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FEB 2 3 2010

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PPPO-02-594-09

Mr. Edward Winner, FFA Manager
Kentucky Department for Environmental Protection
Division of Waste Management
200 Fair Oaks Lane, 2nd Floor
Frankfort, Kentucky 40601

Dear Mr. Ballard and Mr. Winner:

TRANSMITTAL OF THE 2008 UPDATE OF THE PADUCAH GASEOUS DIFFUSION PLANT SITEWIDE GROUNDWATER FLOW AND TRANSPORT MODEL, (PRS/ENR/0028)

Please find enclosed the *2008 Update of the Paducah Gaseous Diffusion Plant Sitewide Groundwater Flow and Transport Model*, (PRS/ENR/0028). This report was developed in part through meetings and review by the Groundwater Modeling Working Group (Working Group). The Working Group included representatives from the Department of Energy (DOE), U.S. Environmental Protection, Commonwealth of Kentucky Division of Waste Management, Commonwealth of Kentucky Radiation Health Branch, Kentucky Research Consortium for Energy and Environment, and their respective support contractors.

This site-wide flow model provides an update to previous modeling endeavors undertaken at the Paducah Gaseous Diffusion Plant and will be used to complete Tier 4 modeling, as described in the Paducah Risk Methods Document.

Upcoming projects that utilize groundwater modeling or evaluations of site hydrology will benefit from this updated document. Any future model modifications, including modifications that might occur in response to any comments by your agency on this report, will be addressed by the working group and incorporated into a revision of the document.

If you have any questions or require additional information, please contact Rich Bonczek at (859) 219-4051.

Sincerely,

Reinhard Knerr
Paducah Site Lead
Portsmouth/Paducah Project Office

Enclosure:
2008 Update of the PGDP Sitewide GW Flow & Transport Model

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PRS-ENR-0028

2008 Update of the Paducah Gaseous Diffusion Plant Sitewide Groundwater Flow Model

A PRODUCT OF THE
PADUCAH GASEOUS DIFFUSION
PLANT SITE
GROUNDWATER MODELING
WORKING GROUP

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PRS-ENR-0028

2008 Update of the Paducah Gaseous Diffusion Plant Sitewide Groundwater Flow Model

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ACRONYMS

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DNAPL	dense nonaqueous-phase liquid
DOE	U.S. Department of Energy
EPA	U. S. Environmental Protection Agency
FD	Finite Difference
GHB	general head boundary
k_d	partition coefficient
KDEP	Kentucky Department for Environmental Protection
MOC	Method of Characteristics
MW	monitoring well
PGDP	Paducah Gaseous Diffusion Plant
RGA	Regional Gravel Aquifer
SAIC	Science Applications International Corporation
SDS	sum of the difference squared
SWMU	solid waste management unit
^{99}Tc	technetium-99
TCE	trichloroethene
TMR	telescopic mesh refinement
TVA	Tennessee Valley Authority
TVD	Total Variation Diminishing
UCRS	Upper Continental Recharge System
V3PP	Visual Three-Point Plus

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1. INTRODUCTION

The Paducah Gaseous Diffusion Plant (PGDP) Sitewide Groundwater Flow Model was developed to simulate groundwater flow within the Regional Gravel Aquifer (RGA) and is an update to previous modeling endeavors undertaken for the PGDP. This model will be used to complete the modeling tasks as described in the Paducah Risk Methods Document (DOE 2008a). As described in the Paducah Risk Methods Document, the modeling is used to assist in the determination of potential additional data needs, evaluate potential remedies, calculate cleanup criteria in decision documents, and develop inputs needed to design the selected remedy. Additionally, this flow model will be used when completing Tier 2 and 3 modeling, which requires flow information in order to select potential points of exposure located away from source areas.

Modeling, as any specialized field, has unique jargon. To facilitate understanding of the document, a few of the more common terms will be defined here. Simplistically, a finite-difference numerical model consists of a specified number of rows and columns whose intersection produces cells. Each cell is assigned property values and sometimes a boundary condition. Boundary cells, sometimes referred to as boundary conditions, are cells that add to or remove or halt the movement of water from the model. An example of a boundary cell frequently used in models is the well cell. Water is removed (pumped) from the model at a specified amount from the location of the well cell. It is important to realize that boundary cells represent real site features. For example, Bayou and Little Bayou Creeks add or remove water from the groundwater flow system and, as such, are considered boundaries at PGDP. The same can be said for the Ohio River.

Aquifer properties control the movement of water between boundary cells. The best known aquifer property is hydraulic conductivity, which provides resistance to flow between the boundary cells. While technically not an aquifer property because it adds water to the flow system, recharge is considered a property by the modeling community. Other examples of aquifer properties include porosity (the volume of voids divided by the total sample volume) and storativity (the volume of water released from storage per unit water level decline per unit area of aquifer).

The term parameter refers to all model input values (boundary and properties) that potentially can be adjusted during model development and subsequent calibration. Some of the more common parameters in a model are hydraulic conductivity and recharge. Parameter also applies to the various components of boundary conditions. For example, a drain boundary cell removes water from the model as a function of the cell's assigned conductance and water level elevation. Simplistically, conductance provides resistance (analogous to hydraulic conductivity) to groundwater flow into the cell; the lower the conductance, the harder it is for water to enter the cell. Both the drain conductance and water level elevation can be adjusted during calibration and thus are parameters.

Targets are any item that can be used to constrain a model during calibration. An example is water level elevation. For a model to be representative, it needs to be able reasonably to replicate site water levels. Other targets used to constrain models include flux targets. At PGDP, an example of a flux target is groundwater discharge to the Ohio River. To be considered calibrated, the model needs to predict similar groundwater discharge volumes to the Ohio River as the flux target.

Finally, model calibration refers to the process during which the model aquifer and boundary conditions are systematically changed until a reasonable match is achieved between the model-predicted and target values.

The contents of the report are as follows:

- Section 2 discusses the technical approach used for the groundwater flow model development and calibration.
- Section 3 presents an evaluation of the previous model developed principally in 1997.
- Section 4 describes data evaluation and analysis performed as part of the flow modeling exercise.
- Section 5 presents the site hydrogeologic conceptual model, essentially a summary of where water enters and leaves the flow system and in what volumes and the factors influencing groundwater movement.
- Section 6 describes groundwater flow model configuration, which is the process by which the site hydrogeologic conceptual model is translated into a numerical model.
- Section 7 discusses groundwater flow model calibration, sensitivity analysis, and model verification.
- Section 8 provides an evaluation of the revised and calibrated groundwater flow model.
- Section 9 assesses whether the modeling objectives are satisfied and provides recommendations regarding the updated groundwater flow.

2. TECHNICAL APPROACH

The project was initiated by first evaluating the existing MODFLOW model (DOE 1997a) with respect to boundary conditions and parameter distributions and values, predicted water level elevations, plume flow paths, and model-predicted groundwater inflow and outflow values. In addition, the existing MODFLOWT (DOE 1997a) transport model also was evaluated. Potential issues with the groundwater flow and transport models were identified and targeted for correction (see Section 3). A companion transport model currently is under development by the modeling discussion group.

This updated Groundwater Flow Model is unique in that it was developed by a modeling discussion group consisting of personnel from the U.S. Department of Energy (DOE), U. S. Environmental Protection Agency (EPA), Kentucky Department for Environmental Protection (KDEP), University of Kentucky, Paducah Remediation Services, LLC, Science Applications International Corporation (SAIC), Performance Results Corporation, and Portage Environmental (Portage). Portage chaired the discussion group and performed all the modeling. While the model was developed by consensus, DOE ultimately is responsible for the flow model documented in this report.

Modeling group discussions determined that the purpose and objectives and potential applications of PGDP groundwater flow model were as follows:

- Optimization of remedial actions
- Evaluation of remedial action alternatives (Dissolved-Phase Plume, Burial Grounds Operable Unit, and on-site disposal facility options)
- Public communication
- Conceptual model evaluation
- Conceptual design development
- Evaluation of changing plant water usage
- Identification of potential data gaps
- Evaluation of influence of changing Ohio River stage on groundwater flow patterns
- Development of cleanup goals
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Cell project support
- Support evaluation of Dissolved-Phase Plume potential remedies

It should be noted that many of the listed tasks will be accomplished by future application of this model and the companion transport model.

- Development of compliance and performance monitoring approaches

- Support Burial Grounds Operable Unit remedial evaluations for Upper Continental Recharge System (UCRS) and RGA such as these:
  - Excavation
  - Capping
  - Secondary treatment
  - Barriers

- Support C-400 Electrical Resistance Heating evaluation

- Support evaluation of C-720 and Solid Waste Management Unit (SWMU) 1 remediation.

Modeling was initiated by evaluating and analyzing groundwater and surface water levels, subsurface hydraulic properties, ambient and anthropogenic recharge potentials, well construction details, and plume geometries. These data serve to constrain the model with regard to expected parameter distributions and typical groundwater flow patterns and discharge volumes. Details regarding data evaluation can be found in Section 4 of this report. The synthesized data were used to develop a conceptual model of groundwater flow at PGDP and surrounding areas (see Section 5). While titled a model, there is no mathematics associated with a conceptual model. Rather, a conceptual model is simply a description of where and in what quantity water enters and leaves the flow system, expected flow patterns, and the factors influencing groundwater movement between recharge and discharge locations. The conceptual model was used to determine the domain of the numerical model and the design of the model grid.

