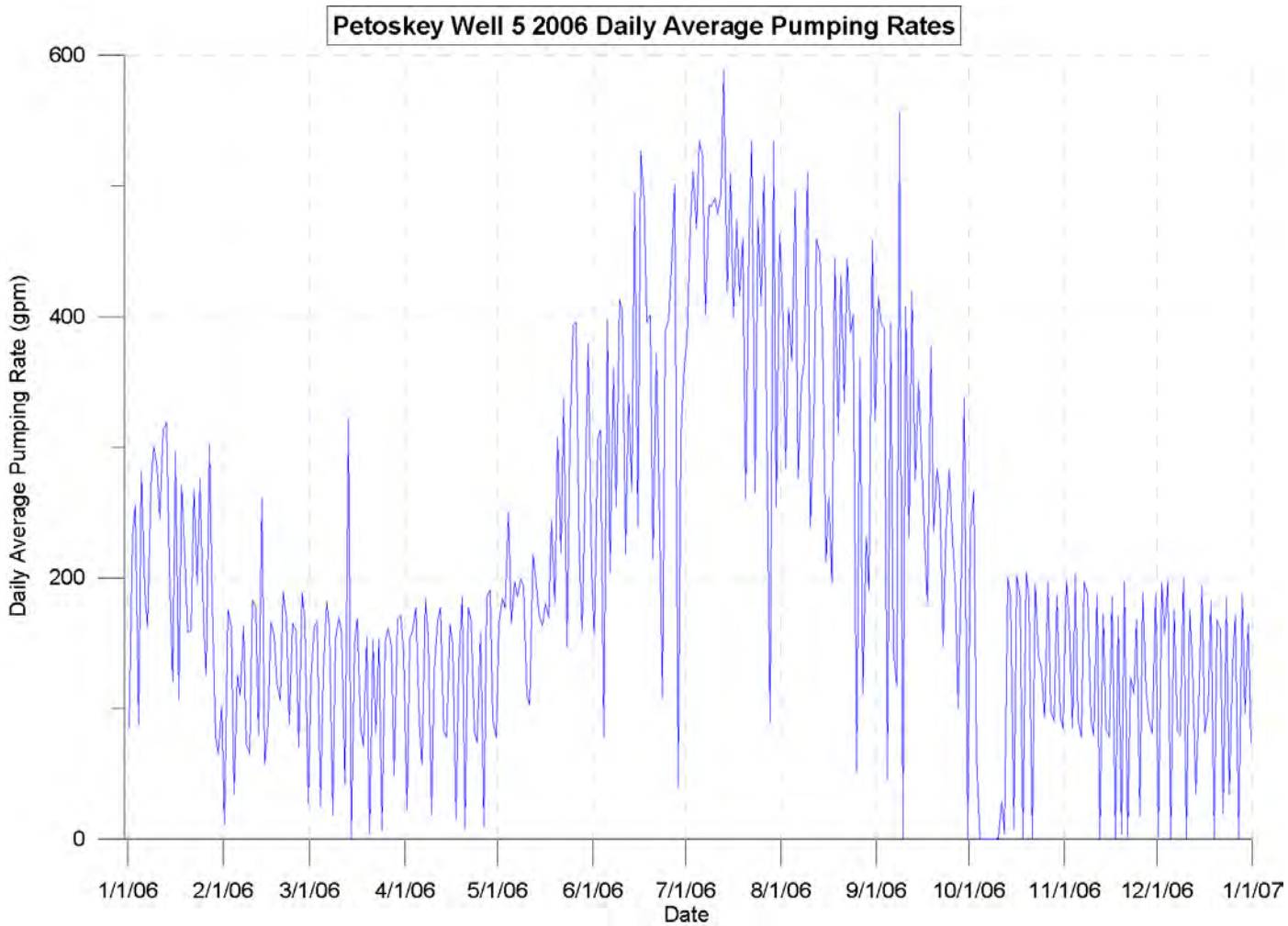


Figure 5-15

Petoskey Well 5 Daily Average Pumping Rates for 2006

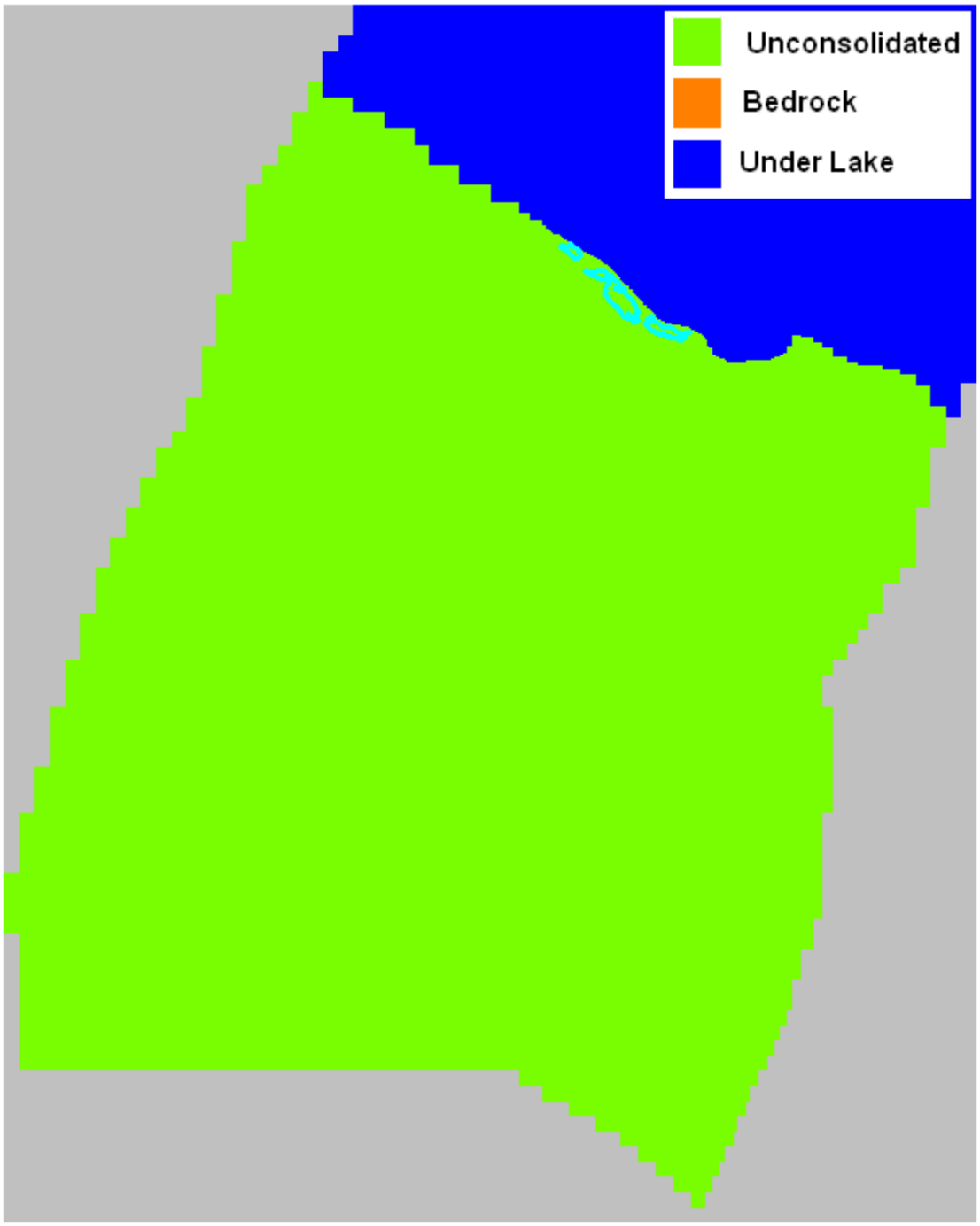


Figure 5-16

Hydraulic Conductivity Zones in Layer 1 of the Regional MODFLOW Model

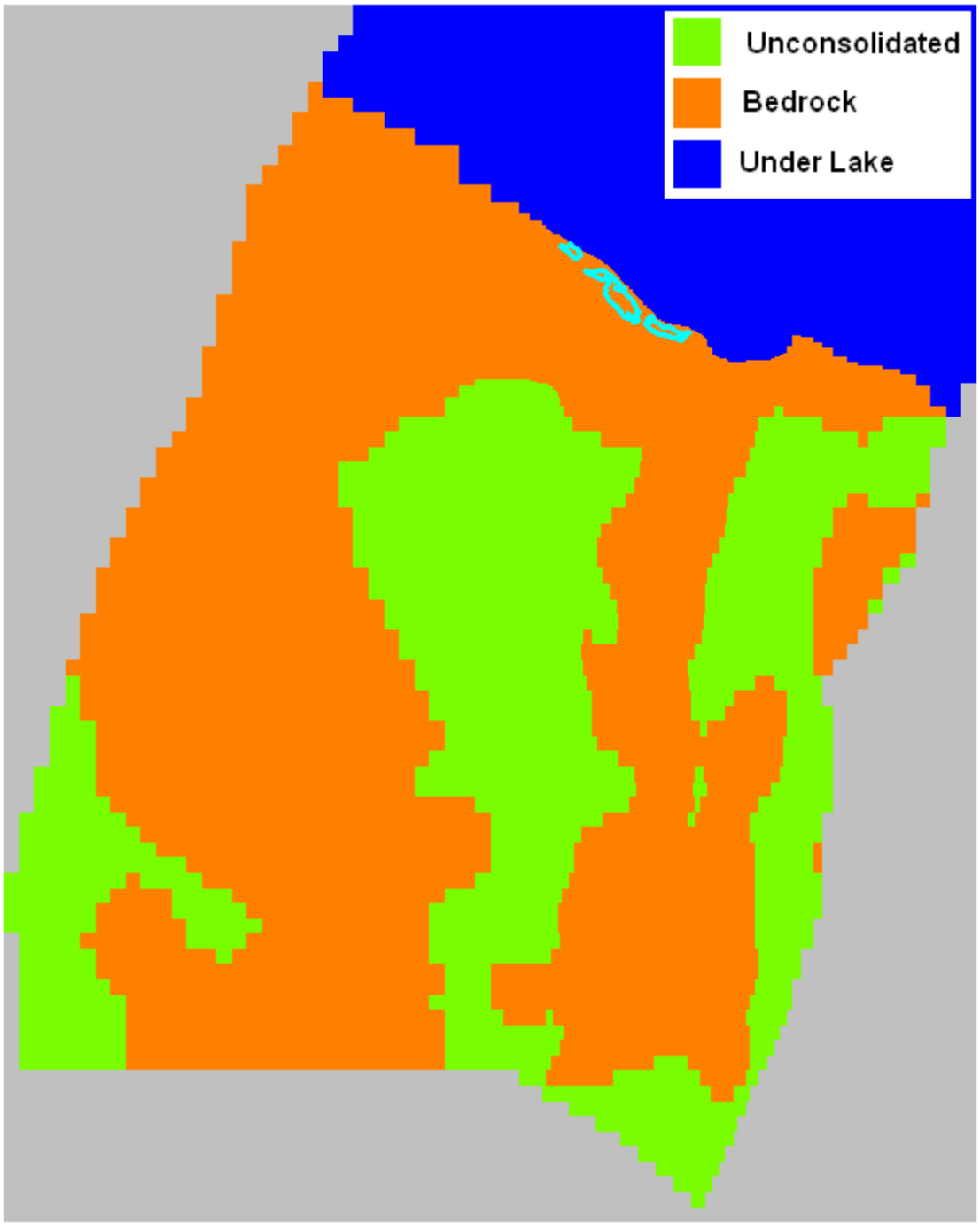


Figure 5-17

Hydraulic Conductivity Zones in Layer 2 of the Regional MODFLOW Model

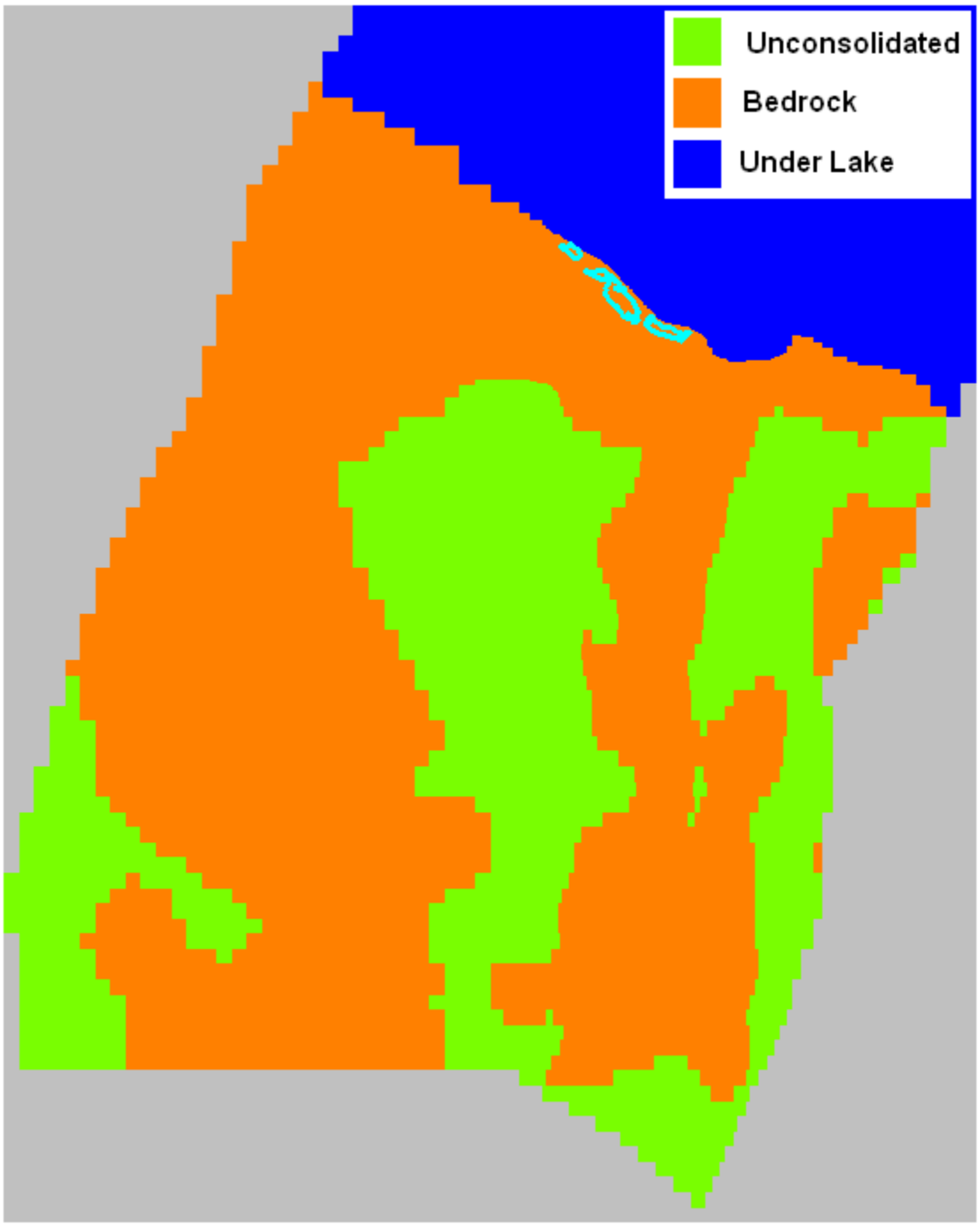


Figure 5-18

Hydraulic Conductivity Zones in Layer 3 of the Regional MODFLOW Model

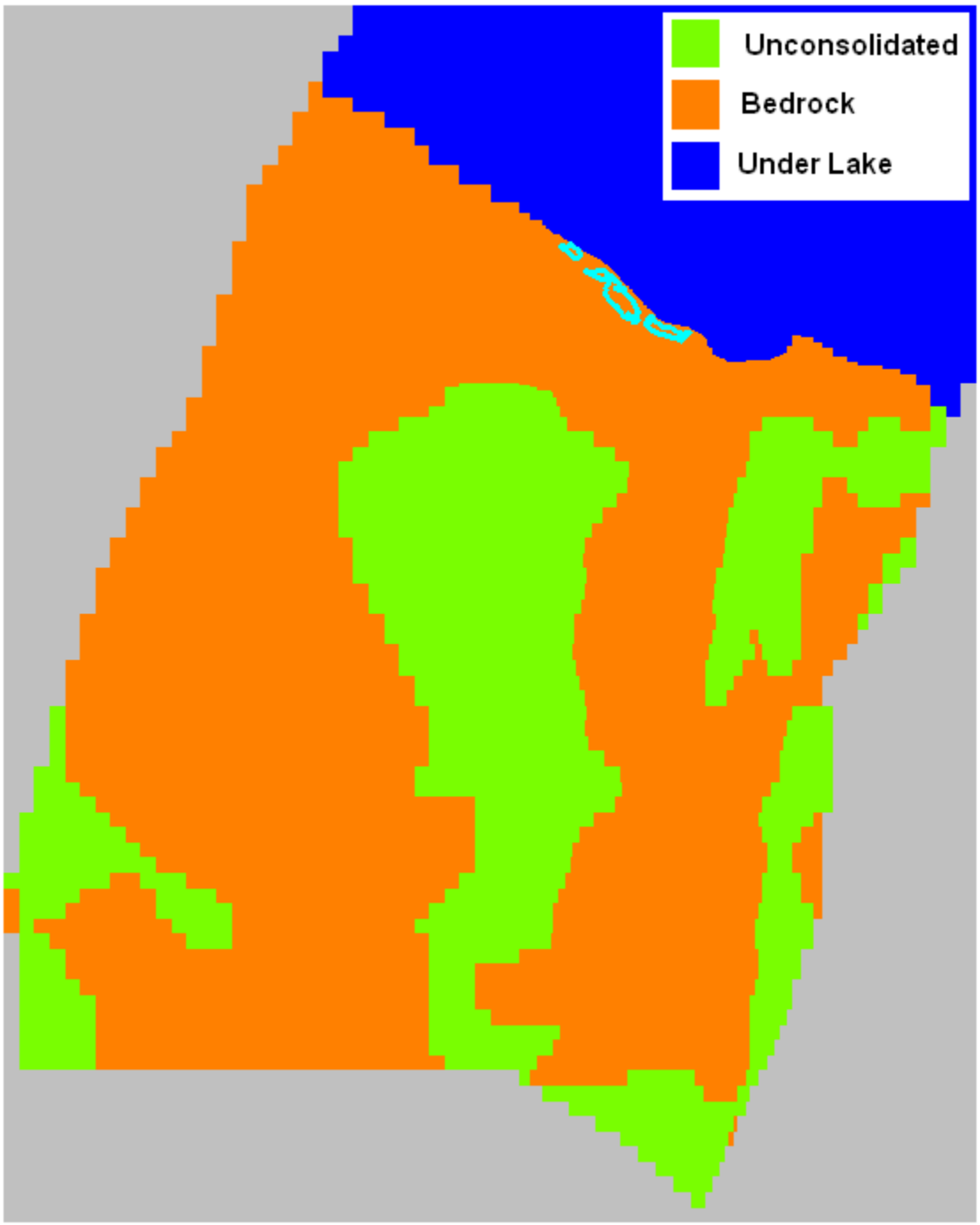


Figure 5-19

Hydraulic Conductivity Zones in Layer 4 of the Regional MODFLOW Model

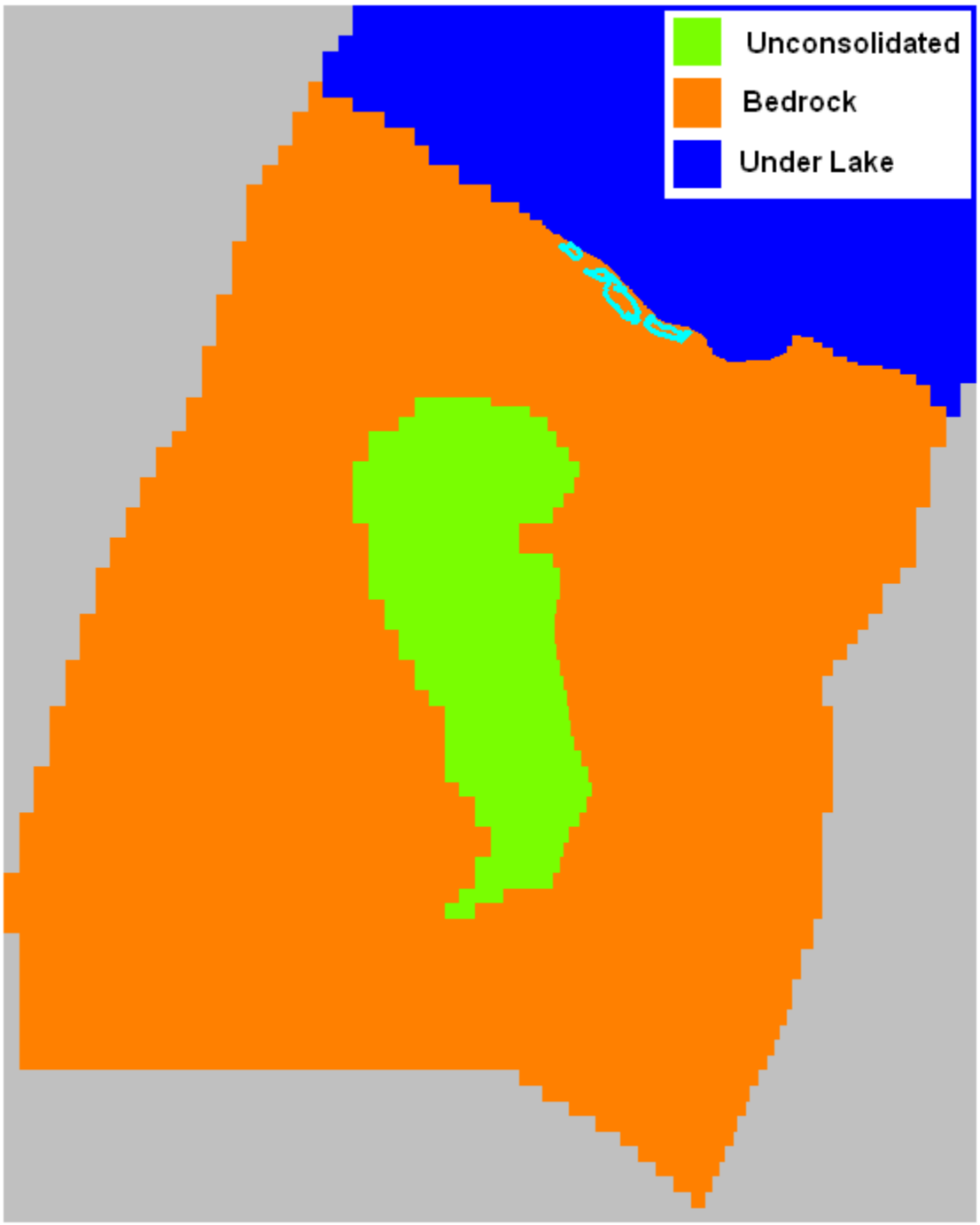


Figure 5-20

Hydraulic Conductivity Zones in Layer 5 of the Regional MODFLOW Model

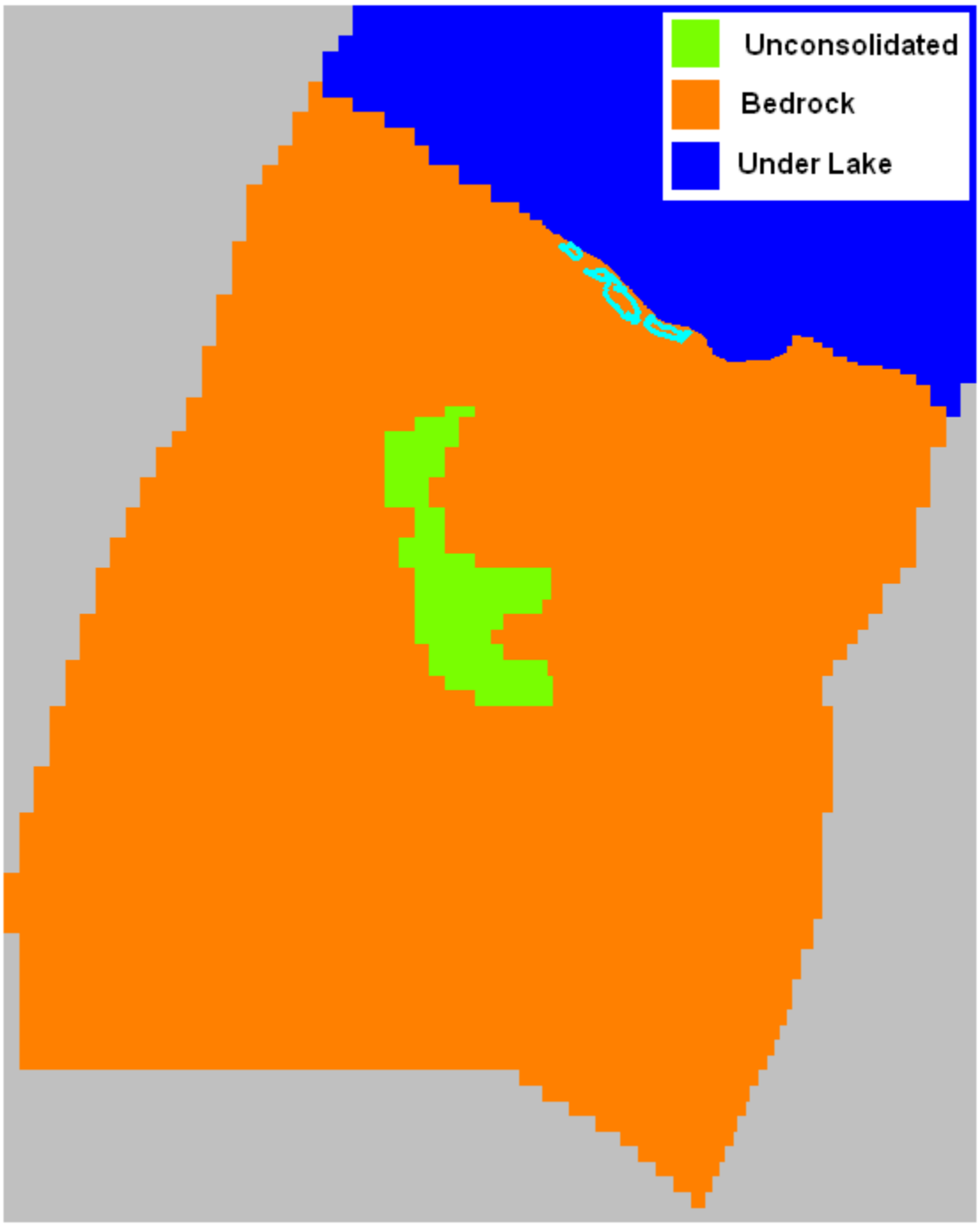


Figure 5-21

Hydraulic Conductivity Zones in Layer 6 of the Regional MODFLOW Model

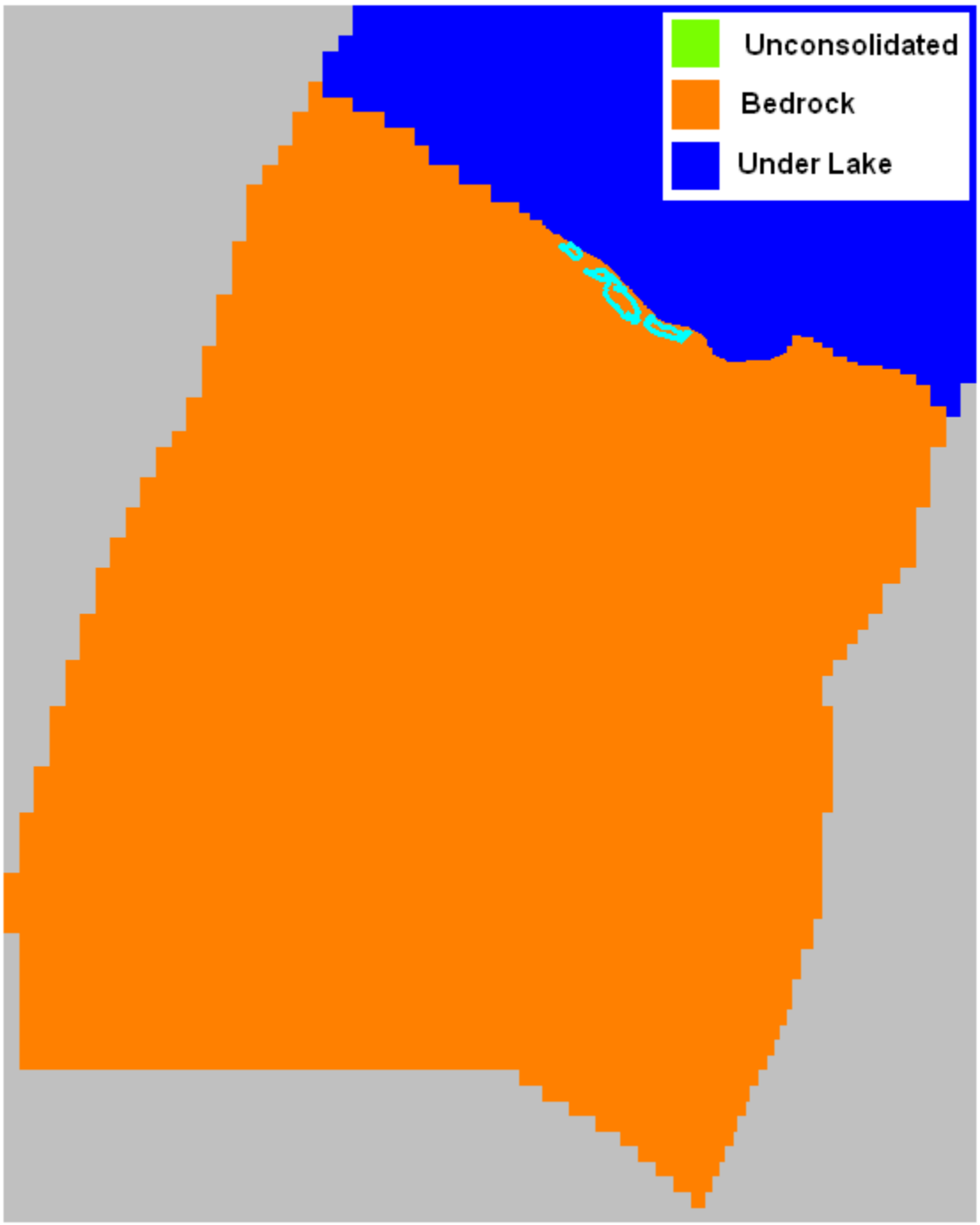


Figure 5-22

Hydraulic Conductivity Zones in Layers 7 and 8 of the Regional MODFLOW Model

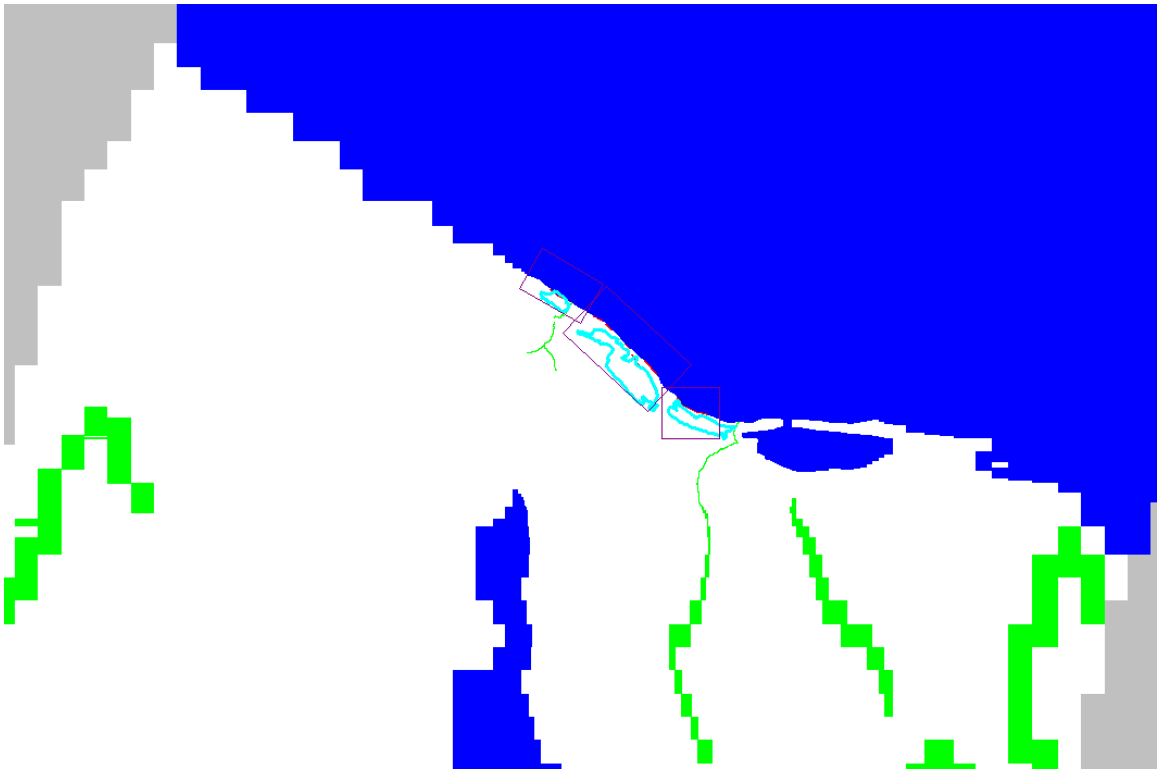


Figure 5-23

Locations of the TMR Models in the Regional Flow Model

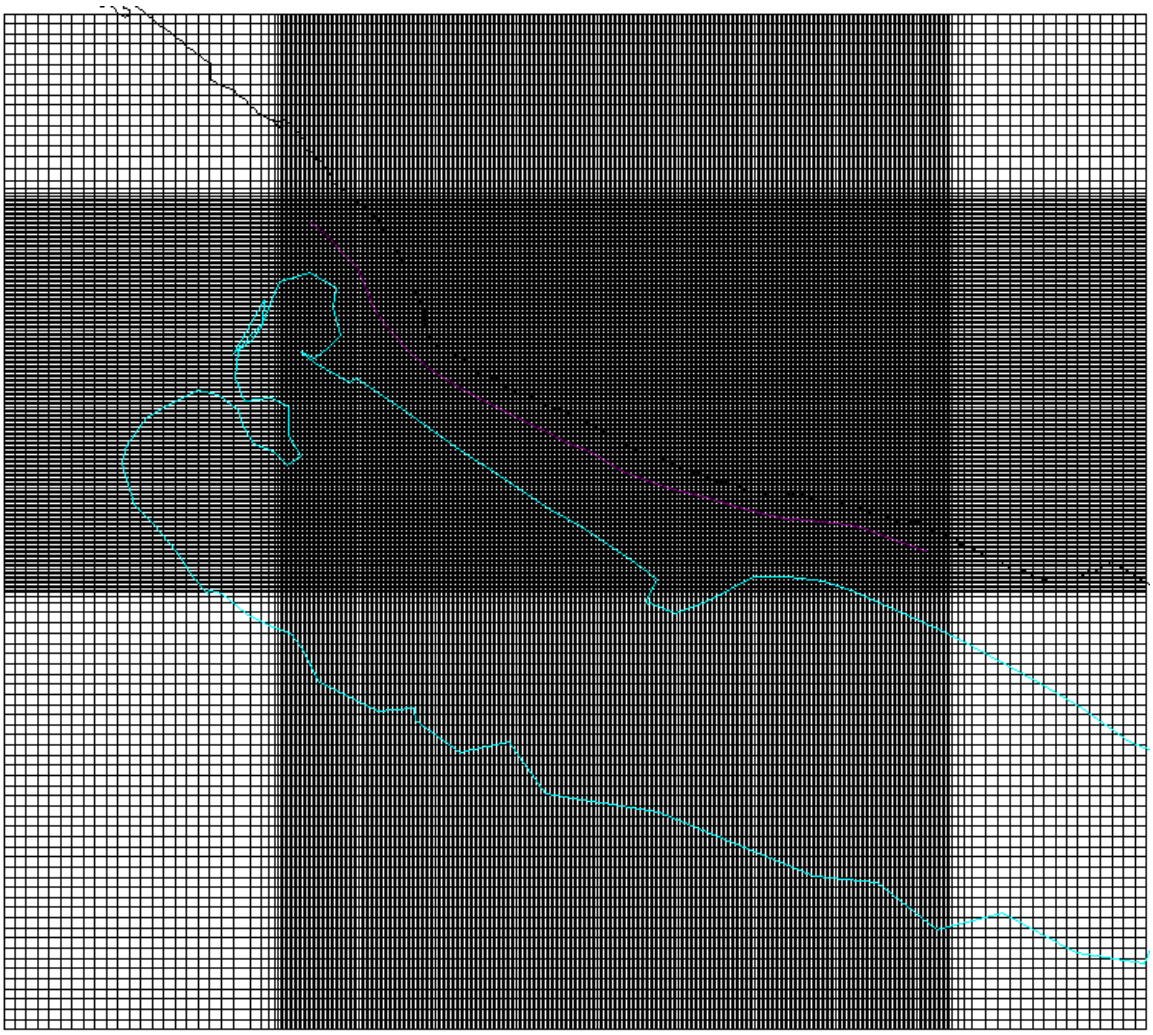


Figure 5-24

MODFLOW Grid for the Seep 1 TMR Model

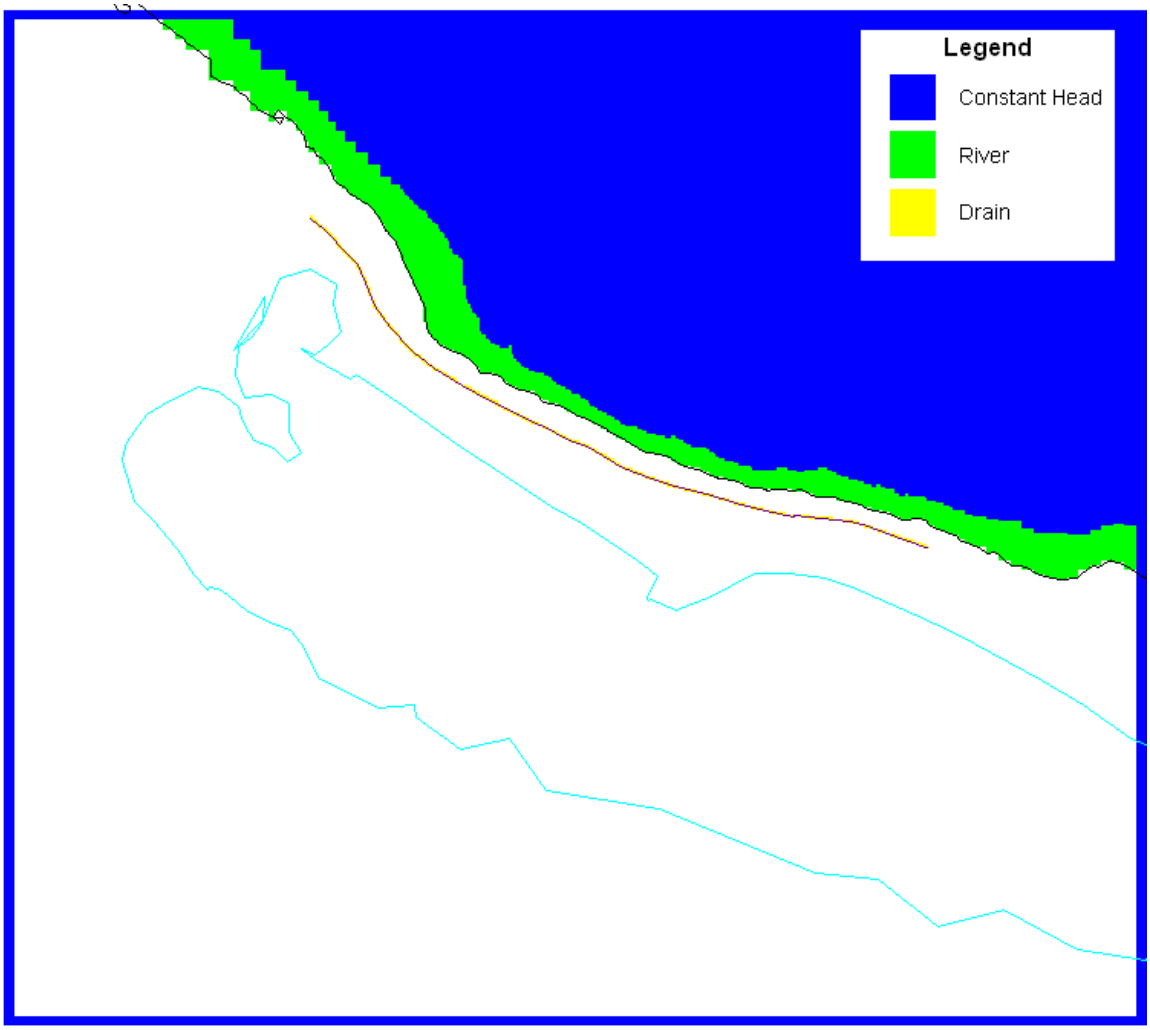


Figure 5-25

Boundary Conditions for Layer 1 of the Seep 1 TMR Model

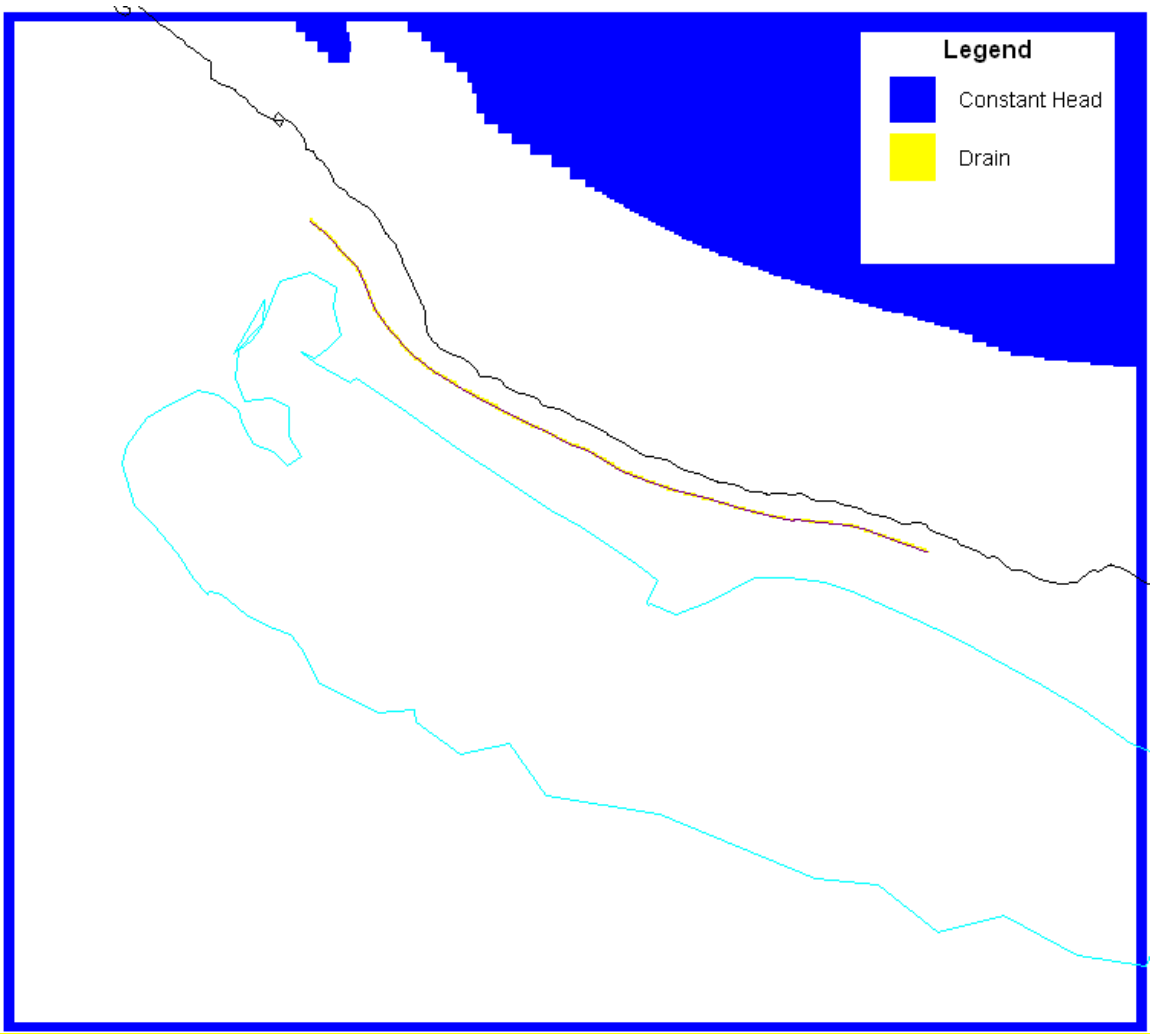


Figure 5-26

Boundary Conditions for Layer 2 of the Seep 1 TMR Model

