

Appendix B

Groundwater Flow and Contaminant Transport Modelling (Al Laase Hydrologic Consulting, 2007)

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-FINAL-

**ORICA SITE, 2 CHRISTINA ROAD,
VILLAWOOD, NSW:
GROUNDWATER FLOW AND
CONTAMINANT TRANSPORT
MODELING**

June 2007

For:

**HLA-Envirosciences Pty Limited
Level 5, 828 Pacific Highway
Gordon, New South Wales
Australia**

By:

**Alan D. Laase
A. D. Laase Hydrologic Consulting**

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Alan D. Laase, Hydrologist

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ACRONYMS, ABBREVIATIONS AND INITIALISMS

AHD – Australian Height Datum
 EDC – 1, 2-Dichloroethane also known as Ethylene Dichloride
 d – day
 K_d – distribution coefficient
 K_{oc} – organic carbon fraction distribution coefficient
 NSW – New South Wales
 m – meter
 mm - millimeter
 TMR – telescopic mesh refinement
 ug – micrograms

EXECUTIVE SUMMARY

Orica Site, 2 Christina Road, Villawood, NSW was used to manufacture a wide range of chemicals including pesticides, chlorobenzenes, and agricultural and pharmaceutical chemicals by various owners and operators since its inception in 1946 until closure in 2000.

Manufacturing and disposal activities have resulted in a number of plumes being present in the fractured bedrock (Bringelly and Ashfield Shales) beneath the site. This modeling study was performed to develop a better understanding of how groundwater moves and contaminants migrate in the fractures and block matrix of these shales.

The study found that recharge from precipitation to the subsurface beneath Villawood is likely between 1 and 5% of total precipitation, depending on land usage. Total daily groundwater discharge to the length of Byrnes Creek extending from Chester Hill to Villawood is relatively small (approximately 262 m³/d). It is probable that all groundwater beneath Villawood discharges to Byrnes Creek and underflow and subsequent discharge to distant Prospect Creek does not occur. Finally, the simulated travel times to Byrnes Creek for Villawood groundwater at elevations deeper than 0 m AHD (approximately 25 m below land surface) was 240 years or more.

With regard to contaminant migration, modeling shows that plumes at Villawood grow fairly rapidly following source release but then migration slows down and the plumes becomes essentially static. Based on the results of this modeling study it is unlikely that contamination will reach Byrnes Creek within 100 years of present day.

1 INTRODUCTION

Orica Site, 2 Christina Road, Villawood, NSW was used to manufacture a wide range of chemicals including pesticides, chlorobenzenes, and agricultural and pharmaceutical chemicals by various owners and operators since its inception in 1946 until closure in 2000. Manufacturing and disposal activities have resulted in a number of plumes being present in the fractured bedrock (Bringelly Shale) beneath the site. This modeling study was performed to develop a better understanding of how groundwater moves and contaminants migrate in the fractures and block matrix of these shales.

Groundwater Vistas Version 4 (Rumbaugh 2004) was used during the study to create the MODFLOW (McDonald and Harbaugh 1984), MODPATH (Pollack 1988) and MT3DMS (Zheng 1999) input files, launch the models and post-process the resultant model output files. In addition to these software, during flow model calibration, PEST (Doherty 1999) and PEST-SVD (Doherty 2004), parameter estimation codes, were used during model calibration to determine the best-fit parameter values and hydraulic conductivity distributions for the model as configured. Trial-and-error calibration was employed during transport model calibration.

The contents of the report are as follows:

Section 2 discusses the technical approach used for the study.

Section 3 presents Villawood hydrogeology.

Section 4 describes three-dimensional regional model configuration of the Villawood hydrogeologic system.

Section 5 discusses three-dimensional regional model calibration.

Section 6 discusses cross-sectional flow modeling.

Section 7 describes three-dimensional contaminant transport modeling.

Section 8 summarizes the conclusions of the modeling exercise.

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2 TECHNICAL APPROACH

This modeling study was performed to develop a better understanding of groundwater flow and dissolved phase contaminant migration at the Orica Site, 2 Christina Road, Villawood, NSW. Henceforth, in this report the site will be called Orica Villawood. Orica Villawood was initially part of a larger chemical complex owned by the Commonwealth of Australia and used to manufacture munitions for World War II. After the War, the site was sold to Taubmans Pty, Ltd who used the facility to manufacture a wide range of chemicals including pesticides and chlorobenzenes. The southern portion of the Villawood Site was purchased in 1953 by ICIANZ Pty Ltd, who later became Orica Australia Pty Ltd. Orica manufactured agricultural and pharmaceutical chemicals until the site was closed in 2000.

Groundwater flow modeling was performed using MODFLOW, the widely used and accepted finite-difference code developed by the United States Geological Survey (McDonald and Harbaugh, 1988). Contaminant transport modeling was performed using MT3DMS (Zheng 1999). Flow model calibration was conducted using PEST (Doherty 1999) and PEST-SVD (Doherty 2004) coupled with pilot points (Doherty 1999). PEST is a parameter estimation code that determines the best parameter values for a model as configured. PEST-SVD is an updated version of PEST that has faster execution times. Parameters are model input values that are adjusted during model calibration. Common examples are recharge, evapotranspiration, and river cell conductance. Pilot points takes auto calibration a step further and determines the best parameter distributions for the model given specific boundary configurations and target values. For this application, pilot points were used to determine the “best” hydraulic conductivity distribution. A detailed description of parameter estimation and pilot points and model calibration methodology can be found in Section 5.

Because of the relatively long simulations times and large uncertainty associated with contaminant release histories and plume geometries, the transport model did not undergo as rigorous calibration as the flow model. Rather, the source loading rates were assumed constant and key transport parameters were adjusted until the simulated plume extent and contaminant distributions reasonably matched the observed plume geometry and concentrations. It should be noted that the objective of the contaminant transport simulations is not achieve an exact concentration match but rather to better understand what transport parameters control plume movement and the implications of the controlling processes on future plume movement and potential remedial endeavors.

The modeling process was initiated by first configuring a three-dimensional regional model of the area surrounding Villawood. A regional model was selected over a localized model as the starting point because the local flow regime at Villawood has not been completely characterized, specifically the groundwater discharge relationship of the site to adjacent Byrnes Creek. A localized model using Byrnes Creek as an external model boundary would have forced all groundwater to discharge to this drainage feature. With a regional model, the elevation of Byrnes Creek in conjunction with the surrounding hydraulic properties controls the influence of the creek on the localized flow patterns and allows for potential underflow of the creek.

Precipitation in the Sydney area averages 1,100 mm/year. It is not known how much of the rainfall infiltrates the subsurface and recharges groundwater at Villawood. Parkland having expanses of grassy areas is thought to receive the greatest amount of recharge. The grass and infrastructure dominated residential areas affords less opportunity for infiltration relative to

parkland but more than the concrete and asphalt dominated industrial areas. Rather than assigning an arbitrary groundwater recharge rates to these areas within the model, four different regional models were calibrated to varying recharge conditions with the hope that the calibrated parameter distributions and target residuals would identify the most likely Villawood recharge regime. The first three models assumed parkland recharge rates of 2%, 5% and 10% of annual average precipitation. Recharge to the residential and industrial areas was assumed to be approximately one-half and one-quarter of recharge to parkland, respectively, for the simulations. For the fourth model, recharge was allowed to vary and the ultimate values determined as part of the calibration process.

In parallel to the regional model calibration effort, a cross-sectional flow model along a row of the regional model that intersected Villawood, Byrnes Creek and Prospect Creek was developed to evaluate the surface water/groundwater relationship and groundwater travel times to the surface water features for various combinations of recharge and hydraulic conductivity. The cross-sectional model was configured using the same topographic, lithologic and parameter constraints as the parent three-dimensional model. While it is recognized that the cross-sectional model only simulates two-dimensional flow and the model will never exactly replicate the flow along the corresponding row of the three-dimensional model from which it was derived, cross-sectional models offer the advantage of computational speed allowing for the evaluation of many model variants. Model variants evaluated were based on the three above mentioned recharge regimes, and included various horizontal to vertical anisotropy ratios and differing hydraulic conductivity values and distributions with depth.

Lastly, a telescopic mesh refinement (TMR) model was cut from the regional model and used to simulate three-dimensional contaminant transport at Orica Villawood. A TMR model only includes a portion of the larger parent model, in this case the regional model, while maintaining the same spatial distribution of model parameters. Boundary conditions along the edge of the TMR model can be either specified heads or fluxes that correspond exactly to the values at those locations in the parent model. The TMR model used finer grid resolution relative to the regional model to better facilitate contaminant transport.

3 GEOLOGY, HYDROLOGIC AND TRANSPORT CHARACTERISTICS

Information presented in this Section is summarized primarily from the Phase 1 Remedial Investigation Orica Site 2 Villawood Report (HLA-Envirosciences, 2005) unless otherwise noted. Data evaluated specifically for this study is identified as such.

3.1 Geology

Orica Villawood is underlain by the Bringelly and Ashfield Shales, which are primarily comprised of interbedded and interbanded shales. Sequentially the Bringelly Shale is underlain by the Ashfield Shale. Lithologically the two shales are similar. Sub-vertical fractures within the Bringelly Shale exist at approximate 1 meter spacing and are orthogonal in nature with individual fracture planes trending 330° and 60° with respect to true north. The bulk of groundwater flow occurs in the fractures. However, the fractures only occupy a small percentage of the total rock matrix, typically 1% or less. Porosity of the shale itself ranges between five and 12-percent (Ezzat 2002).

The upper portion of the Bringelly Shale is deeply weathered resulting in several meters of mottled, dense clay. Along the southern site boundary are colluvial deposits associated with the Byrnes Creek flood plain.

3.2 Hydrogeology

Slug tests on 31 Villawood wells yielded an average bulk hydraulic conductivity of 6.45×10^{-2} m/d with values ranging between 4.00×10^{-4} and 5.70×10^{-1} m/d. The three order of magnitude difference in measured hydraulic conductivity is a function of the characterization method and the variability of hydraulic conductivity in a fractured rock environment. Slug tests, which were used to characterize hydraulic conductivity, produce potentially widely varying results because they test only the aquifer immediately adjacent to the well screen. If the adjacent aquifer is dominated by fractures (or a fracture) the results will reflect the higher fracture permeability. In general, the more fractures present the greater the bulk hydraulic conductivity. Conversely, if the adjacent aquifer is largely unfractured shale, the results will reflect the lower matrix permeability.

Conversations with Noel Merrick (University of Technology, Sydney), who has first hand knowledge of Ashfield Shale hydraulic conductivity testing results for a nearby railway project, suggested that it is likely that hydraulic conductivity decreases with depth, possibly as much as three orders of magnitude from land surface to a depth of 30 meters. Whether hydraulic conductivity continues to decline with depth or becomes asymptotic is not known. With respect to Villawood, if near ground surface bulk hydraulic conductivity is within the 10^{-1} m/d range then bulk hydraulic conductivity with depth could be as low as 10^{-4} m/d.

Calculated groundwater seepage velocities at the site are reported to be as high as 200 m/year.

3.3 Groundwater Flow Components

The following sections discuss Bringelly Shale recharge and discharge components.

3.3.1 Recharge Components of the Groundwater Flow System

Precipitation is believed to be the greatest source of water to Bringelly Shale in the vicinity of Villawood and averages 1,100 mm/year as measured at Kingsford Smith Airport. Precipitation falls on three distinct recharge zones characterized by open grassy parklands, residential development and industrial usage. Parkland, residential and industrial areas account for 2.9, 8.9 and 3.9 million m² of the model domain respectively (**Figure 3.3.1-1**). Assuming parkland recharge ranges from 2 to 10% of precipitation, residential recharge from 1% to 4% of precipitation and industrial recharge from 0.5% to 2% of precipitation, cumulative recharge to the model domain is between approximately between 500 and 2,200 m³/d. In addition to recharge from precipitation, anthropogenic sources such as leaky underground water supply and fire lines contribute water to the aquifer but the location and magnitude of the leaks is unknown.

3.3.2 Discharge Components of the Groundwater Flow System

Groundwater within the model domain discharges to the numerous concrete lined “creeks” within the modeling domain and to Prospect Creek. Given that there is no significant groundwater extraction from the regional aquifer, it is assumed that the groundwater discharge is equal to the recharge. Thus, based on the recharge estimates, total discharge through the model domain should range between 500 and 2,200 m³/d.

Of the drainage features, Byrnes Creek, located downgradient of Orica Villawood is of greatest interest because of its potential to intercept contaminated groundwater. Although concrete lined, Byrnes Creek is designed to receive groundwater discharge through a series of seepage holes in the concrete (**Figure 3.3.2-1**). Reconnaissance of the creek did not show groundwater entering the creek through these features but groundwater was observed seeping in through joints and cracks in the concrete at a number of locations (**Figure 3.3.2-2**). Flow in the creek has not been measured but based on visual assessment is typically relatively small with the depth of water in the creek bottom is usually a centimeter or less (**Figure 3.3.2-3**). Of the observed discharge, it is unknown what percentage is associated with groundwater infiltration or industrial/residential process water. Through application of Darcy's Law, groundwater discharge to Byrnes Creek is estimated to be between 40 and 400 m³/d.

Groundwater also exits the model domain via evapotranspiration. While this phenomenon does occur, it was not explicitly evaluated. Rather, an assumption was made that evapotranspiration can be accounted for by reduced precipitation infiltration. Simplistically, the net result of evapotranspiration is a reduction in recharge.

3.3.3 Water Balance

Estimated inflow and outflow to the model domain is between 500 and 2,200 m³/d.

3.4 Water-Level Elevations

Water levels have been collected at Orica Villawood sporadically since the first monitoring well was installed in 2001. In addition, water-level measurements have been collected at Chester Hill; an Orica site located approximately 1 kilometer south of Orica Villawood. HLA maintains a database of all water-level measurements collected at both sites. The largest comprehensive round of water level measurements at both sites occurred in late 2006. A more detail discussion of Villawood and Chester Hill water levels is presented in Section 5.1.1.

3.5 Water Quality

Manufacturing and waste disposal activities at the Villawood Site has contaminated site groundwater, primarily with 1,2 dichloroethane (EDC), chlorobenzenes and organochlorine pesticides (primarily DDT). Five separate contaminant plumes have been identified and range in length from approximately 50 m to 150 m (**Figure 3.5-1** and **3.5-2**) with maximum on site concentrations of 1, 2 dichloroethane and chlorobenzenes of approximately 100,000 ug/L. Based on initial manufacturing dates in the 1960s, the plumes are assumed to have been migrating for approximately 40 years. Based on site groundwater seepage velocities of up to 200 m/year the plumes, if moving at the speed of groundwater, the plumes should be considerably longer. While the exact transport mechanisms controlling plume migration are not known, the plumes are being significantly retarded.

3.6 Transport Properties

Organic carbon was measured in rock cores collect during site investigations and was found to be 0.525%. Using rock cores collected from the site, laboratory testing determined bulk porosity to be 9%. Fracture mapping of exposed shale at a nearby rock quarry estimated fracture porosity to be 0.48%.

3.7 Villawood Conceptual Model

Recharge to groundwater within the model domain is mostly from precipitation and is variable depending on land use; the greater the percentage of open lands the higher the recharge rate, but given the presence of underlying shale is likely to be less than 10% of total precipitation. In addition to recharge from precipitation, anthropogenic sources such as leaky underground water supply and fire lines may also contribute water to the aquifer, however, the location and magnitude of the leaks is unknown.

Groundwater discharges to a Prospect Creek and a series of engineered creeks (i.e. concrete lined), the discharge volume being a function of the difference between the creek stage elevation and adjacent groundwater elevations. Estimated inflow and outflow to the model domain is between 500 and 2,200 m³/d.

While the greatest majority of groundwater is contained within the Bringelly Shale block matrix, active groundwater flow occurs primarily within fractures (0.48% porosity) Based on slug testing results, the bulk hydraulic conductivity of the shallow more weathered portion of the Bringelly Shale, is likely between 10^{-2} and 1 m/d. A study of shale hydraulic conductivity distribution performed as part of a railroad construction project determined that hydraulic conductivity decrease with depth, possibly as much as three orders of magnitude within 30 m of land surface.

Calculated groundwater seepage velocities range between 2 to 200 m/year. The longest plume from the Orica Villawood site has migrated less the 150 m in 40 years. While the exact transport mechanism controlling plume migration has not yet been confirmed, the Villawood plumes are being significantly retarded, most likely due to matrix diffusion.

4 REGIONAL MODEL CONFIGURATION

Model configuration involves translating the site conceptual hydrogeological model onto a two- or three-dimensional grid and locating boundary conditions and individual aquifer parameter zones within the model domain. Grid spacing and model layer thickness (discretization) are a function of model purpose. Regional models typically have large grid spacing while tighter spacing is required for design simulation. Boundary conditions represent hydraulic features such as surface water bodies, pumping wells and impermeable rock outcrops. Parameter zones represent areas of recharge and hydraulic conductivity within the model domain having the same numerical value. This section details the translation of the Villawood conceptual model into a groundwater flow model.

4.1 Model Discretization

The model used for this study was discretized into eight model layers and consists of 94 rows and 94 columns with a constant width of 50 m (**Figure 4.1-1**). The top elevation of model layer 1 corresponds to land surface elevation and the bottom of layer 8 corresponds to the top of the Hawkesbury Sandstone (**Figure 4.1-2**). In general the model layers are approximately 10 m thick. An exception is the thickness of model layer 1 which was increased in the higher topographic regions of the model to alleviate dry cell issues caused by the modeled water table dropping below the bottom of model layer 1 during model calibration.

4.2 Model Boundary Conditions

Model boundary conditions contribute, remove or prevent the movement of water within the model domain. Boundary conditions can be further characterized as located along the exterior and within the interior of the model domain. An example of an exterior model boundary is Prospect Creek. Byrnes Creek, being located within the edges of the model domain, is an interior model boundary. While technically a boundary condition, recharge is viewed as a parameter (analogous to hydraulic conductivity) within the modeling community and as such will be discussed in Section 4.3.

All the external and internal model boundaries are located in model layer 1 (**Figure 4.2-1**). Prospect Creek is simulated using river cells. Simplistically, river boundary cells have head and conductance components that control the amount of water entering or leaving the cell. If adjacent groundwater levels are higher than the specified river cell head value then water enters the river cell. Conversely, if groundwater levels are lower than the specified river cell head value then water flows from the river cell into the aquifer. The river cell conductance, which represents the silt layer at the bottom of rivers, provides resistance to flow in and out of the river cells. Given that Prospect Creek is a regional discharge feature it is unlikely that the creek recharges groundwater. Prospect Creek was assigned a river stage of 2 m AHD based on topographic elevations.

Byrnes Creek and the unnamed tributary creek to the north of Villawood are simulated using drain cells (**Figure 4.2-1**) and were assigned a head values corresponding to the invert levels. Different than river cells, drain cells can only remove water from the model as a function of the difference between adjacent groundwater levels and the drain stage. When adjacent groundwater levels drop below the assigned drain stage, groundwater no longer enters the drain cell. Additionally

drain cells have a conductance term, which is analogous to hydraulic conductivity, which provides resistance to flow into the cell. The greater the drain conductance value the easier it is for groundwater to enter the drain.

The black areas shown in **Figure 4.2-1** are no flow cells and, as the name implies, water does not enter or leave these cells. The name no-flow conjures images of dense rock. While the image is often appropriate, no-flow sections of models can be parametrically identical to active portions of the model. For example, along a topographic high groundwater flows in opposite directions. While groundwater flow on either side of the divide is essentially identical, the two flow systems are hydraulically isolated. Thus, the side of the topographic high outside the study area is represented using no flow cells. No flow cells along the western edge of the model domain represent portions of the flow system on the other side of a groundwater divide. The flow area east of Prospect Creek is geologically identical to the active portion of the model across the feature to the west. Prospect Creek is believed to be a groundwater divide and hydraulically isolates groundwater flow on either side of the surface water feature. For computational efficiency, areas east of Prospect Creek were designated as no-flow cells.

While not explicitly represented, the bottom of model layer 8 corresponds to the top of the relatively impermeable Hawkesbury Sandstone.

4.3 Parameter Distributions

While model boundary conditions contribute, remove or prevent the movement of water, simplistically model parameters control the rate of water movement within the model domain. An example of a model parameter is hydraulic conductivity. The ease at which water moves through the model domain is directly correlated to hydraulic conductivity. The higher the hydraulic conductivity value the more transmissive the porous media. Others, such as recharge, while technically a boundary condition, control the location and magnitude of water entering the model domain and as such will be discussed in this section.

4.3.1 Hydraulic Conductivity Zonation

Horizontal and vertical hydraulic conductivity distribution within the model domain was determined using pilot-points, a technique developed by Australian John Doherty, a prominent groundwater modeler. To implement the technique pilot points are located within the model domain and assigned initial, minimum and maximum hydraulic conductivity values. Automated model calibration adjusts the pilot points between the minimum and maximum hydraulic conductivity values using nonlinear techniques. Kriging is used to interpolate hydraulic conductivities between the points for each pilot point modification. The “calibrated” hydraulic conductivity configuration is the continuous hydraulic conductivity field that produces the best match with the calibration targets.

Pilot points were used to determine horizontal and vertical hydraulic conductivity distribution in model layers 1 through 3 (**Figure 4.3.1-1**). Greater pilot point density was used in the vicinity of the Orica sites at Villawood and Chester Hill to allow for more detailed discretization of hydraulic conductivity in these areas.

Model layers 1 through 3 pilot points were assigned initial horizontal hydraulic conductivity values of 0.5, 0.1 and 0.05 m/d, respectively and constrained to plus or minus one order of magnitude. Model layers 1 through 3 pilot points were assigned initial vertical hydraulic conductivity values of 0.05, 0.01 and 0.005 m/d, respectively and constrained to plus or minus one order of magnitude. Model layers 4 through 8 were assigned constant horizontal and vertical hydraulic conductivity values (**Table 4.3.1-1**) because a pre-calibration sensitivity analysis showed that these layers were insensitive (**Figure 4.3.1-2**).

Pilot points can be assigned locations and initial hydraulic conductivity values corresponding to well location and aquifer test results, respectively. This was not done for this modeling exercise because of concern that the slug test derived hydraulic conductivity values might overly constrain the calibration. Slug tests characterize only that portion of the aquifer in the immediate vicinity of the well screen. If the adjacent aquifer is dominated by fractures (or a fracture) the results will reflect the higher fracture permeability. Conversely, if the adjacent aquifer is largely unfractured shale, the results will reflect the lower matrix permeability. The volume of aquifer contained within a model grid cell is much larger than the volume of aquifer characterized by a slug test and contains both fractures and unfractured shale. Thus, use of the slug test hydraulic conductivity values, which are a function of the presence or absence of fractures, as pilot point constraints could potentially result in biased permeability fields.

4.3.2 Recharge Zonation

Recharge from precipitation was divided into three zones within the model domain depending on land use; the greater the percentage of open lands the higher the recharge rate (**Figure 3.3.1-1**). Recharge rates for the three zones were variable depending on the recharge scenario being evaluated (**Table 4.3.2-1**).

4.3.3 Other Parameters

Fracture porosity within the model domain was assigned a value of 1%. Matrix porosity was assigned values ranging from 8.5% to 12%, depending on the flow or transport scenario evaluated.

5 REGIONAL MODEL CALIBRATION

Model calibration was performed using PEST and PEST-SVD coupled with pilot points (Doherty 1999). PEST (Doherty 1999), from which PEST-SVD (Doherty 2004) is based, is a parameter estimation code that determines the best parameter values for a model as configured. Parameters are model input values that are adjusted during model calibration. Common examples are recharge, evapotranspiration, and river cell conductance. Pilot points takes auto calibration a step further and determines the best parameter distributions for the model given specific boundary configurations and target values. For this application, pilot points were used to determine the “best” hydraulic conductivity distribution. PEST-SVD is an improvement over PEST in that using it results in significant reductions in simulation times. For example, with this model a single PEST iteration required 4,024 model runs and as many as 30 iterations to achieve calibration resulting in a total run time of more than 10 days. Using the same model PEST-SVD determined the “best” parameter set to achieve calibration in two days of computer run time. PEST-SVD owes its increase in execution time to the formation of super groups based on parameter sensitivities. Simplistically the less sensitive parameters are grouped with the more sensitive parameters which allows for fewer model runs per PEST iteration which translates to faster simulation times. It should be noted that even with the faster simulation run times as many as four state-of-the-art computers were used in parallel, all simulating different model variants, to achieve the “best” calibrated model. While PEST clearly is a better way to calibrate models the computational requirements are formidable.

While the underlying mathematics comprising parameter estimation and pilot points is formidable and complex, the concept behind the parameter estimation algorithm is really rather simple and is identical to the thought process used with traditional trial-and-error calibration, which is, find the combination of parameters that results in the smallest difference between observed and model-predicted water levels and groundwater discharges. While conceptually similar, parameter estimation offers several advantages over trial-and-error model calibration. First, parameter estimation guarantees a non-biased answer for a given model configuration. The estimated parameters will always be the set of parameter values that results in the lowest calibration error for the model as configured. Second, in addition to determining the best unbiased parameter values, parameter estimation also calculates statistics and sensitivities that can be used to evaluate the robustness of the predictions.

Four different models were calibrated to steady-state conditions representative of four different long-term average rainfall conditions. The first three models assumed parkland recharge rates of 2%, 5% and 10% of annual average precipitation. Recharge to the residential and industrial areas was assumed to be approximately one-half and one-quarter of recharge to parkland, respectively, for the simulations. For the fourth model, recharge was allowed to vary and the ultimate values determined as part of the calibration process.

5.1 Calibration Targets

Model calibration requires calibration targets as bench marks for evaluating the reliability of the model. The easiest calibration targets to obtain and the most common are groundwater level elevations obtained from wells. Flux targets, such as stream base flow, are more difficult to obtain and are typically less available but are also used to evaluate model calibration. Parameter values themselves, such as hydraulic conductivity derived from pumping tests, can be used as calibration targets too. Finally, groundwater flow paths to and from key hydrologic features within the model can be used to qualitatively evaluate model calibration. This section describes the calibration targets used in the model and the process undertaken in selecting the targets.

5.1.1 Water-Level Elevation Targets

The Orica Villawood and former Orica Chester Hill site water-level databases were combined and evaluated to determine the appropriate targets to use for model calibration. Both sites are located within one kilometer of each other. Because characterization efforts at both sites are in their infancies, relatively speaking, the current rounds of water-level measurements contain more data because of the addition of wells with time. Thus it was decided to combine the most recent water-level measurements (November 2006) from both sites as calibration targets (**Table 5.1.1-1**). At the time model calibration was initiated no off-site wells had been identified for use as targets. Evaluation determined that there were 126 target locations in model layers 1 through 3 available to calibrate the model with the majority of targets located in model layer 1 (**Figure 5.1.1-1** through **5.1.1-3**).

Occasionally more than one water-level elevation target was located within a model cell. To avoid biasing the calibration, when more than one target was located in a cell the targets were assigned a weighting factor corresponding to the inverse of the number of targets in the cell. For example, when two targets are located in the same cell the targets are assigned weights of 0.5.

Similarly, some of the wells from which the water-levels were collected had well screens spanning more than one model layer. For these wells, the water-level elevation target was assigned to both model layers.

5.1.2 Flux Targets

No flux targets were used in calibrating this model as Byrnes Creek flows have yet to be measured.

5.1.3 Pilot Point Targets

Pilot points were assigned to model layers 1 through 3 as shown in **Figures 4.3.1-1**. During the automated calibrated process both horizontal and vertical hydraulic conductivity were estimated at each pilot point. An explanation of how pilot points are used in the calibration process is

presented in Section 4.3.1. To add stability to the parameter estimation process, the pilot point initial values are added to the regression analysis as targets (termed regularization, a technique that penalizes estimates that stray far from the initial values). Model layer 1 through 3 pilot points were assigned initial horizontal and vertical hydraulic conductivity values of 0.5/0.05 m/d, 0.1/0.01 m/d and 0.05/0.005 m/d, respectively. Pilot points were not assigned to model layers 4 through 8 because pre-calibration sensitivity analysis showed that the hydraulic conductivity associated with these to be insensitive. As noted in Section 4.3.1 these layers were assigned horizontal and vertical hydraulic conductivity values that were not adjusted during the calibration process.

5.2 Calibration Results

Four different models representing different recharge scenarios were calibrated to the above mentioned water-level targets. The calibration results for the four model variants are compared, contrasted and discussed in the following sections.

5.2.1 Estimated Hydraulic Conductivity Values

The estimated horizontal hydraulic conductivity distributions for the four recharge scenario model variants for model layer 1 are shown in **Figures 5.2.1-1 through 5.2.1-4**. All four recharge scenarios predict higher hydraulic conductivity (>1 m/d) along the northern and southern edges of the Orica Villawood site. Within the site boundaries, predicted horizontal hydraulic conductivity is estimated to range from approximately 0.1 to 1.0 m/d. Additionally, as recharge increases the average Orica Villawood site layer 1 hydraulic conductivity increases correspondingly (**Tables 5.2.1-1 through 5.2.1-4**).

There are variations in estimated hydraulic conductivity away from the Orica Villawood site. However, the overall model average model layer 1 horizontal hydraulic conductivity is relatively consistent suggesting that the variations are slight (**Tables 5.2.1-1 through 5.2.1-4**). Given the absence of targets away from Orica Villawood and the former Orica Chester Hill site it is not surprising that the variations are minimal.

Figures 5.2.1-5 through 5.2.1-8 show the estimated horizontal hydraulic conductivity distributions for model layer 2. A band of higher hydraulic conductivity (>0.5 m/d) is present in the central portion of the Orica Villawood site for all scenarios. On either side of the higher hydraulic conductivity zone hydraulic conductivities are at least one order of magnitude less. The predicted model layer 2 average horizontal hydraulic conductivity is similar for all scenarios.

As with model layer 1, there are variations in estimated horizontal hydraulic conductivity away from the Orica Villawood site in model layer 2. However, the overall model average model layer 2 horizontal hydraulic conductivity is relatively consistent suggesting that the variations are slight (**Tables 5.2.1-1 through 5.2.1-4**).

The estimated horizontal hydraulic conductivity distributions for the four recharge scenario model variants for model layer 3 are shown in **Figures 5.2.1-9 through 5.2.1-12**. All four recharge scenarios show higher hydraulic conductivities (>0.1 m/d) on site relative to off-site. The Orica Villawood site model layer 3 horizontal hydraulic conductivity stays relatively constant as

recharge increases (**Tables 5.2.1-1** through **5.2.1-3**). The minimal horizontal hydraulic conductivity variation is likely a function of a lack of targets (4) in the model layer.

As with model layers 1 and 2, there are variations in estimated horizontal hydraulic conductivity away from the Orica Villawood site in model layer 3 (**Figure 5.2.1-9** through **5.2.1-12**). However the overall model average hydraulic conductivity stays relatively constant suggesting that the variations are slight (**Tables 5.2.1.1** through **5.2.1-4**). Given absence of calibration targets much of the variation can likely be attributed to “noise” associated with prediction uncertainty.

Different than the model layer 1 horizontal hydraulic conductivity estimates, the on-site estimates of vertical hydraulic conductivity are less than the off-site estimates (Figs. 5.2.1-13 – 5.2.1-16) (**Tables 5.2.1-1** through **5.2.1-4**). The same vertical hydraulic distribution trend is apparent for model layers 2 and 3 (Figs. 5.2.1-17 through 5.2.1-24) (**Tables 5.2.1-1** through **5.2.1-4**).

The decrease in on-site vertical hydraulic conductivity coupled with an increase in horizontal hydraulic conductivity relative to off-site values results in horizontal to vertical hydraulic conductivity ratios being higher on-site relative to off-site (Figs. 5.2.1-25 through 5.2.1-36) (**Tables 5.2.1-1** through **5.2.1-4**).

It needs to be reiterated that the absence of off-site targets (i.e. distributed throughout the model domain) influences the predicted hydraulic conductivity distributions. The absence of targets away from the Orica Villawood and former Orica Chester Hill sites precludes the need to adjust horizontal and vertical hydraulic conductivities to match water-level elevation targets. If off-site targets were available, there likely would be greater hydraulic conductivity spatial variations throughout the model.

5.2.2 Estimated Recharge Values

Recharge for the first three model variants calibrated was constant and as such not part of the calibration process (**Table 5.2.2-1**). However, for the fourth model variant recharge was determined during the calibration process but the results are not in agreement with the conceptual model that the greatest amount of recharge occurs on parkland, then residential and lastly industrial areas. For the simulation, parkland recharge is greater than industrial recharge followed by residential recharge. Conceptually, residential recharge is expected to be greater than industrial recharge. This and the fact that parkland recharge is predicted to be 49% of precipitation (which is unlikely considering the underlying shale) suggests that model variant four is not representative and should be discarded.

5.2.3 Estimated Model Throughflow and Byrnes Creek Discharge

The four calibrated model variants produced Byrnes Creek flow estimates between 135 and 930 m³/d (**Table 5.2.3-1**). Although the flow in the creek has never been measured, a visual assessment suggests that the volume is small (**Figure 3.3.2-3**). The visual assessment is supported by analytical calculations which show daily Byrnes Creek flow volumes of between 40 and 400 m³ (**Section 3.3.2**). Thus, based on estimated flow volumes, it is more likely that the calibrated models representing recharge scenarios 1 and 2, which predict Byrnes Creek daily flow volumes of 135 and 262 m³, respectively, are more representative than the other two model variants.

5.2.4 Model-Predicted Water Levels

Model calibration is assessed by comparing model-predicted water levels to measured, or target water levels. The closer the agreement between the two the better calibrated the model is assumed to be. Comparison of model-predicted and target water levels for the four models results in sum of the differences squared values ranging between 120 and 148 m² (**Table 5.2.3-1**). As the name implies, the calibration metric sum of the differences squared is calculated by subtracting model-predicted water-level elevation from the corresponding target water-level elevation, squaring the difference (residual) and lastly, summing the squared differences. Of the four recharge scenarios evaluated, scenario 3 produces the lowest sum of the difference squared value.

Figures 5.2.4-1 through 5.2.4-4 are graphical comparisons of model-residuals and measured water-level elevations for the four calibrated models. While the majority of measured water levels were matched within one meter, a number are off considerably, especially the higher elevation water levels (**Figure 5.2.4-5**). Additionally, there are a number of layer 2 and 3 predictions associated with water-level elevation targets between 15 and 20 m AHD that are over-predicted. Note positive and negative residuals represent under- and over-predictions, respectively. **Tables 5.2.4-1 through 5.2.4-4** list individual calibration residuals for every target in the model.

The scatter shown in **Figures 5.2.4-1 through 5.2.4-4** is likely the result of model discretization and fracture effects. The model was discretized using 10 m thick model layers. Within a model cell the water level is the same everywhere. If well is screened at an elevation corresponding to the upper or lower portions of the model layer and vertical gradients are present, the target may not be representative of the water-level in that cell which theoretically represents an elevation corresponding to the middle of the cell. The fix for this dilemma is the addition of more model layers but for this application PEST calibration runs times were already excessive such that the addition of more model layers was not practicable.

Also, it is harder to match water levels when modeling a fractured system relative to a porous media. Depending on the pressure relationship between the block matrix and the fractures, which is temporally variable as a function of recharge, the fractures can drain or recharge the block matrix. Wells having screens intersecting fractures can have different water levels than those in the block matrix. The model which is comprised of bulk properties does not explicitly simulate the fractures and as such can not exactly replicate the response nuances associated with fractured systems. Finally, target wells within a model layer likely do not intersect the same fracture system. As a result, while in the same model layer and screened at similar elevations, two adjacent wells can have vastly different water-level elevations. In summary, because the model assumes bulk properties and in reality it is the fracture orientation, density, and connectivity that control groundwater flow, it should be understood that the model will not match target water-level elevations as precisely as would be expected of a model simulating groundwater flow in unconsolidated sediments.

Modeled potentiometric surfaces for model layer 1 for the four calibrated models are shown in **Figures 5.2.4-6 through 5.2.4-9**. All four models predict a steeper horizontal hydraulic gradient at the western site boundary relative to the rest of the site. Byrnes Creek and the unnamed tributary to the north of the site influence the shape of the potentiometric surface by intercepting

groundwater. Some of the model variants predict mounds at the north and south ends of the model domain but the mounds are likely an artifact of model configuration and not the flow regime. Potentiometric surfaces for the four calibrated models for all eight model layers can be found in Appendix A.

5.2.5 Plume Flow Paths

Particles were placed within the model domain in model layers 1 through 3 at locations roughly corresponding to known source areas and allowed to migrate with the predicted groundwater flow fields (**Fig 5.2.5-1** through **5.2.5-12**). The ability to replicate the plume flow path is a qualitative measure of model calibration, with the closer agreement suggesting a more representative model. The plots show that all four models reasonably replicate the plume flow paths, especially in model layer 1. However, closer examination shows that recharge scenario 2, corresponding to a parkland recharge rate of 5% annual precipitation (22 mm/yr) has particle tracks that more closely replicate the observed plume flow paths.

5.3 Calibration Sensitivity Analysis

During the parameter estimation process PEST calculates sensitivities for all estimated parameters. As the name implies, sensitivities are a measure of how changes in a parameter value affect the calibration statistics. Insensitive parameters are parameters that no matter the assigned value produce the same calibration results. Conversely, minimal changes to the assigned values for highly sensitive parameters induce significant changes in the calibration statistics. Because of this responsiveness, it is easier to find “unique” parameter values for sensitive parameters relative to insensitive parameters. A rule of thumb for parameter estimation modeling is that parameters having sensitivities within two orders of magnitude of the most sensitive parameter can be estimated for the specified model configuration and target set (Hill 1998).

While PEST-SVD offers incredible increases in execution speed relative to PEST, rather than reporting individual parameter sensitivities the sensitivities of the super groups are reported. The only model calibrated using PEST rather than PEST-SVD was the variant where recharge was allowed to fluctuate. Thus, individual parameter sensitivities are only available for that recharge variant model and not the other three calibrated models. Because of the availability of individual parameter sensitivities, the following discussion on parameter sensitivity will be specific to that model. However, given that all four models were calibrated to the same target set the discussion will be generally applicable to the other model variants.

To facilitate sensitivity analysis, estimated parameters were grouped into three parameter categories; horizontal and vertical hydraulic conductivity, drain conductance and recharge. Next the sensitivities were sorted within each category from highest to lowest and then normalized by dividing the sensitivities by the largest value. **Figures 5.3-1** through **5.3-6** show the sensitivities associated with the horizontal and vertical pilot point locations. The presences of a colored rectangle indicate that hydraulic conductivity could be uniquely estimated at that pilot point location. The absence of a rectangle indicates that it may not be possible to uniquely estimate hydraulic conductivity at the corresponding pilot point location. With regard to horizontal hydraulic conductivity, there are a number of pilot point locations in the vicinity of the Orica Villawood and former Orica Chester Hill sites in model layers 1 and 2 that are relatively insensitive. This

insensitivity is partially due to the location of these pilot points with respect to Byrnes Creek and the unnamed tributary. The surrounding creek has a fixed head which exerts significant control over nearby water levels. Near the creek, no matter what the hydraulic conductivity, water levels will change only minimally. Additionally, target distribution controls sensitivity. In the model the targets are generally tightly clustered which further reduces sensitivity.

The horizontal hydraulic conductivity pilot points for model layer 3 and vertical hydraulic conductivity pilot points are spatially more sensitive than the horizontal hydraulic conductivity pilot points in model layers 1 and 2. Decreases to model layer 3 horizontal hydraulic conductivities and model layers 1 through 3 vertical hydraulic conductivities prop up the water table resulting in a better match of the erroneous water level which translates to greater parameter sensitivity.

Of the three recharge zones, residential recharge is the most sensitive (1.00) followed by industrial recharge (0.26) and parkland (0.10). Residential recharge owes its sensitivity to being the most widely distributed recharge variant. Small changes in residential recharge rate change water levels everywhere in the model. Almost all of the model targets are located within the industrial recharge zone so changes to this parameter are easily observable. Parkland is not the most widely distributed recharge variant and is lacking targets located within its domain. Thus, this recharge zone is less sensitive relative to the other zones.

The drain conductance for Byrnes Creek (1.00) is approximately twice as sensitive as the drain conductance associated with the unnamed tributary (0.55).

5.4 Regional Model Calibration Summary

Four models representing different recharge scenarios were calibrated to the same water-level elevation target set. The first three models assumed parkland recharge rates of 2%, 5% and 10% of annual average precipitation. Recharge to the residential and industrial areas was assumed to be approximately one-half and one-quarter of recharge to parkland, respectively, for the simulations. For the fourth model, recharge was allowed to vary and the ultimate values determined as part of the calibration process.

Observations gleaned from the calibrating the four regional models include the following:

- Calibration statistics alone can not be used to discern which of the four models is most representative because in fractured rock it is difficult to achieve exact matches between target and model-predicted water-levels. The inability to exactly match target water levels is mostly a function of the pressure relationship between the block matrix and the fractures, which is temporally variable as a function of recharge; the fractures can drain or recharge the block matrix. Wells having screens intersecting fractures can have different water levels than those in the block matrix. Lastly, wells maybe screened across different fracture systems that are not interconnected. The model which is comprised of bulk properties does not explicated simulate the fractures and as such can not exactly replicate the response nuances associated with fractured systems.
- Model variants 1 and 2 predict daily Byrnes Creek discharge volumes of 138 and 262 m³/d, which is within the range of the calculated estimates (40 to 400 m³/d). Based on ability to match

calculated daily discharge volumes, Recharge Scenarios 1 and 2 are likely more representative than recharge scenarios 3 and 4.

- All four model variants reasonably matched plume flow paths. However, recharge scenario 2 has particle tracks that more closely replicate the observed plume flow paths than the other variants.
- Conceptually residential recharge is expected to be greater than industrial recharge. Recharge Scenario 4, where both hydraulic conductivity and recharge are estimated, predicts industrial recharge to be greater than residential recharge. Given the unlikelihood of industrial recharge being greater than residential recharge, Recharge Scenario 4 was considered unrealistic and was discarded.
- Based on approximating Byrnes Creek daily discharge volumes and more closely replicating plume flow paths, Recharge Scenario 2, corresponding to a parkland recharge rate of 5% annual precipitation (55 mm/yr), is the most representative of the four recharge scenarios.

6 CROSS-SECTIONAL FLOW MODELING

Cross-sectional flow was undertaken concurrently with the regional flow model calibration in order to better understand groundwater interaction with Byrnes Creek, specifically what hydraulic parameter combinations could potentially cause groundwater to underflow Byrnes Creek and discharge to Prospect Creek.

6.1 Model Configuration

The cross-sectional model was constructed by taking a slice along Row 42 of the regional model (**Figure 6.1-1**). The row was chosen because groundwater flow upgradient of Byrnes Creek is, based on plume orientation, essentially parallel to Row 42. Both horizontal and vertical lengths were preserved in the cross-sectional model (**Figure 6.1-2**).

For the analysis the model the recharge distribution along Row 42 corresponding to residential, industrial and parkland areas was preserved (**Fig 6.1-3**). Regional model calibration efforts have shown that calibrating the individual recharge zones is problematic. Often the expected recharge relationship (Parkland > Residential > Industrial) is not preserved so, rather than trying to calibrate individual zone recharge rates the zones were assigned fixed recharge rates (**Table 5.2.2-1**). Three different recharge rate groupings were evaluated corresponding to parkland recharge rates of 2, 5 and 10-percent of annual precipitation.

The model was discretized vertically into three hydraulic conductivity zones (**Figure 6.1-4**). For the analysis, model layers 4-6 and 7-8 were assigned fixed values of hydraulic conductivity for each scenario evaluated (**Table 6.1-1**). For each scenario evaluated the bulk hydraulic conductivity of model layers 1-3 was calibrated to the differing fixed recharge rates (Scenarios 1–3) listed in **Table 5.2.2-1**. Additionally, the horizontal to vertical hydraulic conductivity anisotropy ratio of the three hydraulic conductivity zones was assigned values between 10:1 and 100:1 during the evaluation.

Porosity was assigned a value of 1% throughout the model. This was done more than for convenience rather than because the value is truly representative, although it could be. Effective porosity has never been measured but due to the fractures is assumed to be relatively small. Travel times are inversely proportional to porosity, the smaller the porosity the faster the groundwater velocity. Use of a porosity value of 1% allows for easy scaling of the travel time results. For example, converting the 1% porosity predicted travel times to 5% porosity travel times requires multiplying the 1% travel times by 5.

Byrnes Creek is simulated in the cross-sectional model using drain cells (**Figure 6.1-5**). The drain cells were assigned a head value corresponding to the invert level of Byrnes Creek. Note that three drain cells were used to simulate Byrnes Creek in the cross-section. This is because the creek semi-parallel model row 42 and as such the creek projects on to more than one model cell along the cross-section. Drain cells can only remove water from the model as a function of the difference between adjacent groundwater levels and the drain stage. When adjacent groundwater levels drop below the assigned drain stage, groundwater no longer enters the drain cell. Additionally drain cells have a conductance term, which is analogous to hydraulic conductivity, which provides resistance to flow into the cell. The greater the drain conductance value the easier it is for groundwater to enter the drain.

Prospect Creek was simulated in the cross-sectional model using river cells (**Figure 6.1-5**). River cells function similar to drain cells but allow water to move in and out of the cell depending on the groundwater river cell stage relationship and the river cell conductance. The river cell was assigned a stage of 2 m AHD.

Water-level elevation targets located along Row 42 were imported into the cross-sectional model for calibration purposes (**Table 6.1-2** and **Figure 6.1-6**). Due to an absence of targets in model layer 3, two water-level calibration targets located in nearby columns were projected onto the cross-section and used for calibration purposes. Occasionally more than one water-level elevation target was located within a model cell. To avoid biasing the calibration, when more than one target was located in a cell the targets were assigned a weighting factor corresponding to the inverse of the number of targets in the cell. For example, when two targets are located in the same cell the targets are assigned weights of 0.5. A synthetic target positioned approximately halfway between Byrnes and Prospect Creeks and having a head value corresponding to an elevation two meters below ground surface was used in an attempt to keep groundwater level from projecting above land surface.

Lastly, particles were placed in the middle of each model layer beneath the Orica Villawood site to characterize shallow, intermediate and deep groundwater flow paths.

6.2 Methodology

PEST was used to calibrate thirty-six different cross-sectional MODFLOW models having systematic varying combinations of the model hydraulic parameter (**Tables 6.1-1** and **5.2.2-1**, Scenarios 1–3). During calibration only the bulk hydraulic conductivity of model layers 1-3 and the drain conductance were calibrated. Drain conductance proved to be relatively insensitive, meaning the values had little effect on the target residuals, and in hindsight probably should have been assigned a fixed value.

After calibration was achieved particle tracking was performed using MODPATH to visually assess shallow, intermediate and deep groundwater flow paths.

6.3 Cross-Sectional Flow Modeling Results

Specific cross-sectional flow model evaluation results are presented for the 36 Scenarios evaluated and are followed by a more general discussion. Usually results are discussed first in general terms before discussing specifics. The unusual presentation order was used to better facilitate understanding of the results.

Scenarios 1-9

The hydraulic conductivity of model layers 4 through 8 for Scenarios 1 through 9 is uniform and has values ranging between 1×10^{-2} and 1×10^{-4} m/d and a horizontal to vertical anisotropy ratio of 10:1 (**Table 6.1-1**). The different uniform model layer 4 through 8 hydraulic conductivity values were combined with three different recharge regimes to produce the results displayed in **Table 6.3-1**. The column labeled SDS (Sum of the Difference Squared) shows that all nine model Scenarios are similarly calibrated with regard to matching water level targets despite differing combinations of hydraulic parameters. This is because without a flux target (i.e. flow in Byrnes Creek) there are many combinations of recharge and hydraulic conductivity that will produce virtually the same calibration results with respect to the water-level targets. Also note that model calibration is non-unique with respect to the hydraulic conductivity assigned model layers 4 through 8. Two orders of magnitude difference in the hydraulic conductivity of model layers 4 through 8 produces similar model calibration error and estimates of the bulk hydraulic conductivity of model layers 1 through 3 for correspondingly similar recharge rates.

Particle tracking shows that for all combinations of hydraulic conductivity and recharge, particles originating in model layers 1 through 8 migrate to Byrnes Creek (**Figs. 6.3-1** through **6.3-9**). Particle travel time in model layers 1 through 3 ranges between 4 and 25 years (**Table 6.3-1**). Note that the travel times represent groundwater velocities not contaminant migration rates. Due to matrix diffusion, retardation and other plume attenuation effects, contaminant migration rates will be considerably less than the above reported groundwater velocities. Travel times in model layers 4 through 8 are much slower and range between 242 and 49,281 years.

Scenarios 10-18

Similar to Scenarios 1 through 9, the Scenarios 10 through 18 have uniform hydraulic conductivity for model layers 4 through 8 that ranges from 1×10^{-2} and 1×10^{-4} m/d (**Table 6.3-1**). Differing from the previous Scenarios is the assumption that the horizontal to vertical anisotropy ratio has increased from 10:1 to 100:1. Again, the different uniform model layer 4 through 8 hydraulic conductivity values were combined with three different recharge regimes to produce the results displayed in **Table 6.3-1**.

All nine simulation yielded similar calibration values with respect to SDS and hydraulic conductivity estimates for the three different recharge regimes as Scenarios 1-9 (**Table 6.3-1**). This suggests in addition to the model being insensitive to the hydraulic conductivity assigned model layers 4 through 8; the model also is insensitive to, with respect to hydraulic head, varying horizontal to vertical anisotropy ratios.

Particle tracking shows that for all combinations of hydraulic conductivity and recharge, particles originating in model layers 1 through 3 migrate to Byrnes Creek (**Figs. 6.3-10** through **6.3-18**). However, due to anisotropy, particles originating in model layers 4-8 do not discharge to Byrnes Creek; rather the particles migrate upward to layer 3 and then plunge downward into the deeper less permeable model layers before discharging to Prospect Creek. An exception is Scenario 16 where particles originating in model layers 4-6 discharge to Byrnes Creek while particles in deeper layers migrate to Prospect Creek (**Figure 6.3-16**). The change in flow paths relative to the other scenarios is likely due to the pairing of increased vertical hydraulic conductivity and lower recharge rates. Travel time in model layers 1 through 3 is similar to those of Scenarios 1-9

and ranges between 4 and 25 years (Table 6.3-1). Particle travel times in model layers 4 through 8 range between 342 and 197,947 years. The significant increase in travel times is due to the longer flow paths (discharge to Prospect Creek versus Byrnes Creek) and the increased horizontal to vertical anisotropy ratio.

Scenarios 19-27

These Scenarios utilize the same hydraulic parameter configurations as Scenarios 1-9, including a 10:1 horizontal to vertical anisotropy ratio, but the hydraulic conductivity of model layers 7-8 is an order of magnitude less than that of model layers 4-6. The simulations yielded similar calibration values with respect to SDS and hydraulic conductivity estimates for the three different recharge regimes as Scenarios 1-18 (Table 6.3-1). The results demonstrate that the model is not only insensitive to the hydraulic conductivity values assigned to model layers 4-6 but is also insensitive to hydraulic conductivity decreasing with depth.

Particle tracking shows that even with increasing hydraulic conductivity with depth Byrnes Creek is the ultimate discharge location for particles originating in model layers 1-8 (**Figs. 6.3-19 through 6.3-27**). Travel time in model layers 1 through 3 is similar to those of Scenarios 1-9 and ranges between 4 and 23 years (**Table 6.3-1**). Travel times in model layers 4-8 range from 244 to 355,921 years. The significantly longer maximum travel time relative to the previous Scenarios is due to the order of magnitude decrease in the hydraulic conductivity in model layers 7-8 which results in slower groundwater velocities.

Scenarios 28-36

Scenarios 28-36 utilize the same hydraulic parameter configurations as Scenarios 1-9 except the hydraulic conductivity of model layers 7-8 is an order of magnitude greater than that of model layers 4-6. As with the previous 27 Scenarios, all nine simulations (28-36) yielded similar calibration values with respect to SDS and hydraulic conductivity estimates for the three different recharge regimes (**Table 6.3-1**). The results demonstrate that the model is not only insensitive to the hydraulic conductivity values assigned to model layers 4-6 but is also insensitive to hydraulic conductivity either increasing or decreasing with depth.

Particle tracking shows for all combinations of hydraulic parameters, particles originating in model layers 1-8 discharge to Byrnes Creek (**Figs. 6.3-28 through 6.3-36**). Travel time in model layers 1 through 3 is similar to those of the previous 27 Scenarios and ranges between 4 and 22 years (**Table 6.3-1**). Travel times for particles originating in the deeper layers (4-8) range from 802 to 122,930 years.

General

While particle tracks show there is downward groundwater movement beneath the Orica Villawood Site, the movement is not steep enough for advection alone to be responsible for contamination observed with depth. It is possible that Dense Non-Aqueous Phase Liquids (DNAPL) migrating vertically through fractures is responsible for the contamination with depth.

The results also show that for all Scenarios travel times for particles originating in model layers 4-8 are large (>242 years). It should be noted that these travel times relate to groundwater velocities and contaminant migration rates are likely to be much slower due to matrix diffusion,

retardation and other plume attenuation processes. If DNAPL has migrated to the deeper portions of the flow system it is unlikely that the associated dissolved phase has migrated very far and it is equally unlikely that the deeper contamination will reach either Byrnes or Prospect Creek in the foreseeable future.

The predicted bulk hydraulic conductivity for all Scenarios for model layers 1-3 ranges between 0.11 and 0.76 m/d (**Table 6.3-1**). The narrow range is certainly within the error of our ability to measure hydraulic conductivity in the field. Thus, it is not possible to determine which of the three recharge rate groupings is the most representative, which again illustrates the non-uniqueness of the model. However, recharge and hydraulic conductivity appear correlated. Parkland recharge in the various scenarios increased by factors of 2.5 and 5 relative to the lowest value simulated. The associated predicted bulk hydraulic conductivity for model layer 1-3 increased by factors of 2.3 and 4.9 as recharge increased. The similar factor increase in the two parameters illustrates that the parameters are correlated to some degree.

6.4 Summary

The following conclusions can be drawn from the cross-sectional modeling analysis:

- Calibration statistics suggest that due to an absence of targets, hydraulic conductivity at depth is insensitive and can not be estimated during calibration. Therefore, it is necessary to adopt a fixed assumed hydraulic conductivity profile with depth for the Orica Villawood two- and three-dimensional groundwater flow simulations.
- Orica Villawood shallow groundwater located between the water table and -10 m AHD discharges to Byrnes Creek for all possible combinations of recharge, hydraulic conductivity and horizontal to vertical hydraulic conductivity anisotropy ratios.
- The horizontal to vertical hydraulic conductivity anisotropy ratio ultimately controls where deep (-10 m AHD) groundwater from the Orica Villawood site discharges. If the horizontal to vertical anisotropy ratio is 10:1 or less the groundwater discharges to Byrnes Creek. For horizontal to vertical anisotropy ratios greater than 100:1 deeper groundwater from the Orica Villawood site discharges to Prospect Creek.
- Particle flow paths suggest that if contamination is present with depth the contamination migrated to that depth as free phase (DNAPL) and not as a result of advection.
- If contamination is present at depths below -10 m AHD; the migration rates to either Byrnes or Prospect Creek will be very slow. Particles originating at depth required a minimum of 242 years to reach a surface water feature when porosity was 1%. The 242 years represents groundwater velocity and not the expected contaminant migration rates. Orica Villawood groundwater flow velocities have been reported to be as high as 200 m/year (Section 3.2). The longest plume originating from the Orica Villawood site is approximately 150 m in length (**Section 3.5**). Assuming a 40 year migration period, the plume has migrated at slightly less than 4 m/year. Comparison of the plume migration and groundwater flow velocities suggests that Villawood groundwater contamination is retarded by a factor of 50. Applying this retardation rate to the minimum modeled groundwater travel time (242 years) produces a contaminant travel time of more than 12,000 years.

7 THREE-DIMENSIONAL CONTAMINANT TRANSPORT MODELING

Future potential plume movement from the Orica Villawood site was evaluated using MT3D's dual porosity capabilities (Zheng 1999). The transport model was calibrated by adjusting the dual porosity input parameters and source loading rates until a reasonable match was obtained between the observed and simulated plumes. Fracture and bulk porosity and the distribution coefficient (K_d) were held constant during calibration at measured values. After calibration the transport model was used evaluate potential plume movement 100 years into the future. Lastly, because of the inherent uncertainty associated with transport modeling (i.e. where are the sources, what are the release histories, what is the organic carbon fraction, etc.) sensitivity analysis was performed by varying the transport input parameters and mass loading rates to see if uncertainty in the transport input parameters could result in migration to Byrnes Creek.

7.1 Telescopic Mesh Refinement Model Configuration

The calibrated regional model grid spacing and the model domain are too large to use for transport simulations. The regional model grid could have been refined to facilitate transport modeling but likely the overall model size, with respect to computer memory requirements, would have become excessive. Rather than work with a cumbersome model, a TMR model encompassing the Orica Villawood site was cut from the regional model (**Figure 7.1-1**). A TMR model preserves the parent model calibrated flow field by including the same spatial distribution of parameters and including specified heads or fluxes derived from the parent model along the edges of the model domain. Specified fluxes rather than specified heads were used with this TMR model. For this application 5 m by 5 m grid spacing was used. In addition, from the water table to a depth of approximately -10 m AHD, 5 m thick model layers were used rather than the 10 m thick layers used in the regional model. Below -10 m AHD 10 m layer thicknesses were used.

7.2 Calibration Methodology

Transport model calibration was achieved by simulating 40 years of contaminant transport with constant sources at the head of the plumes in model layers 1 through 5 and comparing the predicted plume geometries to the observed plume geometries (**Figure 7.2-1**). The transport model was assumed calibrated when a reasonable match between the predicted and observed plume geometries was achieved. It is recognized that the contaminant loading rate is not likely temporally static but rather is a function of waste disposal history and source material depletion. However, without detailed disposal records' developing a variable contaminant loading history is considered impracticable. Thus, constant contaminant loading rates were assumed and adjusted during transport model calibration to achieve better plume matches, primarily the concentration distribution.

Only the dual porosity mass transfer and reaction rate input parameters and constant source mass loading rates were adjusted during calibration. The remaining transport parameters were held constant at the values listed in **Table 7.2-1**. Fracture porosity was calculated based on data

collected at a nearby rock quarry. Bulk density porosity was measured in the laboratory using rock cores collected on site. The distribution coefficient (K_d) was calculated based on laboratory measurements of organic carbon content and a literature reported EDC K_{oc} value.

Of the four recharge scenarios evaluated, Recharge Scenario 2 having parkland recharge equal 5% of annual precipitation was deemed most representative. The flow field from this model was used for the contaminant transport simulations.

7.3 Three-Dimensional Contaminant Transport Model Calibration

Calibrating contaminant transport models is a time consuming endeavor. A forty year simulation required more than two hours on the fastest computer available. Approximately 100 model runs were made during the calibration process. Given the simulation run times it is not possible to calibrate transport models for all the contaminants present at the Orica Villawood site. To expedite the modeling process only one contaminant (EDC) was simulated. EDC is widely dispersed, relatively soluble and relatively mobile compared to the other site contaminants. Thus, EDC is considered a conservative surrogate for other dissolved contaminants originating at the Orica Villawood site. Conclusions resulting from the EDC transport exercise are assumed applicable to the other contaminants of concern.

As stated previously, only the dual porosity mass transfer and reaction rate input parameters and constant source mass loading rates were adjusted during calibration. With regard to MT3D dual porosity input parameters, a mass transfer rate of $1.0 \times 10^{-6} \text{ d}^{-1}$ and reaction rates of 200 d^{-1} were determined to produce the “best” plume match. Source loading rates ranged from 7 to 500 mg/L (**Figure 7.3-1**).

Figure 7.3-2 shows the model-predicted distribution of the EDC plumes after 40 years of migration from the source areas. The illustrations of the simulated plumes are created by projecting the maximum concentration in any model layer onto a single layer. Thus, the depicted plumes represent the maximum simulated concentrations and extent.

The calibrated model reasonably replicates the extent of the EDC plumes although the simulated plumes are jagged compared to the illustrated plumes. The jaggedness results from variations in hydraulic conductivity caused by the pilot point calibration process. With the exception of the most northern plume, all the plumes follow the trajectory of the actual plume. While the trajectories are not in agreement, the extent of the simulated plume is reasonable.

7.4 Three-Dimensional Contaminant Transport Model Predictions

Dual porosity slows contamination migration through matrix diffusion which results from concentration gradients. As dissolved contamination emanates from the source, contaminant concentrations within the fractures are higher than those in the block matrix. As a result of the concentration differences contaminant migrates (diffuses) from the fracture into the block matrix. Simplistically, contaminant migration continue along the fractures until the total diffusive capacity

of block matrix in contact with the dissolved contamination approaches the contaminant mass loading rate emanating from the source. At that point plume migration slows dramatically. Plume migration continues but at the new much slower pace along the fracture flow path because “fresh rock” along with “dirty rock” having remaining diffusive capacity are available to facilitate diffusion at a rate equal to the contaminant loading rate.

Contaminant transport modeling results support the above hypothesis and show the Orica Villawood plumes developed rapidly during the first year following contaminant release to the subsurface (**Figs. 7.4-1**). After one year plume development slows considerably and becomes relatively static as the years progress (**Figs. 7.4-2** through **7.4-6**). None of the plumes reach Byrnes Creek within 100 years of present day, approximately 140 years since source release (**Figure 7.4-7**).

7.5 Sensitivity Analysis

Sensitivity analysis was performed to evaluate whether the uncertainty in transport model input parameters could result in simulated contamination reaching Byrnes Creek. Sensitivity analysis was performed by individually varying the transport model input parameters listed in **Table 7.5-1**. In all ten sensitivity simulations were performed. Not all parameter combinations were evaluated. For example, increased K_d was not evaluated because increasing the parameter would produce a smaller plume. Similarly, decreases in source loading rates were not evaluated because a decrease would result in smaller plumes.

Changing the parameter input parameters results in plumes of different lengths and concentration distributions than the calibrated plumes but none of the changes produce plumes that discharge to Byrnes Creek within 100 years of present day (**Figs. 7.5-1** through **7.5-10**). Thus, it is unlikely that dissolved contamination will reach Byrnes Creek within 100 years of present day regardless of parameter uncertainty.

It is interesting to note that many of the changes to the transport modeling input parameters produce plumes virtually identical to other sensitivity analysis simulations, which demonstrates the non-uniqueness of transport models and highlights the difficulty of achieving calibration. Also, note that increasing fracture porosity by 50% has the same effect on plume configuration as decreasing bulk porosity by 50%. This is because the two scenarios have the same fracture porosity to bulk porosity ratios. Contaminant transport within fractured media is controlled by the ratio of the two porosity values.

7.6 Summary

The following conclusions can be drawn from the three-dimensional contaminant transport modeling analysis:

- Modeling predicts that due to the effects of matrix diffusion, Villawood plumes develop rapidly and then migration slows considerably until relatively static conditions are reached. Plume growth from this point forward is very slow requiring tens of years to migrate a few meters.

- After 100 years of plume migration from present day none of the Villawood plumes reach Byrnes Creek.
- Sensitivity analysis shows that while varying transport input parameters produces plumes of different configurations than the calibrated plumes, none of the plumes reach Byrnes Creek within 100 years of present day. Thus, it is unlikely, even considering uncertainties in various parameters, that dissolved contamination of any from the Orica Villawood site (EDC being the most mobile) will reach Byrnes Creek within 100 years of present day.
- While the modeling results alone demonstrate robustly that it is unlikely that groundwater contamination will reach Byrnes Creek within the next 100 years, it is important to note that the observed plume configurations support this conclusion. Site groundwater velocities are reported to be as high as 200 m/year yet the plumes have migrated less than 100 m. Clearly the plumes are being significantly attenuated through matrix diffusion, a phenomenon replicated by the transport model.

8 CONCLUSIONS

As part of the Orica Villawood modeling exercise four regional flow models were calibrated to differing recharge scenarios. In addition 36 cross-sectional flow models having differing recharge, hydraulic conductivity and anisotropy ratios were developed and analyzed to develop a better understanding of the groundwater flow. Lastly, a three-dimensional contaminant transport model based on the regional flow model was configured, calibrated and used to evaluate future plume movement of dissolved phase contamination originating at the Orica Villawood site. Sensitivity analysis was performed using the transport model to evaluate how parameter uncertainty could effect model predicts, specifically whether or not the plume would reach Byrnes Creek within 100 years of present day. The following conclusions are based on the results of the above modeling exercises.