Model configuration involves translating the site hydrogeological conceptual model onto a two- or three-dimensional grid and defining 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 transport and remedial design simulations. Boundary conditions represent hydraulic features such as surface water bodies, pumping wells, and impermeable strata such as the Porters Creek Clay. Parameter zones represent areas of recharge and hydraulic conductivity within the model domain having the same numerical value. Details regarding data evaluation can be found in Section 6 of this report.

Groundwater flow modeling was performed using MODFLOW2000 (Harbaugh *et al.* 2000), the successor to MODFLOW, the widely used and accepted finite-difference code developed by the U.S. Geological Survey (McDonald and Harbaugh 1988). 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 and drain cell conductance. Pilot points take parameter estimation a step further and determine 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 7.

After groundwater flow model calibration, a sensitivity analysis (Section 7) was performed to determine which input parameters have the greatest influence on the resulting calibrated flow model. Typically, sensitivity analysis is conducted by individually adjusting input parameters and evaluating how the manipulation changes the water level calibration statistics. While the water level statistics provide an assessment of how input parameter adjustment influences predicted water levels, the sensitivity analysis does not evaluate how parameter changes influence predicted plume trajectories, which is ultimately more important with regard to the potential to simulate remedial contaminant behavior in groundwater. For this model, the sensitivity analysis evaluated how individual parameter adjustment (one at a time) affects simulated plume trajectories.

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3. EXISTING MODEL EVALUATION

This section evaluates the 1997 groundwater flow model and the 1998 and 1999 transport models for the purpose of determining necessary changes to improve the model's predictive capabilities. The identified changes will be incorporated in the flow and transport models currently under development.

3.1 HISTORY OF PGDP GROUNDWATER FLOW AND TRANSPORT MODELING

Numerous numerical modeling configuration and calibration efforts have been conducted at the PGDP, the first in 1990 and the more recent effort in 1999. The calibrated groundwater flow model (DOE 1997b) was used as recently as 2006 to make capture zone predictions. This summary of modeling activities will focus on models that underwent configuration and calibration, and not recent applications. For brevity, the modeling chronology will be summarized in tabular form. For additional information about a specific model, please review the associated reference listed in Table 3.1. Model evaluation documented in this section pertains to the 1997 flow model and 1998 and 1999 transport models.

Table 3.1. Historical Summary of PGDP Numerical Models

Model Type	Codes	Year	Author	Report Title	Reference
3-D Steady-State Flow Model	MODFLOW	1990	GeoTrans	*Numerical Modeling of Groundwater Flow at the Paducah Gaseous Diffusion Plant, Phase I and II*	GeoTrans 1990
3-D Steady-State Flow Model	MODFLOW	1992	GeoTrans	*Groundwater Modeling and Off-site Containment Evaluation at the Paducah Gaseous Diffusion Plant*	GeoTrans 1992
3-D Steady-State Flow Model	MODFLOW	1992	C. L. McConnell	*A Steady State Computer Model of the C-404 Landfill Area*	McConnell 1992
3-D Steady-State Flow Model	MODFLOW	1994	C. L. McConnell	*A Steady State Computer Model of the C-747-A Landfill Area*	McConnell 1994a
2-D Steady-State Transport Model	MT3D	1994	C. L. McConnell	*A Containment Transport Model of Trichloroethylene and Technetium in the Regional Gravel Aquifer*	McConnell 1994b
3-D Steady-State Flow Model	MODFLOW	1994	Jacobs EM Team	*Feasibility Study for Solid Waste Management Units 2 and 3 of Waste Area Group 22 at the Paducah Gaseous Diffusion Plant Paducah, Kentucky*	DOE 1994

Table 3.1. Historical Summary of PGDP Numerical Models (Continued)

Model Type	Codes	Year	Author	Report Title	Reference
3-D Steady-State Flow Model	MODFLOW	1996	Jacobs EM Team	*Feasibility Study for Waste Groups 1 and 7 and Kentucky Ordnance Works Solid Waste Management Units 94, 95 and 157 at the Paducah Gaseous Diffusion Plant Paducah, Kentucky*	DOE 1996
3-D Steady-State Flow and Transport Models	MODFLOW and MODFLOWT	1997	Jacobs EM Team	*Numerical Ground-Water Model Recalibration and Evaluation of the Northwest Plume Remedial Action Report for the Paducah Gaseous Diffusion Plant Paducah, Kentucky*	DOE 1997b
3-D Steady-State Flow Model	MODFLOW	1997	Oak Ridge National Laboratory	*Paducah Gaseous Diffusion Plant Northwest Plume Interceptor System Evaluation*	Laase and Clausen 1997
3-D Steady-State Transport Model	MODFLOWT	1998	Jacobs EM Team	*Transport Modeling Results for the Northeast Plume Interim Remedial Action and the Northwest Plume at the Paducah Gaseous Diffusion Plant Paducah, Kentucky*	DOE 1998
3-D Steady-State Transport Model	MODFLOWT	1999	Jacobs EM Team	*Transport Modeling Results for the Northwest Plume at the Paducah Gaseous Diffusion Plant Paducah, Kentucky*	DOE 1999

3.2 EXISTING PGDP MODEL CONFIGURATION AND CALIBRATION

This section describes and evaluates configuration and calibration of the existing PGDP flow and transport model.

3.2.1 Model Discretization

The existing 1997 MODFLOW (McDonald and Harbaugh 1988) flow model consists of 167 rows, 190 columns, and four layers (Figures 3.1 and 3.2). Cell size range from a minimum of 50 by 50 ft to a maximum of 425 by 425 ft, and are produced by combinations of rows and columns having variable widths ranging from 50 to 425 ft. Corresponding to upper and lower UCRS, RGA, and McNairy Formations, the four model layers are variable in thickness, ranging from less than 1 ft to more than

100 ft. In all, the model contains 126,920 cells, 95,215 of which are active and cover an area of 26.5 square miles (7.4×10^8 ft^2).

Recent remedial design and transport models use smaller cell sizes than the 50- by 50-ft cells used in the existing PGDP flow model. Steady-state flow model simulation run times were reported to be approximately 20 minutes on the fastest computer available at the time. Halving both row and column widths in the model would increase the number of cells by a factor of four and correspondingly increase run times by a factor of four (80 minutes). Realistically, at the time the model was configured and calibrated, use of smaller cell sizes was not an option. It should be noted that computer processor speed has increased dramatically since the PGDP flow model was configured and calibrated.