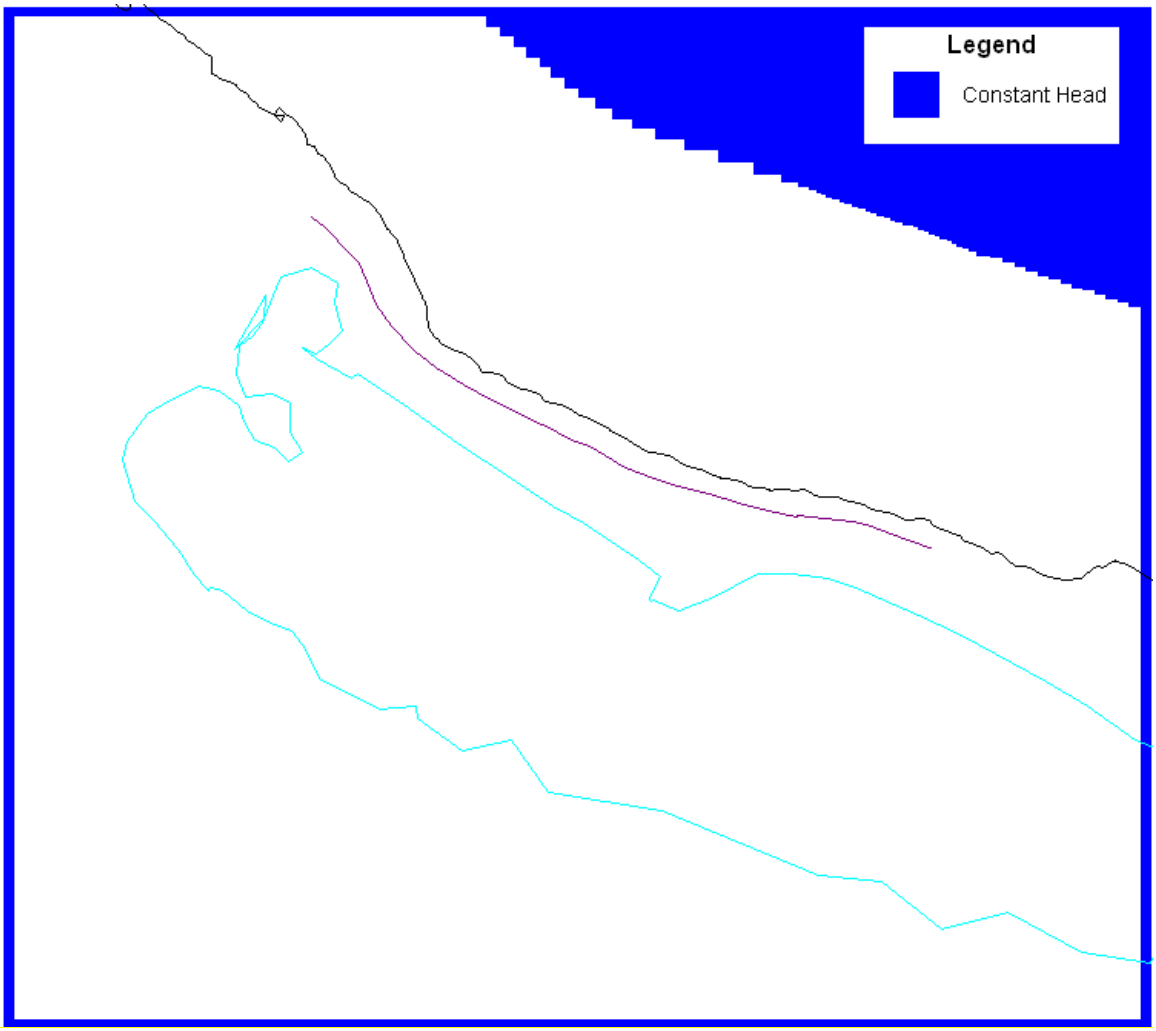


Figure 5-27

Boundary Conditions for Layer 3 of the Seep 1 TMR Model

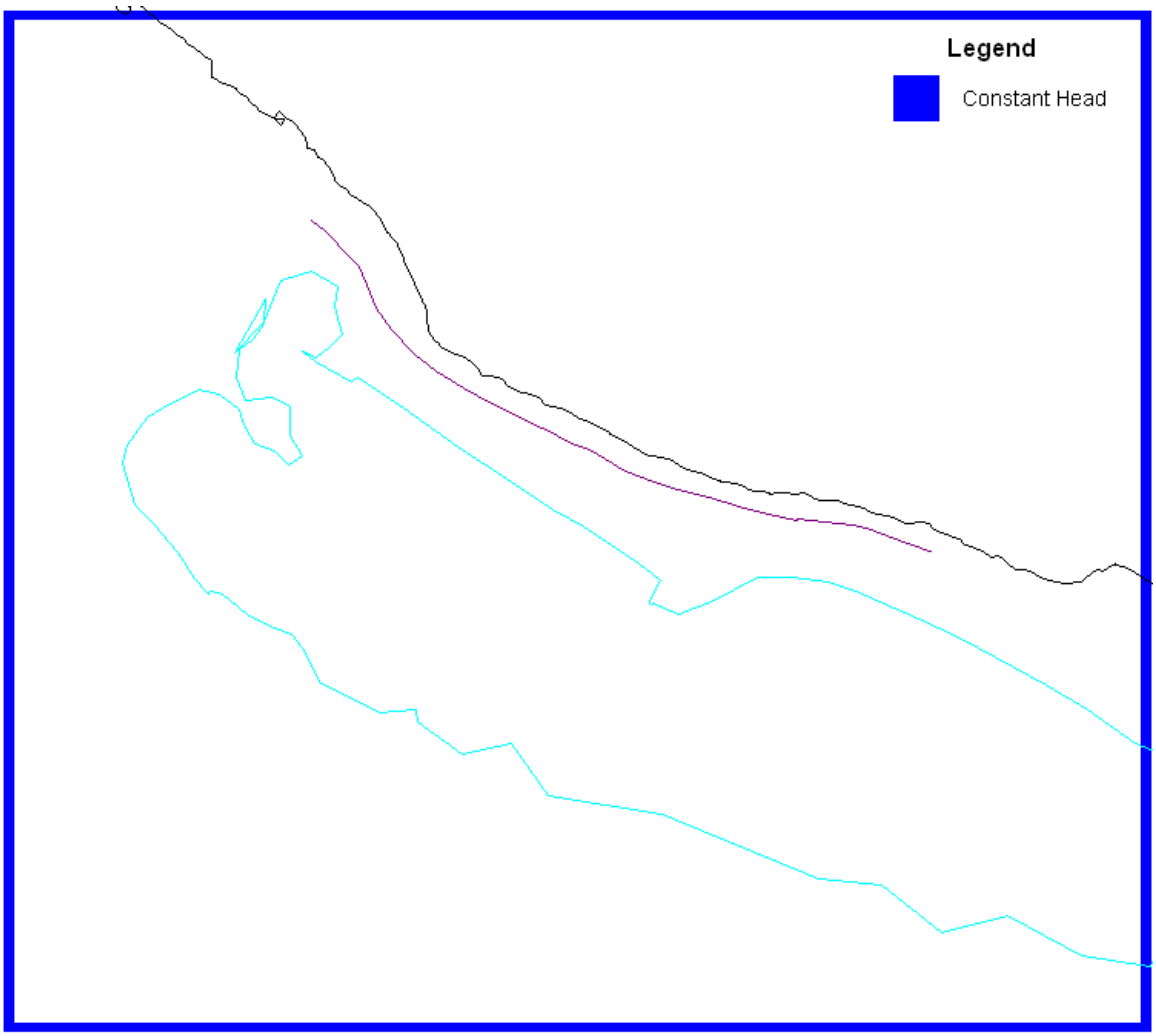


Figure 5-28

Boundary Conditions for Layers 4-8 of the Seep 1 TMR Model

Parameter (in/yr)	Estimated	Modeled
Recharge on golf course 9/14/2006	NA	21.6
Overall recharge 9/14/2006	6.0	10.1
Recharge on golf course 1/02/2007	6.0	12.0
Overall recharge 1/02/2007	6.0	12.0

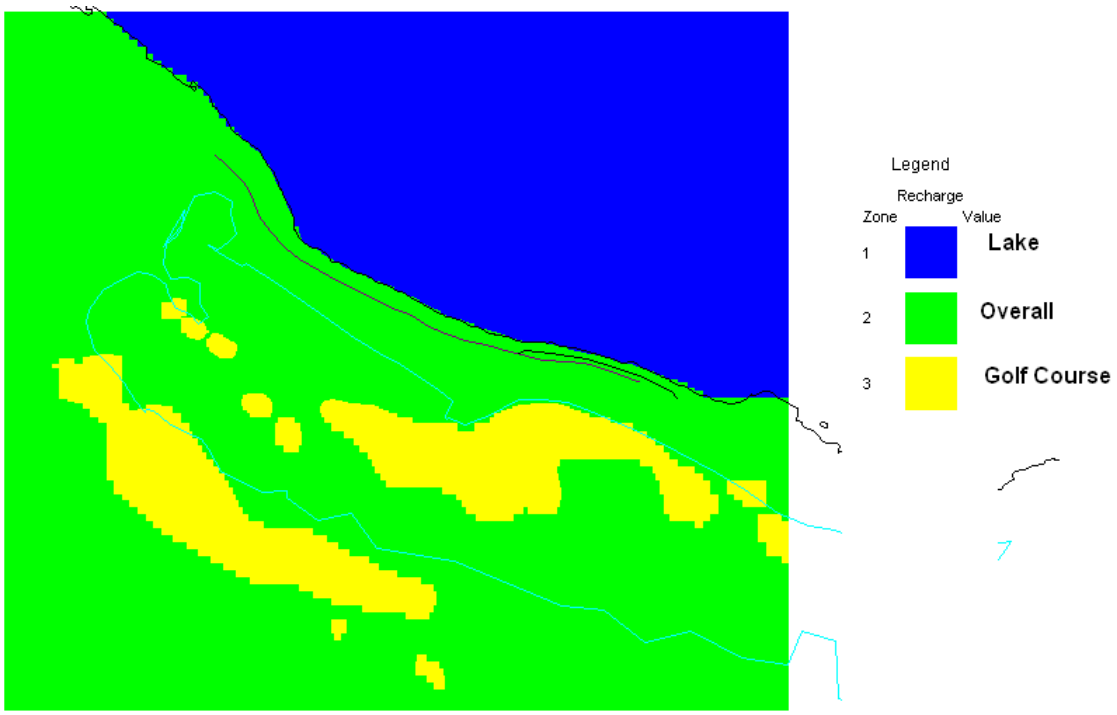


Figure 5-29

Recharge Zonation for the Seep 1 TMR Model

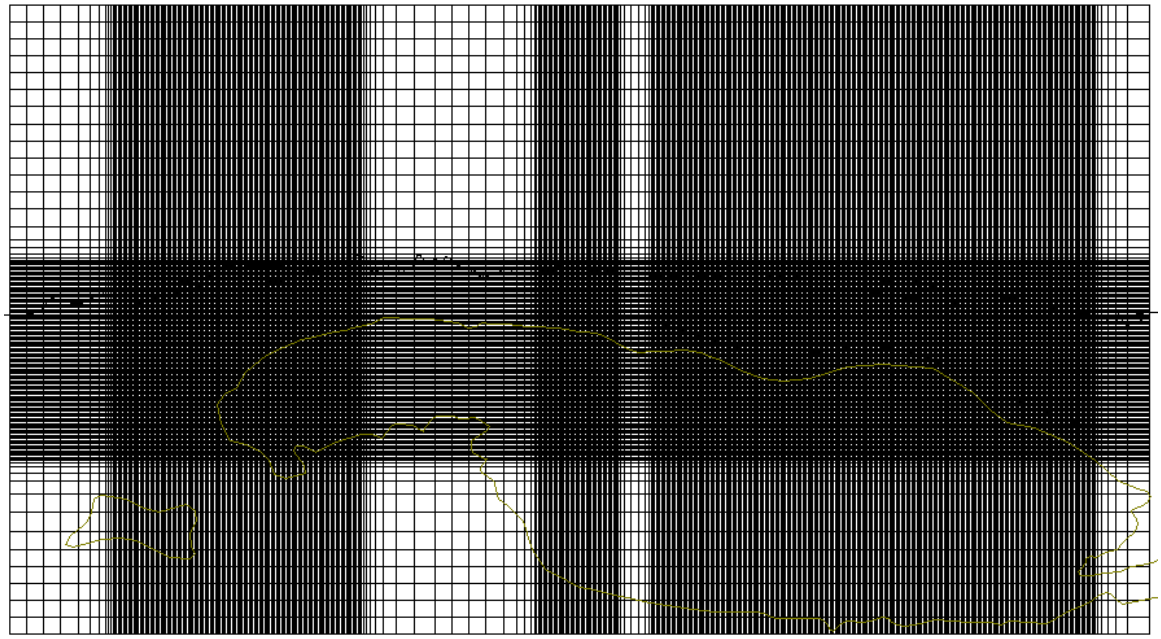


Figure 5-30. MODFLOW Grid for the Seep 2 TMR Model

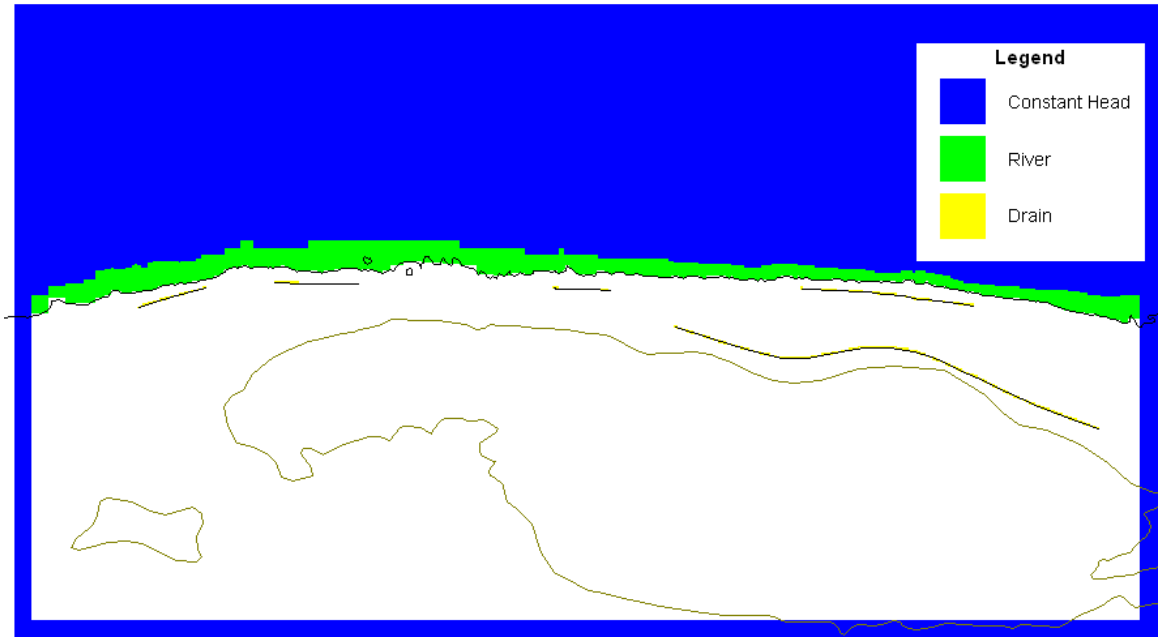


Figure 5-31. Boundary Conditions for Layer 1 of the Seep 2 TMR Model

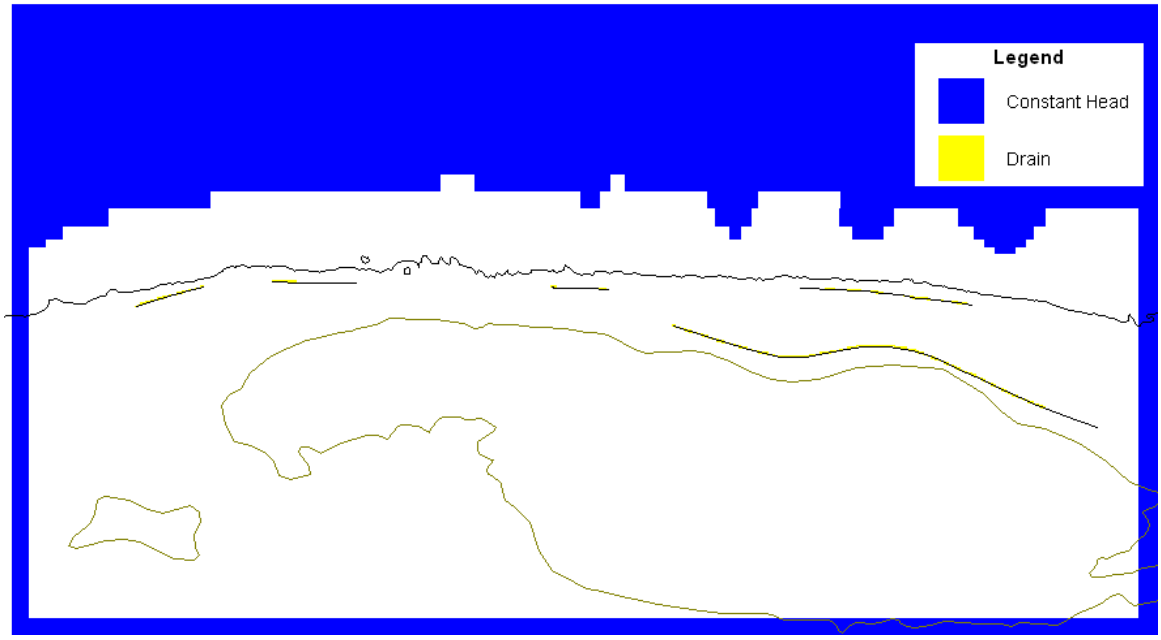


Figure 5-32. Boundary Conditions for Layer 2 of the Seep 2 TMR Model

Figure 5-33. Boundary Conditions for Layer 3 of the Seep 2 TMR Model

Figure 5-34. Boundary Conditions for Layer 4 of the Seep 2 TMR Model

Figure 5-35. Boundary Conditions for Layers 5-8 of the Seep 2 TMR Model

Parameter (in/yr)	Estimated	Modeled
Recharge on golf course 9/14/2006	NA	24.4
Recharge Secs. 4&5 9/14/2006	NA	8.4
Recharge Sec. 9 9/14/2006	6.0	0.4
Recharge Sec. 8 9/14/2006	8.0	0.4
Recharge on golf course 1/02/2007	NA	1.2
Recharge Secs. 4&5 1/02/2007	NA	0.4
Recharge Sec. 9 1/02/2007	6.0	1.2
Recharge Sec. 8 1/02/2007	8.0	9.6

State Values for Sections 4 and 5 were 0 because these are primarily in Little Traverse Bay