- Based on approximating Byrnes Creek daily discharge volumes and more closely replicating plume flow paths, recharge scenario 2, corresponding to a parkland recharge rate of 5% annual precipitation (55 mm/yr), is likely the most representative of the four recharge scenarios.
- Cross-sectional flow modeling demonstrates that except for when the horizontal to vertical anisotropy ratio is 100: 1 or greater, all groundwater beneath the Orica Villawood site ultimately discharges to Byrnes Creek. Given that many of the fractures are oriented nearly vertical, it is unlikely that horizontal to vertical hydraulic conductivity ratios exceed 100:1. Since there is a high probability that all groundwater beneath the Orica Villawood site discharges to Byrnes Creek, if future modeling is performed at Villawood it is recommended that Byrnes Creek be specified as an external model boundary. By reducing the model domain the grid can be made finer and without resulting in excessively long simulation run times.
- Cross-sectional flow suggest that contamination, if present, at depths greater than -10 m AHD will not migrate significant distances within 100 years. Flow model sensitivity analysis shows that even for hydraulic conductivity values as high as 10^{-2} m/d at depths below 0 m AHD groundwater travel times to Byrnes Creek will be in excess of 200 years. Because of plume attenuation, primarily through matrix diffusion, contaminant migration to Byrnes Creek will be even slower.
- Three-dimension contaminant transport modeling simulating matrix diffusion effects predict relatively rapid plume expansion flowed by a dramatic decrease in plume migration rates. Once the “slow” migration period is reached plume concentrations and extent are relatively static. It is believed that the plumes originating from the Orica Villawood site are no longer rapidly expanding and are now relatively static with respect to concentrations and extent.
- Sensitivity analysis shows that while varying transport input parameters produces plumes of different configurations than the calibrated plumes, none of the plumes reach Byrnes Creek within 100 years of present day. Thus, it is unlikely, even considering the uncertainties, that dissolved contamination from the Orica Villawood site (EDC being the most mobile) will reach Byrnes Creek within 100 years of present day.
- While the modeling results alone demonstrate robustly that it is unlikely that groundwater contamination will reach Byrnes Creek within the next 100 years, it is important to note that the observed plume configurations support this conclusion. Site groundwater velocities are reported to be as high as 200 m/year yet the plumes have migrated less than 100 m. Clearly the plumes are being significantly attenuated, a phenomenon replicated by the transport model.

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TABLES

Table 4.3.1-1. Model layer 4 – 8 hydraulic conductivity values.

Model Layer	Horizontal Hydraulic Conductivity, m/d	Vertical Hydraulic Conductivity, m/d
4	1×10^{-2}	1×10^{-3}
5	5×10^{-3}	5×10^{-4}
6	1×10^{-3}	1×10^{-4}
7	5×10^{-4}	5×10^{-5}
8	1×10^{-4}	1×10^{-5}

Table 4.3.2-1. Scenario recharge rates.

Scenario	Recharge rate, mm/yr and percentage of precipitation		
	Residential	Parkland	Industrial
1	11 (1%)	22 (2%)	5.5 (0.5%)
2	22 (2%)	55 (5%)	11 (1%)
3	44 (4%)	110 (10%)	22 (2%)
4	Calibrated	Calibrated	Calibrated

Table 5.1.1-1. Water-elevation target values.

Well/Piezometer	Model Layer	Observed	Site	Well/Piezometer	Model Layer	Observed	Site
MW48	1	18.85	Villawood	MW46B	1	15.83	Villawood
MW101S	1	21.81	Chester Hill	OS09B	1	17.85	Villawood
MW111S	1	19.93	Chester Hill	MW241S	1	21.09	Chester Hill
OS06A	2	15.63	Villawood	OS05A	1	17.31	Villawood
MW33	1	17.21	Villawood	OS09A	1	18.78	Villawood
MW244S	1	20.09	Chester Hill	MW103D	1	20.69	Chester Hill
OS04A	1	17.87	Villawood	MW19	2	18.82	Villawood
MW105S	1	20.13	Villawood	MW108D	1	17.19	Chester Hill
OS03B	1	18.34	Villawood	BP103	3	18.92	Villawood
MW103S	1	20.02	Chester Hill	MW230D	1	17.37	Chester Hill
MW51	1	18.34	Villawood	MW21	2	18.91	Villawood
MW52	2	18.86	Villawood	MW41	1	16.37	Villawood
OS03A	1	18.37	Villawood	MW36	1	19.09	Villawood
MW238D	1	20.59	Chester Hill	OS02B	1	19.01	Villawood
MW40	1	16.28	Villawood	MW31	1	17.74	Villawood
MW53B	2	18.48	Villawood	MW37	1	18.94	Villawood
MW53A	2	18.90	Villawood	MW7	2	19.00	Villawood
MW23	1	16.19	Villawood	MW35	1	19.01	Villawood
OS06B	2	15.55	Villawood	MW50	1	19.37	Villawood
MW22	1	18.88	Villawood	MW14	1	18.77	Villawood
MW108S	1	20.27	Chester Hill	MW42	1	16.07	Villawood
MW25	1	15.90	Villawood	MW20	1	18.87	Villawood
MW106D	1	20.58	Chester Hill	MW13	1	18.77	Villawood
MW228S	1	20.34	Chester Hill	ML237/1	1	21.88	Chester Hill
MW24	1	16.21	Villawood	MW6	1	18.78	Villawood
MW43C	2	17.61	Villawood	BP104	3	17.97	Villawood
MW29	1	16.19	Villawood	MW46C	2	16.99	Villawood
MW201D	1	20.45	Chester Hill	MW78	1	17.82	Villawood
MW104S	1	20.35	Chester Hill	MW5	2	18.04	Villawood
MW201S	1	20.47	Chester Hill	MW27	1	17.00	Villawood
MW26	1	15.93	Villawood	MW77	1	17.59	Villawood
MW39	1	18.46	Villawood	MW32	1	17.97	Villawood
MW106S	1	20.79	Chester Hill	MW102S	1	20.86	Chester Hill
MW44B	1	18.05	Villawood	MW107S	1	20.58	Chester Hill
MW107D	1	19.37	Chester Hill	MW18	1	24.47	Villawood
MW43A	1	18.04	Villawood	OS01A	1	19.66	Villawood
MW44A	1	18.04	Villawood	OS10A	1	16.34	Villawood
OS01B	1	18.62	Villawood	OS08A	1	19.10	Villawood
MW38	1	18.47	Villawood	MW229S	1	20.60	Chester Hill
OS07B	2	16.15	Villawood	MW34	1	18.97	Villawood
MW109D	1	20.59	Chester Hill	MW49	1	19.70	Villawood
MW239S	1	20.97	Chester Hill	MW15	1	27.41	Villawood
ML235/1	1	21.02	Chester Hill	BP102	3	18.04	Villawood
MW30	1	16.37	Villawood	BP101	3	18.46	Villawood
MW111D	1	20.17	Chester Hill	MW8	1	19.44	Villawood
ML234/1	1	21.06	Chester Hill	MW11	2	21.99	Villawood
OS06C	1	16.04	Villawood	BP104	2	17.97	Villawood
MW45	1	17.01	Villawood	MW259S	1	18.41	Chester Hill
MW47	1	18.41	Villawood	MW1	1	19.90	Villawood
OS07A	1	16.11	Villawood	MW10	2	16.03	Villawood
MW43B	1	17.08	Villawood	BP103	2	18.92	Villawood
MW53C	2	18.09	Villawood	MW18	2	24.47	Villawood
MW46A	1	15.95	Villawood	MW28	1	14.82	Villawood
MW22	2	18.88	Villawood	MW3	2	22.22	Villawood
ML236/1	1	21.25	Chester Hill	BP102	2	18.04	Villawood
OS02A	1	18.70	Villawood	BP101	2	18.46	Villawood
BP105	2	18.48	Villawood	MW16	2	19.11	Villawood
MW48	2	18.85	Villawood	BP106	3	18.91	Villawood
MW44C	2	17.66	Villawood	MW16	1	19.11	Villawood
MW17	1	18.63	Villawood	MW15	2	27.41	Villawood
ML246/1	1	21.00	Chester Hill	MW2	1	24.30	Villawood
MW109S	1	21.01	Chester Hill	BP106	2	18.91	Villawood
ML238/1	1	20.93	Chester Hill	MW4	1	32.55	Villawood

Table 5.2.1-1. Recharge scenario 1 model-predicted hydraulic conductivities.

Model Layer	Average Hydraulic Conductivity, m/d					
	Overall Model			Villawood Site		
	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio
1	3.94×10^{-1}	5.09×10^{-2}	7.74	1.24×10^0	4.21×10^{-2}	29.45
2	6.56×10^{-2}	1.00×10^{-2}	6.56	1.49×10^{-1}	8.84×10^{-3}	16.77
3	4.38×10^{-2}	4.68×10^{-3}	9.36	1.73×10^{-1}	3.71×10^{-3}	46.63
4	1.00×10^{-2}	1.00×10^{-3}	10.00	1.00×10^{-2}	1.00×10^{-3}	10.00
5	5.00×10^{-3}	5.00×10^{-4}	10.00	5.00×10^{-3}	5.00×10^{-4}	10.00
6	1.00×10^{-3}	1.00×10^{-4}	10.00	1.00×10^{-3}	1.00×10^{-4}	10.00
7	5.00×10^{-4}	5.00×10^{-5}	10.00	5.00×10^{-4}	5.00×10^{-5}	10.00
8	1.00×10^{-4}	1.00×10^{-5}	10.00	1.00×10^{-4}	1.00×10^{-5}	10.00

Note: Model layer 4-8 hydraulic conductivities were fixed during model calibration.

Table 5.2.1-2. Recharge scenario 2 model-predicted hydraulic conductivities.

Model Layer	Average Hydraulic Conductivity, m/d					
	Overall Model			Villawood Site		
	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio
1	5.92×10^{-1}	4.96×10^{-2}	11.94	1.41×10^0	5.83×10^{-2}	24.19
2	1.49×10^{-1}	9.40×10^{-3}	15.85	2.19×10^{-1}	1.34×10^{-2}	16.34
3	8.66×10^{-2}	5.41×10^{-3}	16.01	2.71×10^{-1}	5.42×10^{-3}	50.00
4	1.00×10^{-2}	1.00×10^{-3}	10.00	1.00×10^{-2}	1.00×10^{-3}	10.00
5	5.00×10^{-3}	5.00×10^{-4}	10.00	5.00×10^{-3}	5.00×10^{-4}	10.00
6	1.00×10^{-3}	1.00×10^{-4}	10.00	1.00×10^{-3}	1.00×10^{-4}	10.00
7	5.00×10^{-4}	5.00×10^{-5}	10.00	5.00×10^{-4}	5.00×10^{-5}	10.00
8	1.00×10^{-4}	1.00×10^{-5}	10.00	1.00×10^{-4}	1.00×10^{-5}	10.00

Note: Model layer 4-8 hydraulic conductivities were fixed during model calibration.

Table 5.2.1-3. Recharge scenario 3 model-predicted hydraulic conductivities.

Model Layer	Average Hydraulic Conductivity, m/d					
	Overall Model			Villawood Site		
	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio
1	1.65×10^0	4.70×10^{-2}	35.11	1.47×10^0	3.24×10^{-2}	45.37
2	2.17×10^{-1}	8.29×10^{-3}	26.18	2.94×10^{-1}	1.05×10^{-2}	28.00
3	6.20×10^{-2}	4.98×10^{-3}	12.45	2.23×10^{-1}	4.00×10^{-3}	55.75
4	1.00×10^{-2}	1.00×10^{-3}	10.00	1.00×10^{-2}	1.00×10^{-3}	10.00
5	5.00×10^{-3}	5.00×10^{-4}	10.00	5.00×10^{-3}	5.00×10^{-4}	10.00
6	1.00×10^{-3}	1.00×10^{-4}	10.00	1.00×10^{-3}	1.00×10^{-4}	10.00
7	5.00×10^{-4}	5.00×10^{-5}	10.00	5.00×10^{-4}	5.00×10^{-5}	10.00
8	1.00×10^{-4}	1.00×10^{-5}	10.00	1.00×10^{-4}	1.00×10^{-5}	10.00

Note: Model layer 4-8 hydraulic conductivities were fixed during model calibration.

Table 5.2.1-4. Recharge scenario 4 model-predicted hydraulic conductivities.

Model Layer	Average Hydraulic Conductivity, m/d					
	Overall Model			Villawood Site		
	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio	Horizontal	Vertical	Horizontal to Vertical Anisotropy Ratio
1	6.95×10^{-1}	4.89×10^{-2}	14.21	1.49×10^0	4.79×10^{-2}	31.11
2	1.07×10^{-1}	9.53×10^{-3}	11.23	2.67×10^{-1}	9.78×10^{-3}	27.30
3	5.29×10^{-2}	4.90×10^{-3}	10.80	1.38×10^{-1}	4.39×10^{-3}	31.44
4	1.00×10^{-2}	1.00×10^{-3}	10.00	1.00×10^{-2}	1.00×10^{-3}	10.00
5	5.00×10^{-3}	5.00×10^{-4}	10.00	5.00×10^{-3}	5.00×10^{-4}	10.00
6	1.00×10^{-3}	1.00×10^{-4}	10.00	1.00×10^{-3}	1.00×10^{-4}	10.00
7	5.00×10^{-4}	5.00×10^{-5}	10.00	5.00×10^{-4}	5.00×10^{-5}	10.00
8	1.00×10^{-4}	1.00×10^{-5}	10.00	1.00×10^{-4}	1.00×10^{-5}	10.00

Note: Model layer 4-8 hydraulic conductivities were fixed during model calibration.

Table 5.2.2-1. Modeled recharge rates.

Scenario	Recharge rate, mm/yr and percentage of precipitation		
	Residential	Parkland	Industrial
1	11 (1%)	22 (2%)	5.5 (0.5%)
2	22 (2%)	55 (5%)	11 (1%)
3	44 (4%)	110 (10%)	22 (2%)
4	11 (1%)	535 (49%)	97 (9%)

Note: Recharge rates for Scenarios 1-3 were fixed during model calibration. Scenario 4 recharge rates were determined as part of the calibration process.

Table 5.2.3-1. Calibration statistics and water balance information.

Scenario	Calibration Statistics	Flow, m ³ /d	
	Sum of Difference Squared, m ²	Model Through Flow	Byrnes Creek Discharge
1	148	499	138
2	132	998	262
3	120	2,168	624
4	129	5,495	930

Table 5.2.4-1. Recharge scenario 1 comparison of measured and model-predicted water levels.

Name	Layer	Target	Model	Residual	Site	Name	Layer	Target	Model	Residual	Site
MW23	1	16.19	16.20	0.00	Villawood	OS05A	1	17.31	17.11	0.20	Villawood
OS03B	1	18.34	18.33	0.01	Villawood	OS06C	1	16.04	15.84	0.20	Villawood
MW101S	1	21.81	21.82	-0.01	Chester Hill	MW53C	2	18.09	18.94	-0.21	Villawood
MW238D	1	20.59	20.58	0.01	Chester Hill	OS07B	2	16.15	15.94	0.21	Villawood
MW29	1	16.19	16.20	-0.01	Villawood	MW20	1	18.87	18.65	0.22	Villawood
MW53A	2	18.90	18.95	-0.01	Villawood	MW36	1	19.09	18.65	0.22	Villawood
MW244S	1	20.09	20.04	0.01	Chester Hill	MW241S	1	21.09	19.69	0.23	Chester Hill
OS03A	1	18.37	18.33	0.02	Villawood	MW46B	1	15.83	16.30	-0.24	Villawood
MW33	1	17.21	17.23	-0.02	Villawood	BP105	2	18.48	18.72	-0.24	Villawood
MW103S	1	20.02	19.95	0.02	Chester Hill	MW103D	1	20.69	19.95	0.24	Chester Hill
MW105S	1	20.13	20.02	0.02	Chester Hill	BP103	3	18.92	19.16	-0.24	Villawood
MW52	2	18.86	18.95	-0.02	Villawood	MW22	1	18.88	19.13	-0.24	Villawood
MW48	2	18.85	18.83	0.03	Villawood	MW14	1	18.77	18.51	0.26	Villawood
OS04A	1	17.87	17.84	0.03	Villawood	OS02B	1	19.01	18.48	0.26	Villawood
MW24	1	16.21	16.15	0.03	Villawood	OS09B	1	17.85	18.38	-0.27	Villawood
MW21	2	18.91	18.87	0.03	Villawood	MW108D	1	17.19	19.65	-0.27	Chester Hill
MW43C	2	17.61	17.65	-0.04	Villawood	MW230D	1	17.37	19.92	-0.28	Chester Hill
MW111S	1	19.93	20.00	-0.04	Chester Hill	MW41	1	16.37	17.52	-0.29	Villawood
OS06A	2	15.63	15.68	-0.05	Villawood	MW6	1	18.80	18.51	0.29	Villawood
MW48	1	18.85	18.96	-0.05	Villawood	MW50	1	19.37	18.78	0.29	Villawood
MW39	1	18.46	18.36	0.05	Villawood	MW35	1	19.01	18.42	0.30	Villawood
OS01B	1	18.62	18.51	0.05	Villawood	MW13	1	18.77	18.44	0.33	Villawood
MW17	1	18.63	18.56	0.07	Villawood	MW31	1	17.74	17.41	0.33	Villawood
MW108S	1	20.27	19.66	0.07	Chester Hill	MW42	1	16.07	17.46	-0.35	Villawood
MW106D	1	20.58	19.93	0.07	Chester Hill	ML237/1	1	21.88	19.64	0.37	Chester Hill
MW228S	1	20.34	19.97	0.07	Chester Hill	MW78	1	17.82	17.44	0.38	Villawood
MW19	2	18.82	18.75	0.08	Villawood	MW77	1	17.59	17.18	0.41	Villawood
MW7	2	19.00	18.92	0.08	Villawood	MW27	1	17.00	16.56	0.43	Villawood
MW201D	1	20.45	19.96	0.08	Chester Hill	MW102S	1	20.86	20.40	0.46	Chester Hill
MW104S	1	20.35	19.94	0.08	Chester Hill	MW8	1	18.55	18.08	0.47	Villawood
MW111D	1	20.17	20.00	0.08	Chester Hill	MW107S	1	20.58	19.63	0.47	Chester Hill
MW201S	1	20.47	19.96	0.09	Chester Hill	MW32	1	17.97	17.49	0.48	Villawood
MW51	1	18.34	18.52	-0.09	Villawood	MW46C	2	16.99	16.46	0.53	Villawood
MW106S	1	20.79	19.93	0.10	Chester Hill	BP104	3	17.97	18.51	-0.54	Villawood
MW25	1	15.90	16.11	-0.10	Villawood	OS01A	1	19.66	18.52	0.57	Villawood
MW22	2	18.88	18.99	-0.11	Villawood	MW5	2	18.06	18.64	-0.58	Villawood
OS02A	1	18.70	18.48	0.11	Villawood	OS08A	1	19.10	18.45	0.65	Villawood
MW43A	1	18.04	17.59	0.11	Villawood	OS10A	1	16.34	17.06	-0.72	Villawood
MW53B	2	18.48	18.94	-0.12	Villawood	MW229S	1	20.60	19.87	0.73	Chester Hill
MW26	1	15.93	16.16	-0.12	Villawood	MW34	1	18.97	18.22	0.75	Villawood
MW44B	1	18.05	17.81	0.12	Villawood	MW1	1	19.16	18.39	0.77	Villawood
MW44A	1	18.04	17.80	0.12	Villawood	MW49	1	19.70	18.91	0.80	Villawood
MW109D	1	20.59	19.85	0.12	Chester Hill	BP103	2	18.92	19.87	-0.95	Villawood
MW239S	1	20.97	19.85	0.12	Chester Hill	BP102	3	18.04	19.14	-1.10	Villawood
OS06B	2	15.55	15.67	-0.12	Villawood	BP101	3	18.46	19.65	-1.19	Villawood
ML235/1	1	21.02	19.89	0.13	Chester Hill	BP104	2	17.97	19.27	-1.30	Villawood
MW40	1	16.28	16.41	-0.13	Villawood	MW11	2	22.09	19.20	1.44	Villawood
ML234/1	1	21.06	19.90	0.13	Chester Hill	MW10	2	16.03	19.20	-1.59	Villawood
MW107D	1	19.37	19.63	-0.13	Chester Hill	MW259S	1	18.41	20.02	-1.61	Chester Hill
MW43B	1	17.08	17.61	-0.13	Villawood	MW4	1	26.48	24.77	1.71	Villawood
MW44C	2	17.66	17.80	-0.14	Villawood	BP102	2	18.04	19.78	-1.74	Villawood
ML236/1	1	21.25	19.83	0.16	Chester Hill	MW18	1	24.47	22.66	1.81	Villawood
MW45	1	17.01	17.16	-0.16	Villawood	MW28	1	14.82	16.80	-1.98	Villawood
OS07A	1	16.11	15.95	0.16	Villawood	MW18	2	24.47	22.06	2.41	Villawood
MW30	1	16.37	16.53	-0.16	Villawood	MW16	2	19.11	21.59	-2.48	Villawood
MW38	1	18.47	18.79	-0.16	Villawood	BP101	2	18.46	21.14	-2.68	Villawood
MW46A	1	15.95	16.31	-0.18	Villawood	MW3	2	22.27	19.52	2.75	Villawood
MW47	1	18.41	18.77	-0.18	Villawood	MW16	1	19.11	21.93	-2.82	Villawood
ML246/1	1	21.00	20.05	0.19	Chester Hill	MW15	1	27.41	24.54	2.87	Villawood
MW109S	1	21.01	19.86	0.19	Chester Hill	BP106	3	18.91	22.10	-3.19	Villawood
ML238/1	1	20.93	19.97	0.19	Chester Hill	MW15	2	27.41	23.65	3.76	Villawood
OS09A	1	18.78	18.40	0.19	Villawood	MW2	1	24.35	19.94	4.41	Villawood
MW37	1	18.94	18.74	0.20	Villawood	BP106	2	18.91	24.12	-5.21	Villawood

Table 5.2.4-2. Recharge scenario 2 comparison of measured and model-predicted water levels.

Name	Layer	Target	Model	Residual	Site	Name	Layer	Target	Model	Residual	Site
MW228S	1	20.34	20.34	0.00	Chester Hill	MW46B	1	15.83	16.25	-0.21	Villawood
OS03B	1	18.34	18.34	0.00	Villawood	BP105	2	18.48	18.70	-0.22	Villawood
MW105S	1	20.13	20.14	0.00	Chester Hill	OS09A	1	18.78	18.35	0.22	Villawood
BP103	3	18.92	18.91	0.01	Villawood	MW44C	2	17.66	17.88	-0.22	Villawood
MW33	1	17.21	17.19	0.01	Villawood	MW36	1	19.09	18.64	0.22	Villawood
OS03A	1	18.37	18.35	0.01	Villawood	MW21	2	18.91	18.68	0.22	Villawood
MW52	2	18.86	18.80	0.01	Villawood	MW50	1	19.37	18.92	0.23	Villawood
OS06A	2	15.63	15.65	-0.02	Villawood	MW7	2	19.00	18.76	0.24	Villawood
ML246/1	1	21.00	20.90	0.02	Chester Hill	MW20	1	18.87	18.62	0.24	Villawood
MW244S	1	20.09	20.15	-0.02	Chester Hill	MW38	1	18.47	18.96	-0.25	Villawood
MW40	1	16.28	16.30	-0.02	Villawood	OS09B	1	17.85	18.34	-0.25	Villawood
MW39	1	18.46	18.52	-0.03	Villawood	MW47	1	18.41	18.96	-0.28	Villawood
MW53A	2	18.90	18.78	0.03	Villawood	MW103D	1	20.69	19.84	0.28	Chester Hill
MW109D	1	20.59	20.40	0.03	Chester Hill	MW78	1	17.82	17.54	0.28	Villawood
MW238D	1	20.59	20.63	-0.03	Chester Hill	MW35	1	19.01	18.42	0.29	Villawood
MW108S	1	20.27	19.97	0.03	Chester Hill	MW41	1	16.37	17.55	-0.30	Villawood
MW106D	1	20.58	20.25	0.04	Chester Hill	MW14	1	18.77	18.48	0.30	Villawood
MW201S	1	20.47	20.72	-0.04	Chester Hill	MW111D	1	20.17	19.57	0.30	Chester Hill
MW102S	1	20.86	20.82	0.04	Chester Hill	MW13	1	18.77	18.48	0.30	Villawood
MW201D	1	20.45	20.73	-0.05	Chester Hill	OS05A	1	17.31	17.01	0.30	Villawood
MW23	1	16.19	16.09	0.05	Villawood	ML237/1	1	21.88	20.05	0.30	Chester Hill
BP104	3	17.97	18.02	-0.05	Villawood	OS02B	1	19.01	18.40	0.31	Villawood
MW104S	1	20.35	20.07	0.05	Chester Hill	MW108D	1	17.19	19.96	-0.31	Chester Hill
MW106S	1	20.79	20.27	0.06	Chester Hill	MW230D	1	17.37	20.40	-0.34	Chester Hill
MW22	2	18.88	18.82	0.06	Villawood	MW31	1	17.74	17.40	0.34	Villawood
MW103S	1	20.02	19.83	0.06	Chester Hill	MW22	1	18.88	19.23	-0.35	Villawood
MW29	1	16.19	16.13	0.06	Villawood	MW42	1	16.07	17.47	-0.35	Villawood
MW24	1	16.21	16.08	0.07	Villawood	MW6	1	18.80	18.45	0.35	Villawood
OS04A	1	17.87	17.94	-0.07	Villawood	MW77	1	17.59	17.21	0.38	Villawood
MW53B	2	18.48	18.77	-0.07	Villawood	MW8	1	18.55	18.17	0.38	Villawood
MW44B	1	18.05	17.90	0.08	Villawood	MW107S	1	20.58	19.78	0.40	Chester Hill
OS06C	1	16.04	15.96	0.08	Villawood	MW5	2	18.06	18.48	-0.42	Villawood
MW44A	1	18.04	17.88	0.08	Villawood	MW32	1	17.97	17.51	0.46	Villawood
ML235/1	1	21.02	20.26	0.08	Chester Hill	MW27	1	17.00	16.52	0.48	Villawood
MW25	1	15.90	16.08	-0.09	Villawood	MW46C	2	16.99	16.46	0.53	Villawood
MW101S	1	21.81	21.90	-0.09	Chester Hill	MW49	1	19.70	19.09	0.61	Villawood
MW239S	1	20.97	20.16	0.09	Chester Hill	OS10A	1	16.34	16.96	-0.62	Villawood
MW43C	2	17.61	17.71	-0.09	Villawood	OS01A	1	19.66	18.36	0.65	Villawood
OS06B	2	15.55	15.65	-0.10	Villawood	MW229S	1	20.60	19.93	0.67	Chester Hill
MW109S	1	21.01	20.43	0.10	Chester Hill	MW34	1	18.97	18.25	0.72	Villawood
MW43A	1	18.04	17.64	0.10	Villawood	MW1	1	19.16	18.41	0.75	Villawood
MW26	1	15.93	16.13	-0.10	Villawood	OS08A	1	19.10	18.33	0.77	Villawood
ML234/1	1	21.06	20.09	0.11	Chester Hill	BP102	3	18.04	18.84	-0.80	Villawood
ML236/1	1	21.25	20.28	0.11	Chester Hill	MW4	1	26.48	25.58	0.90	Villawood
ML238/1	1	20.93	20.33	0.12	Chester Hill	BP101	3	18.46	19.37	-0.91	Villawood
OS07A	1	16.11	15.99	0.12	Villawood	MW11	2	22.09	19.33	1.38	Villawood
OS01B	1	18.62	18.36	0.13	Villawood	MW18	1	24.47	22.99	1.48	Villawood
MW30	1	16.37	16.50	-0.13	Villawood	MW259S	1	18.41	19.90	-1.49	Chester Hill
MW51	1	18.34	18.62	-0.14	Villawood	BP104	2	17.97	19.48	-1.51	Villawood
MW37	1	18.94	18.79	0.15	Villawood	MW10	2	16.03	19.33	-1.65	Villawood
MW43B	1	17.08	17.67	-0.15	Villawood	BP103	2	18.92	20.60	-1.68	Villawood
MW19	2	18.82	18.67	0.15	Villawood	MW16	2	19.11	21.08	-1.97	Villawood
OS02A	1	18.70	18.40	0.15	Villawood	MW28	1	14.82	16.79	-1.97	Villawood
MW241S	1	21.09	20.18	0.15	Chester Hill	MW15	1	27.41	25.26	2.16	Villawood
MW46A	1	15.95	16.25	-0.15	Villawood	MW3	2	22.27	20.05	2.22	Villawood
MW45	1	17.01	17.16	-0.16	Villawood	MW18	2	24.47	21.94	2.53	Villawood
MW48	1	18.85	19.17	-0.16	Villawood	BP102	2	18.04	20.58	-2.54	Villawood
OS07B	2	16.15	15.99	0.16	Villawood	MW16	1	19.11	21.80	-2.69	Villawood
MW48	2	18.85	18.69	0.17	Villawood	BP101	2	18.46	21.33	-2.87	Villawood
MW53C	2	18.09	18.77	-0.17	Villawood	BP106	3	18.91	21.89	-2.98	Villawood
MW111S	1	19.93	19.58	0.17	Chester Hill	MW2	1	24.35	20.52	3.83	Villawood
MW17	1	18.63	18.44	0.18	Villawood	MW15	2	27.41	23.13	4.28	Villawood
MW107D	1	19.37	19.78	-0.20	Chester Hill	BP106	2	18.91	23.39	-4.48	Villawood

Table 5.2.4-3. Recharge scenario 3 comparison of measured and model-predicted water levels.

Well/Piezometer	Layer	Target	Model	Residual	Site	Well/Piezometer	Layer	Target	Model	Residual	Site
MW244S	1	20.09	20.10	-0.01	Chester Hill	MW32	1	17.97	17.58	0.39	Villawood
MW40	1	16.28	16.30	-0.02	Villawood	MW77	1	17.59	17.19	0.40	Villawood
MW53A	2	18.90	18.87	0.02	Villawood	MW27	1	17.00	16.59	0.41	Villawood
MW52	2	18.86	18.88	-0.03	Villawood	MW46C	2	16.99	16.56	0.43	Villawood
MW22	2	18.88	18.91	-0.03	Villawood	MW46B	1	15.83	16.26	-0.43	Villawood
OS06A	2	15.63	15.67	-0.04	Villawood	MW107D	1	19.37	19.83	-0.46	Chester Hill
MW105S	1	20.13	20.08	0.06	Chester Hill	MW108S	1	20.27	19.80	0.47	Chester Hill
MW37	1	18.94	18.88	0.06	Villawood	MW5	2	18.06	18.54	-0.48	Villawood
MW238D	1	20.59	20.65	-0.06	Chester Hill	MW39	1	18.46	18.95	-0.49	Villawood
MW33	1	17.21	17.27	-0.06	Villawood	MW106D	1	20.58	20.09	0.49	Chester Hill
MW17	1	18.63	18.56	0.06	Villawood	BP105	2	18.48	19.00	-0.52	Villawood
MW19	2	18.82	18.75	0.07	Villawood	MW111D	1	20.17	19.64	0.52	Chester Hill
MW103S	1	20.02	19.94	0.07	Chester Hill	MW51	1	18.34	18.88	-0.54	Villawood
MW101S	1	21.81	21.88	-0.07	Chester Hill	OS02B	1	19.01	18.46	0.55	Villawood
MW29	1	16.19	16.11	0.08	Villawood	MW35	1	19.01	18.46	0.55	Villawood
OS03A	1	18.37	18.46	-0.09	Villawood	MW109D	1	20.59	20.02	0.57	Chester Hill
OS06C	1	16.04	15.95	0.09	Villawood	OS10A	1	16.34	16.91	-0.57	Villawood
MW45	1	17.01	17.10	-0.09	Villawood	MW15	1	27.41	26.84	0.57	Villawood
MW21	2	18.91	18.80	0.10	Villawood	OS09B	1	17.85	18.43	-0.58	Villawood
MW4	1	26.48	26.58	-0.10	Villawood	MW43B	1	17.08	17.72	-0.64	Villawood
OS03B	1	18.34	18.45	-0.11	Villawood	MW229S	1	20.60	19.95	0.64	Chester Hill
OS04A	1	17.87	17.99	-0.12	Villawood	MW34	1	18.97	18.30	0.67	Villawood
MW23	1	16.19	16.07	0.12	Villawood	MW106S	1	20.79	20.09	0.70	Chester Hill
MW48	2	18.85	18.97	-0.12	Villawood	BP101	3	18.46	19.17	-0.71	Villawood
OS07B	2	16.15	16.03	0.12	Villawood	BP102	3	18.04	18.75	-0.71	Villawood
OS06B	2	15.55	15.67	-0.12	Villawood	MW103D	1	20.69	19.95	0.74	Chester Hill
MW25	1	15.90	16.03	-0.13	Villawood	MW107S	1	20.58	19.83	0.75	Chester Hill
MW78	1	17.82	17.69	0.13	Villawood	ML246/1	1	21.00	20.23	0.77	Chester Hill
MW44B	1	18.05	17.92	0.13	Villawood	OS08A	1	19.10	18.33	0.78	Villawood
BP104	3	17.97	18.10	-0.13	Villawood	MW53C	2	18.09	18.86	-0.78	Villawood
MW102S	1	20.86	20.72	0.14	Chester Hill	ML238/1	1	20.93	20.12	0.81	Chester Hill
MW20	1	18.87	18.73	0.14	Villawood	MW48	1	18.85	19.67	-0.82	Villawood
OS07A	1	16.11	15.97	0.14	Villawood	MW38	1	18.47	19.41	-0.94	Villawood
MW44A	1	18.44	17.90	0.14	Villawood	ML235/1	1	21.02	20.08	0.94	Chester Hill
MW30	1	16.37	16.52	-0.15	Villawood	MW239S	1	20.97	20.02	0.94	Chester Hill
MW7	2	19.00	18.85	0.15	Villawood	MW109S	1	21.01	20.03	0.98	Chester Hill
BP103	3	18.92	18.76	0.16	Villawood	ML234/1	1	21.06	20.02	1.04	Chester Hill
MW43C	2	17.61	17.77	-0.16	Villawood	MW47	1	18.41	19.57	-1.16	Villawood
MW24	1	16.21	16.05	0.16	Villawood	MW18	1	24.47	23.26	1.21	Villawood
MW50	1	19.37	19.20	0.17	Villawood	BP103	2	18.92	20.13	-1.21	Villawood
MW1	1	19.16	18.98	0.18	Villawood	ML236/1	1	21.25	20.03	1.22	Chester Hill
MW26	1	15.93	16.11	-0.18	Villawood	OS01A	1	19.66	18.42	1.24	Villawood
MW14	1	18.77	18.59	0.18	Villawood	MW41	1	16.37	17.62	-1.25	Villawood
MW13	1	18.77	18.58	0.19	Villawood	MW241S	1	21.09	19.81	1.29	Chester Hill
OS05A	1	17.31	17.12	0.19	Villawood	BP104	2	17.97	19.41	-1.44	Villawood
MW49	1	19.70	19.50	0.20	Villawood	MW42	1	16.07	17.55	-1.47	Villawood
OS01B	1	18.62	18.42	0.21	Villawood	MW259S	1	18.41	20.00	-1.59	Chester Hill
MW228S	1	20.34	20.12	0.22	Chester Hill	MW18	2	24.47	22.57	1.90	Villawood
OS02A	1	18.70	18.47	0.24	Villawood	MW28	1	14.82	16.75	-1.93	Villawood
MW6	1	18.80	18.55	0.25	Villawood	ML237/1	1	21.88	19.75	2.13	Chester Hill
MW31	1	17.74	17.47	0.26	Villawood	BP102	2	18.04	20.23	-2.19	Villawood
MW44C	2	17.66	17.93	-0.26	Villawood	MW16	2	19.11	21.33	-2.21	Villawood
MW111S	1	19.93	19.65	0.28	Chester Hill	BP106	3	18.91	21.46	-2.55	Villawood
MW201D	1	20.45	20.14	0.31	Chester Hill	MW3	2	22.27	19.67	2.60	Villawood
MW104S	1	20.35	20.02	0.32	Chester Hill	MW108D	1	17.19	19.80	-2.61	Chester Hill
MW46A	1	15.95	16.27	-0.33	Villawood	MW230D	1	17.37	20.11	-2.74	Chester Hill
MW201S	1	20.47	20.14	0.34	Chester Hill	BP101	2	18.46	21.21	-2.75	Villawood
MW8	1	18.55	18.21	0.34	Villawood	MW11	2	22.09	19.34	2.75	Villawood
MW43A	1	18.04	17.69	0.35	Villawood	MW16	1	19.11	22.03	-2.92	Villawood
OS09A	1	18.78	18.43	0.35	Villawood	MW10	2	16.03	19.34	-3.31	Villawood
MW22	1	18.88	19.25	-0.37	Villawood	MW15	2	27.41	23.66	3.75	Villawood
MW36	1	19.09	18.71	0.38	Villawood	MW2	1	24.35	20.02	4.33	Villawood
MW53B	2	18.48	18.87	-0.39	Villawood	BP106	2	18.91	23.49	-4.58	Villawood

Table 5.2.4-4. Recharge scenario 4 comparison of measured and model-predicted water levels.

Well/Piezometer	Layer	Target	Model	Residual	Site	Well/Piezometer	Layer	Target	Model	Residual	Site
MW244S	1	20.09	20.10	-0.01	Chester Hill	MW32	1	17.97	17.58	0.39	Villawood
MW40	1	16.28	16.30	-0.02	Villawood	MW77	1	17.59	17.19	0.40	Villawood
MW53A	2	18.90	18.87	0.02	Villawood	MW27	1	17.00	16.59	0.41	Villawood
MW52	2	18.86	18.88	-0.03	Villawood	MW46C	2	16.99	16.56	0.43	Villawood
MW22	2	18.88	18.91	-0.03	Villawood	MW46B	1	15.83	16.26	-0.43	Villawood
OS06A	2	15.63	15.67	-0.04	Villawood	MW107D	1	19.37	19.83	-0.46	Chester Hill
MW105S	1	20.13	20.08	0.06	Chester Hill	MW108S	1	20.27	19.80	0.47	Chester Hill
MW37	1	18.94	18.88	0.06	Villawood	MW5	2	18.06	18.54	-0.48	Villawood
MW238D	1	20.59	20.65	-0.06	Chester Hill	MW39	1	18.46	18.95	-0.49	Villawood
MW33	1	17.21	17.27	-0.06	Villawood	MW106D	1	20.58	20.09	0.49	Chester Hill
MW17	1	18.63	18.56	0.06	Villawood	BP105	2	18.48	19.00	-0.52	Villawood
MW19	2	18.82	18.75	0.07	Villawood	MW111D	1	20.17	19.64	0.52	Chester Hill
MW103S	1	20.02	19.94	0.07	Chester Hill	MW51	1	18.34	18.88	-0.54	Villawood
MW101S	1	21.81	21.88	-0.07	Chester Hill	OS02B	1	19.01	18.46	0.55	Villawood
MW29	1	16.19	16.11	0.08	Villawood	MW35	1	19.01	18.46	0.55	Villawood
OS03A	1	18.37	18.46	-0.09	Villawood	MW109D	1	20.59	20.02	0.57	Chester Hill
OS06C	1	16.04	15.95	0.09	Villawood	OS10A	1	16.34	16.91	-0.57	Villawood
MW45	1	17.01	17.10	-0.09	Villawood	MW15	1	27.41	26.84	0.57	Villawood
MW21	2	18.91	18.80	0.10	Villawood	OS09B	1	17.85	18.43	-0.58	Villawood
MW4	1	26.48	26.58	-0.10	Villawood	MW43B	1	17.08	17.72	-0.64	Villawood
OS03B	1	18.34	18.45	-0.11	Villawood	MW229S	1	20.60	19.95	0.64	Chester Hill
OS04A	1	17.87	17.99	-0.12	Villawood	MW34	1	18.97	18.30	0.67	Villawood
MW23	1	16.19	16.07	0.12	Villawood	MW106S	1	20.79	20.09	0.70	Chester Hill
MW48	2	18.85	18.97	-0.12	Villawood	BP101	3	18.46	19.17	-0.71	Villawood
OS07B	2	16.15	16.03	0.12	Villawood	BP102	3	18.04	18.75	-0.71	Villawood
OS06B	2	15.55	15.67	-0.12	Villawood	MW103D	1	20.69	19.95	0.74	Chester Hill
MW25	1	15.90	16.03	-0.13	Villawood	MW107S	1	20.58	19.83	0.75	Chester Hill
MW78	1	17.82	17.69	0.13	Villawood	ML246/1	1	21.00	20.23	0.77	Chester Hill
MW44B	1	18.05	17.92	0.13	Villawood	OS08A	1	19.10	18.33	0.78	Villawood
BP104	3	17.97	18.10	-0.13	Villawood	MW53C	2	18.09	18.86	-0.78	Villawood
MW102S	1	20.86	20.72	0.14	Chester Hill	ML238/1	1	20.93	20.12	0.81	Chester Hill
MW20	1	18.87	18.73	0.14	Villawood	MW48	1	18.85	19.67	-0.82	Villawood
OS07A	1	16.11	15.97	0.14	Villawood	MW38	1	18.47	19.41	-0.94	Villawood
MW44A	1	18.04	17.90	0.14	Villawood	ML235/1	1	21.02	20.08	0.94	Chester Hill
MW30	1	16.37	16.52	-0.15	Villawood	MW239S	1	20.97	20.02	0.94	Chester Hill
MW7	2	19.00	18.85	0.15	Villawood	MW109S	1	21.01	20.03	0.98	Chester Hill
BP103	3	18.92	18.76	0.16	Villawood	ML234/1	1	21.06	20.02	1.04	Chester Hill
MW43C	2	17.61	17.77	-0.16	Villawood	MW47	1	18.41	19.57	-1.16	Villawood
MW24	1	16.21	16.05	0.16	Villawood	MW18	1	24.47	23.26	1.21	Villawood
MW50	1	19.37	19.20	0.17	Villawood	BP103	2	18.92	20.13	-1.21	Villawood
MW1	1	19.16	18.98	0.18	Villawood	ML236/1	1	21.25	20.03	1.22	Chester Hill
MW26	1	15.93	16.11	-0.18	Villawood	OS01A	1	19.66	18.42	1.24	Villawood
MW14	1	18.77	18.59	0.18	Villawood	MW41	1	16.37	17.62	-1.25	Villawood
MW13	1	18.77	18.58	0.19	Villawood	MW241S	1	21.09	19.81	1.29	Chester Hill
OS05A	1	17.31	17.12	0.19	Villawood	BP104	2	17.97	19.41	-1.44	Villawood
MW49	1	19.70	19.50	0.20	Villawood	MW42	1	16.07	17.55	-1.47	Villawood
OS01B	1	18.62	18.42	0.21	Villawood	MW259S	1	18.41	20.00	-1.59	Chester Hill
MW228S	1	20.34	20.12	0.22	Chester Hill	MW18	2	24.47	22.57	1.90	Villawood
OS02A	1	18.70	18.47	0.24	Villawood	MW28	1	14.82	16.75	-1.93	Villawood
MW6	1	18.80	18.55	0.25	Villawood	ML237/1	1	21.88	19.75	2.13	Chester Hill
MW31	1	17.74	17.47	0.26	Villawood	BP102	2	18.04	20.23	-2.19	Villawood
MW44C	2	17.66	17.93	-0.26	Villawood	MW16	2	19.11	21.33	-2.21	Villawood
MW111S	1	19.93	19.65	0.28	Chester Hill	BP106	3	18.91	21.46	-2.55	Villawood
MW201D	1	20.45	20.14	0.31	Chester Hill	MW3	2	22.27	19.67	2.60	Villawood
MW104S	1	20.35	20.02	0.32	Chester Hill	MW108D	1	17.19	19.80	-2.61	Chester Hill
MW46A	1	15.95	16.27	-0.33	Villawood	MW230D	1	17.37	20.11	-2.74	Chester Hill
MW201S	1	20.47	20.14	0.34	Chester Hill	BP101	2	18.46	21.21	-2.75	Villawood
MW8	1	18.55	18.21	0.34	Villawood	MW11	2	22.09	19.34	2.75	Villawood
MW43A	1	18.04	17.69	0.35	Villawood	MW16	1	19.11	22.03	-2.92	Villawood
OS09A	1	18.78	18.43	0.35	Villawood	MW10	2	16.03	19.34	-3.31	Villawood
MW22	1	18.88	19.25	-0.37	Villawood	MW15	2	27.41	23.66	3.75	Villawood
MW36	1	19.09	18.71	0.38	Villawood	MW2	1	24.35	20.02	4.33	Villawood
MW53B	2	18.48	18.87	-0.39	Villawood	BP106	2	18.91	23.49	-4.58	Villawood

Table 6.1-1. Cross-sectional model hydraulic conductivity combinations.

Model Layer	4-6	7-8
Hydraulic Conductivity, m/d	1×10^{-5} to 1×10^{-2}	1×10^{-5} to 1×10^{-2}

Table 6.1-2. Cross-sectional model water-level elevation calibration targets.

Name	Observed	Layer
MW18	24.47	1
MW36	19.09	1
MW35	19.01	1
MW7	19.00	2
BP106	18.91	3
MW21	18.91	2
MW53A	18.90	2
MW22	18.88	1
MW22	18.88	2
MW52	18.86	2
MW53B	18.48	2
MW53C	18.09	2
BP102	18.04	3
MW45	17.01	1
MW46C	16.99	2
MW30	16.37	1
MW24	16.21	1
MW23	16.19	1
MW29	16.19	1
OS07B	16.15	2
OS07A	16.11	1
MW46A	15.95	1
MW46B	15.83	1
MW28	14.82	1
SYN	14.50	1

Table 6.3-1. Cross-sectional model results for various hydraulic parameter combinations.

Scenario	SDS	Captured by Byrnes Creek	Travel Times, yr				Recharge, mm/yr			Horizontal Hydraulic Conductivity, m/d			Vertical Hydraulic Conductivity, m/d			Drain
			Minimum Layer 1-3	Maximum Layer 1-3	Minimum Layer 4-8	Maximum Layer 4-8	Res.	Parkland	Indust.	Layers 1 - 3	Layers 4 - 6	Layers 7 - 8	Layers 1 - 3	Layers 4 - 6	Layers 7 - 8	
1	50.9	Yes	21	22	25,435	49,281	11	22	5.5	1.46E-01	1.00E-04	1.00E-04	1.46E-02	1.00E-05	1.00E-05	115
2	59.6	Yes	8	9	21,191	37,509	22	55	11	2.85E-01	1.00E-04	1.00E-04	2.85E-02	1.00E-05	1.00E-05	63
3	54.3	Yes	4	4	22,724	41,068	44	110	22	7.51E-01	1.00E-04	1.00E-04	7.51E-02	1.00E-05	1.00E-05	80
4	50.8	Yes	21	21	2,338	3,997	11	22	5.5	1.33E-01	1.00E-03	1.00E-03	1.33E-02	1.00E-04	1.00E-04	4
5	54.5	Yes	7	9	2,278	4,162	22	55	11	3.10E-01	1.00E-03	1.00E-03	3.10E-02	1.00E-04	1.00E-04	301
6	54.3	Yes	4	5	2,264	4,079	44	110	22	6.17E-01	1.00E-03	1.00E-03	6.17E-02	1.00E-04	1.00E-04	104
7	50.1	Yes	25	25	243	402	11	22	5.5	1.12E-01	1.00E-02	1.00E-02	1.12E-02	1.00E-03	1.00E-03	5
8	54.8	Yes	8	9	242	452	22	55	11	3.09E-01	1.00E-02	1.00E-02	3.09E-02	1.00E-03	1.00E-03	111
9	58.1	Yes	4	4	249	471	44	110	22	6.70E-01	1.00E-02	1.00E-02	6.70E-02	1.00E-03	1.00E-03	40
10	50.9	No	20	24	31,759	197,947	11	22	5.5	1.54E-01	1.00E-04	1.00E-04	1.54E-03	1.00E-06	1.00E-06	400
11	53.2	No	9	10	30,664	188,638	22	55	11	3.57E-01	1.00E-04	1.00E-04	3.57E-03	1.00E-06	1.00E-06	14
12	53.4	No	4	5	32,854	191,650	44	110	22	7.76E-01	1.00E-04	1.00E-04	7.76E-03	1.00E-06	1.00E-06	40
13	52.5	No	17	24	3,504	199,863	11	22	5.5	1.68E-01	1.00E-03	1.00E-03	1.68E-03	1.00E-05	1.00E-05	29
14	53.3	No	9	10	2,683	22,231	22	55	11	3.51E-01	1.00E-03	1.00E-03	3.51E-03	1.00E-05	1.00E-05	29
15	54.4	No	4	5	3,231	19,028	44	110	22	7.84E-01	1.00E-03	1.00E-03	7.84E-03	1.00E-05	1.00E-05	400
16	50.8	No	22	25	3,587	2,053	11	22	5.5	1.49E-01	1.00E-02	1.00E-02	1.49E-03	1.00E-04	1.00E-04	400
17	54.8	No	9	11	392	1,936	22	55	11	3.70E-01	1.00E-02	1.00E-02	3.70E-03	1.00E-04	1.00E-04	8
18	53.1	No	4	5	342	1,895	44	110	22	6.92E-01	1.00E-02	1.00E-02	6.92E-03	1.00E-04	1.00E-04	294
19	51.1	Yes	21	21	23,984	320,329	11	22	5.5	1.35E-01	1.00E-04	1.00E-05	1.35E-02	1.00E-05	1.00E-06	6
20	54.6	Yes	8	9	23,546	342,231	22	55	11	3.13E-01	1.00E-04	1.00E-05	3.13E-02	1.00E-05	1.00E-06	365
21	54.9	Yes	4	4	24,093	355,921	44	110	22	6.44E-01	1.00E-04	1.00E-05	6.44E-02	1.00E-05	1.00E-06	44
22	51.9	Yes	17	21	2,415	32,033	11	22	5.5	1.40E-01	1.00E-03	1.00E-04	1.40E-02	1.00E-04	1.00E-05	9
23	54.6	Yes	9	9	2,396	35,044	22	55	11	3.17E-01	1.00E-03	1.00E-04	3.17E-02	1.00E-04	1.00E-05	40
24	54.6	Yes	4	4	2,387	35,044	44	110	22	6.34E-01	1.00E-03	1.00E-04	6.34E-02	1.00E-04	1.00E-05	180
25	50.8	Yes	23	23	247	3,203	11	22	5.5	1.22E-01	1.00E-02	1.00E-03	1.22E-02	1.00E-03	1.00E-05	49
26	54.4	Yes	8	9	244	3,532	22	55	11	3.06E-01	1.00E-02	1.00E-03	3.06E-02	1.00E-03	1.00E-04	35
27	54.8	Yes	4	5	244	3,587	44	110	22	6.32E-01	1.00E-02	1.00E-03	6.32E-02	1.00E-03	1.00E-04	32
28	51.1	Yes	18	21	83,231	112,526	11	22	5.5	1.36E-01	1.00E-05	1.00E-04	1.36E-02	1.00E-06	1.00E-05	58
29	55.7	Yes	9	9	121,561	122,930	22	55	11	3.29E-01	1.00E-05	1.00E-04	3.29E-02	1.00E-06	1.00E-05	3
30	54.5	Yes	4	4	109,514	118,001	44	110	22	6.33E-01	1.00E-05	1.00E-04	6.33E-02	1.00E-06	1.00E-05	400
31	51.0	Yes	18	21	7,830	11,170	11	22	5.5	1.34E-01	1.00E-04	1.00E-03	1.34E-02	1.00E-05	1.00E-04	58
32	55.2	Yes	7	9	12,019	12,183	22	55	11	3.26E-01	1.00E-04	1.00E-03	3.26E-02	1.00E-05	1.00E-04	295
33	54.5	Yes	4	5	10,513	11,663	44	110	22	6.26E-01	1.00E-04	1.00E-03	6.26E-02	1.00E-05	1.00E-04	27
34	51.6	Yes	22	22	802	1,142	11	22	5.5	1.29E-01	1.00E-03	1.00E-02	1.29E-02	1.00E-04	1.00E-03	6
35	54.3	Yes	8	9	1,139	1,205	22	55	11	3.13E-01	1.00E-03	1.00E-02	3.13E-02	1.00E-04	1.00E-03	37
36	54.3	Yes	4	5	1,035	1,172	44	110	22	6.20E-01	1.00E-03	1.00E-02	6.20E-02	1.00E-04	1.00E-03	400

Table 7.2-1. Transport model parameters.

Transport Parameter	Value
Kd (cm ³ /g)	0.66
Bulk Density(g/cm ³)	1.7
Longitudinal Dispersion (m)	0.9
Horizontal Dispersion (m)	0.09
Vertical Dispersion (m)	0.009
Fracture Porosity (-)	0.48%
Bulk Porosity (-)	9%
Organic Carbon Fraction	0.5%
Reaction Rate(d ⁻¹)	200
Mass Transfer Rate(d ⁻¹)	1×10 ⁻⁶

Table 7.5-1. Sensitivity analysis parameter values.

Parameter	Value	Change	Reach Byrnes Creek < 100 years
Kd (L ³ /M)	0.441	50% decrease	No
Fracture Porosity (-)	0.0072	50% increase	No
Fracture Porosity (-)	0.0032	50% decrease	No
Bulk Porosity (-)	0.135	50% increase	No
Bulk Porosity (-)	0.06	50% decrease	No
Reaction Rates (d ⁻¹)	300	50% increase	No
Reaction Rates (d ⁻¹)	100	50% decrease	No
Mass Transfer Rate (d ⁻¹)	10 ⁻⁵	50% increase	No
Mass Transfer Rate (d ⁻¹)	10 ⁻⁷	50% decrease	No
Source Strength (ug/L)	variable	100% increase	No

FIGURES

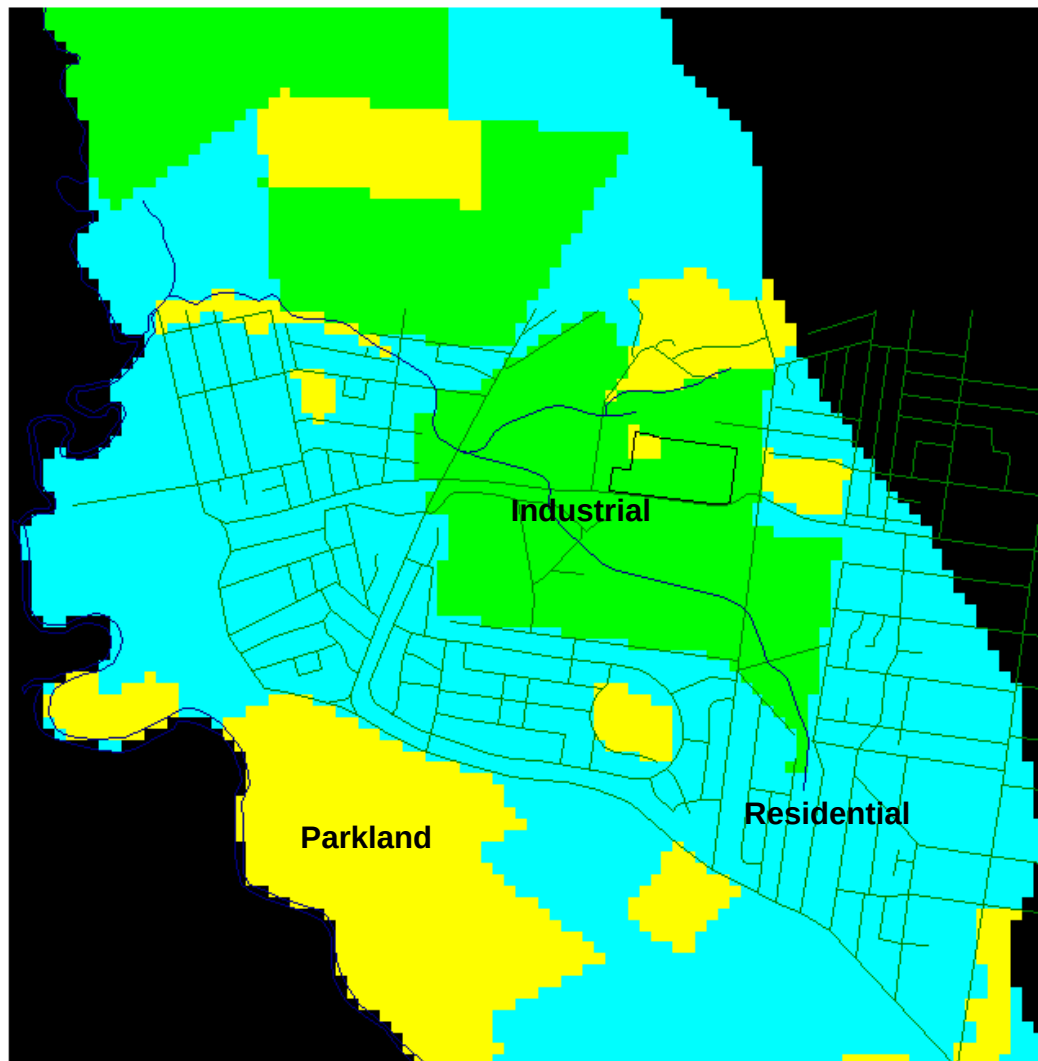


Figure 3.3.1-1. Recharge zoneation.



Figure 3.3.2-1. Byrnes Creek seepage holes.



Figure 3.3.2-2. Groundwater discharge to Byrnes Creek.



Figure 3.3.2-3. Flow in Byrnes Creek.

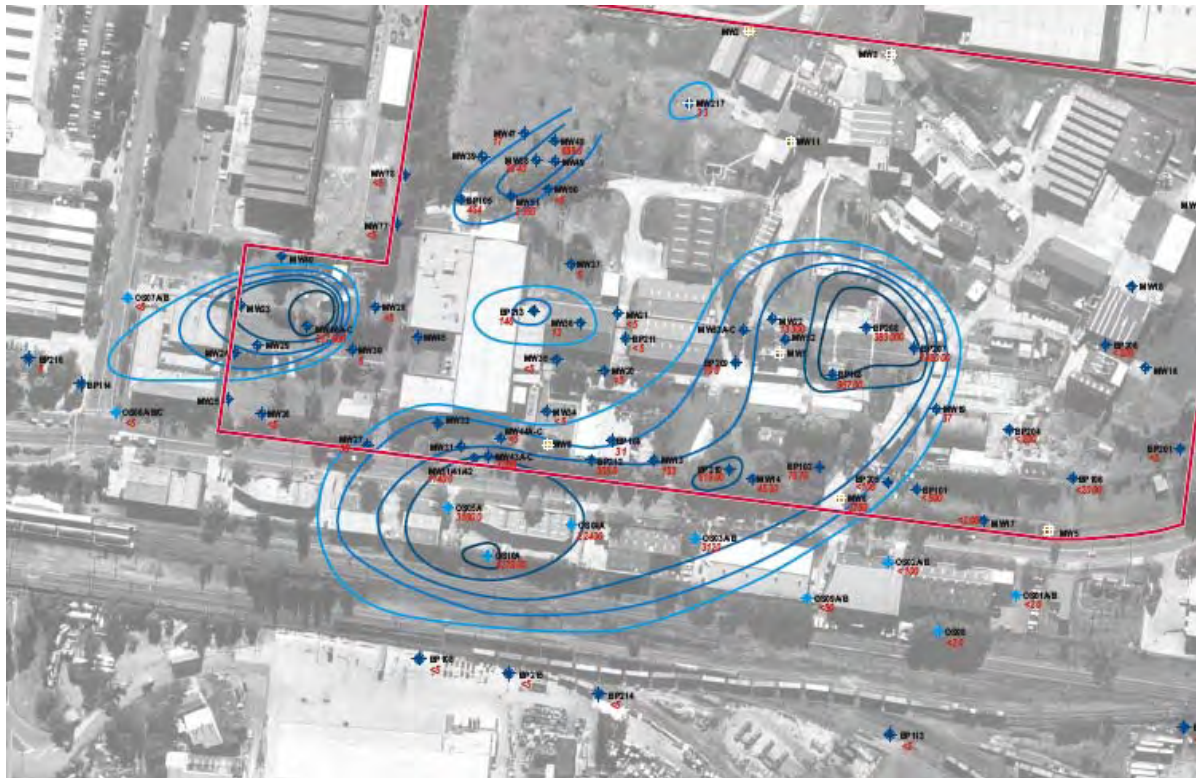


Figure 3.5-1. EDC plumes.

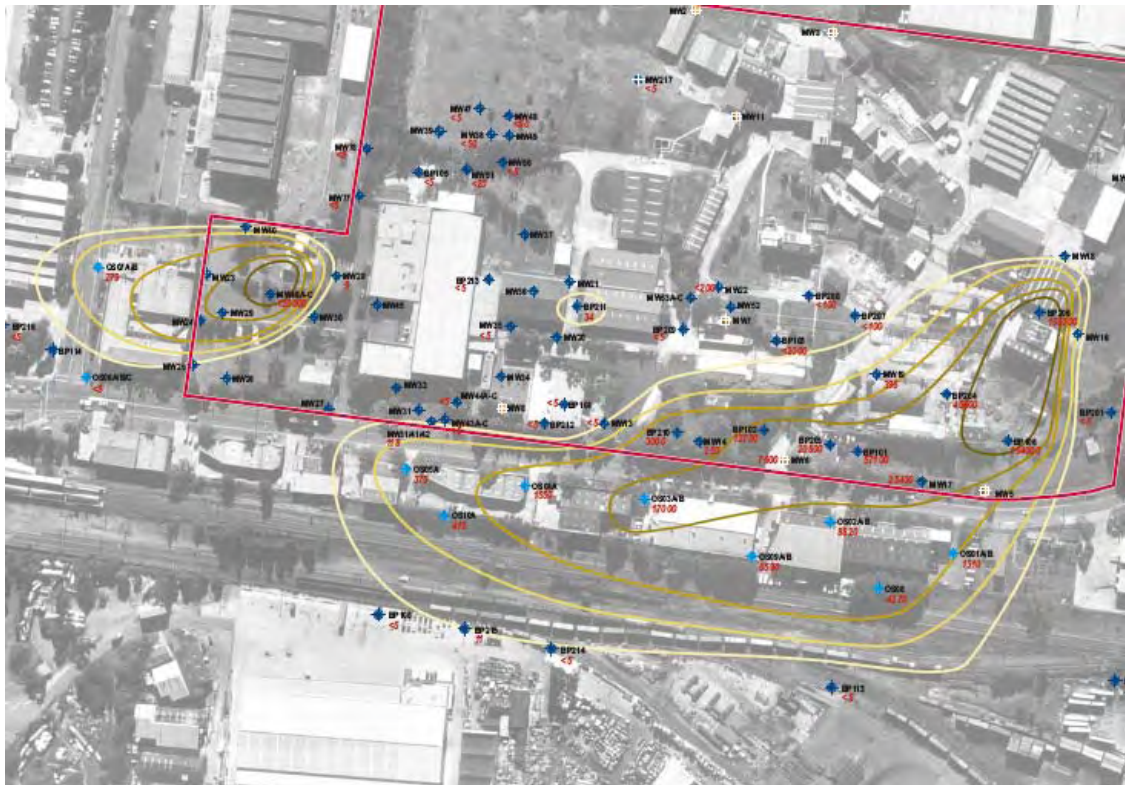


Figure 3.5-2. Chlorobenzene plumes.



Figure 4.1-1. Model horizontal discretization.