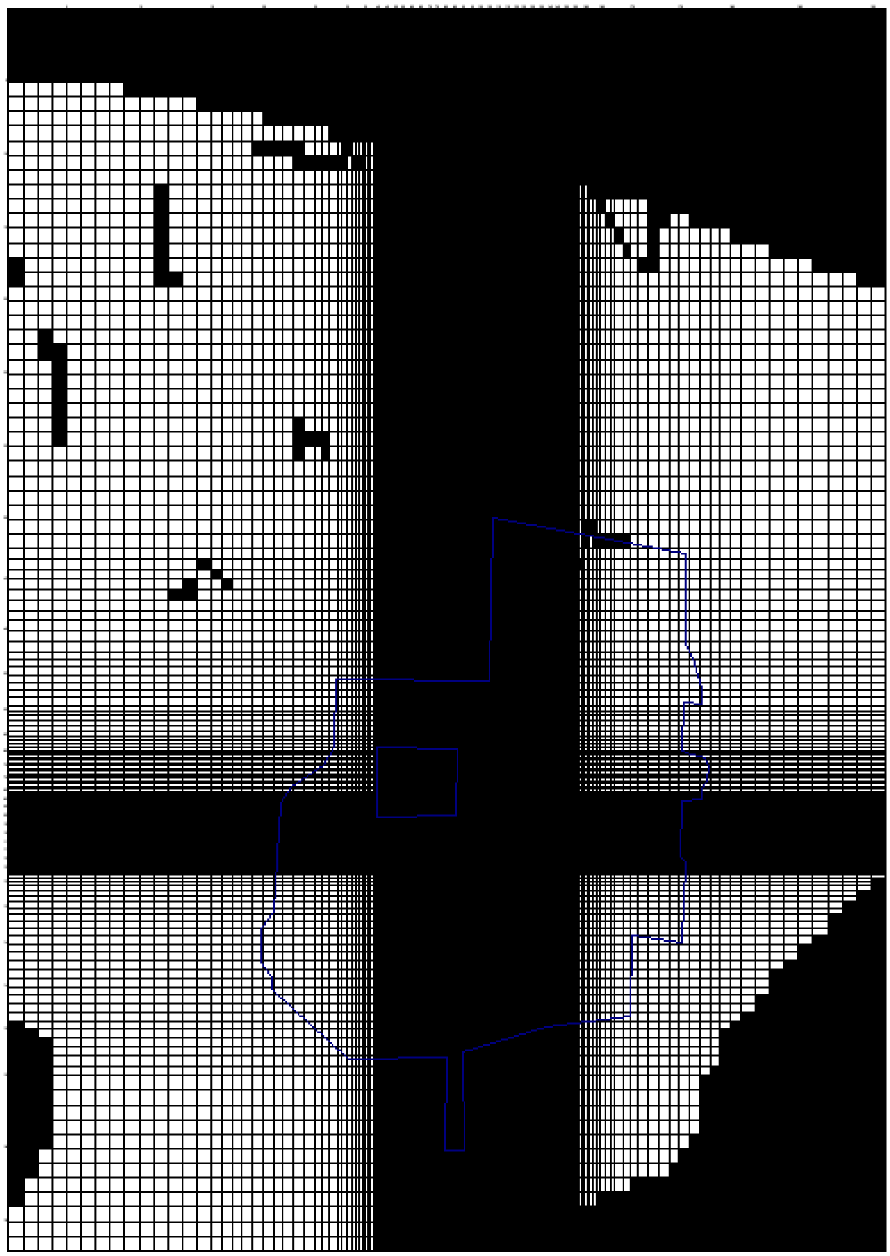


Figure 3.1. Horizontal Model Discretization

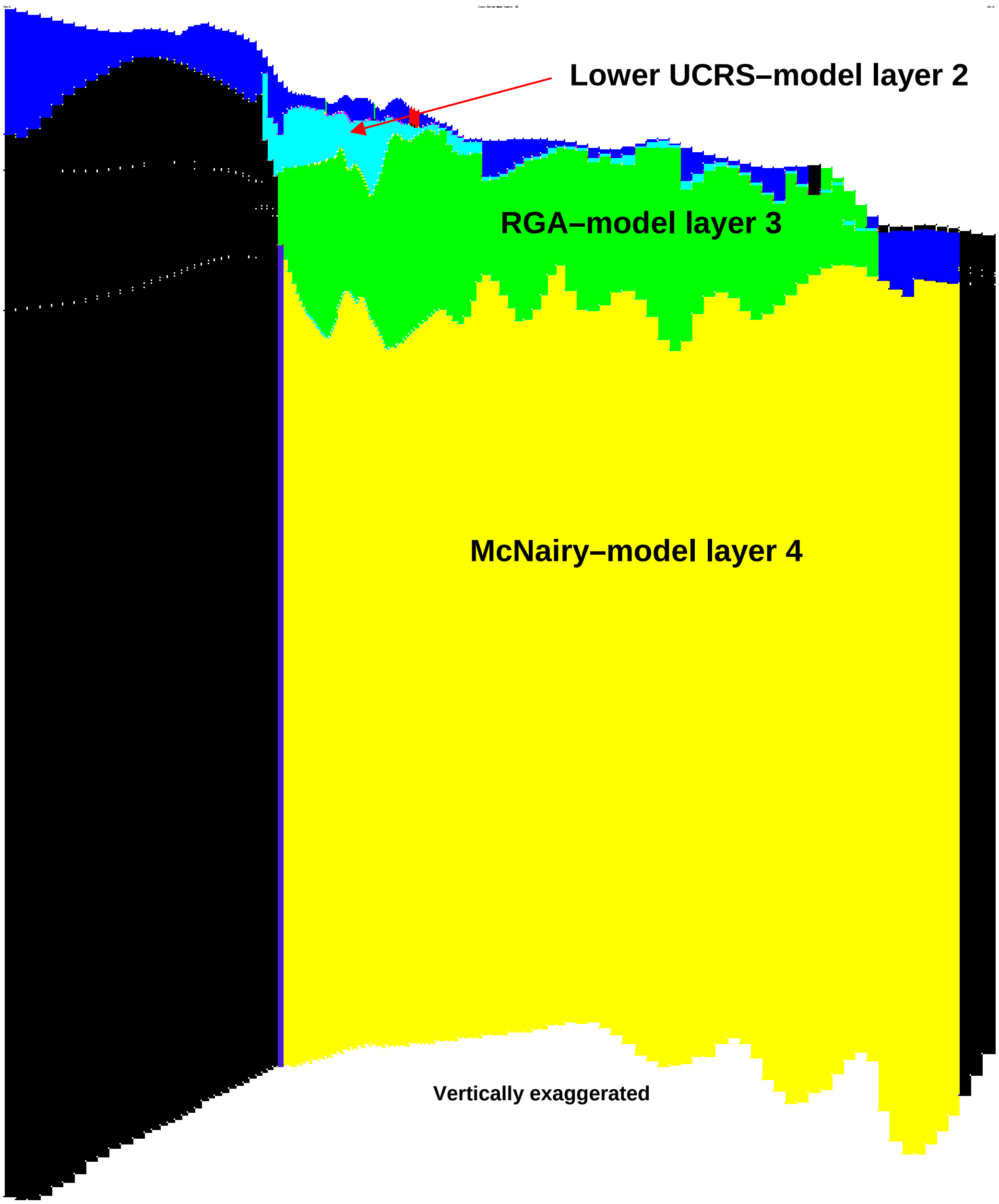


Figure 3.2. Vertical Model Discretization

3.2.2 Model Boundary Conditions

Model boundary conditions contribute, remove, or prevent the movement of water within the model domain. Boundary conditions are located along the exterior and within the interior of the model domain. An example of an exterior model boundary is the Ohio River. Bayou 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 3.2.3.

The Ohio River, located in model layer 3, is represented by constant head boundary cells assigned a stage of 300 ft (Figure 3.3). As the name implies, constant head cells are never varying and always have the same head value throughout the simulation. In fact, MODFLOW does not allow constant head cells to alter stage or location during a simulation, which limits the cells usefulness as surrogates for a river of temporally varying stage. The direction of water movement in and out of a constant head cell is a function of the difference between the predicted head in the adjacent cell and the specified constant head. If the simulated head value in an adjacent cell is greater than the constant head value, water flows into the constant head cell from the adjacent cell. Correspondingly, if the simulated head value in an adjacent cell is less than the constant head value, water flows out of the constant head cell into the adjacent cell. Constant head cells themselves offer no resistance to flow in or out of the constant head cell, rather the volume of water exchanged between the constant head cell and adjacent cell is a function of the hydraulic conductivity of the adjacent cell and the head difference between the two cells. The Ohio River is the most downgradient feature in the model, thus the predicted heads in the adjacent cells are all greater than 300 ft, which insures discharge to the constant head cells.

Upgradient McNairy through flow (an external model boundary) is represented in the model using a line of general head boundary (GHB) cells located in model layer four (Figure 3.4). GHB cells are analogous to constant head cells in that the cells are assigned a constant head value. GHB cells differ in that these cells are also assigned a conductance term that limits flow in and out of the cells. To represent upgradient McNairy through flow the GHB, cells were assigned head values corresponding to expected groundwater level elevations along the boundary and conductance values ranging from approximately 2,500 to 14,000 ft^2/day. Conductance is analogous to hydraulic conductivity in that both quantify resistance to flow. Comparing conductance values is not as straight forward as comparing hydraulic conductivity values because the conductance term is calculated using the area of the simulated boundary (often the area of the cell) and the saturated thickness of the cell. Thus, cells of different size may have different conductance values, but offer the same resistance to flow.

Internal model boundaries include river cells representing Bayou and Little Bayou Creeks, PGDP drainage ditches, gravel pits adjacent to the PGDP, the Tennessee Valley Authority (TVA) discharge Pond, and Metropolis Lake (Figure 3.5). Simplistically, river boundary cells have head, bottom elevation, 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.

River cells representing Bayou Creek were assigned head values corresponding to creek stage and are located in model layers one through three depending on which hydrostratigraphic unit applies (upper and lower UCRS or RGA) at that location (Figure 3.5). Conductance of the river cells ranges from 450 to 17,000 ft^2/day and, as with GHBs, is dependent on cell size.

River cells representing the TVA discharge pond were assigned head values of 346 ft, which is 46 ft higher than the adjacent Ohio River stage and a conductance of 2,130 ft^2/day.

River cells representing drainage ditches at the PGDP were assigned head values corresponding to an elevation a few tenths of a foot greater than the bottom elevation of the ditch and conductance values ranging from 20 to 80 ft^2/day.