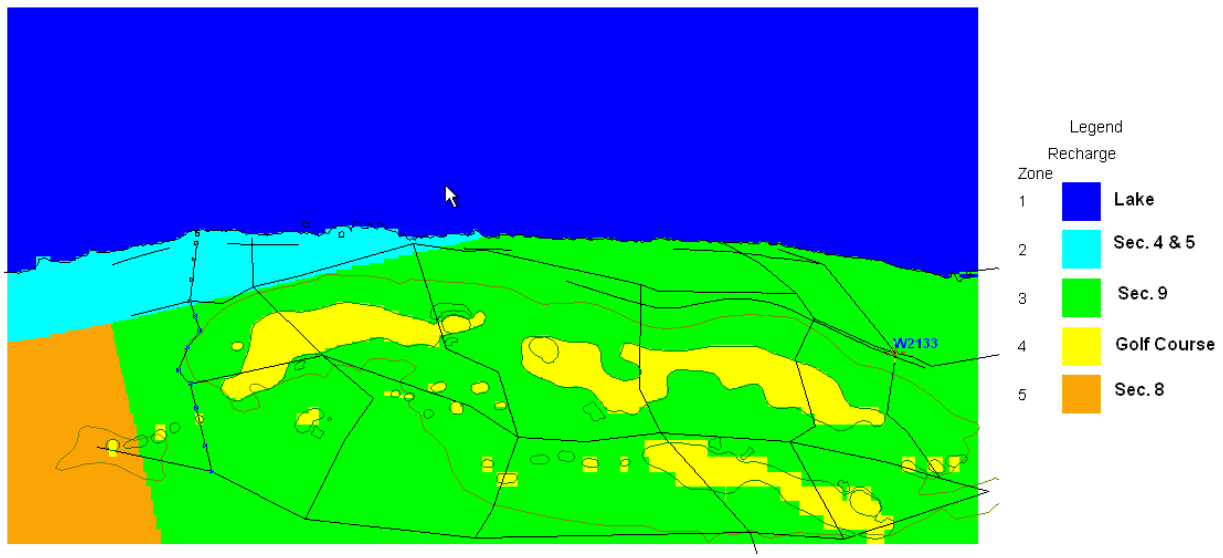


Figure 5-36. Recharge Zonation for the Seep 2 TMR Model

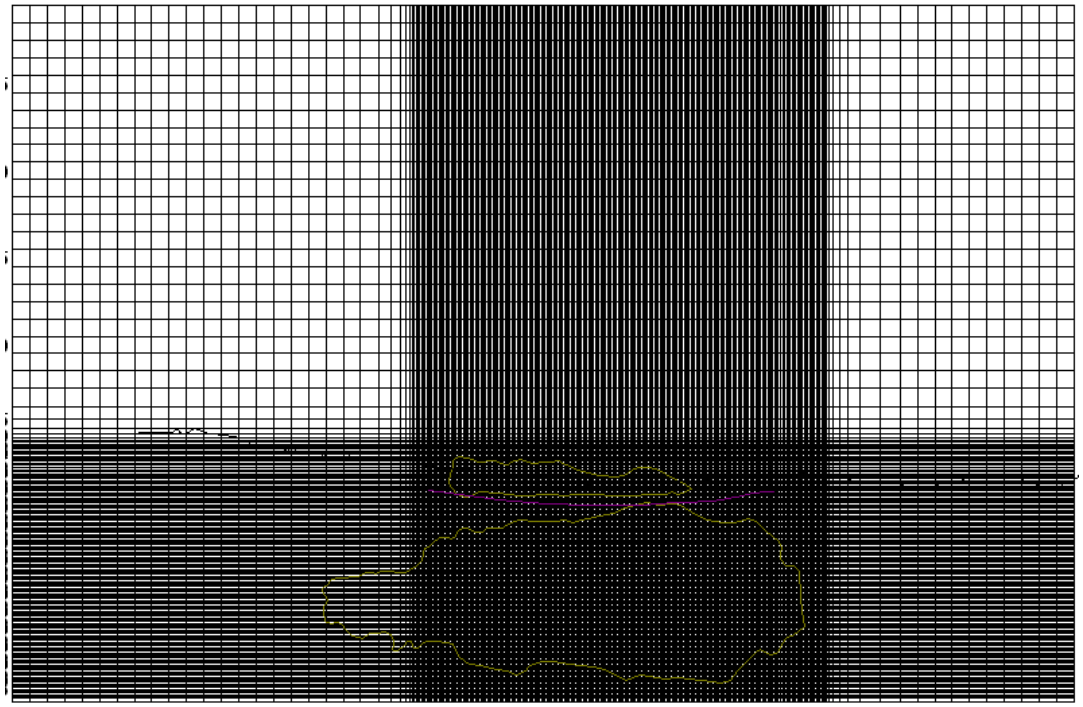


Figure 5-37. MODFLOW Grid for the West CKD TMR Model

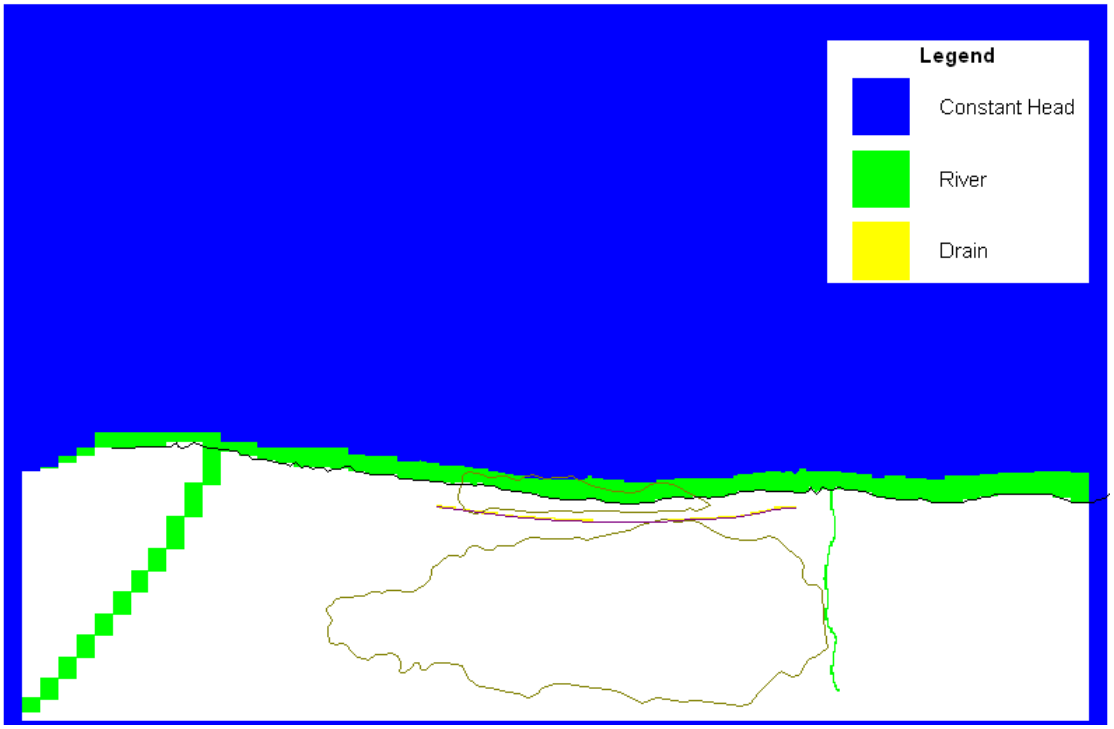


Figure 5-38. Boundary Conditions for Layer 1 of the West CKD TMR Model

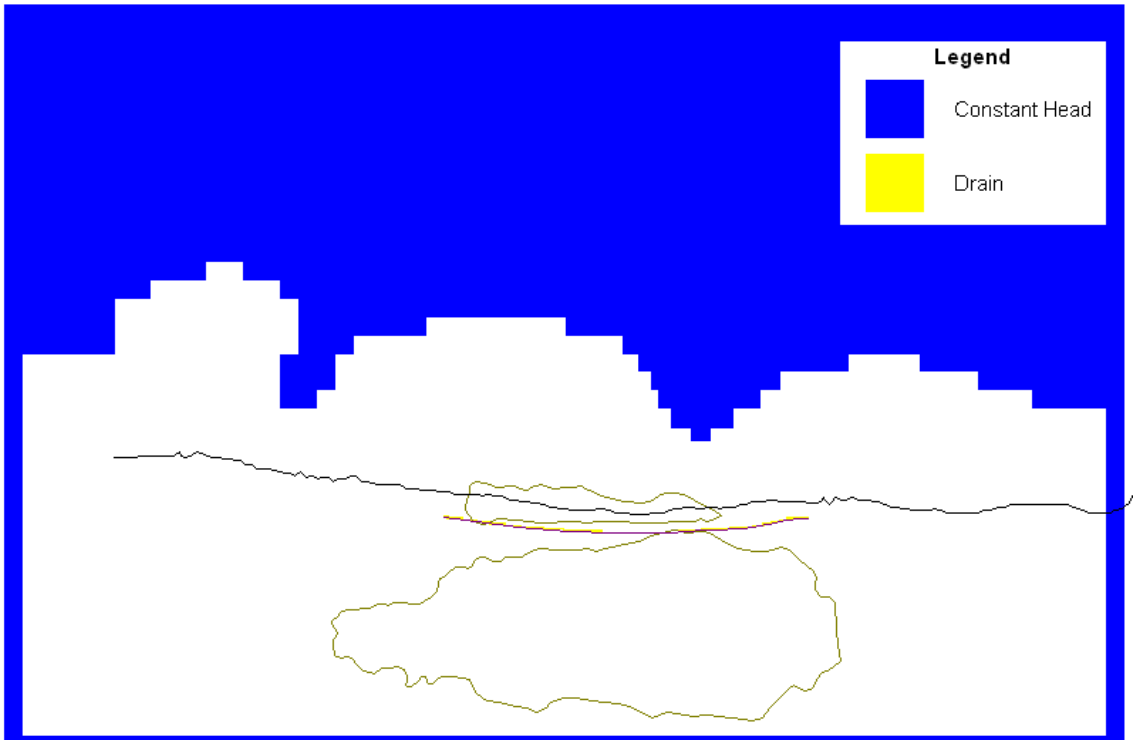


Figure 5-39. Boundary Conditions for Layer 2 of the West CKD TMR Model

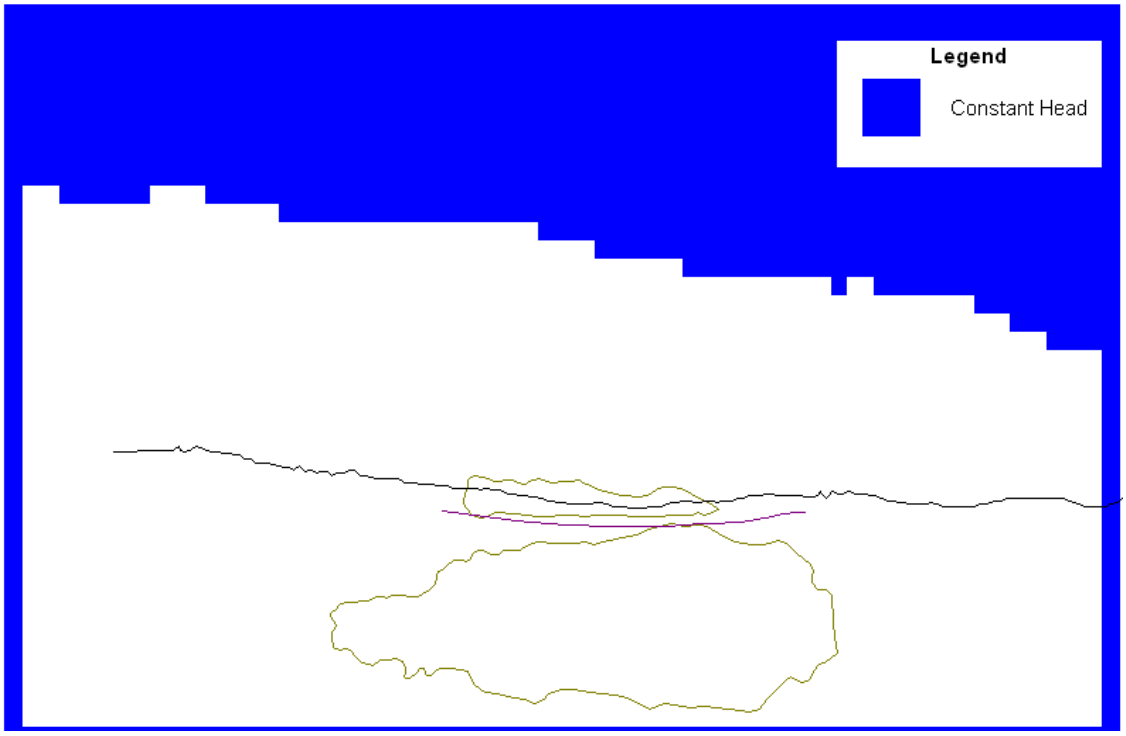


Figure 5-40. Boundary Conditions for Layer 3 of the West CKD TMR Model

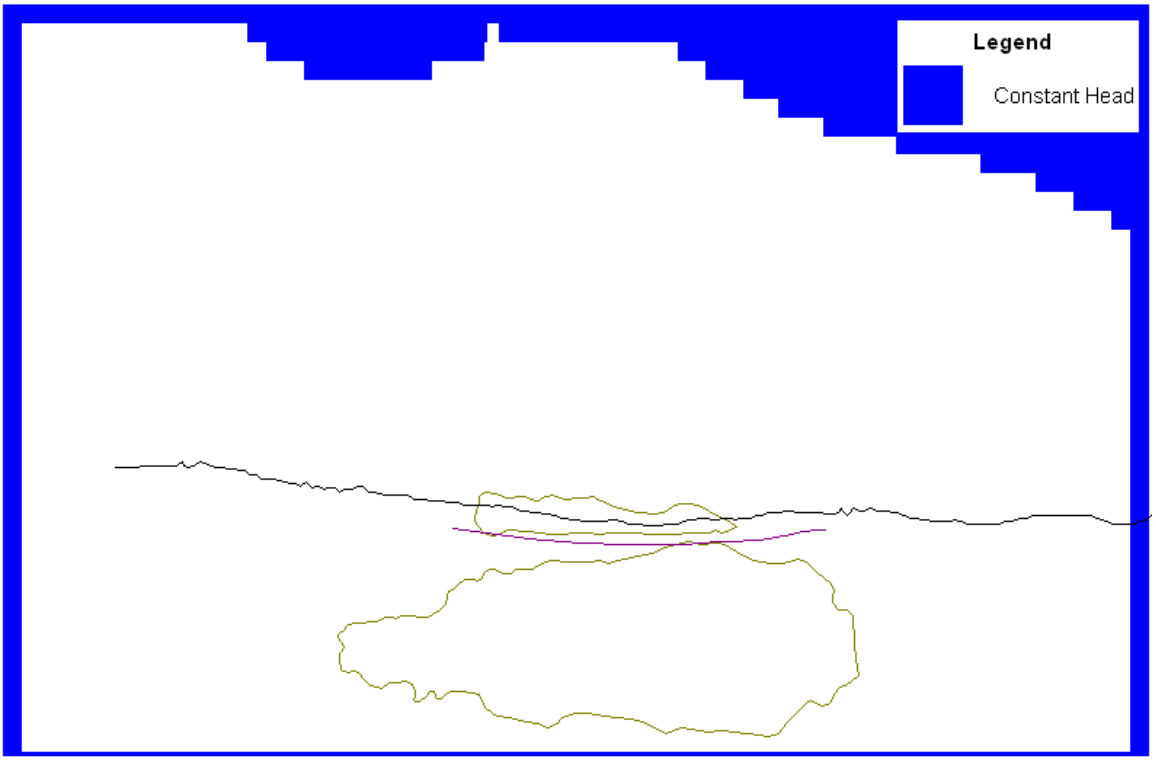


Figure 5-41. Boundary Conditions for Layer 4 of the West CKD TMR Model

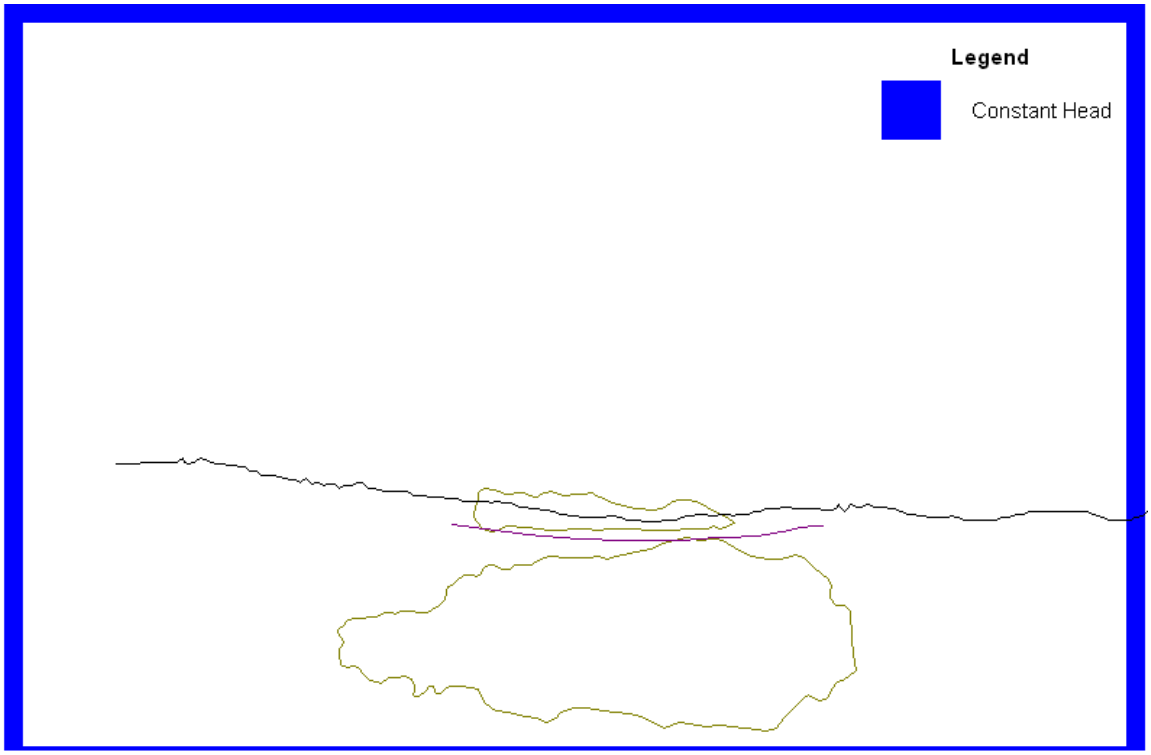


Figure 5-42. Boundary Conditions for Layers 5-8 of the West CKD TMR Model

Parameter (in/yr)	Estimated	Modeled
Recharge on golf course 9/14/2006	NA	16.6
Overall recharge 9/14/2006	NA	0.4
Recharge on golf course 1/02/2007	NA	9.6
Overall recharge 1/02/2007	NA	9.6

State Value for Section 5 was 0 because this section is primarily in Little Traverse Bay

Figure 5-43. Recharge Zonation for the West CKD TMR Model

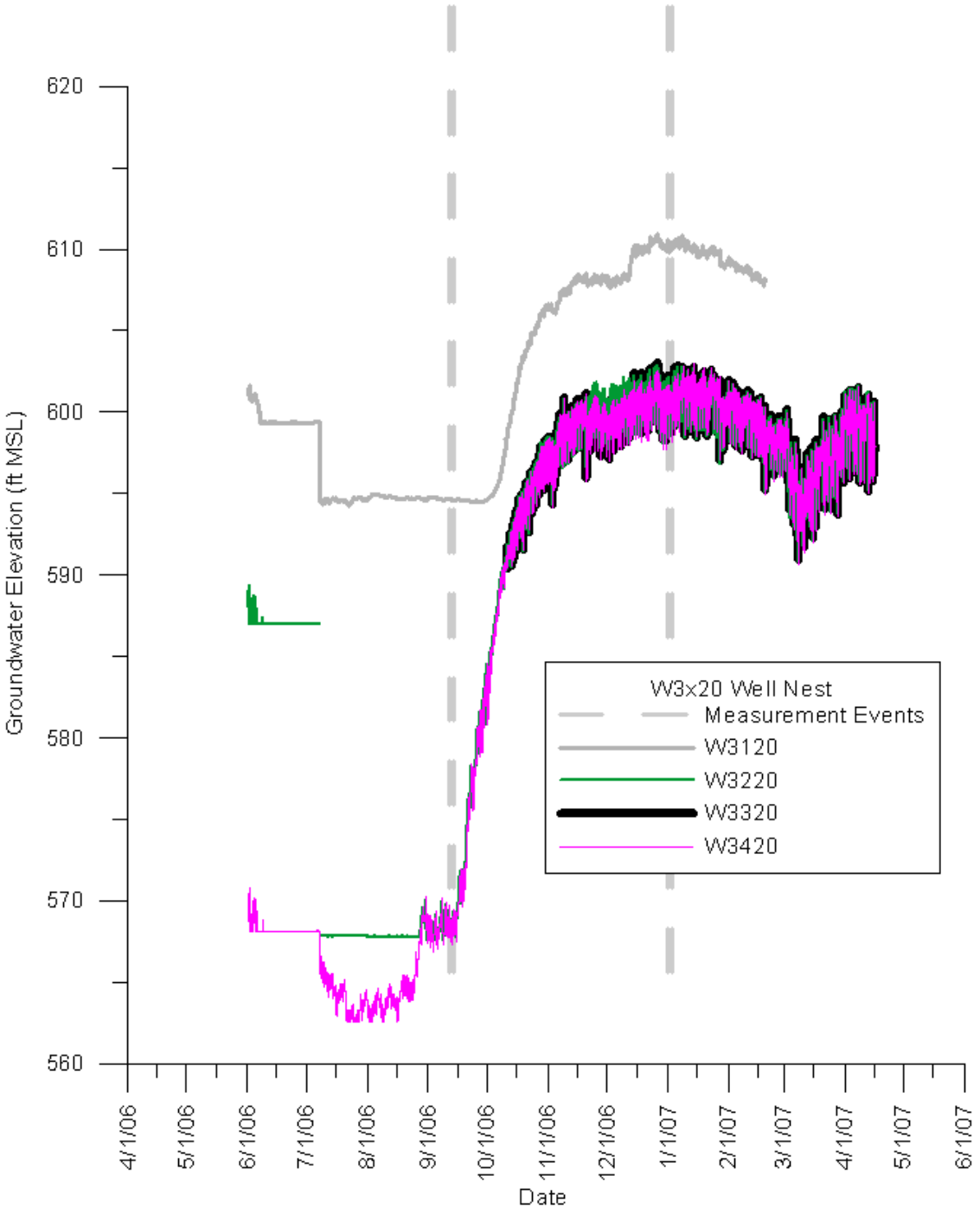


Figure 5-44.

Hydrograph from Well Nest at W3020 Showing Measurement Times used in the Calibration Dataset