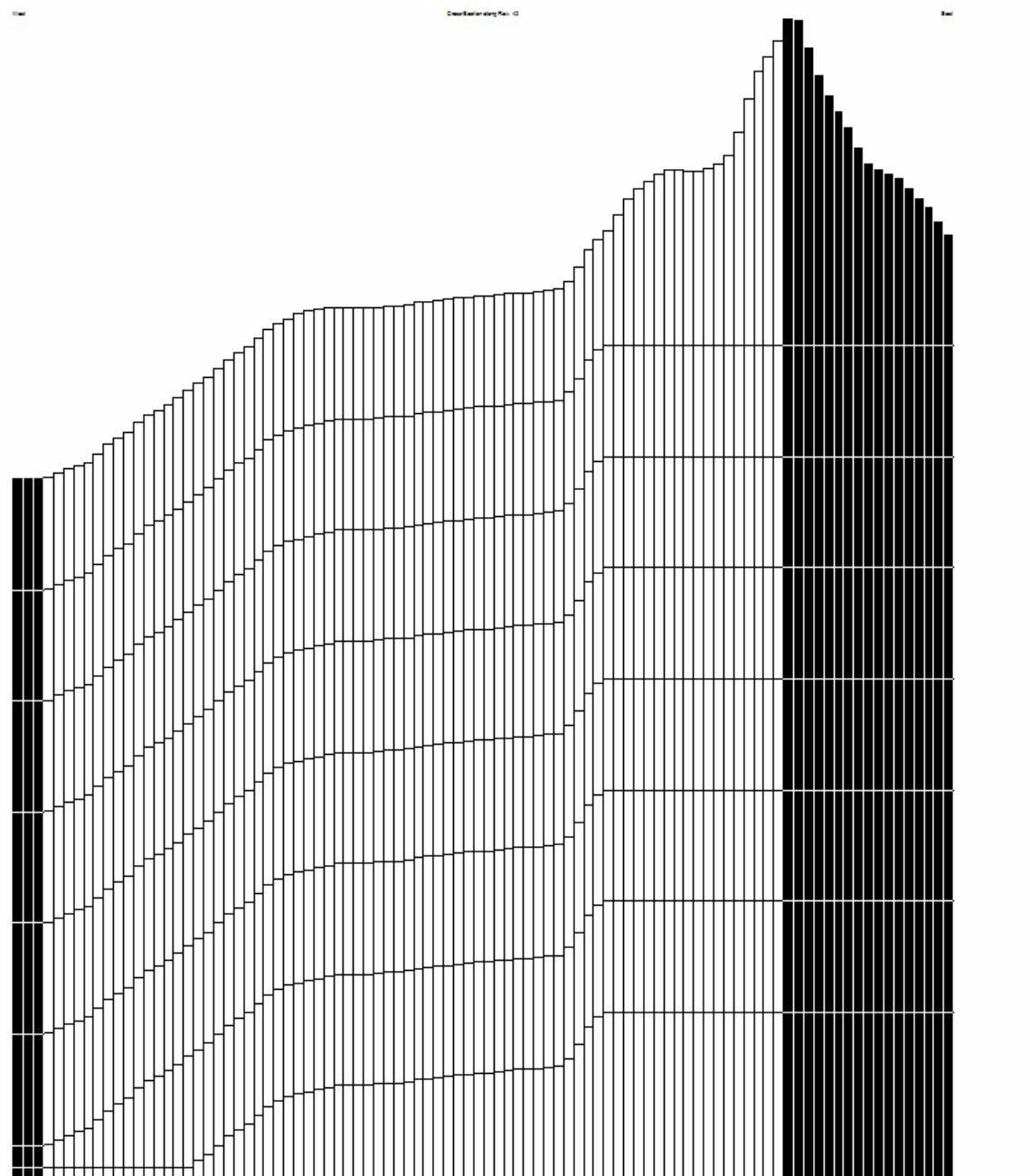


Figure 4.1-2. Model vertical discretization.



Figure 4.2.-1. External and internal Model boundaries.

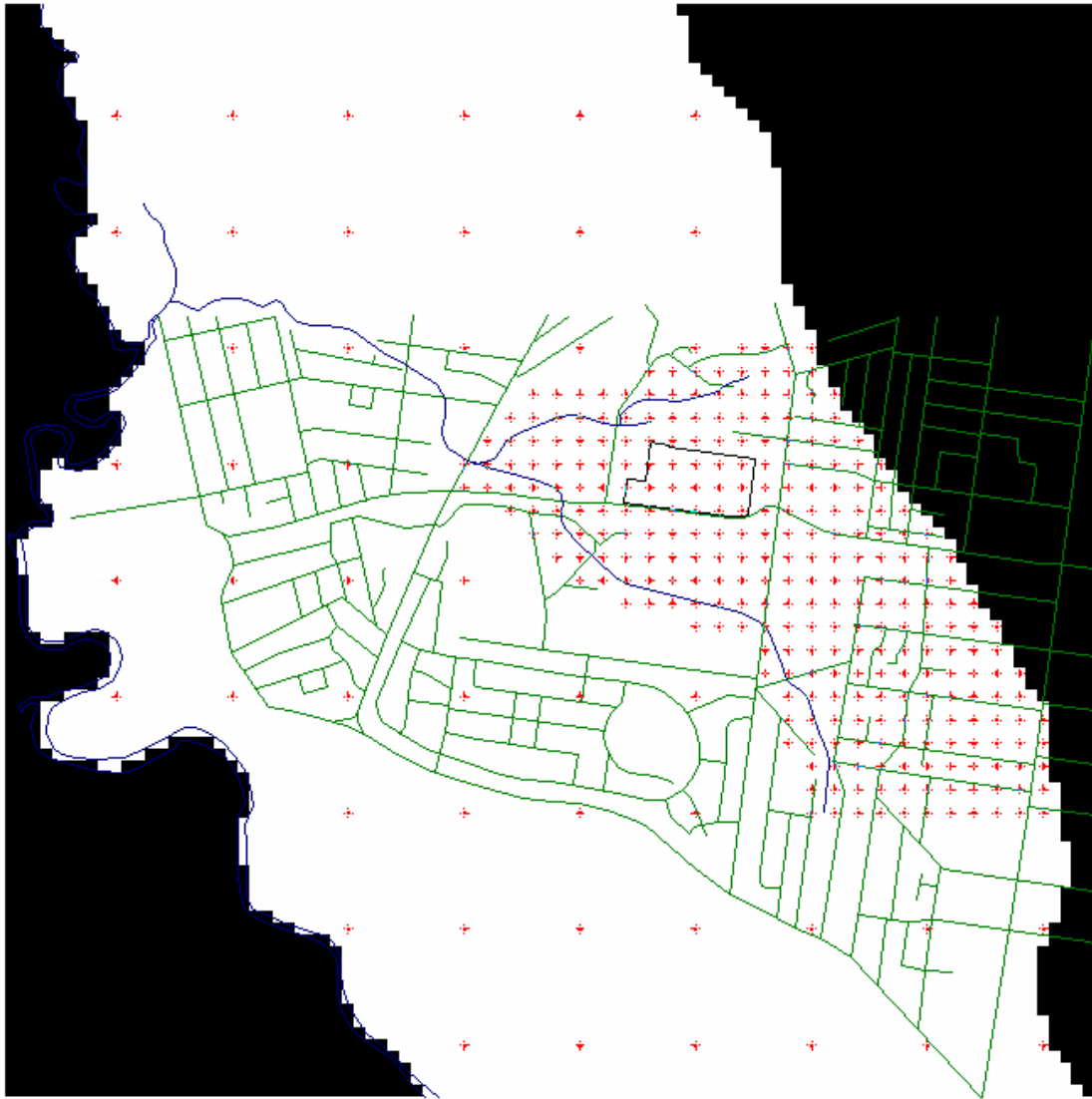


Figure 4.3.1-1. Pilot point locations.

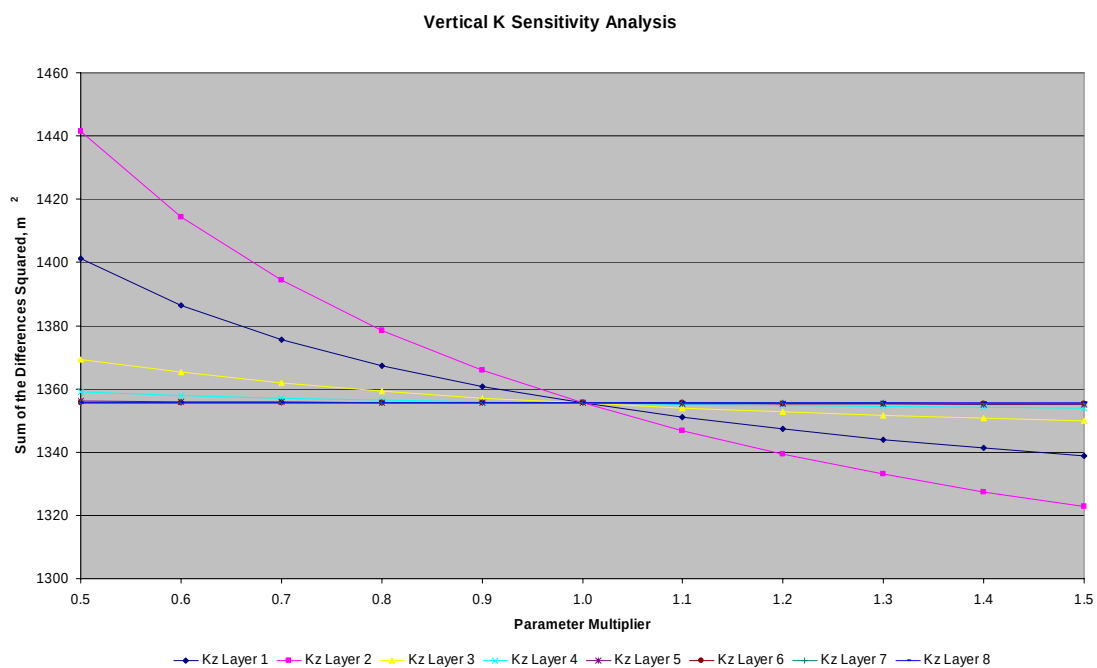
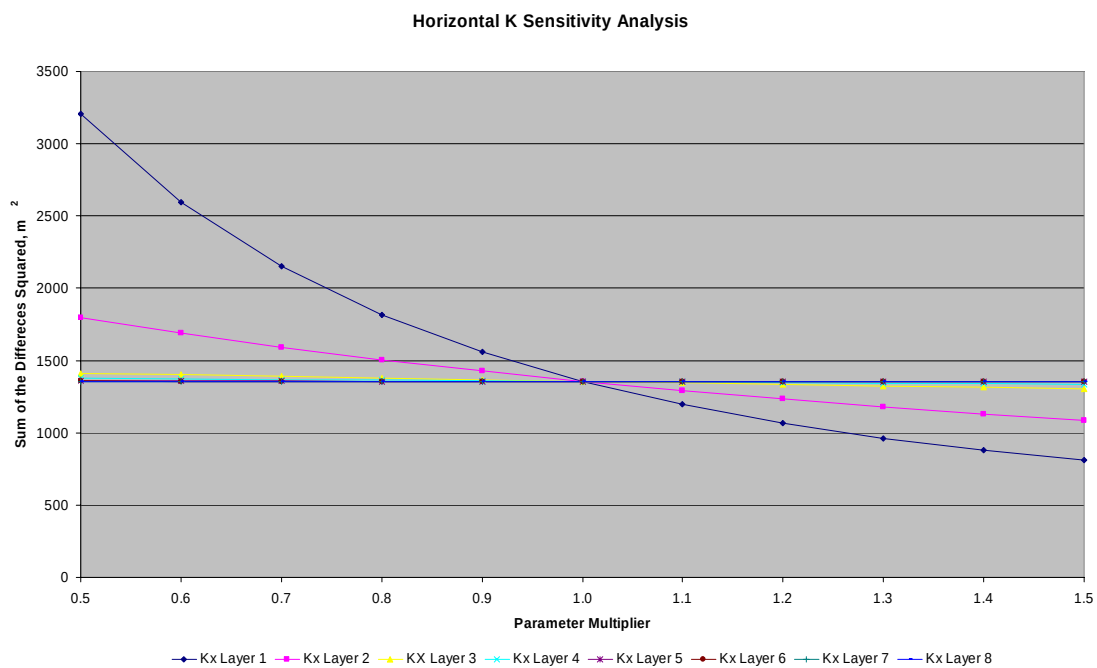


Figure 4.3.1-2. Pre-calibration sensitivity analysis.

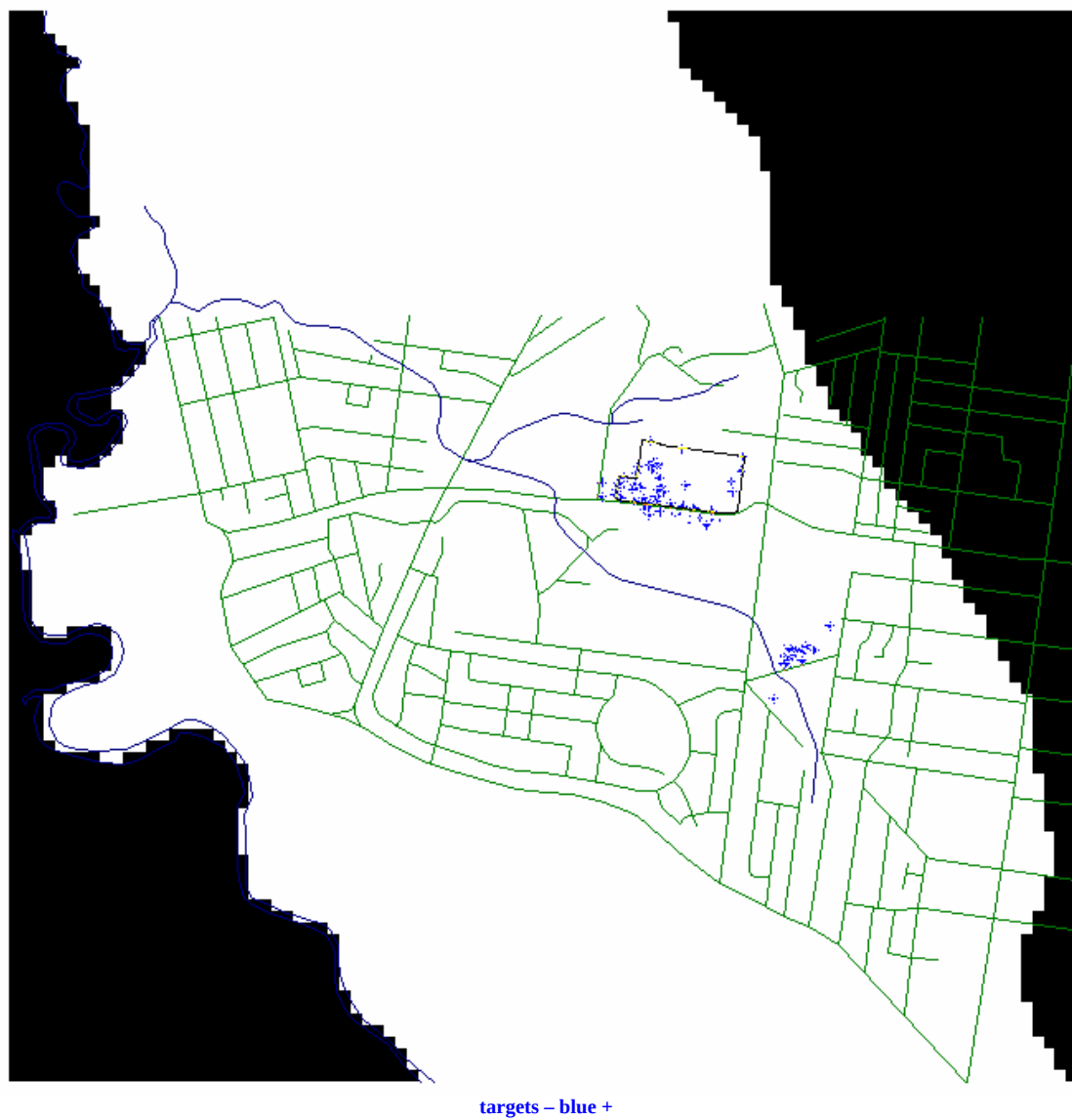


Figure 5.1.1-1. Model layer 1 water-level elevation target locations.

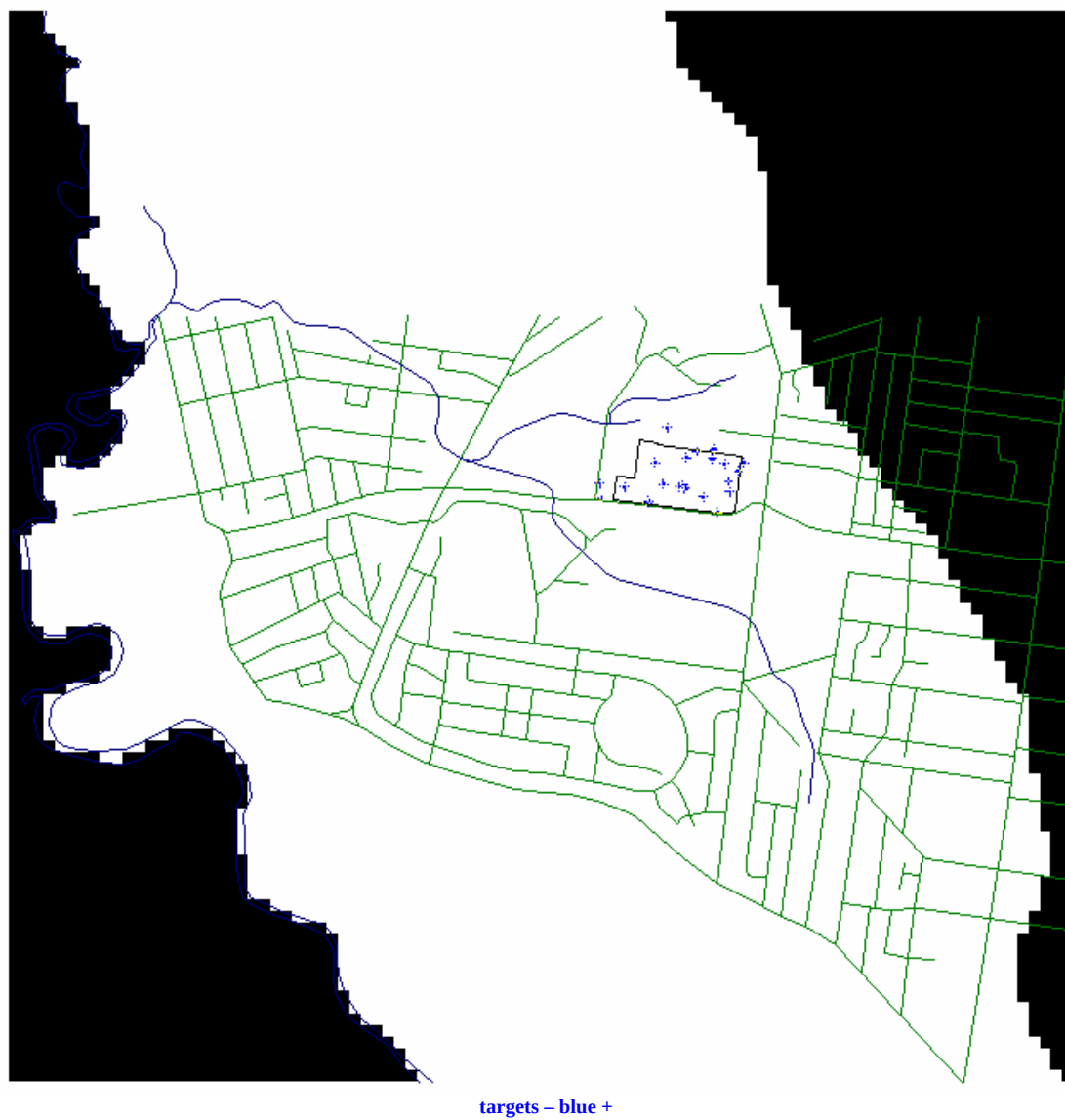


Figure 5.1.1-2. Model layer 2 water-level elevation target locations.

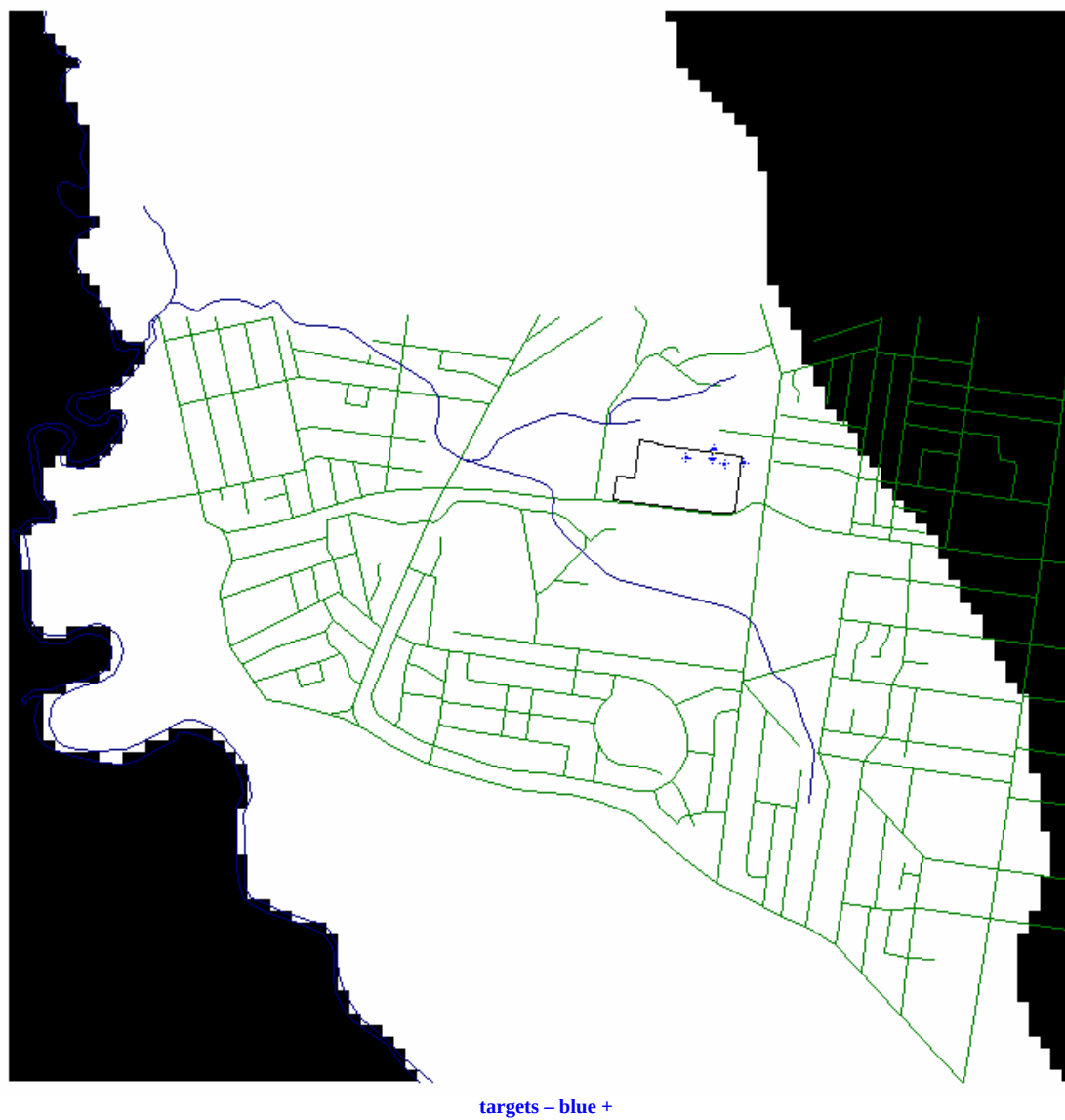


Figure 5.1.1-3. Model layer 3 water-level elevation target locations.

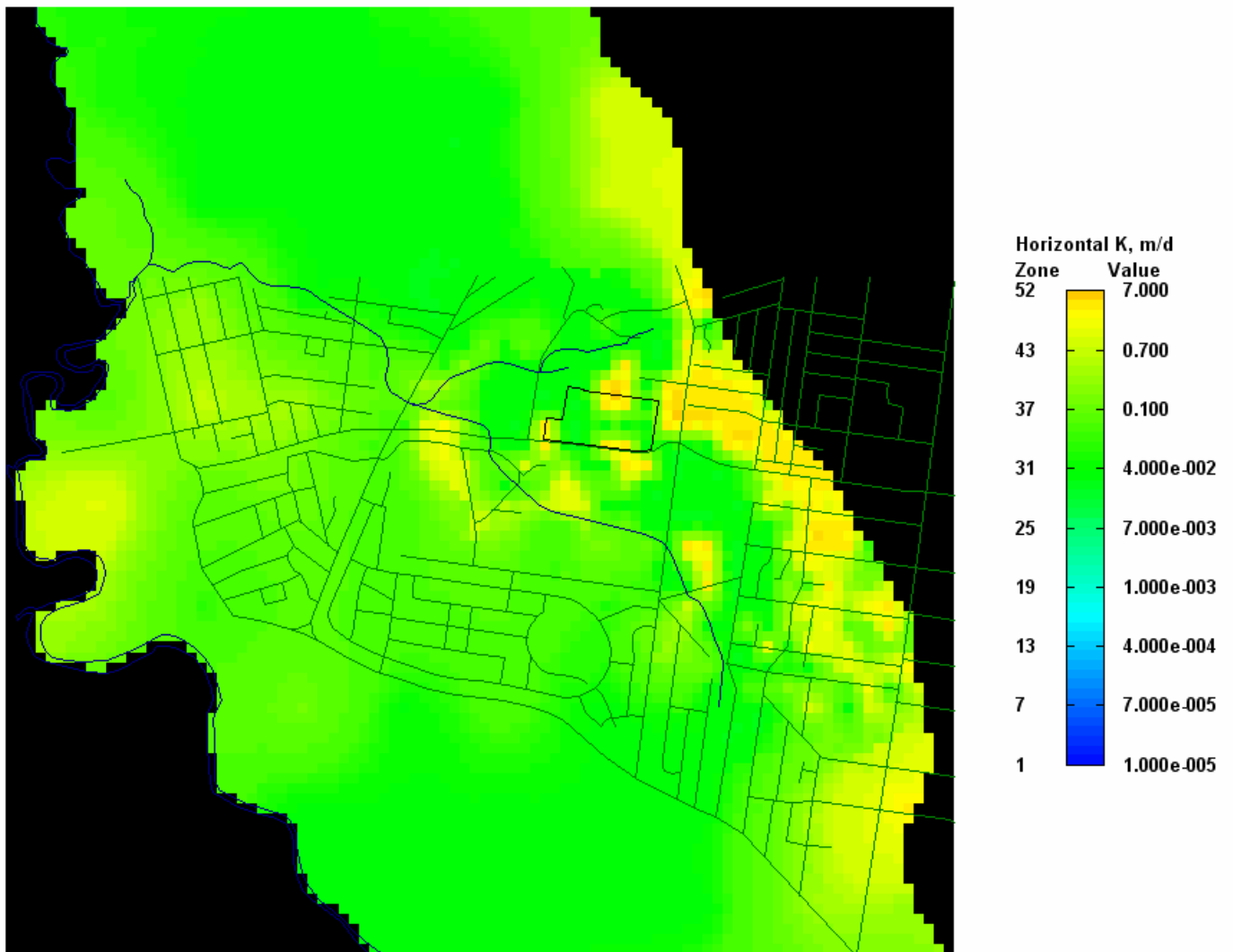


Figure 5.2.1-1. Recharge Scenario 1, model layer 1 horizontal hydraulic conductivity distribution.

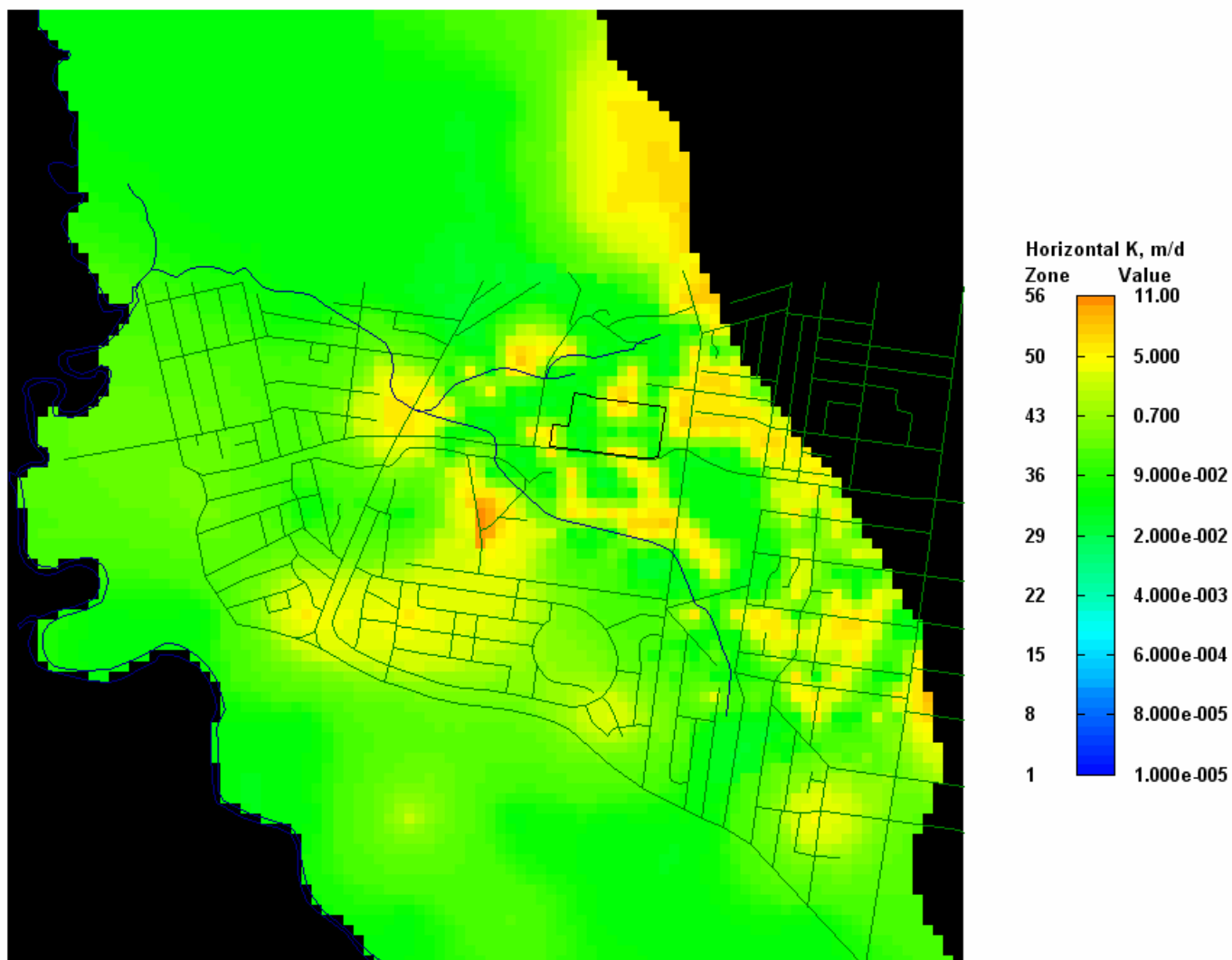


Figure 5.2.1-2. Recharge Scenario 2, model layer 1 horizontal hydraulic conductivity distribution.

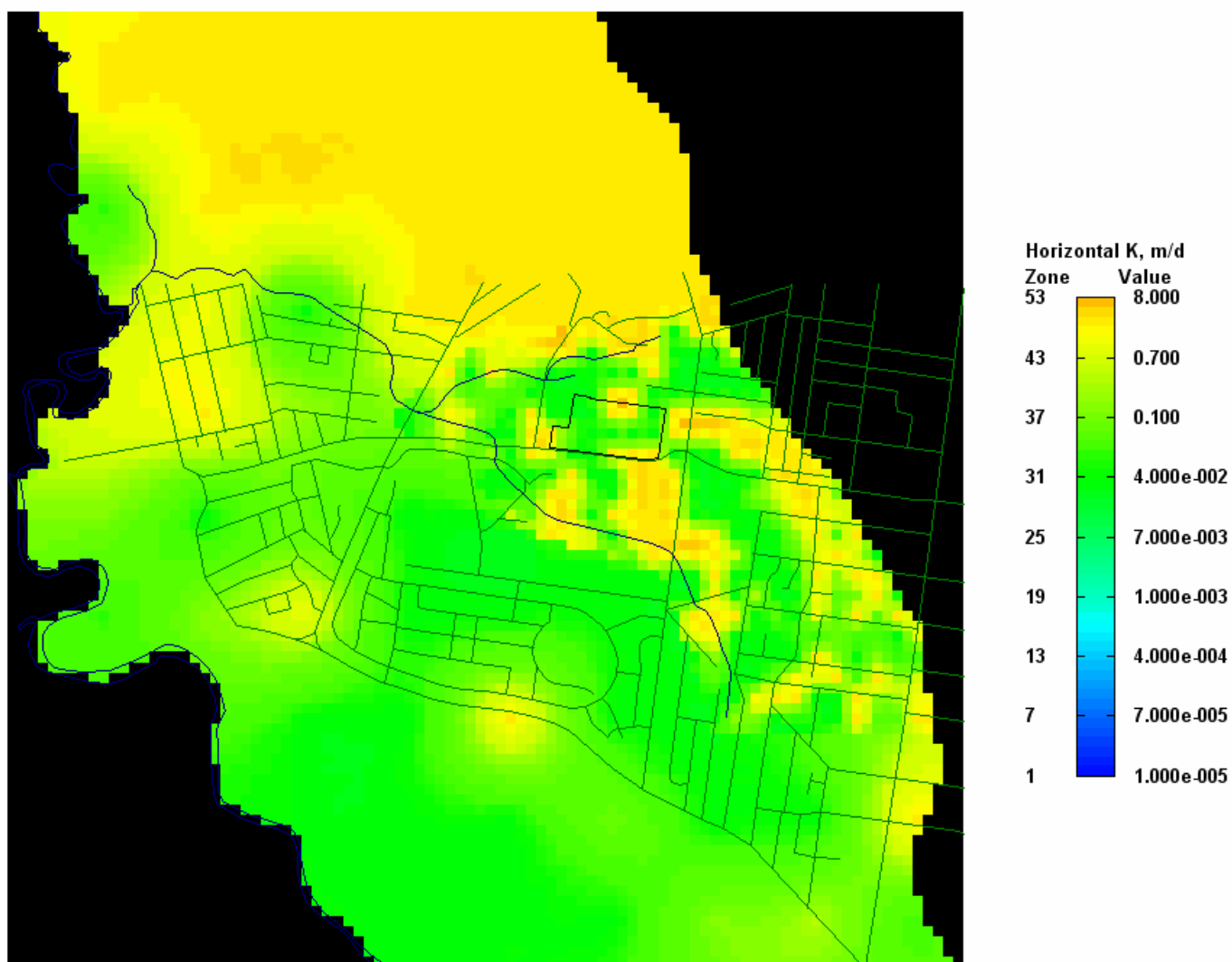


Figure 5.2.1-3. Recharge Scenario 3, model layer 1 horizontal hydraulic conductivity distribution.

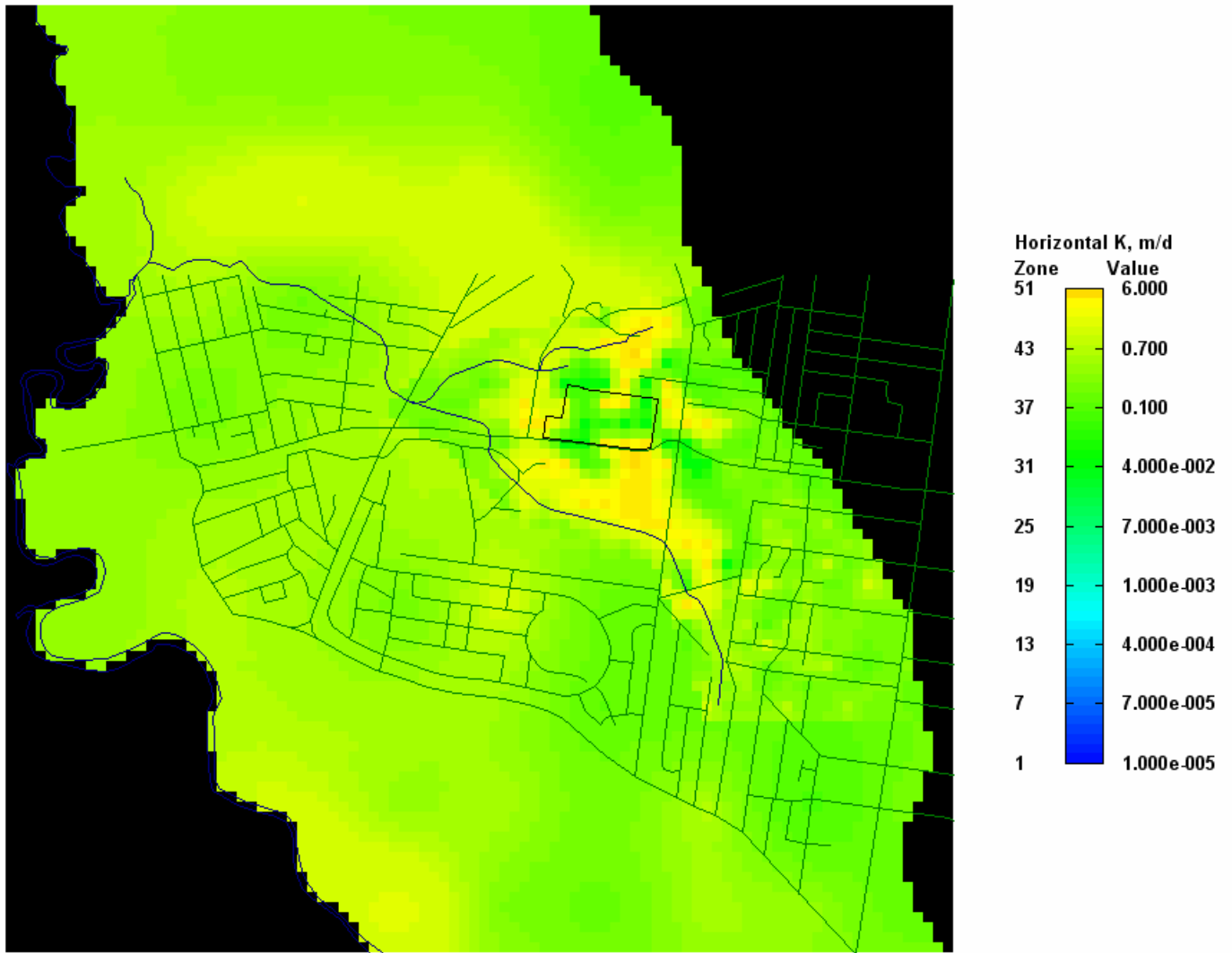


Figure 5.2.1-4. Recharge Scenario 4, model layer 1 horizontal hydraulic conductivity distribution.

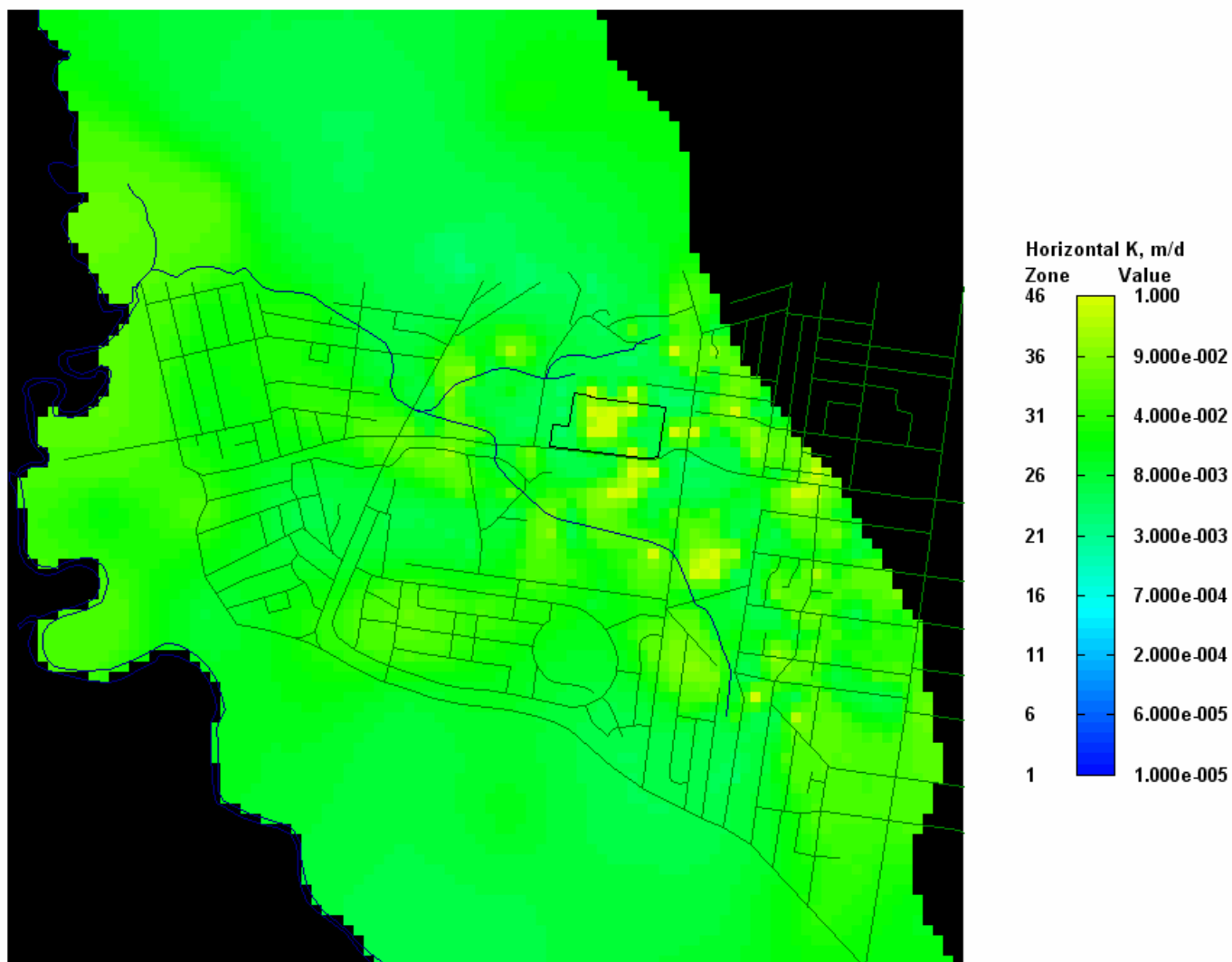


Figure 5.2.1-5. Recharge Scenario 1, model layer 2 horizontal hydraulic conductivity distribution.

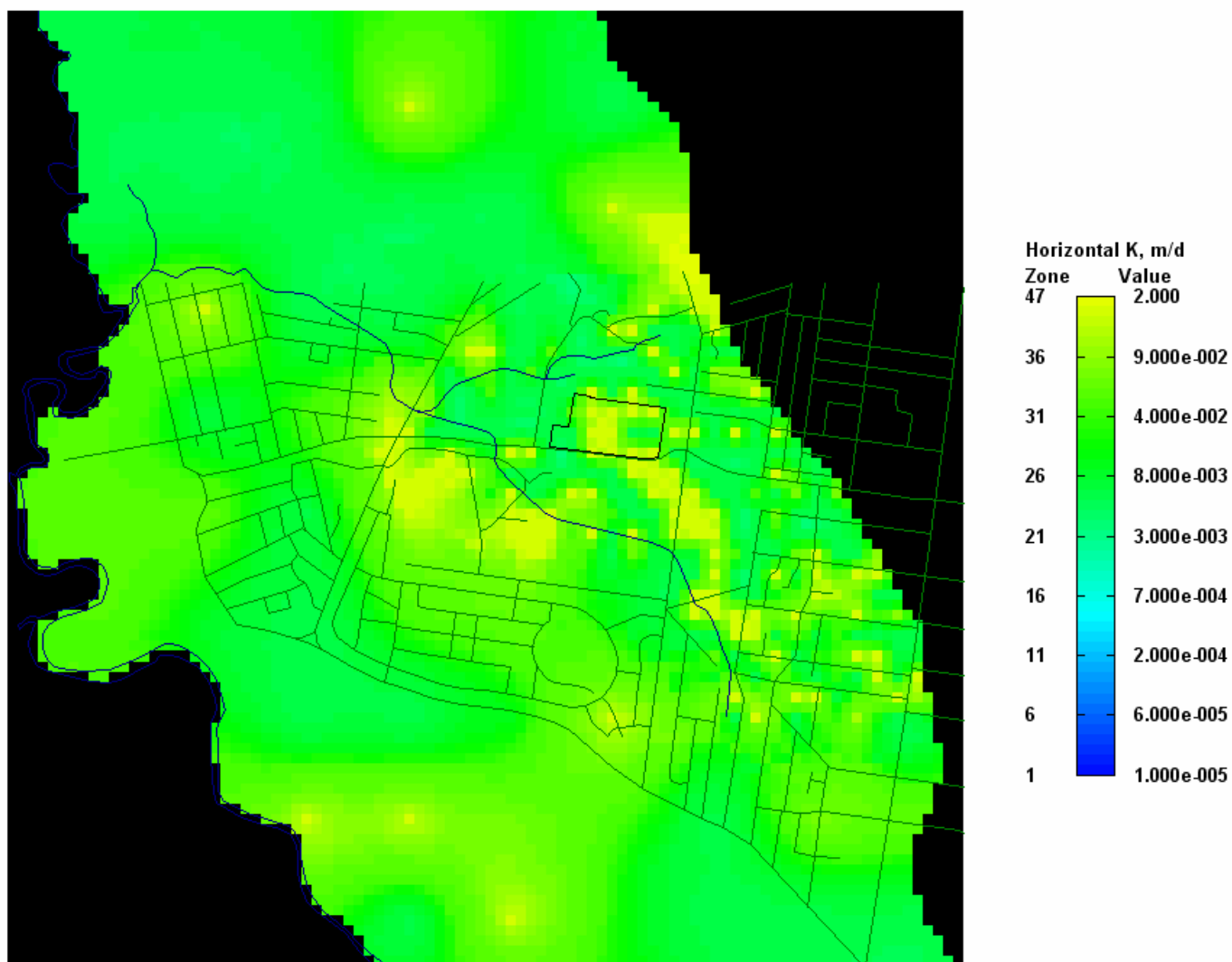


Figure 5.2.1-6. Recharge Scenario 2, model layer 2 horizontal hydraulic conductivity distribution.

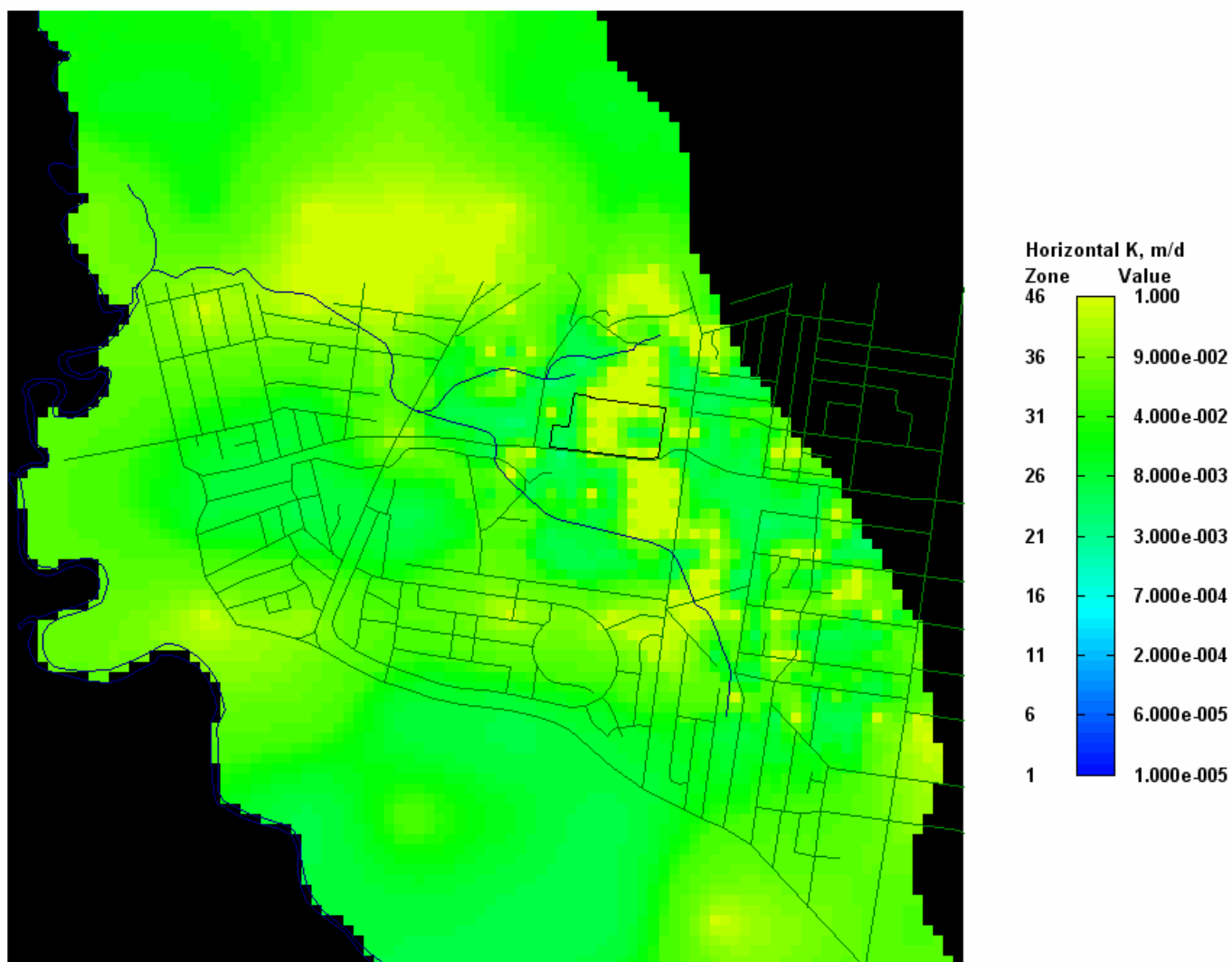


Figure 5.2.1-7. Recharge Scenario 3, model layer 2 horizontal hydraulic conductivity distribution.

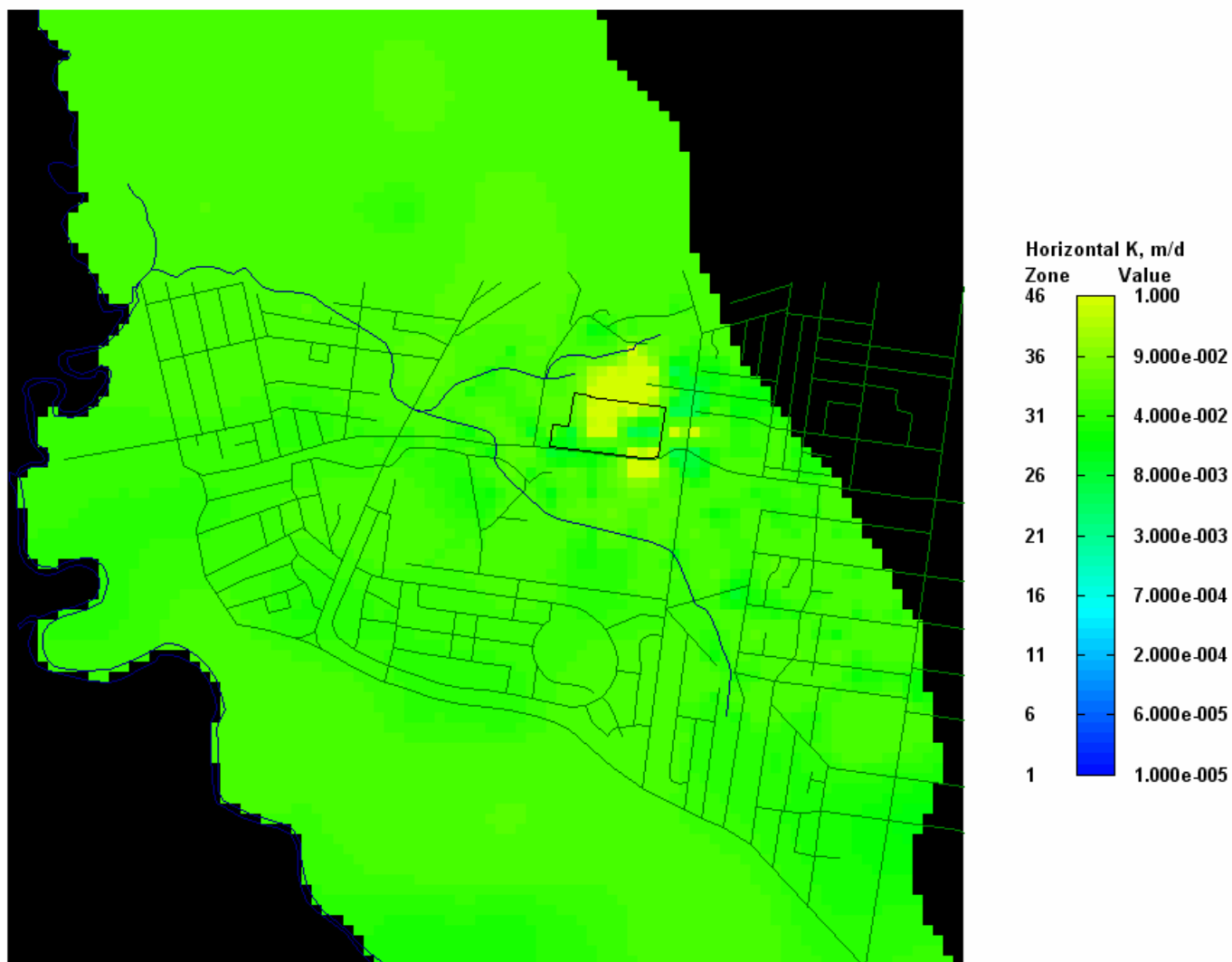


Figure 5.2.1-8. Recharge Scenario 4, model layer 2 horizontal hydraulic conductivity distribution.

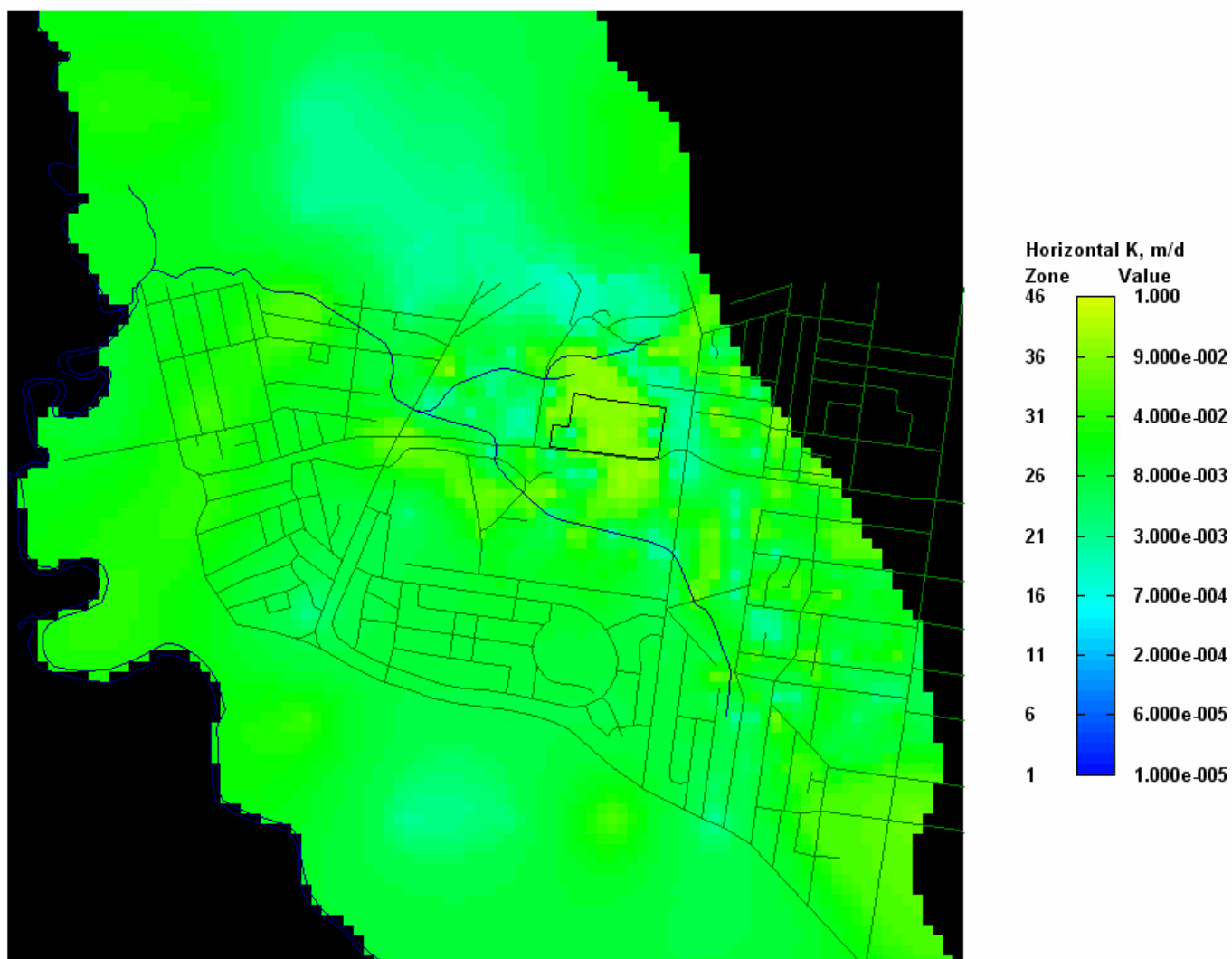


Figure 5.2.1-9. Recharge Scenario 1, model layer 3 horizontal hydraulic conductivity distribution.

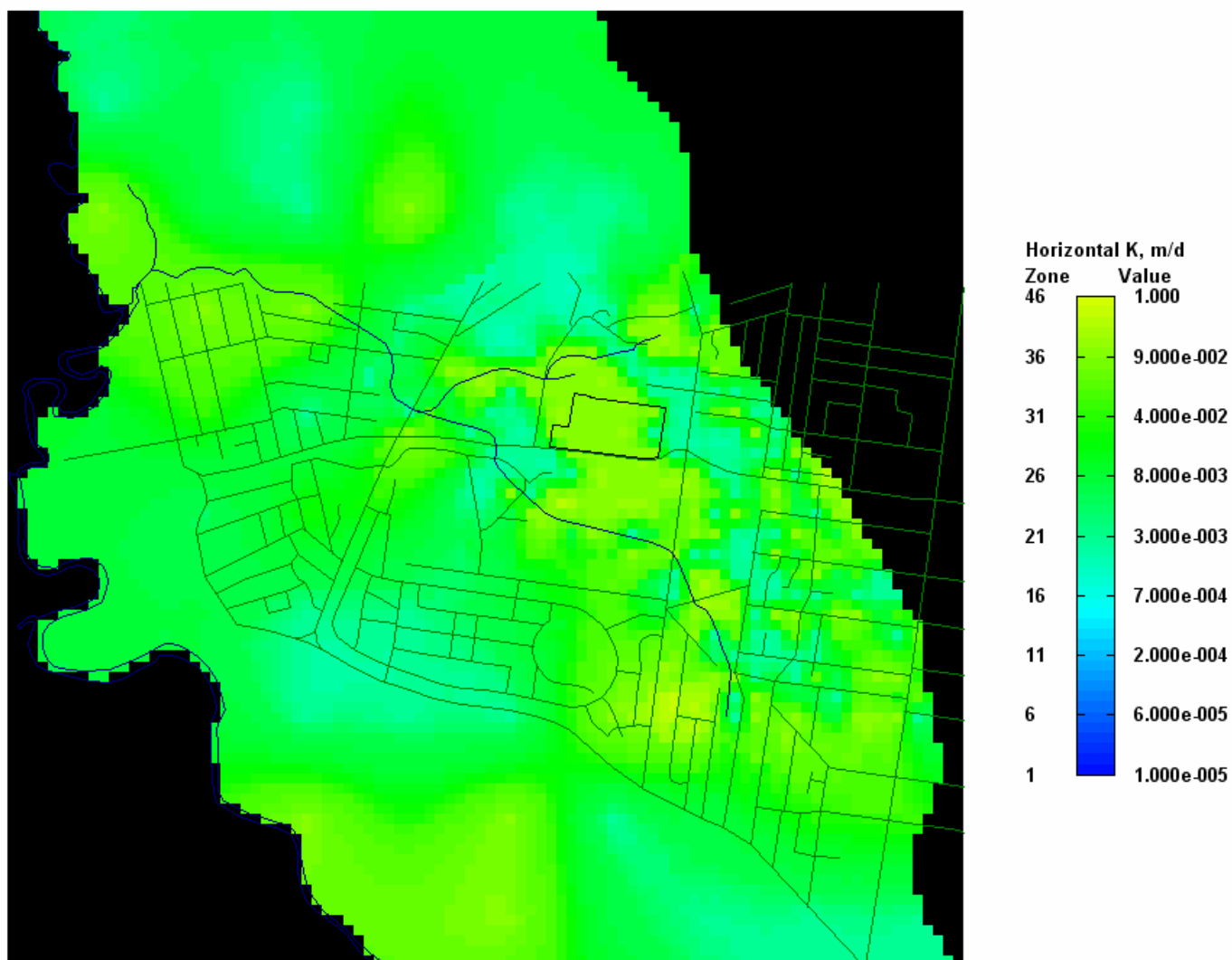


Figure 5.2.1-10. Recharge Scenario 2, model layer 3 horizontal hydraulic conductivity distribution.

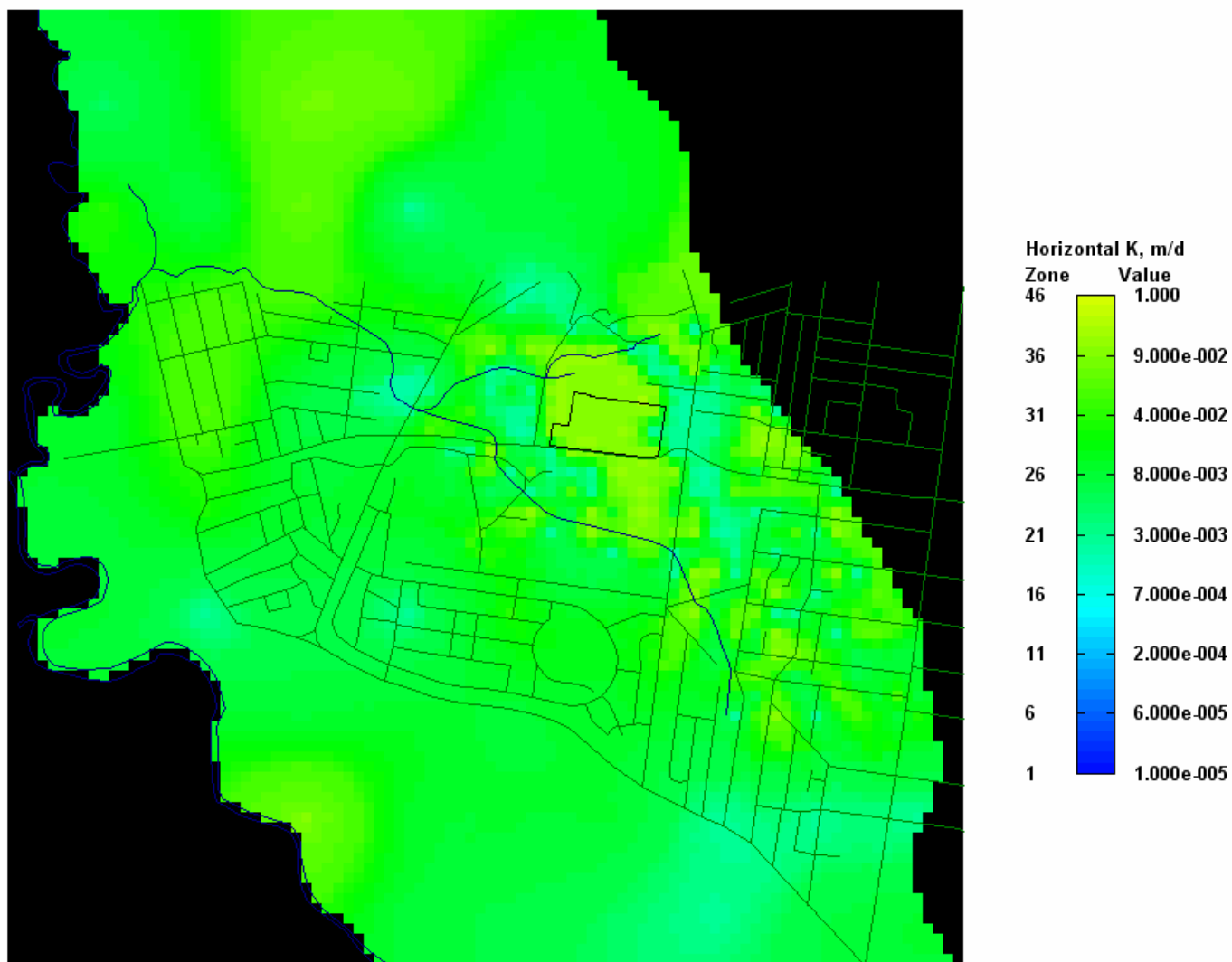


Figure 5.2.1-11. Recharge Scenario 3, model layer 3 horizontal hydraulic conductivity distribution.