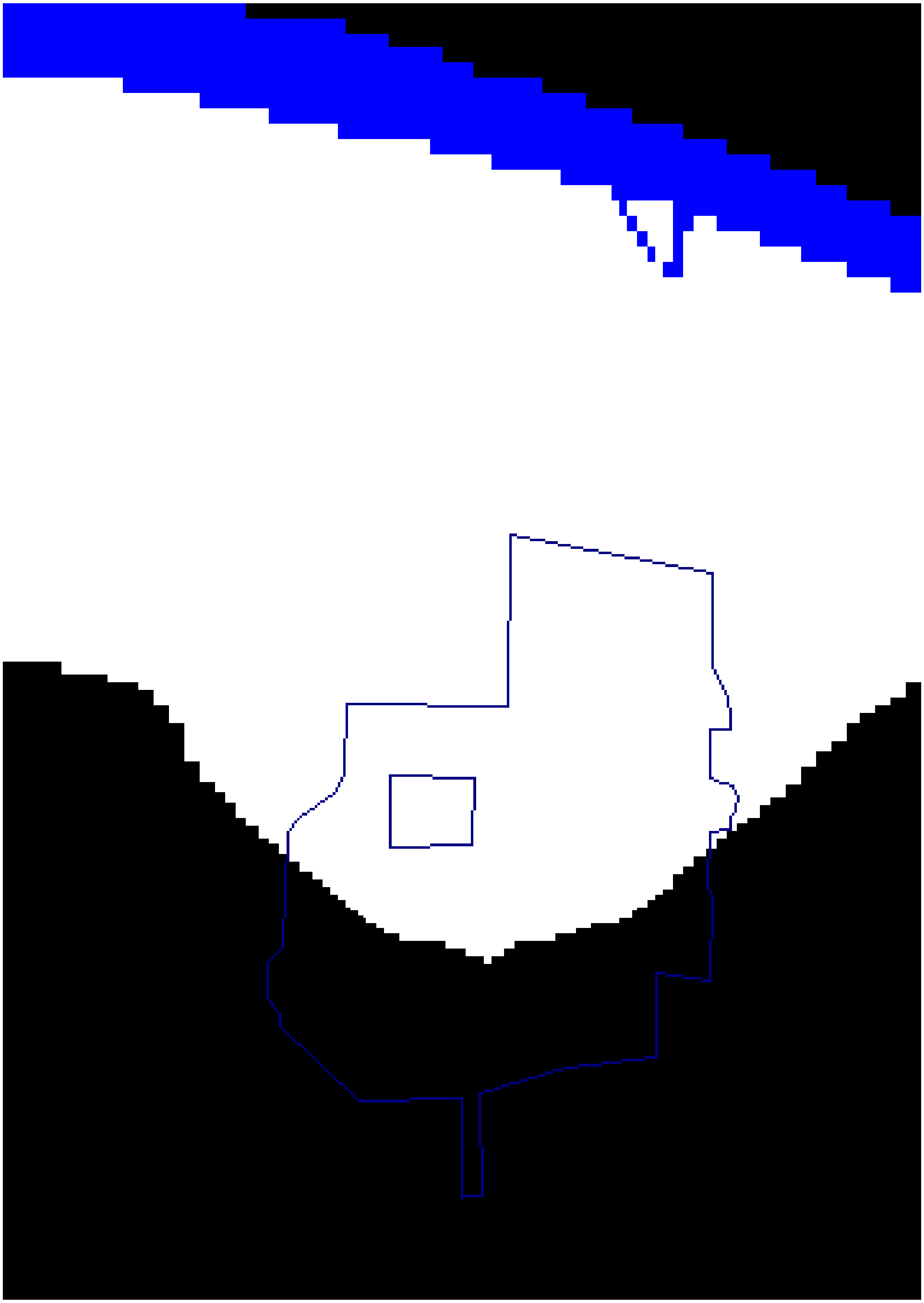


Figure 3.3. Ohio River in Model

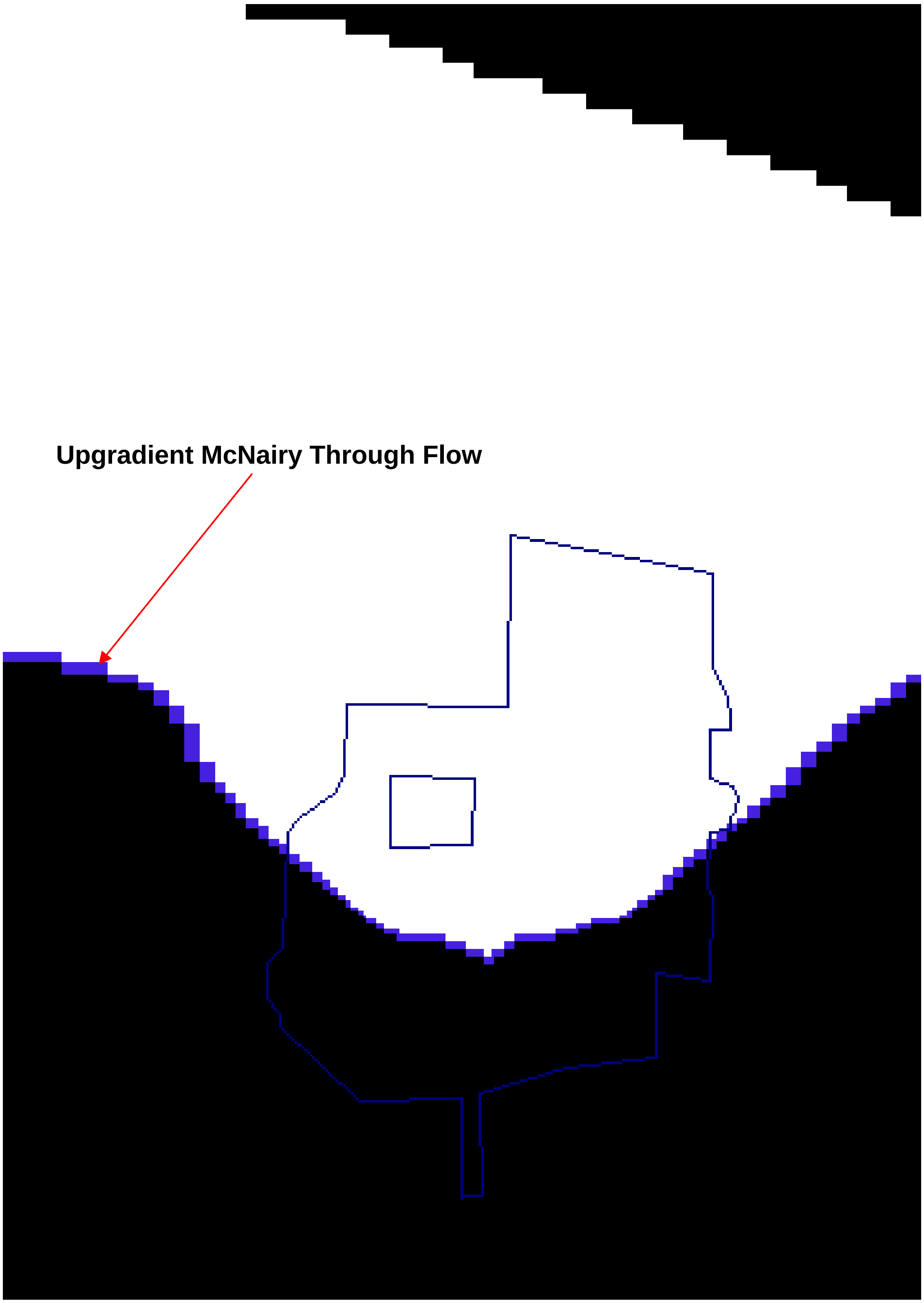


Figure 3.4. Upgradient McNairy Through Flow

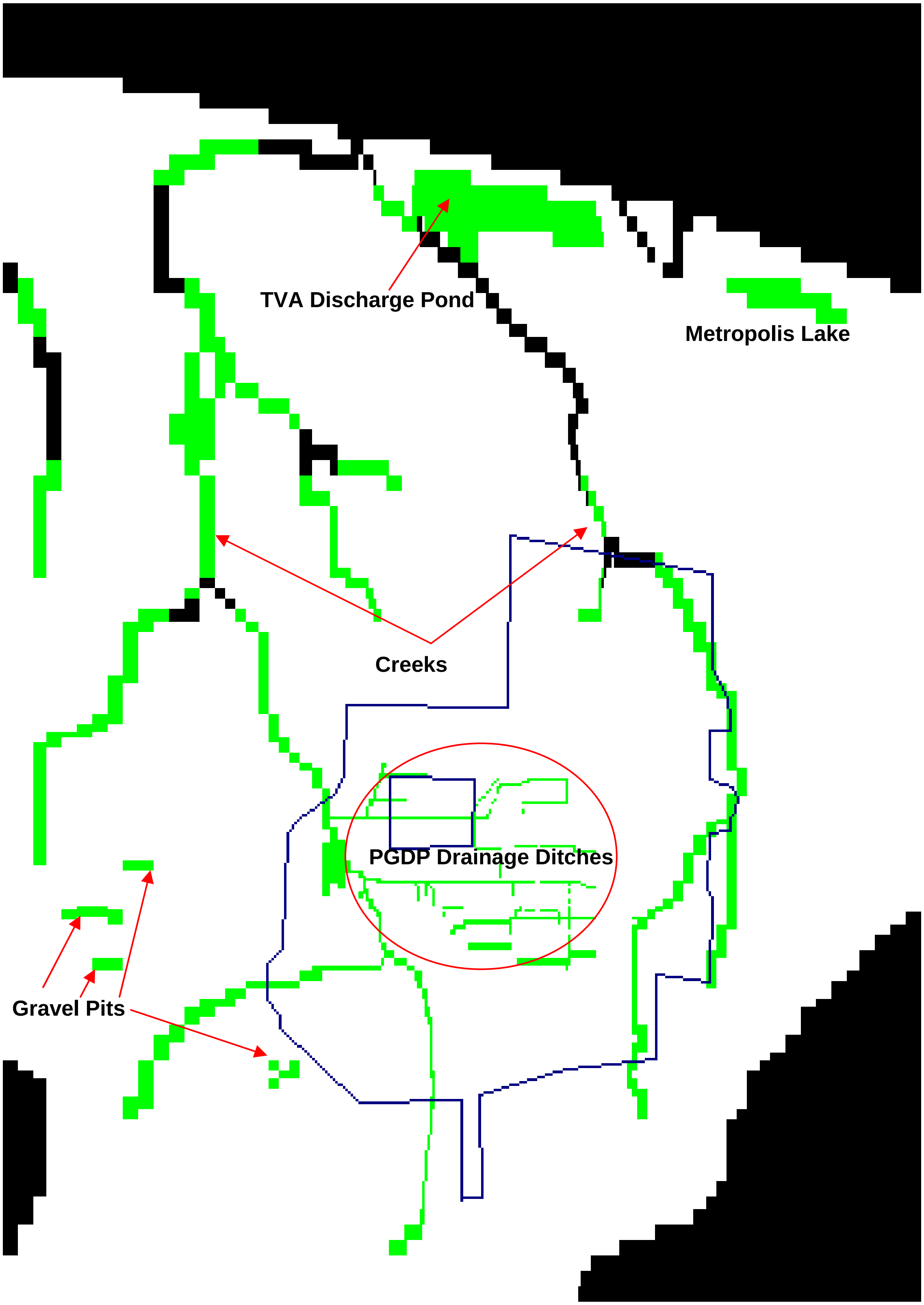


Figure 3.5. River Cell Boundaries

The gravel pits and Metropolis Lake are surface expressions of the groundwater table. These features intersect the water table and the stage of the pits/lake is representative of local groundwater levels. When groundwater levels are high, the pit/lake levels are correspondingly high. Similarly, when groundwater levels are low the pit/lake levels are low. River cells representing the four gravel pits were assigned head values ranging between 405 ft and 430 ft and conductance values ranging from 2,125 to 8,500 ft^2/day. Metropolis Lake was assigned a head value of 315 ft and a conductance of 18,000 ft^2/day.

Well cells (internal model boundaries) were used to simulate recharge from a lagoon and four cooling towers (Figure 3.6). A well cell adds or removes water from the model at a specified amount and that amount can vary temporally. In the existing PGDP model, well cell injection rates were constant for the duration of the simulation. Individual cooling tower and lagoon cumulative injection rates (the combined injection rate for all the well cells representing the cooling tower or lagoon) ranged from 478 ft^3/day (~2.5 gpm) to 1,401 ft^3/day (~7 gpm).

The black areas shown in Figures 3.7 through 3.10 are no flow cells and, as the name implies, water does not enter or leave these cells. No flow cells are used in model layers 1 and 2 at the location of the Ohio River and where Bayou and Little Bayou Creeks extends into the underlying model layer. As configured in the model, the Ohio River stage is less than the bottom elevations of model layers 1 and 2 at the location of the river. Thus, no