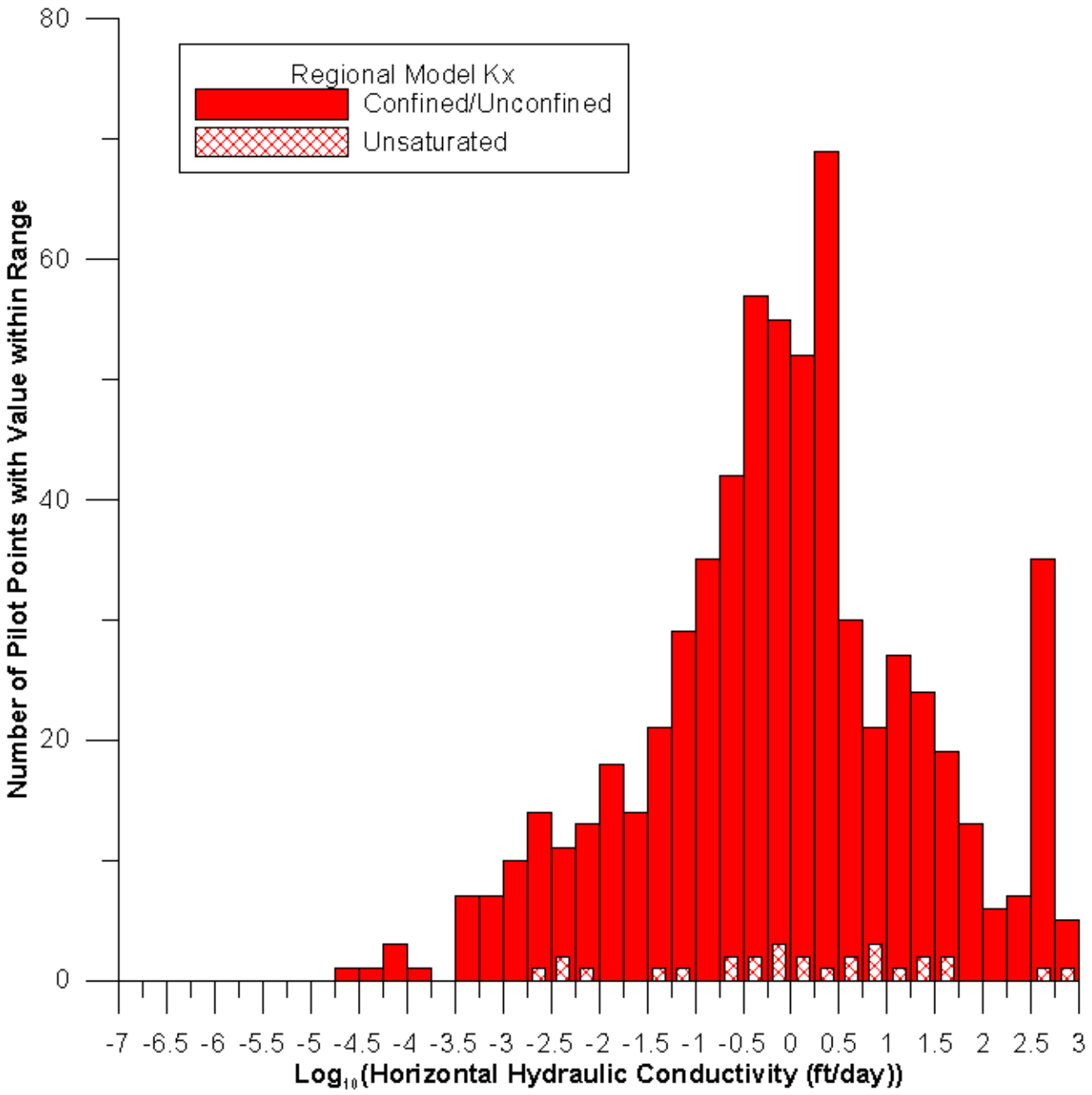


Figure 6-1a

Histogram of Horizontal Hydraulic Conductivity Values for the Regional Model

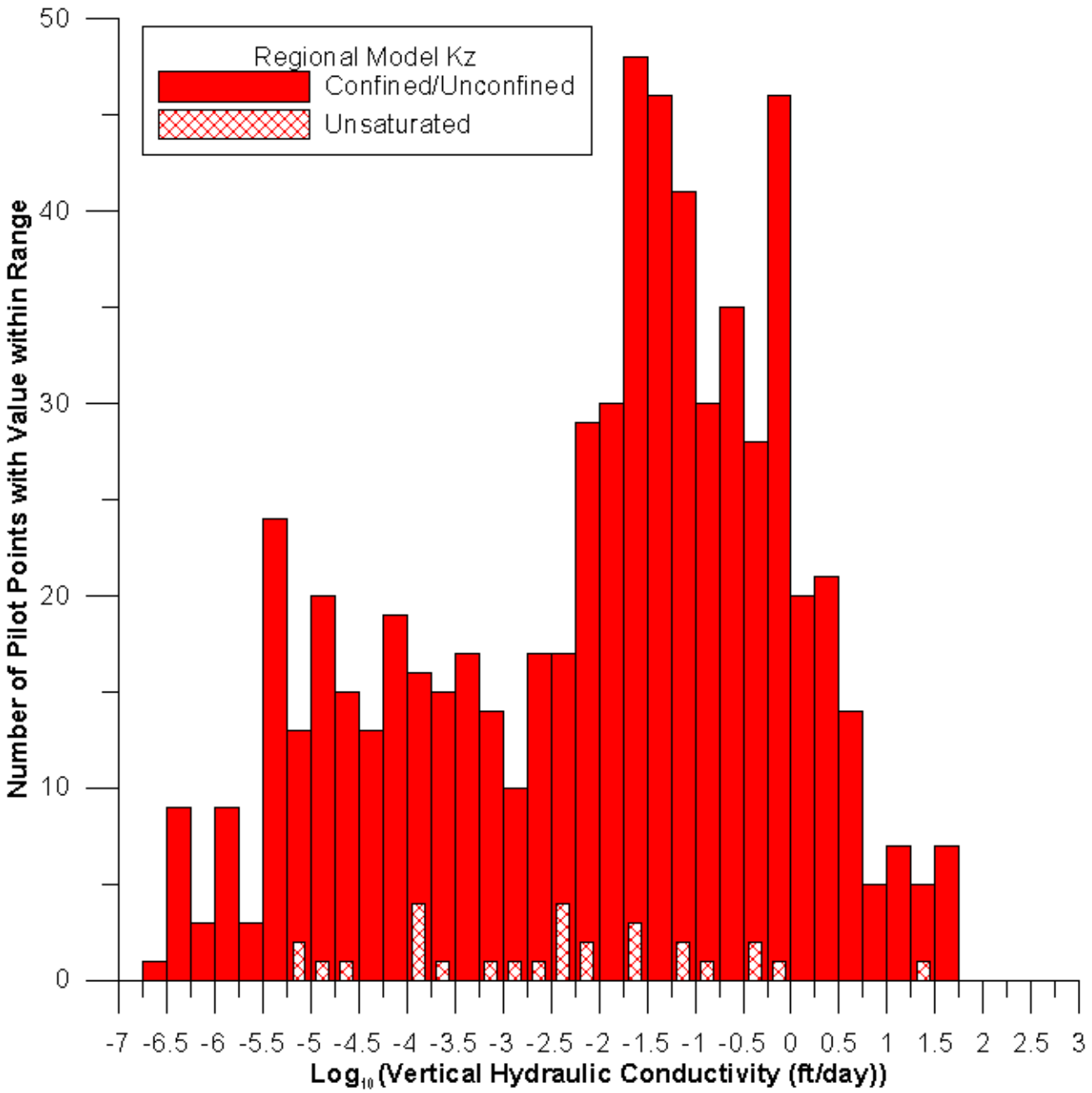


Figure 6-1b

Histogram of Vertical Hydraulic Conductivity Values for the Regional Model

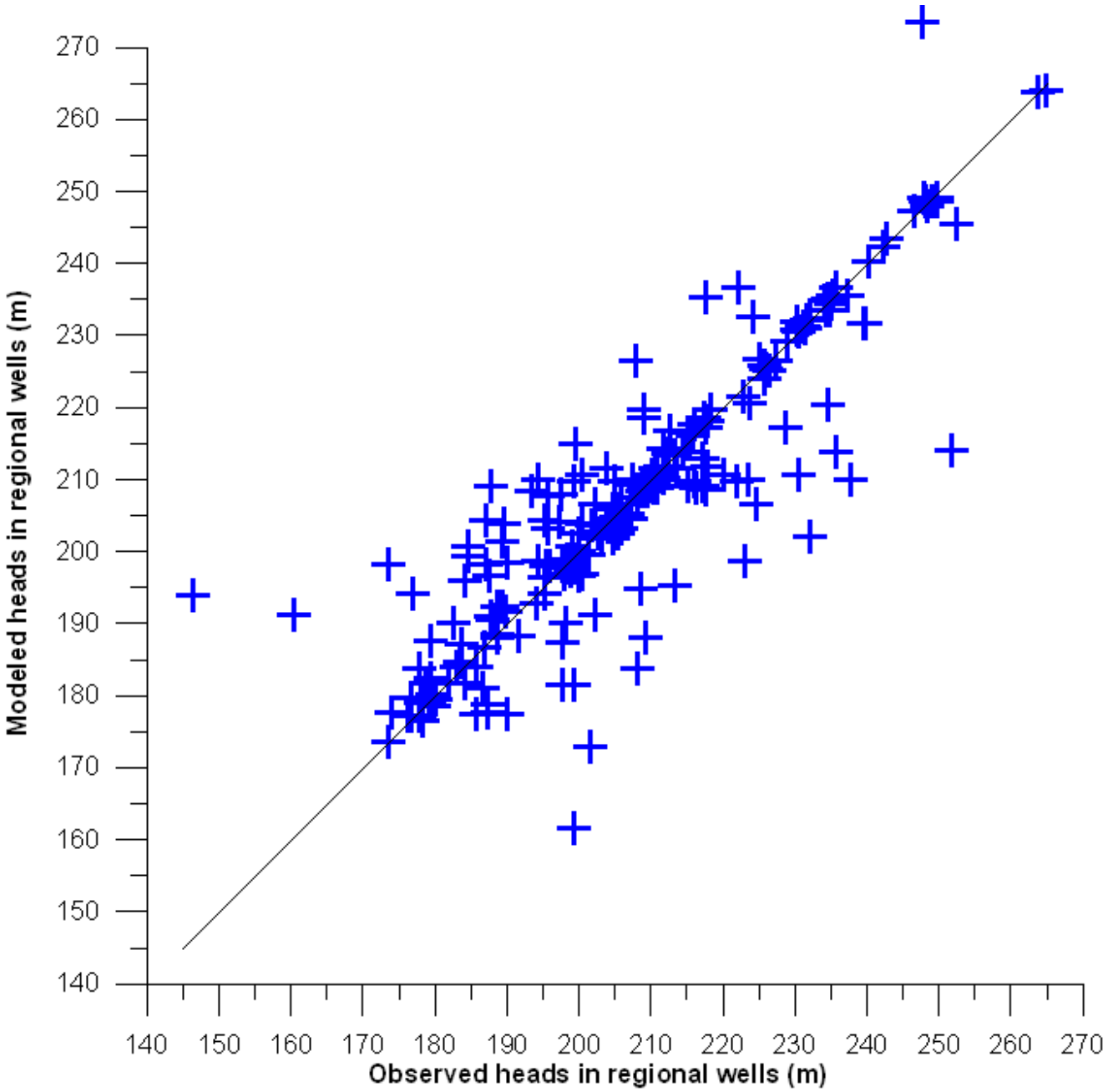


Figure 6-2

Scatter Plot of Regional Heads for the Regional MODFLOW Model Calibration

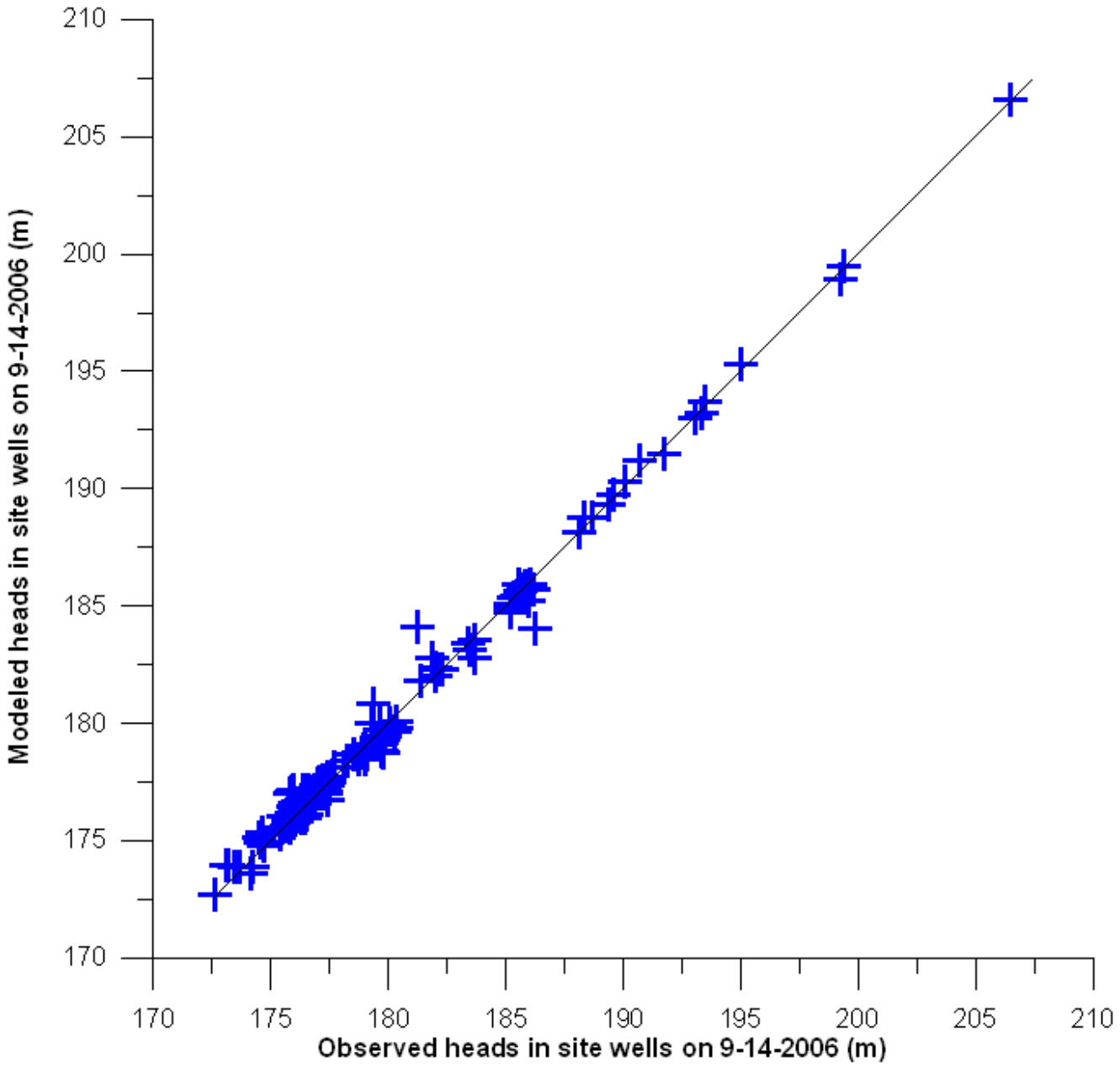


Figure 6-3

Scatter Plot of Heads on 9/14/2006 for the Regional MODFLOW Model Calibration

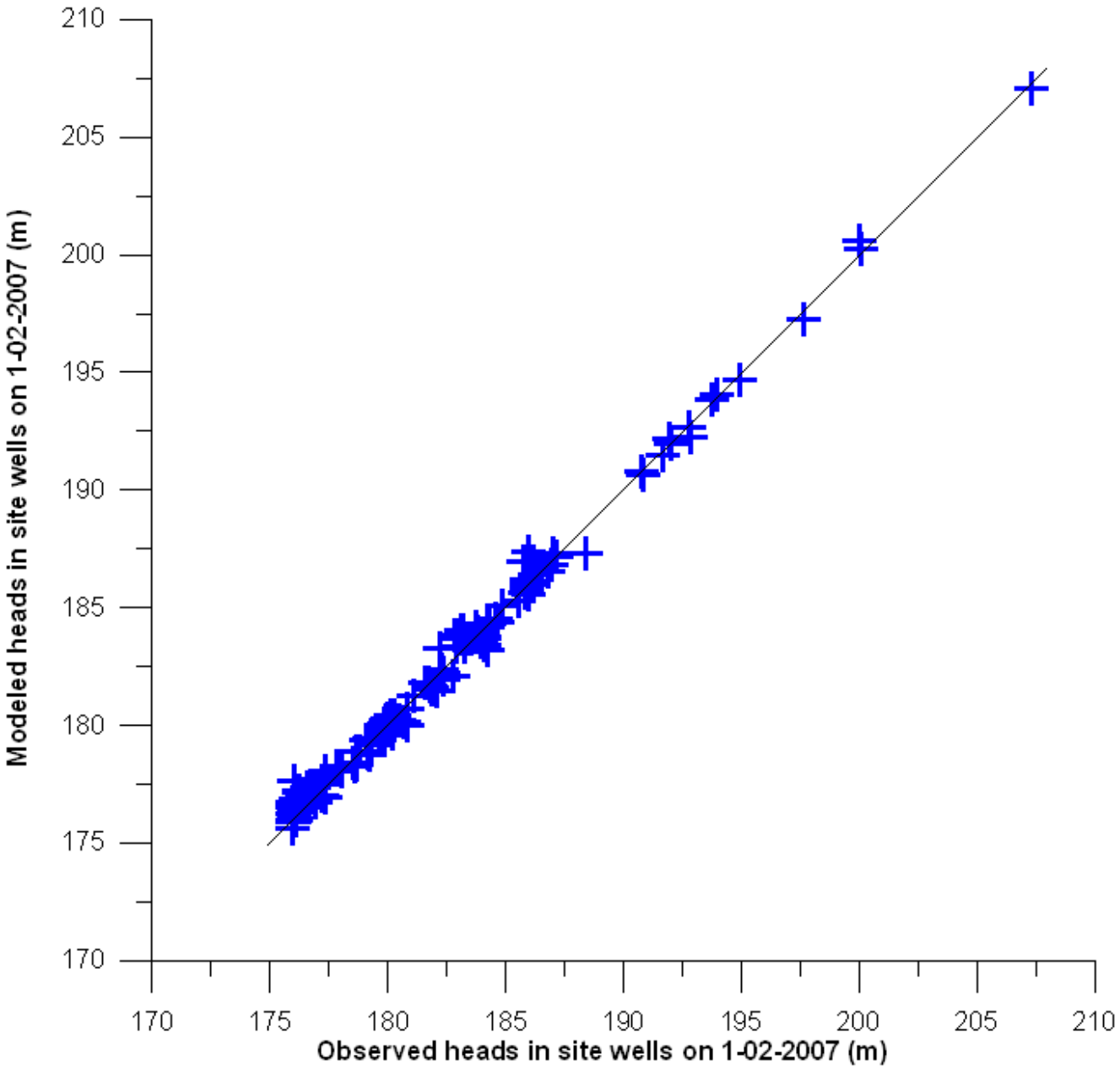


Figure 6-4

Scatter Plot of Heads on 1/02/2007 for the Regional MODFLOW Model Calibration

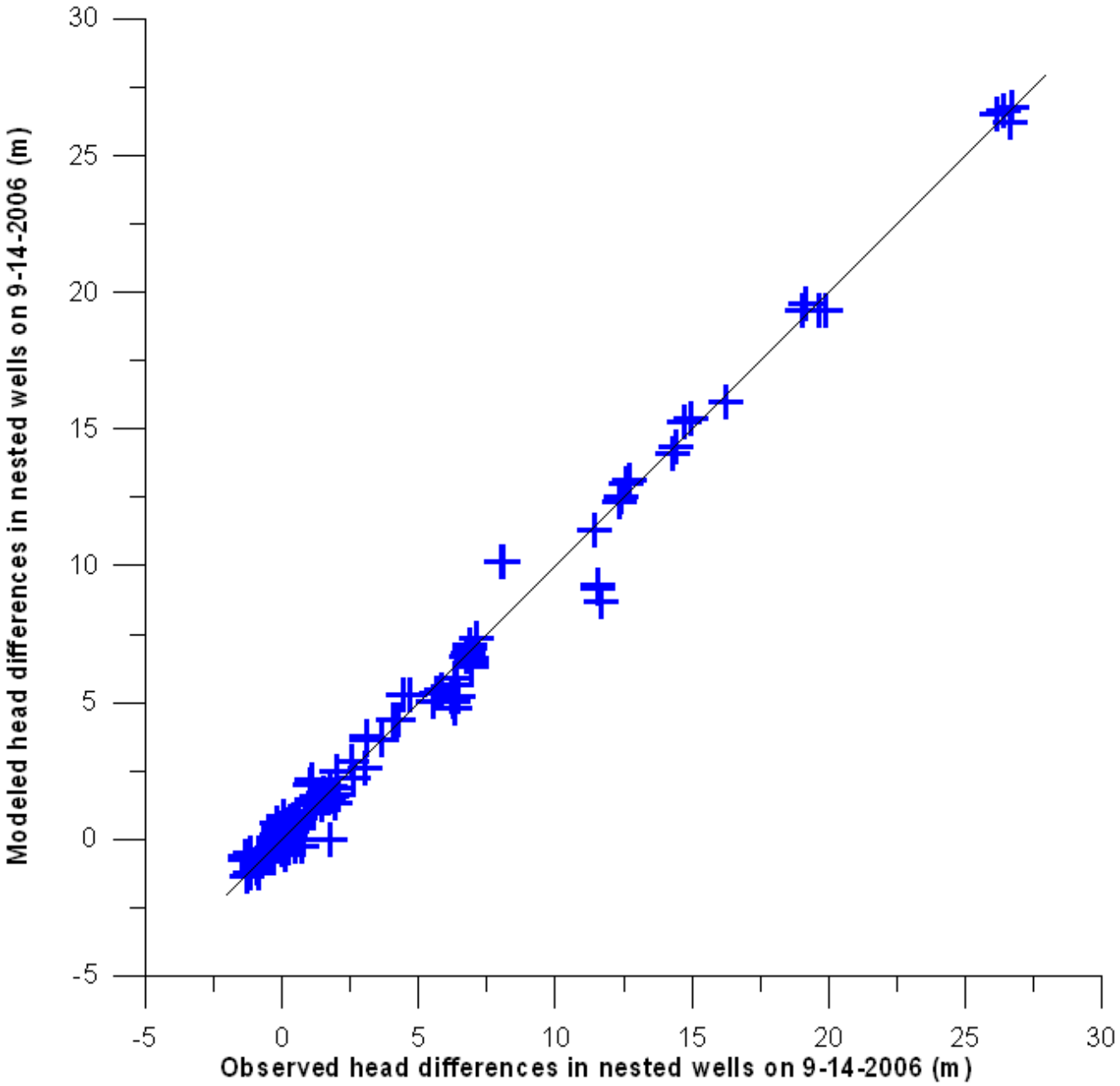


Figure 6-5

Scatter Plot of Heads Differences in Well Nests on 9/14/2006 for the Regional MODFLOW Model Calibration

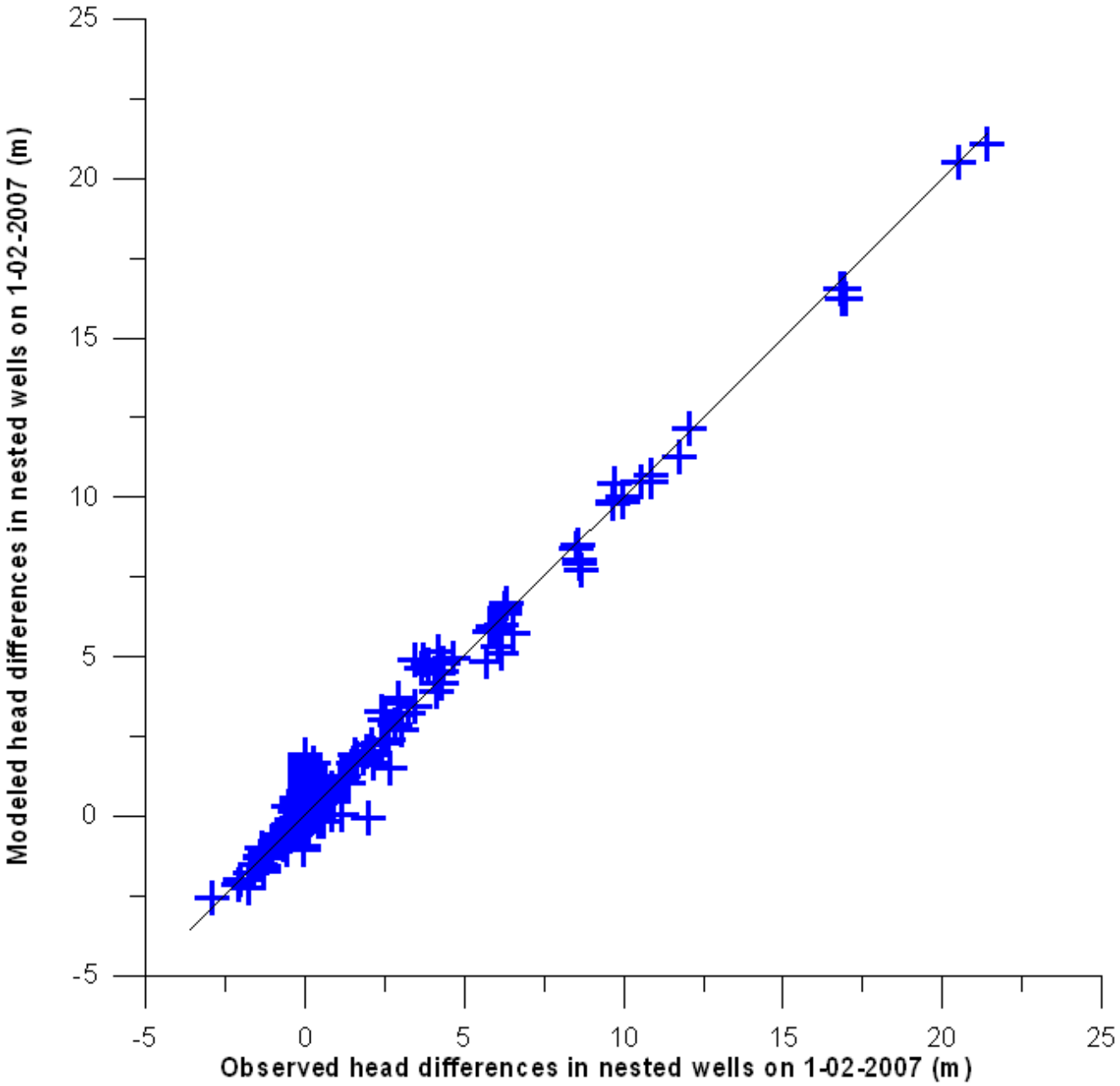


Figure 6-6

Scatter Plot of Heads Differences in Well Nests on 1/02/2007 for the Regional MODFLOW Model Calibration

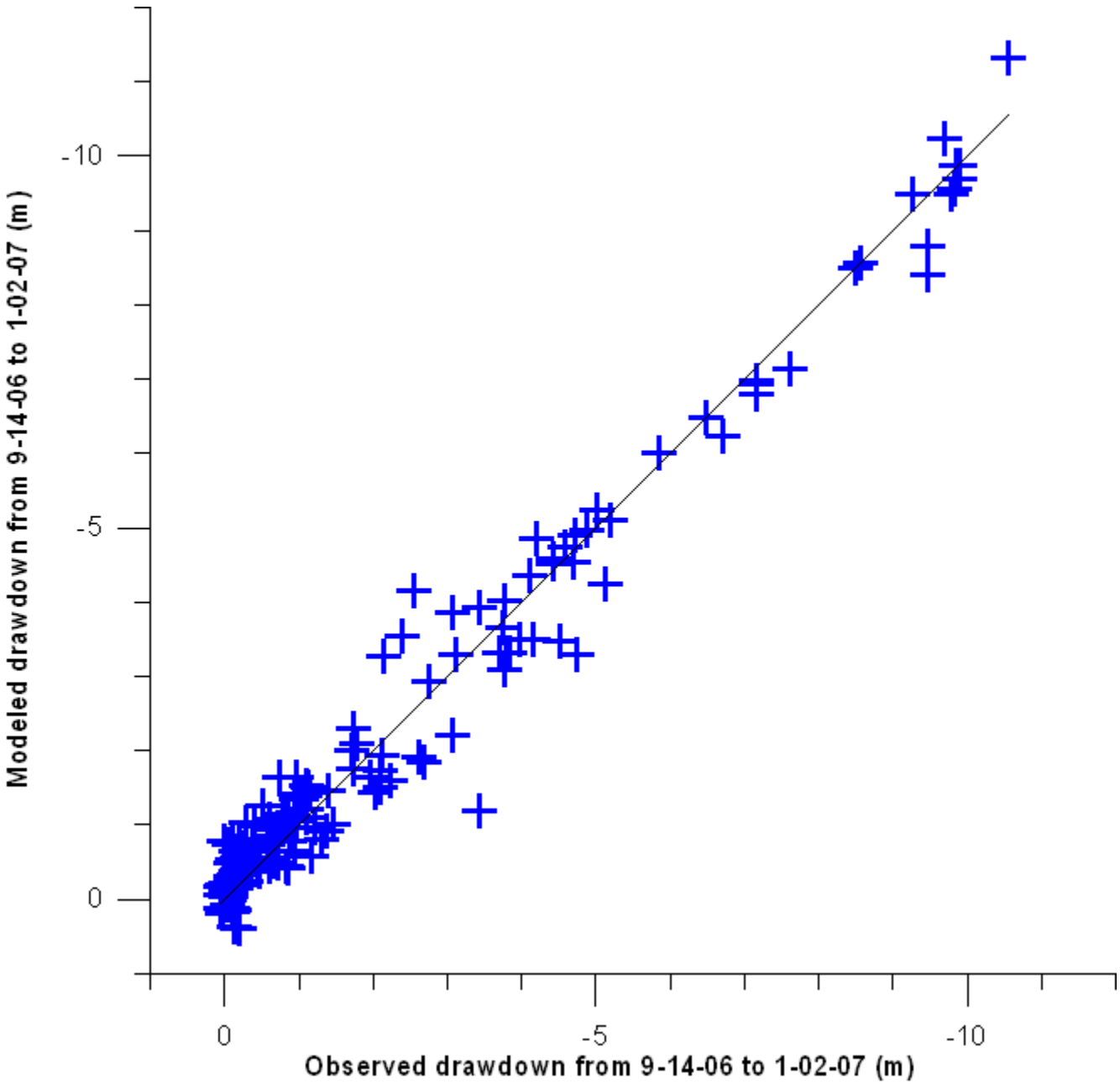


Figure 6-7

Scatter Plot of Differences in Head from 9/14/2006 to 1/02/2007 for the Regional MODFLOW Model Calibration