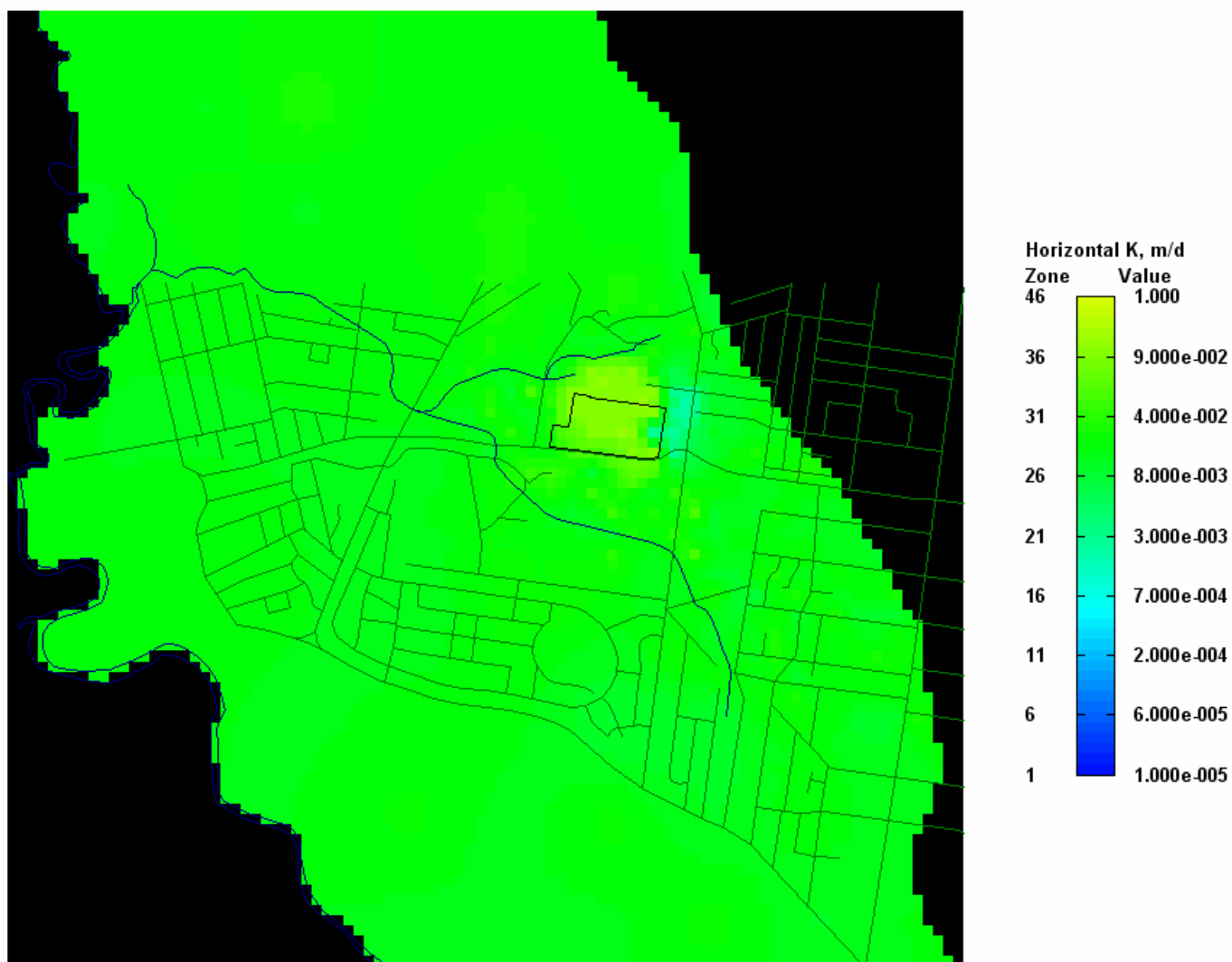


Figure 5.2.1-12. Recharge Scenario 4, model layer 3 horizontal hydraulic conductivity distribution.

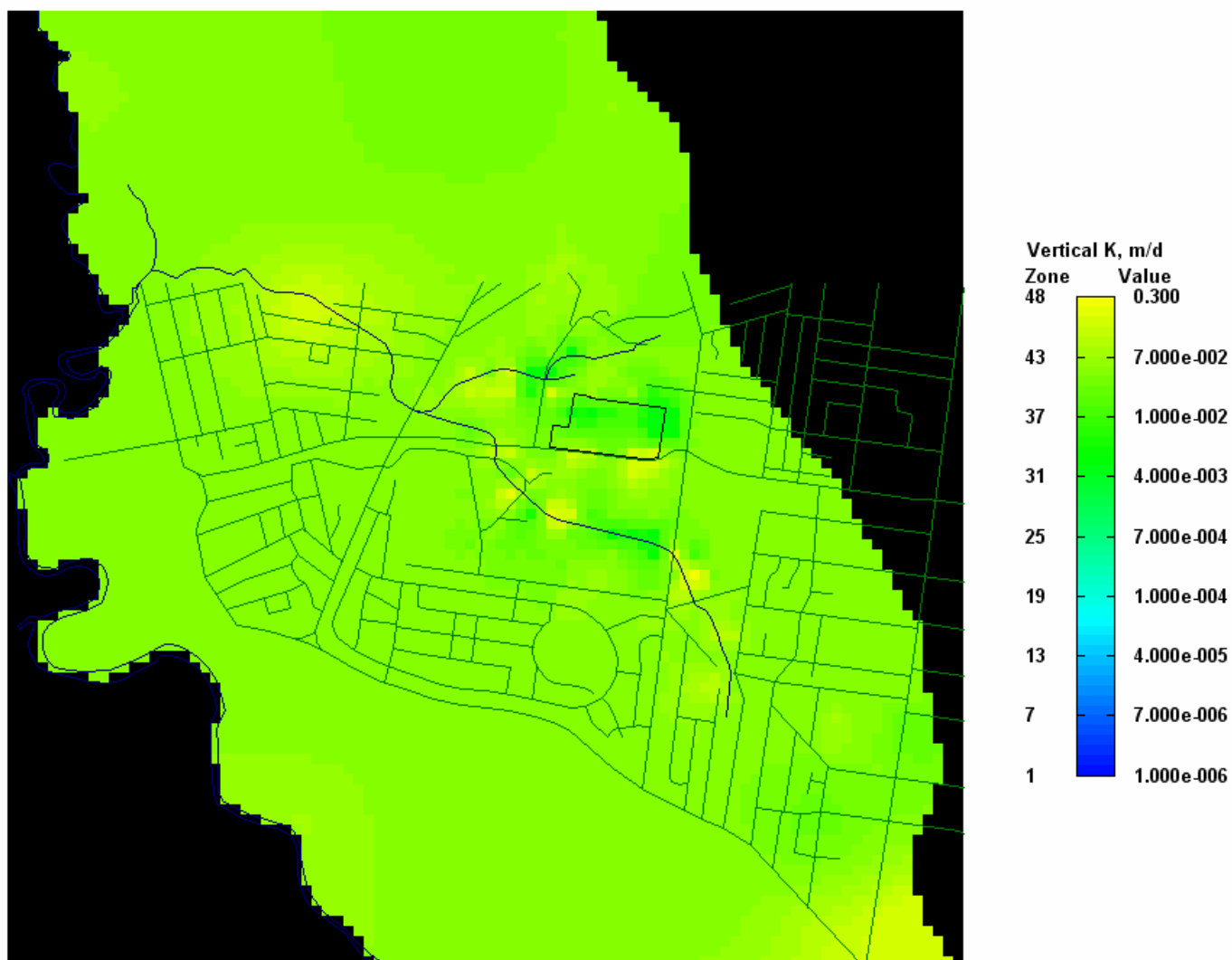


Figure 5.2.1-13. Recharge Scenario 1, model layer 1 vertical hydraulic conductivity distribution.

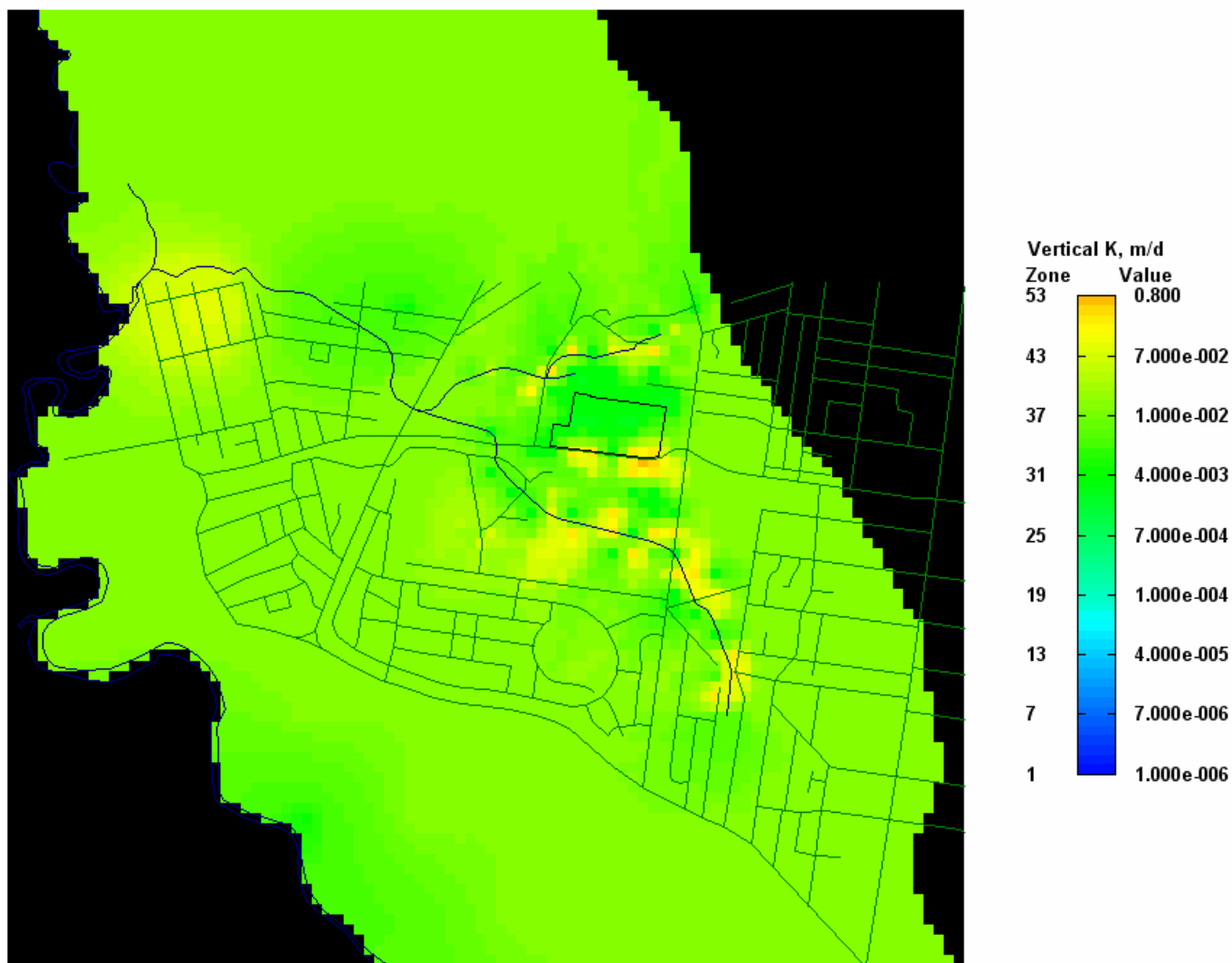


Figure 5.2.1-14. Recharge Scenario 2, model layer 1 vertical hydraulic conductivity distribution.

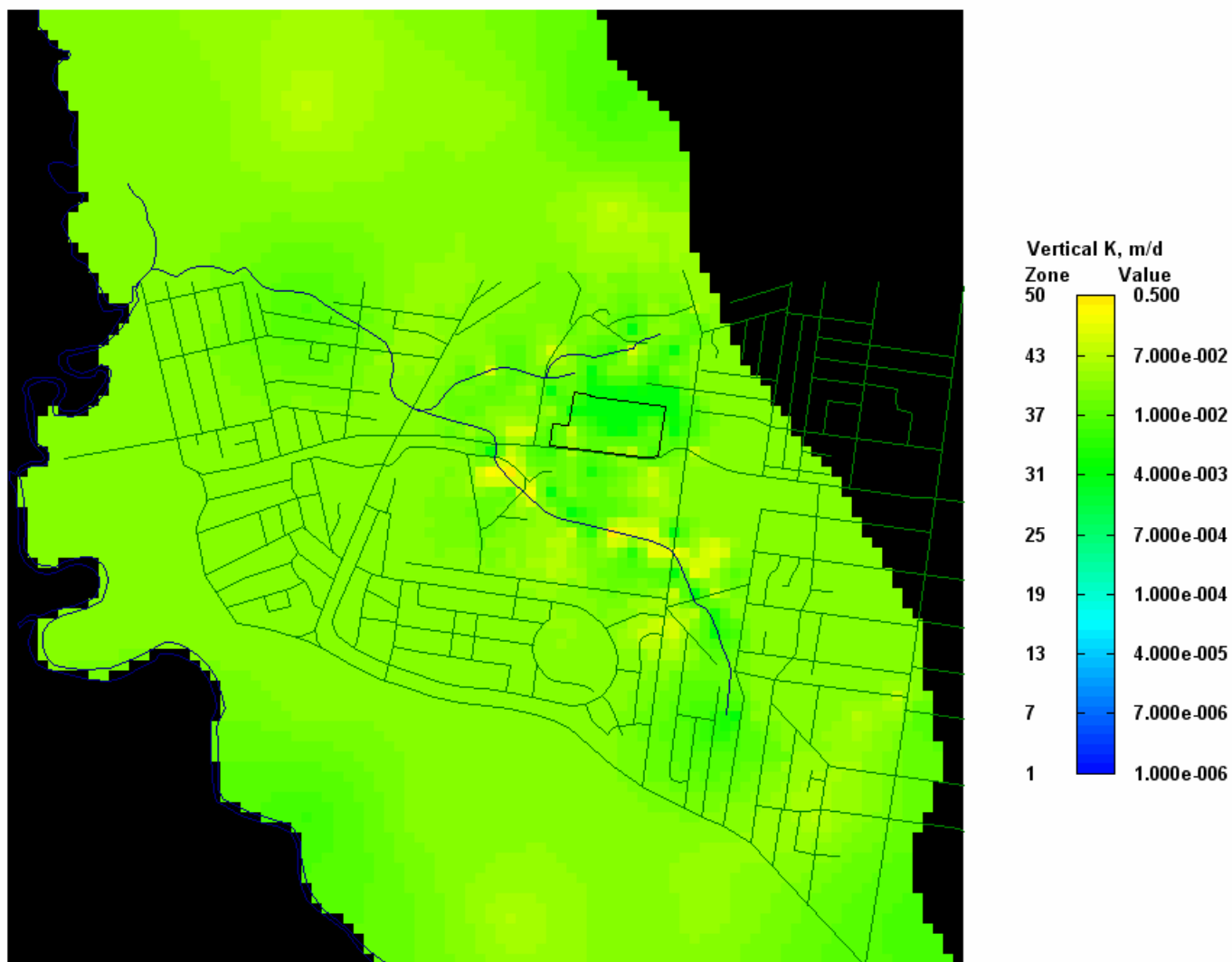


Figure 5.2.1-15. Recharge Scenario 3, model layer 1 vertical hydraulic conductivity distribution.

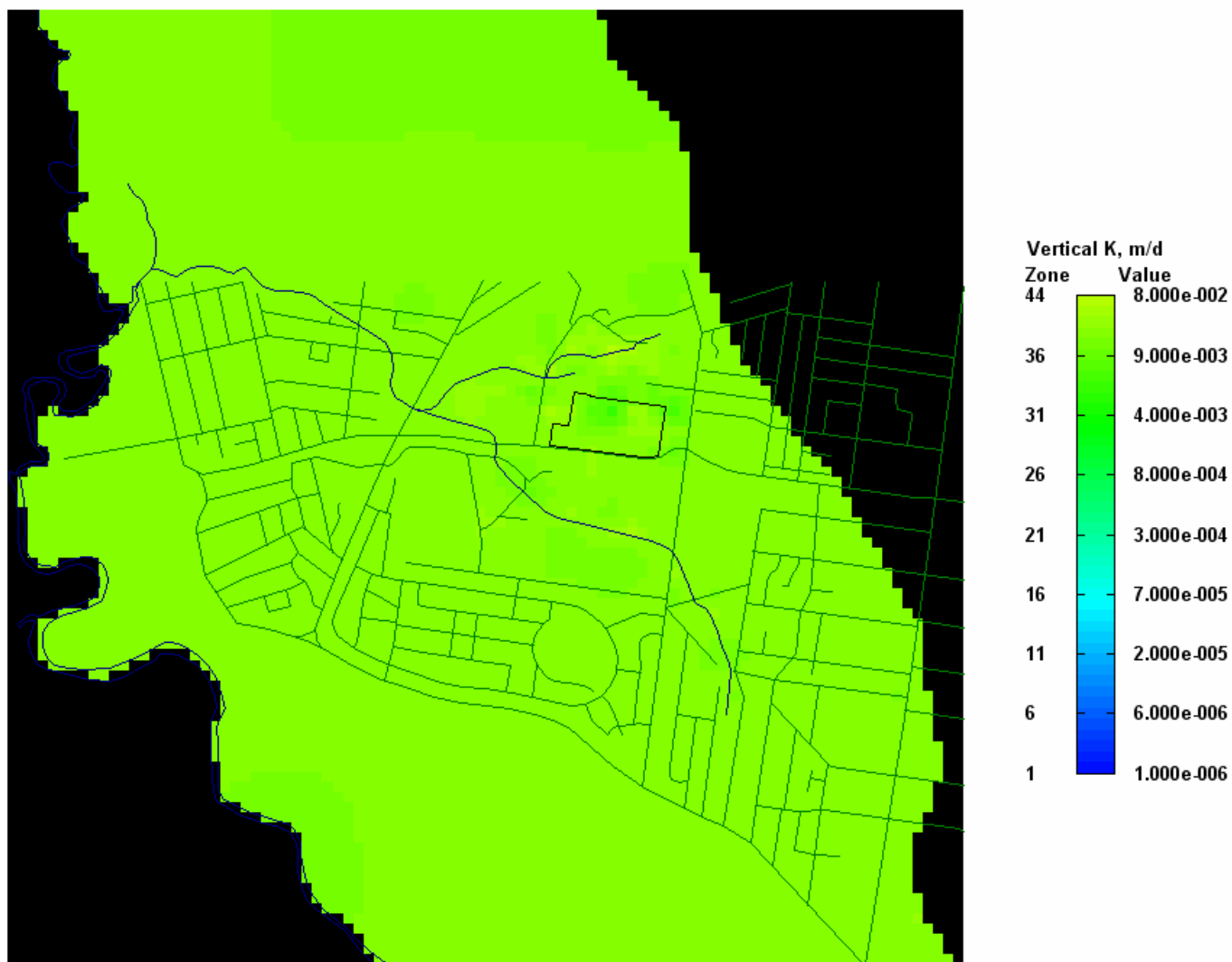


Figure 5.2.1-16. Recharge Scenario 4, model layer 1 vertical hydraulic conductivity distribution.

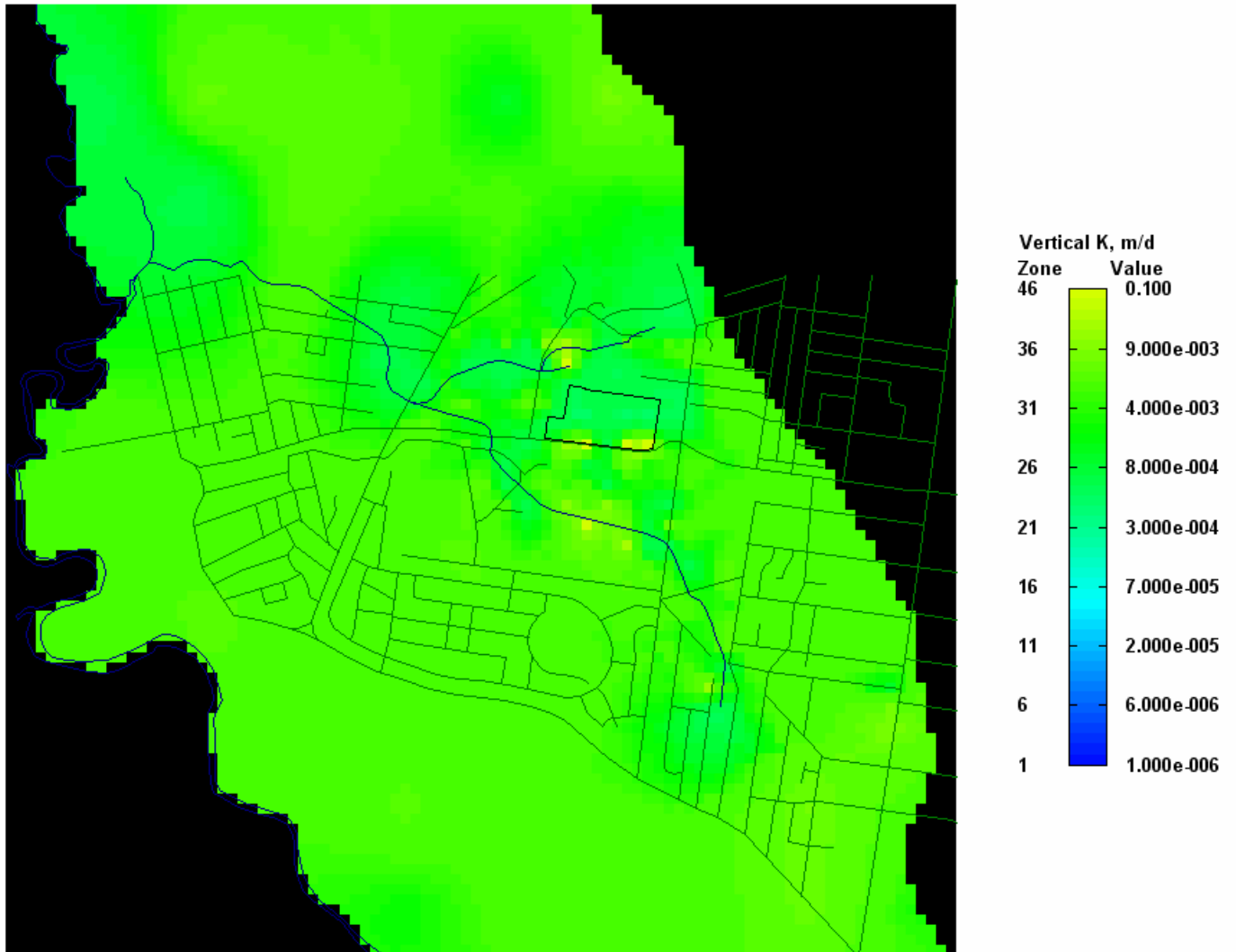


Figure 5.2.1-17. Recharge Scenario 1, model layer 2 vertical hydraulic conductivity distribution.

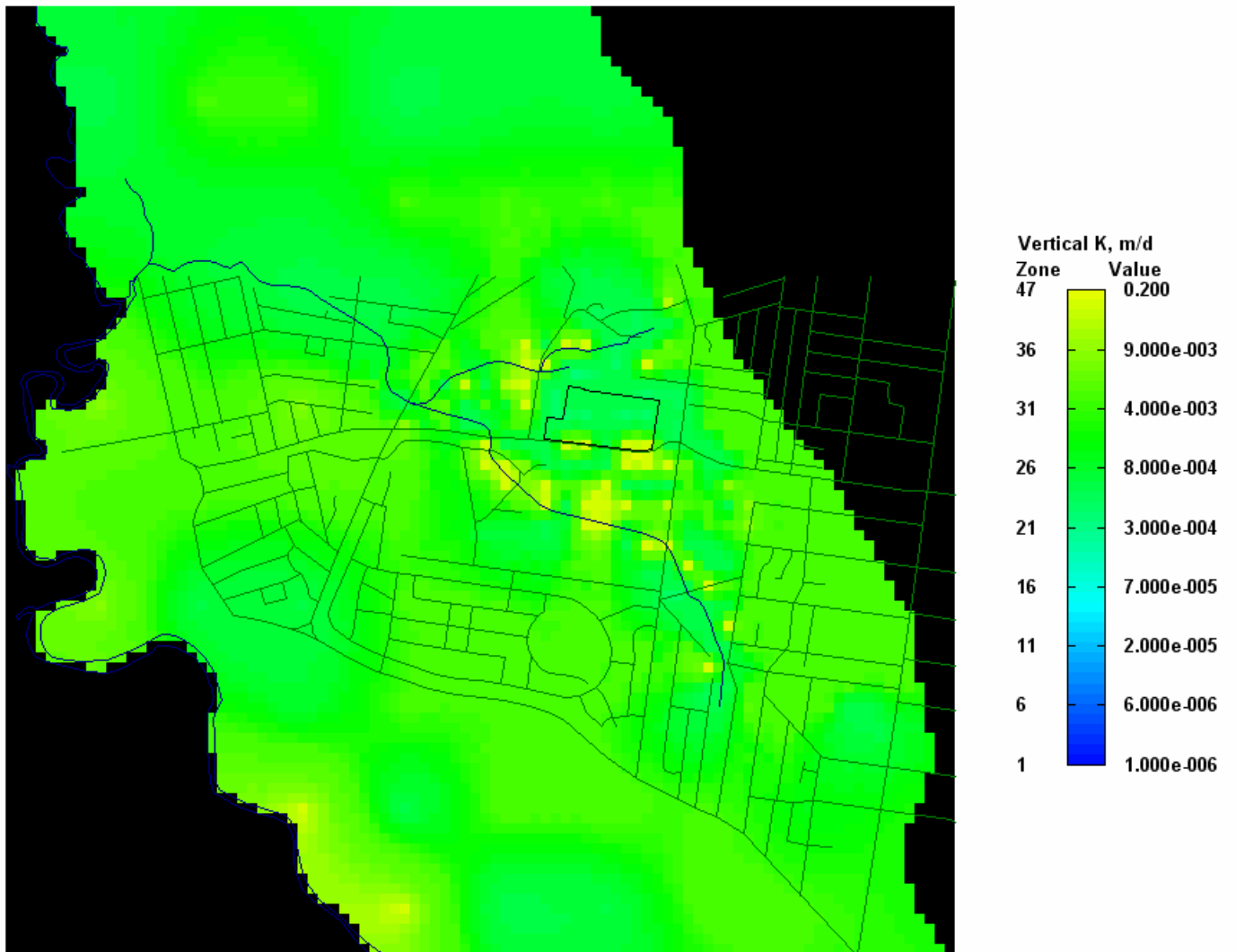


Figure 5.2.1-18. Recharge Scenario 2, model layer 2 vertical hydraulic conductivity distribution.

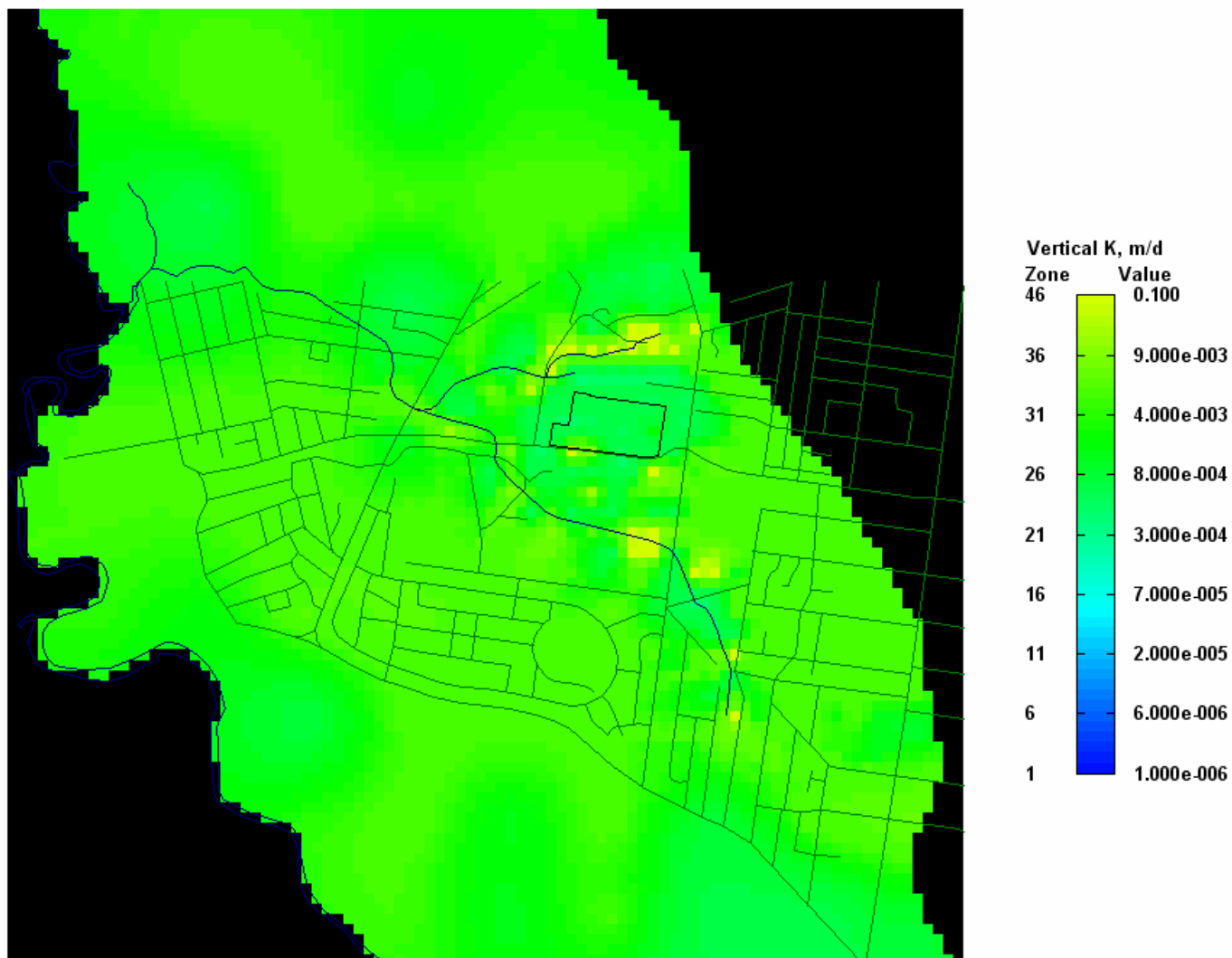


Figure 5.2.1-19. Recharge Scenario 3, model layer 2 vertical hydraulic conductivity distribution.

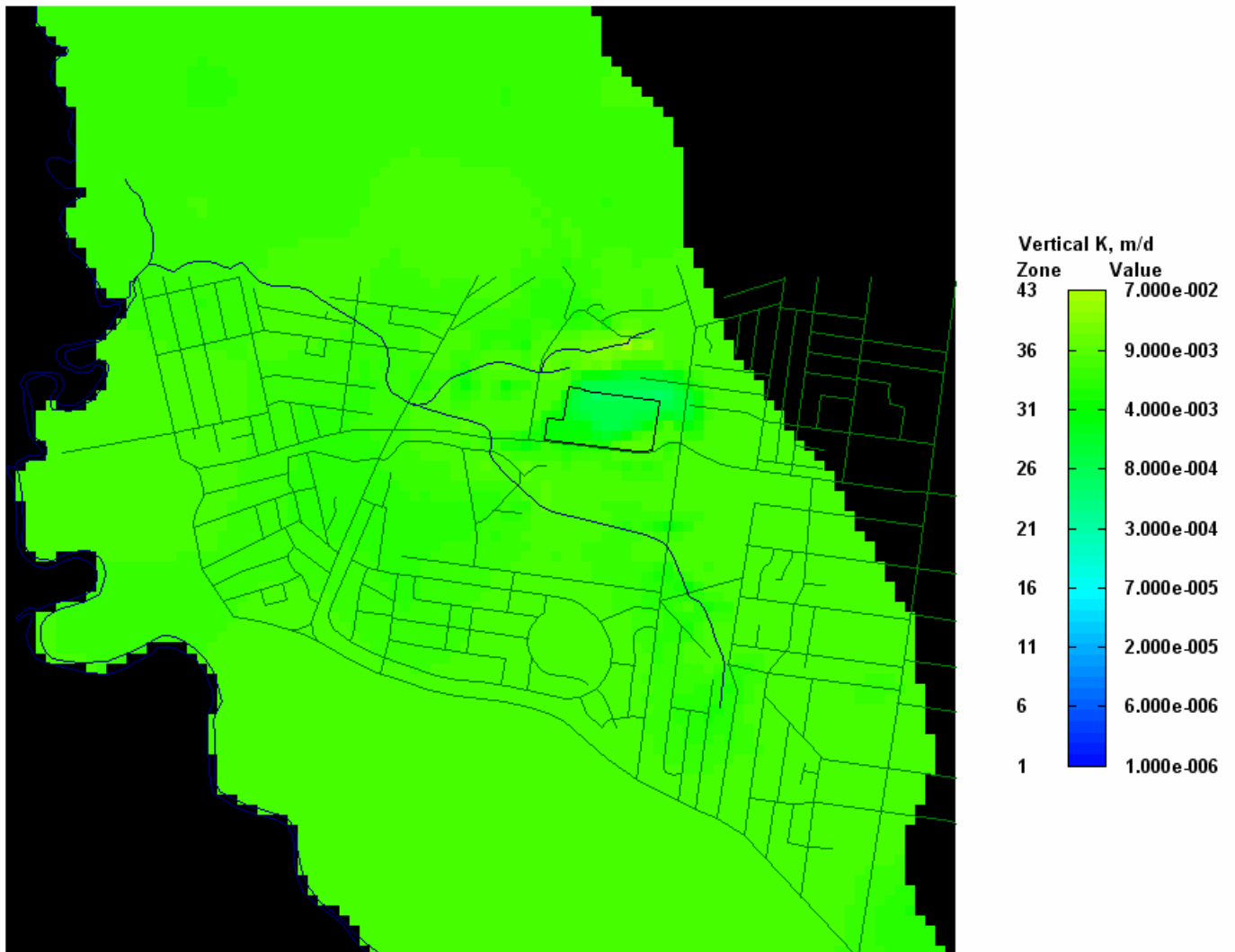


Figure 5.2.1-20. Recharge Scenario 4, model layer 2 vertical hydraulic conductivity distribution.

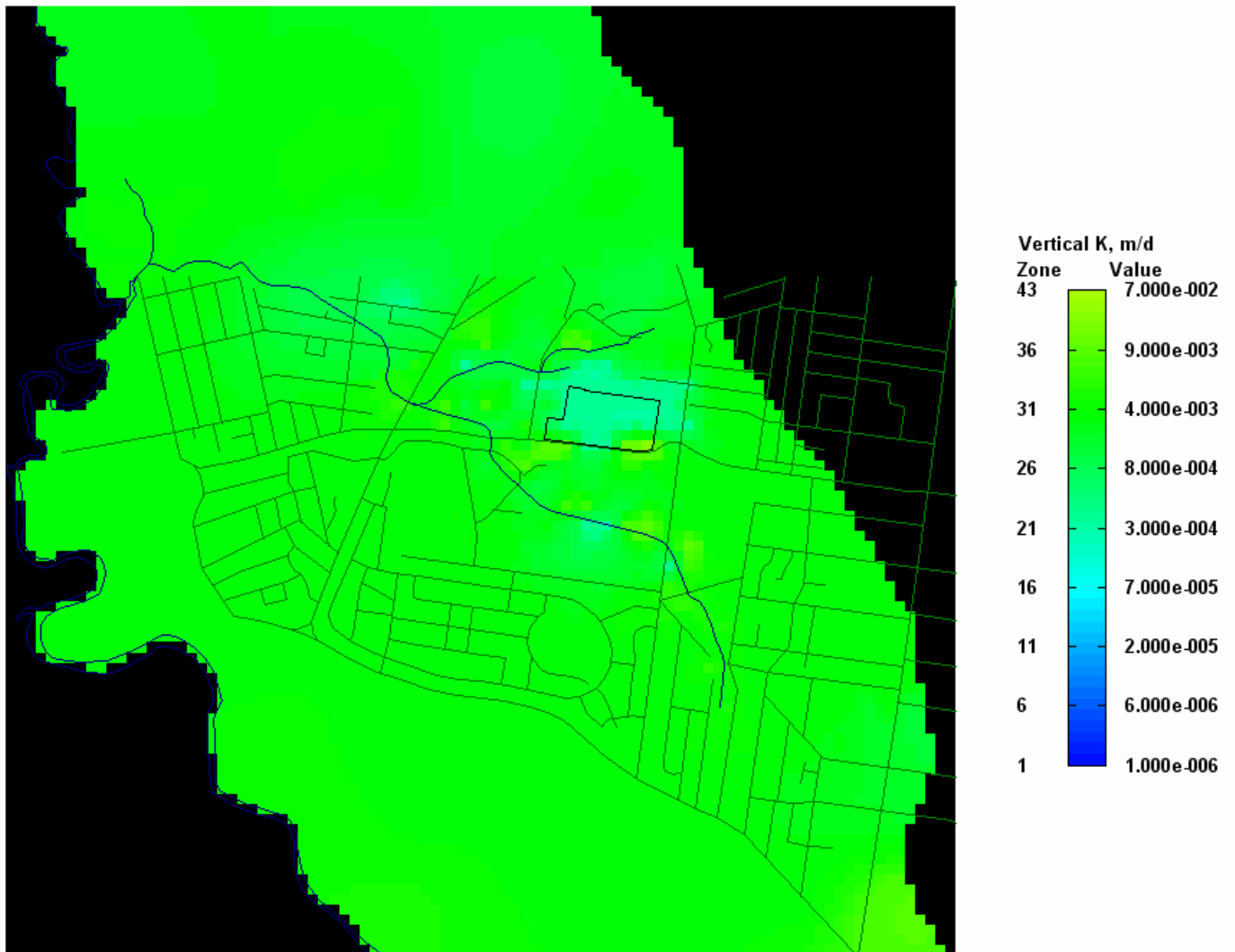


Figure 5.2.1-21. Recharge Scenario 1, model layer 3 vertical hydraulic conductivity distribution.

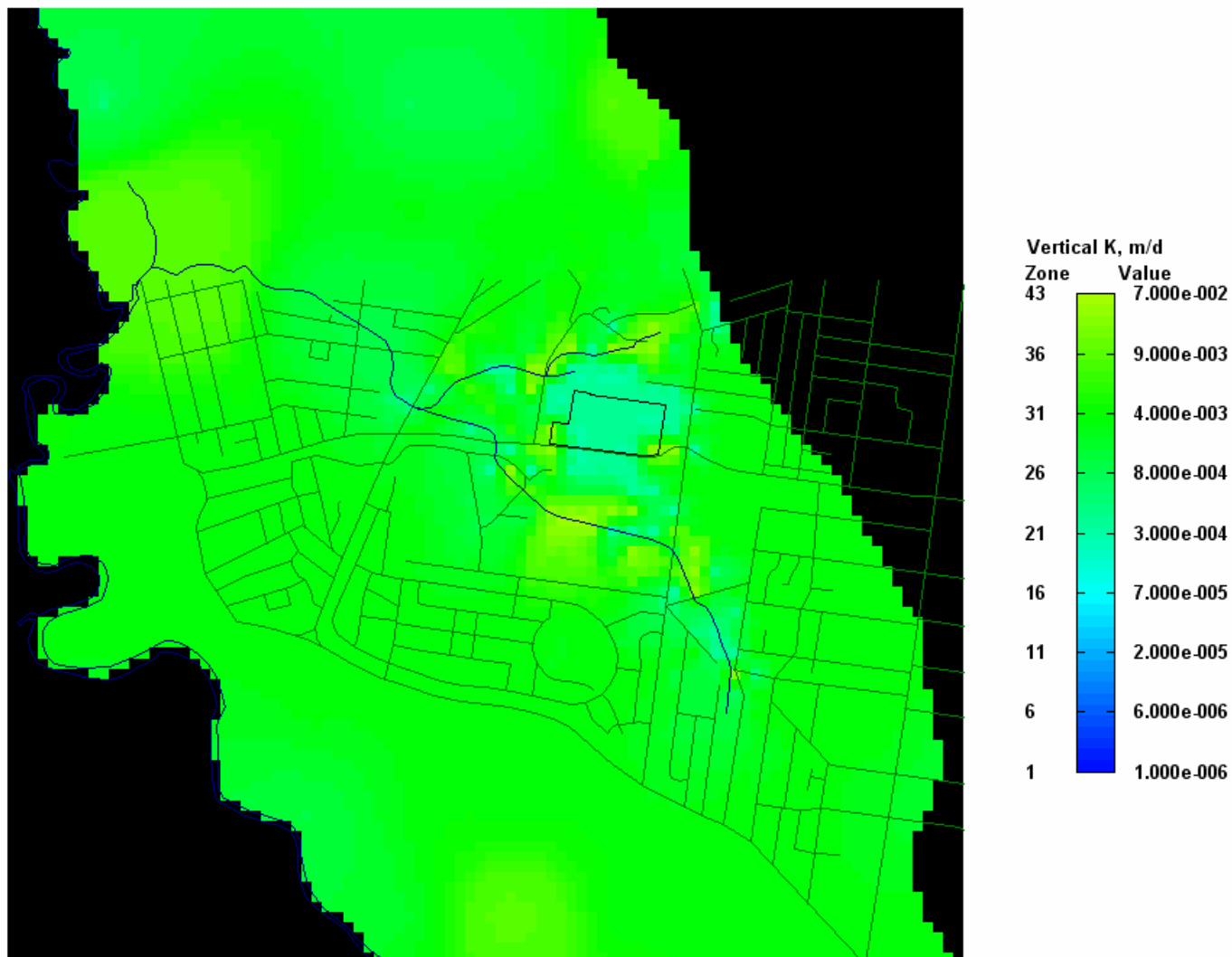


Figure 5.2.1-22. Recharge Scenario 2, model layer 3 vertical hydraulic conductivity distribution.

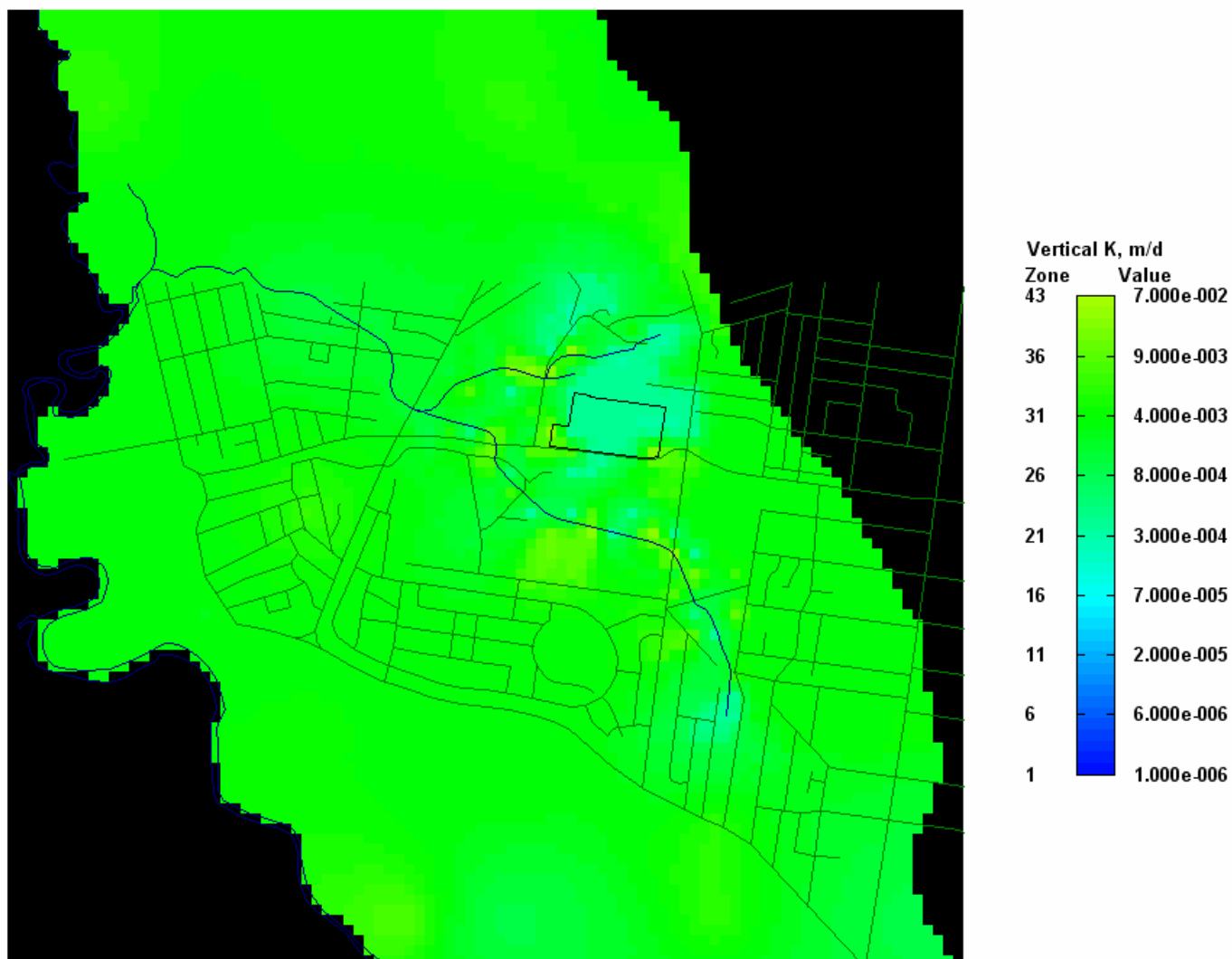


Figure 5.2.1-23. Recharge Scenario 3, model layer 3 vertical hydraulic conductivity distribution.

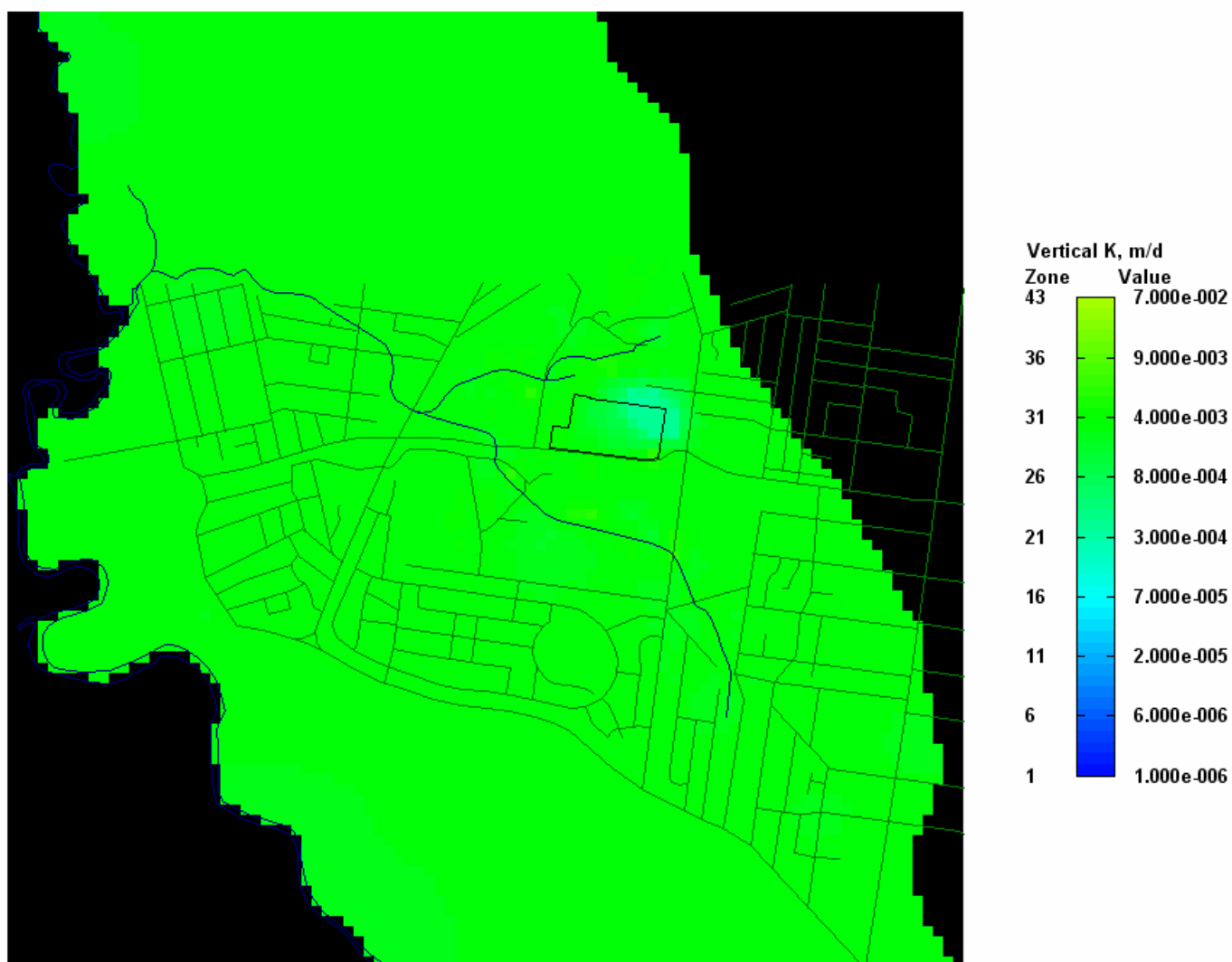


Figure 5.2.1-24. Recharge Scenario 4, model layer 3 vertical hydraulic conductivity distribution.

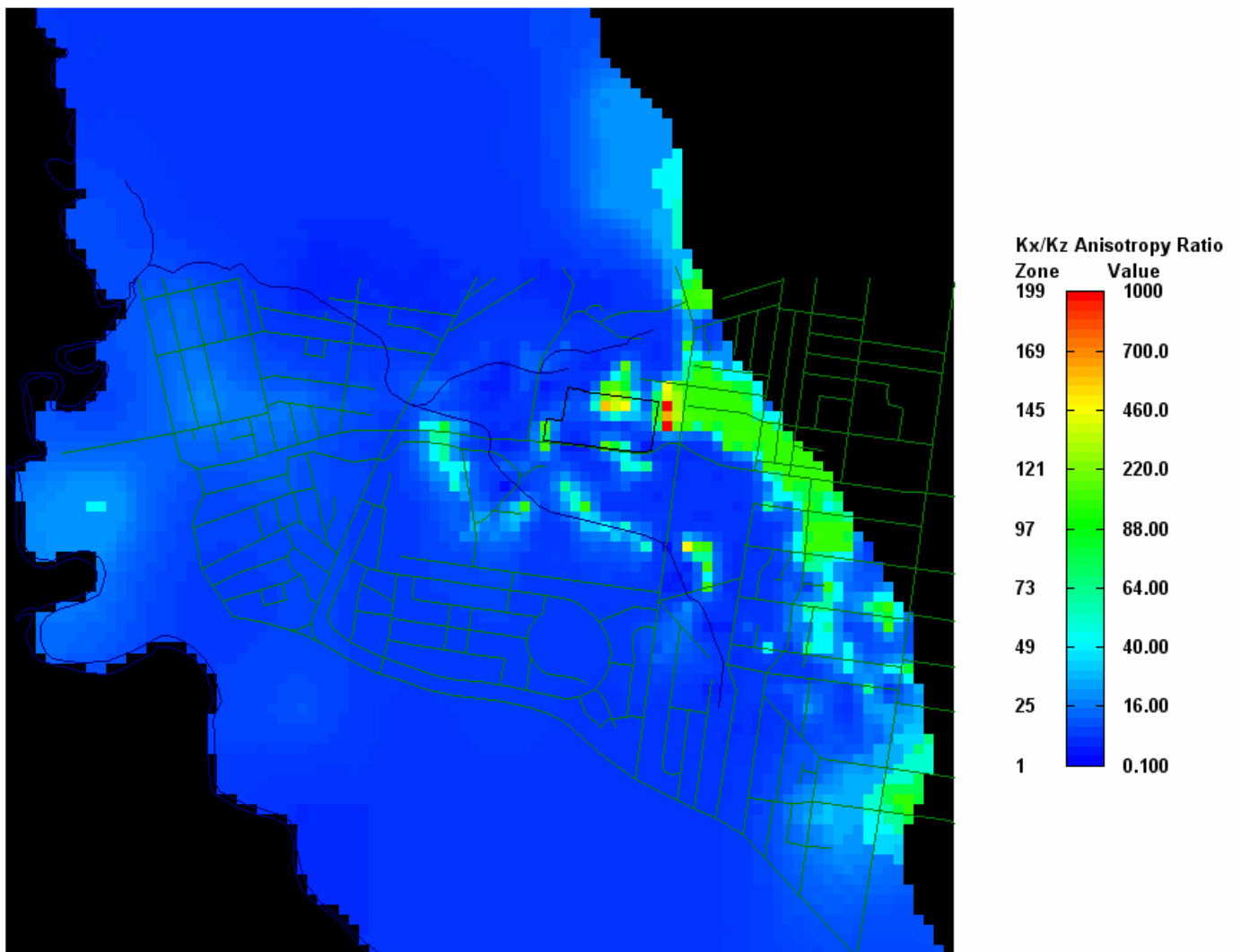


Figure 5.2.1-25. Recharge Scenario 1, model layer 1 hydraulic conductivity anisotropy ratio.

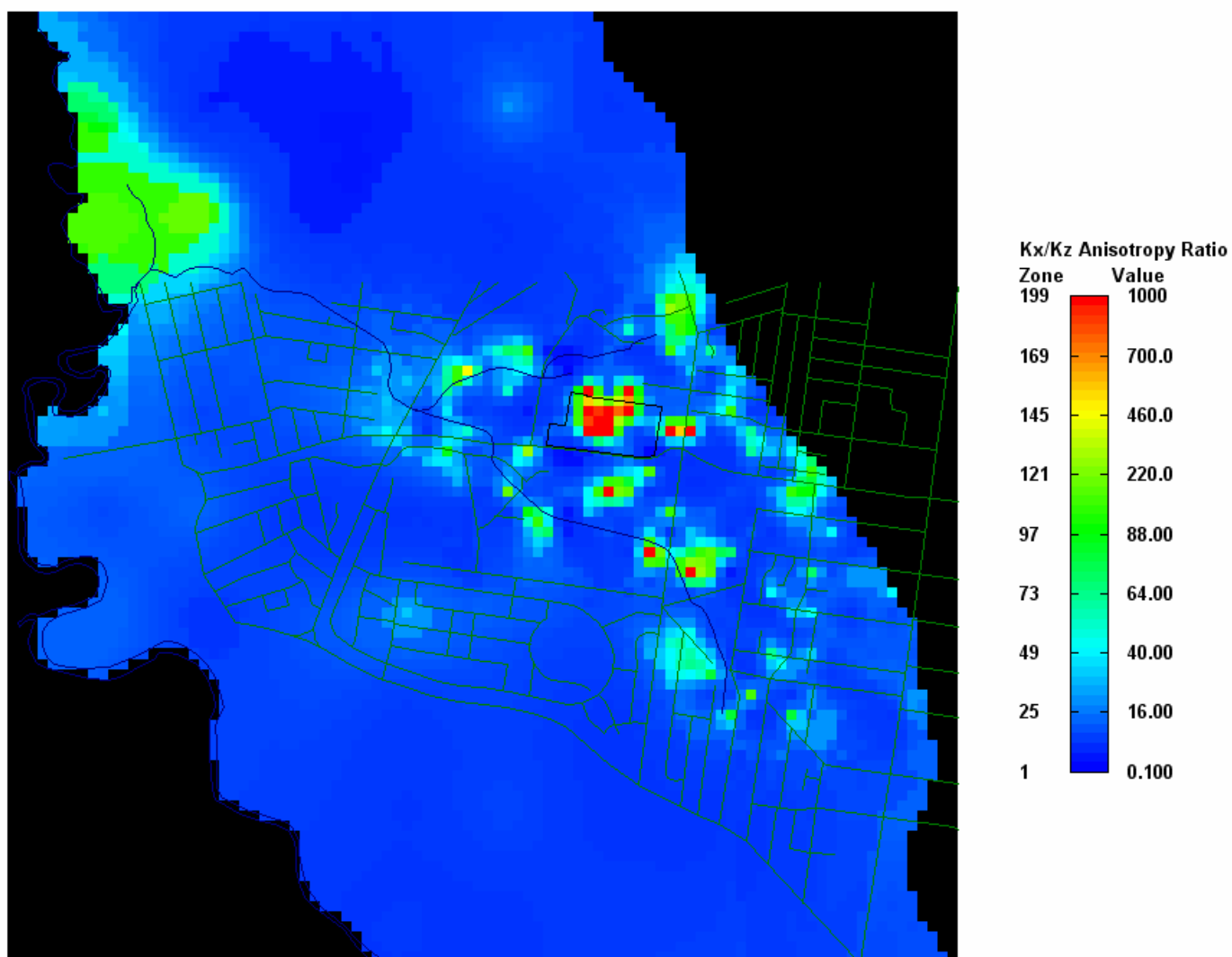


Figure 5.2.1-26. Recharge Scenario 1, model layer 2 hydraulic conductivity anisotropy ratio.

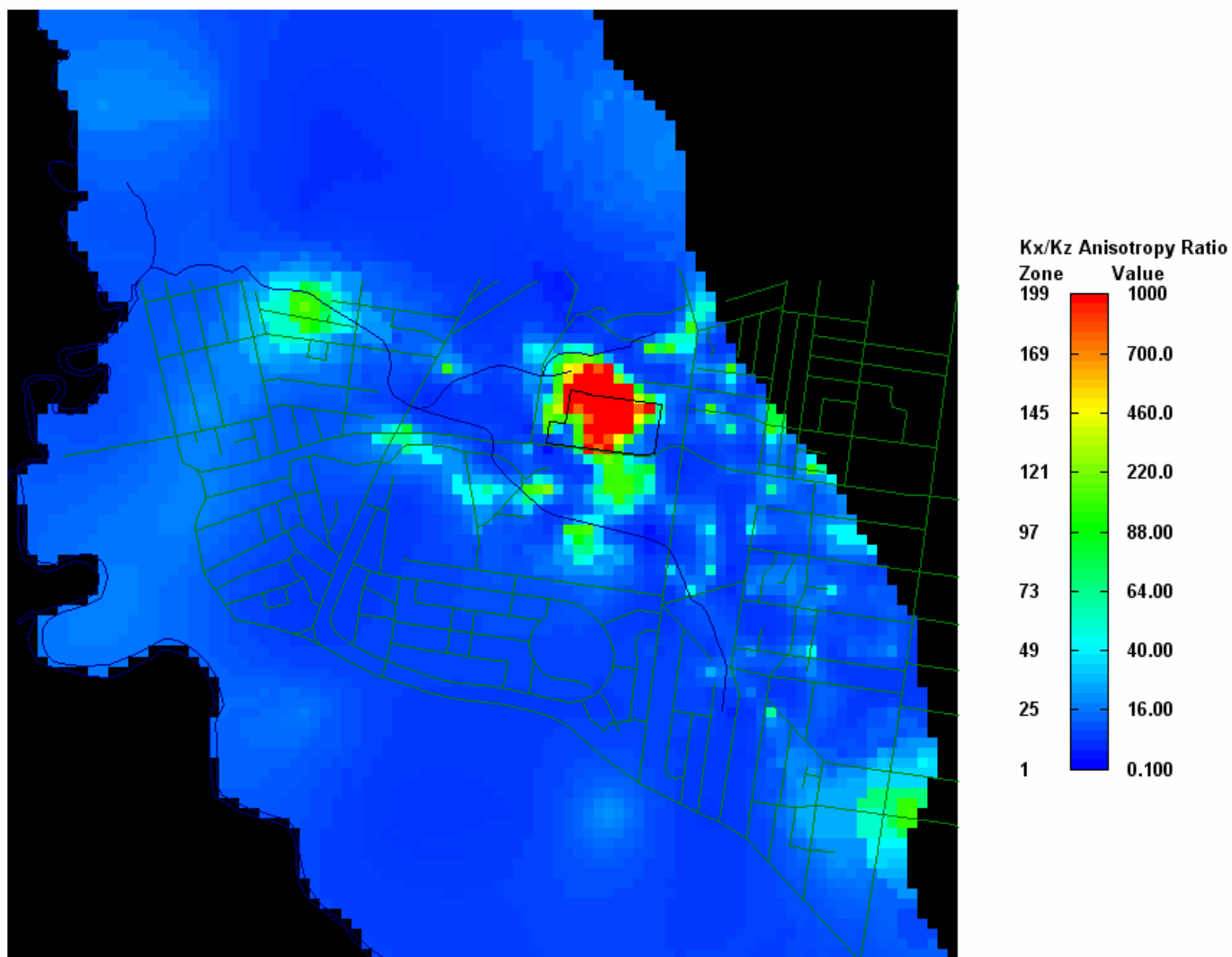


Figure 5.2.1-27. Recharge Scenario 1, model layer 3 hydraulic conductivity anisotropy ratio.

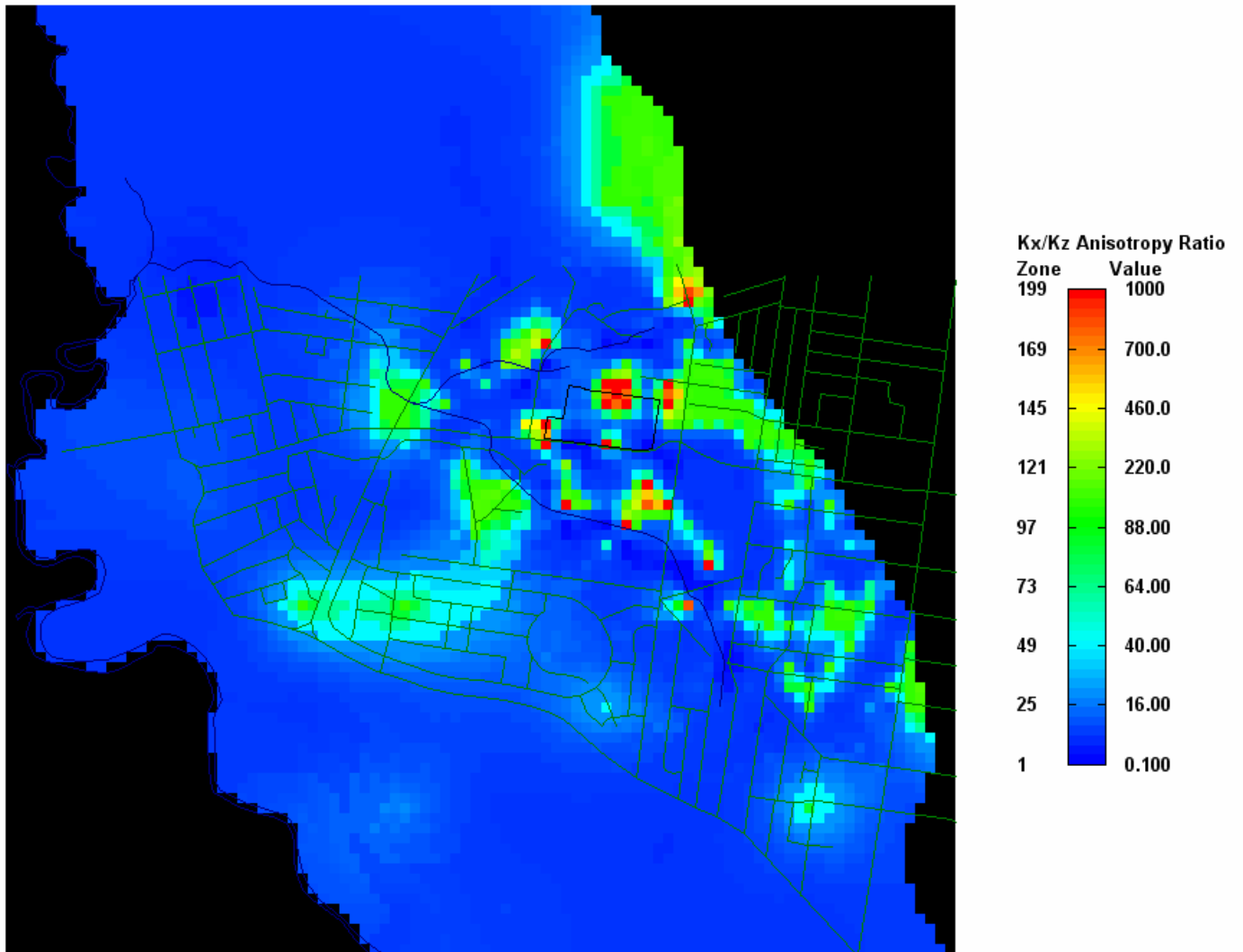


Figure 5.2.1-28. Recharge Scenario 2, model layer 1 hydraulic conductivity anisotropy ratio.