flow cells were assigned at the river locations to remove these cells from the simulated flow regime. No flow cells were also used in model layer 3 to remove portions of the model located north of the Ohio River from the flow regime. The flow area north of the Ohio River is geologically identical to the active portion of the model across the feature to the south. The Ohio River is a regional discharge location and hydraulically isolates groundwater flow on either side of the surface water feature. Because of hydraulic isolation, areas north of the Ohio River were designated as no-flow cells. In model layers 1 through 3, the low permeability Porters Creek Clay, located at the southern edge of the modeling domain, is represented using no flow cells. Lastly, while the McNairy does extend under the Porters Creek Clay, the McNairy was arbitrarily truncated beneath the clay and assigned no flow cells.

3.2.3 Model Parameter Distributions and Calibrated Values

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. Assuming equal sediment thickness, 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.

3.2.3.1 Hydraulic Conductivity Zonation

Model layer 1 (upper UCRS) hydraulic conductivity ranges from 1 to 40 ft/day (Figure 3.11). The highest values are associated with the Terrace Gravel located south of PGDP. UCRS hydraulic conductivity underlying PGDP proper, ranges from 1 to 4.5 ft/day. Adjacent to the Ohio River and the two creeks, UCRS hydraulic conductivity is 3 ft/day.

Similar to model layer 1, model layer 2 (lower UCRS) hydraulic conductivity ranges from 1 to 40 ft/day, with the highest value associated with the Terrace Gravel (Figure 3.12). Adjacent to the Ohio River and the two creeks UCRS hydraulic conductivity is 3 ft/day. UCRS hydraulic conductivity underlying the PGDP proper ranges from 1 to 3.5 ft/day.