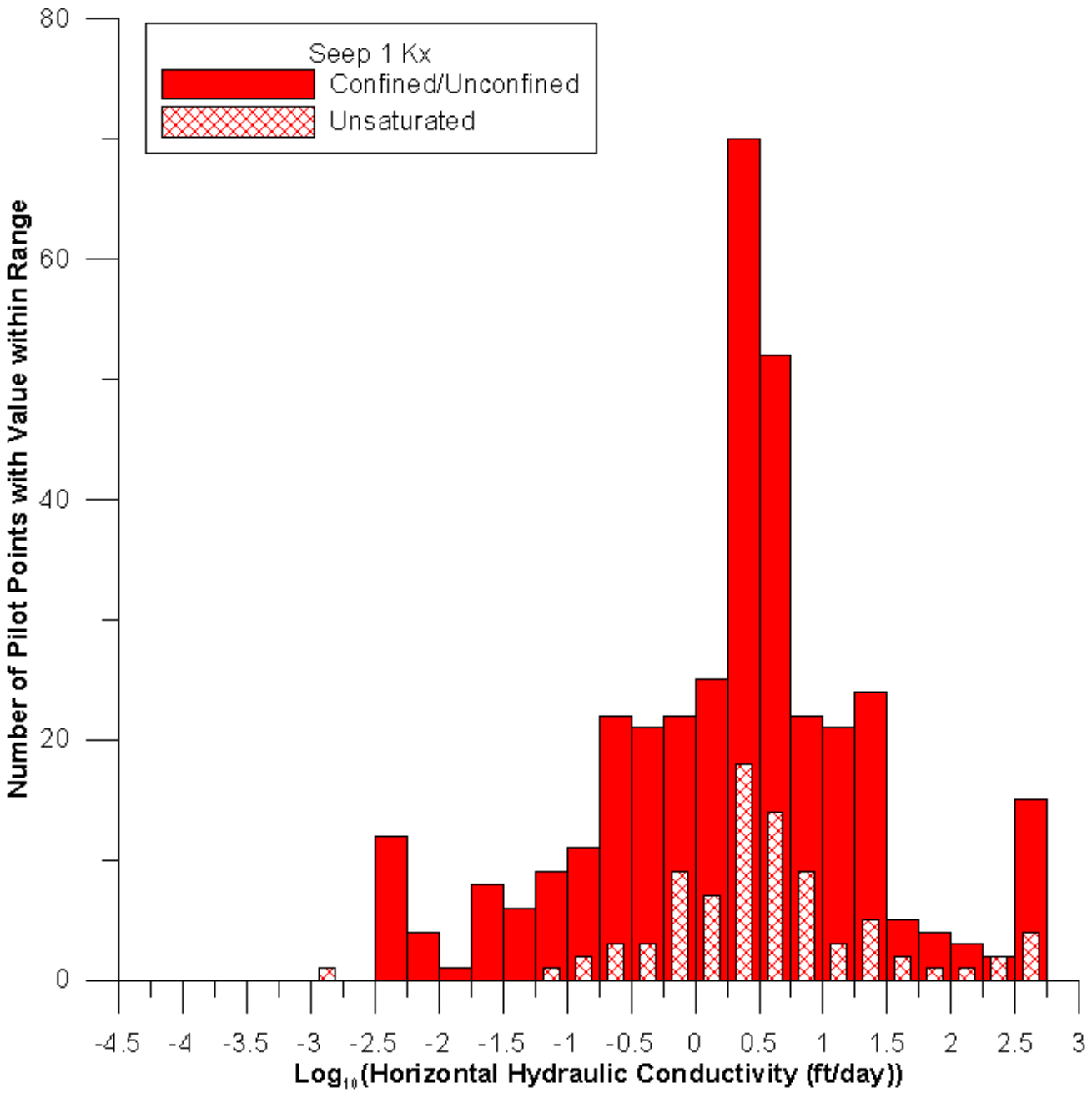


Figure 6-8a

Histogram of Horizontal Hydraulic Conductivity Values for the Seep 1 TMR Model

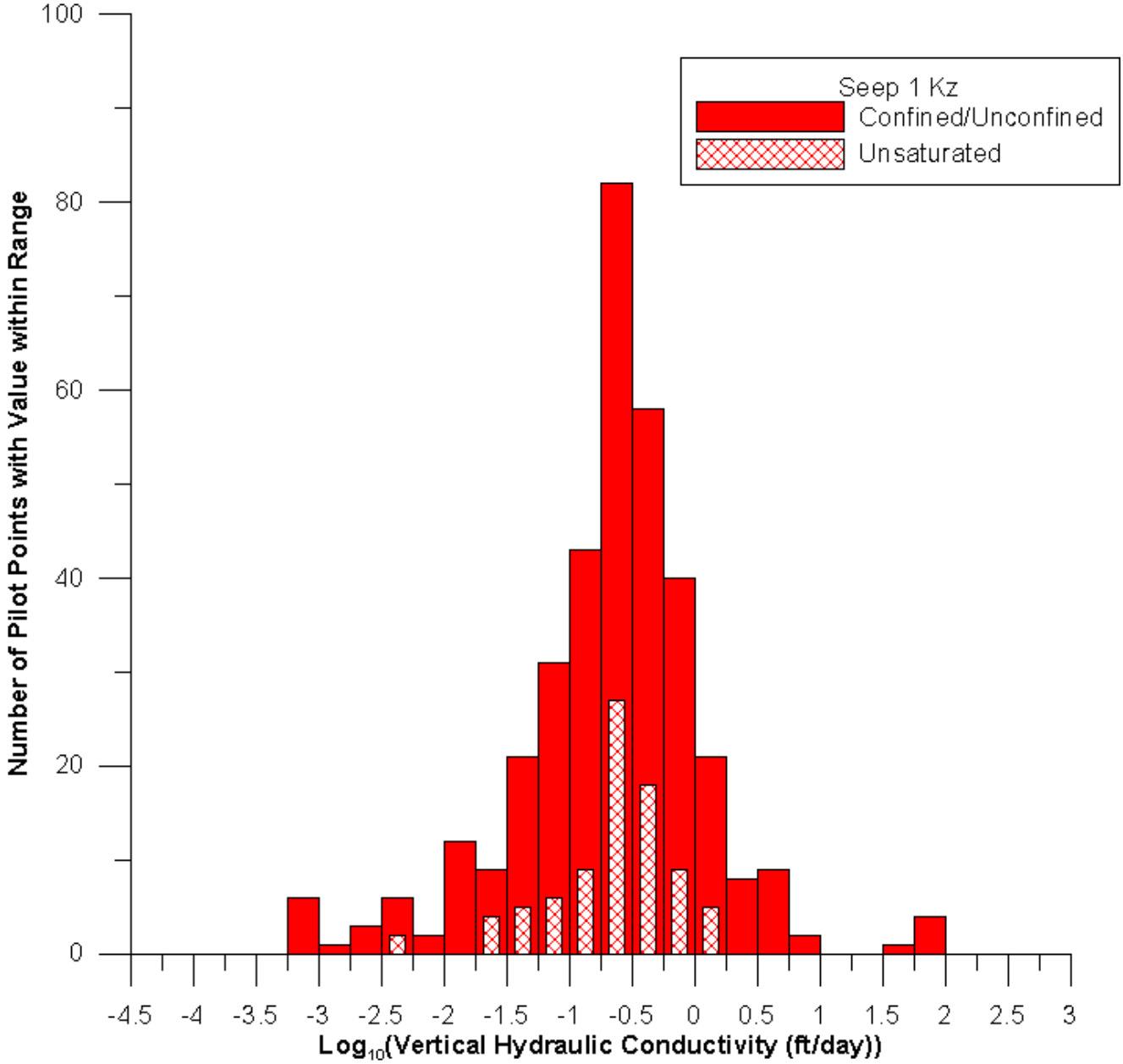


Figure 6-8b

Histogram of Vertical Hydraulic Conductivity Values for the Seep 1 TMR Model

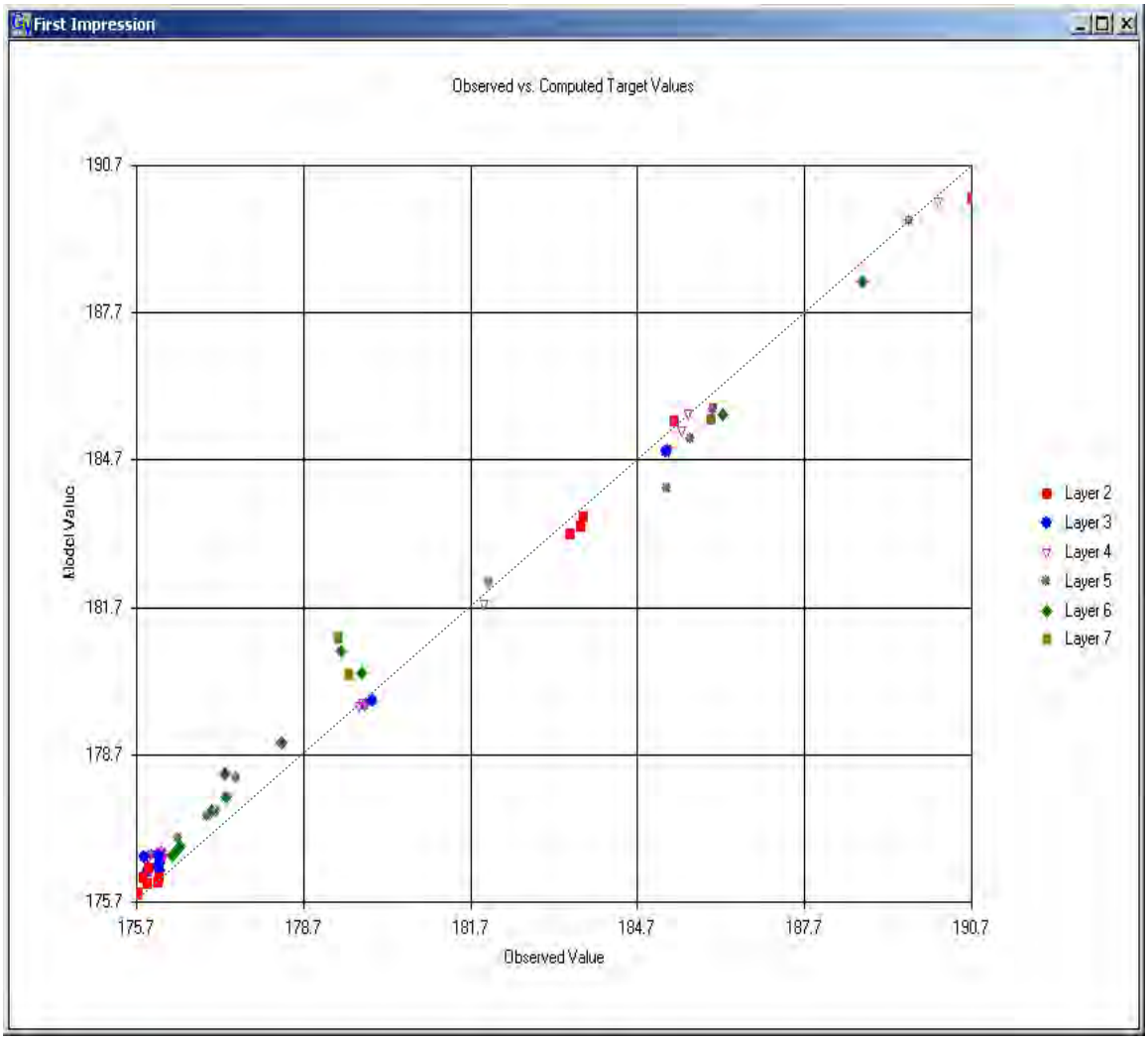


Figure 6-9

Scatter Plot of Heads on 9/14/2006 for the Seep 1 TMR Model Calibration

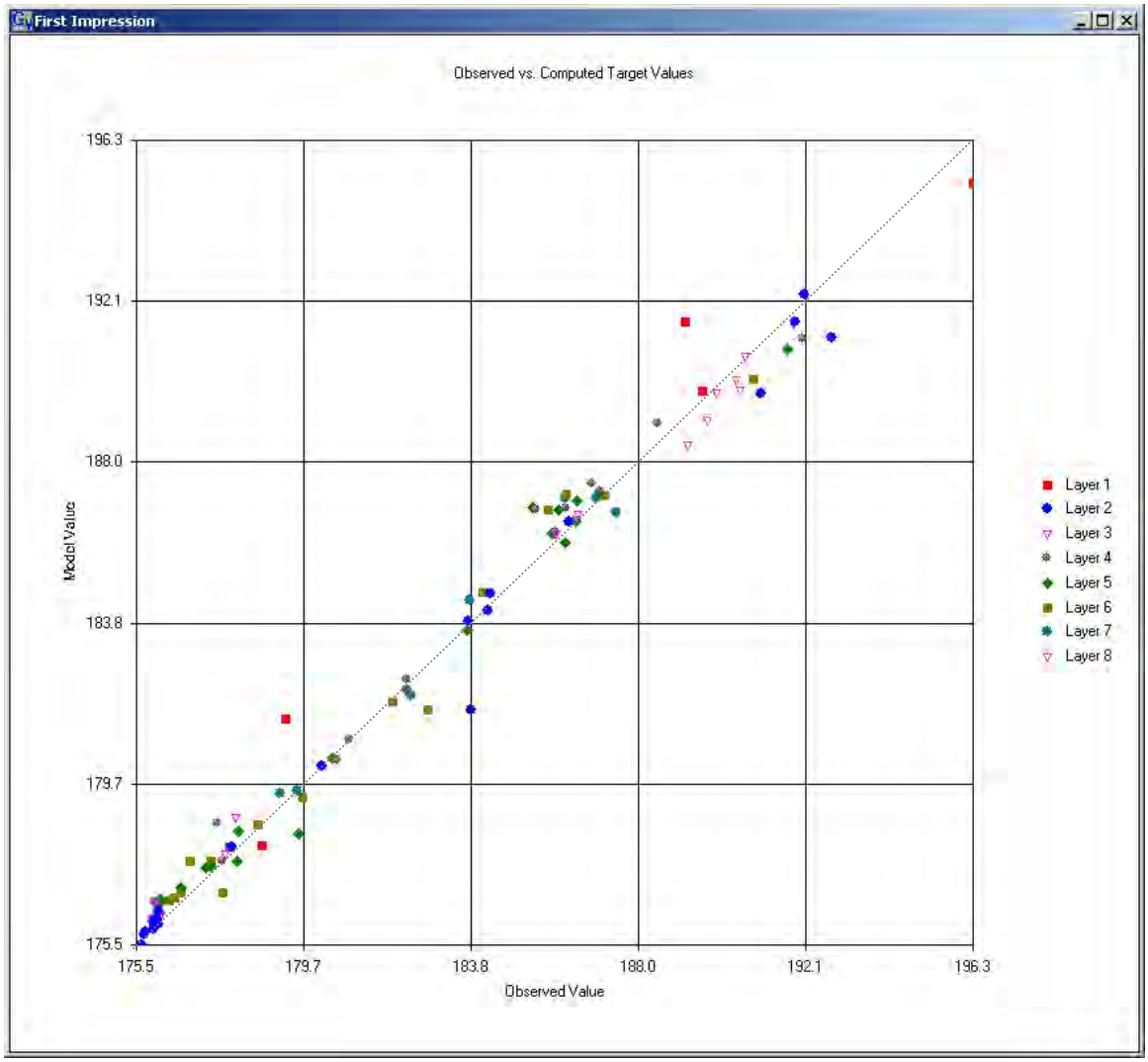


Figure 6-10

Scatter Plot of Heads on 1/02/2007 for the Seep 1 TMR Model Calibration

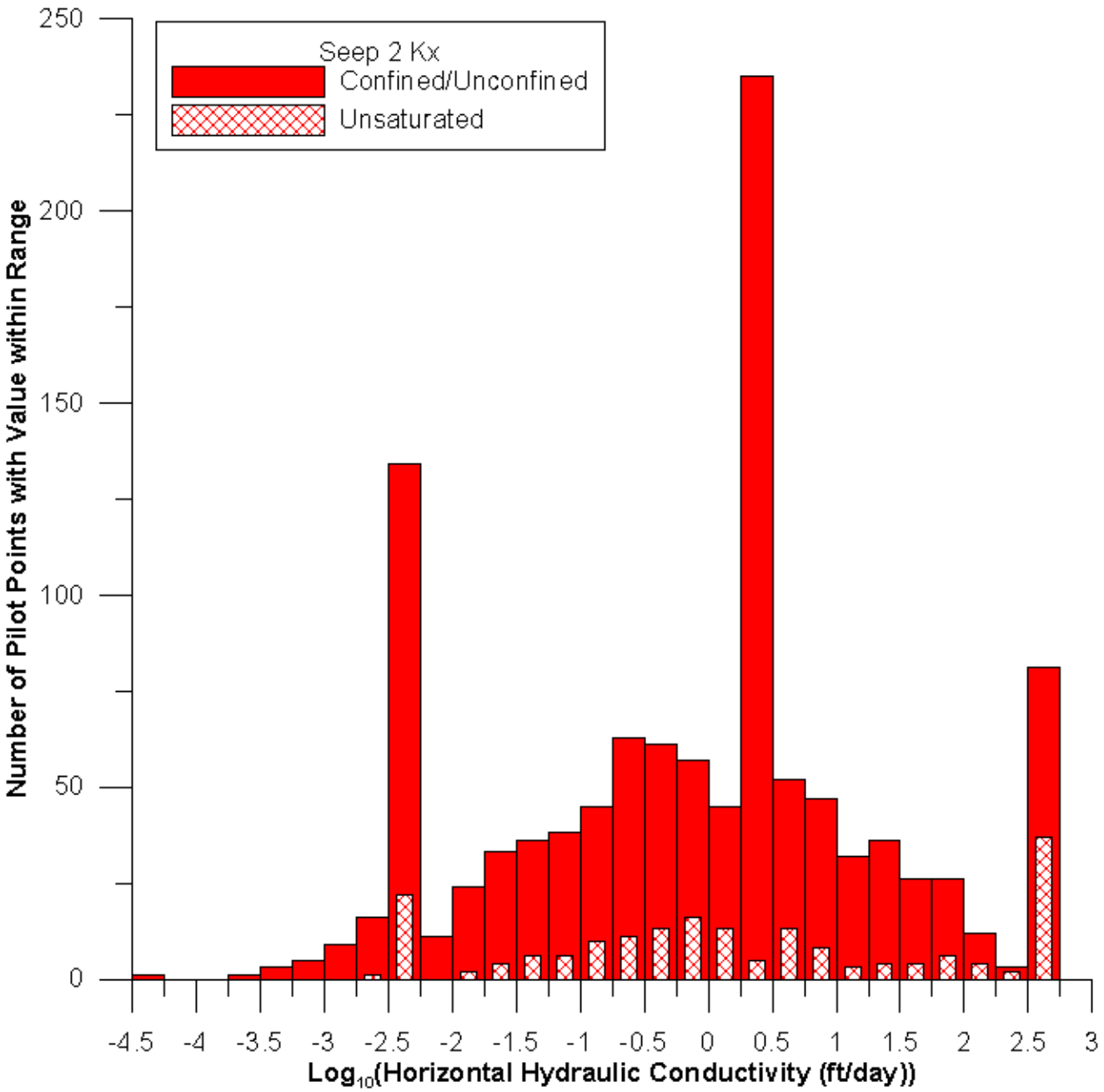


Figure 6-11a

Histogram of Horizontal Hydraulic Conductivity Values for the Seep 2 TMR Model

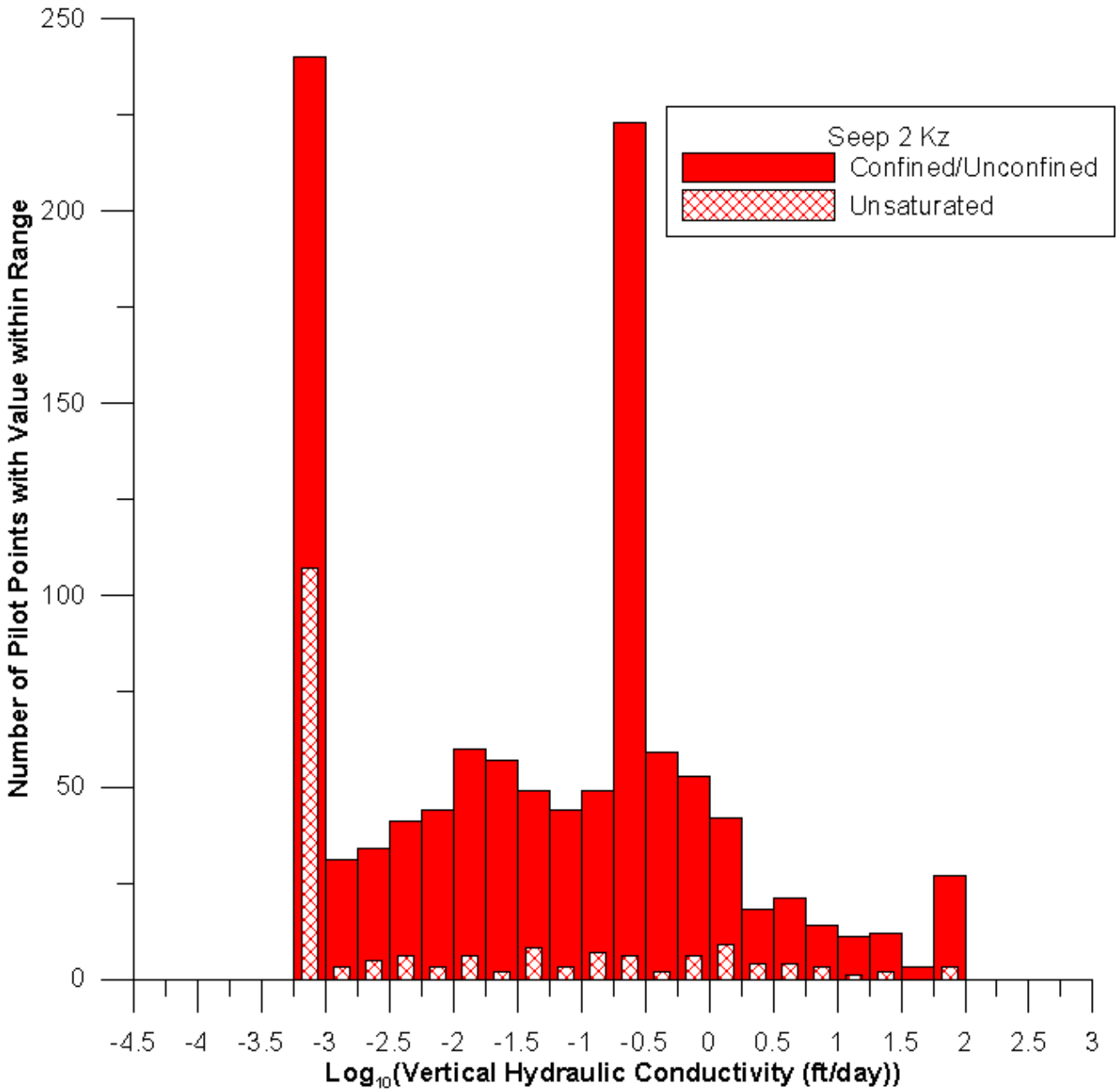


Figure 6-11b

Histogram of Vertical Hydraulic Conductivity Values for the Seep 2 TMR Model

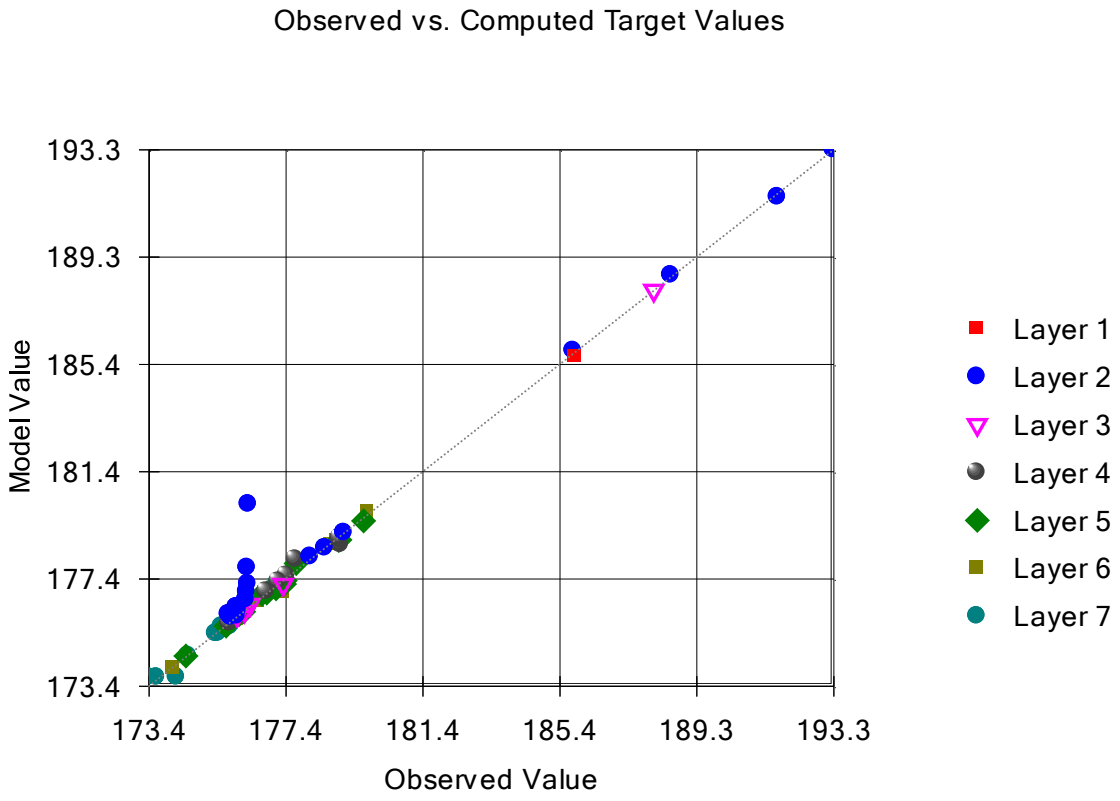


Figure 6-12

Scatter Plot of Heads on 9/14/2006 for the Seep 2 TMR Model Calibration

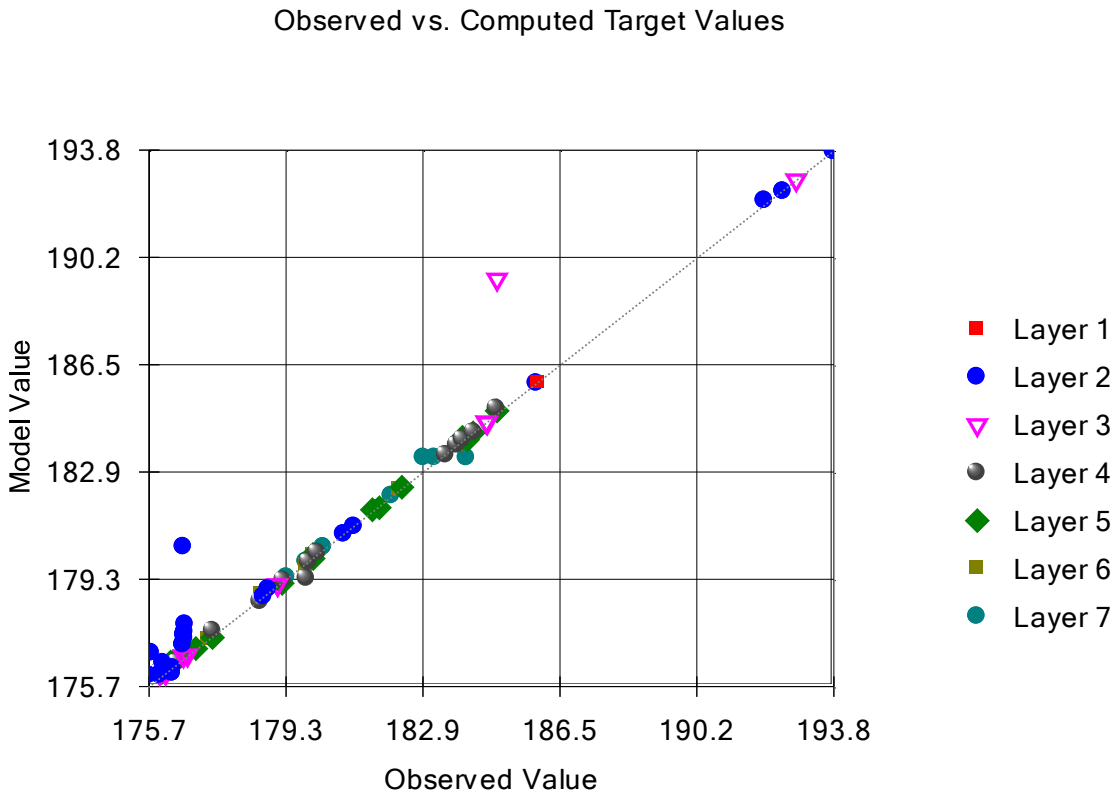


Figure 6-13

Scatter Plot of Heads on 1/02/2007 for the Seep 2 TMR Model Calibration

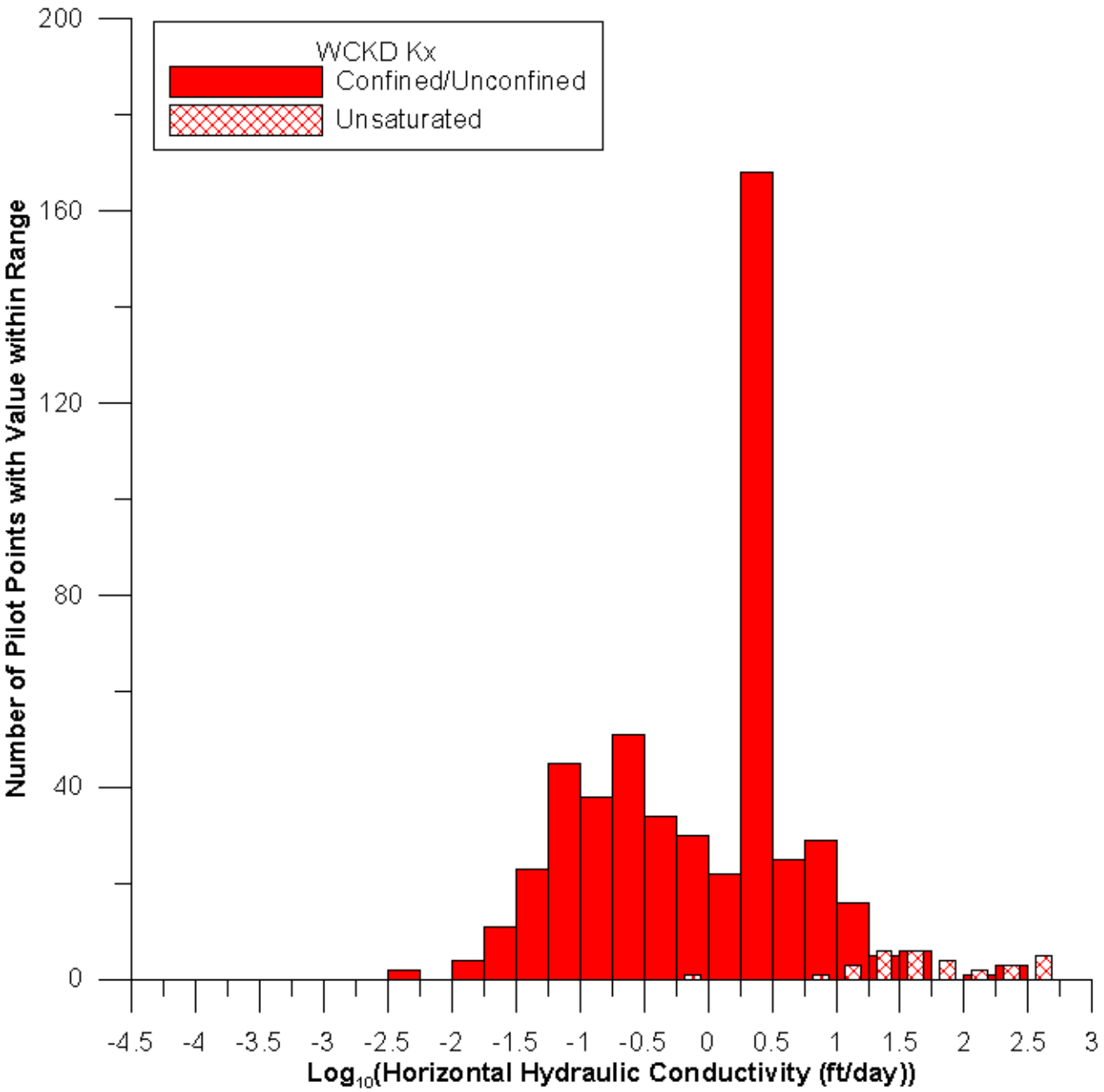


Figure 6-14a

Histogram of Horizontal Hydraulic Conductivity Values for the West CKD TMR Model

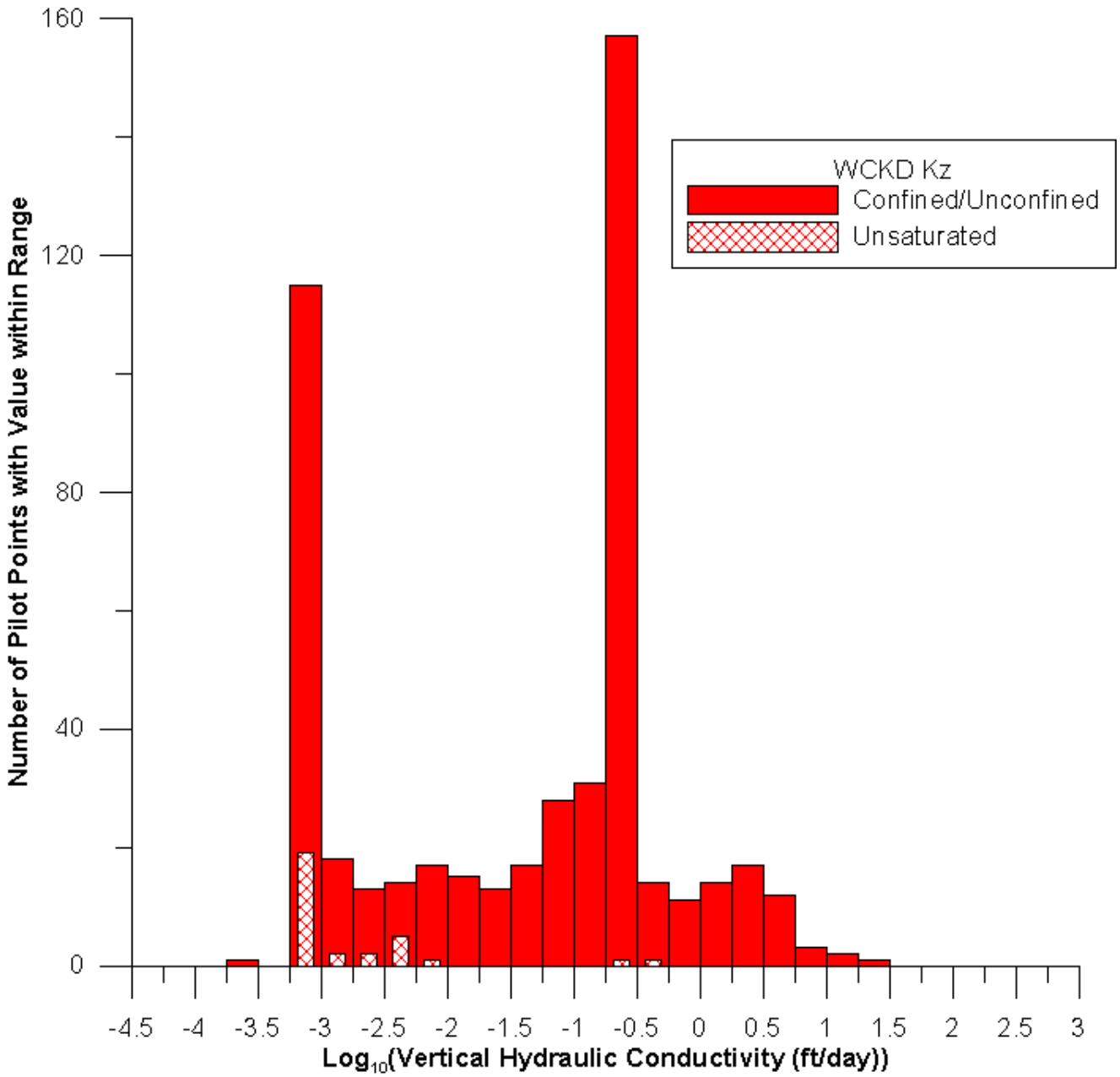


Figure 6-14b

Histogram of Vertical Hydraulic Conductivity Values for the West CKD TMR Model

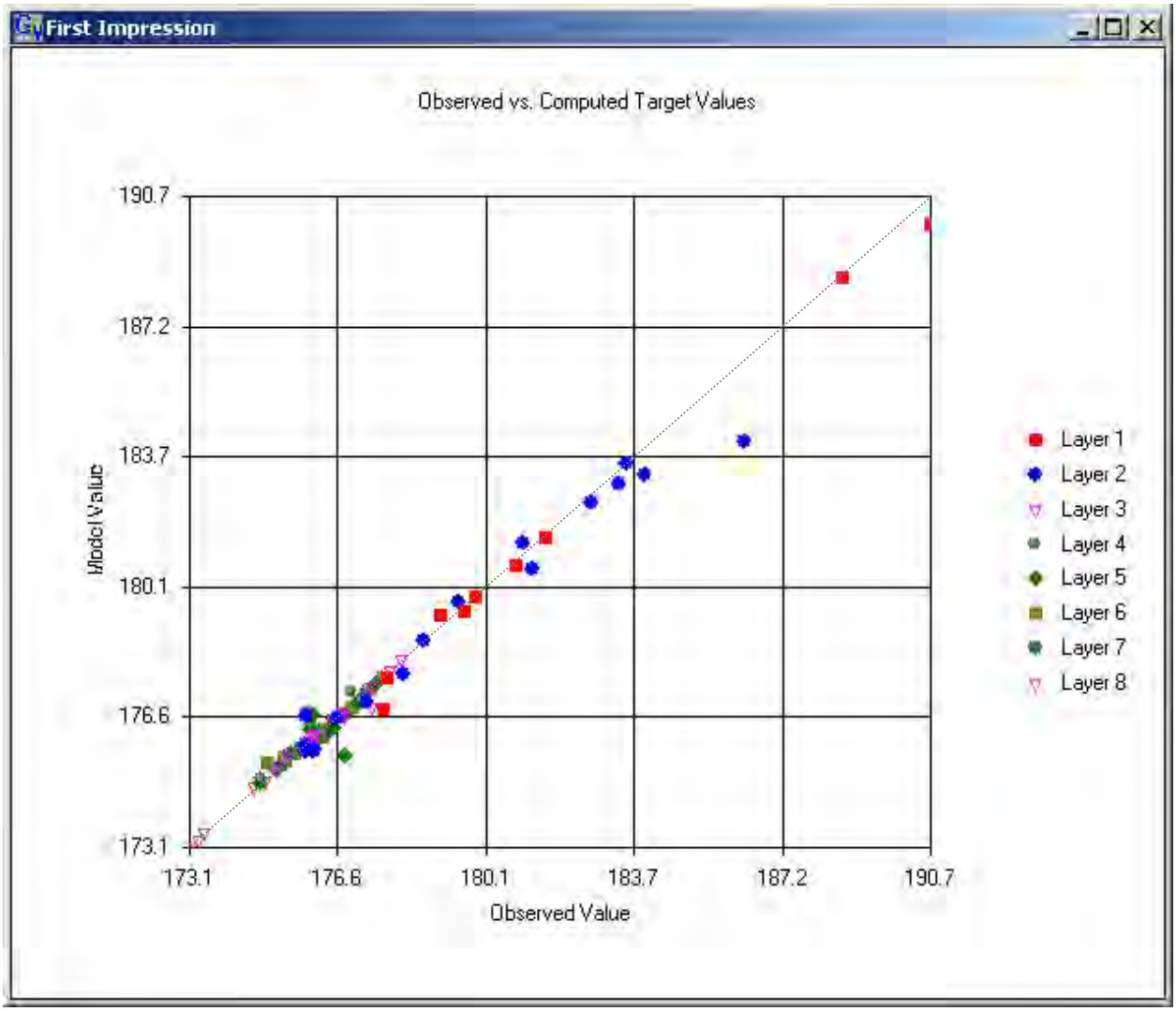


Figure 6-15

Scatter Plot of Heads on 9/14/2006 for the West CKD TMR Model Calibration

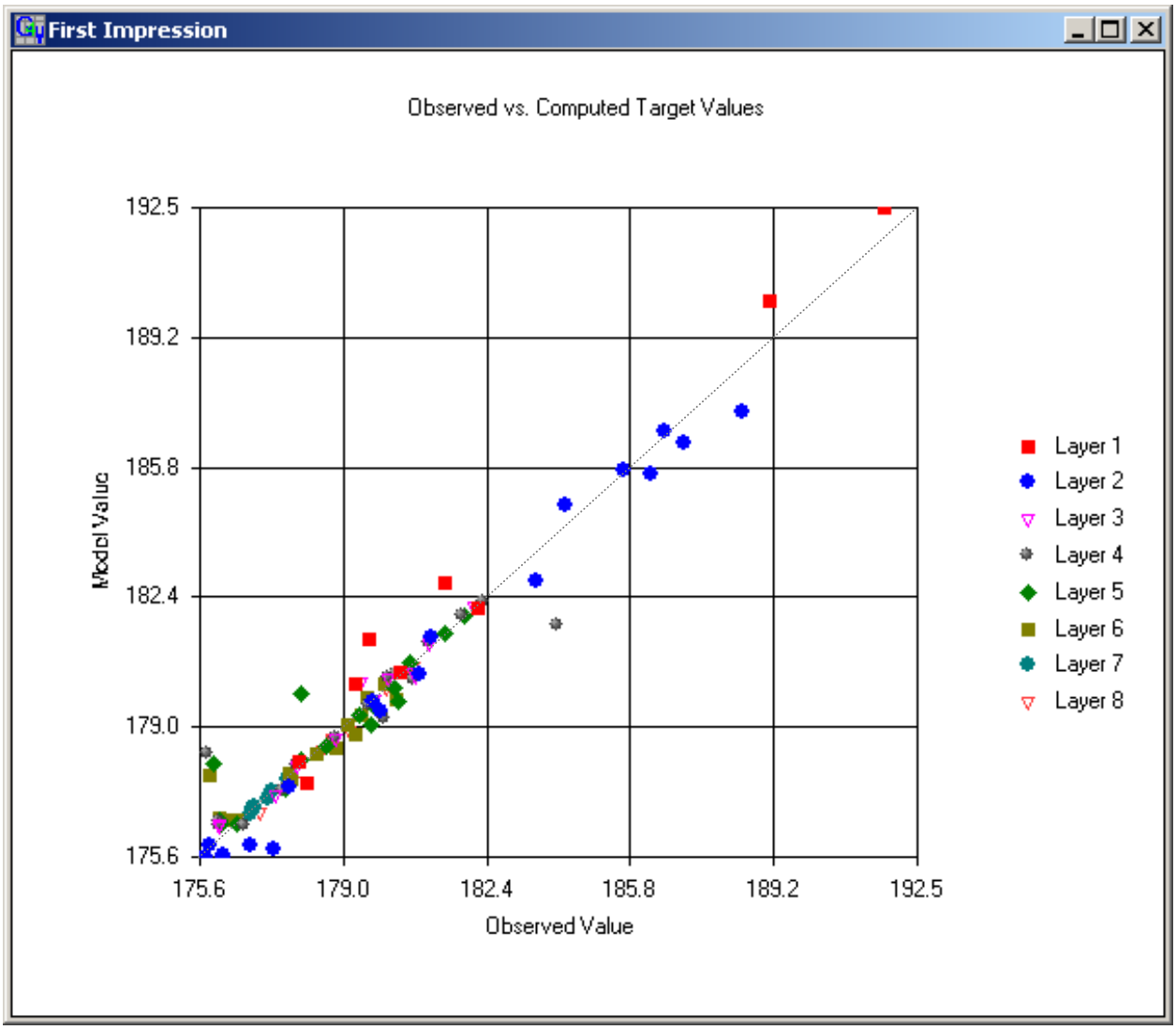
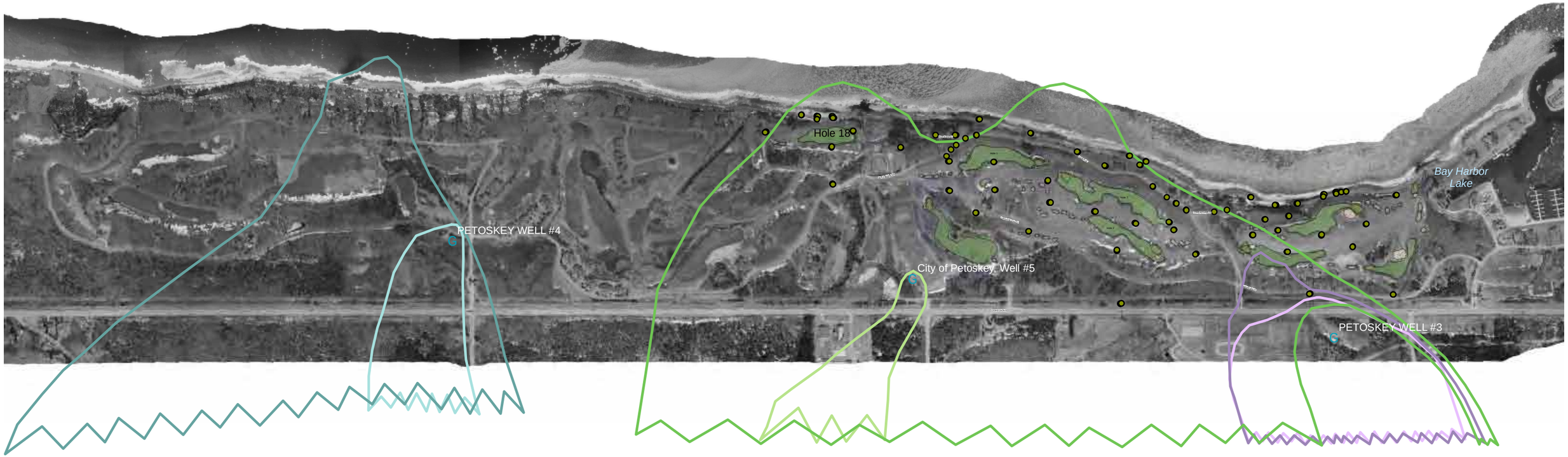


Figure 6-16

Scatter Plot of Heads on 1/02/2007 for the West CKD TMR Model Calibration



Fairway
Green
Sand
Tee Boxes

G Petoskey Municipal Wells
Monitoring Wells
Well 3 Capture Zone: 9-2006
Well 4 Capture Zone: 9-2006
Well 5 Capture Zone: 9-2006
Well 3 Capture Zone: 1-2007
Well 4 Capture Zone: 1-2007
Well 5 Capture Zone: 1-2007

Imagery: April 2005

N

250 0 250 250 500 750 1,000 1,250
Feet

Figure 7-1

PETOSKEY MUNICIPAL
WELLS ESTIMATED CAPTURE ZONES
UNDER 9-2006 AND 1-2007
PUMPING CONDITIONS
Little Traverse Bay
CKD Release Site
Emmet County, Michigan

BARR

Barr Footer: Date: 7/30/2009 10:40:17 AM File: I:\Client\CMS\LTB_CKD_Release_Site\Seep2\Projects\Petoskey_muni_wells_capture_9-2006&1-2007.mxd User: JCG

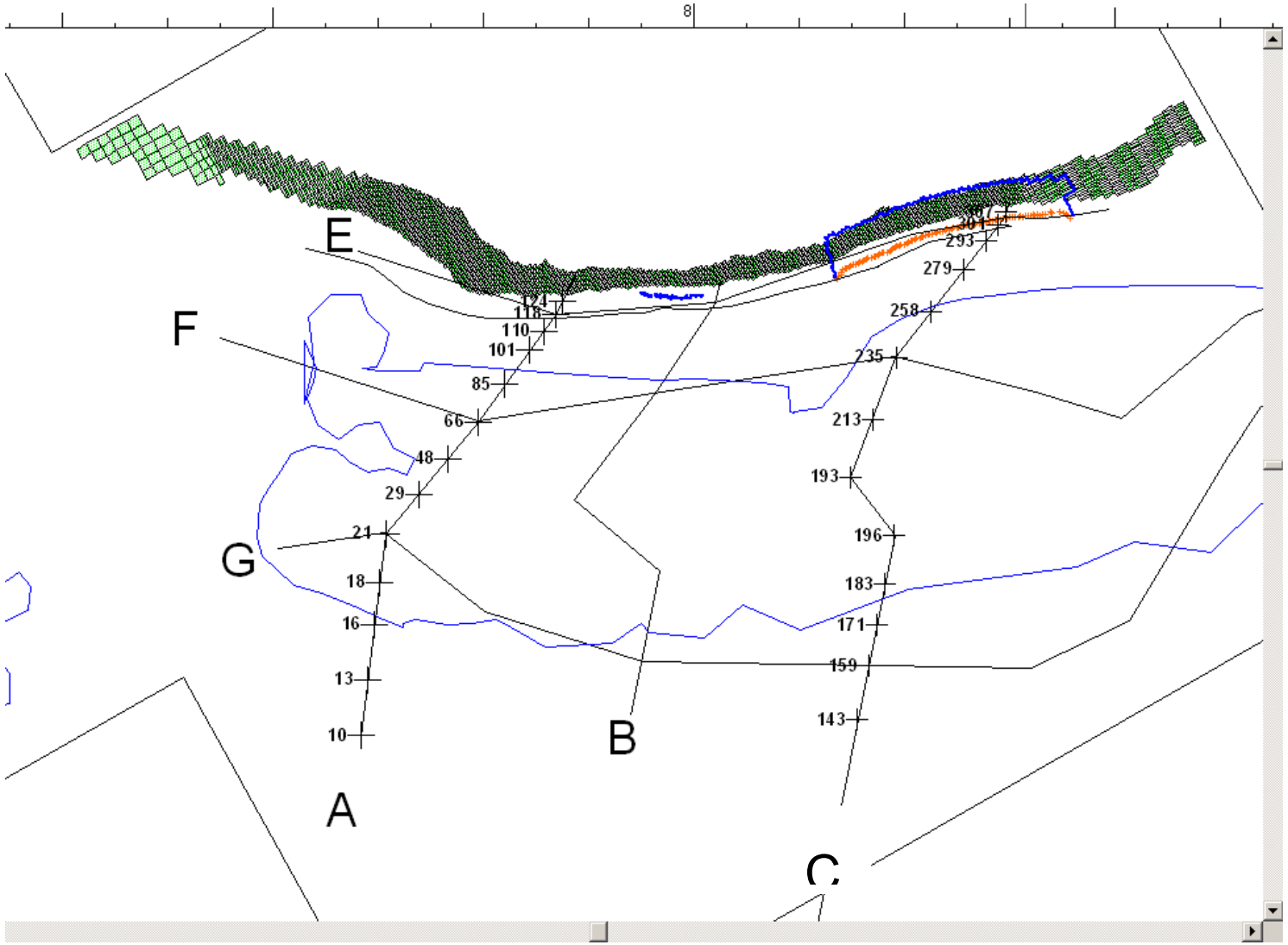


Figure 7-2
Columns in which Traces for Seep 1 Area Cross Sections A-A' and C-C' Originate

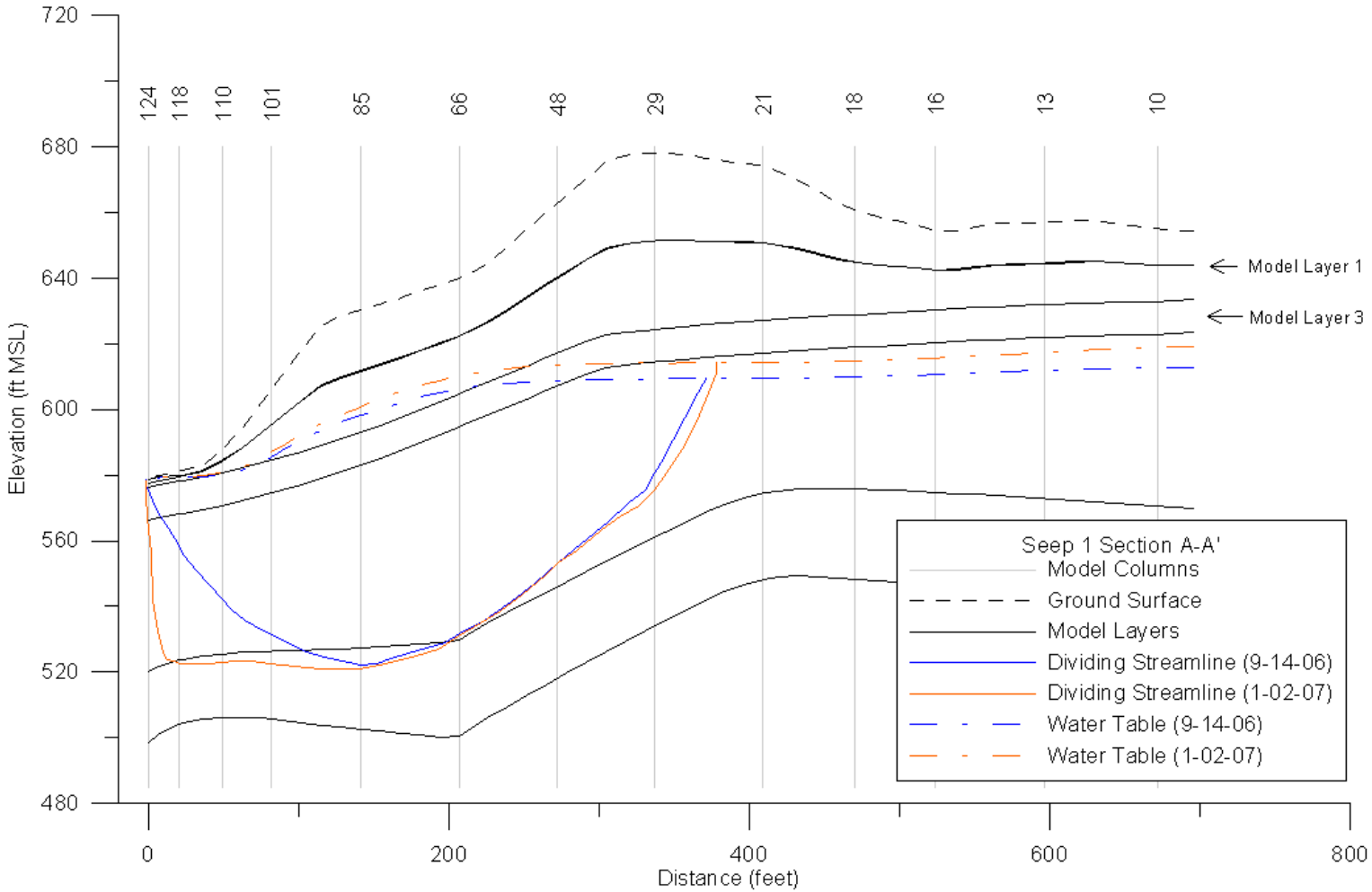


Figure 7-3
Capture Zones in Cross Section A-A' for the Seep 1 Drain in the 9/14/2006 and 1/02/2007 Scenarios