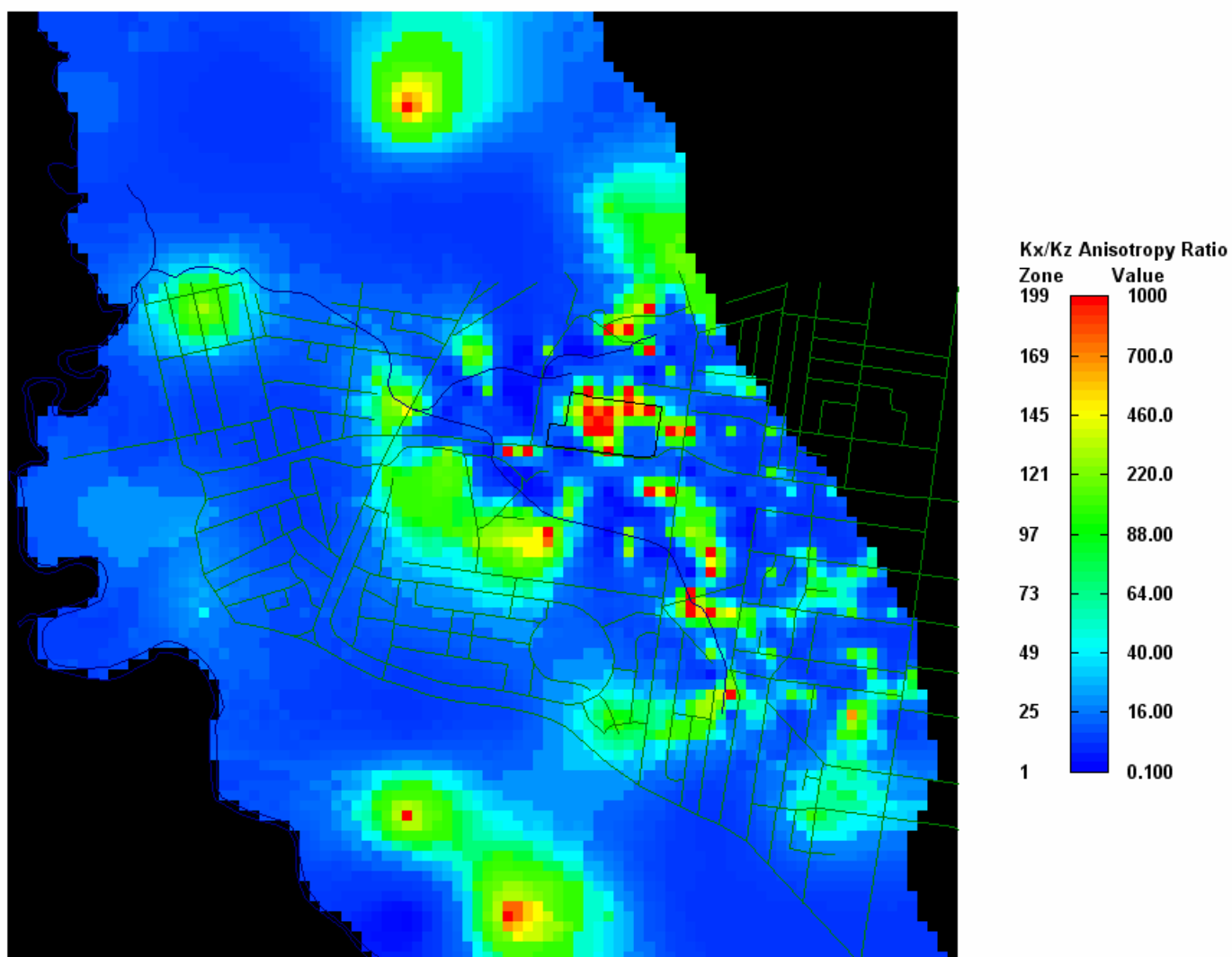


Figure 5.2.1-29. Recharge Scenario 2, model layer 2 hydraulic conductivity anisotropy ratio.

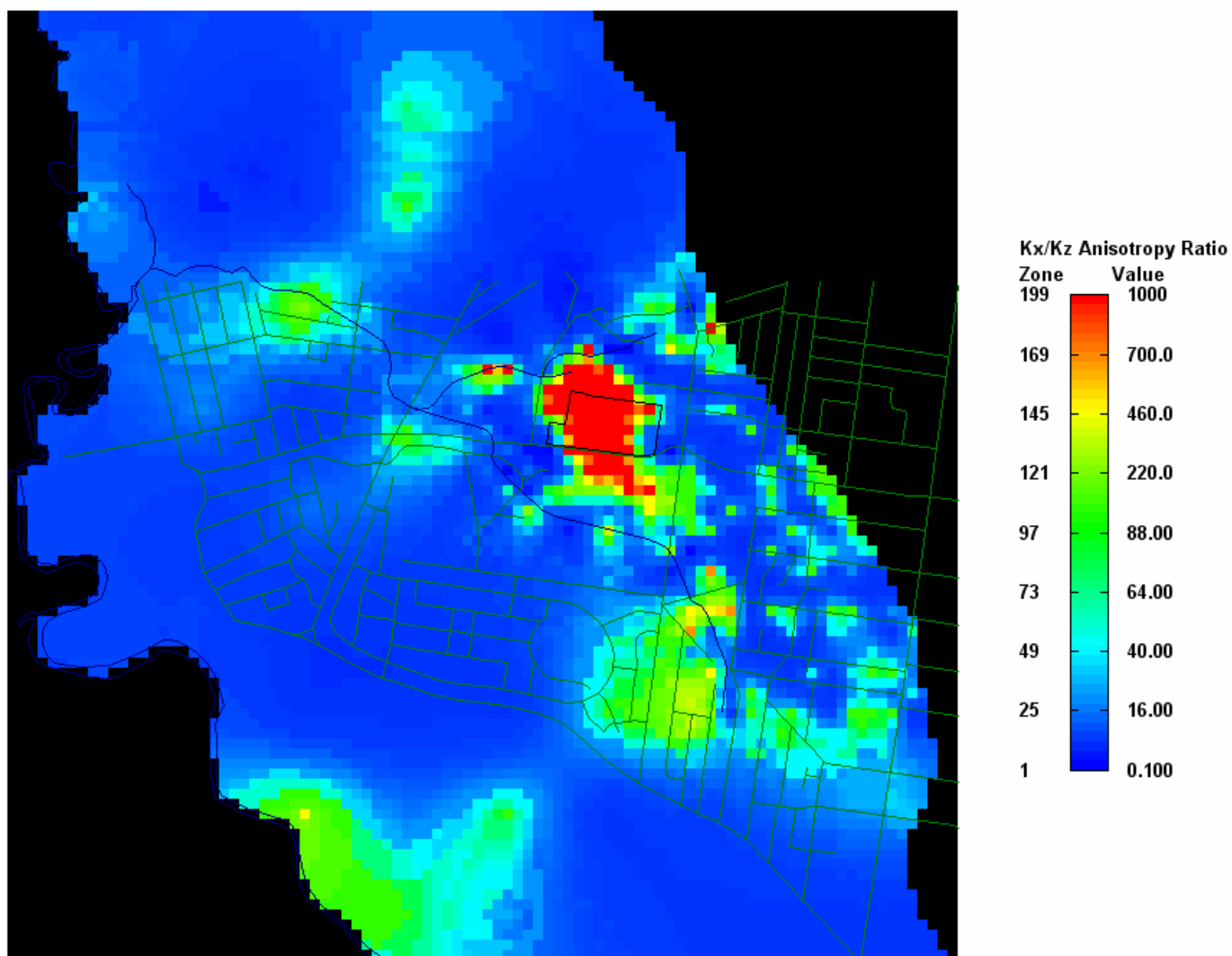


Figure 5.2.1-30. Recharge Scenario 2, model layer 3 hydraulic conductivity anisotropy ratio.

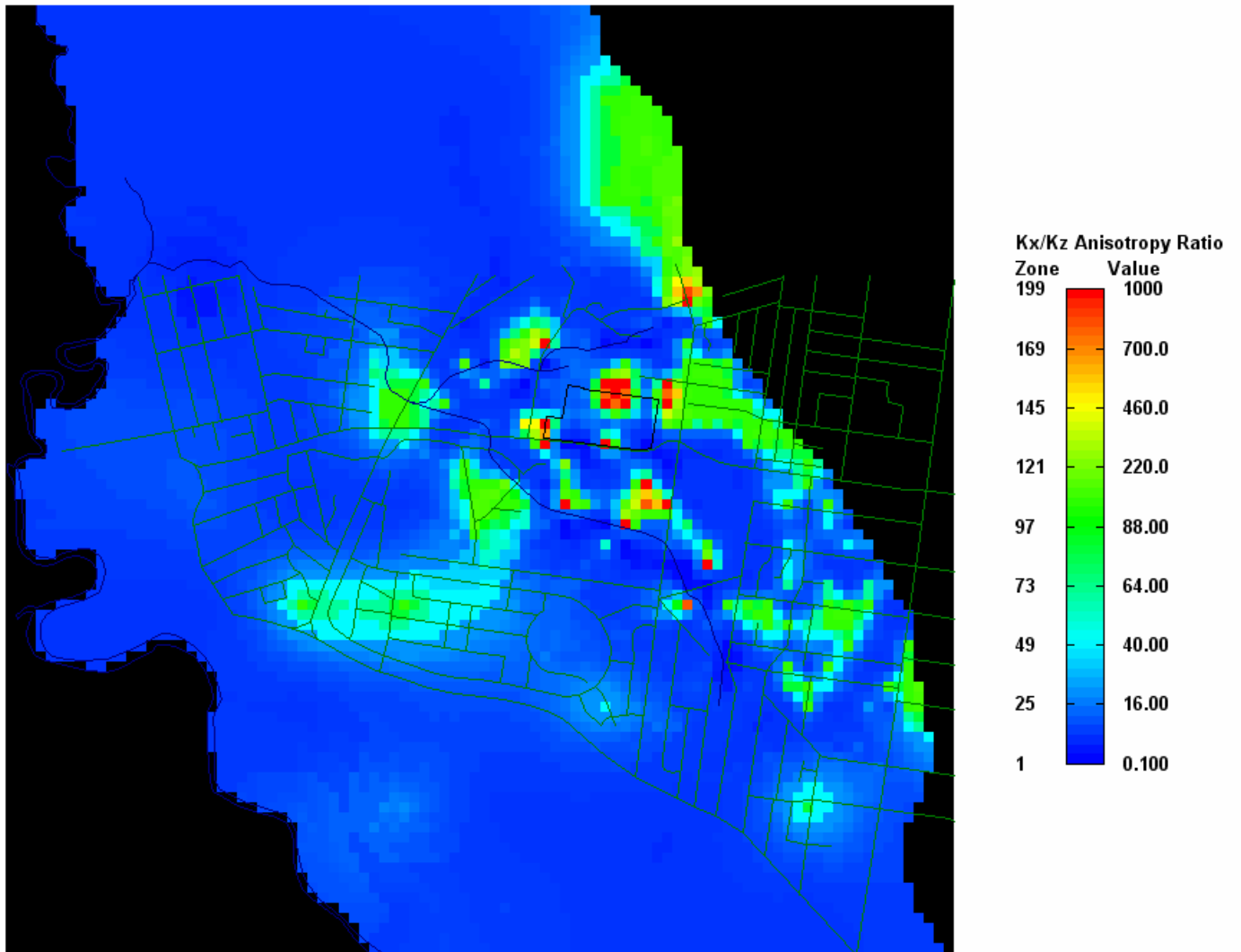


Figure 5.2.1-31. Recharge Scenario 3, model layer 1 hydraulic conductivity anisotropy ratio.

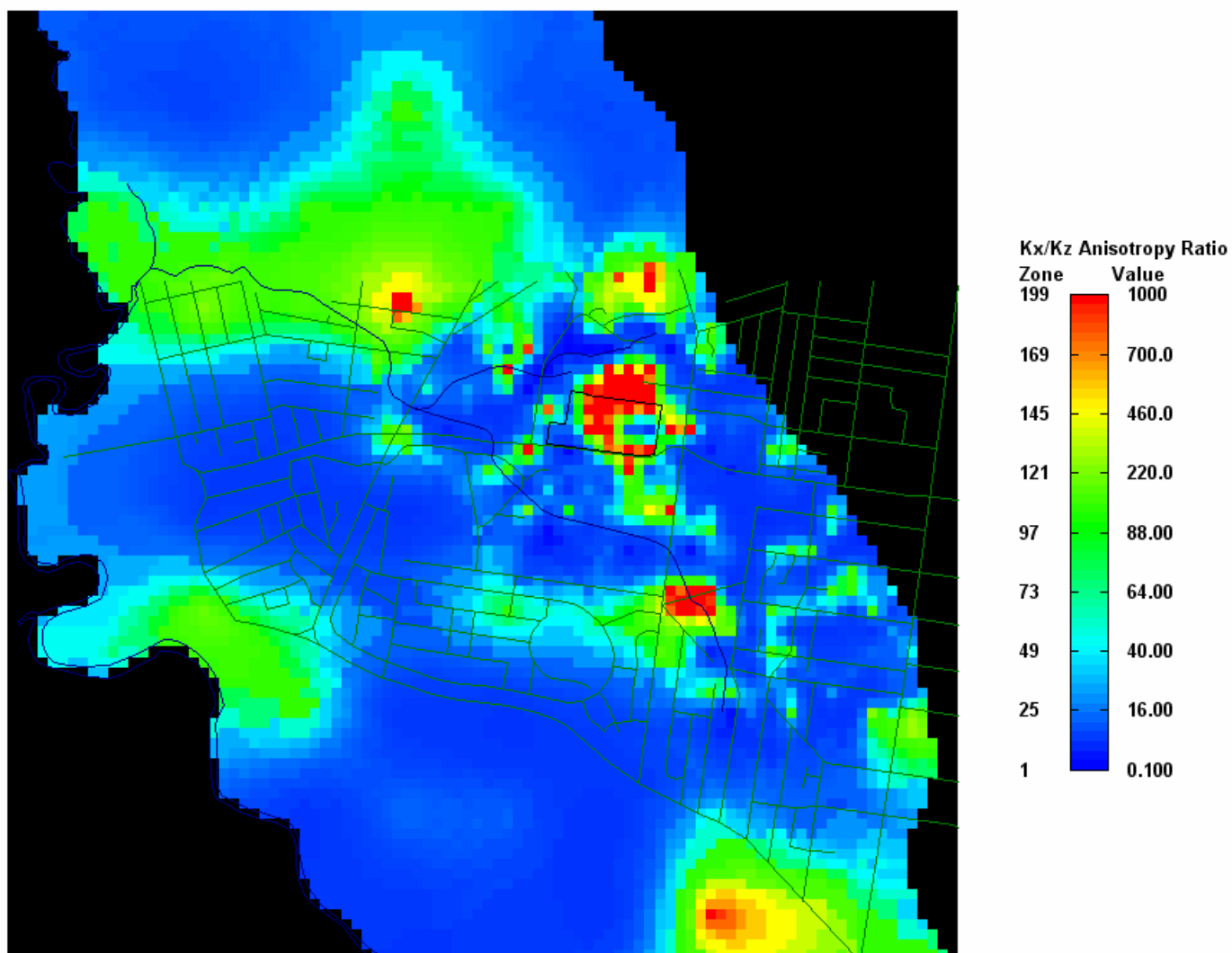


Figure 5.2.1-32. Recharge Scenario 3, model layer 2 hydraulic conductivity anisotropy ratio.

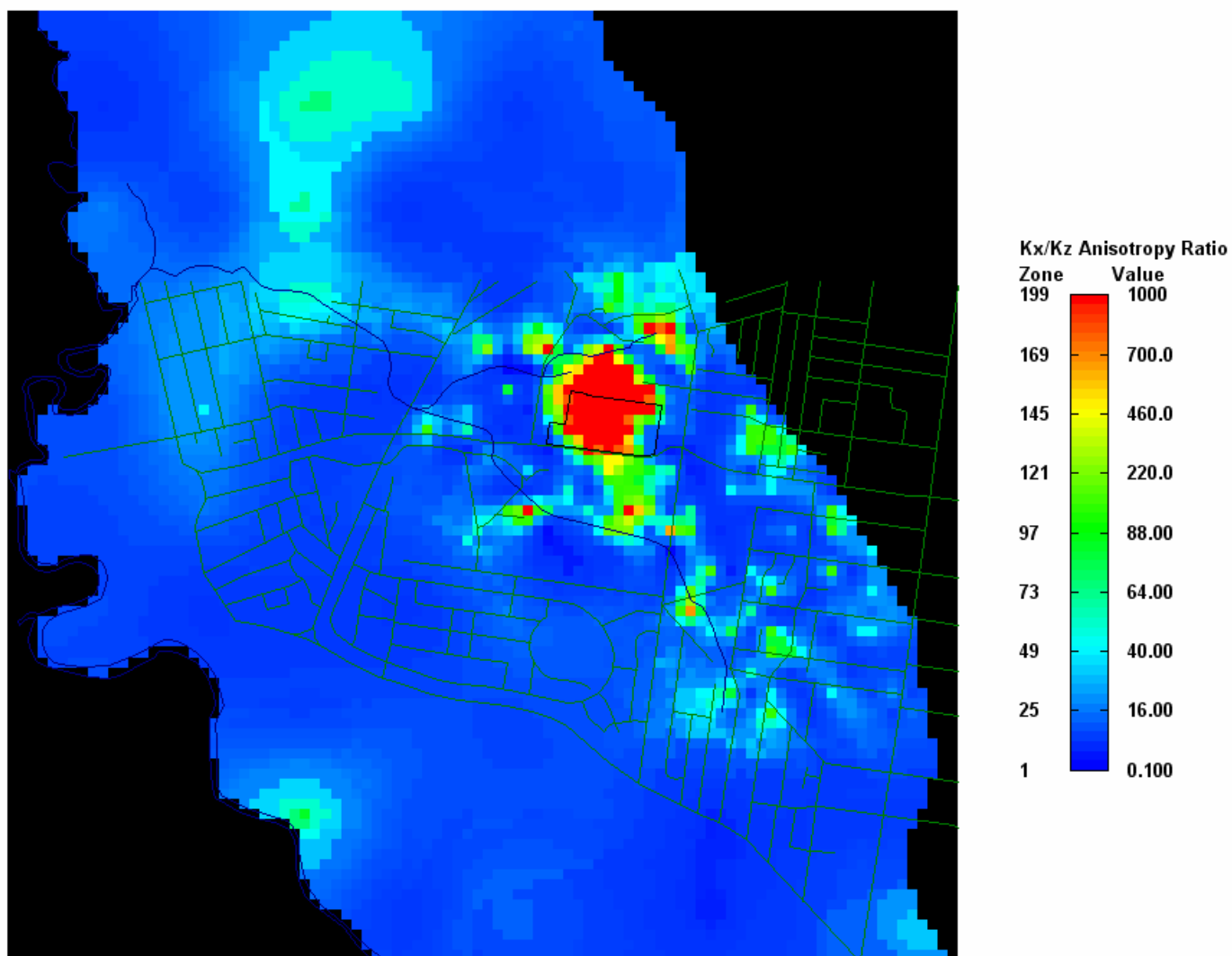


Figure 5.2.1-33. Recharge Scenario 3, model layer 3 hydraulic conductivity anisotropy ratio.

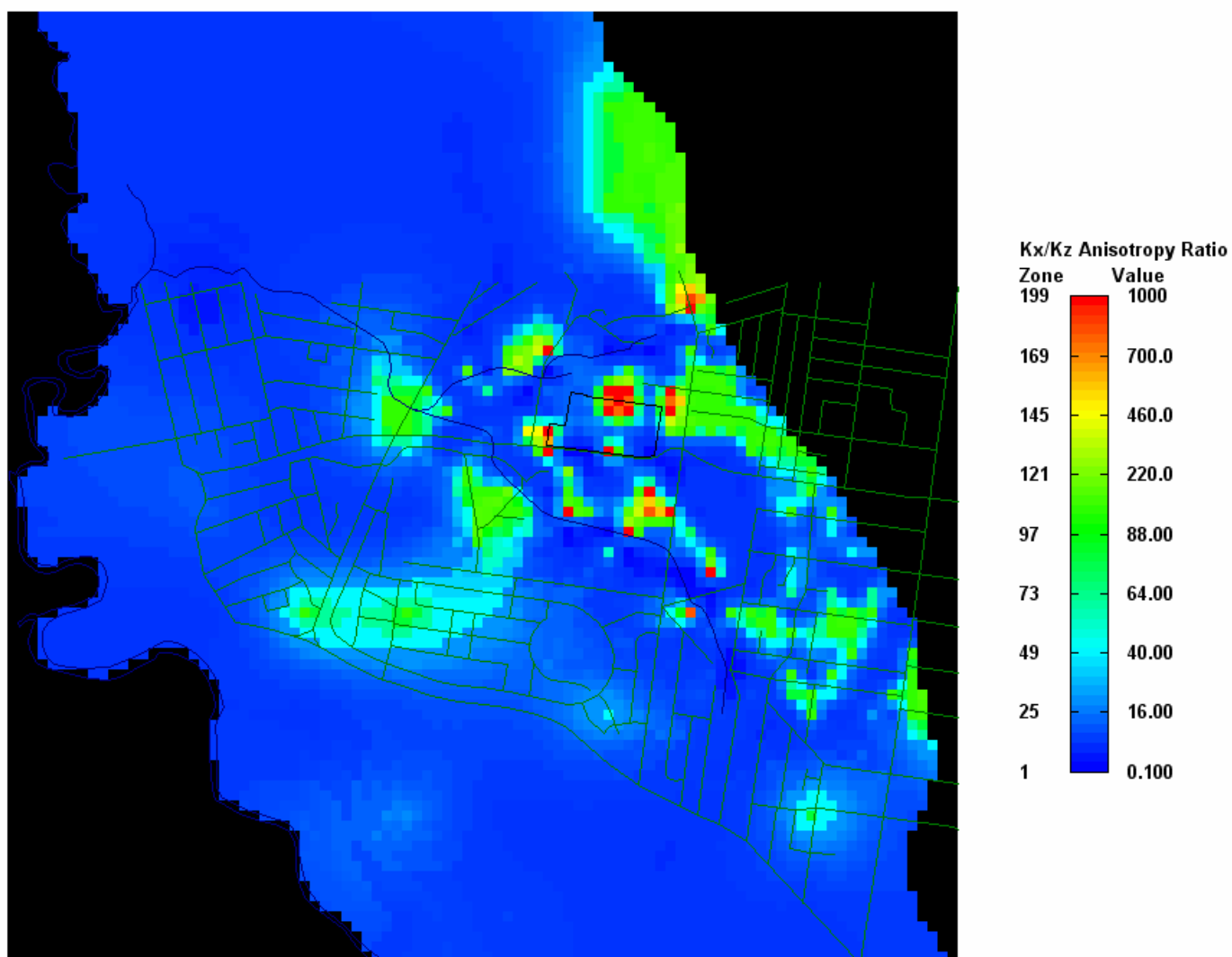


Figure 5.2.1-34. Recharge Scenario 4, model layer 1 hydraulic conductivity anisotropy ratio.

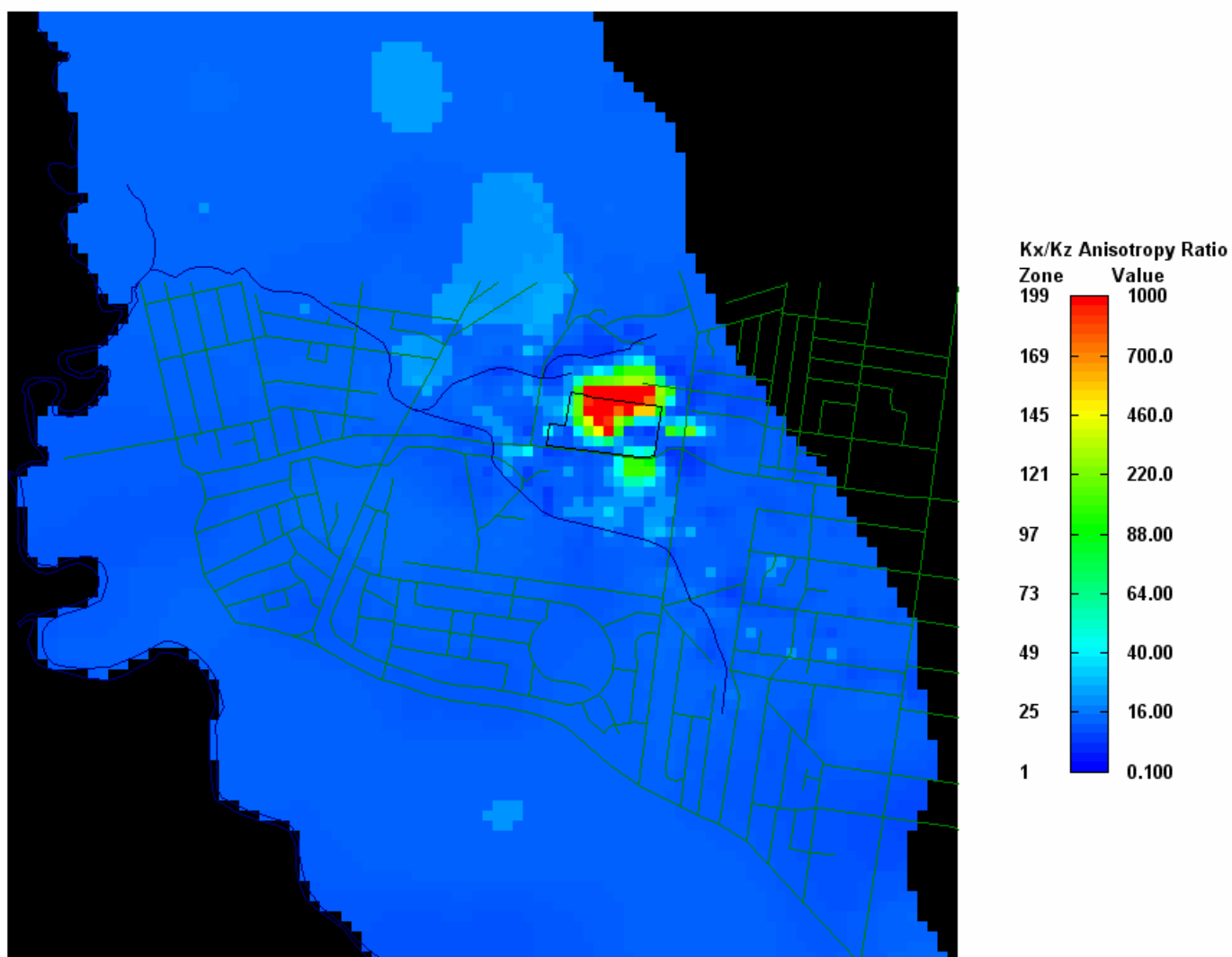


Figure 5.2.1-35. Recharge Scenario 4, model layer 2 hydraulic conductivity anisotropy ratio.

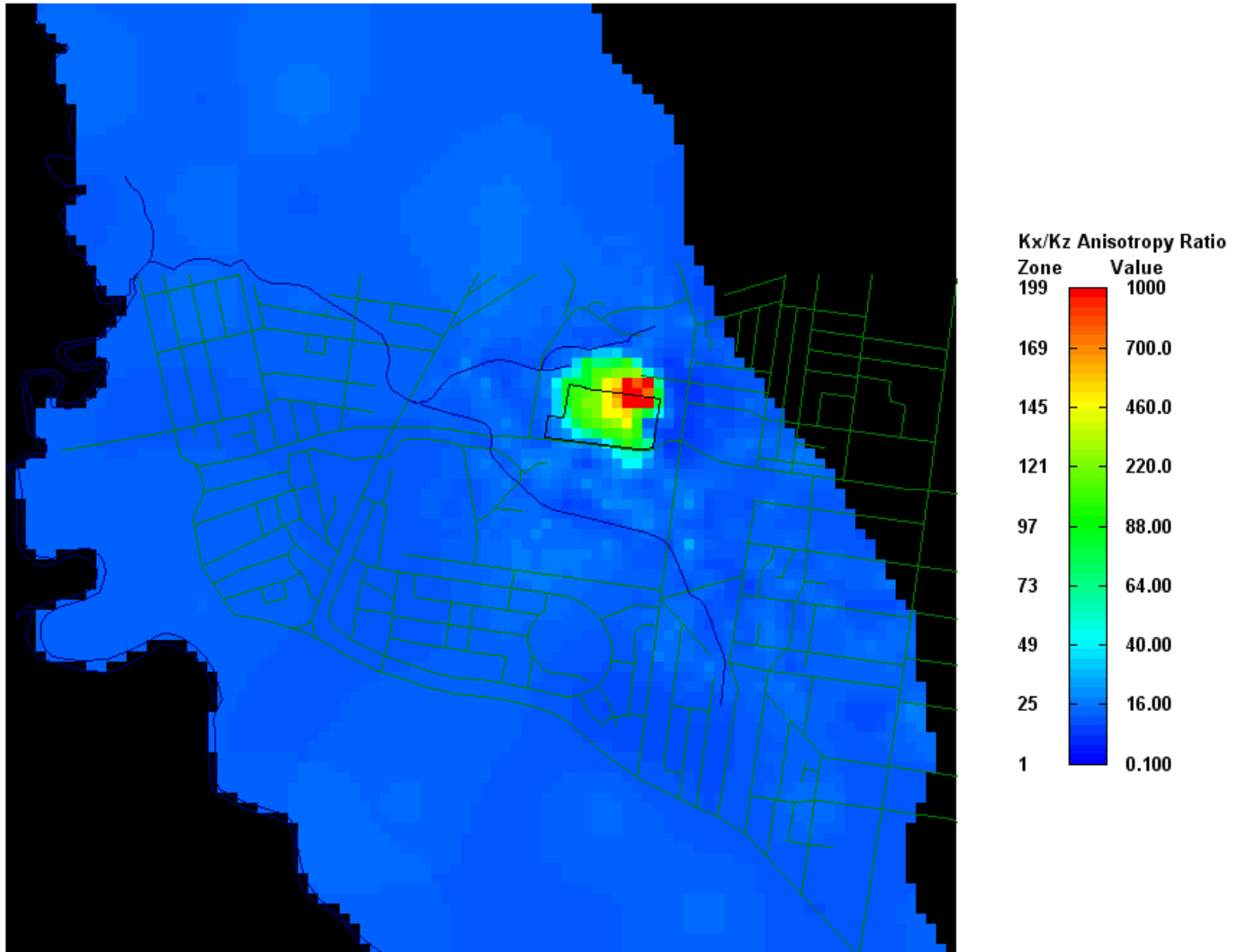


Figure 5.2.1-36. Recharge Scenario 4, model layer 3 hydraulic conductivity anisotropy ratio.

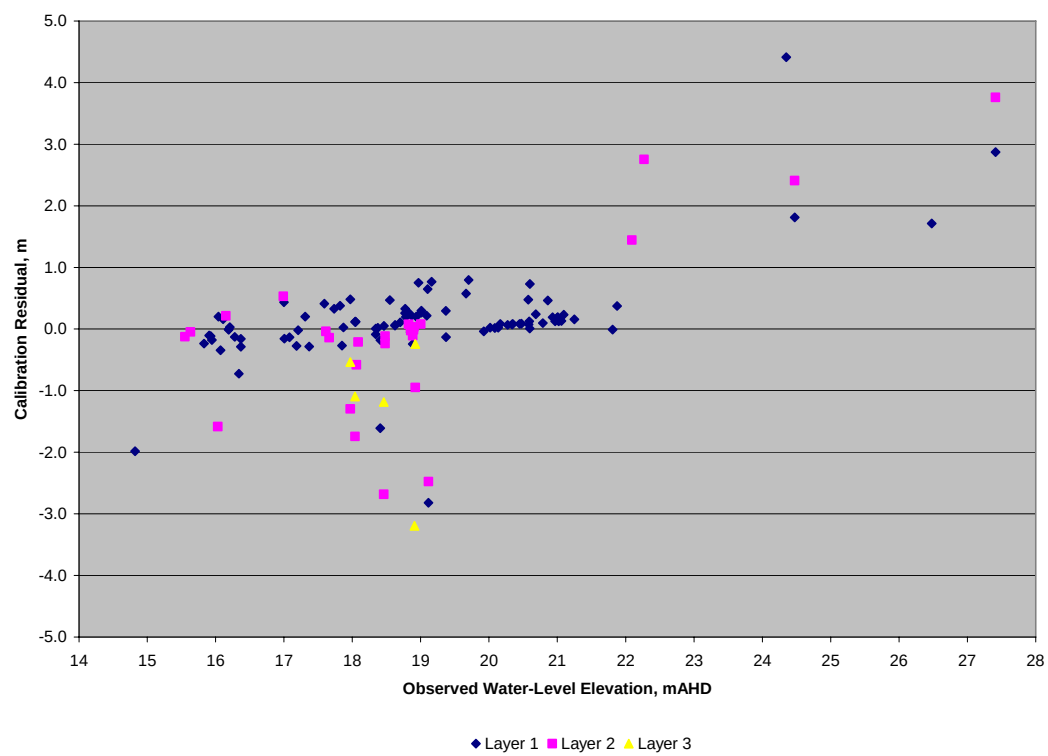


Figure 5.2.4-1. Recharge scenario 1 calibrated model residuals versus measured water-level elevations.

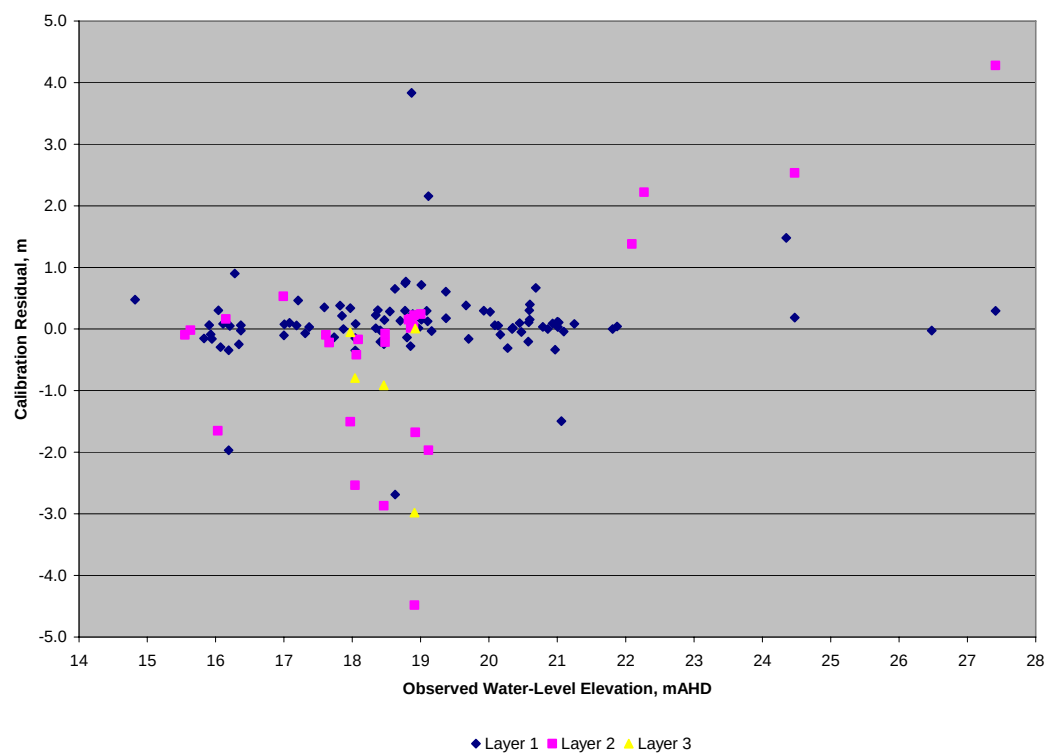


Figure 5.2.4-2. Recharge scenario 2 calibrated model residuals versus measured water-level elevations.

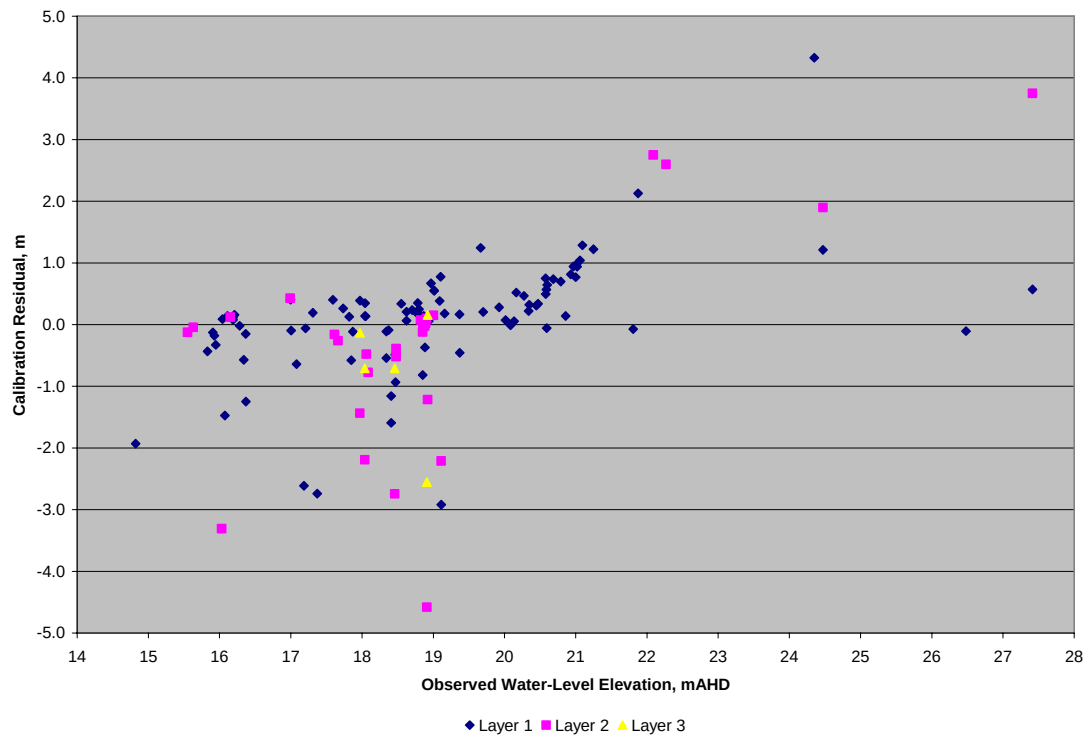


Figure 5.2.4-3. Recharge scenario 3 calibrated model residuals versus measured water-level elevations.

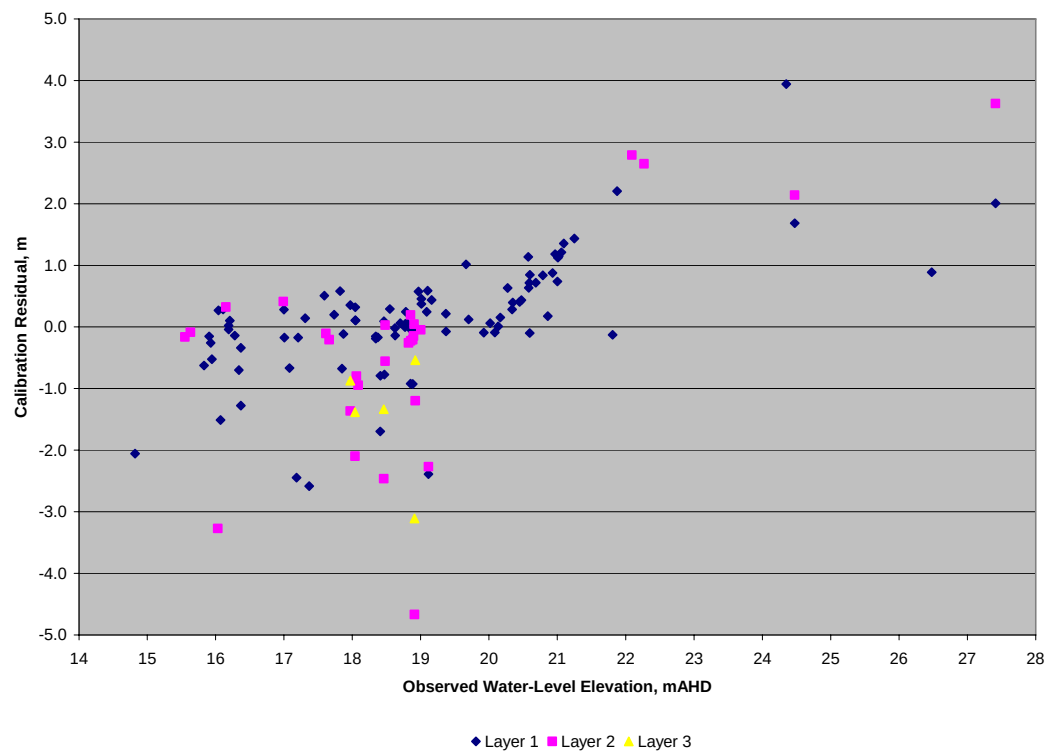
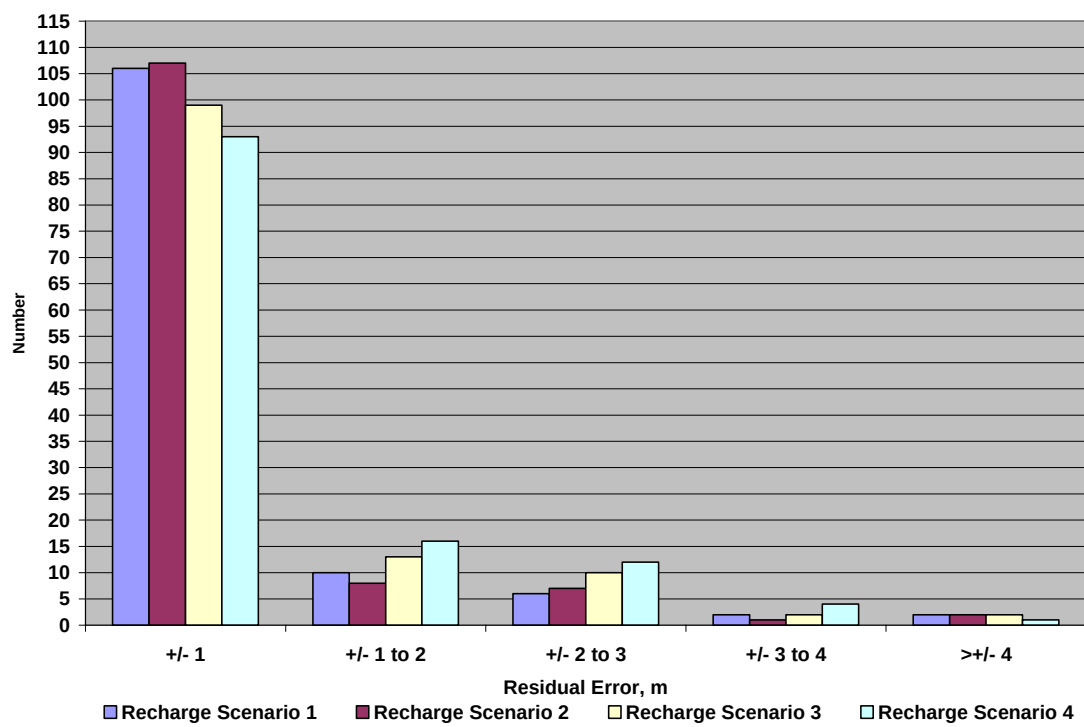


Figure 5.2.4-4. Recharge scenario 4 calibrated model residuals versus measured water-level elevations.



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Figure 5.2.4-5. Distribution of model calibration residuals.

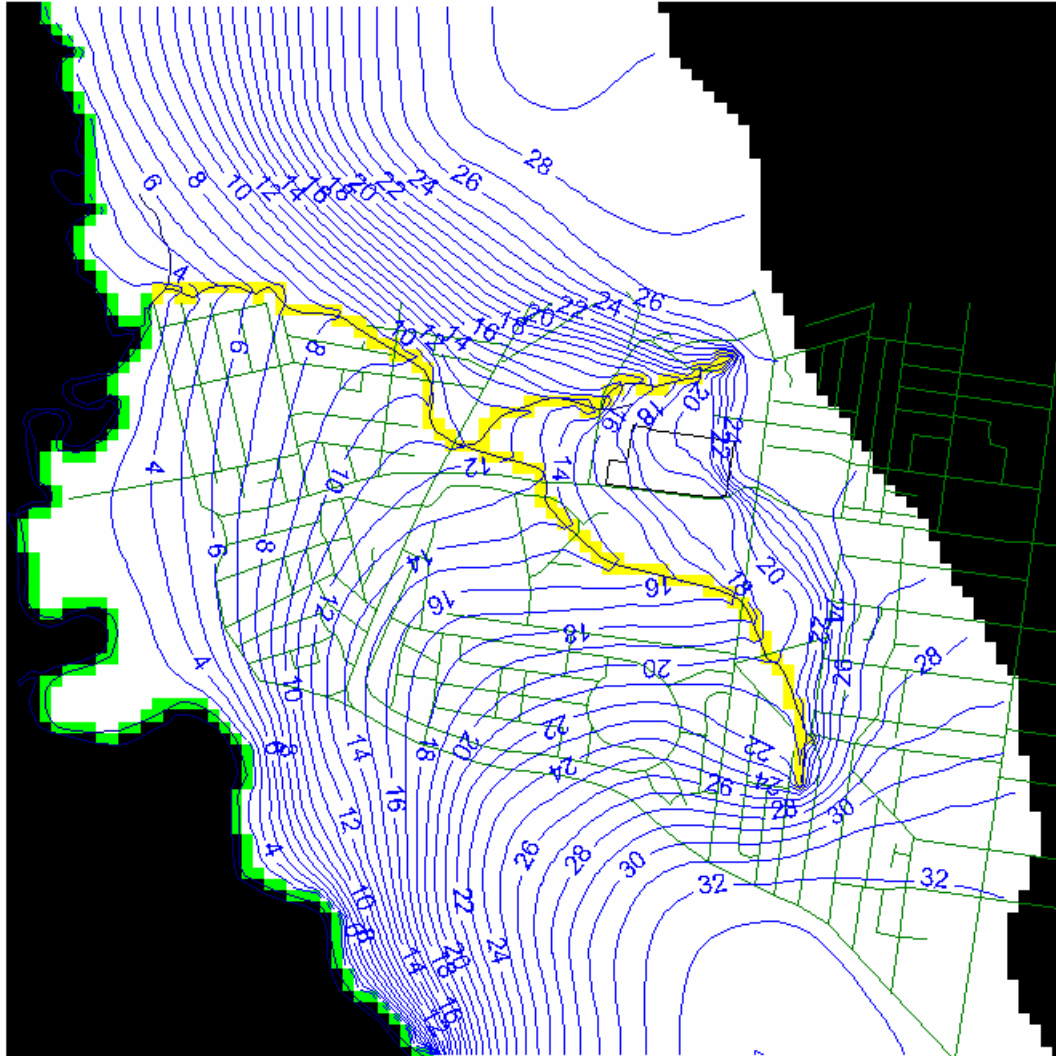


Figure 5.2.4-6. Recharge scenario 1, model layer 1 model-predicted potentiometric surface.

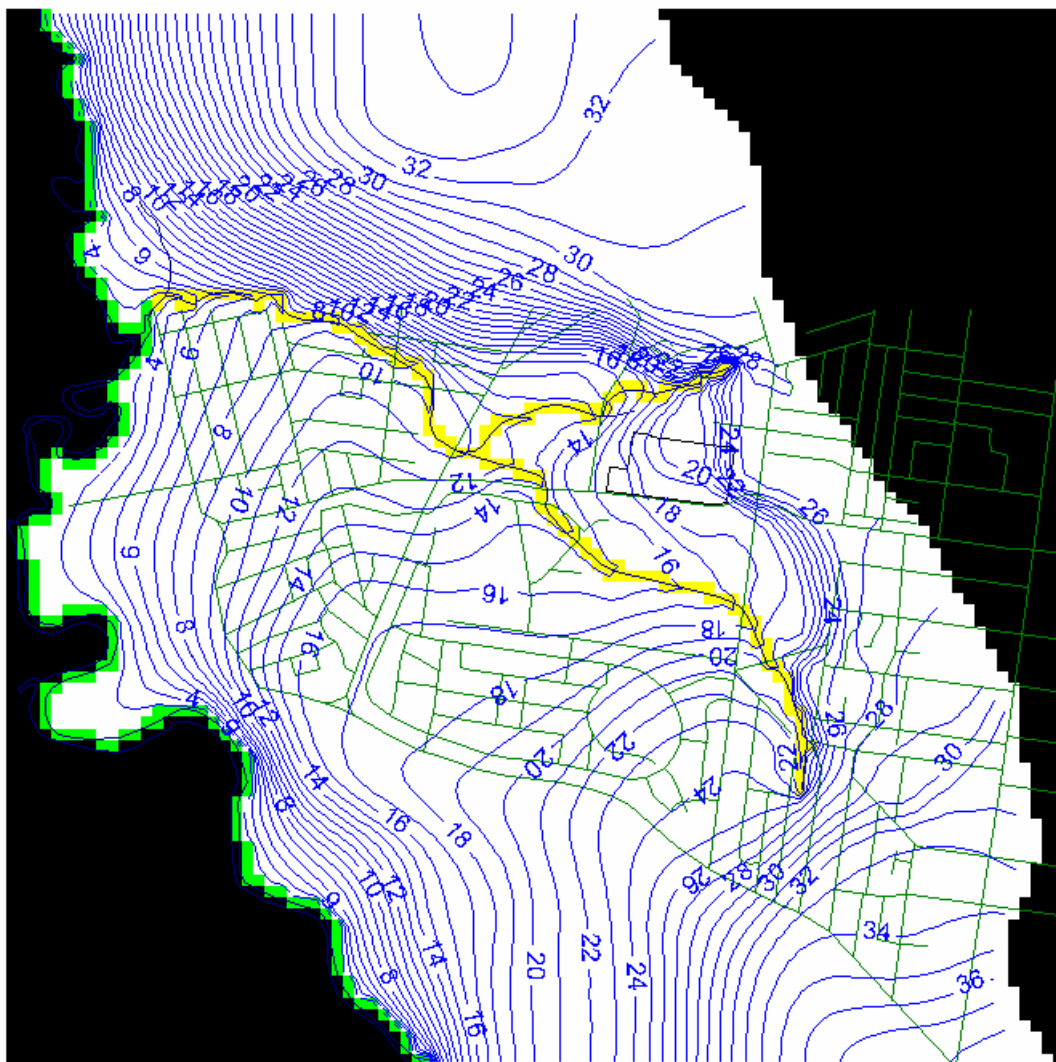


Figure 5.2.4-7. Recharge scenario 2, model layer 1 model-predicted potentiometric surface.

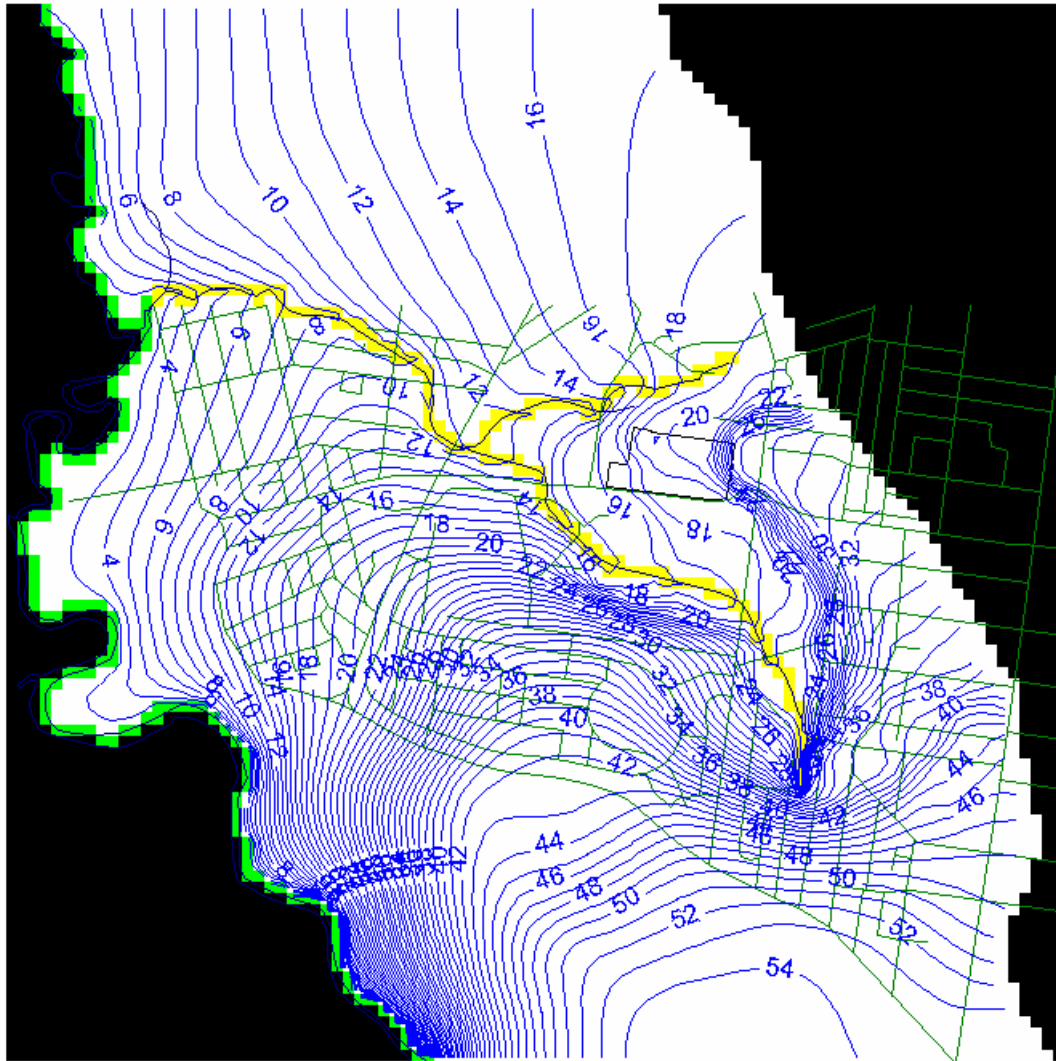


Figure 5.2.4-8. Recharge scenario 3, model layer 1 model-predicted potentiometric surface.

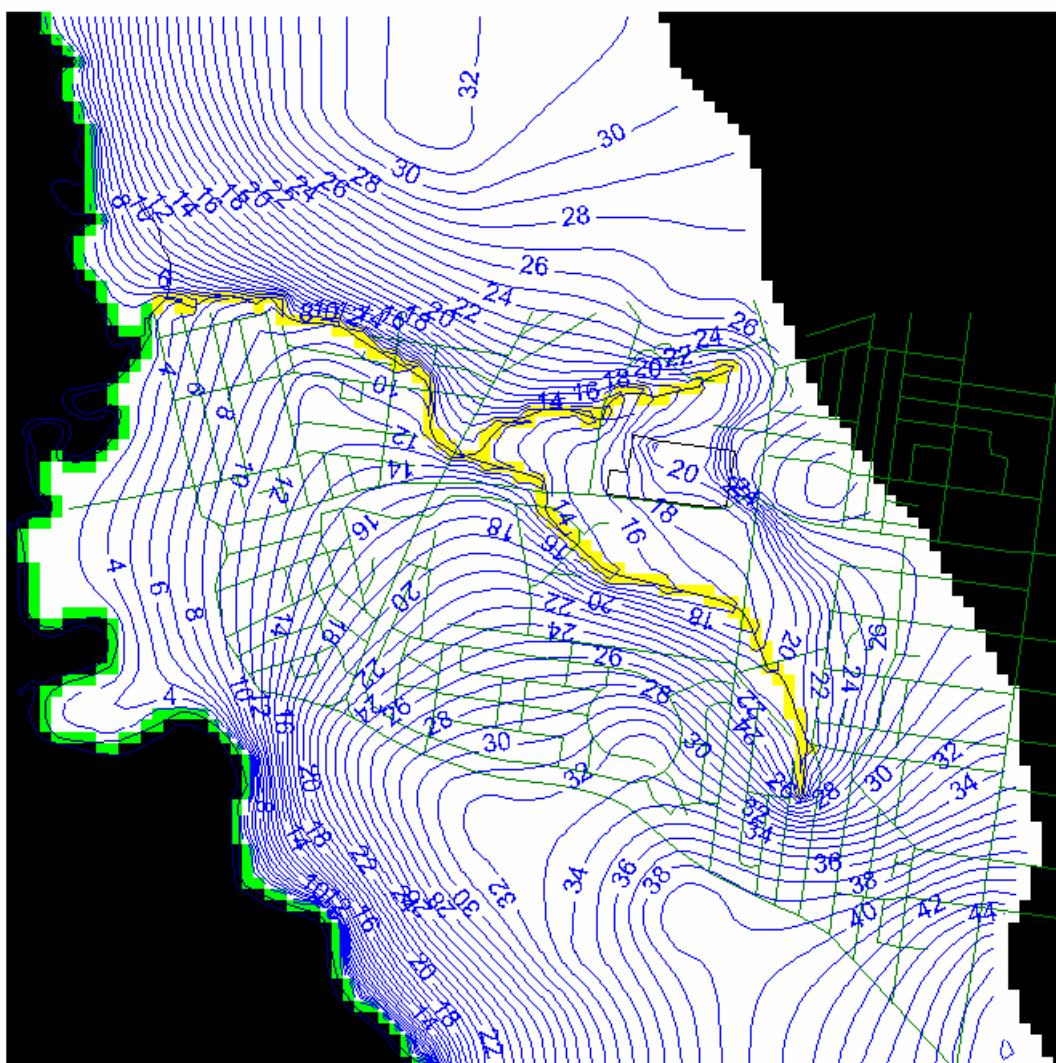


Figure 5.2.4-9. Recharge scenario 4, model layer 1 model-predicted potentiometric surface.

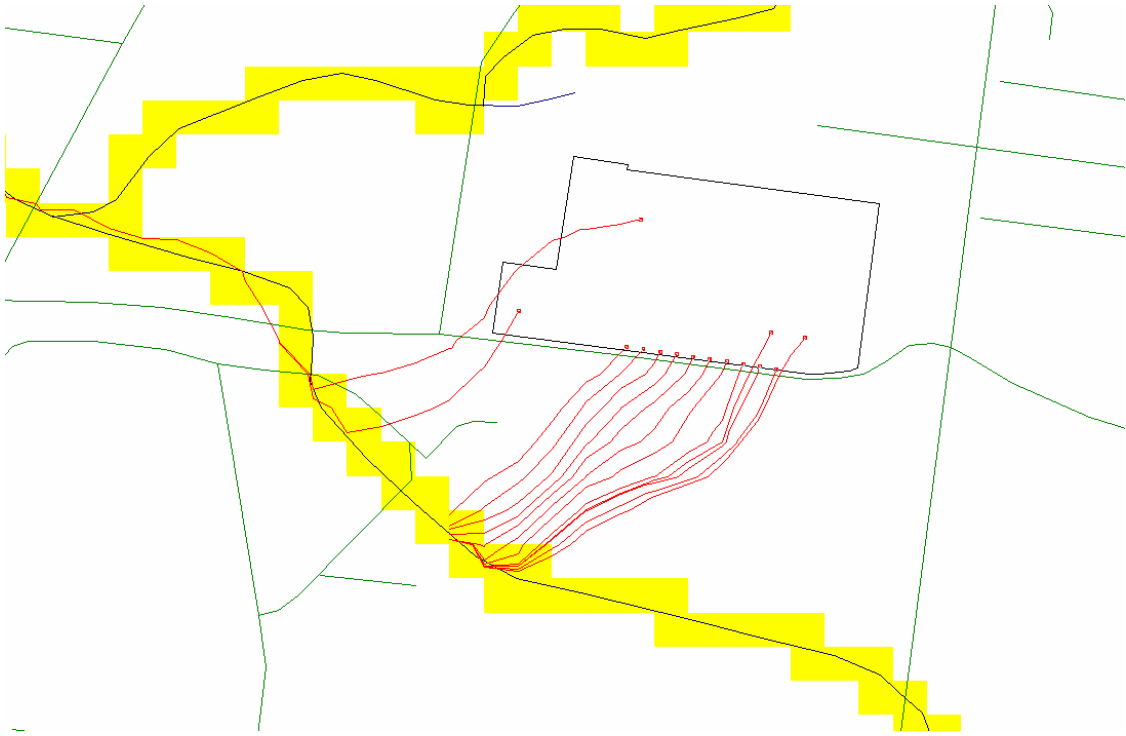


Figure 5.2.5-1. Recharge scenario 1, model layer 1 particle traces.

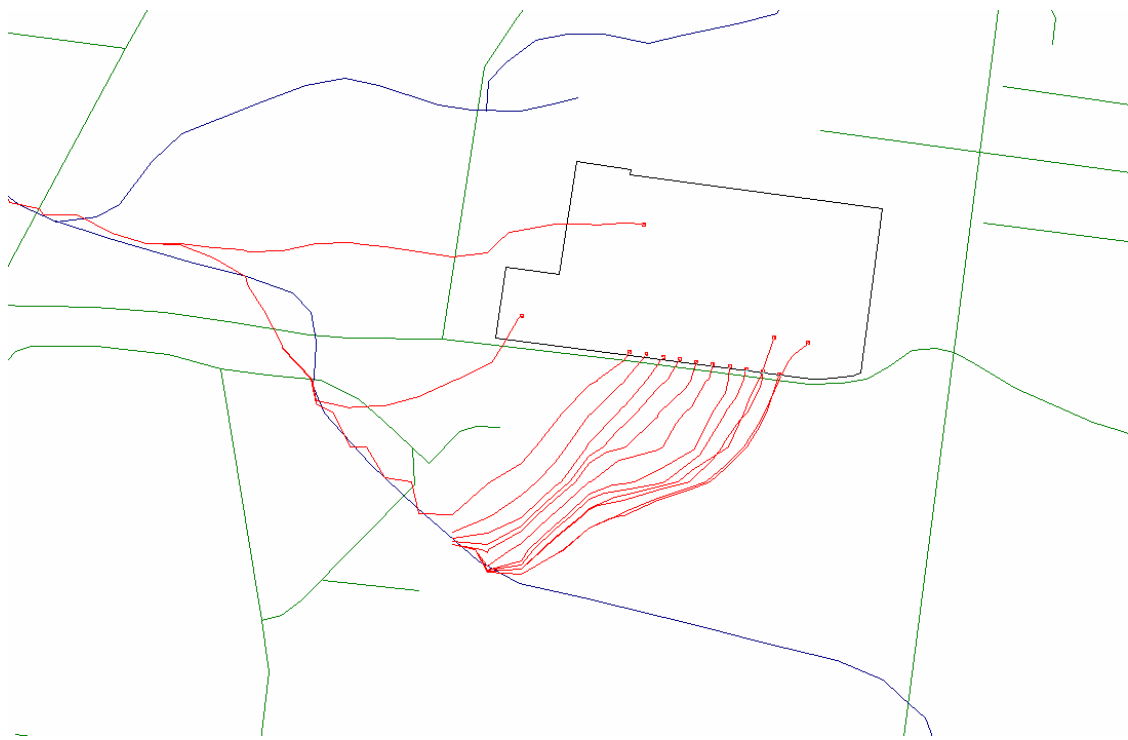


Figure 5.2.5-2. Recharge scenario 1, model layer 2 particle traces.