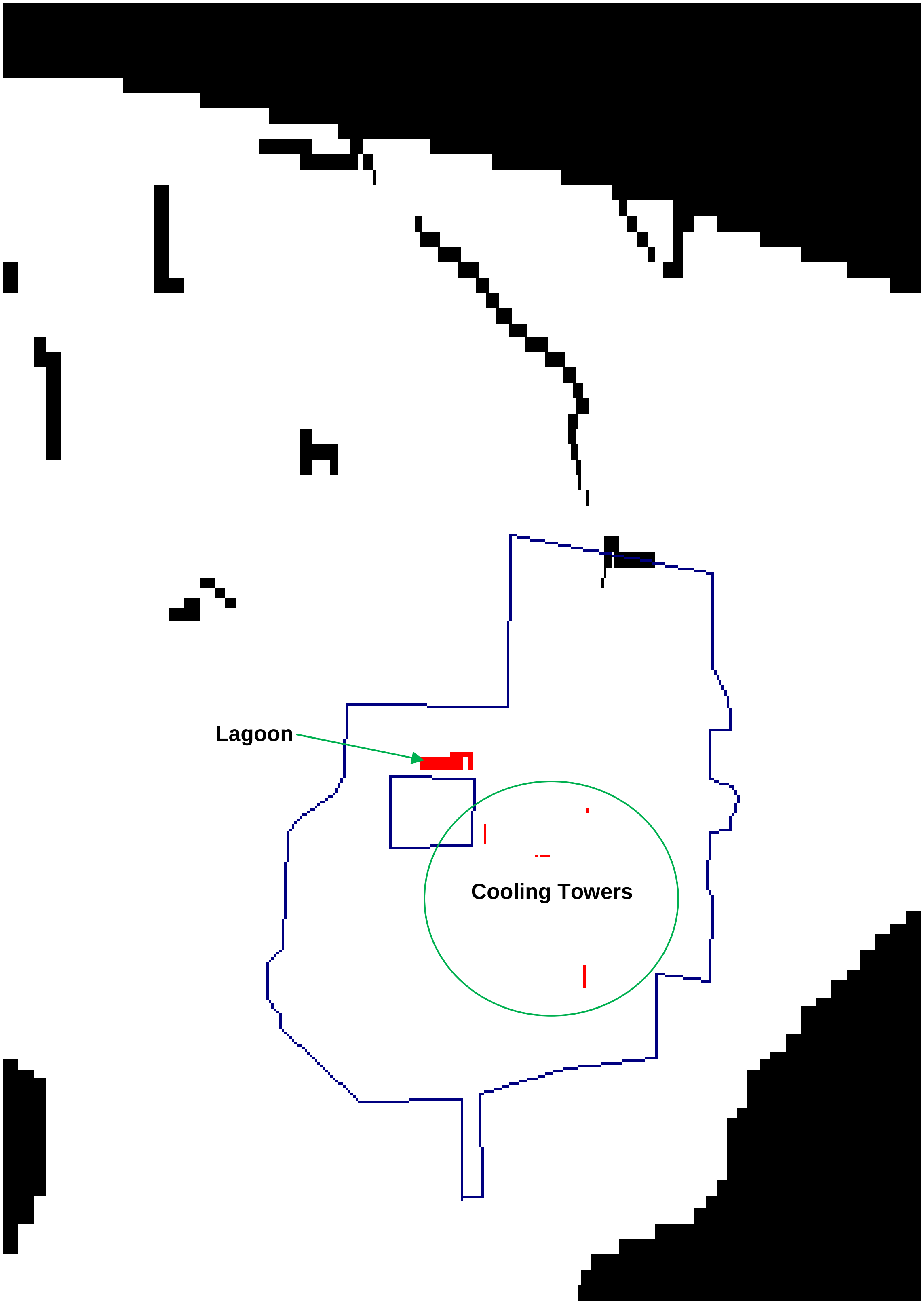


Figure 3.6. Well Cell Boundaries

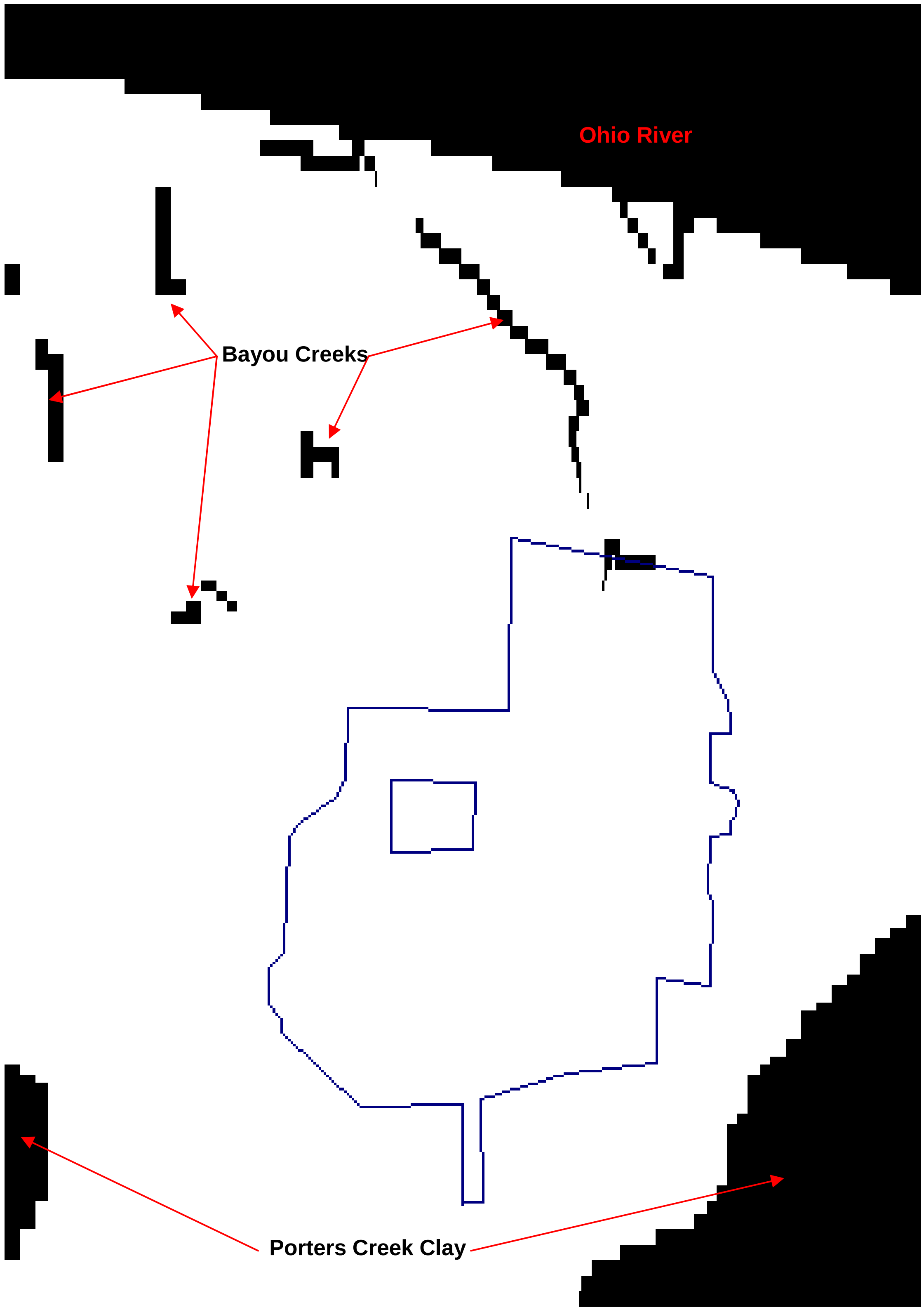


Figure 3.7. Model Layer 1 No Flow Cells

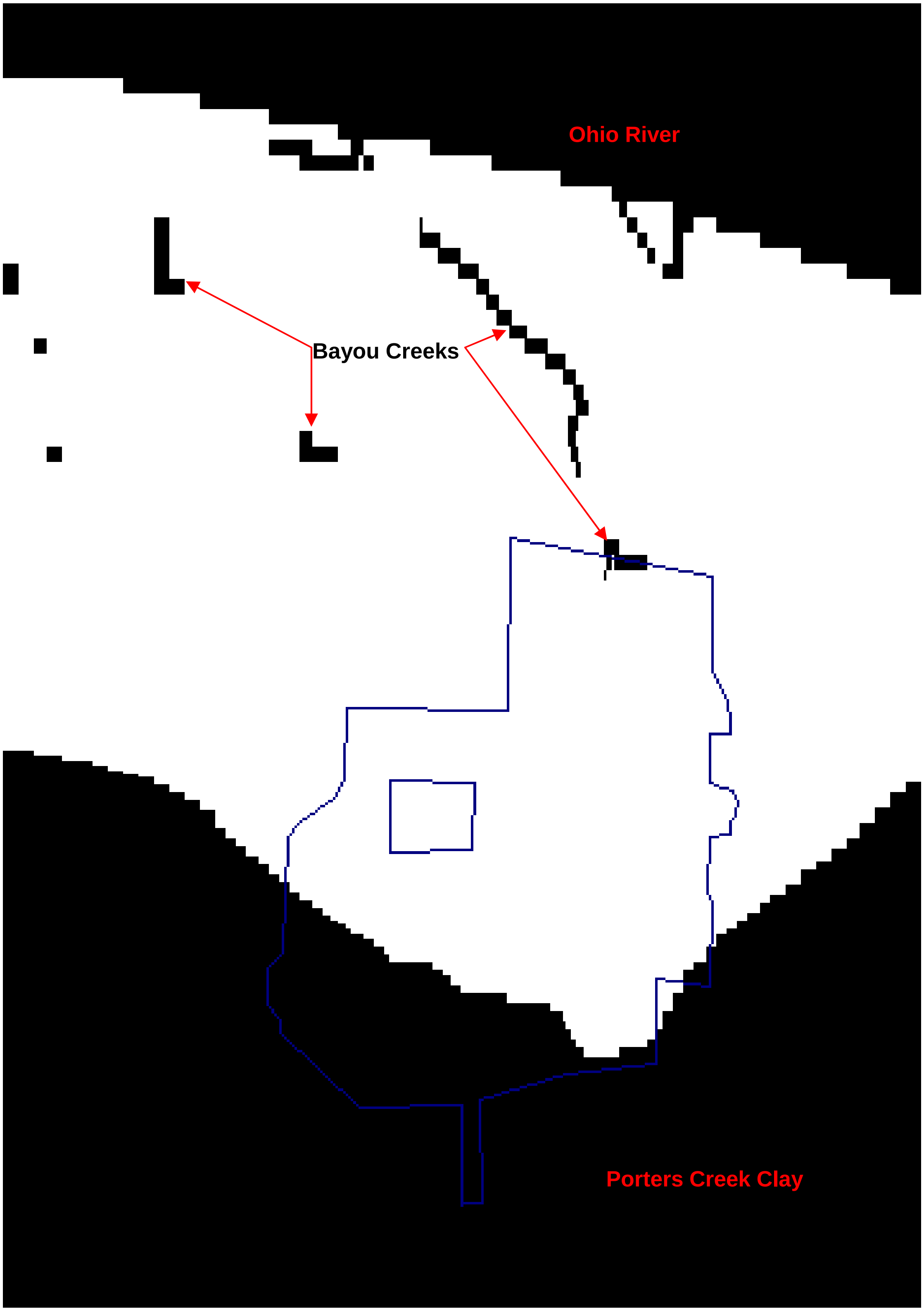


Figure 3.8. Model Layer 2 No Flow Cells

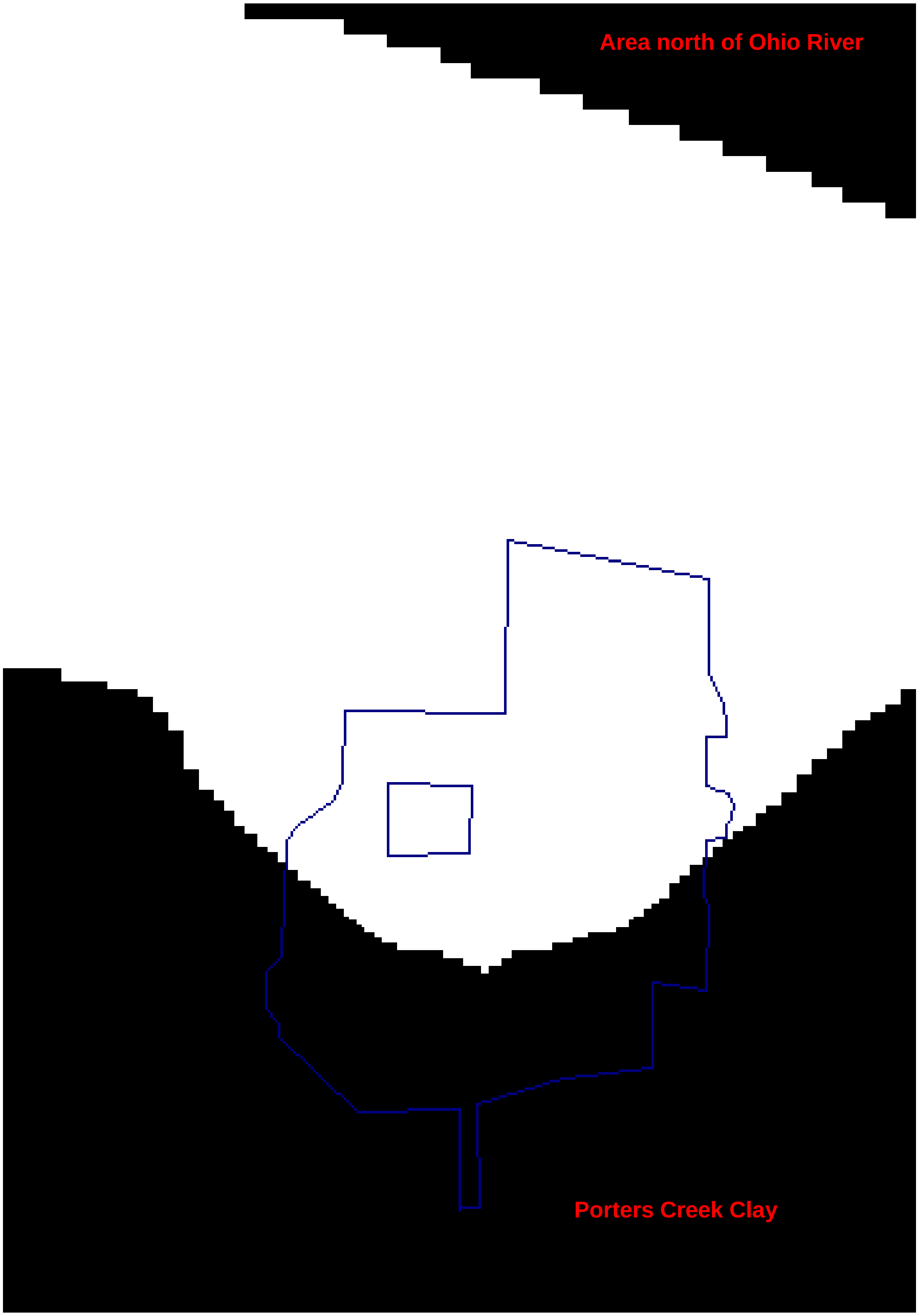


Figure 3.9. Model Layer 3 No Flow Cells

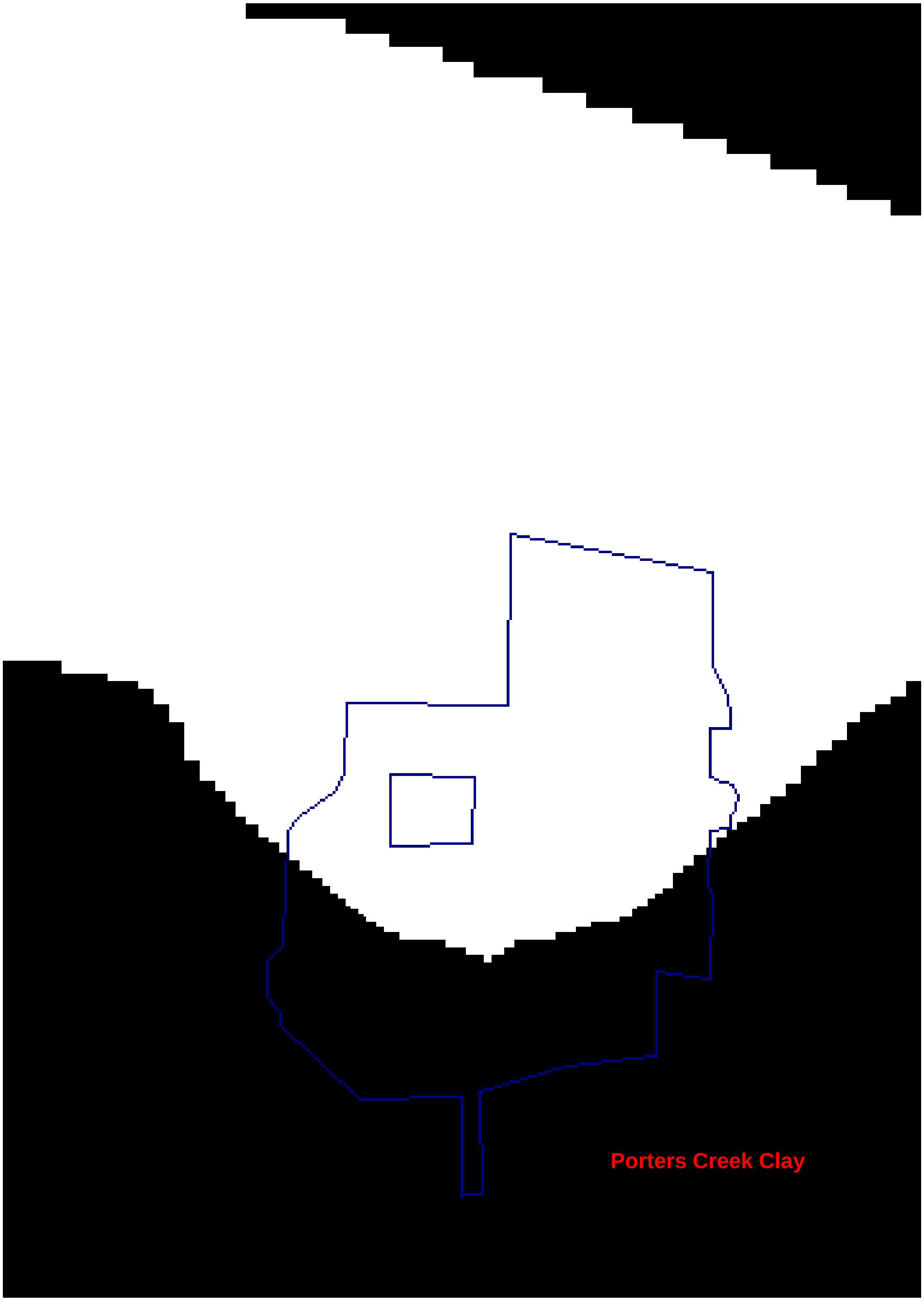


Figure 3.10. Model Layer 4 No Flow Cells

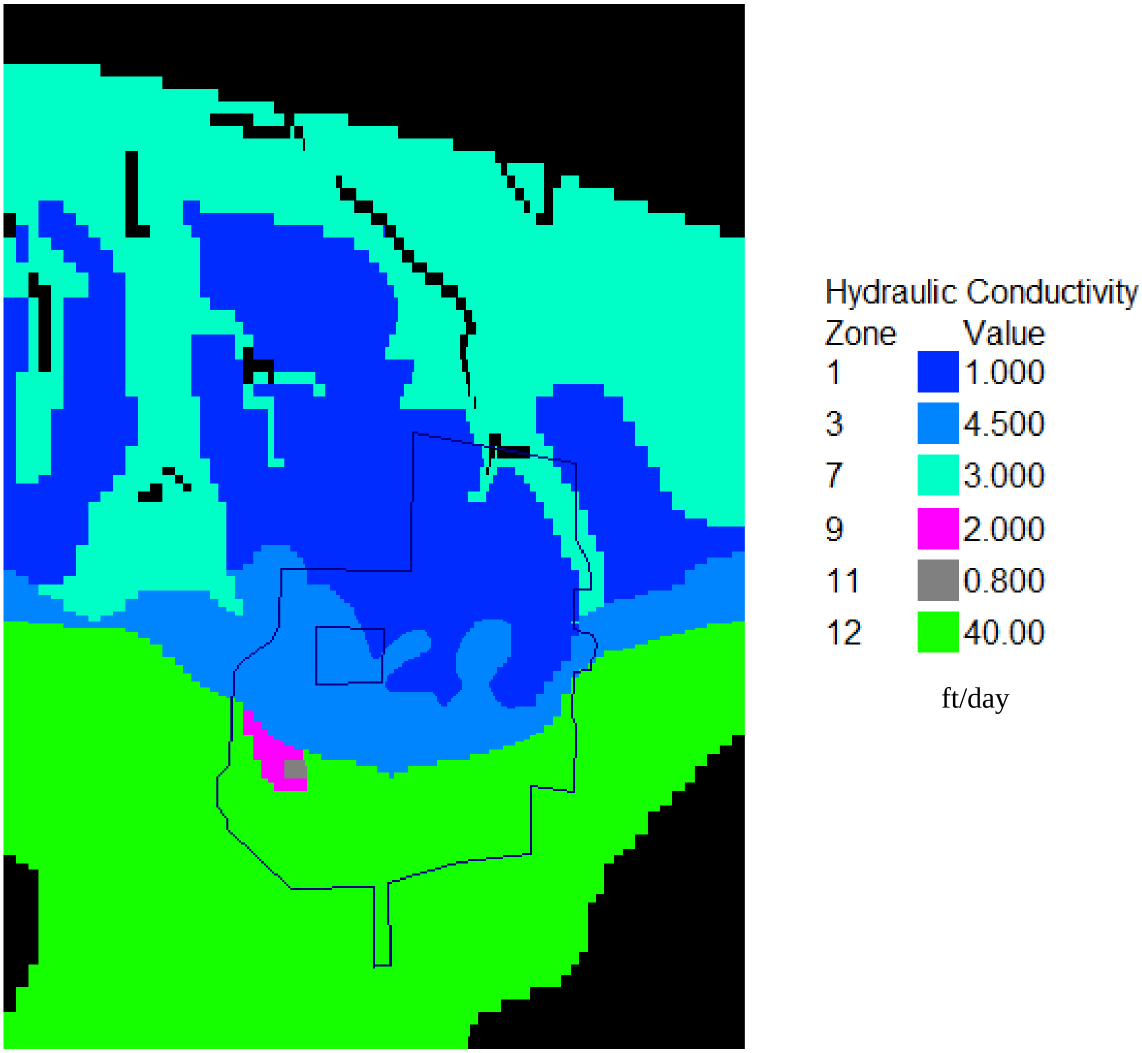


Figure 3.11. Model Layer 1 Hydraulic Conductivity Distribution