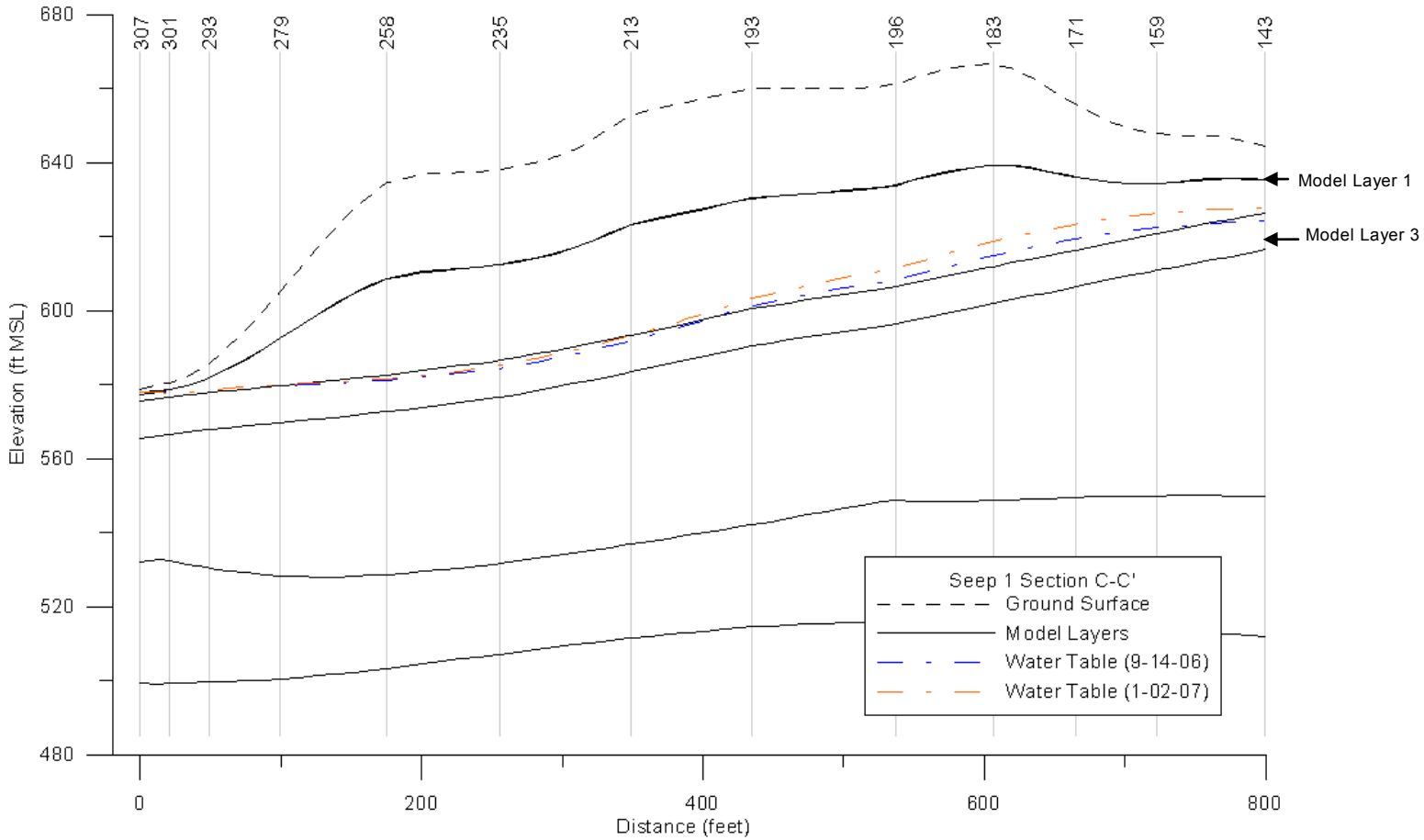


Figure 7-4
Location of Particle Starting Columns and Water Table/Perched Heads in the Two Scenarios for Seep 1 Cross Section C-C'

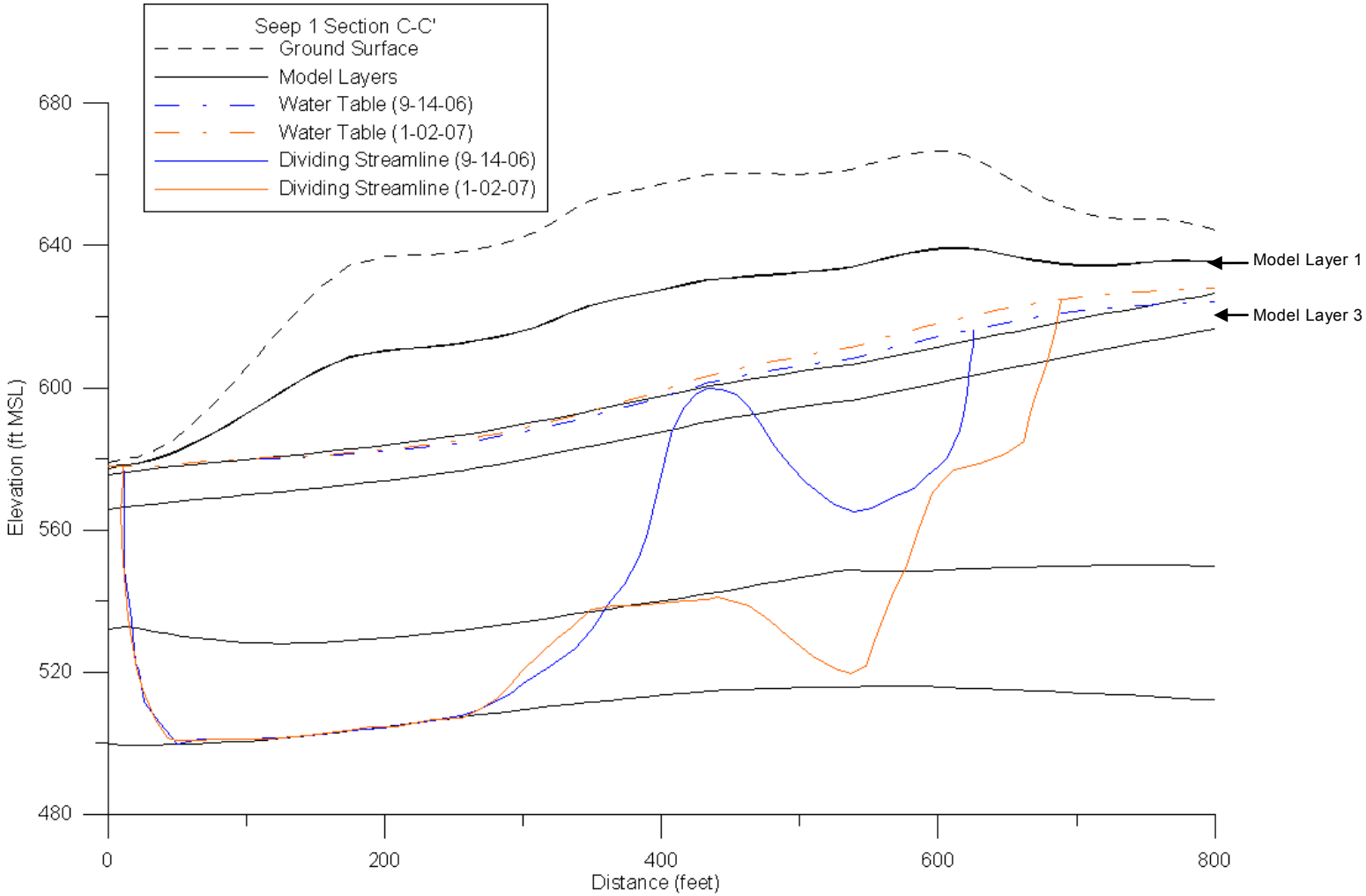


Figure 7-5
Capture Zones in Cross Section C-C' for the Seep 1 Drain in the 9/14/2006 and 1/02/2007 Scenarios

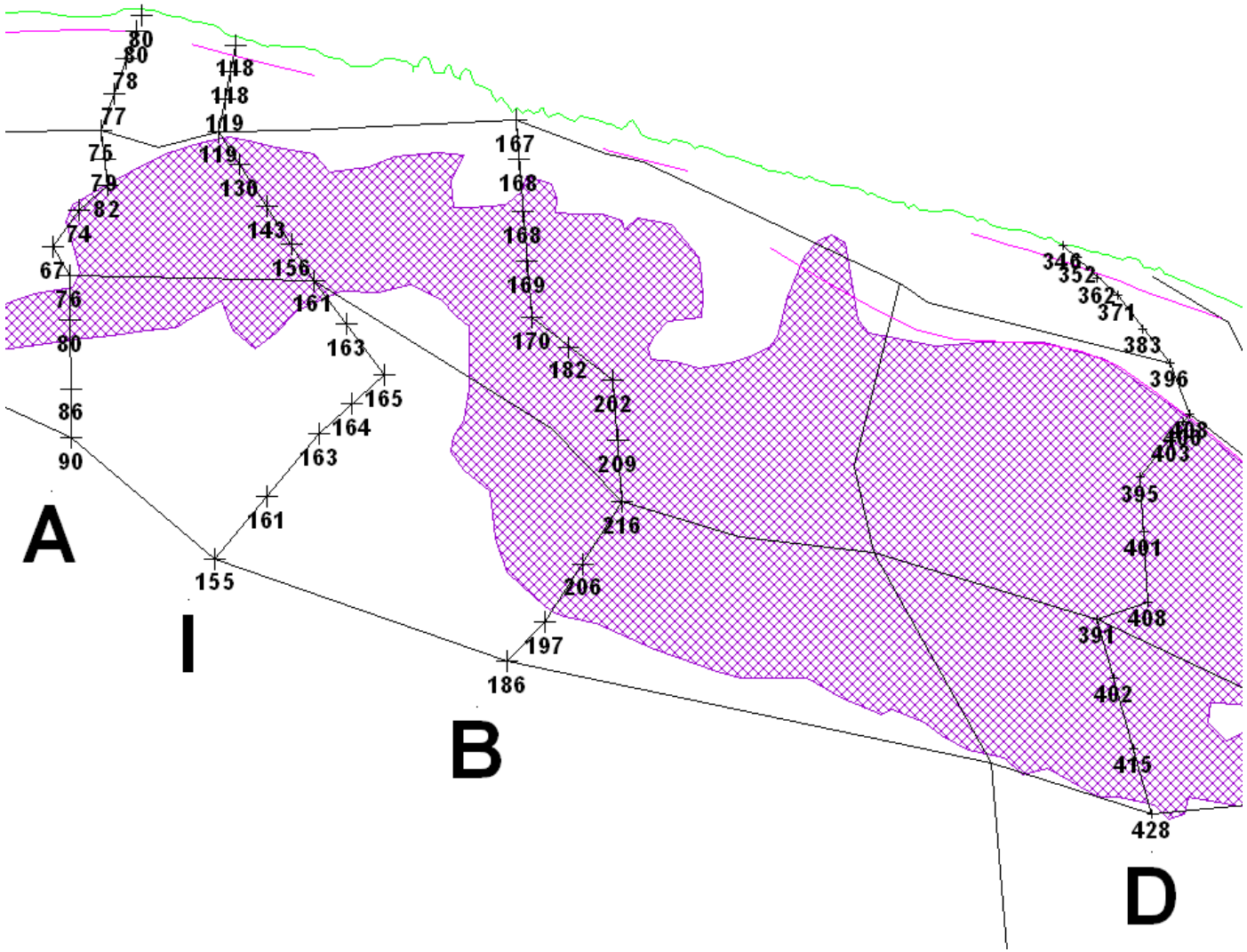


Figure 7-6
Starting Locations (model columns) for Particles along Cross Sections in the Seep 2 TMR Model

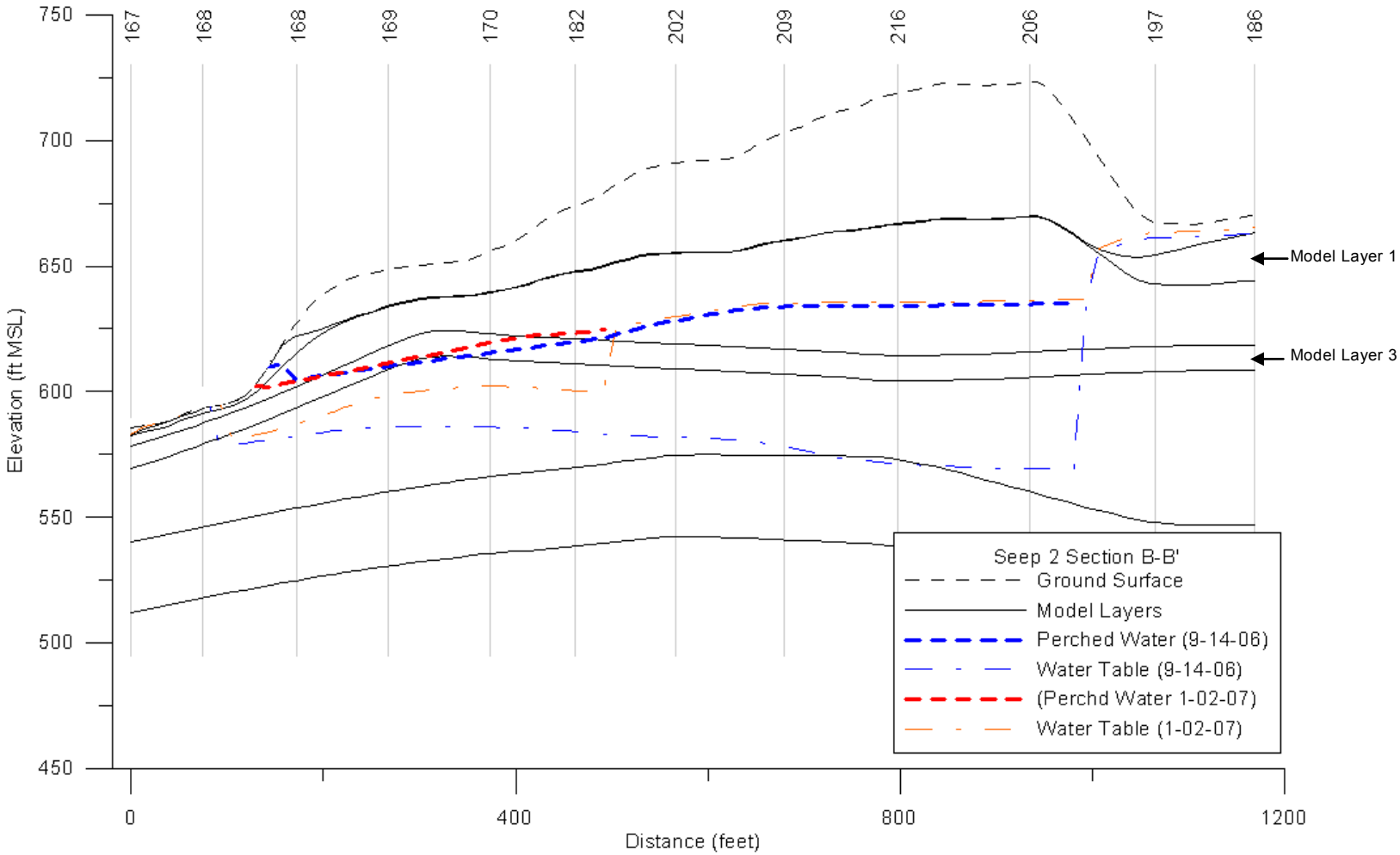


Figure 7-7
Simulated Perched Water and Water Table Elevations for Seep 2 Cross Section B-B'

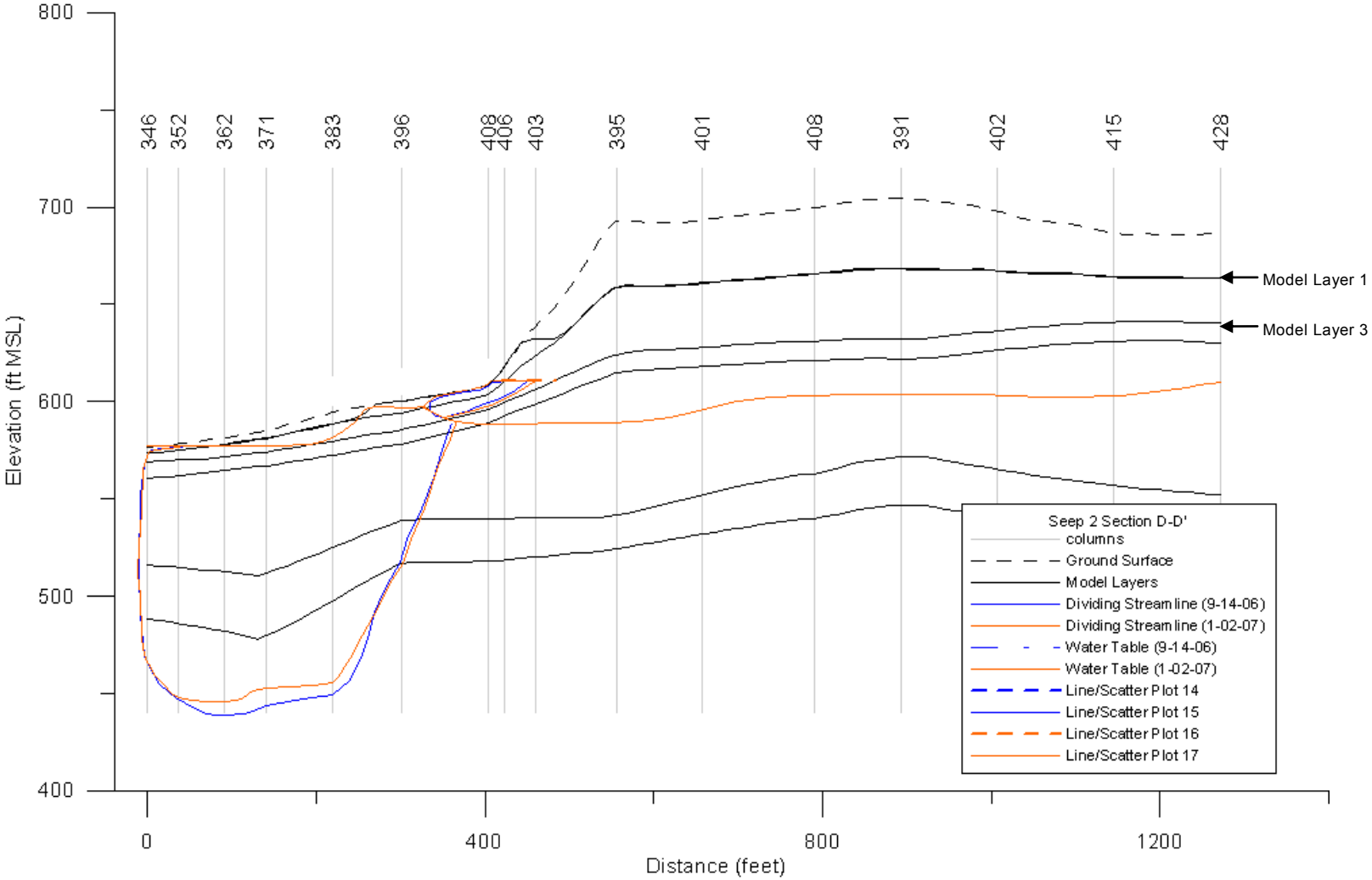


Figure 7-8
Simulated Perched Water and Water Table Elevations for Seep 2 Cross Section D-D'

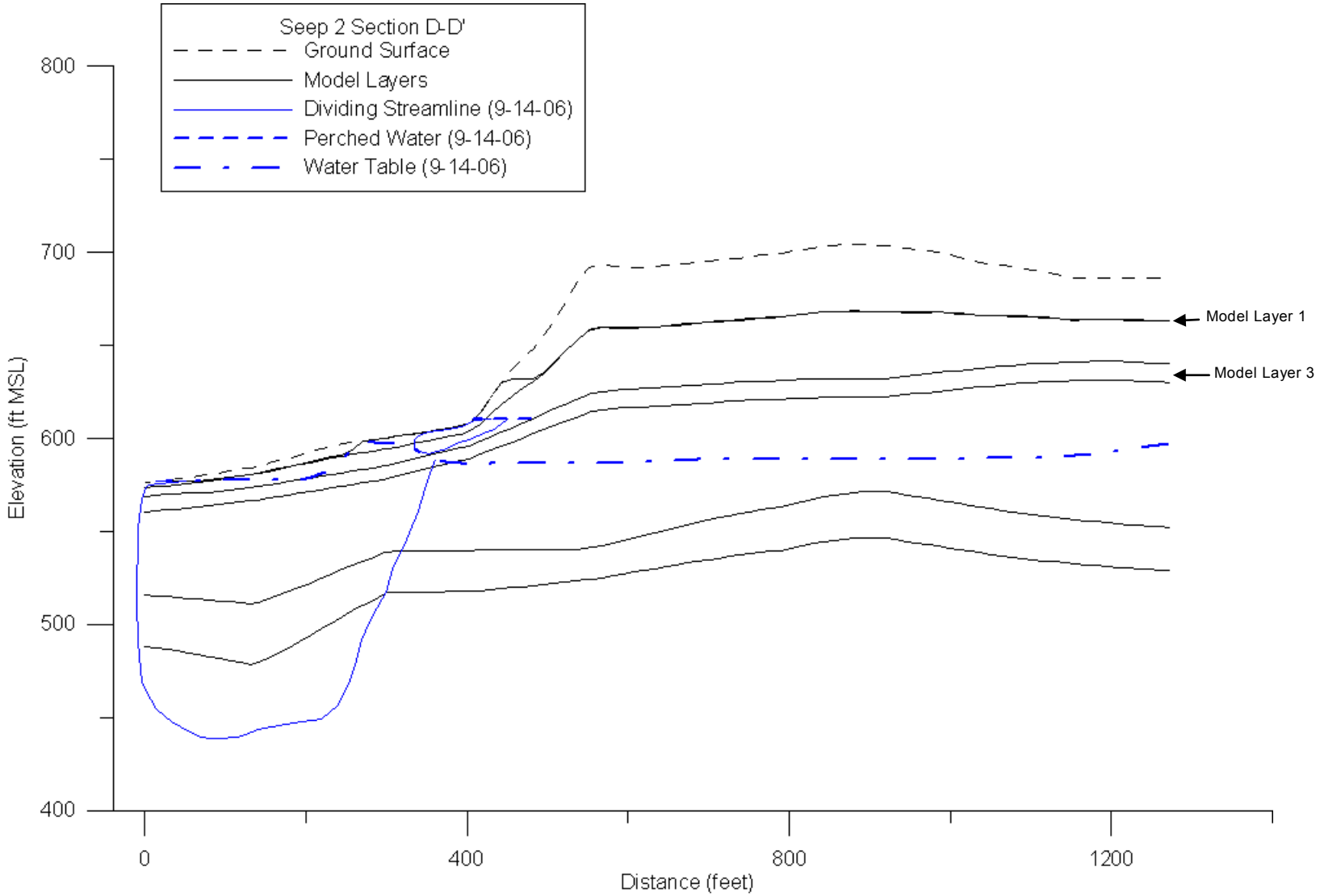


Figure 7-9
Capture Zone in Cross Section D-D' for the Edge Drain and Seep 2 Drain in the 9/14/2006 Scenario

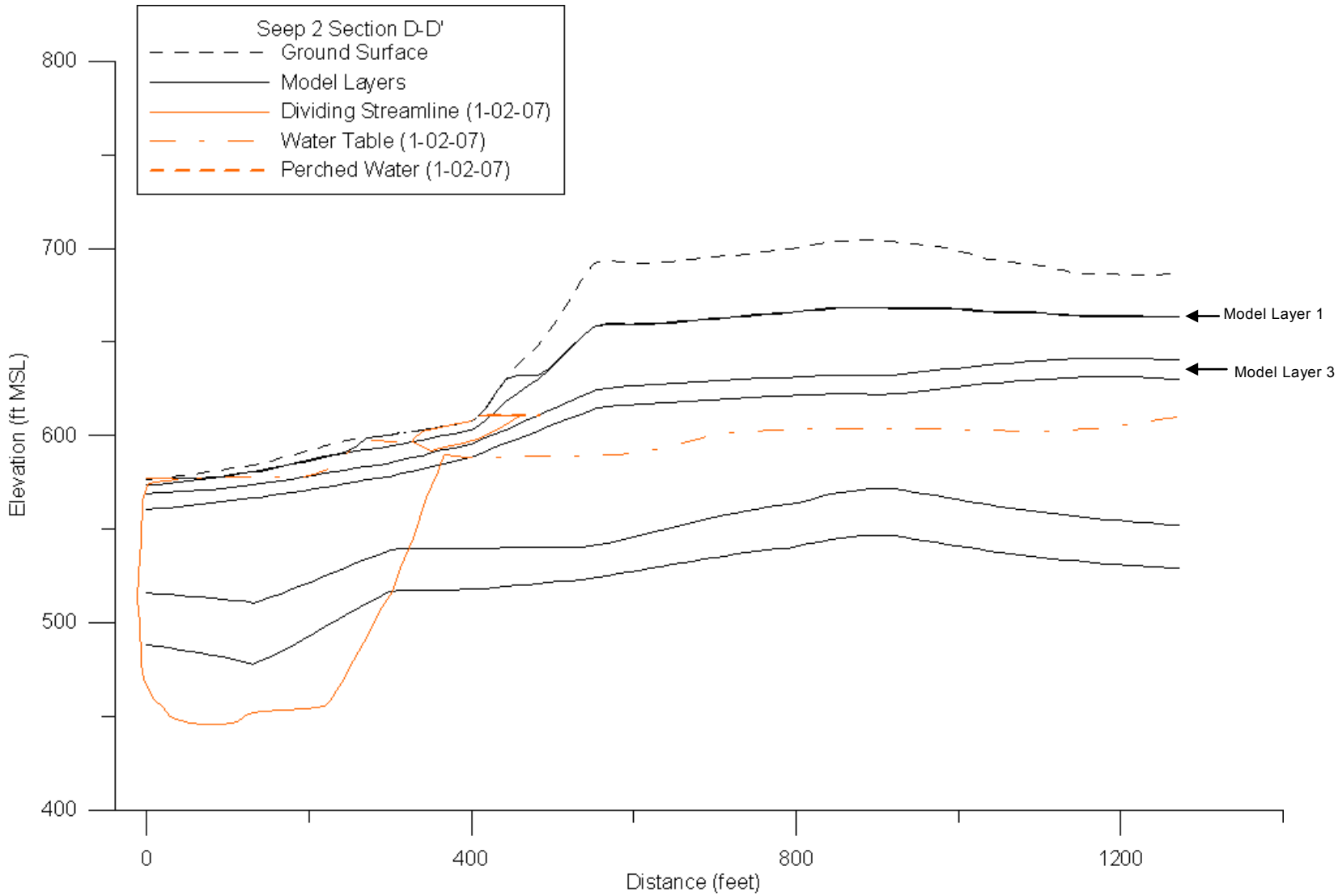


Figure 7-10
Capture Zone in Cross Section D-D' for the Edge Drain and Seep 2 Drain in the 1/02/2007 Scenario

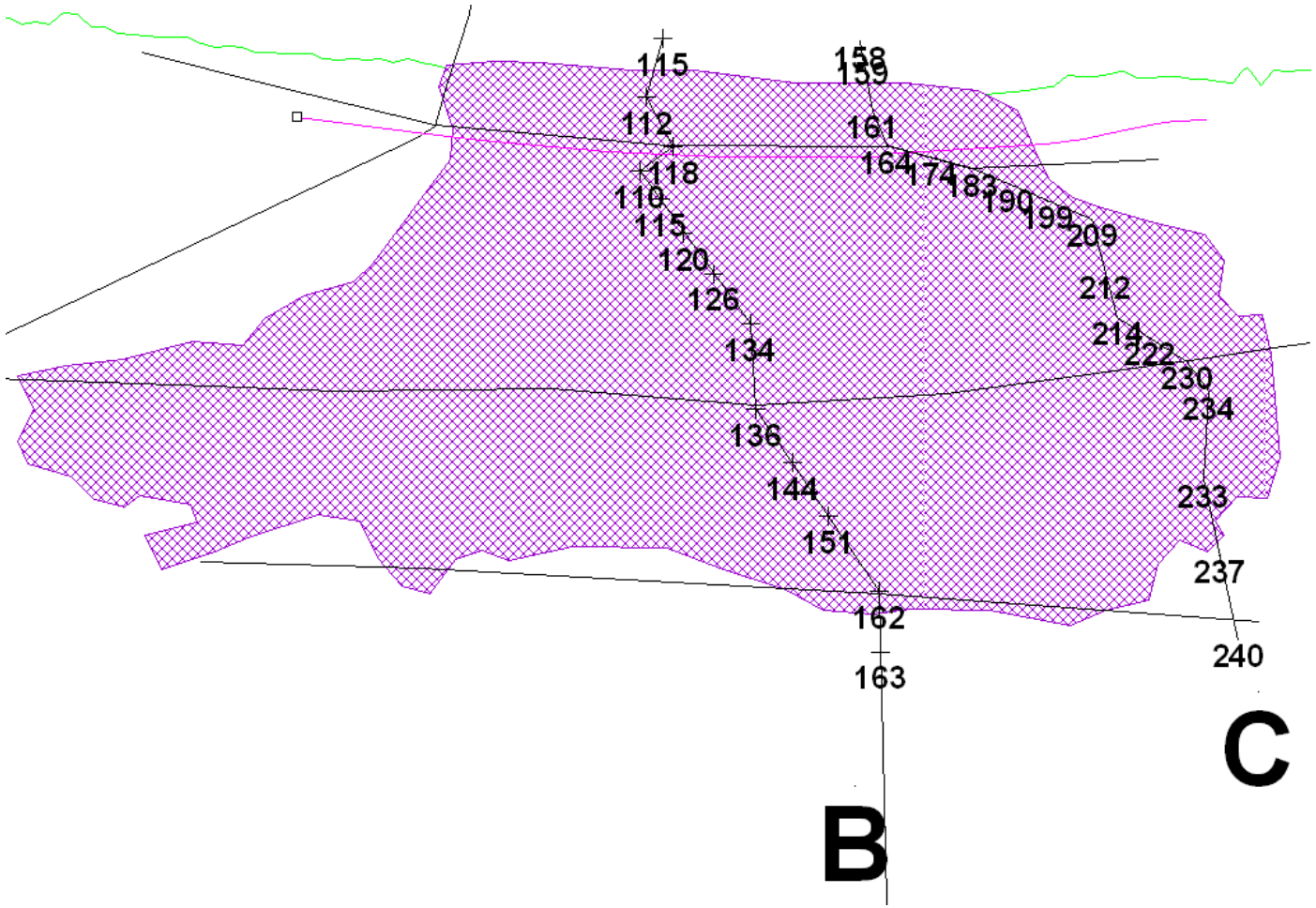


Figure 7-11
Starting Locations (model columns) for Particles along Cross Sections B-B' and C-C' in the West CKD TMR Model

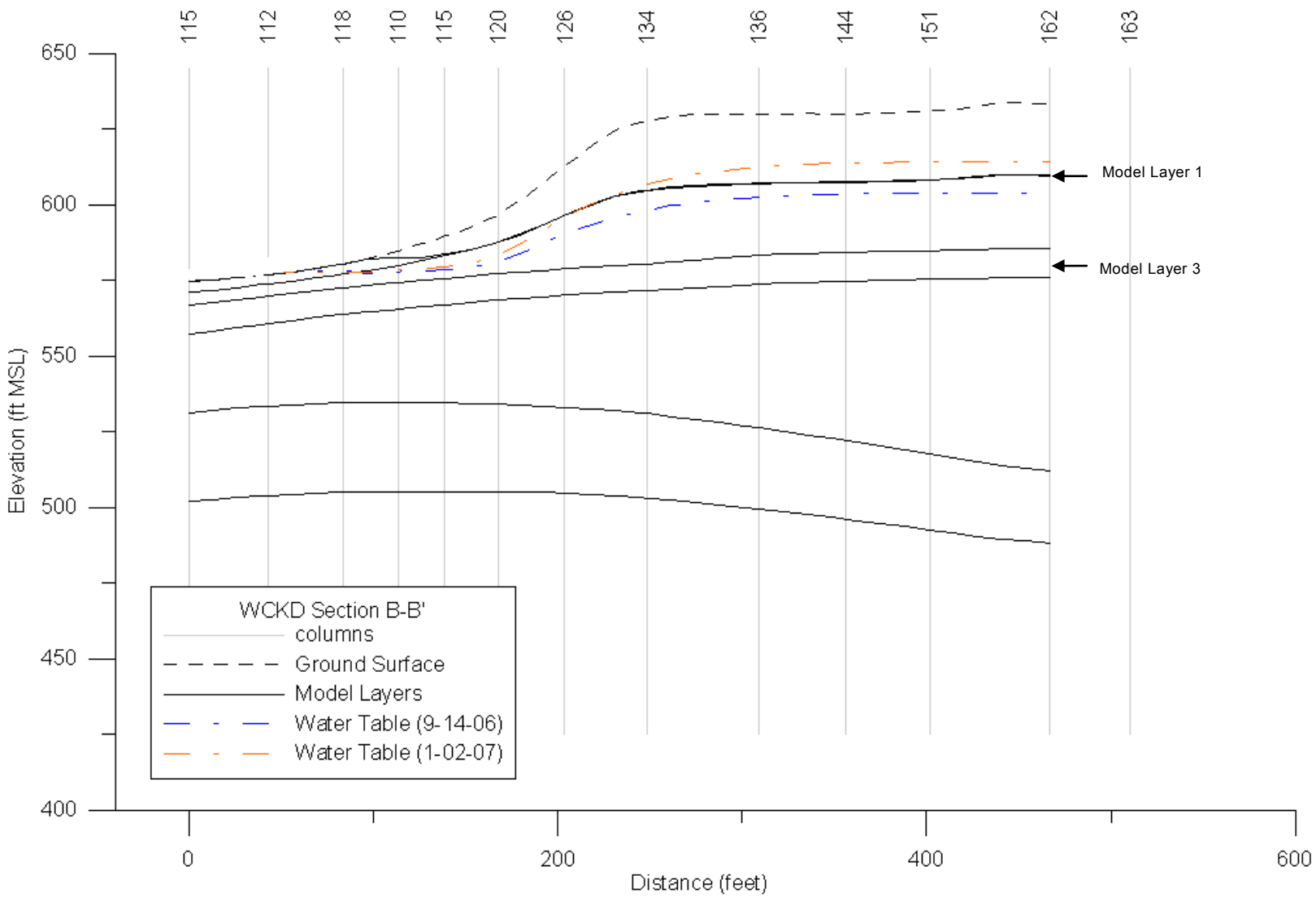


Figure 7-12
Location of Particle Starting Columns and Water Table in the Two Scenarios for West CKD Area Cross Section B-B'