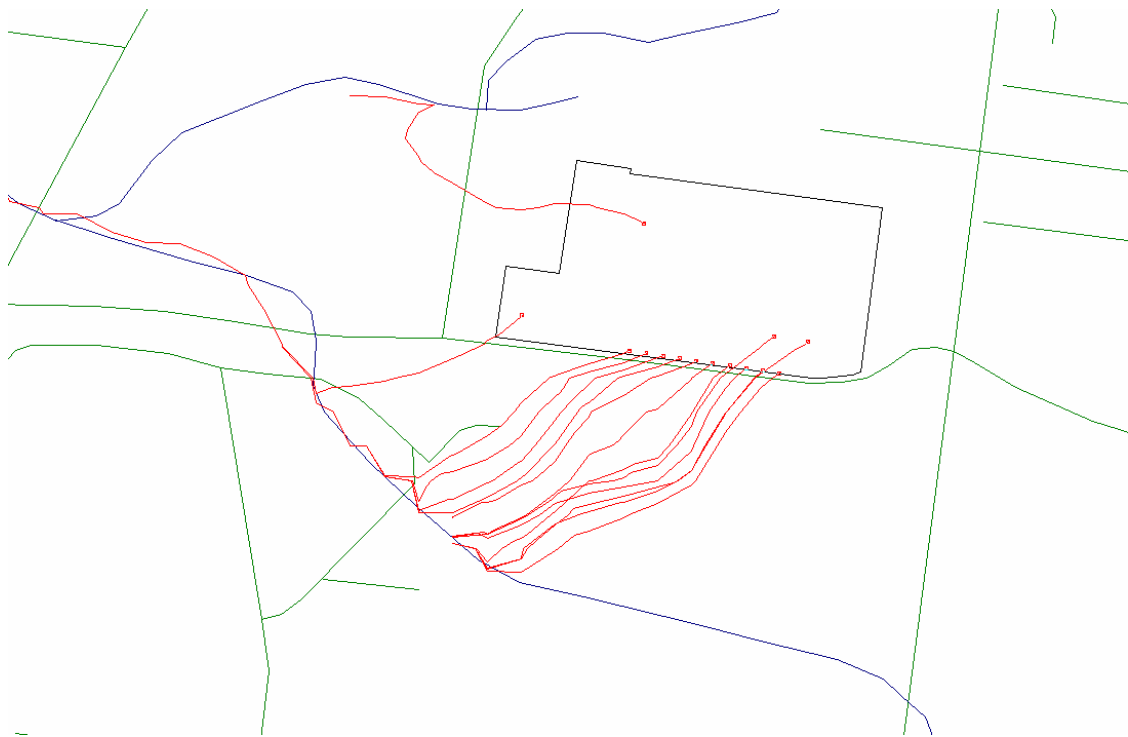


Figure 5.2.4-3. Recharge scenario 1, model layer 3 particle traces.



Figure 5.2.5-4. Recharge scenario 2, model layer 1 particle traces.

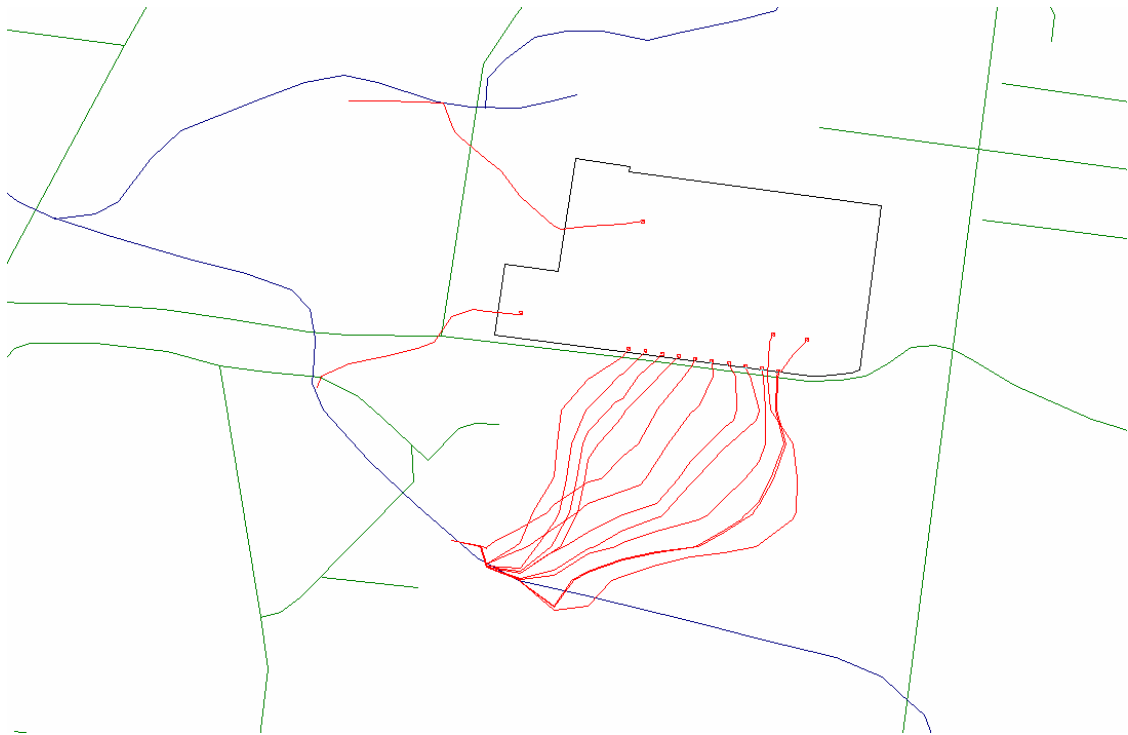


Figure 5.2.5-5. Recharge scenario 2, model layer 2 particle traces.



Figure 5.2.5-6. Recharge scenario 2, model layer 3 particle traces.



Figure 5.2.5-7. Recharge scenario 3, model layer 1 particle traces.

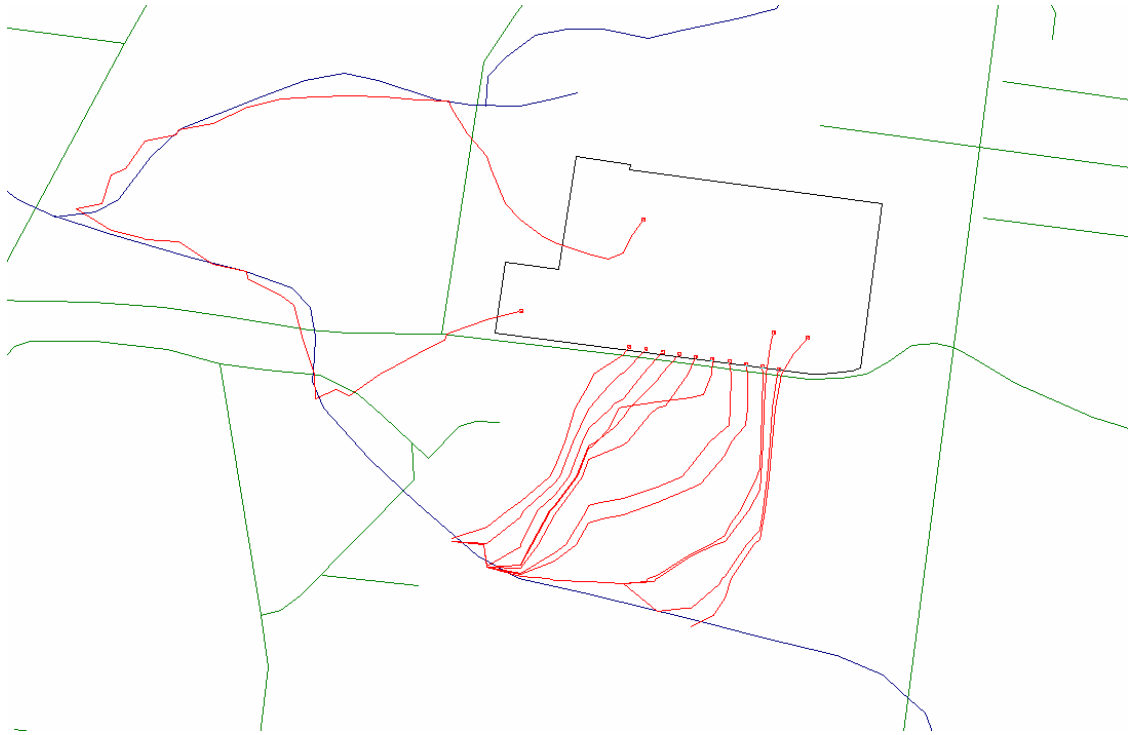


Figure 5.2.5-8. Recharge scenario 3, model layer 2 particle traces.



Figure 5.2.5-9. Recharge scenario 3, model layer 3 particle traces.



Figure 5.2.5-10. Recharge scenario 4, model layer 1 particle traces.



Figure 5.2.5-11. Recharge scenario 4, model layer 2 particle traces.

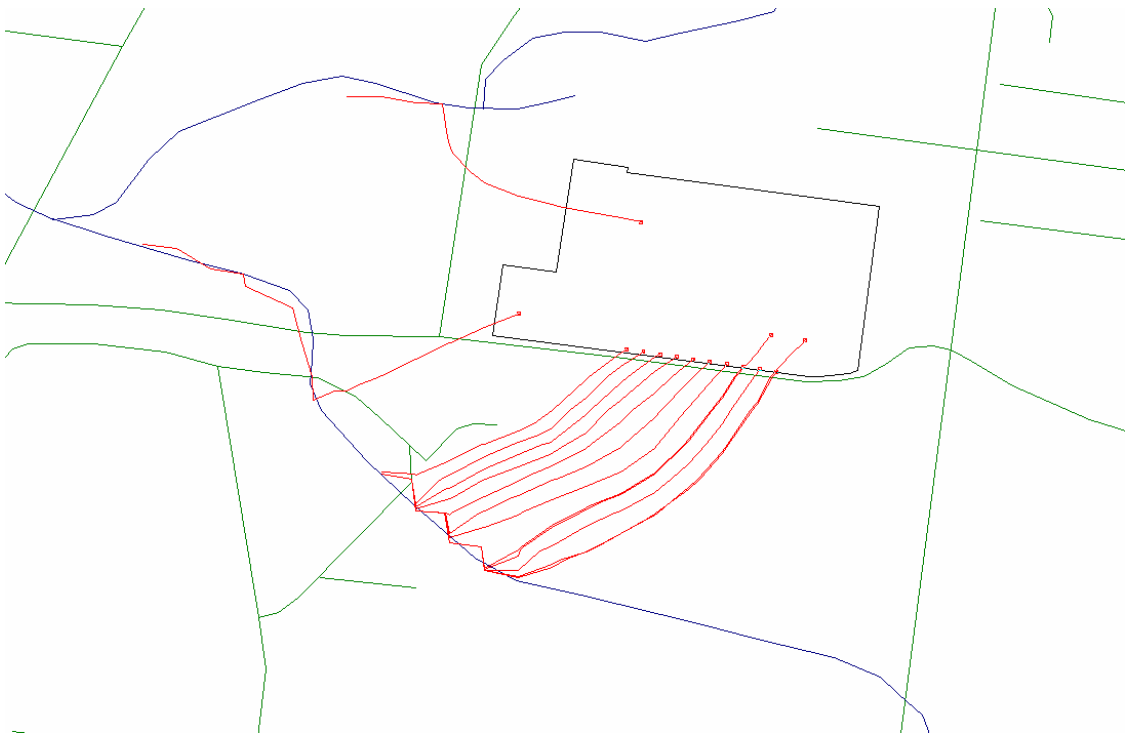


Figure 5.2.5-12. Recharge scenario 4, model layer 3 particle traces.

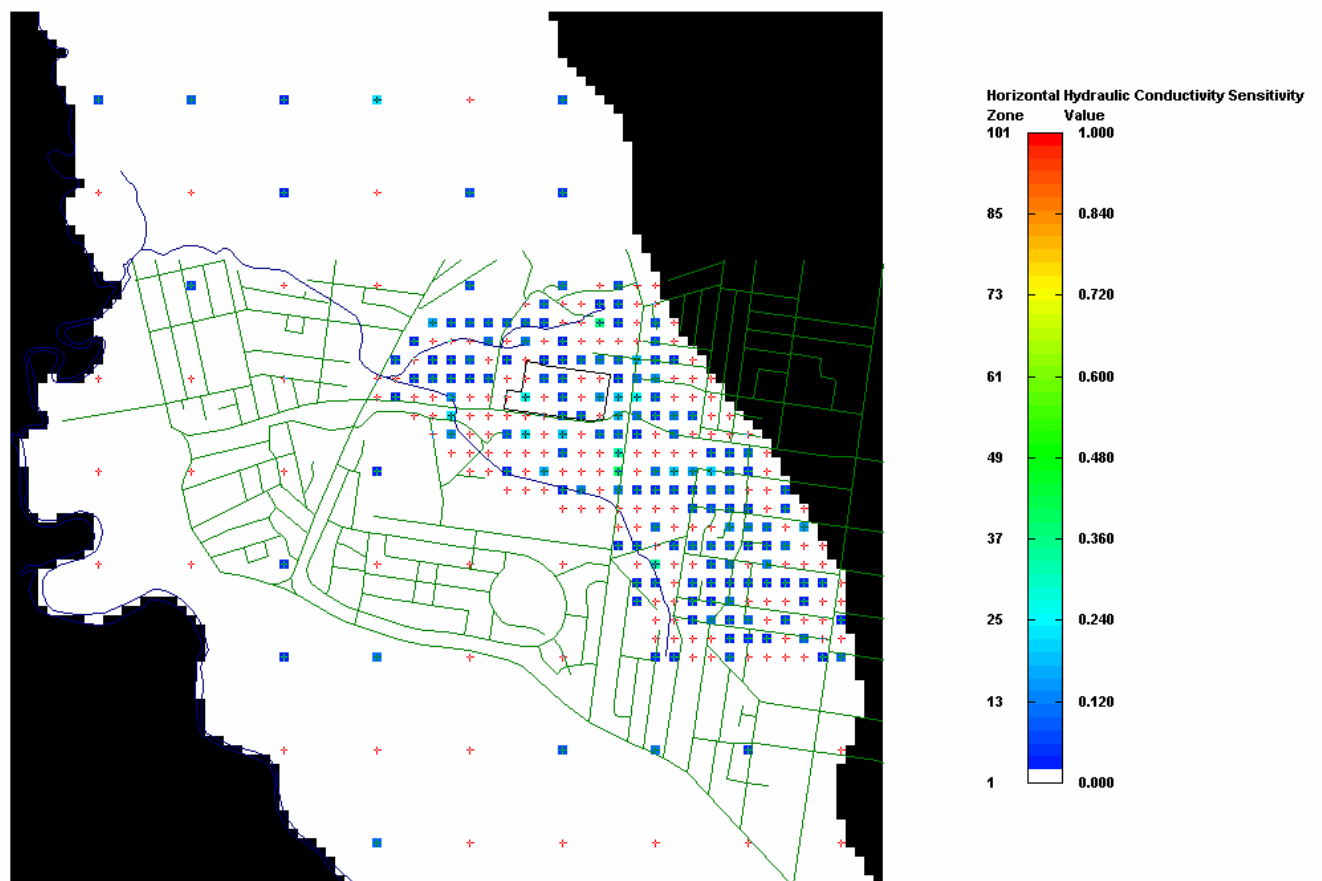


Figure 5.3-1. Horizontal hydraulic conductivity model layer 1 pilot point sensitivities.

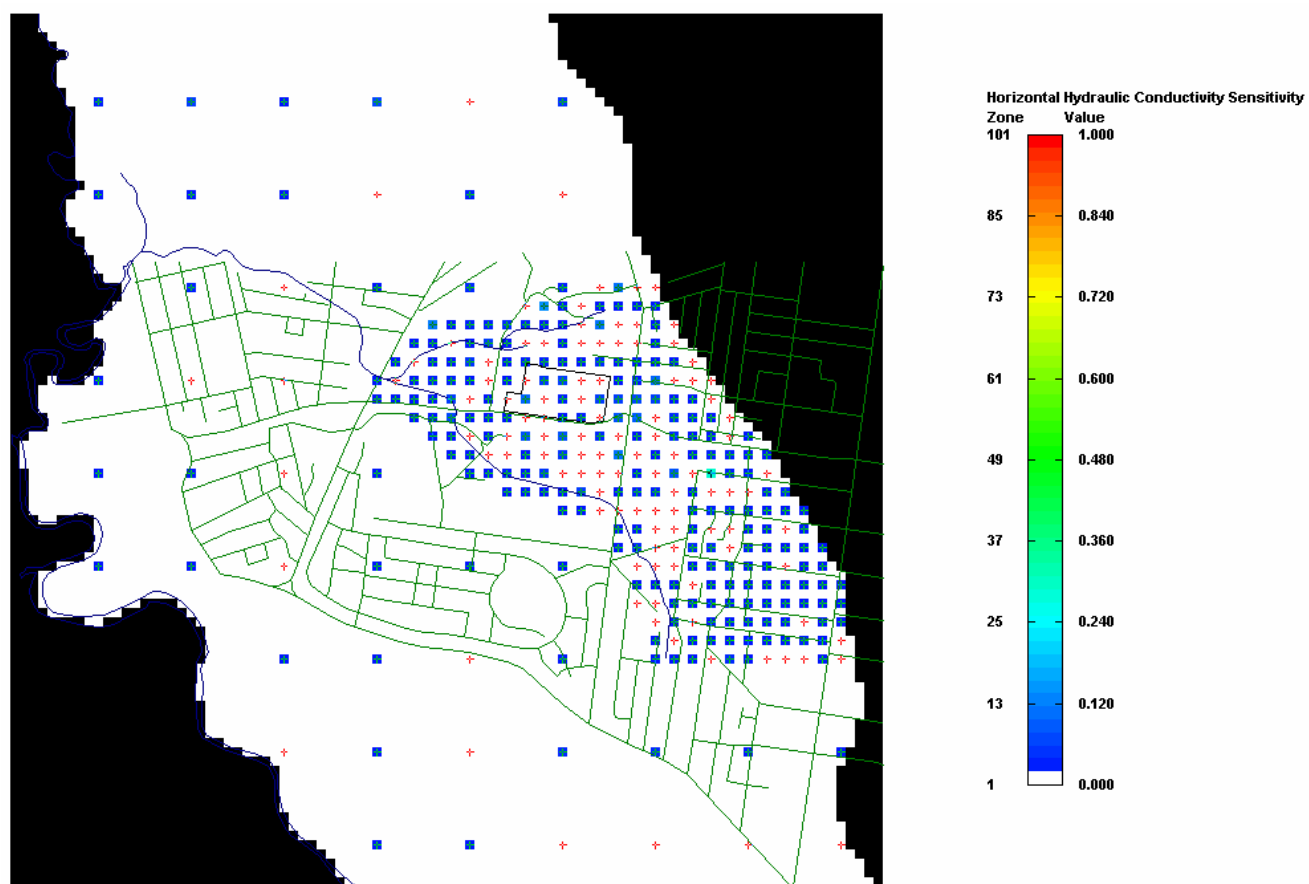


Figure 5.3-2. Horizontal hydraulic conductivity model layer 2 pilot point sensitivities.

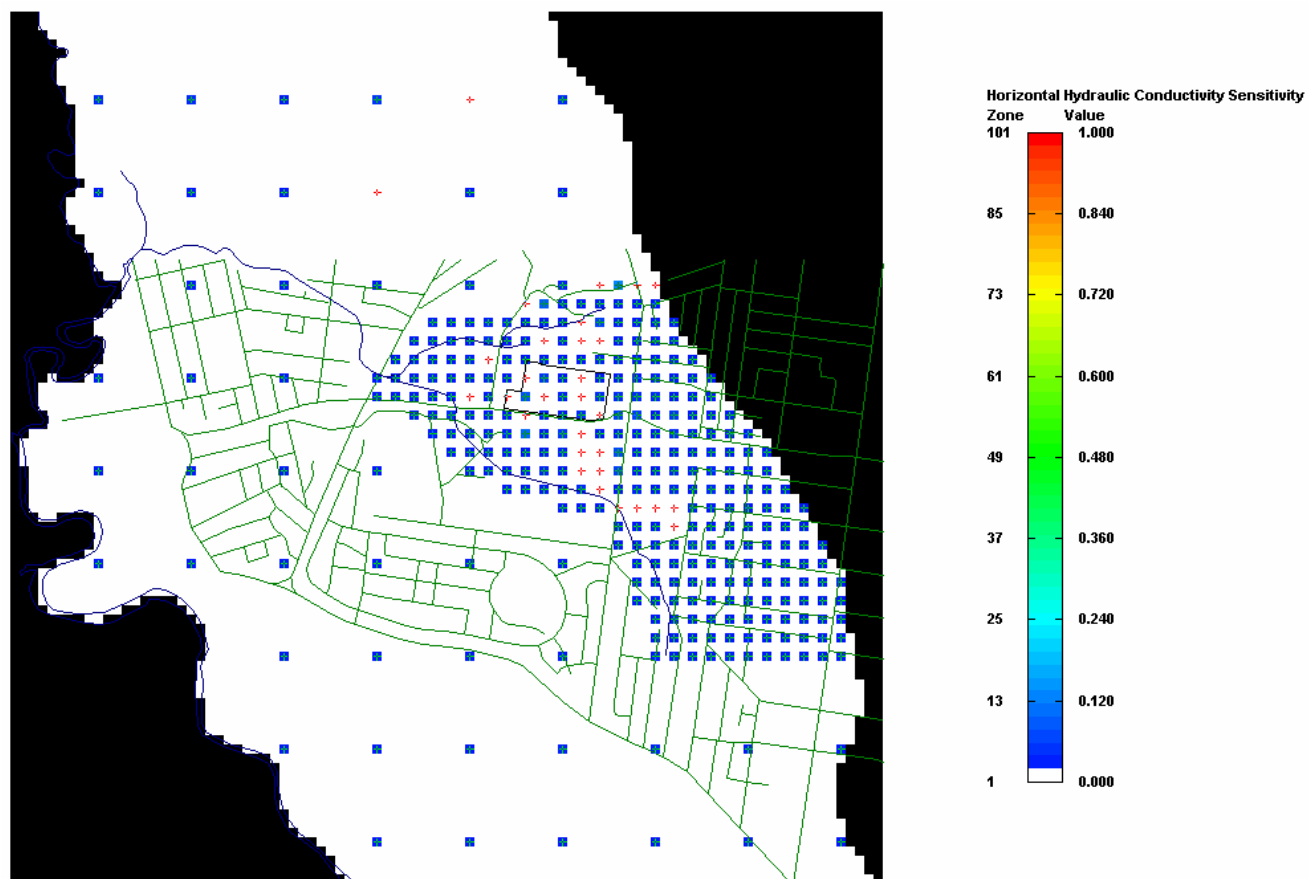


Figure 5.3-3. Horizontal hydraulic conductivity model layer 3 pilot point sensitivities.

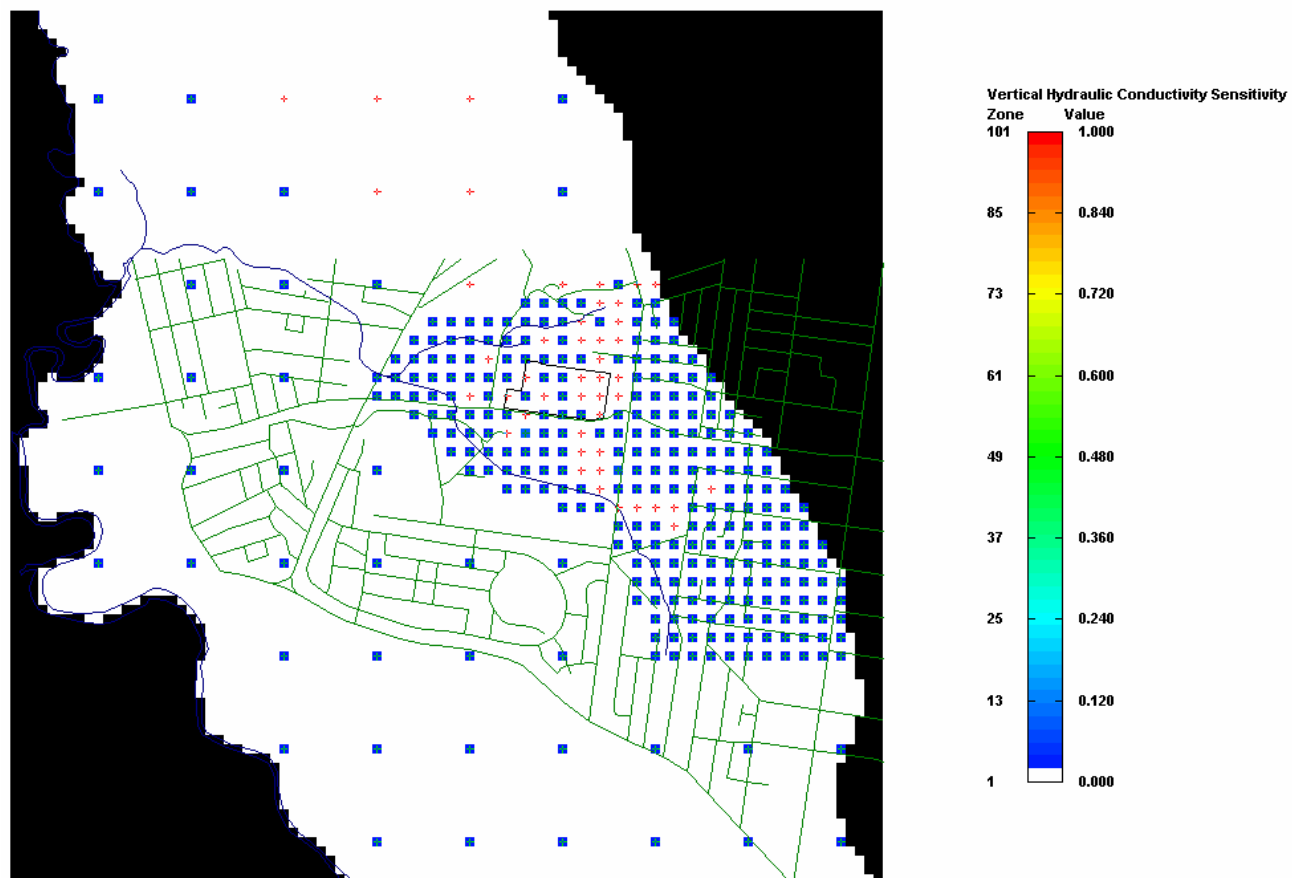


Figure 5.3-4. Vertical hydraulic conductivity model layer 1 pilot point sensitivities.

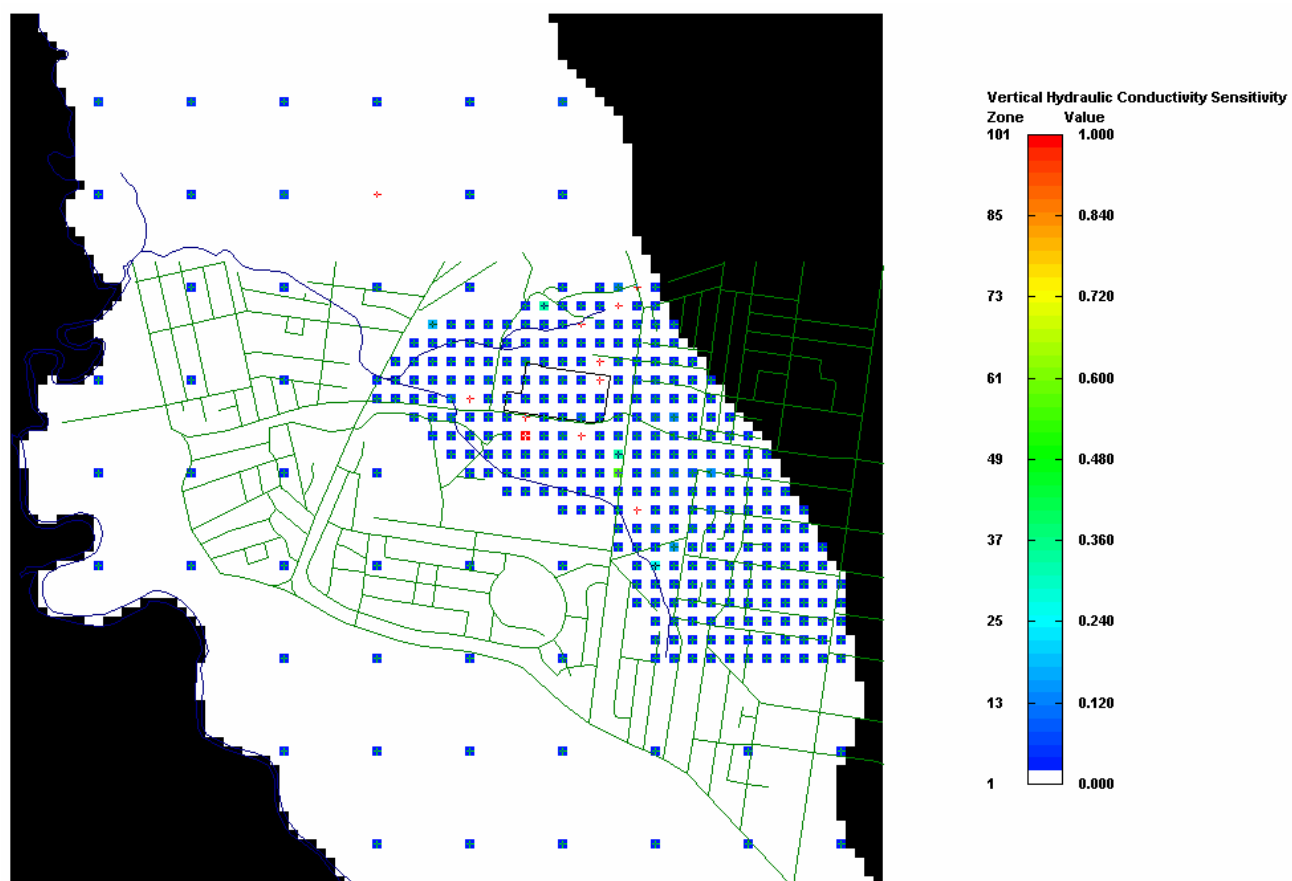


Figure 5.3-5. Vertical hydraulic conductivity model layer 2 pilot point sensitivities.

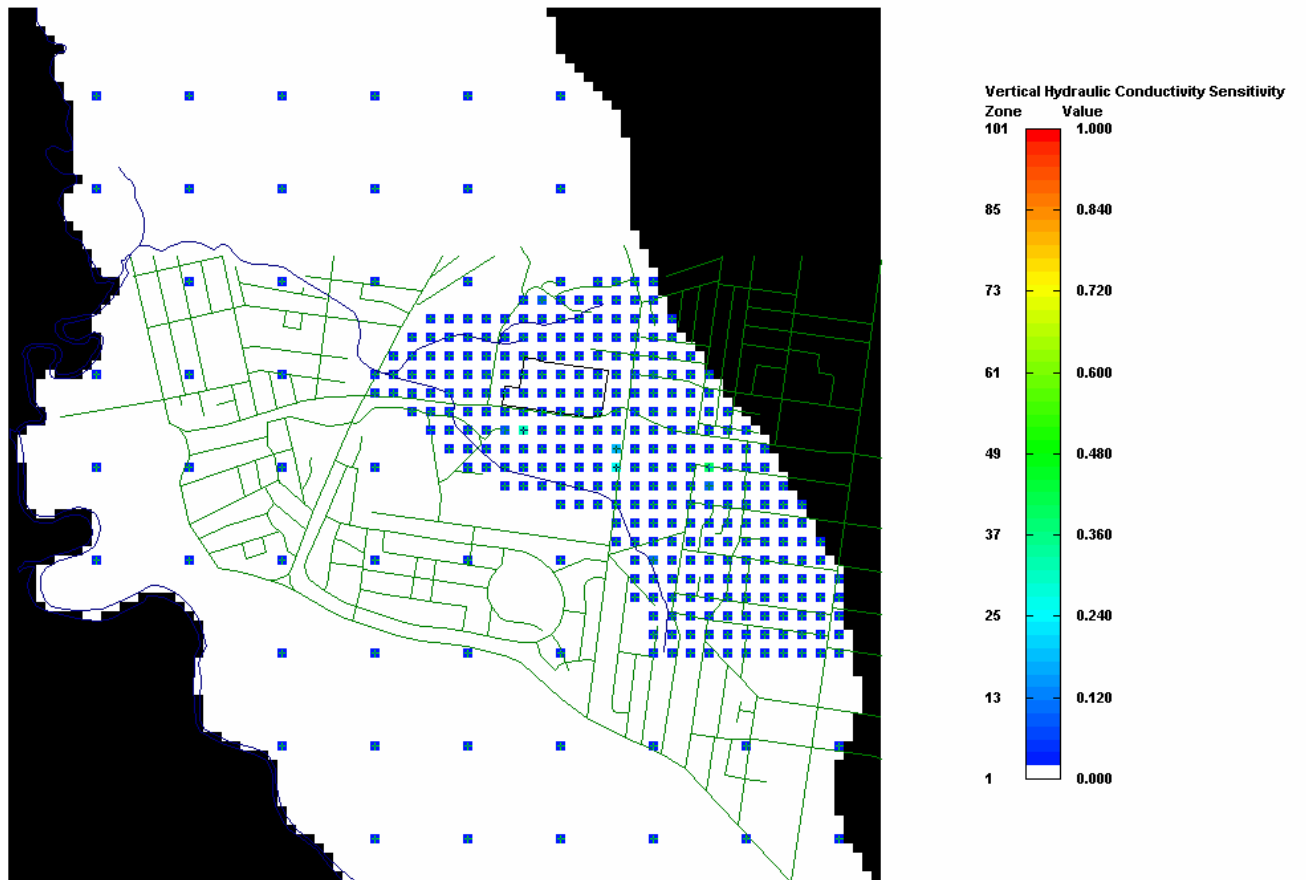


Figure 5.3-6. Vertical hydraulic conductivity model layer 3 pilot point sensitivities.

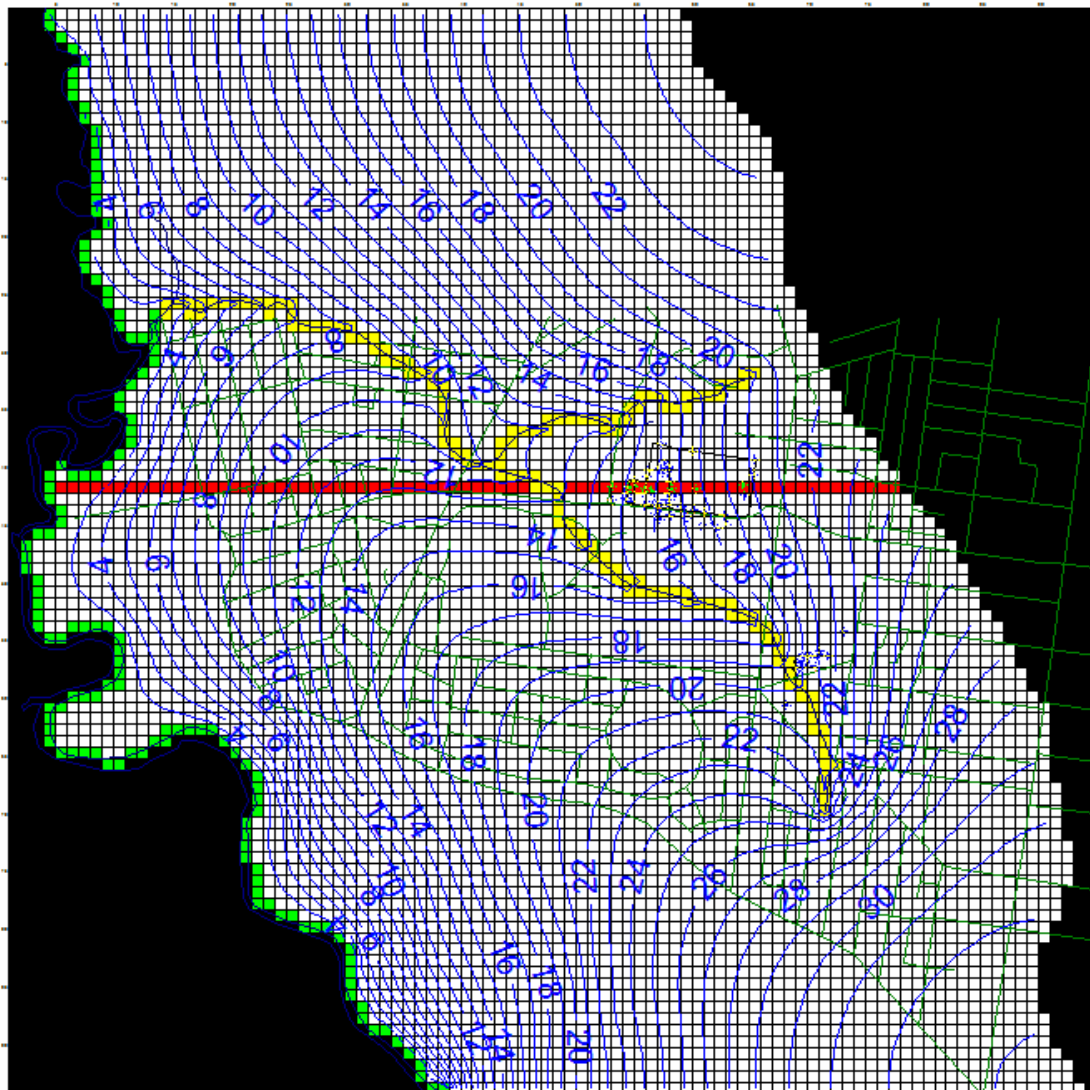


Figure 6.1-1. Location of Row 42 (red) from which the cross-sectional model was derived.

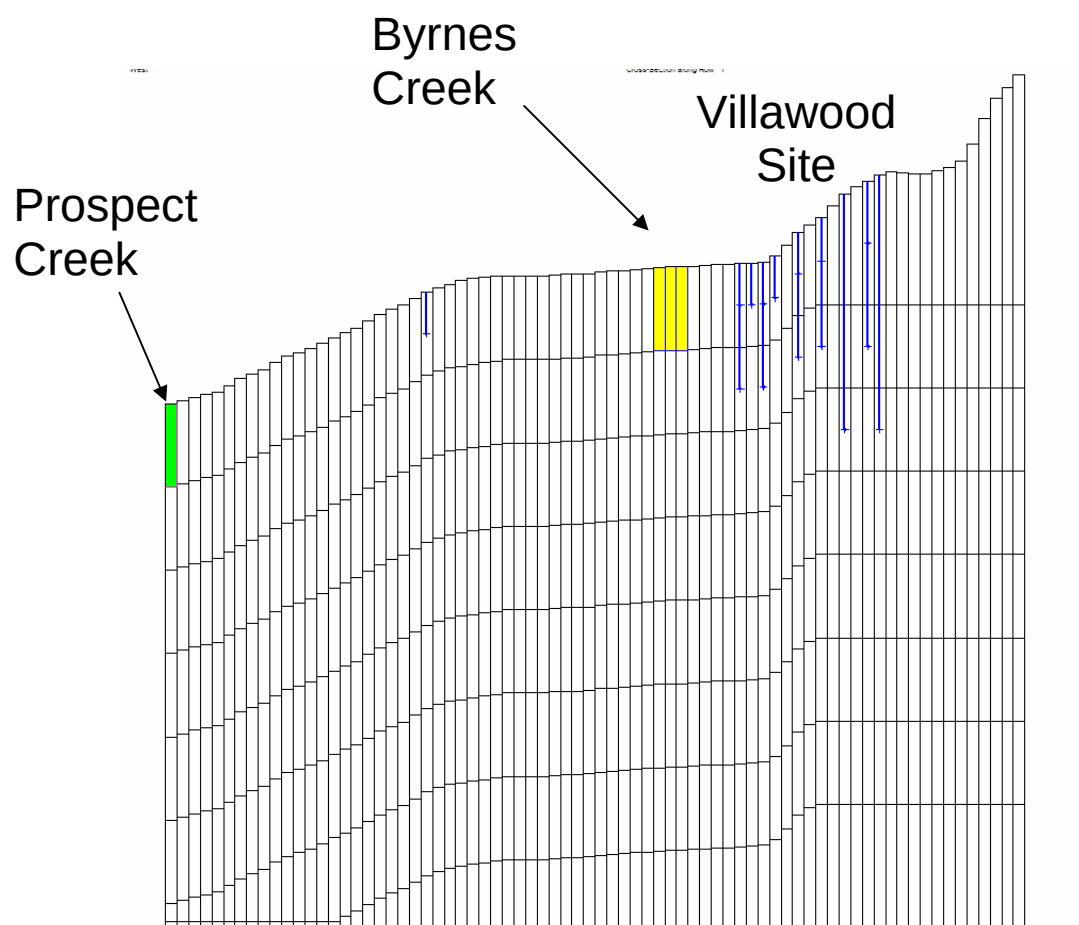


Figure 6.1-2. Cross-sectional model grid.

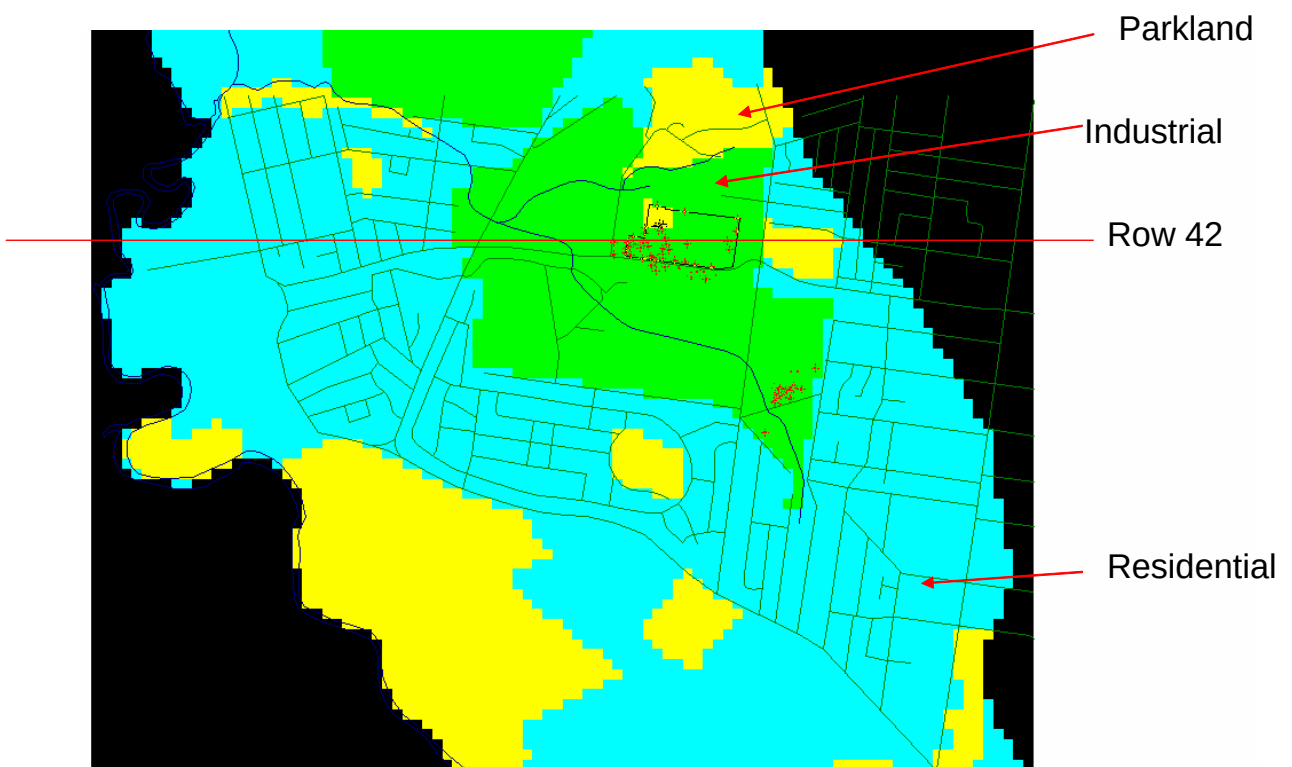


Figure 6.1-3. Recharge distribution along row 42.

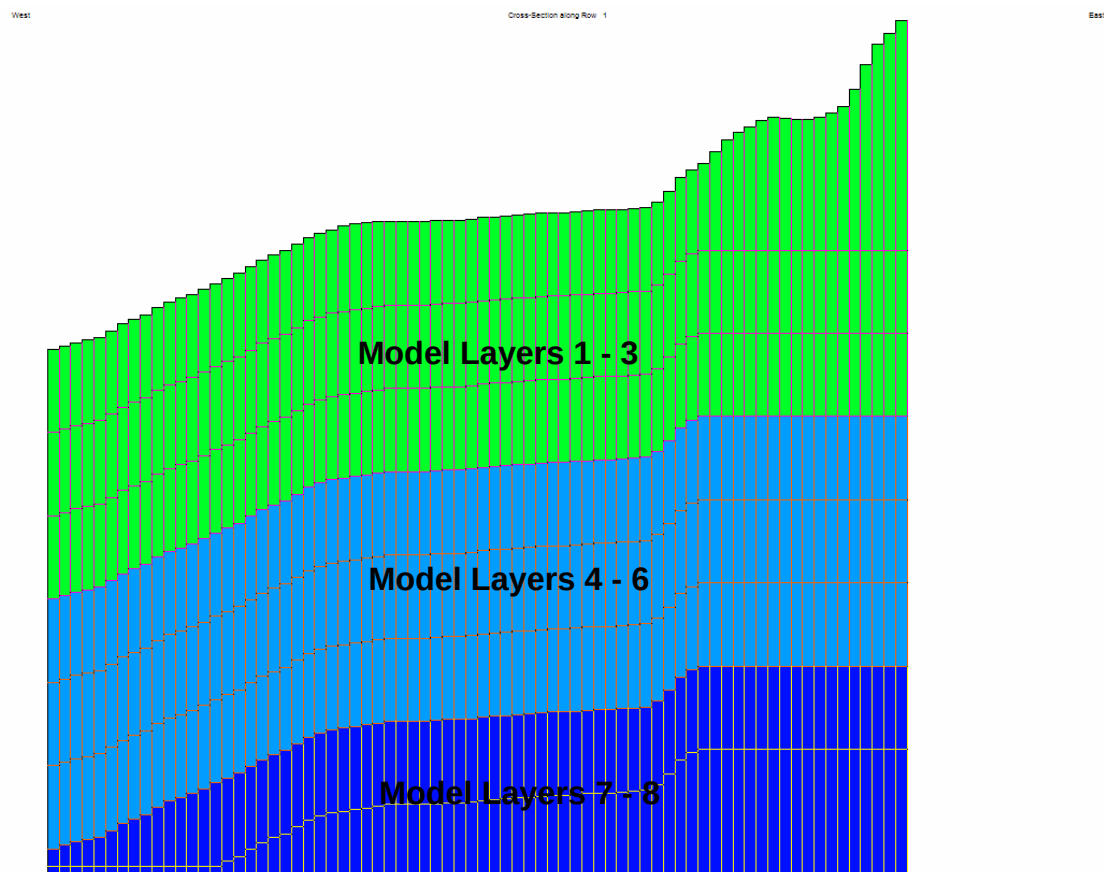


Figure 6.1-4. Hydraulic conductivity zones used in the cross-sectional model analysis.

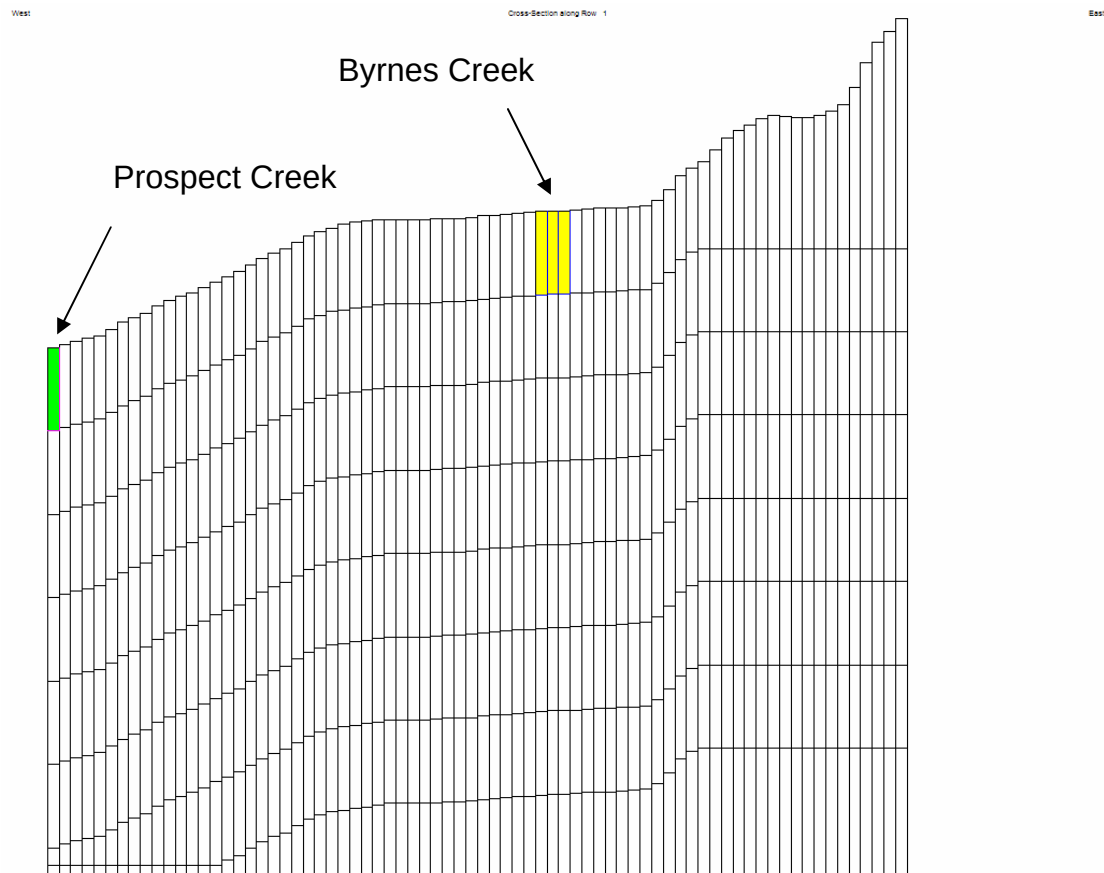


Figure 6.1-5. Boundary conditions along row 42.

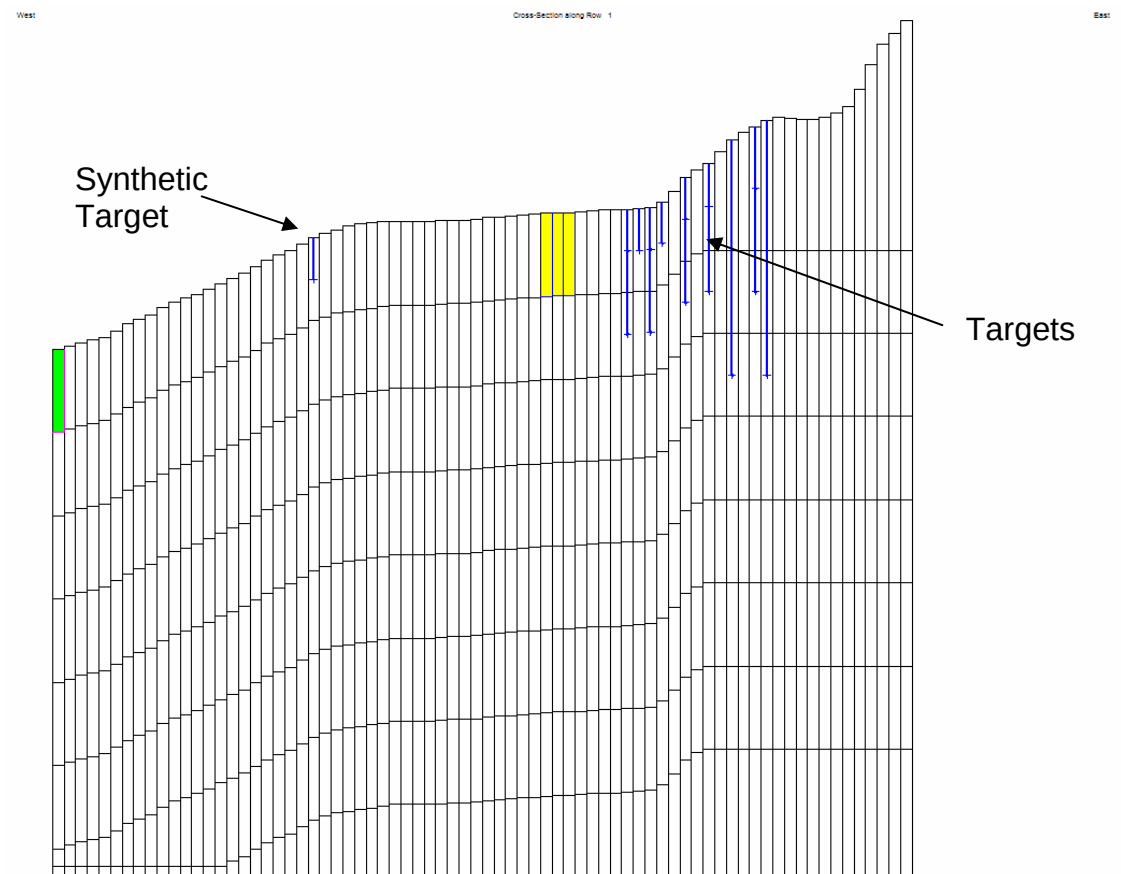


Figure 6.1-6. Location of water-level targets along row 42.

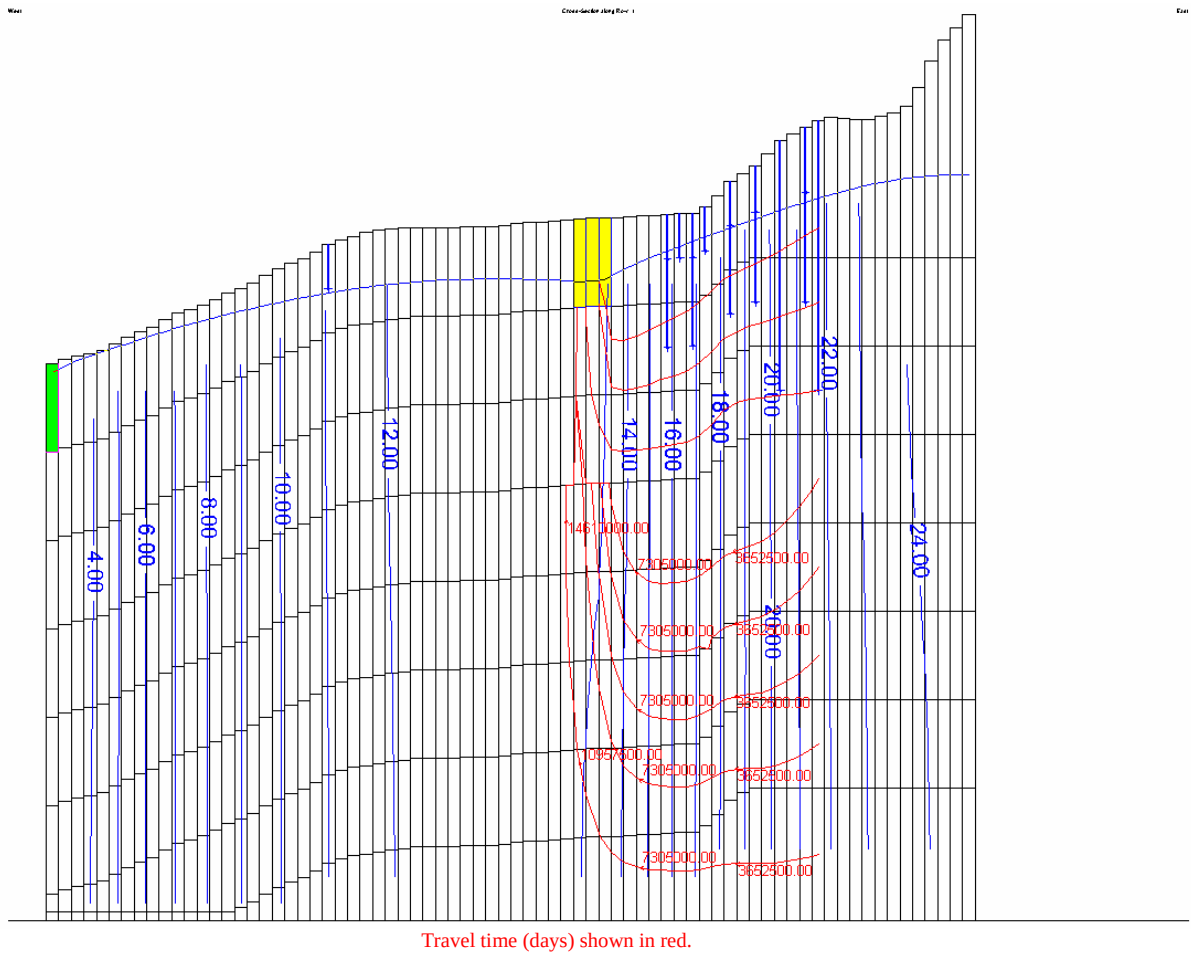


Figure 6.3-3. Scenario 3 particle traces.

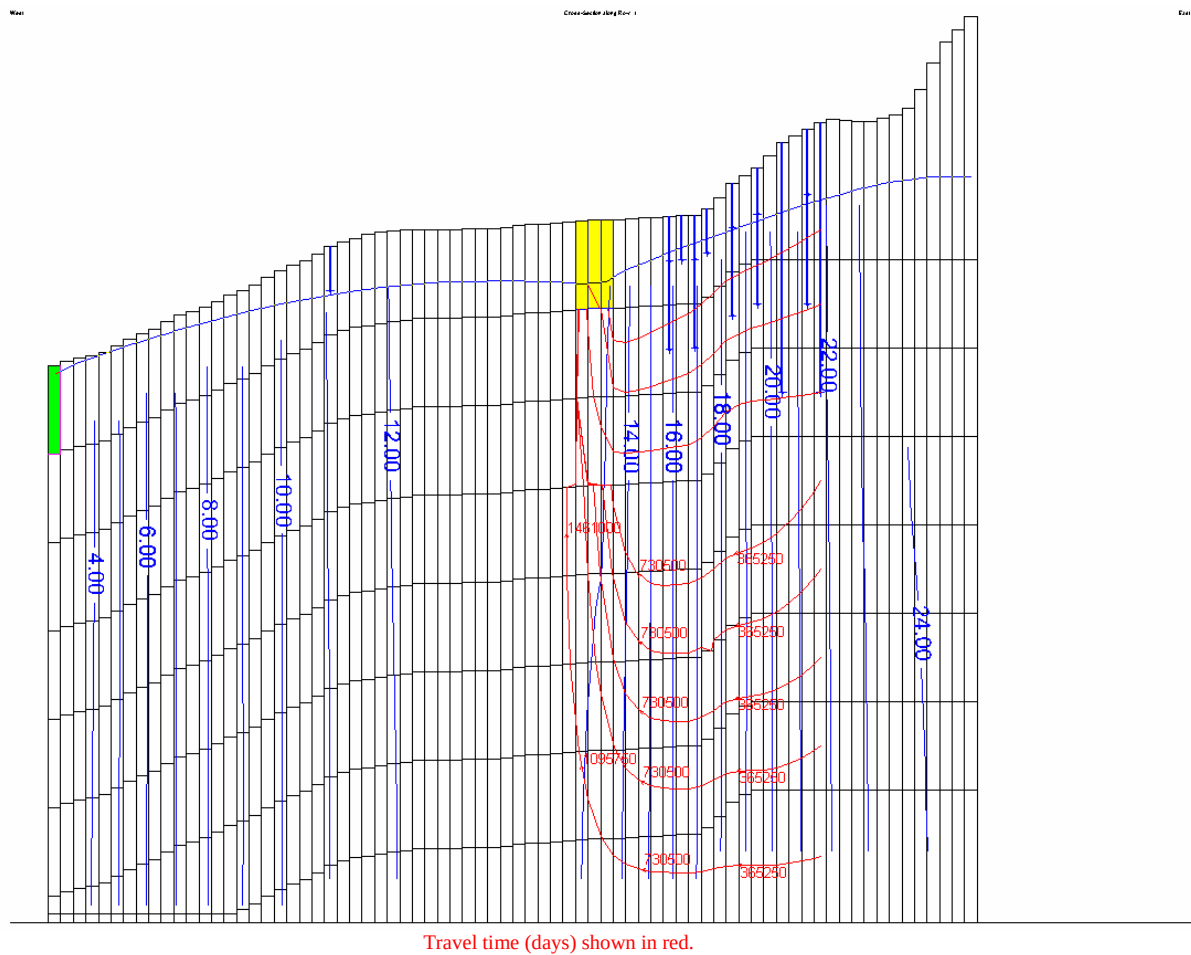


Figure 6.3-5. Scenario 5 particle traces.

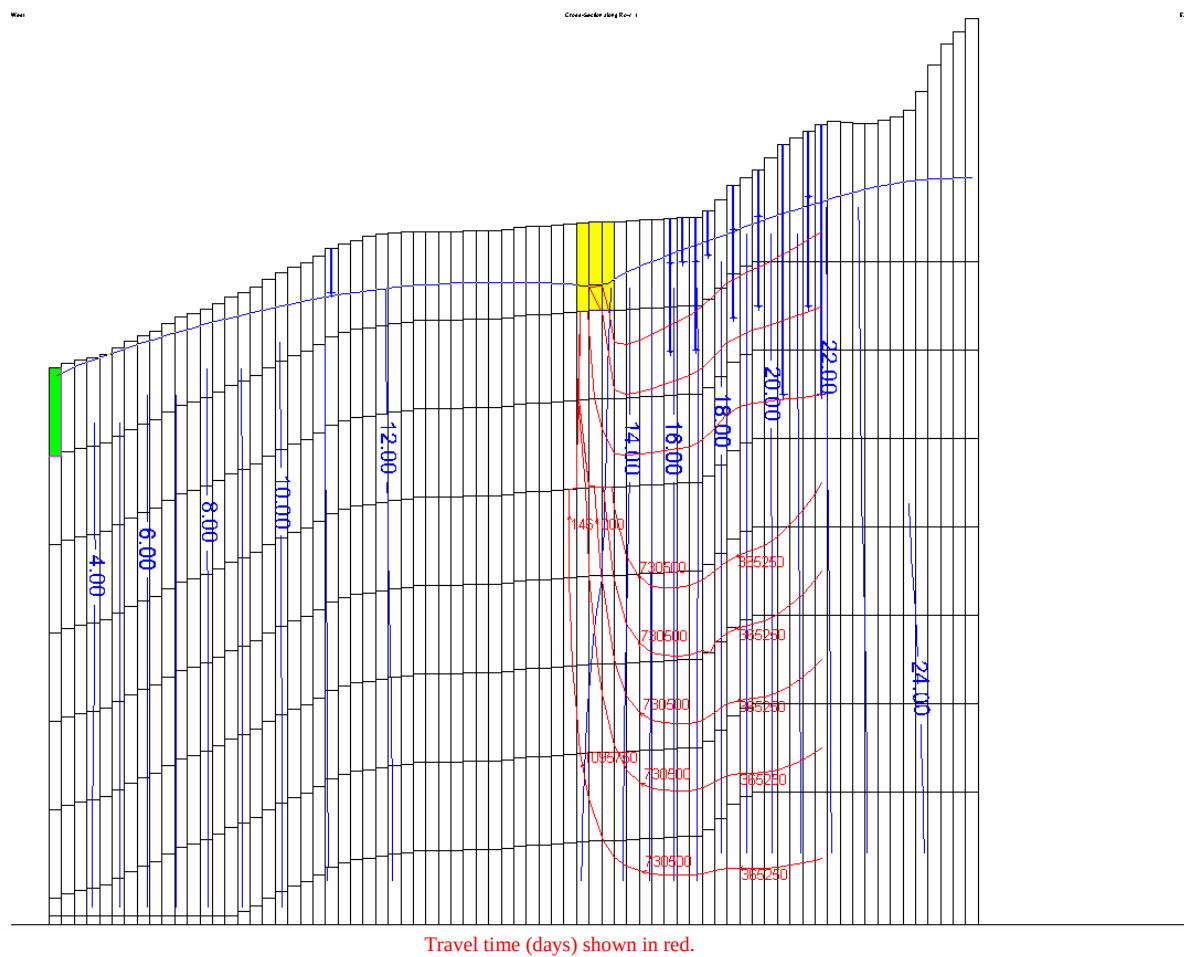


Figure 6.3-5. Scenario 5 particle traces.