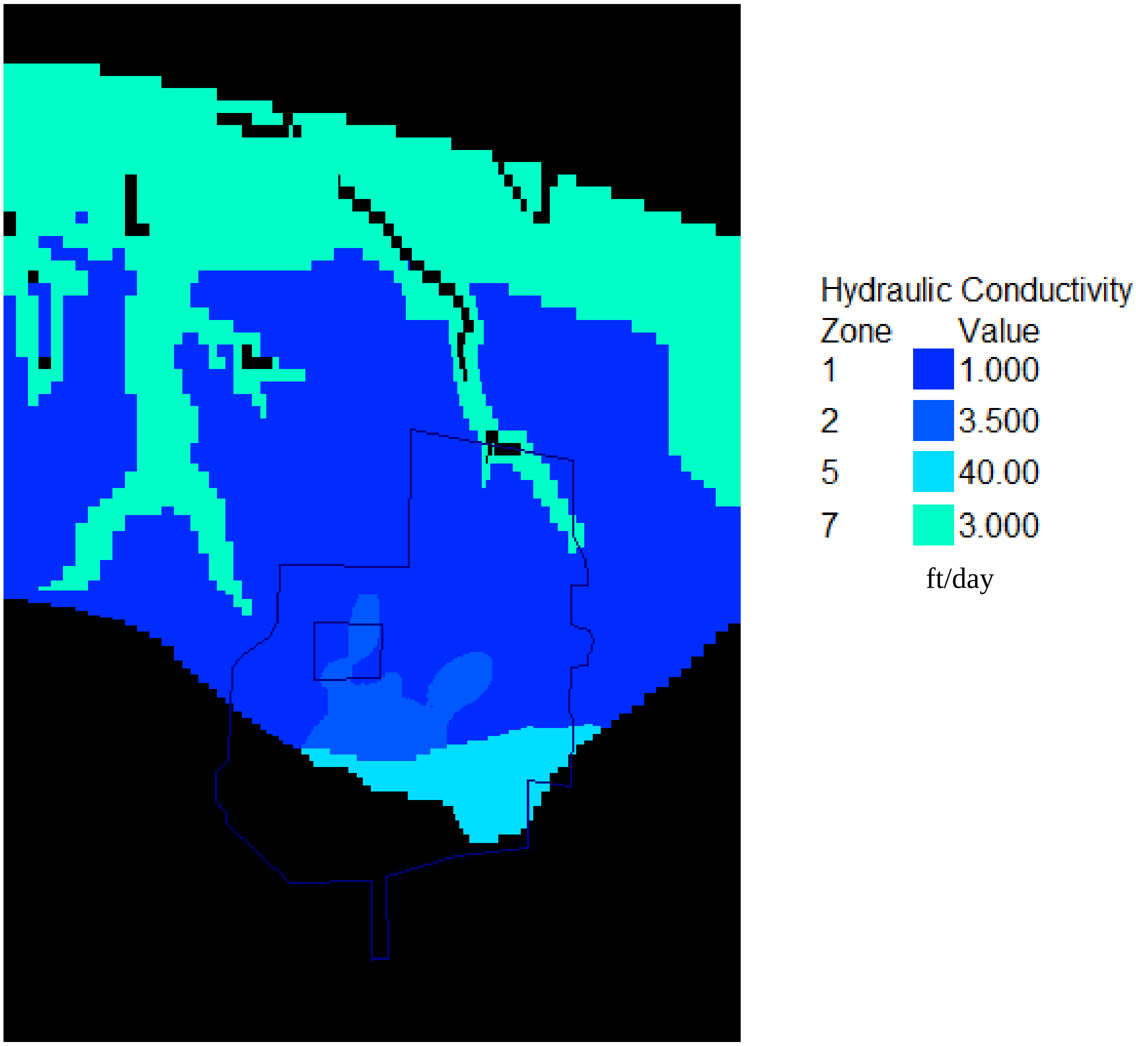


Figure 3.12. Model Layer 2 Hydraulic Conductivity Distribution

Model layer 3 (RGA) hydraulic conductivities range from 75 to 1,500 ft/day (Figure 3.13). The higher hydraulic conductivity is primarily present in a north-south trending zone that extends from the vicinity of the C-400 Building to the Ohio River. Surrounding the higher hydraulic conductivity zone are areas of hydraulic conductivity ranging from 200 to 500 ft/day. It is the contrast in hydraulic conductivity that controls the