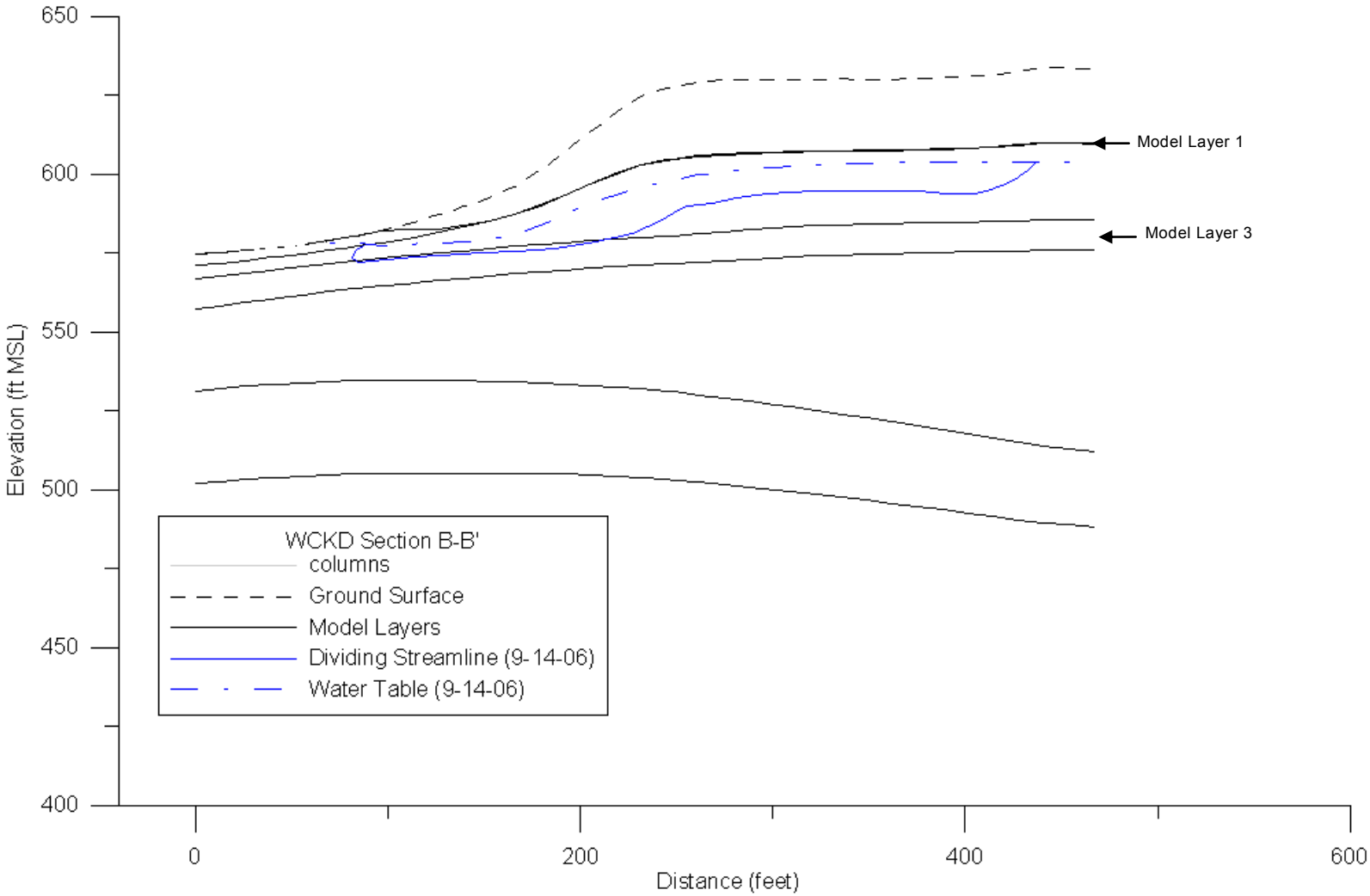


Figure 7-13
Capture Zone in Cross Section B-B' for the West CKD Area Drain in the 9/14/2006 Scenario

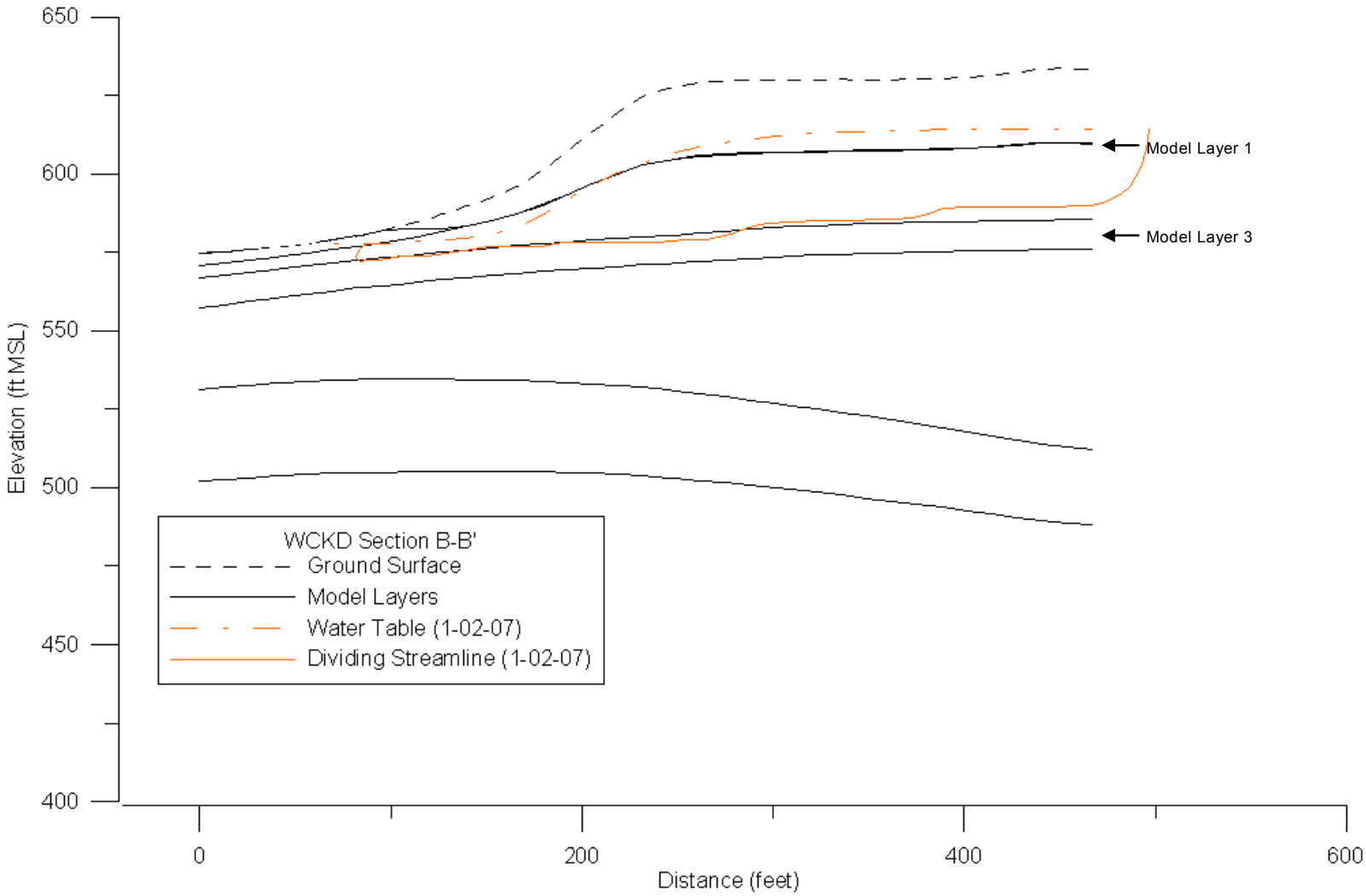


Figure 7-14
Capture Zone in Cross Section B-B' for the West CKD Area Drain in the 1/02/2007 Scenario

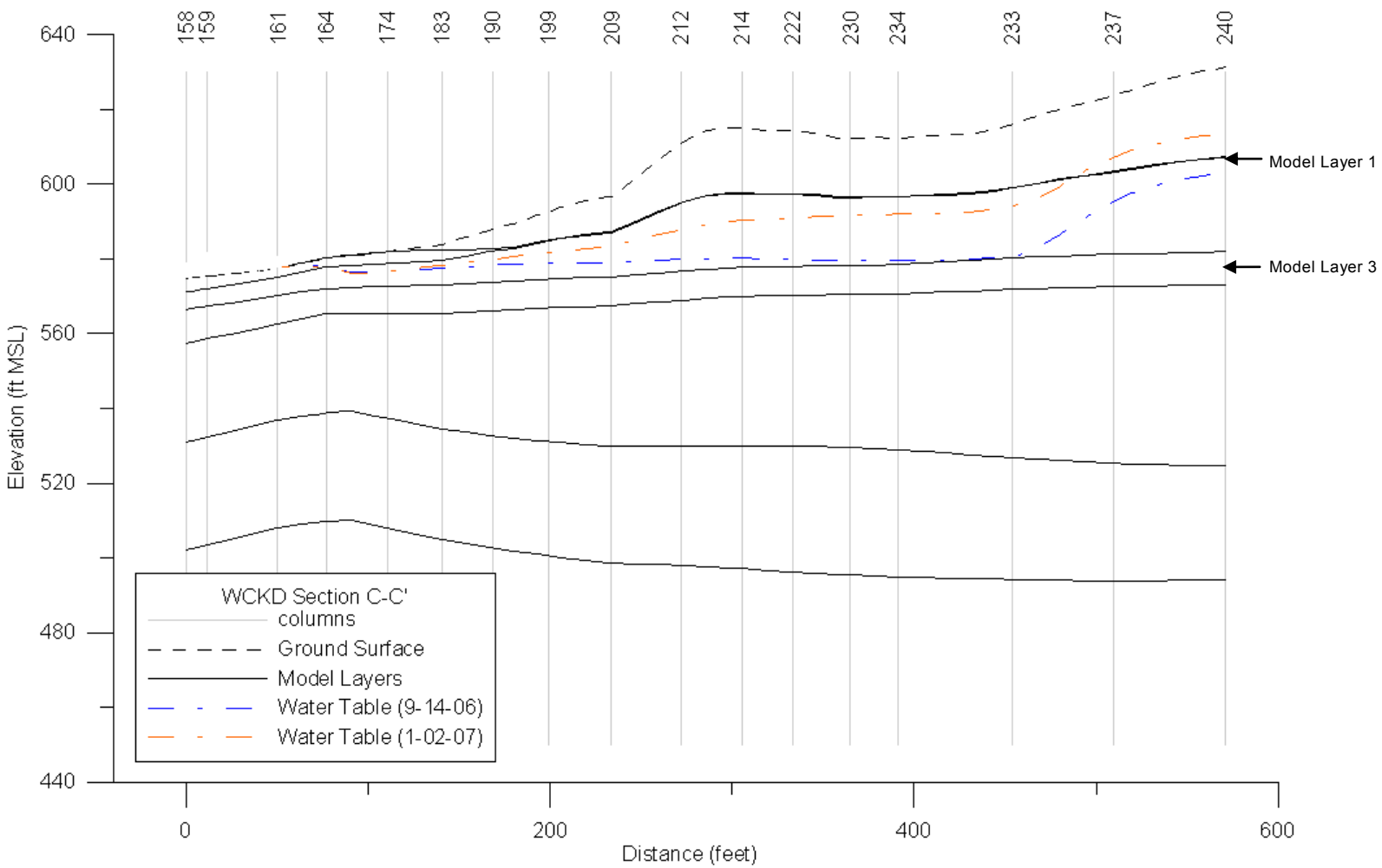


Figure 7-15
Location of Particle Starting Columns and Water Table in the Two Scenarios for West CKD Area Cross Section C-C'

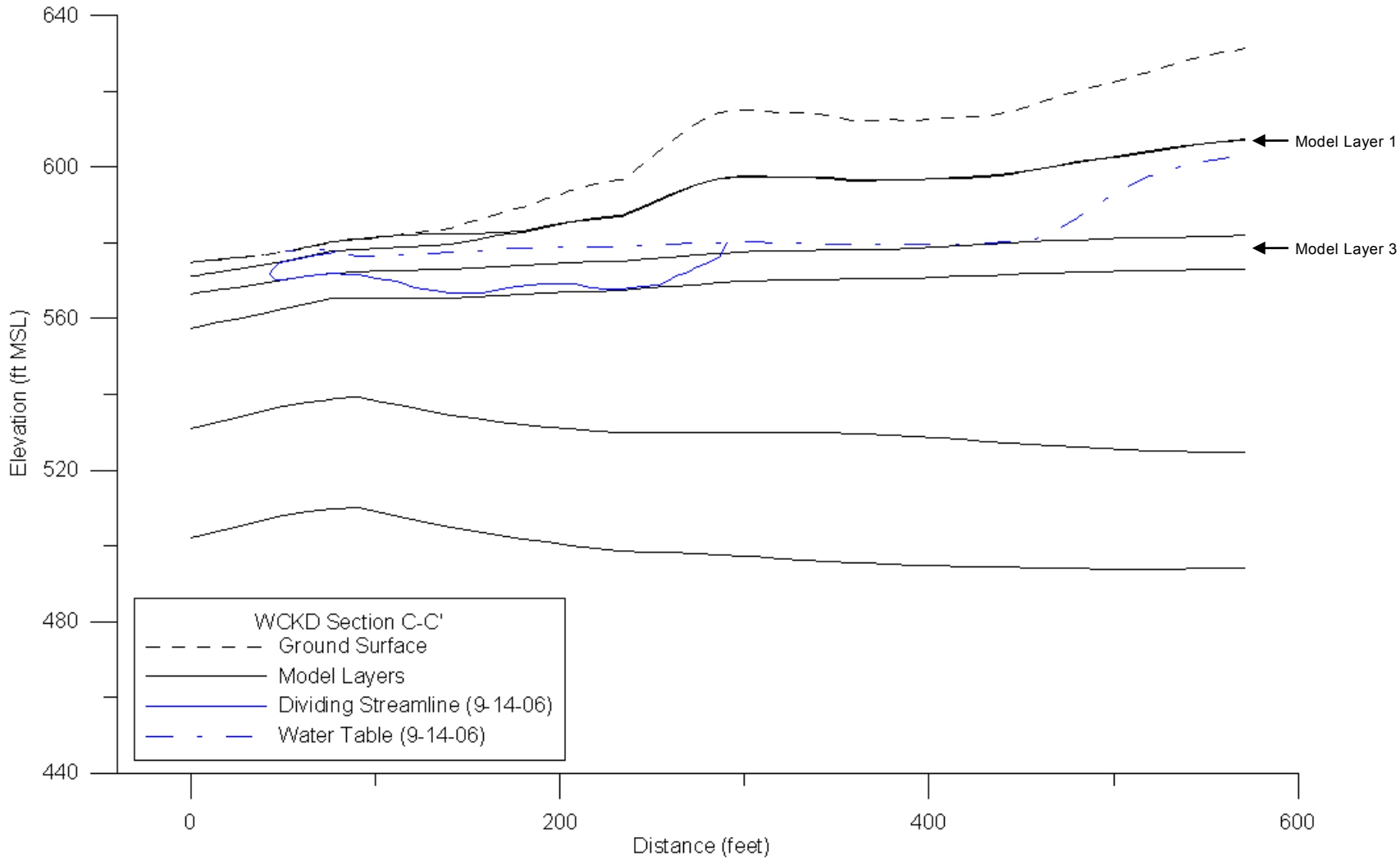


Figure 7-16
Capture Zone in Cross Section C-C' for the West CKD Area Drain in the 9/14/2006 Scenario

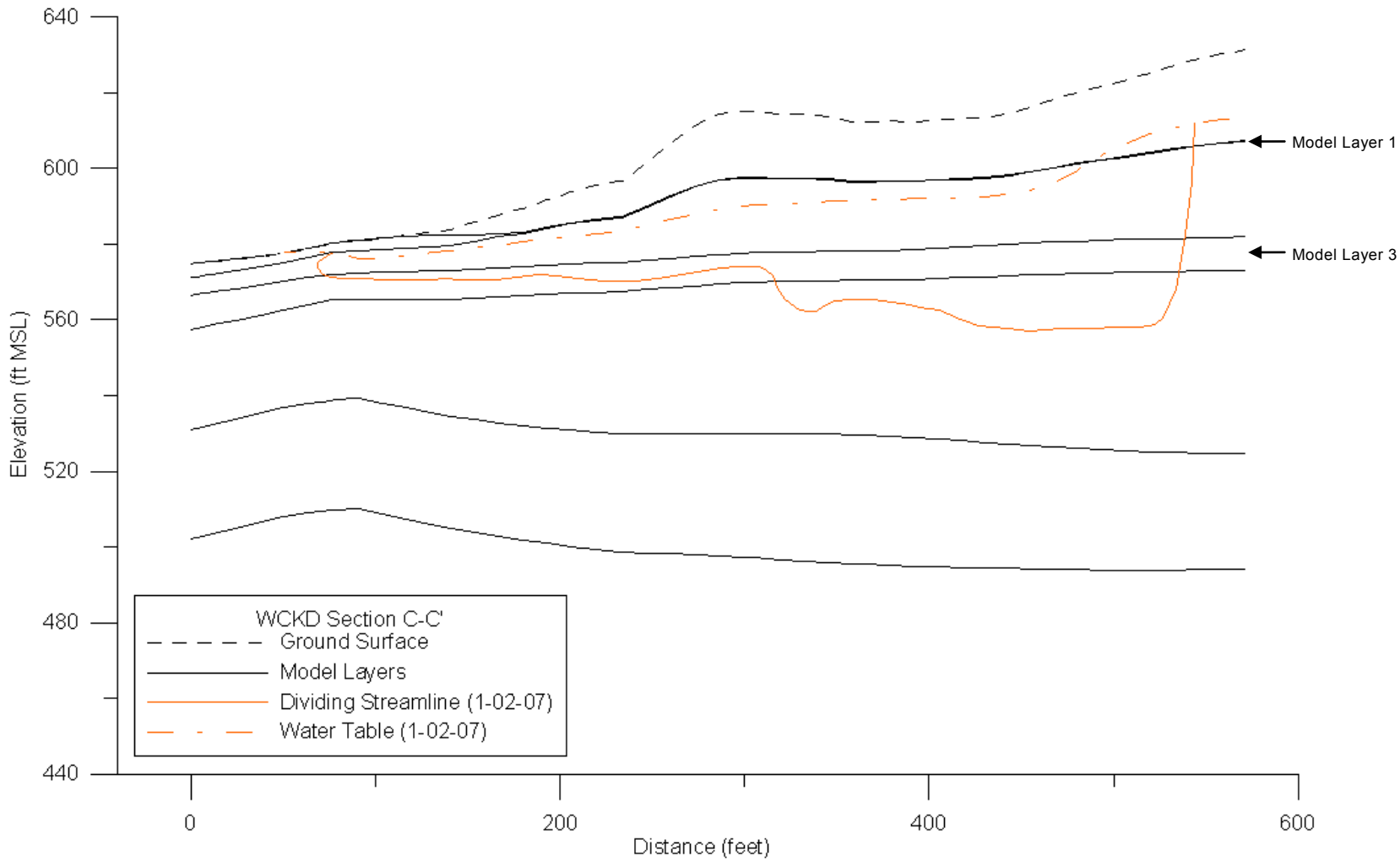


Figure 7-17
Capture Zone in Cross Section C-C' for the West CKD Area Drain in the 1/02/2007 Scenario

Figure 7-18
Modeled Extent of Perched Groundwater in the 9/14/2006 Scenario for the Regional Model

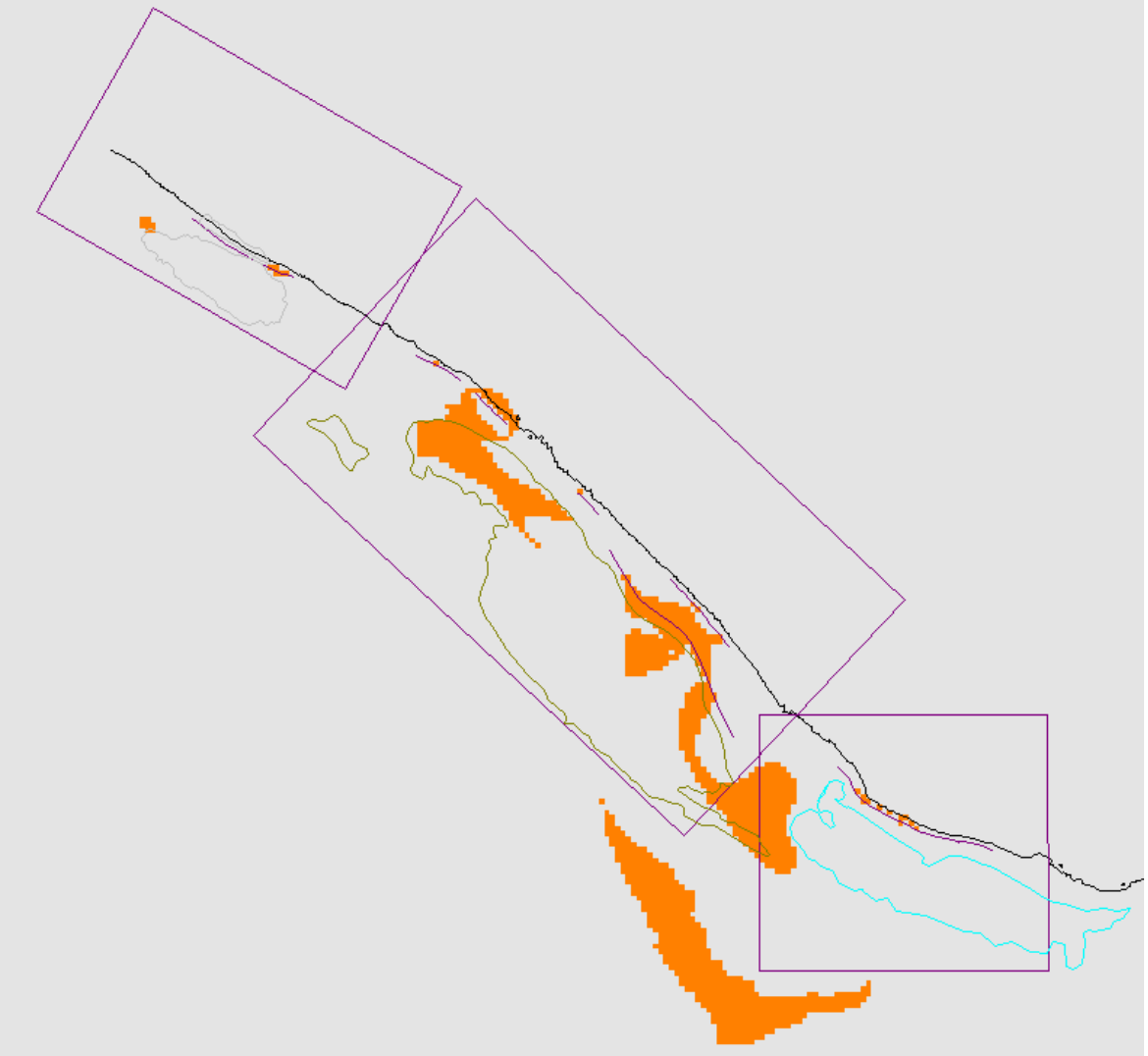


Figure 7-19
Modeled Extent of Perched Groundwater in the 1/02/2007 Scenario for the Regional Model

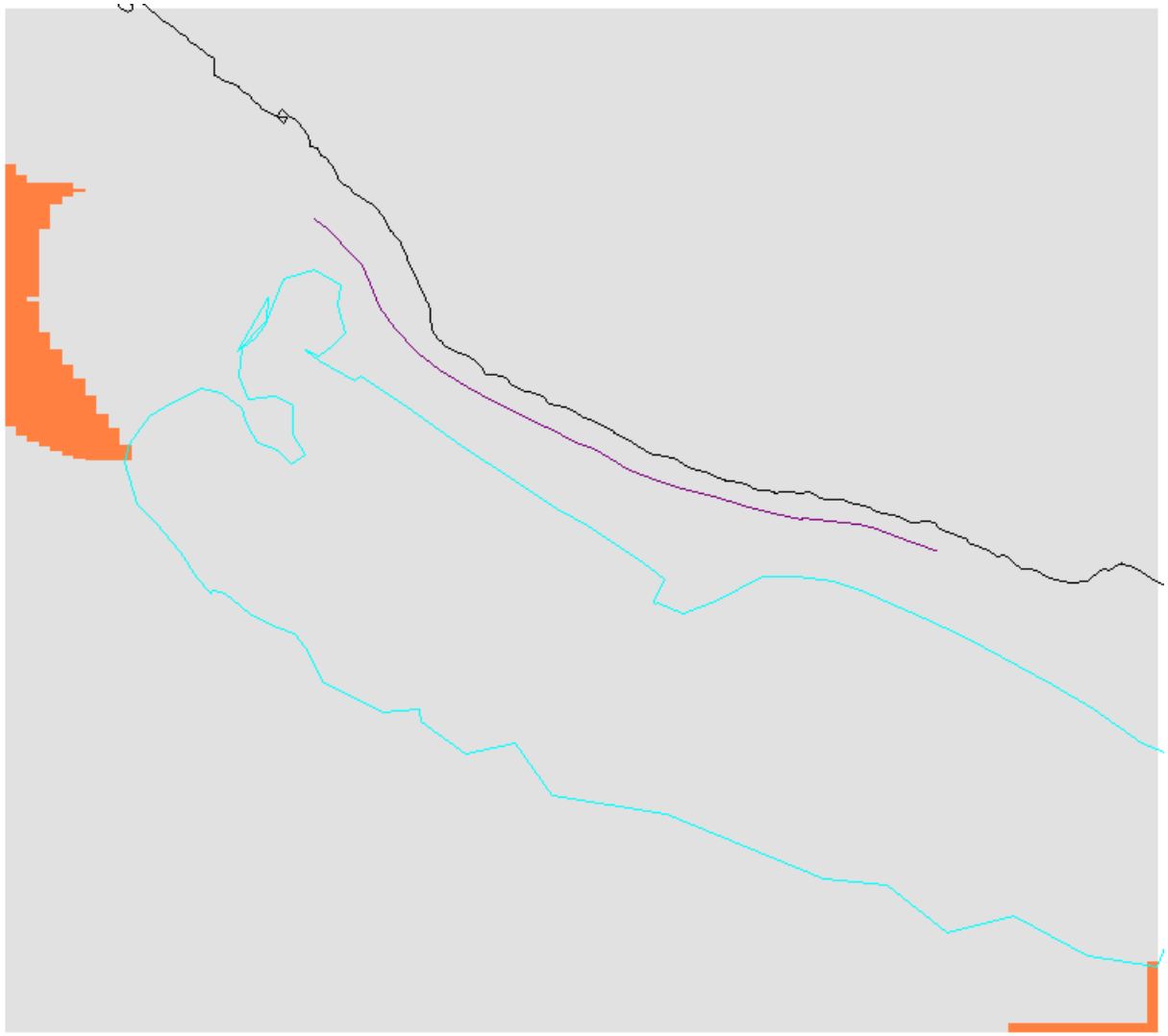


Figure 7-20
Modeled Extent of Perched Groundwater in the 9/14/2006 Scenario for the Seep 1 TMR Model

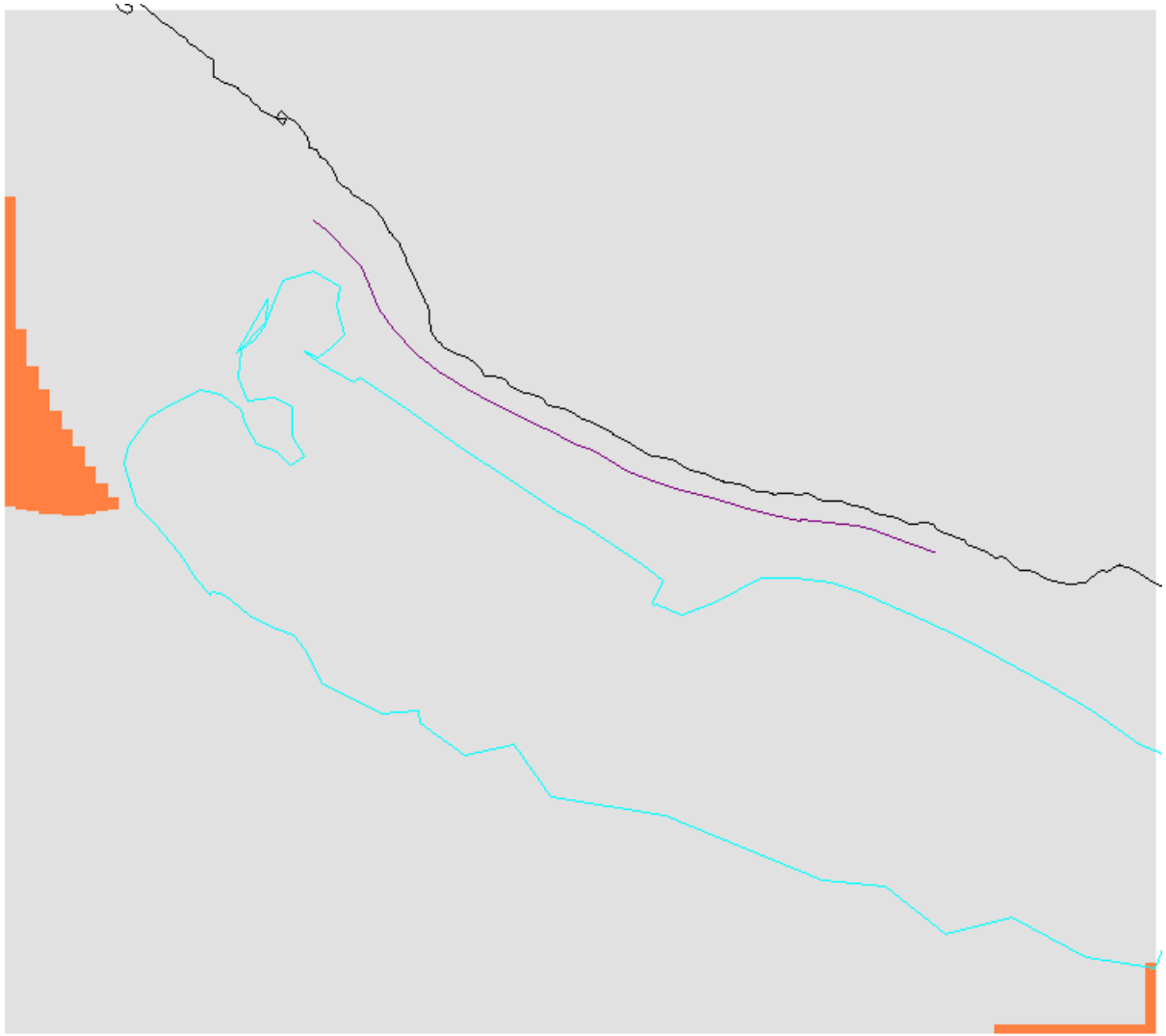


Figure 7-21
Modeled Extent of Perched Groundwater in the 1/02/2007 Scenario for the Seep 1 TMR Model

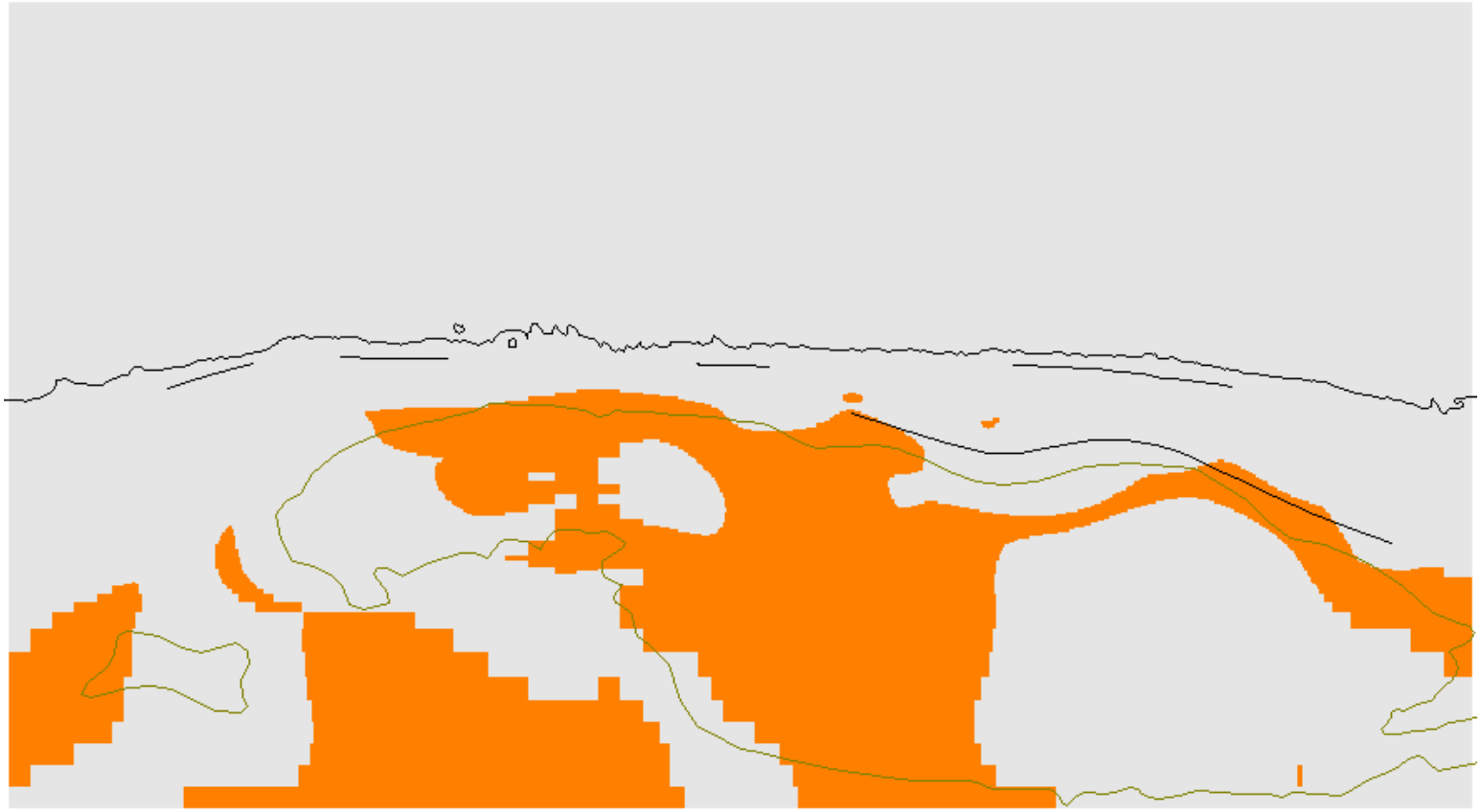


Figure 7-22
Modeled Extent of Perched Groundwater in the 9/14/2006 Scenario for the Seep 2 TMR Model