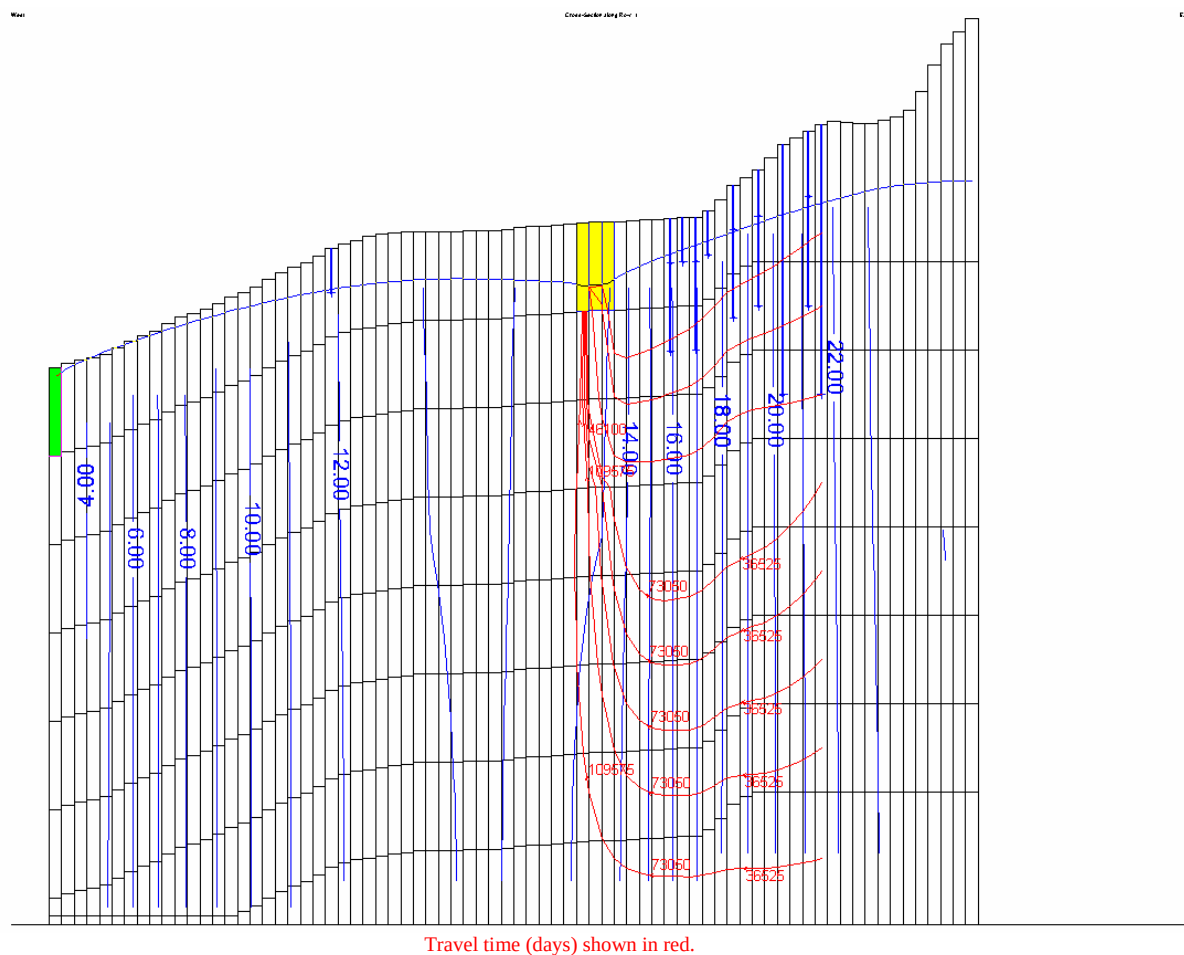


Figure 6.3-6. Scenario 6 particle traces.

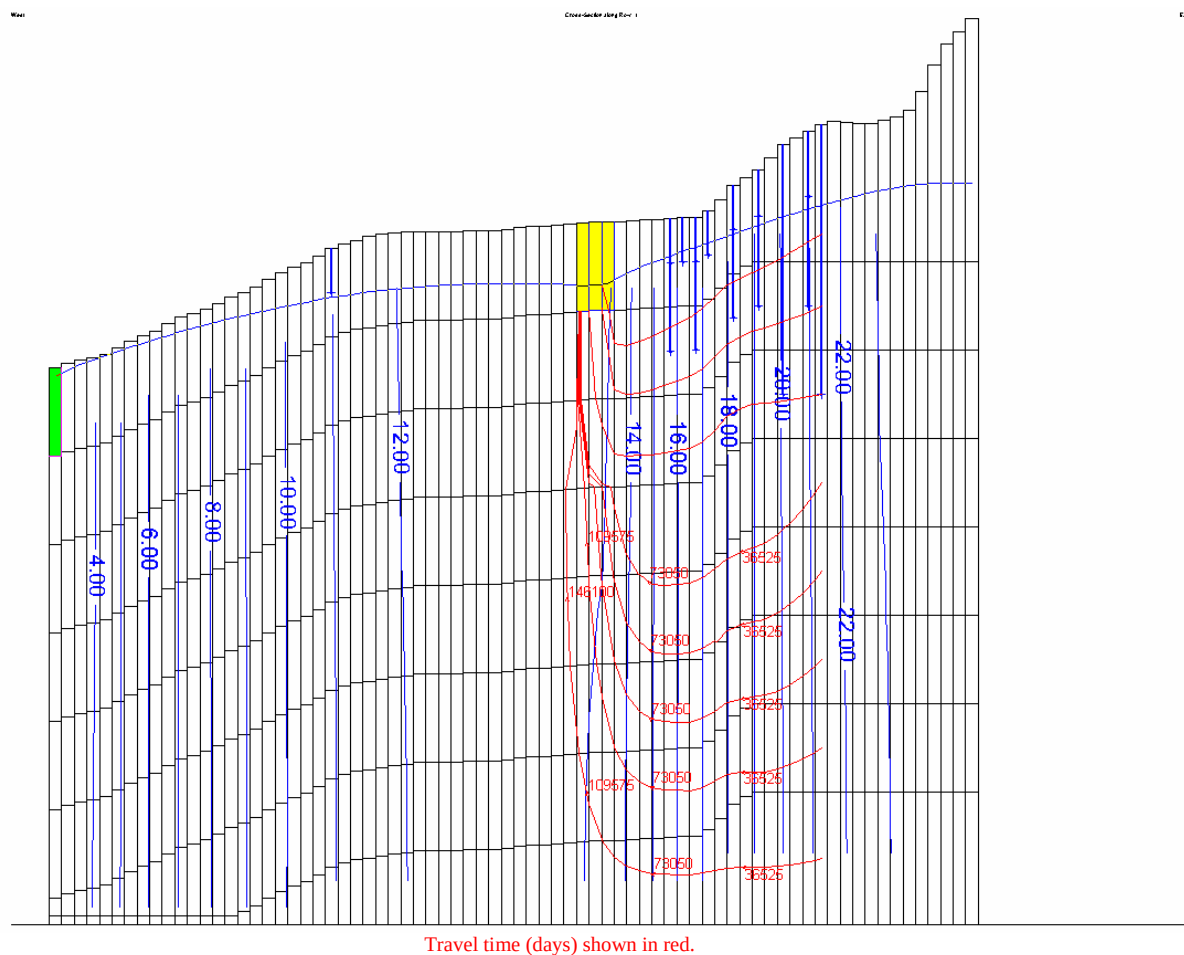


Figure 6.3-8. Scenario 8 particle traces.

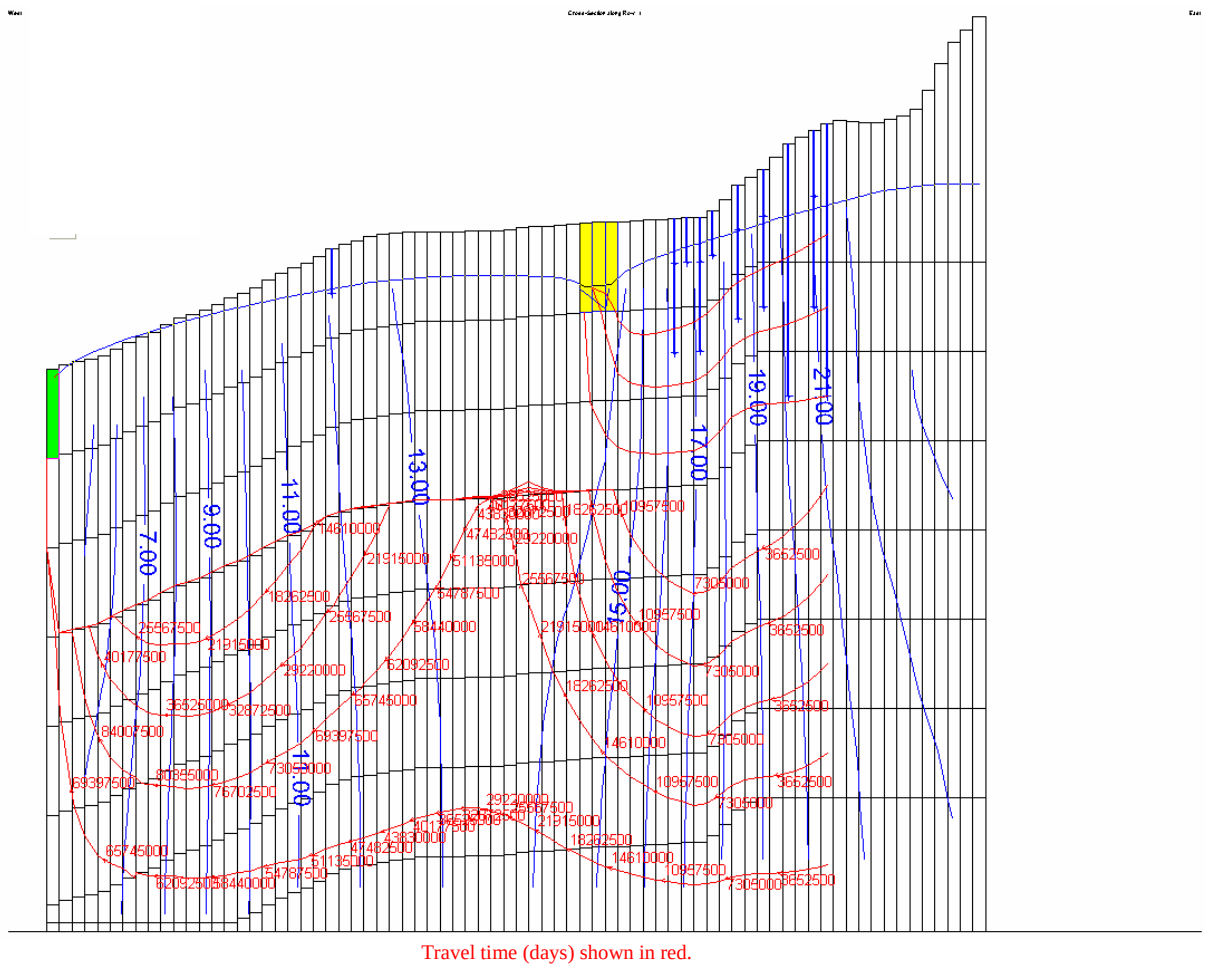


Figure 6.3-10. Scenario 10 particle traces.

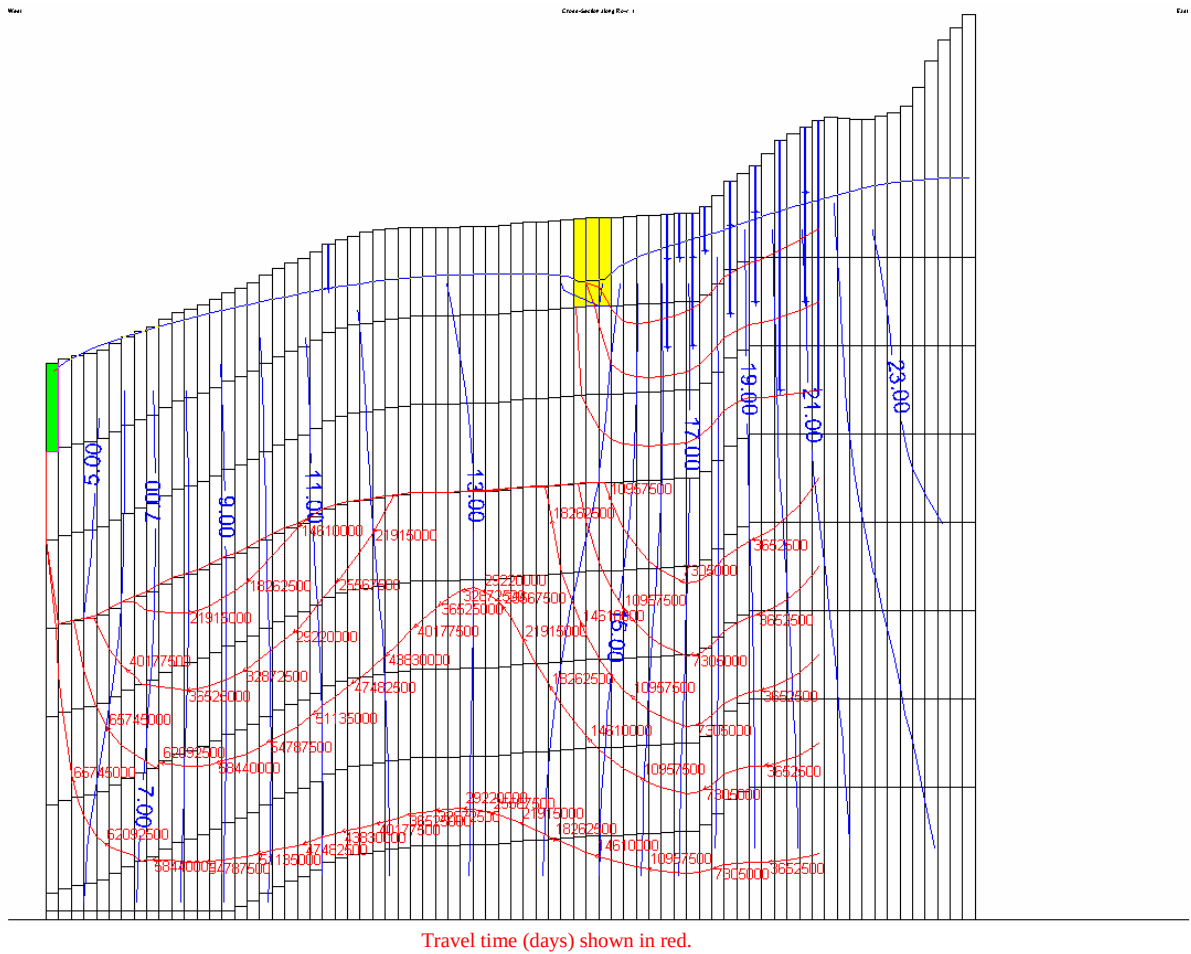


Figure 6.3-11. Scenario 11 particle traces.



Figure 6.3-13. Scenario 13 particle traces.

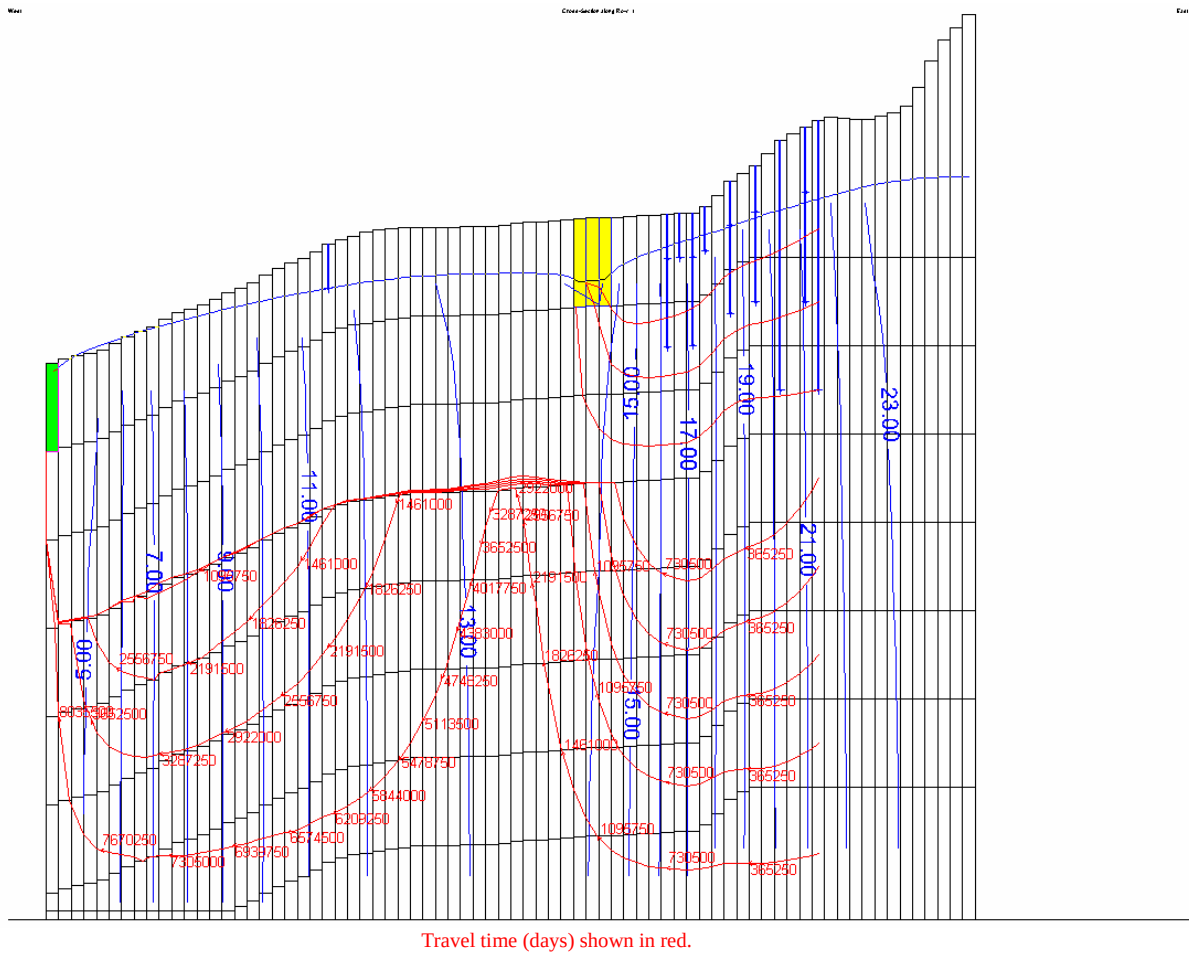


Figure 6.3-14. Scenario 14 particle traces.

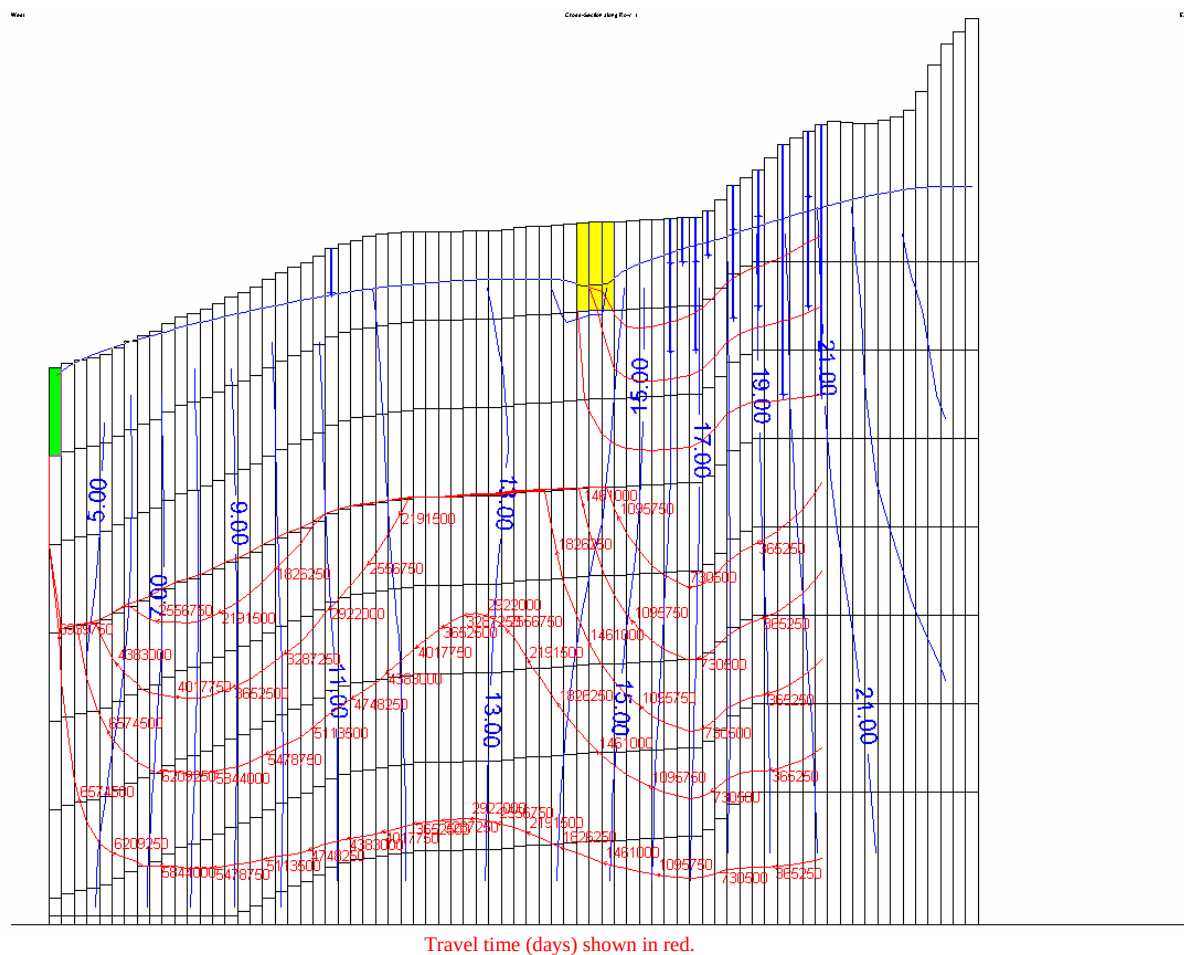


Figure 6.3-15. Scenario 15 particle traces.

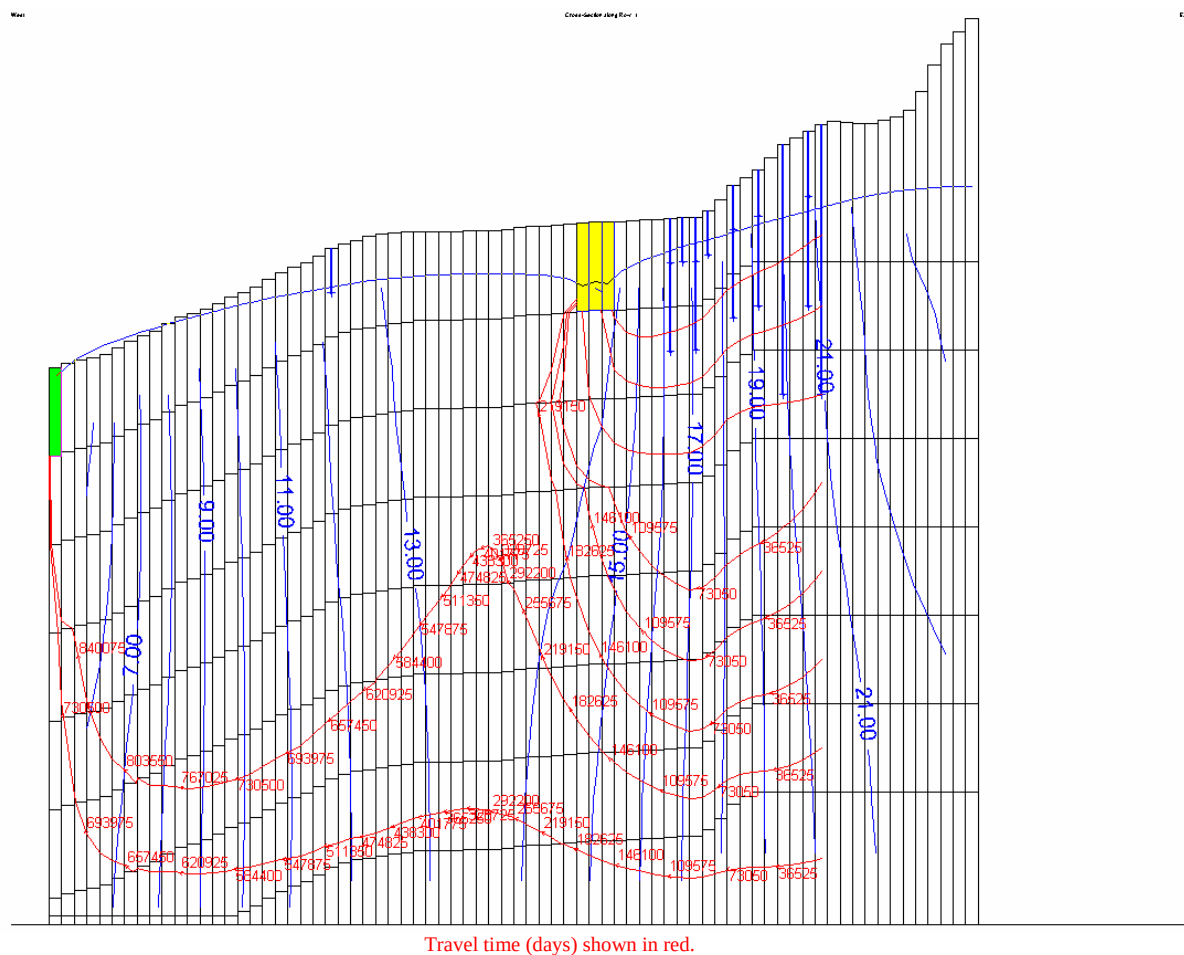


Figure 6.3-16. Scenario 16 particle traces.

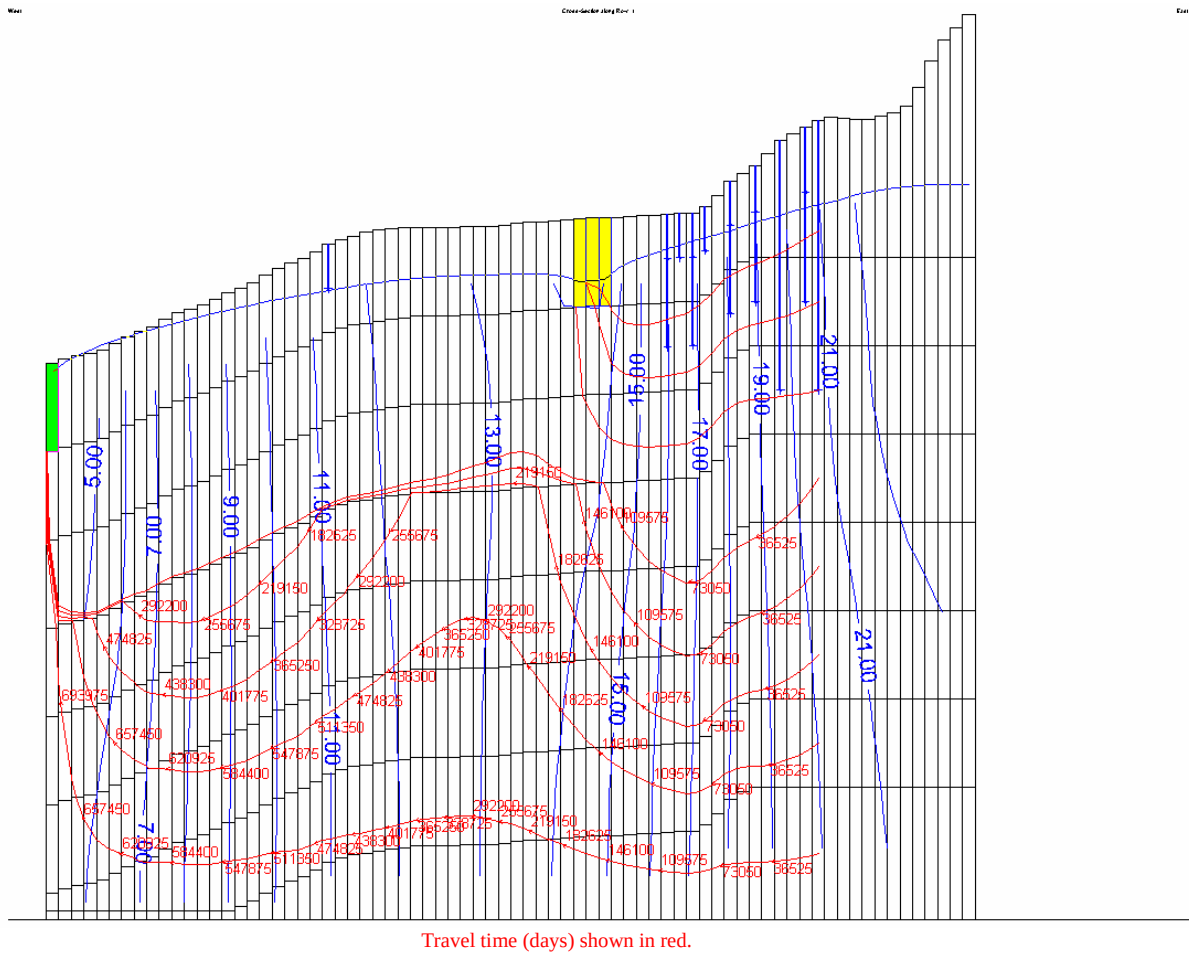


Figure 6.3-17. Scenario 17 particle traces.

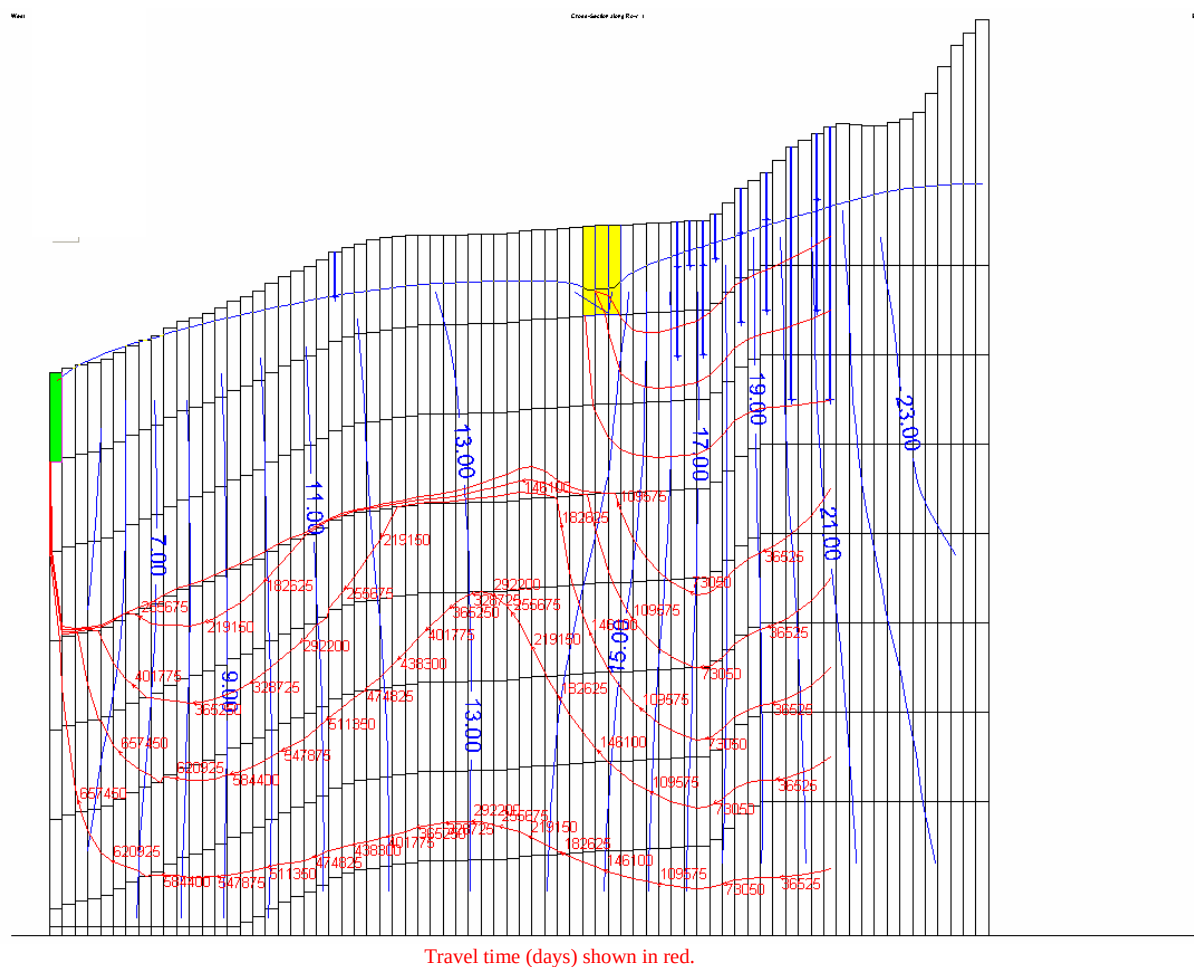


Figure 6.3-18. Scenario 18 particle traces.

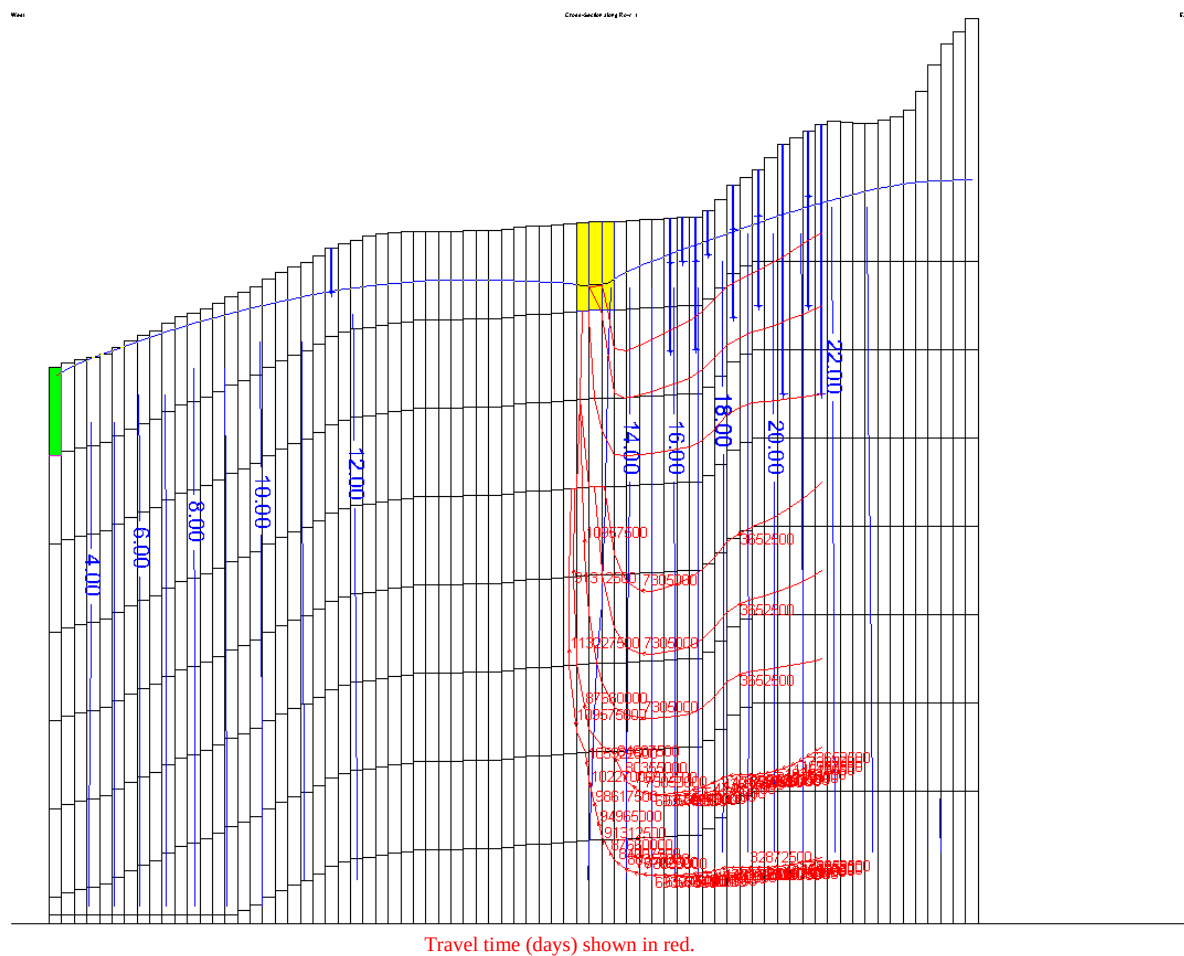


Figure 6.3-19. Scenario 19 particle traces.

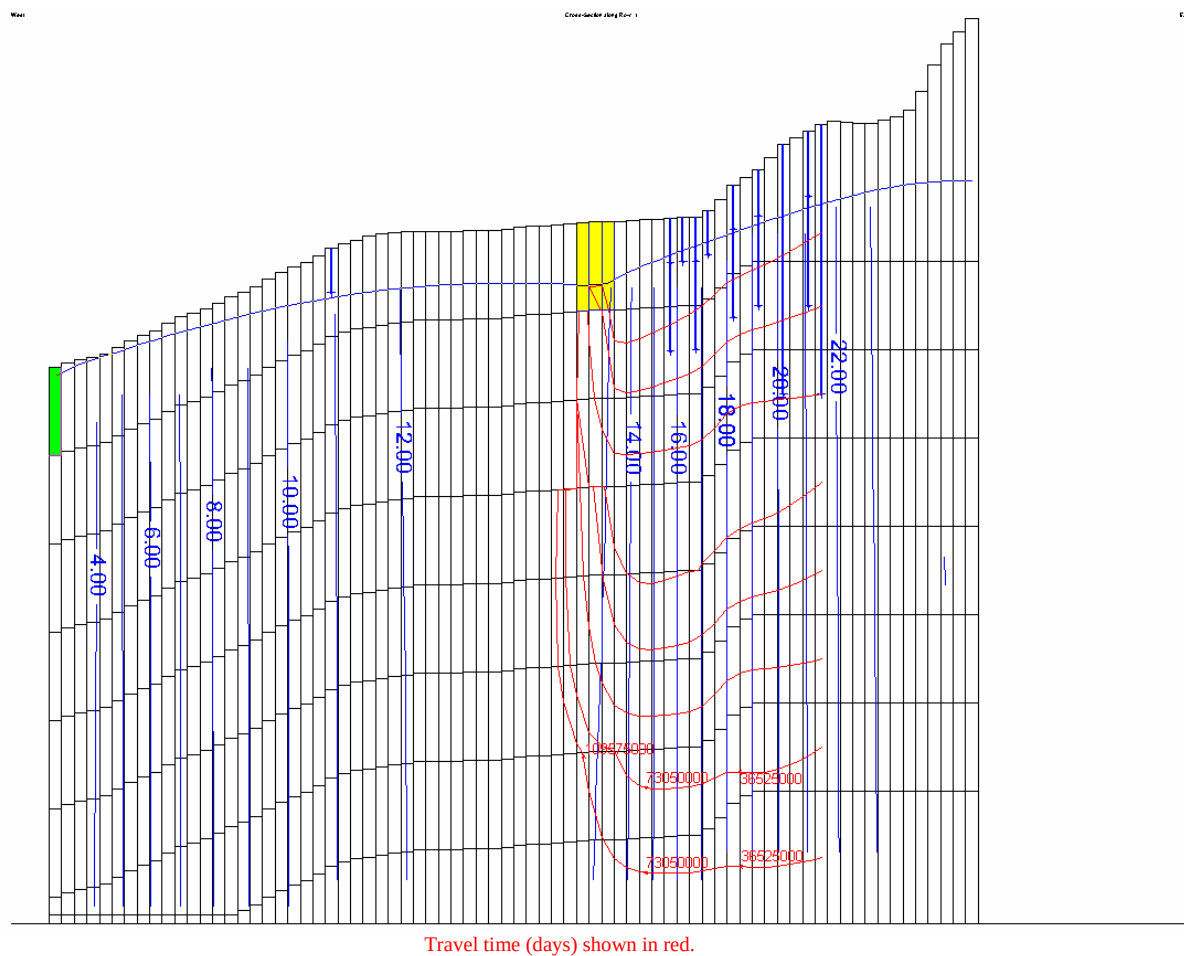


Figure 6.3-21. Scenario 21 particle traces.

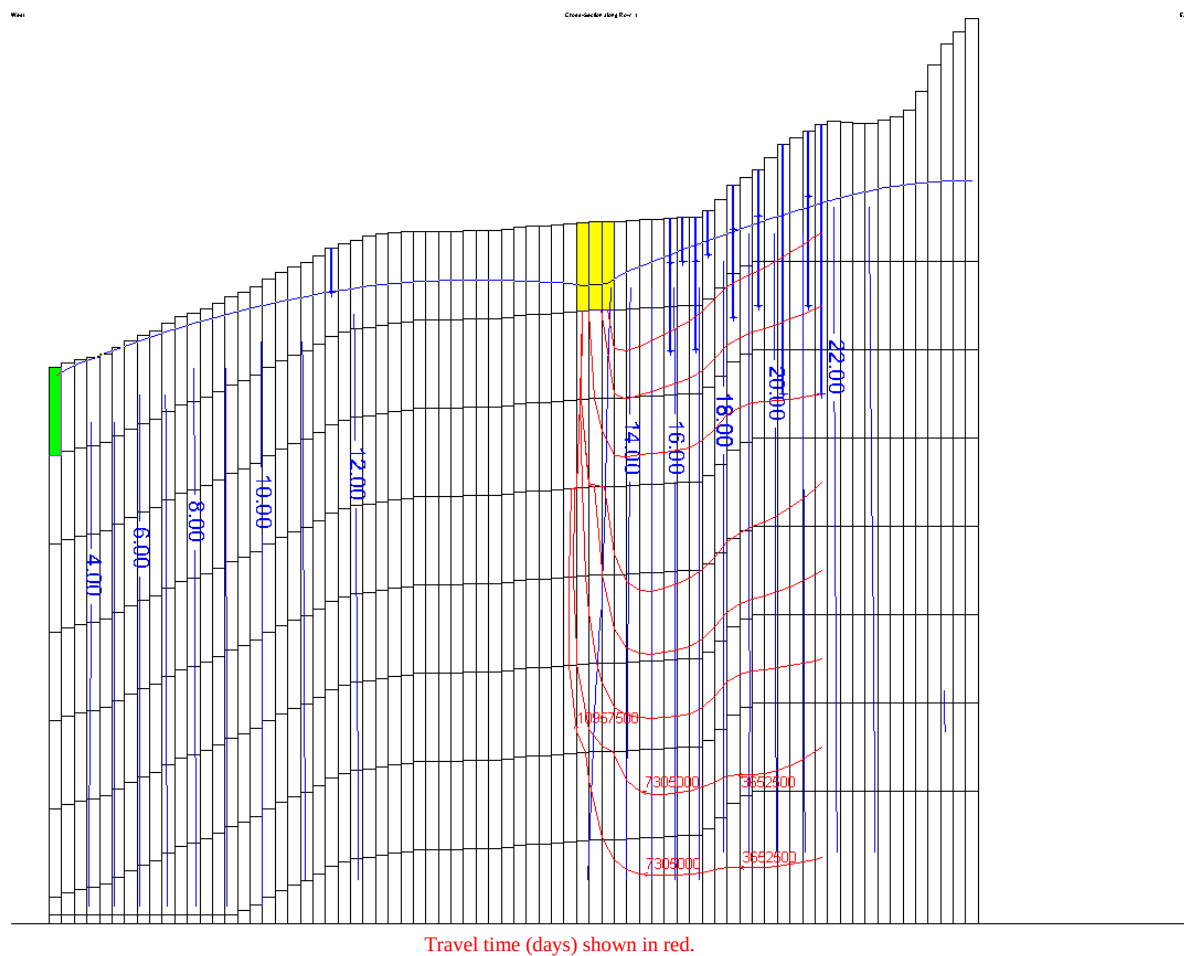


Figure 6.3-22. Scenario 22 particle traces.

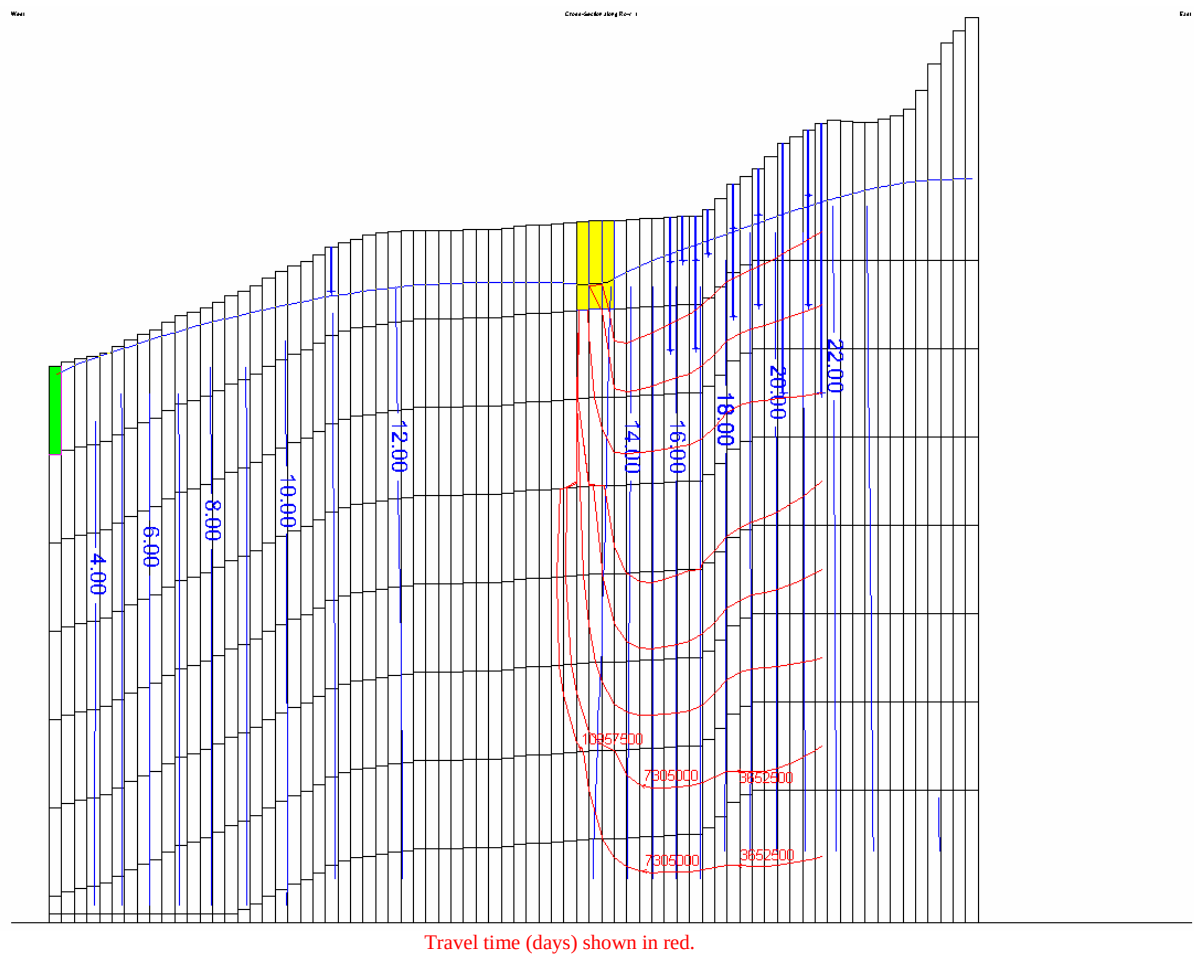


Figure 6.3-23. Scenario 23 particle traces.

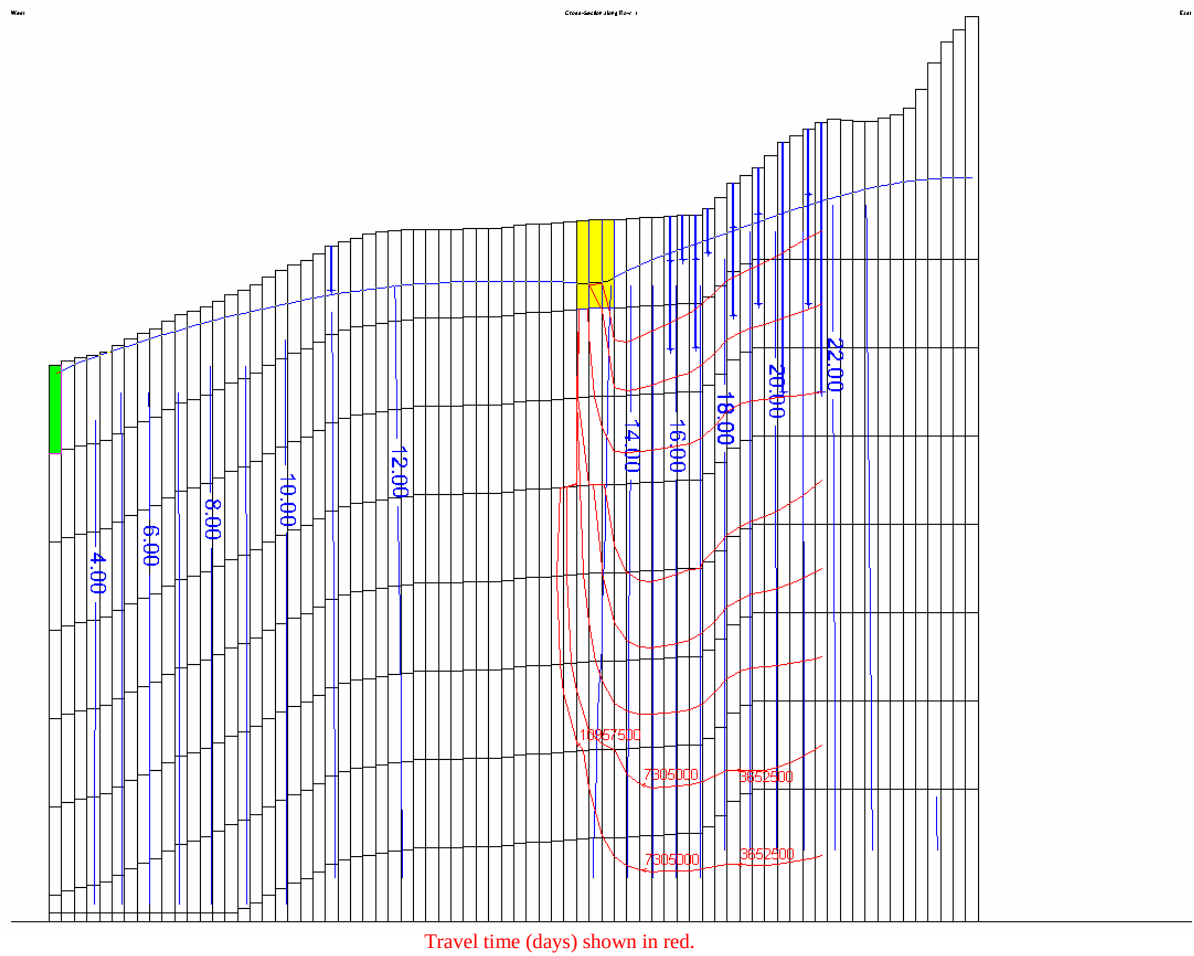


Figure 6.3-24. Scenario 24 particle traces.

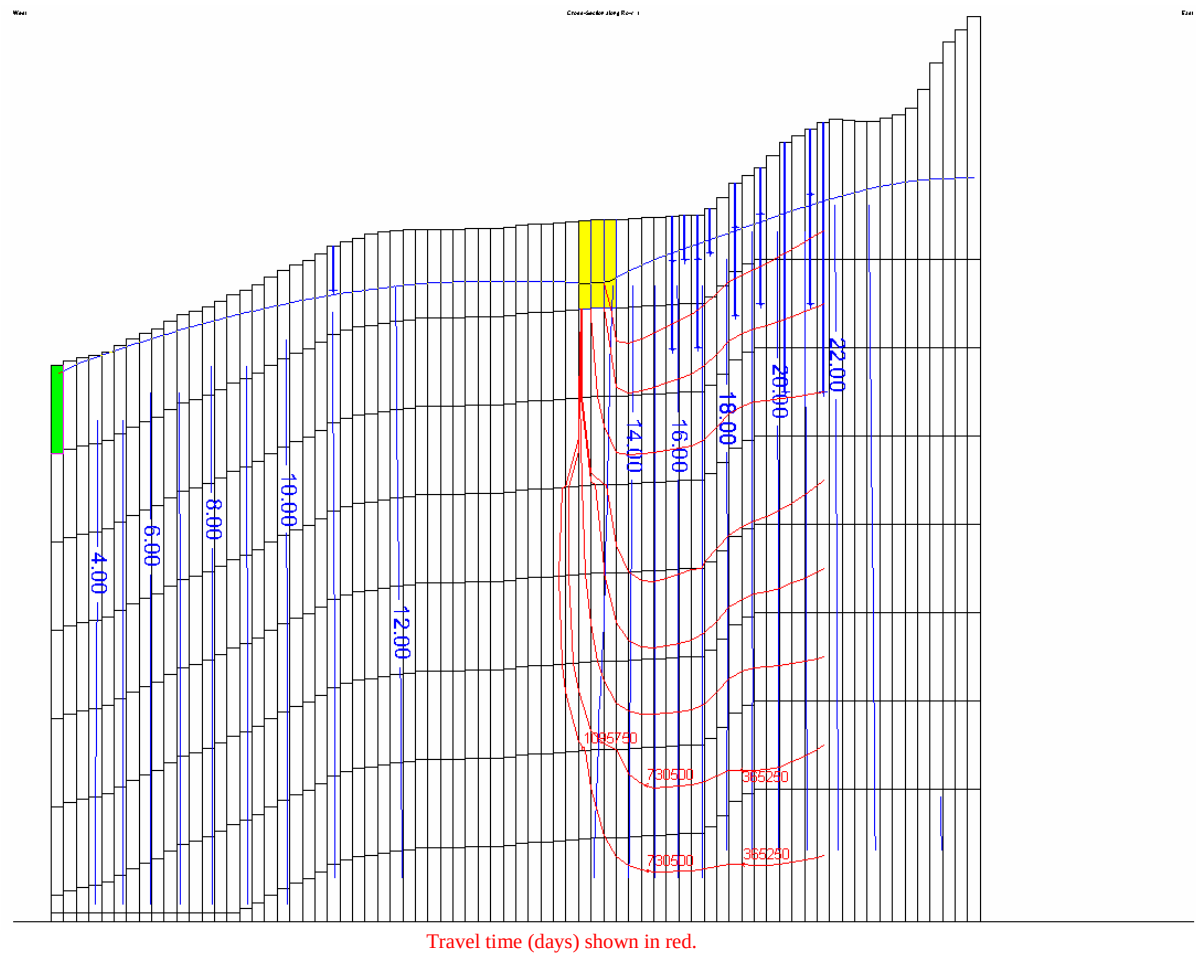


Figure 6.3-26. Scenario 26 particle traces.

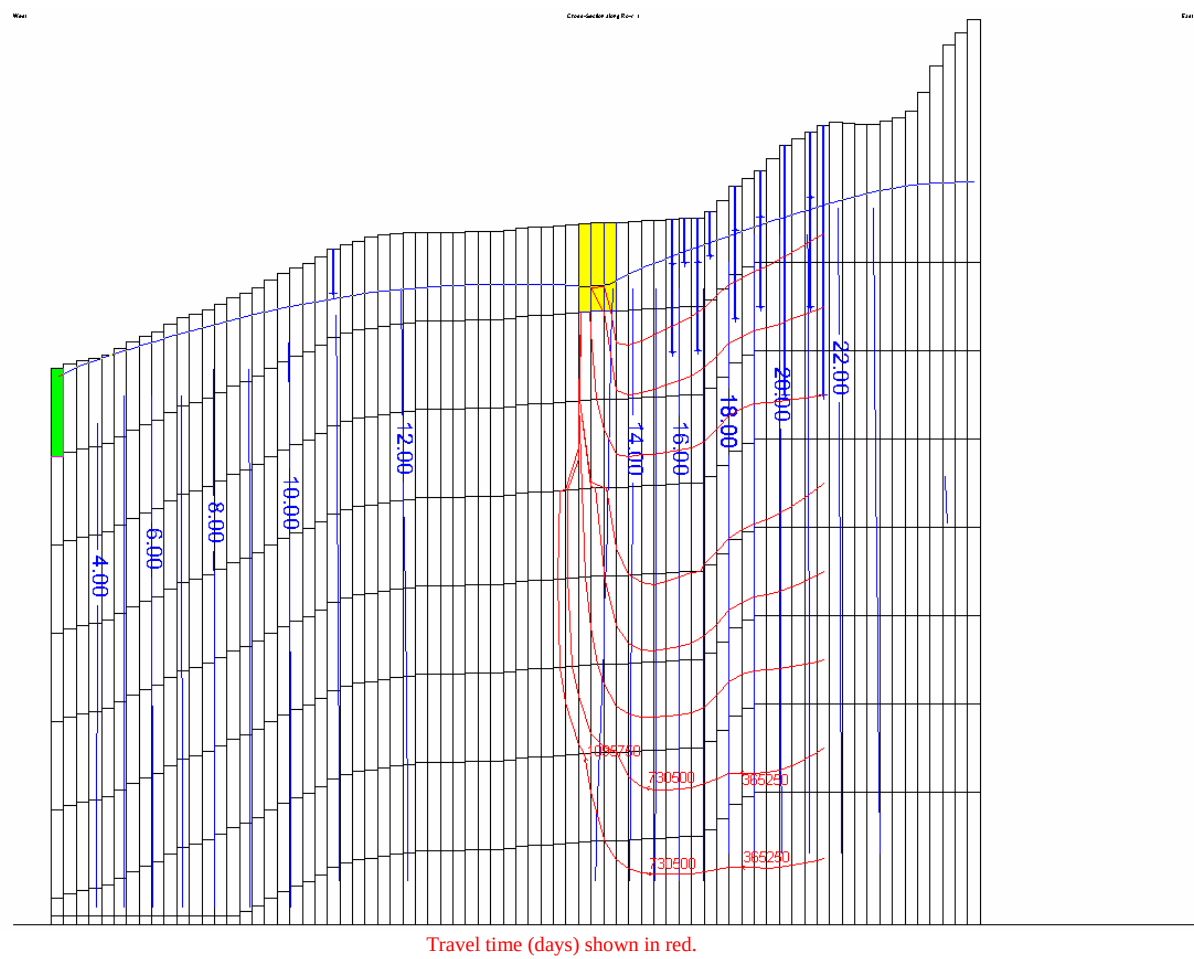


Figure 6.3-27. Scenario 27 particle traces.

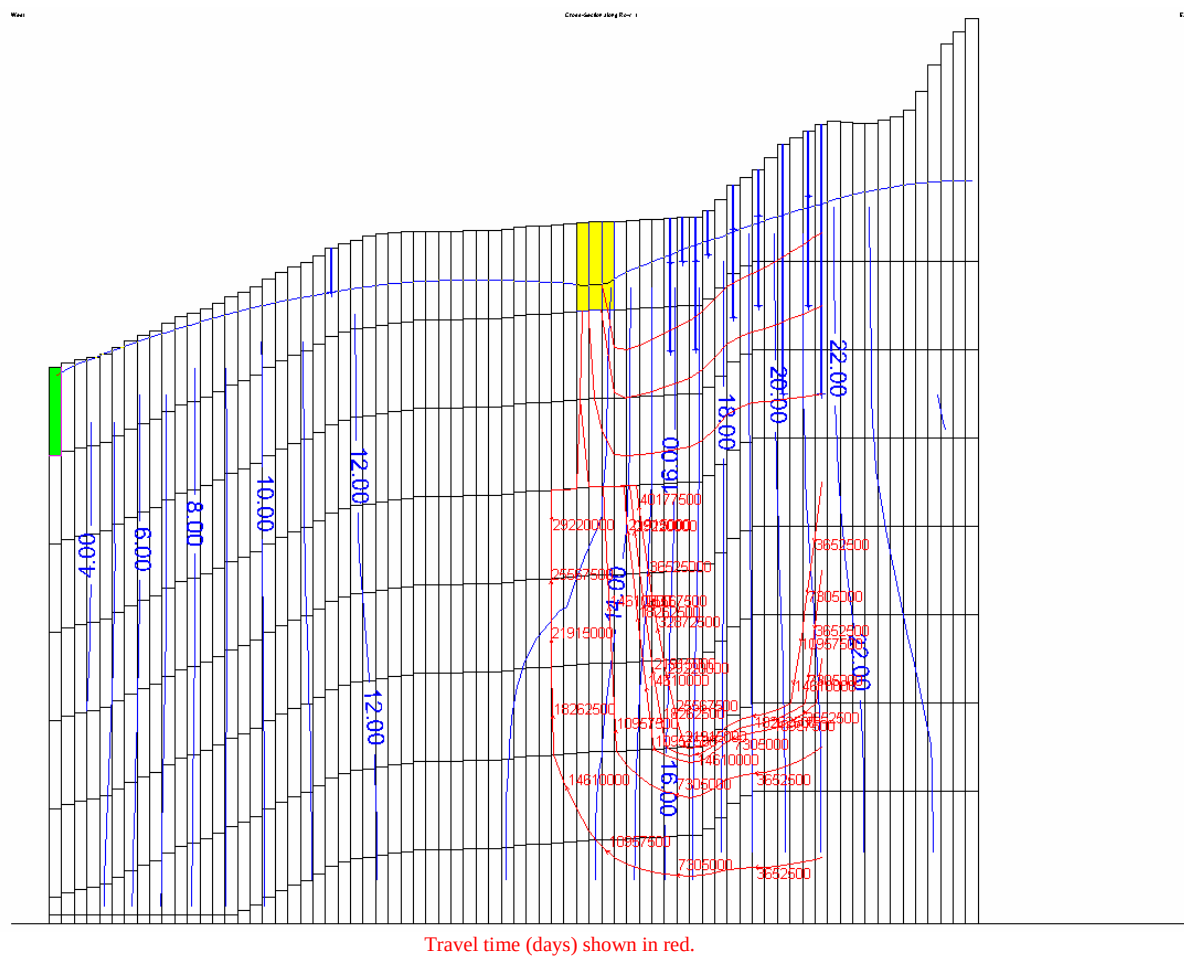


Figure 6.3-28. Scenario 28 particle traces.