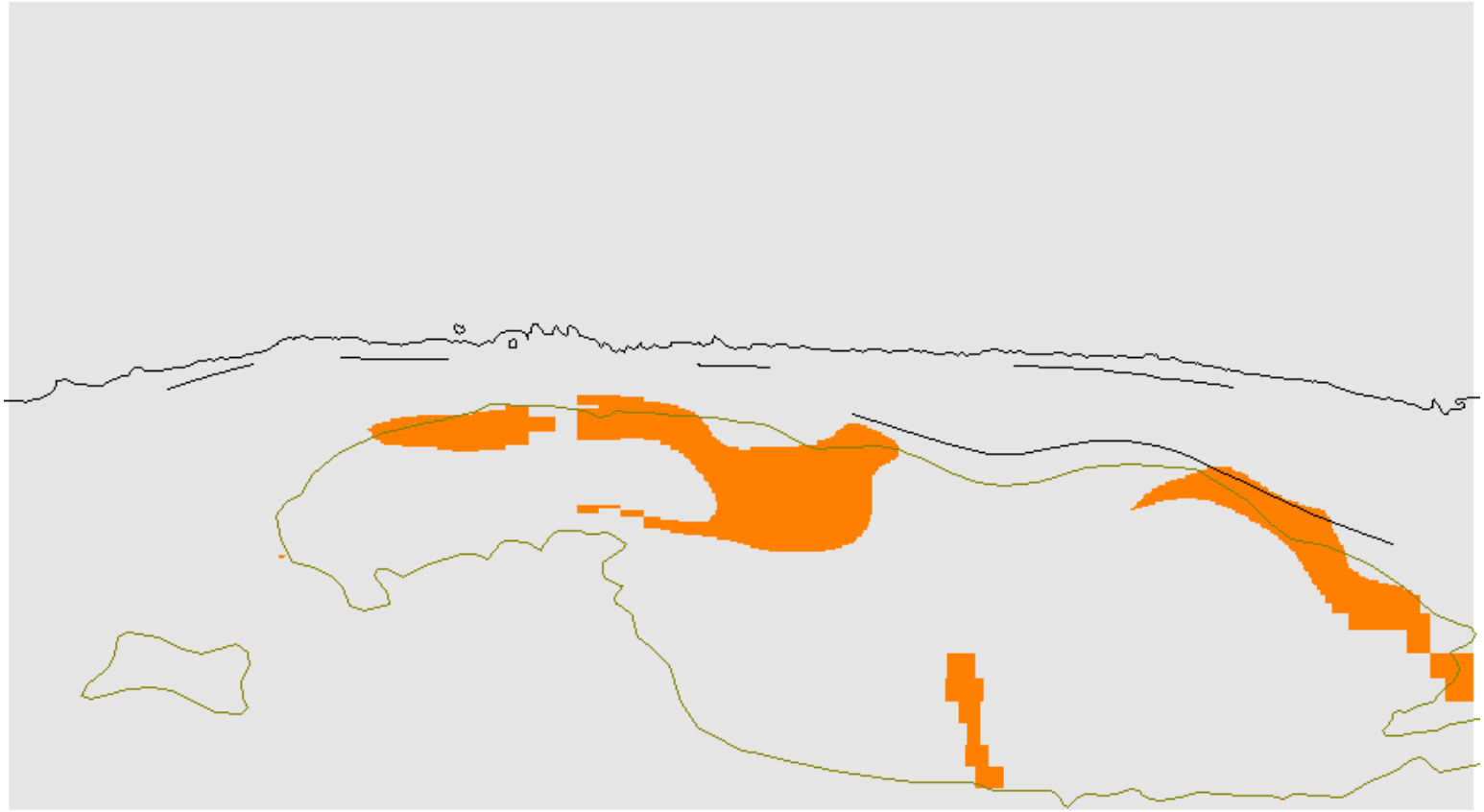


Figure 7-23
Modeled Extent of Perched Groundwater in the 1/02/2007 Scenario for the Seep 2 TMR Model

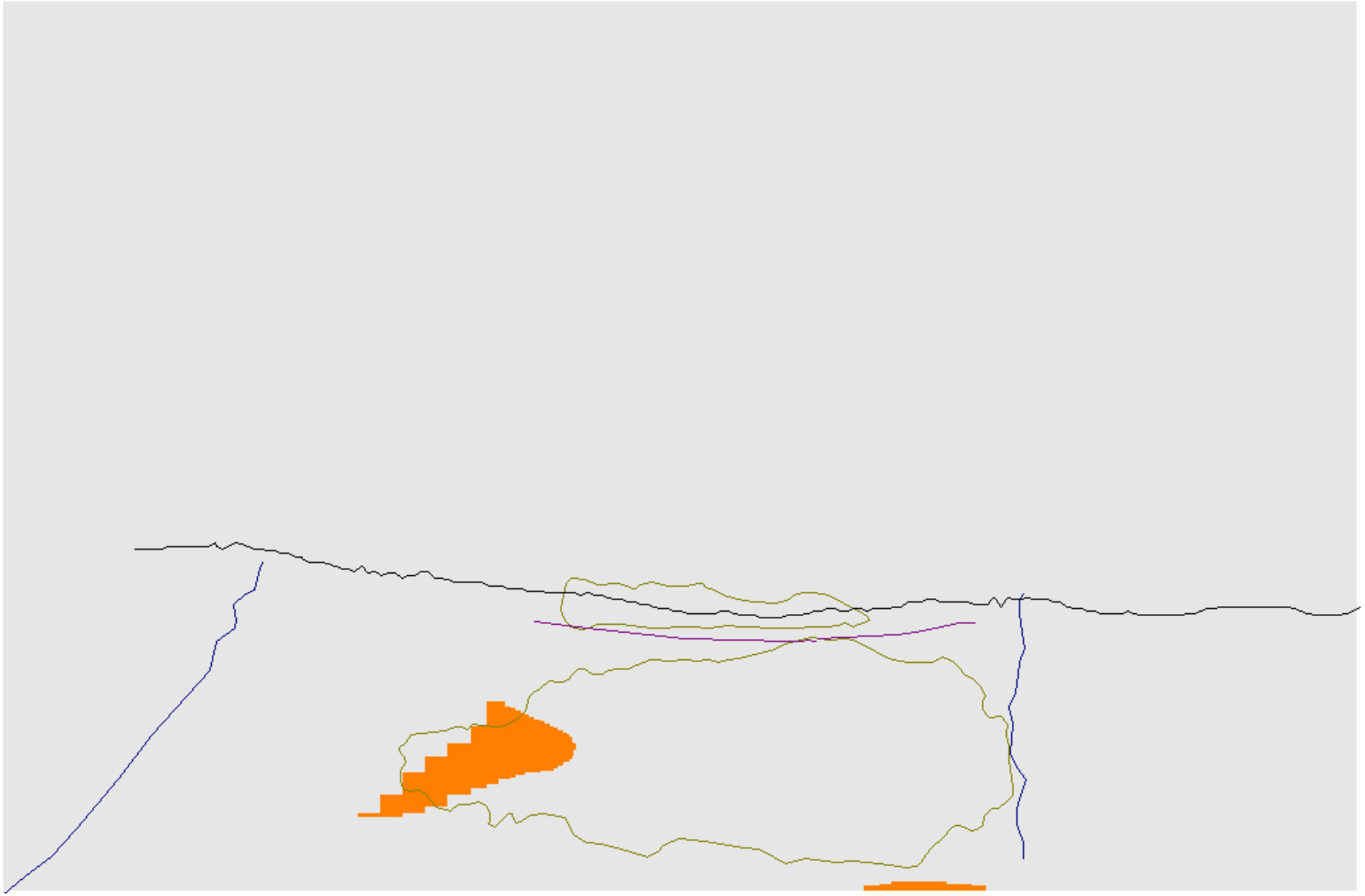


Figure 7-24
Modeled Extent of Perched Groundwater in the 9/14/2006 Scenario for the West CKD TMR Model

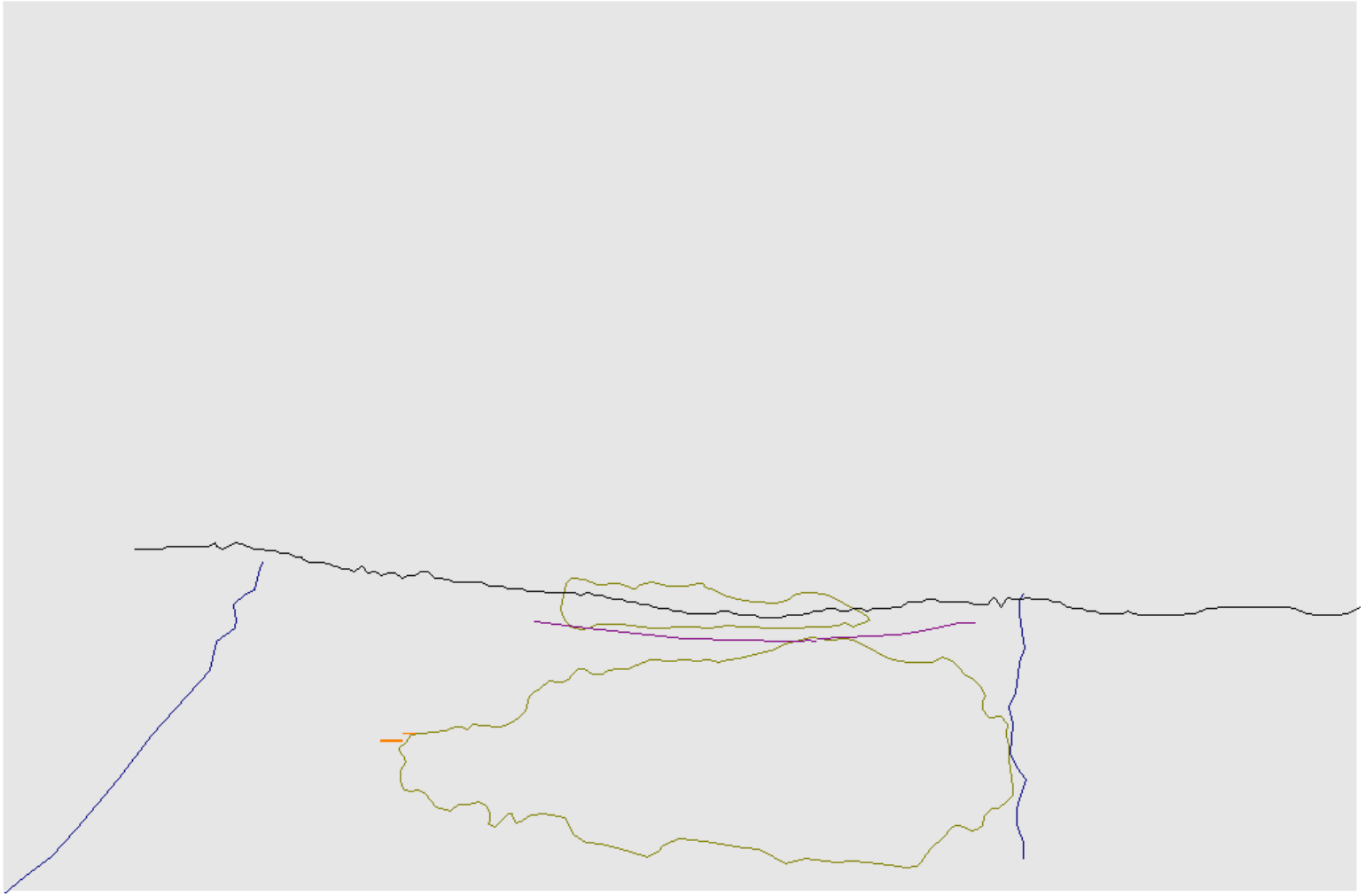


Figure 7-25
Modeled Extent of Perched Groundwater in the 1/02/2007 Scenario for the West CKD TMR Model

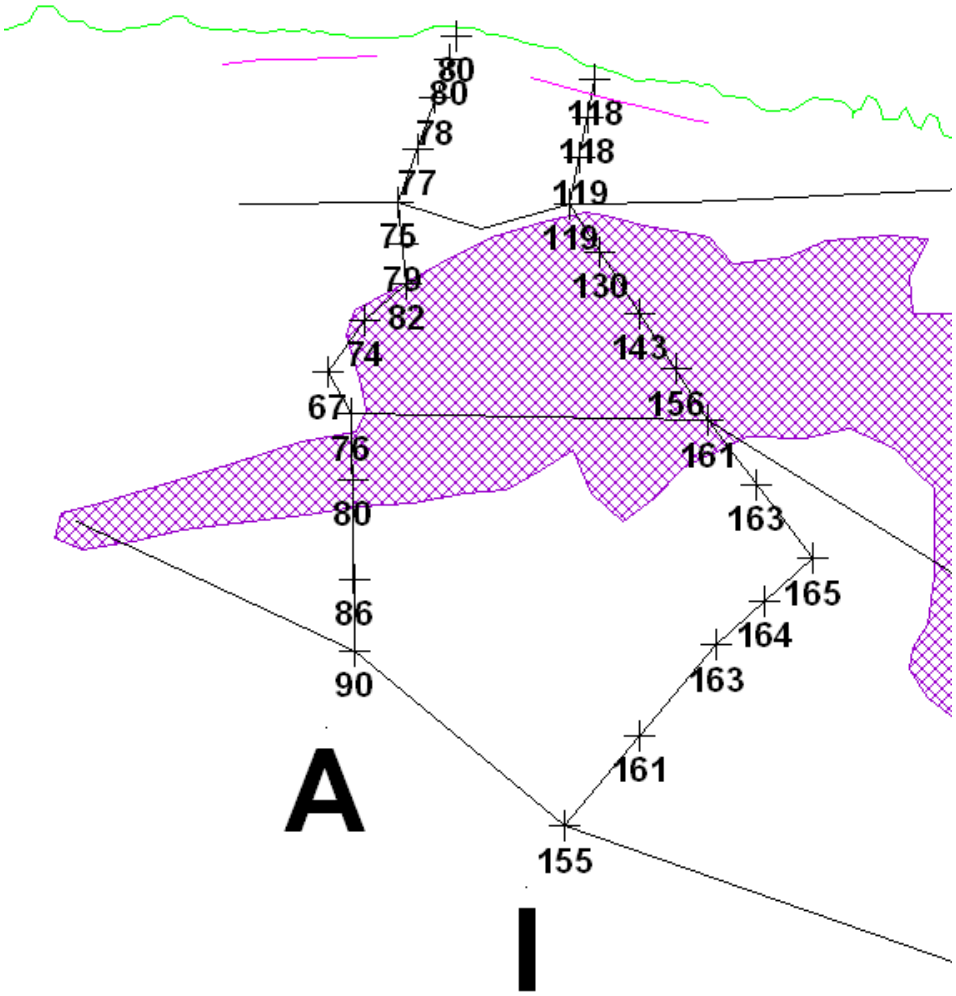


Figure 7-26
Starting Locations (model columns) for Particles along Cross Sections A-A' and I-I' in the Pine Court subarea of the Seep 2 TMR Model

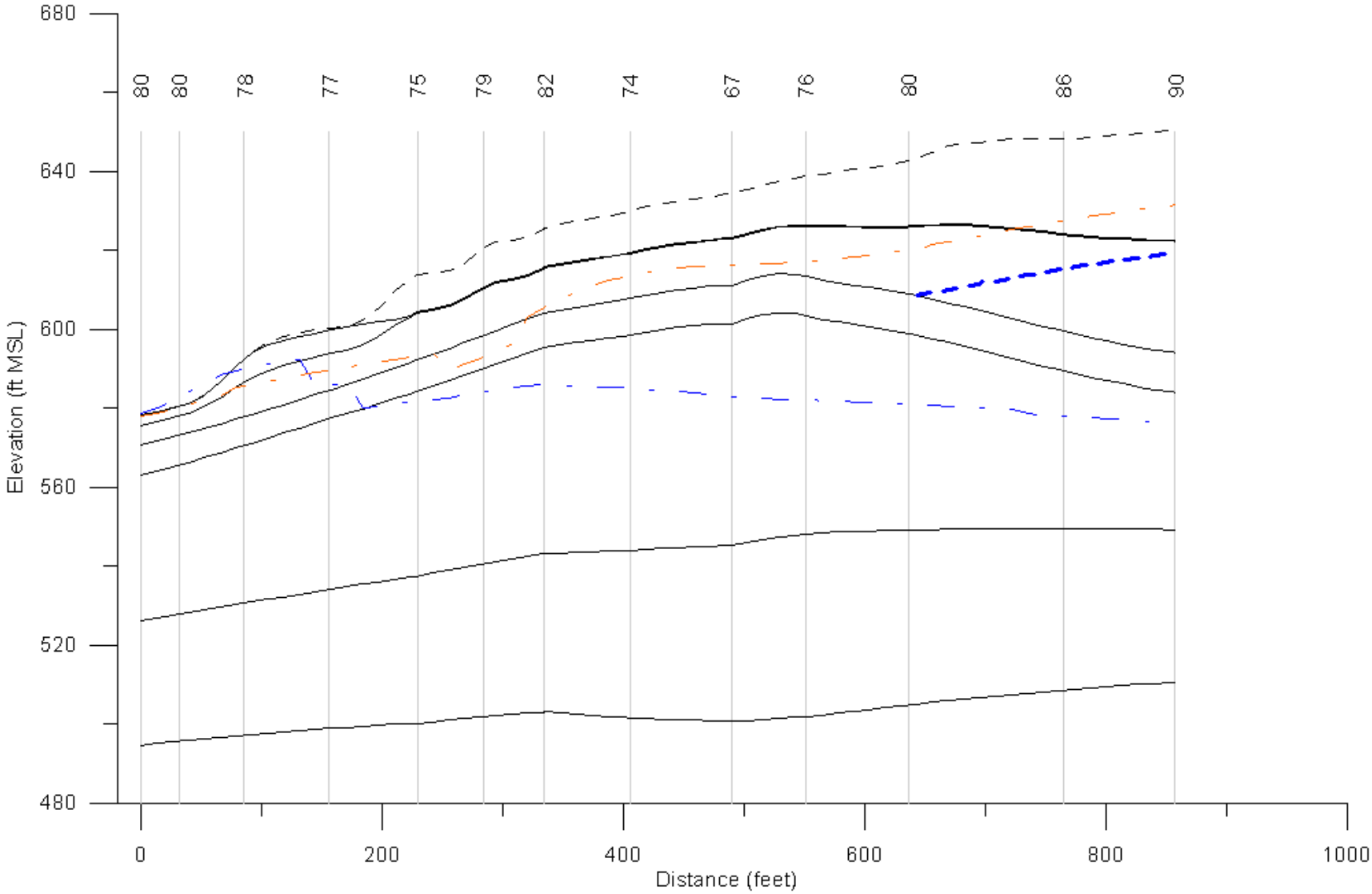


Figure 7-27
Location of Particle Starting Columns and Water Levels in the Two Scenarios for Pine Court Subarea Cross Section A-A'

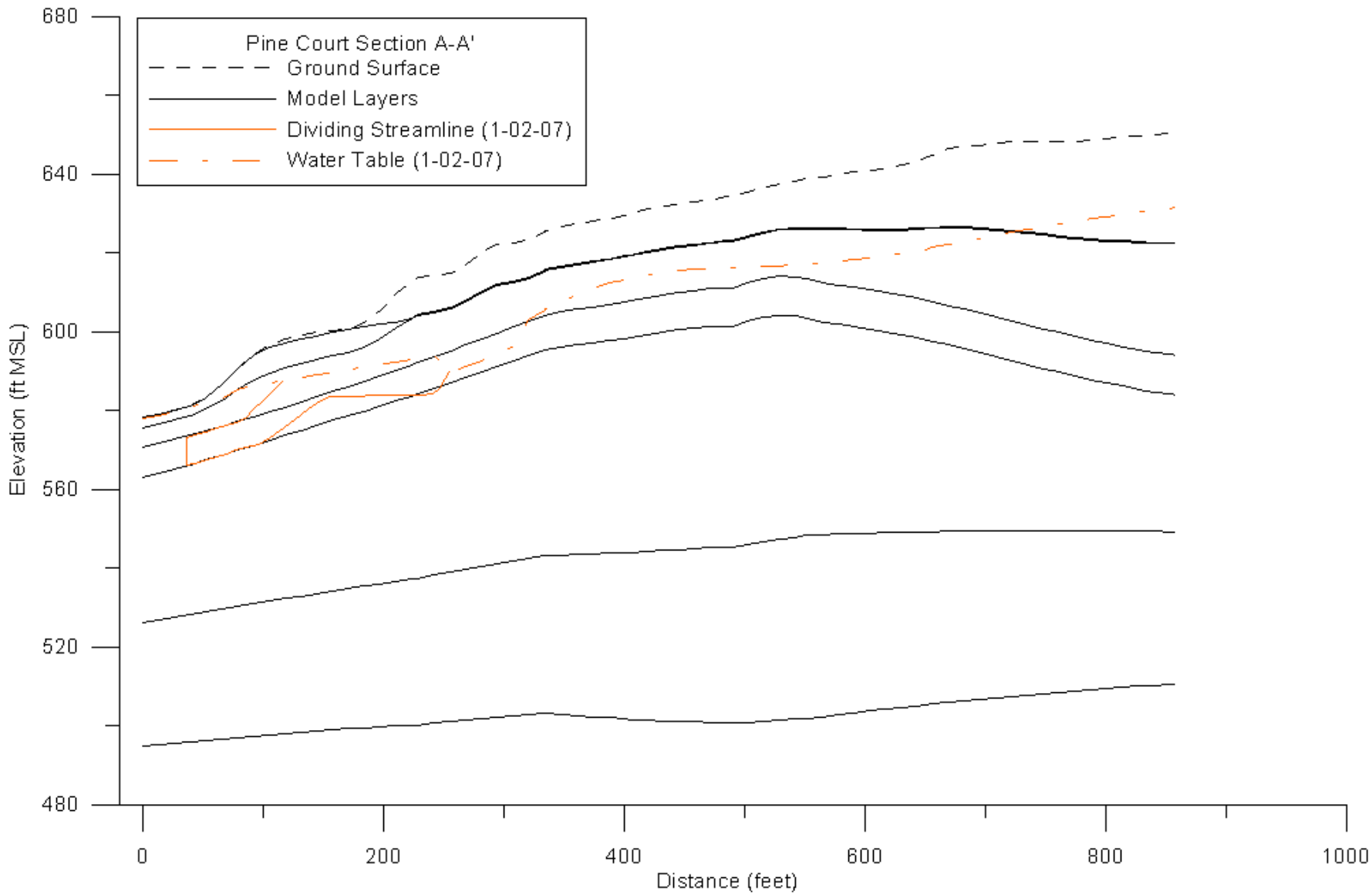


Figure 7-28
Capture Zone in Cross Section A-A' for the Pine Court Subarea Drains in the 1/02/2007 Scenario

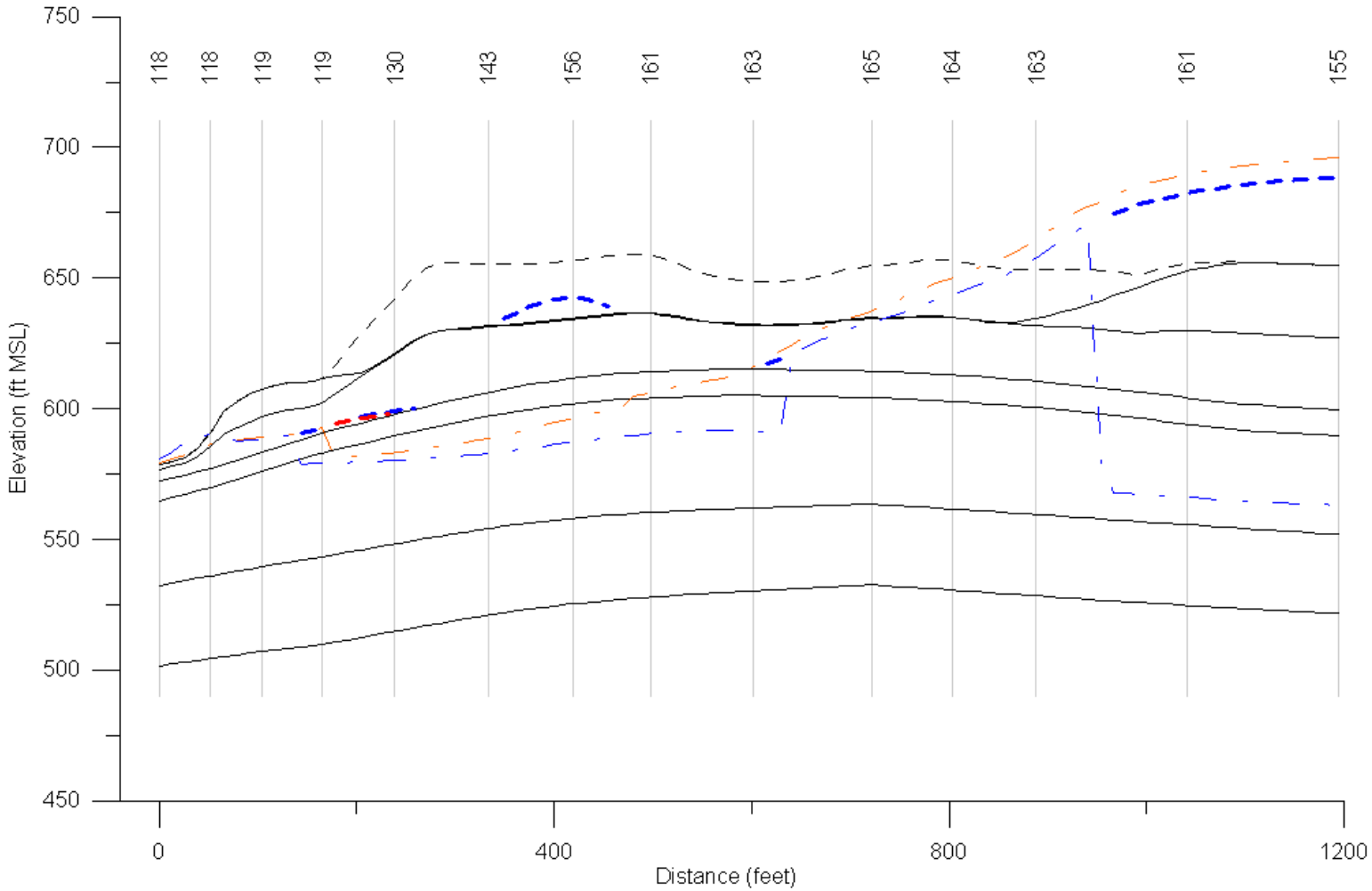


Figure 7-29
Location of Particle Starting Columns and Water Levels in the Two Scenarios for Pine Court Subarea Cross Section I-I'

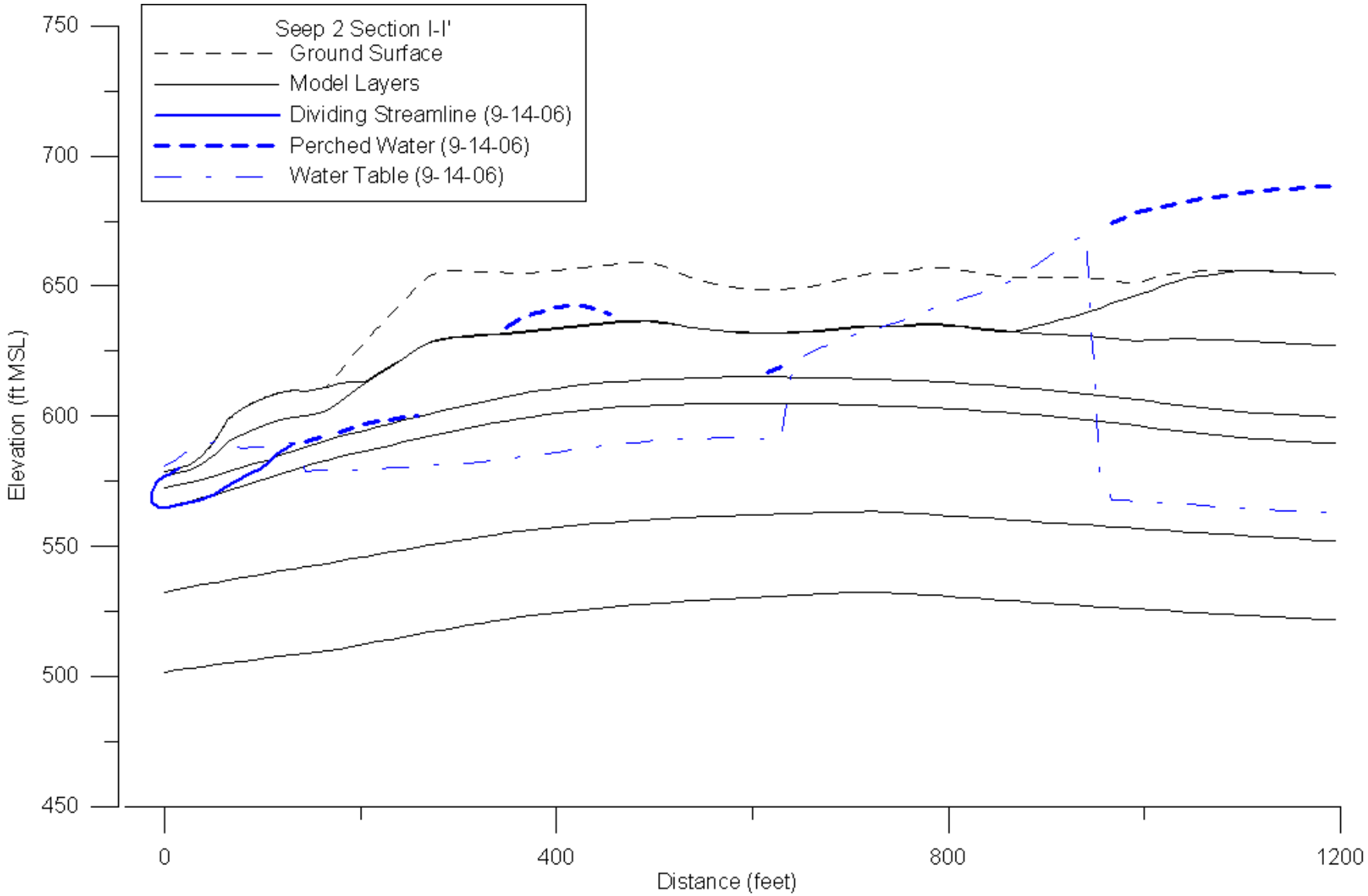


Figure 7-30
Capture Zone in Cross Section I-I' for the Pine Court Subarea Drains in the 9/14/2006 Scenario

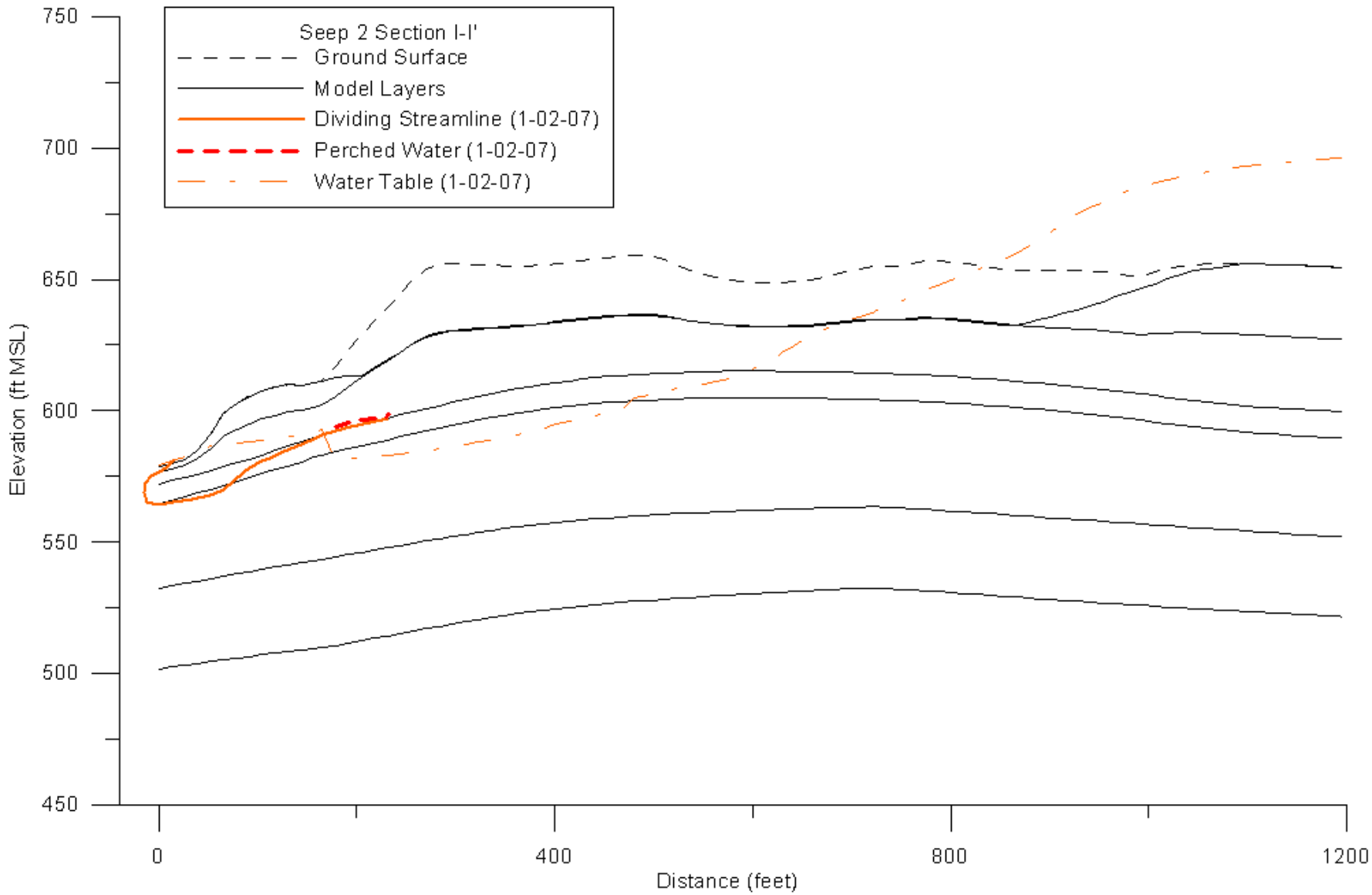


Figure 7-31
Capture Zone in Cross Section I-I' for the Pine Court Subarea Drains in the 1/02/2007 Scenario