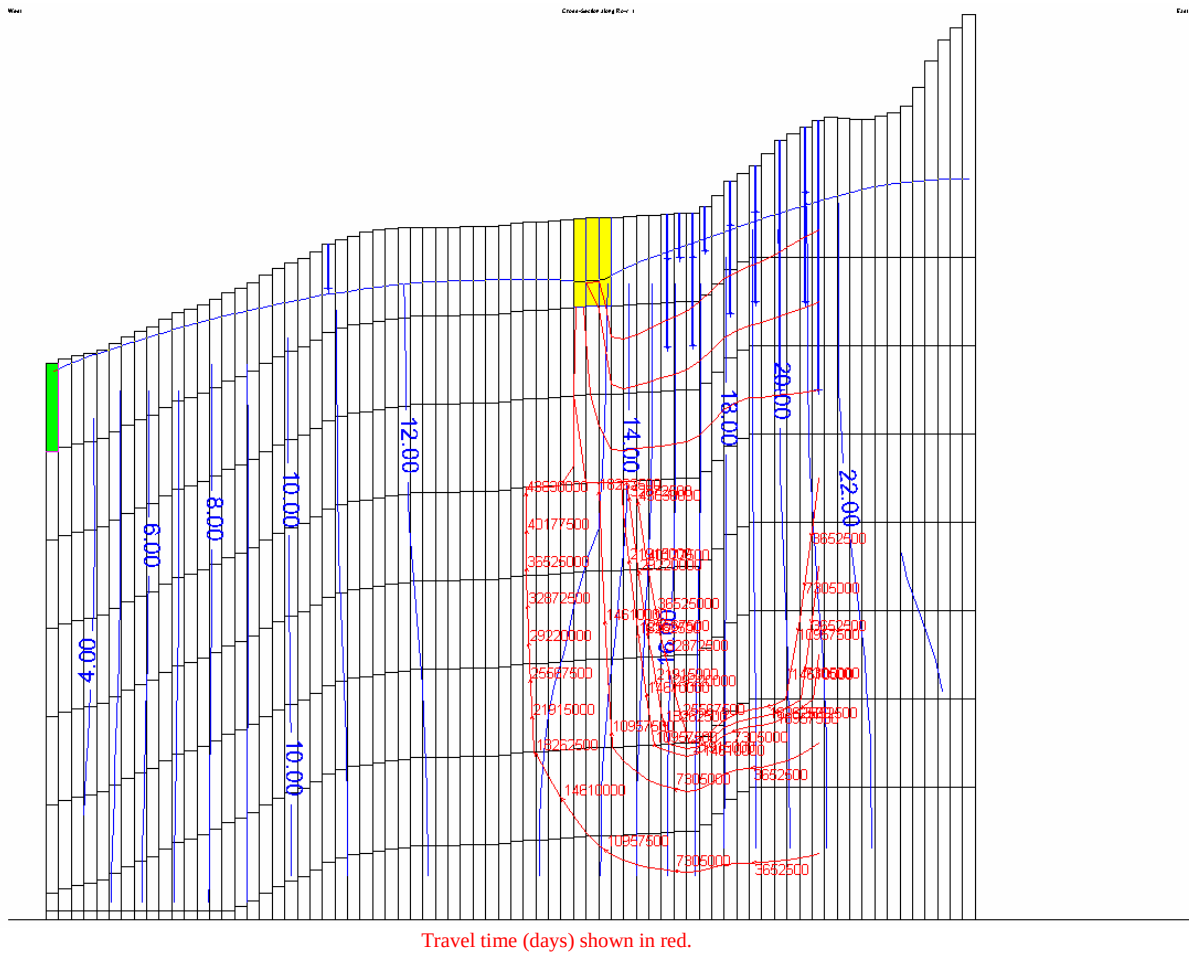


Figure 6.3-29. Scenario 29 particle traces.

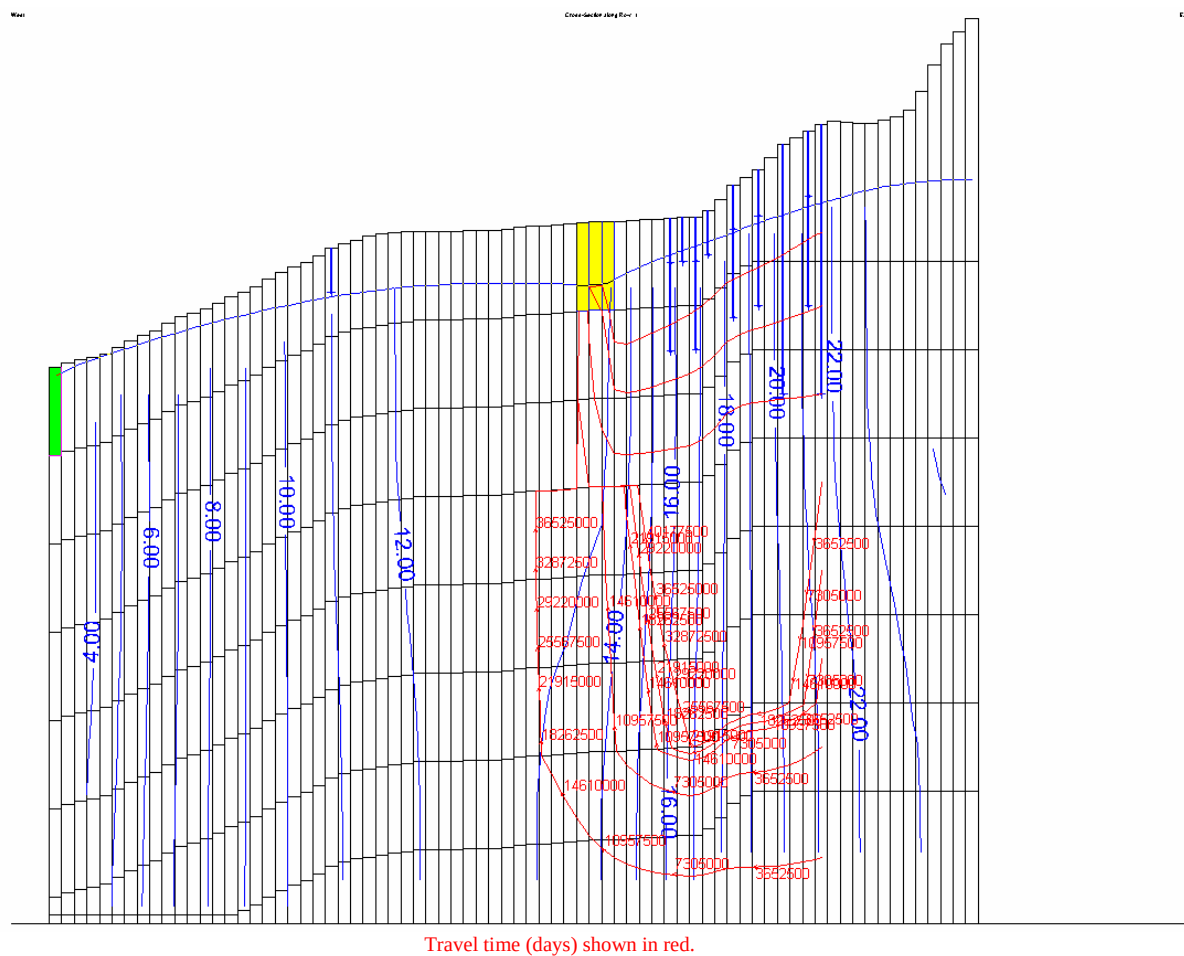


Figure 6.3-30. Scenario 30 particle traces.

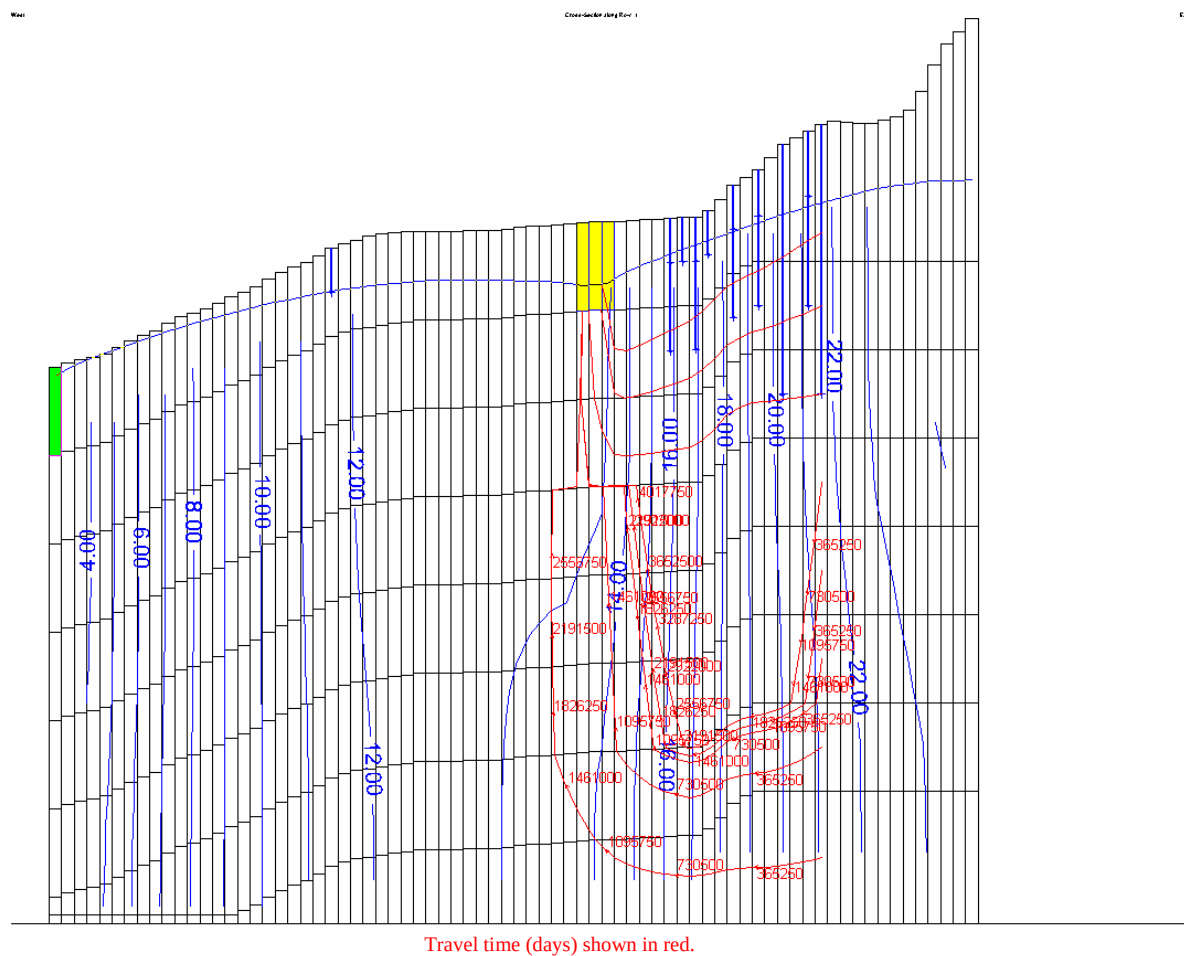


Figure 6.3-31. Scenario 31 particle traces.

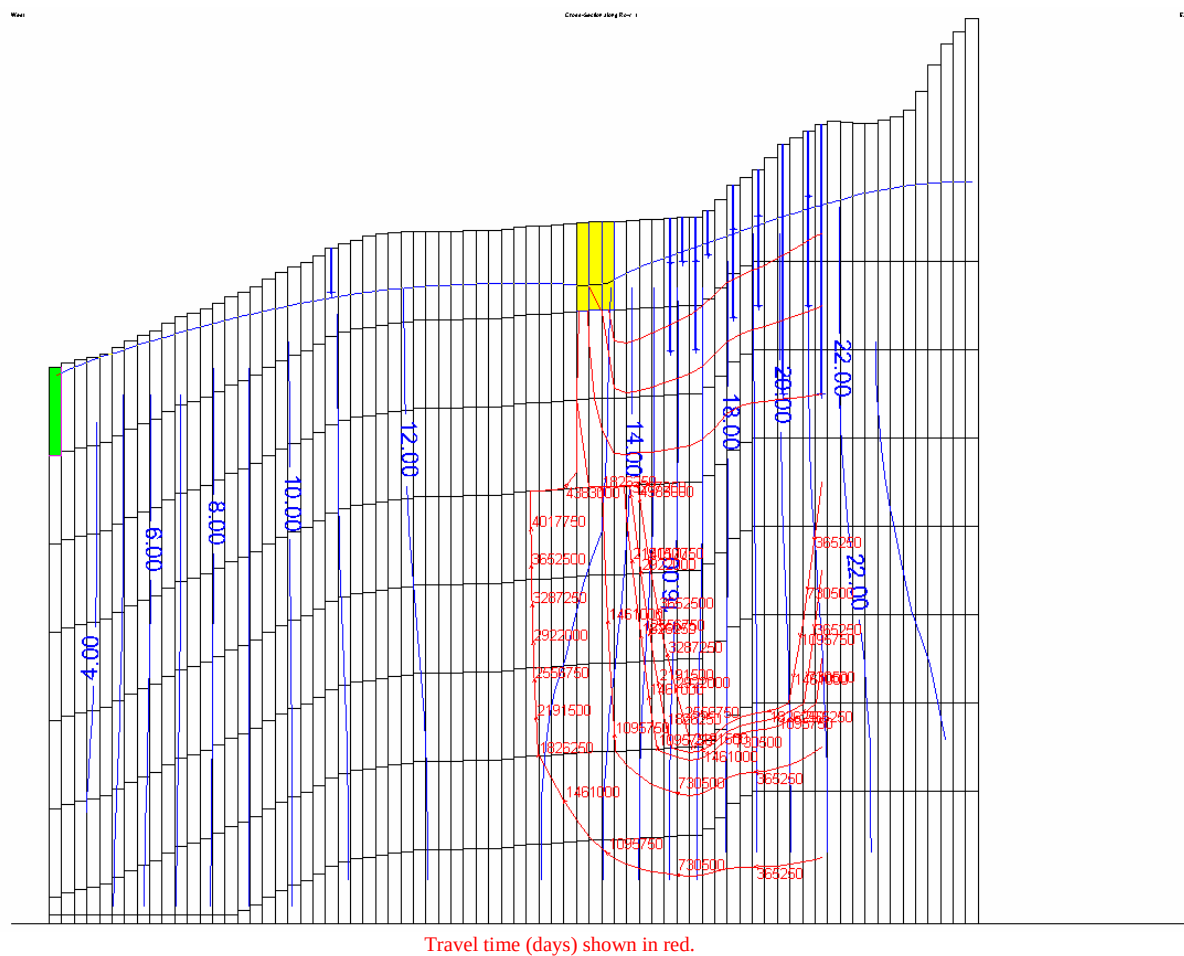


Figure 6.3-32. Scenario 32 particle traces.

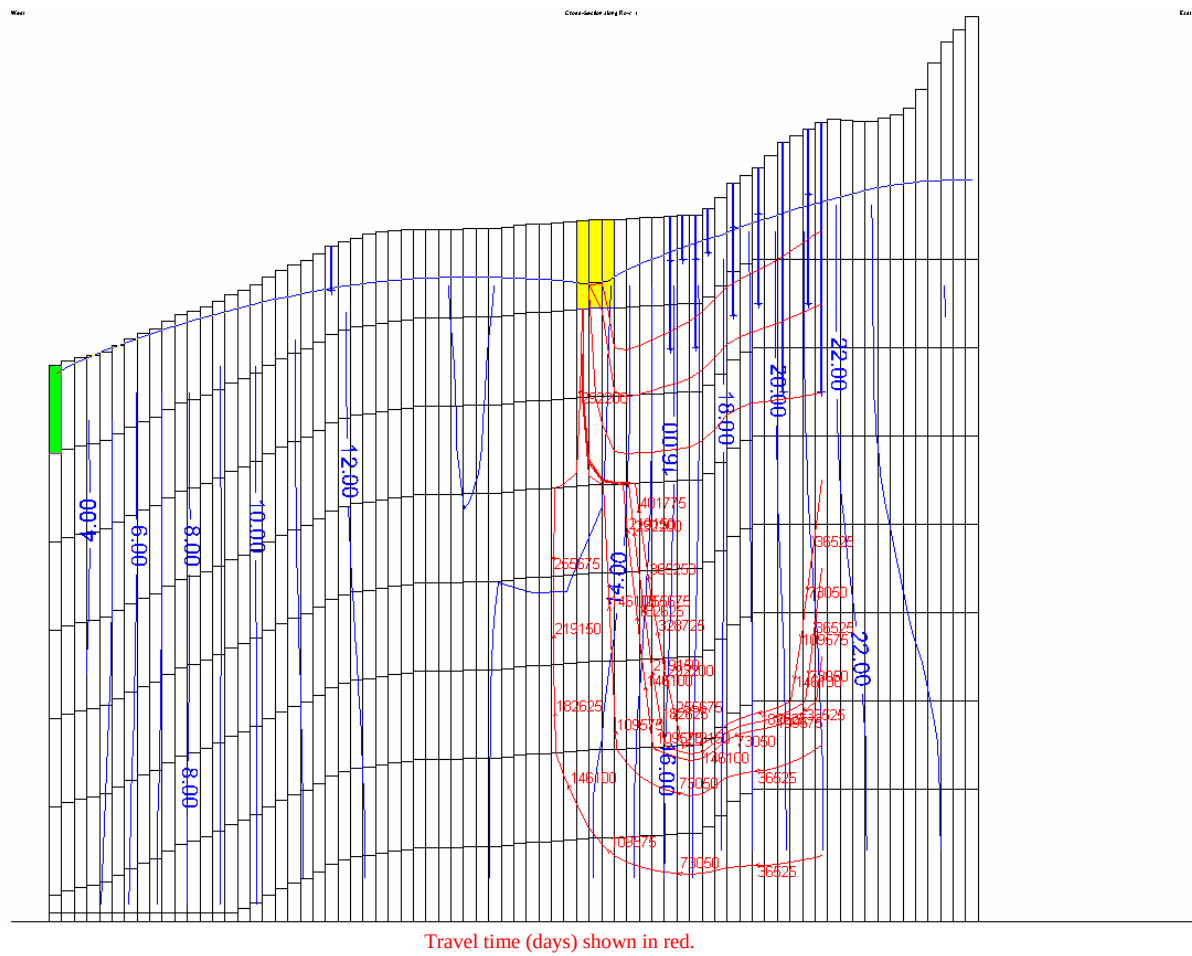


Figure 6.3-34. Scenario 34 particle traces.

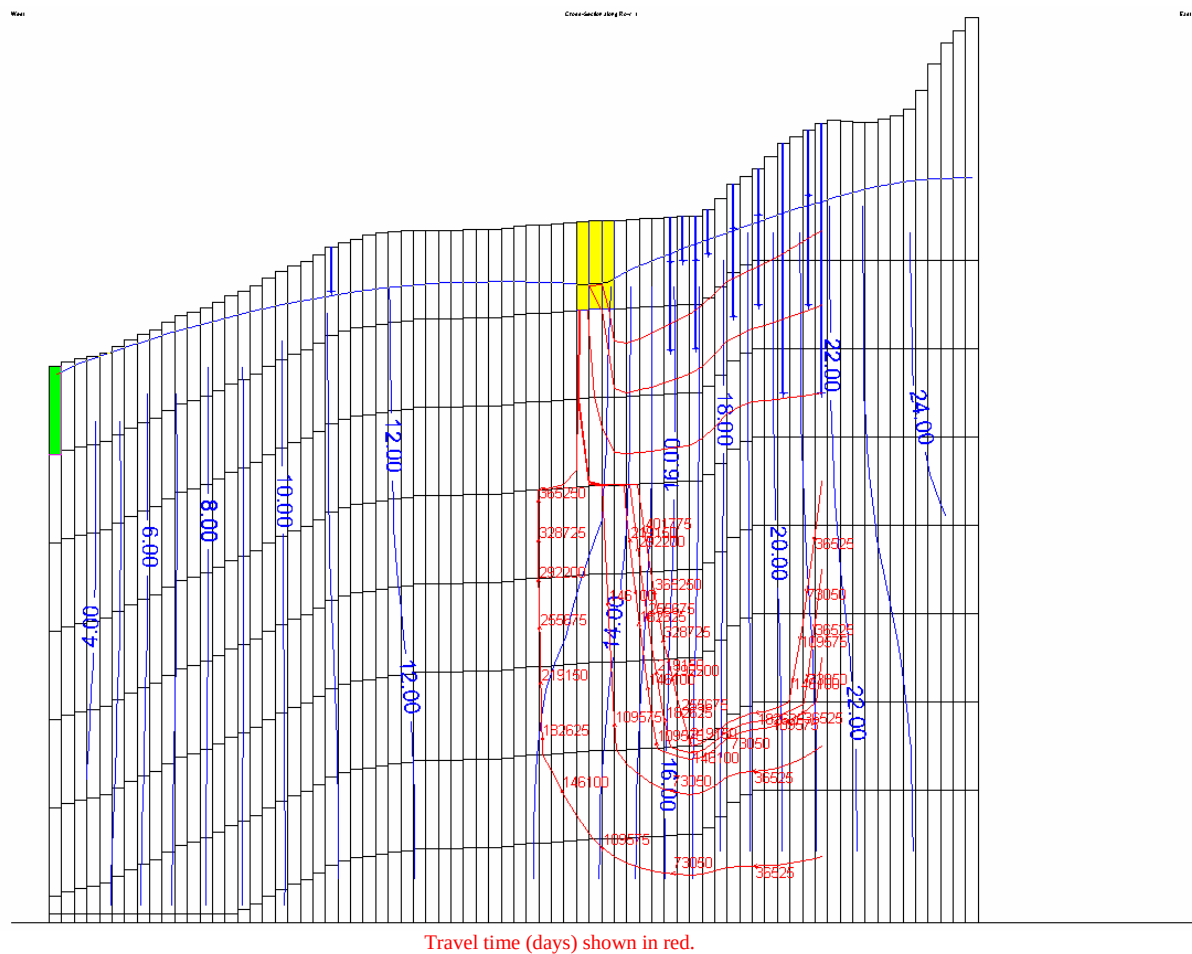


Figure 6.3-36. Scenario 36 particle traces.

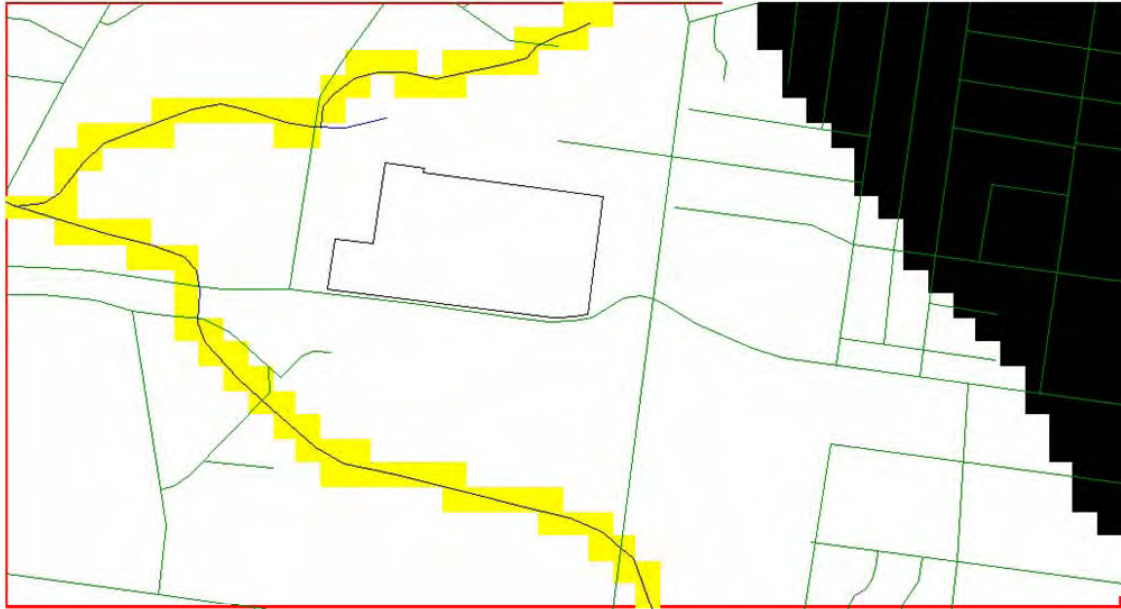


Figure 7.1-1. TMR model domain.



Figure7.2-1. EDC source areas.

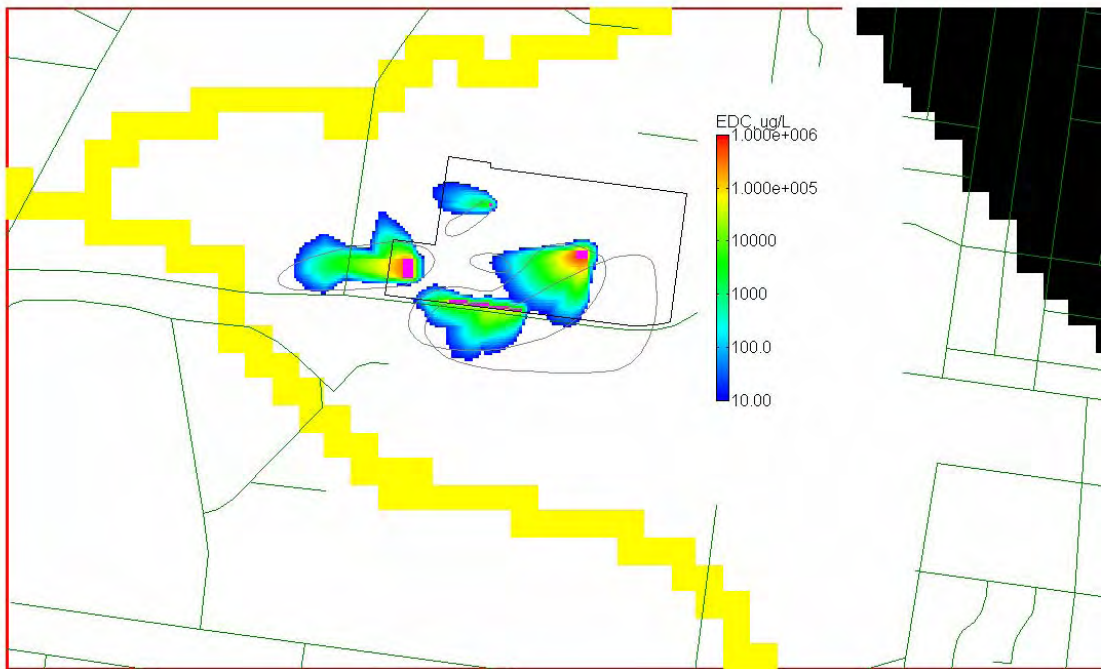


Figure7.2-2. Calibrated EDC plume.

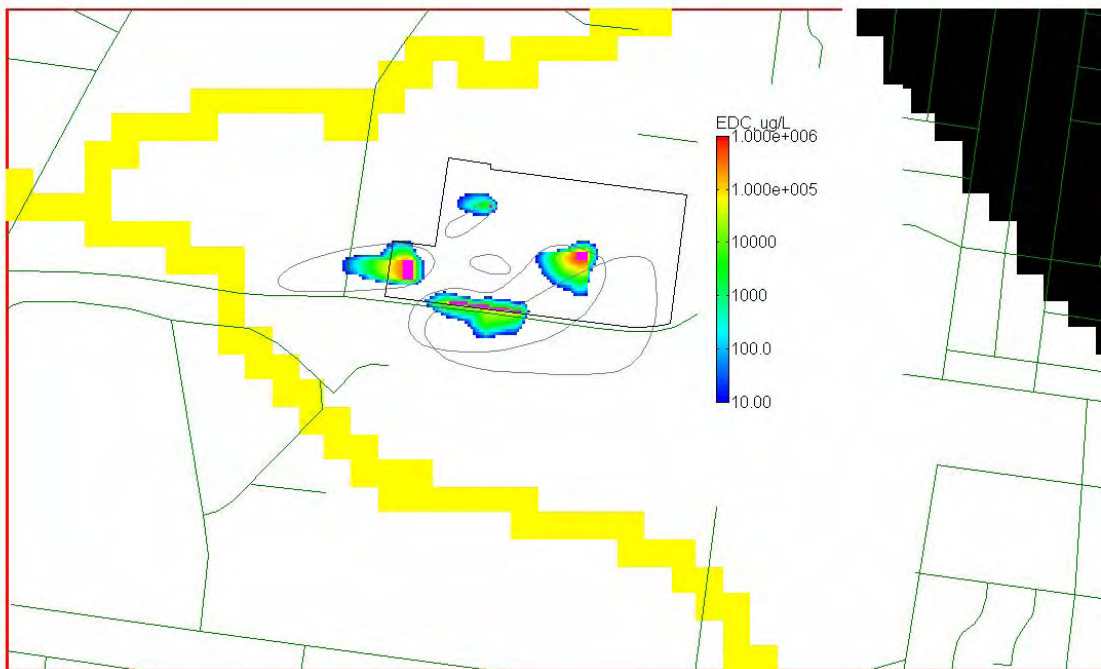


Figure 7.4-1. EDC plume after 1 year migration.

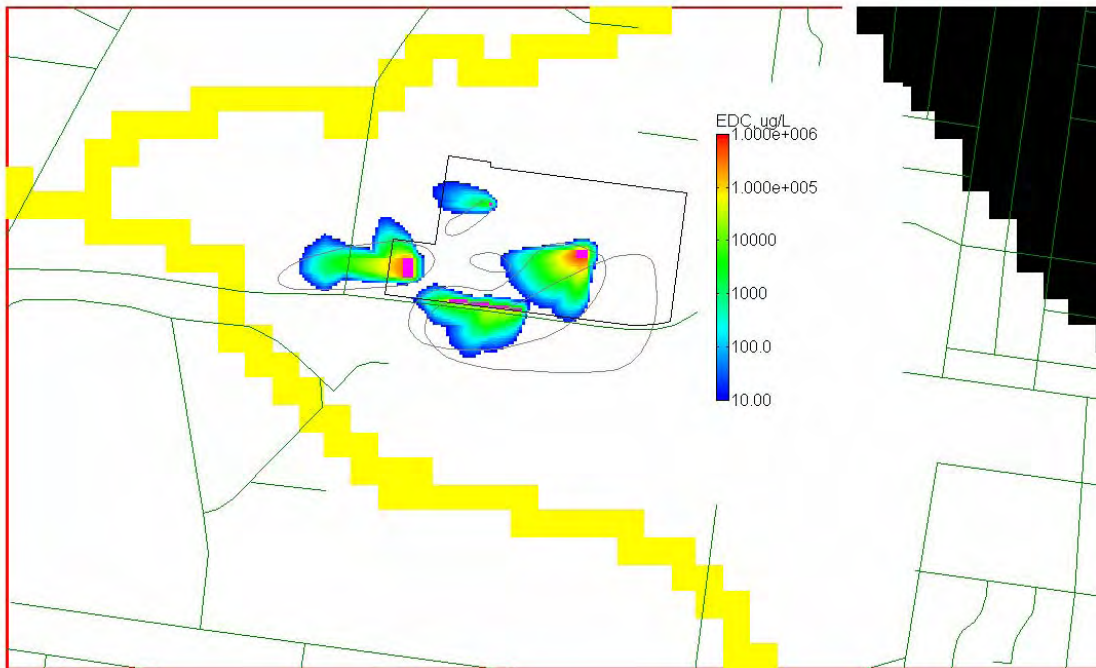


Figure 7.4-2. EDC plume after 5 year migration.

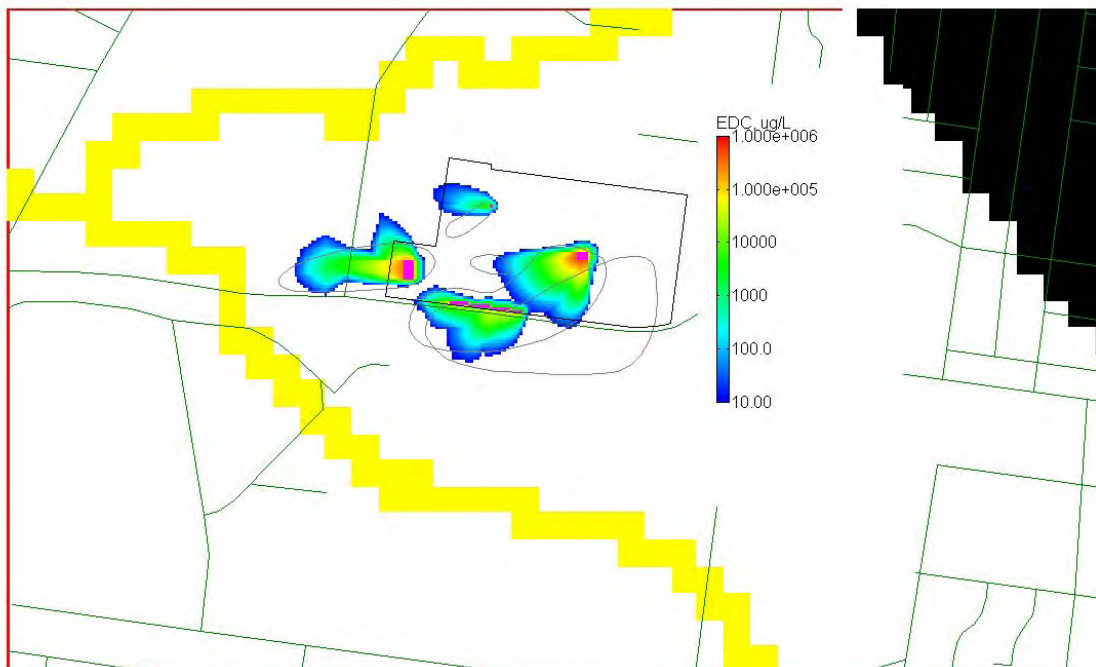


Figure 7.4-3. EDC plume after 10 years migration.

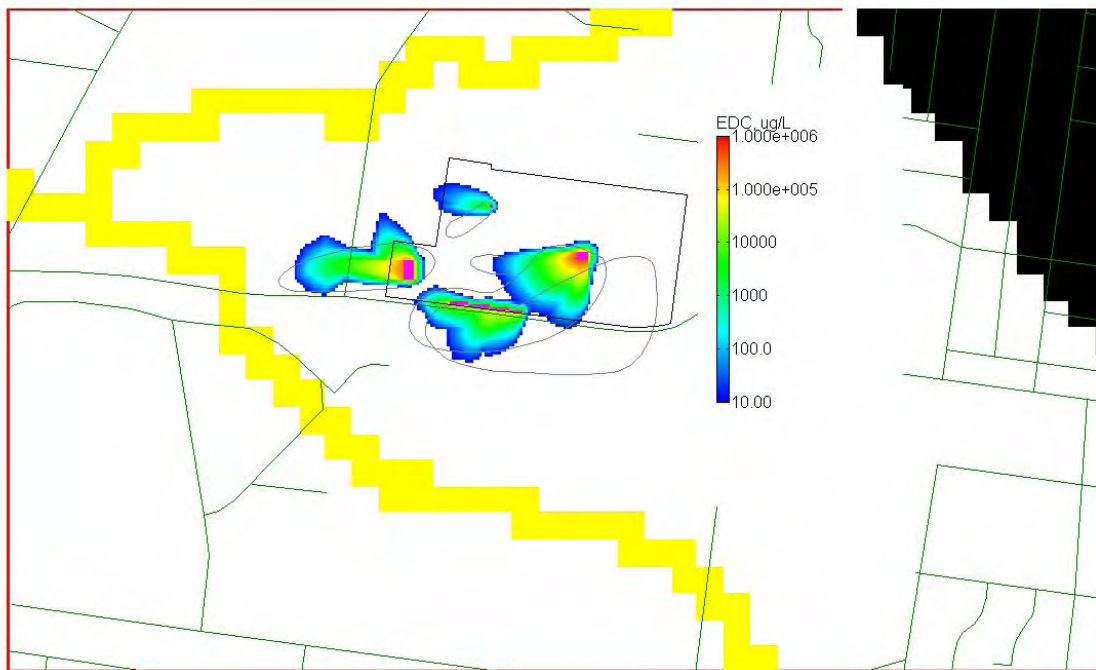


Figure 7.4-4. EDC plume after 25 years migration.

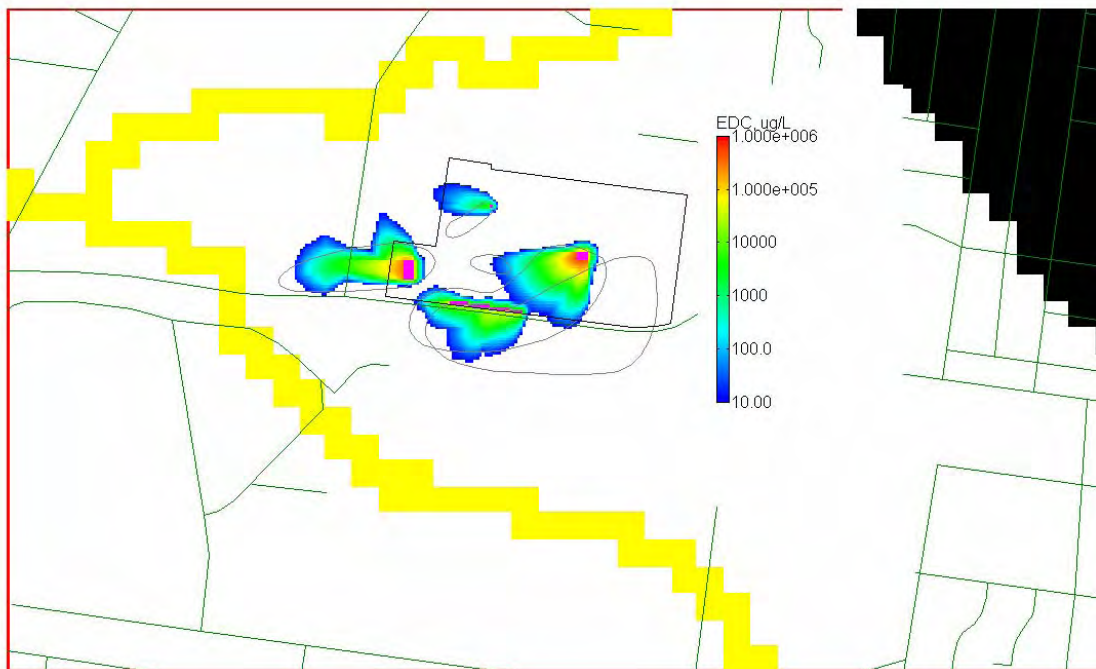


Figure 7.4-5. EDC plume after 40 years migration.

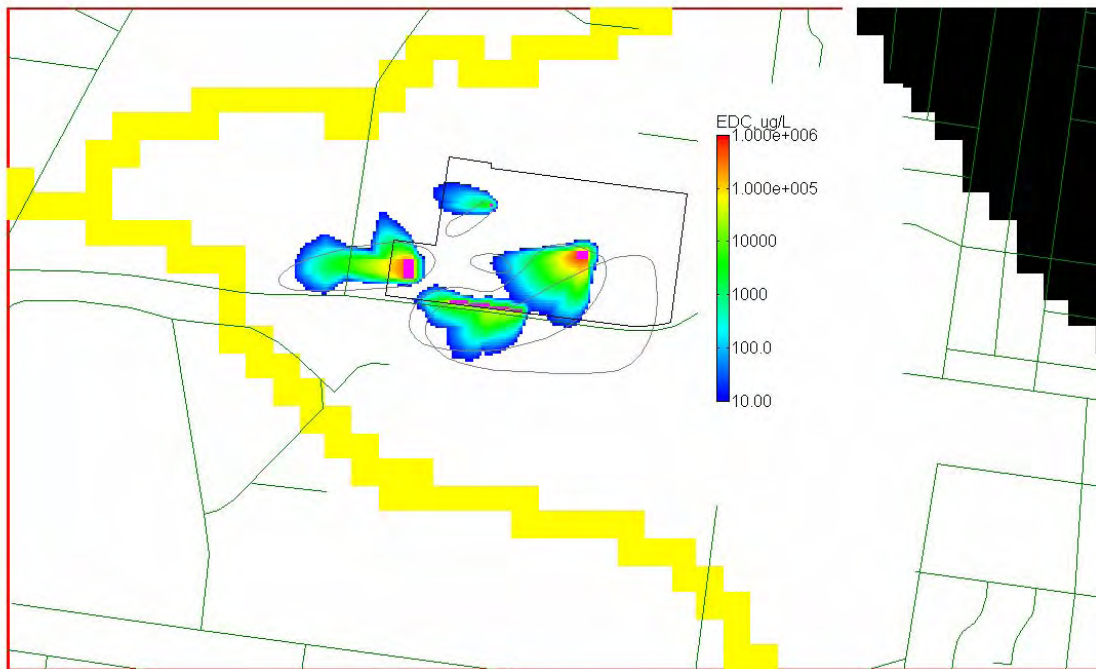


Figure 7.4-6. EDC plume after 100 years migration.

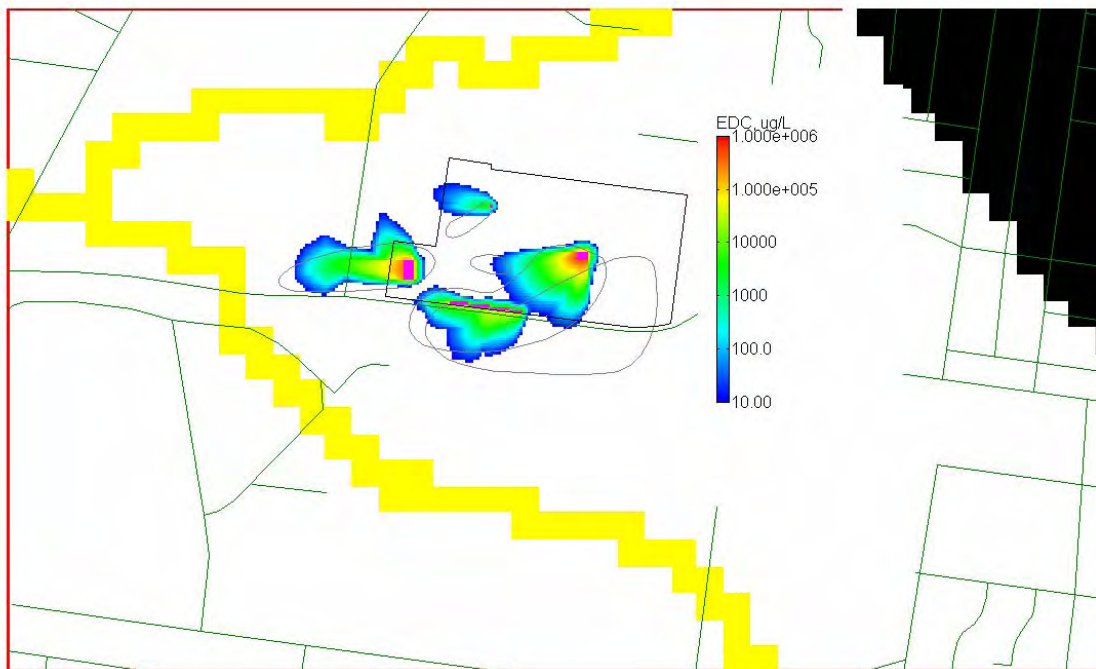


Figure 7.4-7. EDC plume after 140 years migration.

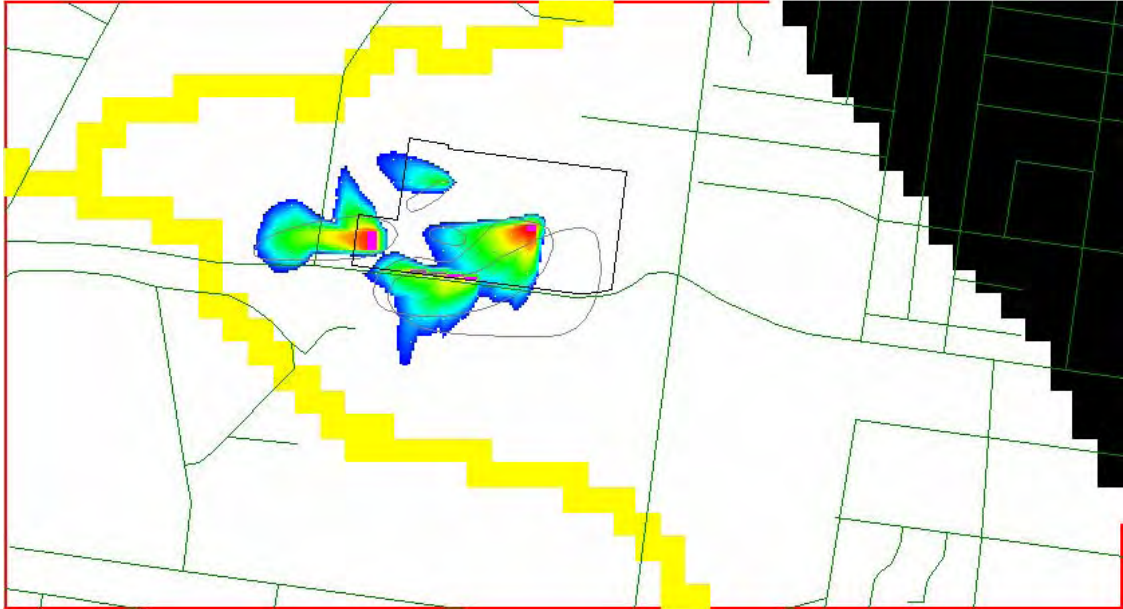


Figure 7.5-1. K_d decreased by 50% - 140 years plume migration.

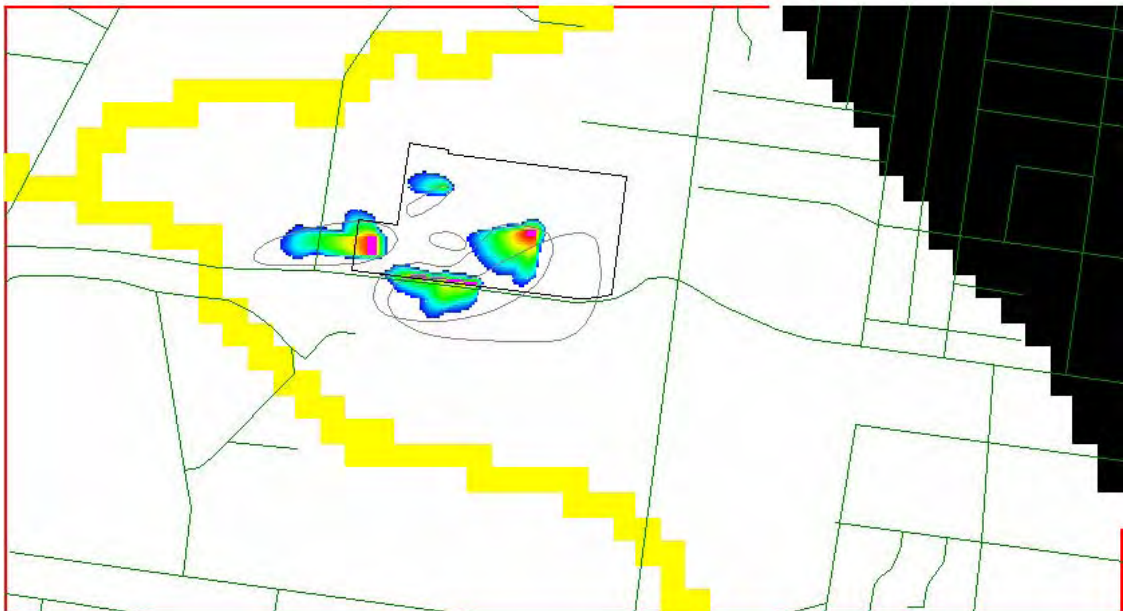


Figure 7.5-2. Fracture porosity increased by 50% - 140 years plume migration.

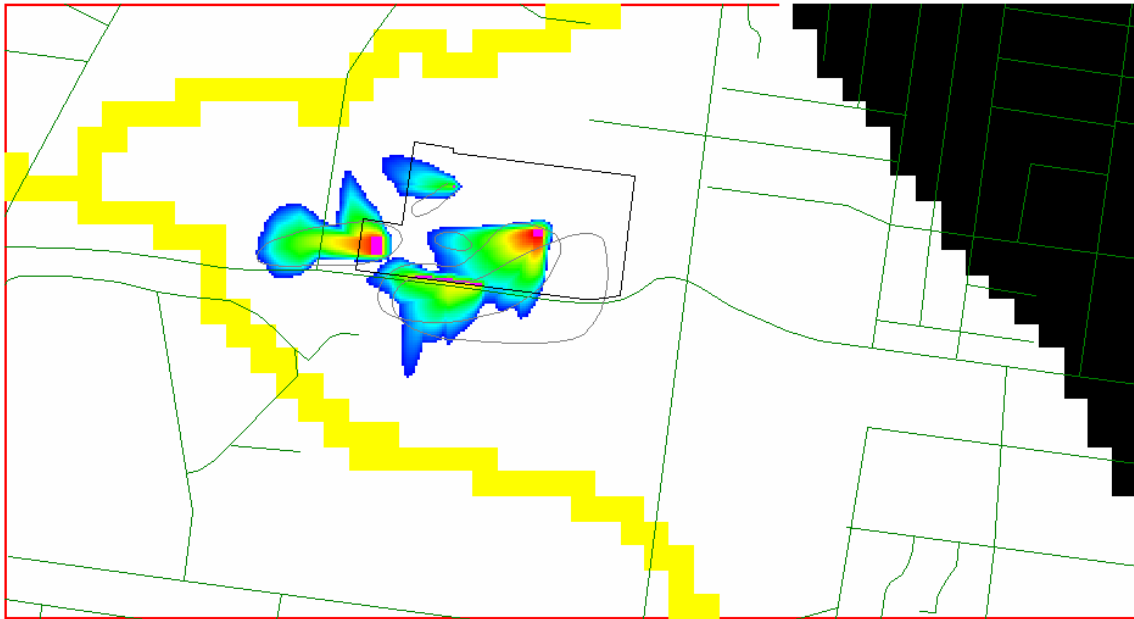


Figure 7.5-3. Fracture porosity decreased by 50% - 140 years plume migration.

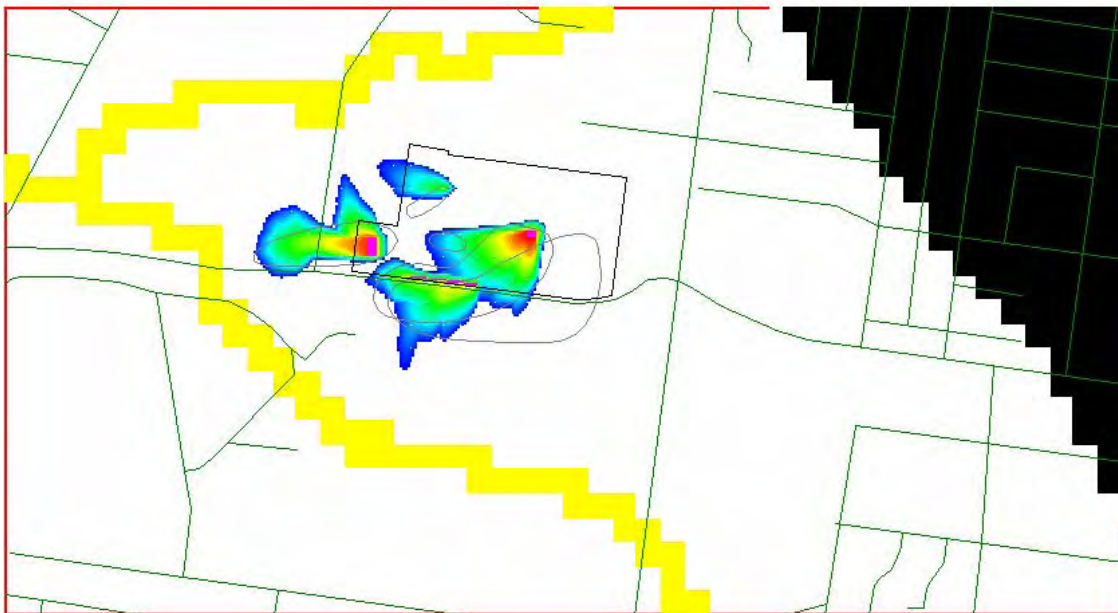


Figure 7.5-4. Bulk porosity increased by 50% - 140 years plume migration.

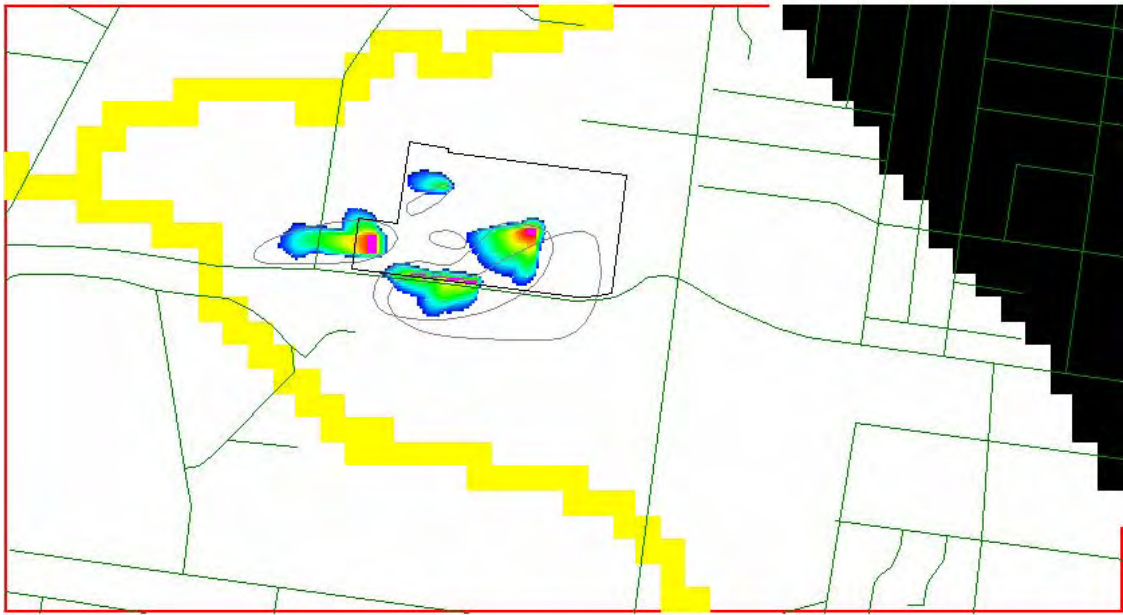


Figure 7.5-5. Bulk porosity decreased by 50% - 140 years plume migration.

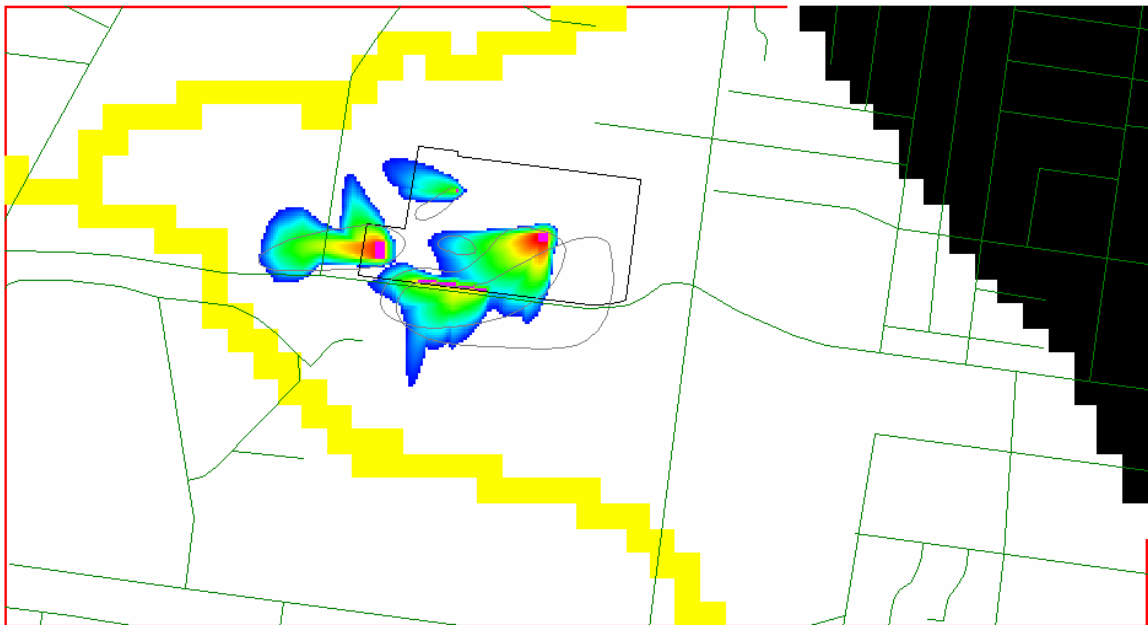


Figure 7.5-6. Reaction rate increased by 50% - 140 years plume migration.

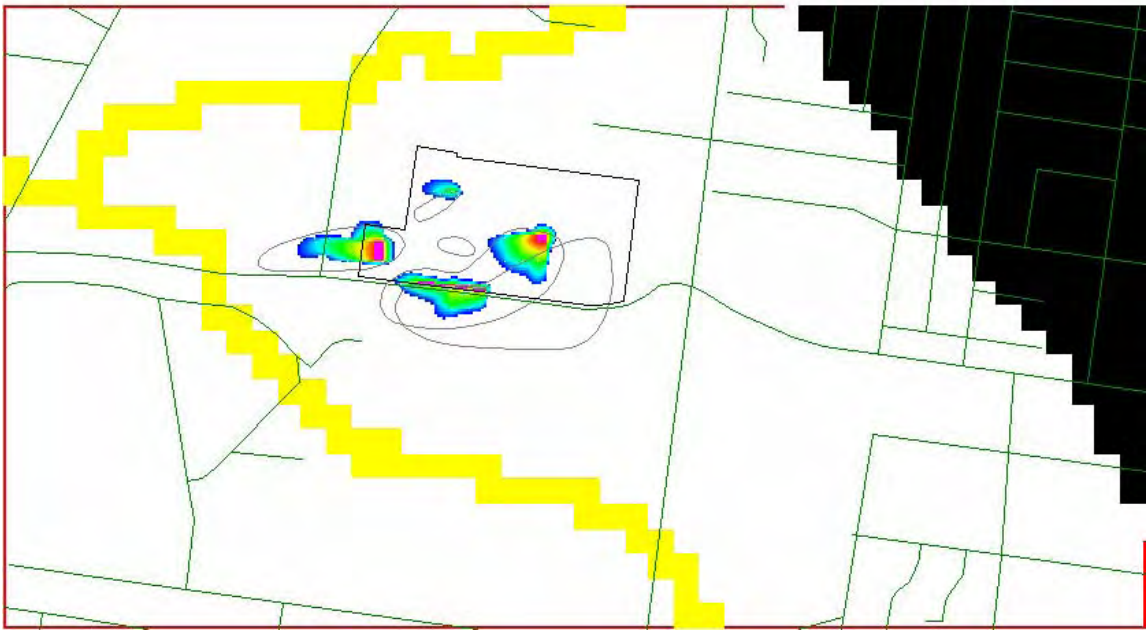


Figure 7.5-7. Reaction rate decreased by 50% - 140 years plume migration.

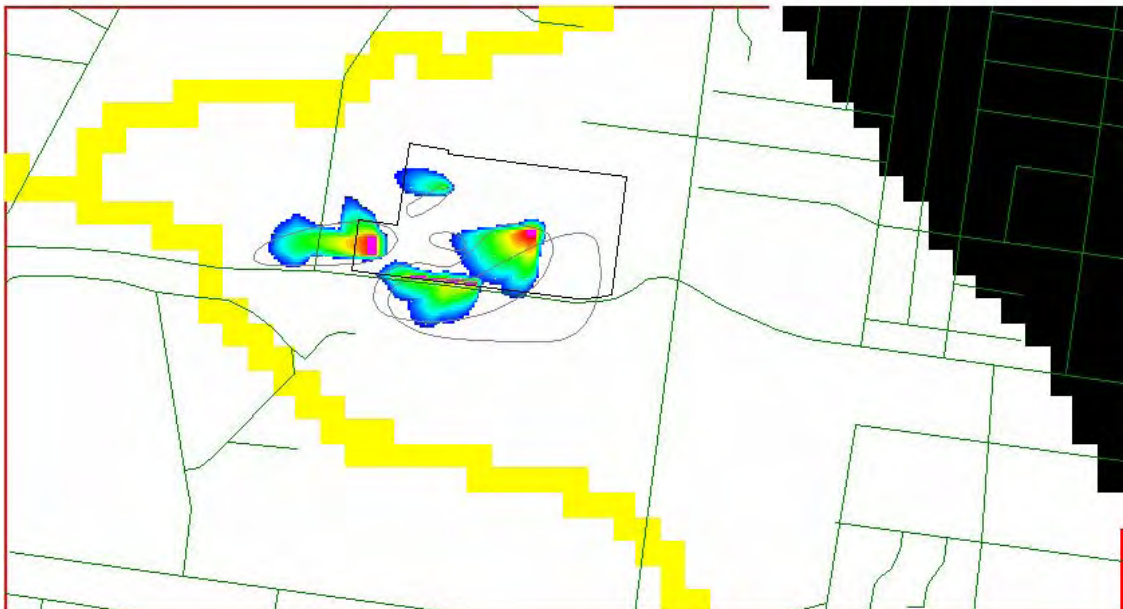


Figure 7.5-8. Mass transfer rate increased by 50% - 140 years plume migration.

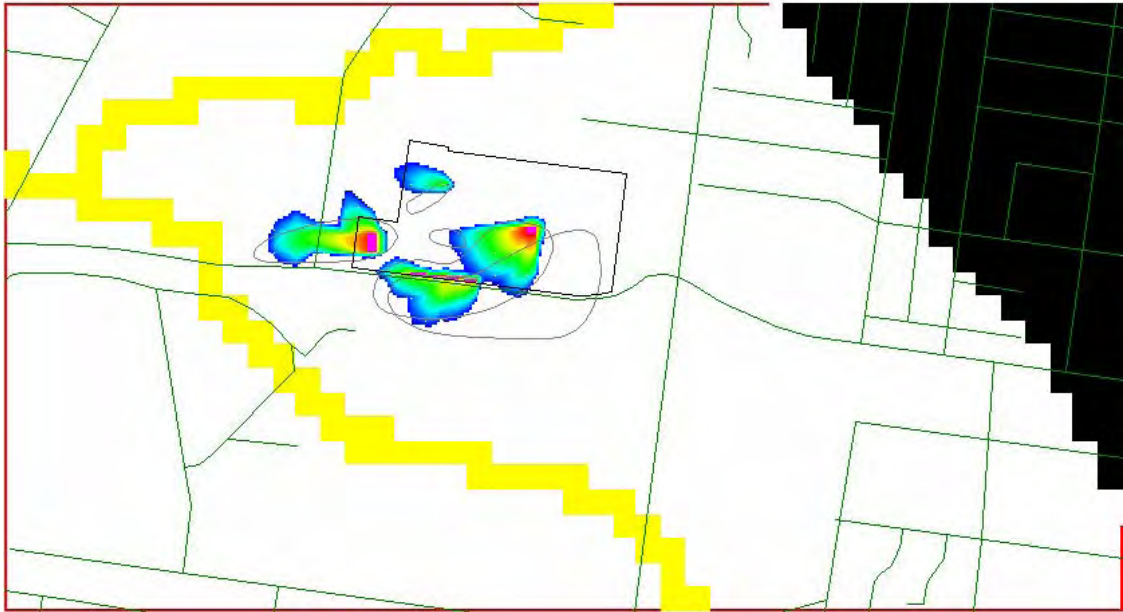


Figure 7.5-9. Mass transfer rate decreased by 50% - 140 years plume migration.

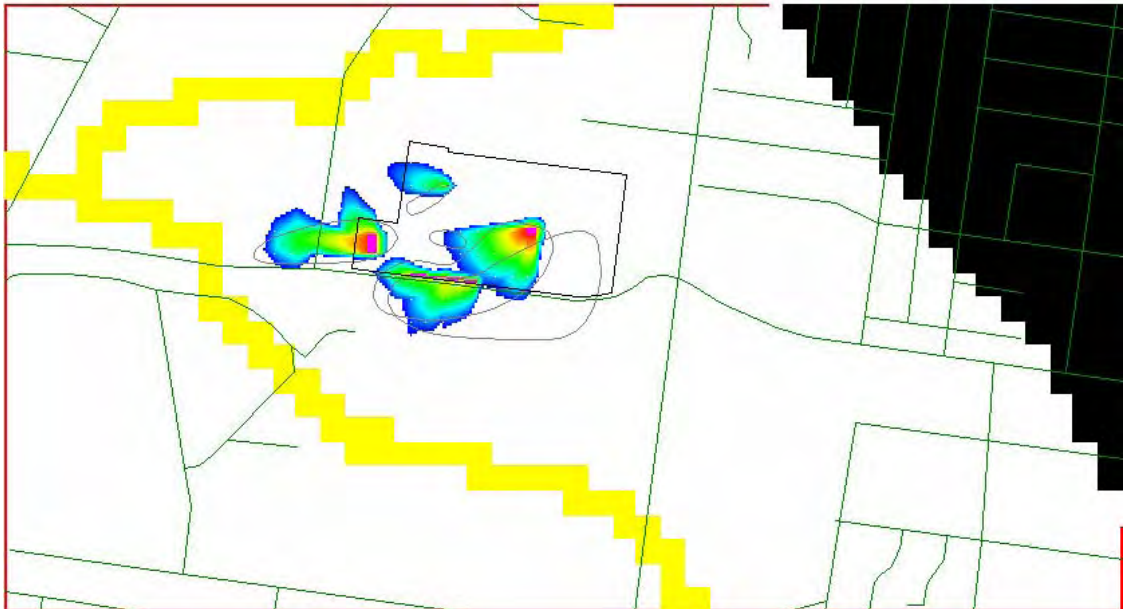


Figure 7.5-10. Source strength doubled - 140 years plume migration.

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