Northwest Plume configuration in the model. Higher hydraulic conductivities also extend from the vicinity of the C-400 Building easterly and then northerly. The Northeast Plume follows the higher hydraulic conductivity material. Hydraulic conductivities diminish along the Ohio River (300 ft/day).

McNairy hydraulic conductivity (model layer 4) is divided into two zones having values of 12 and 50 ft/day (Figure 3.14).

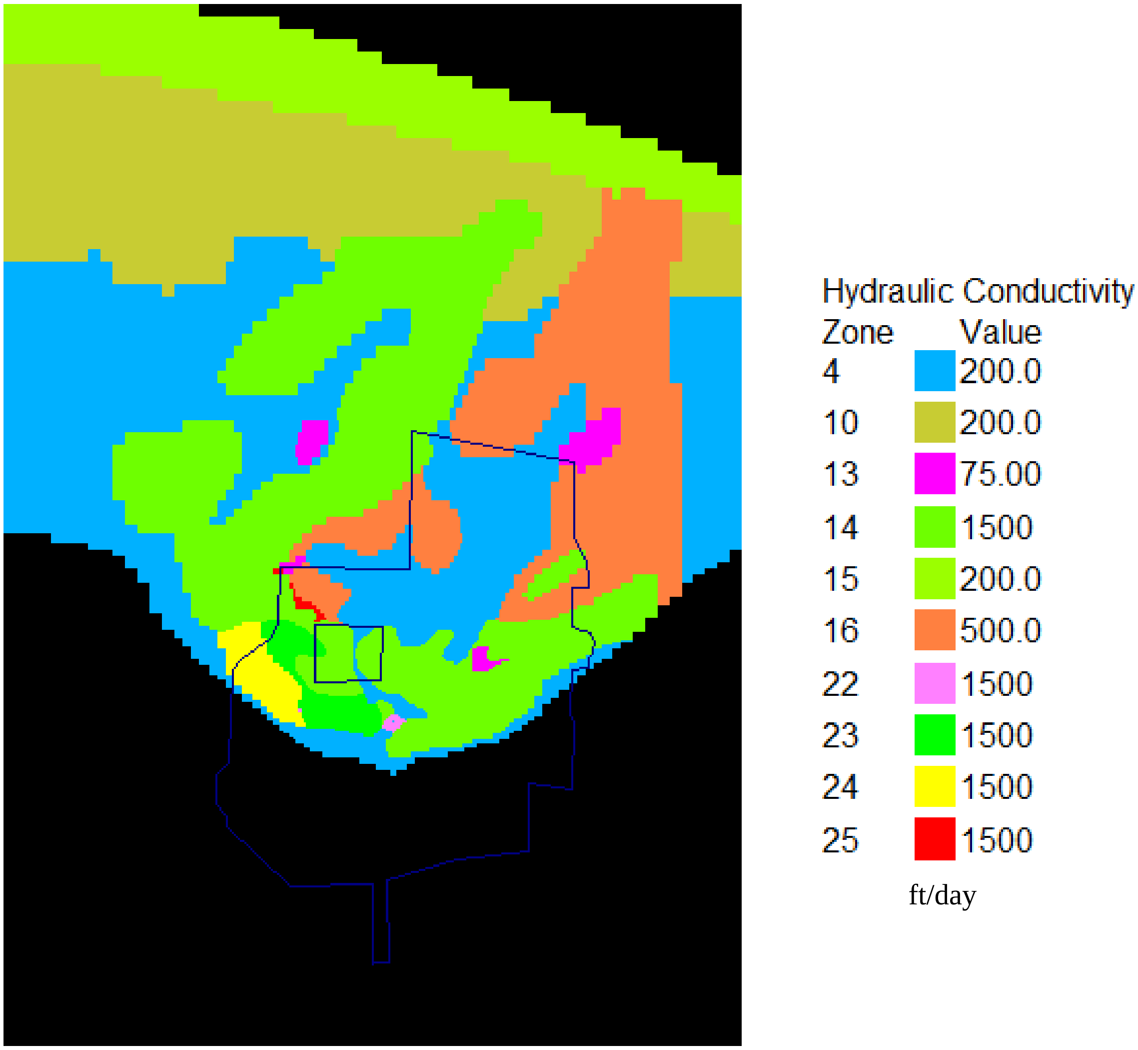


Figure 3.13. Model Layer 3 Hydraulic Conductivity Distribution

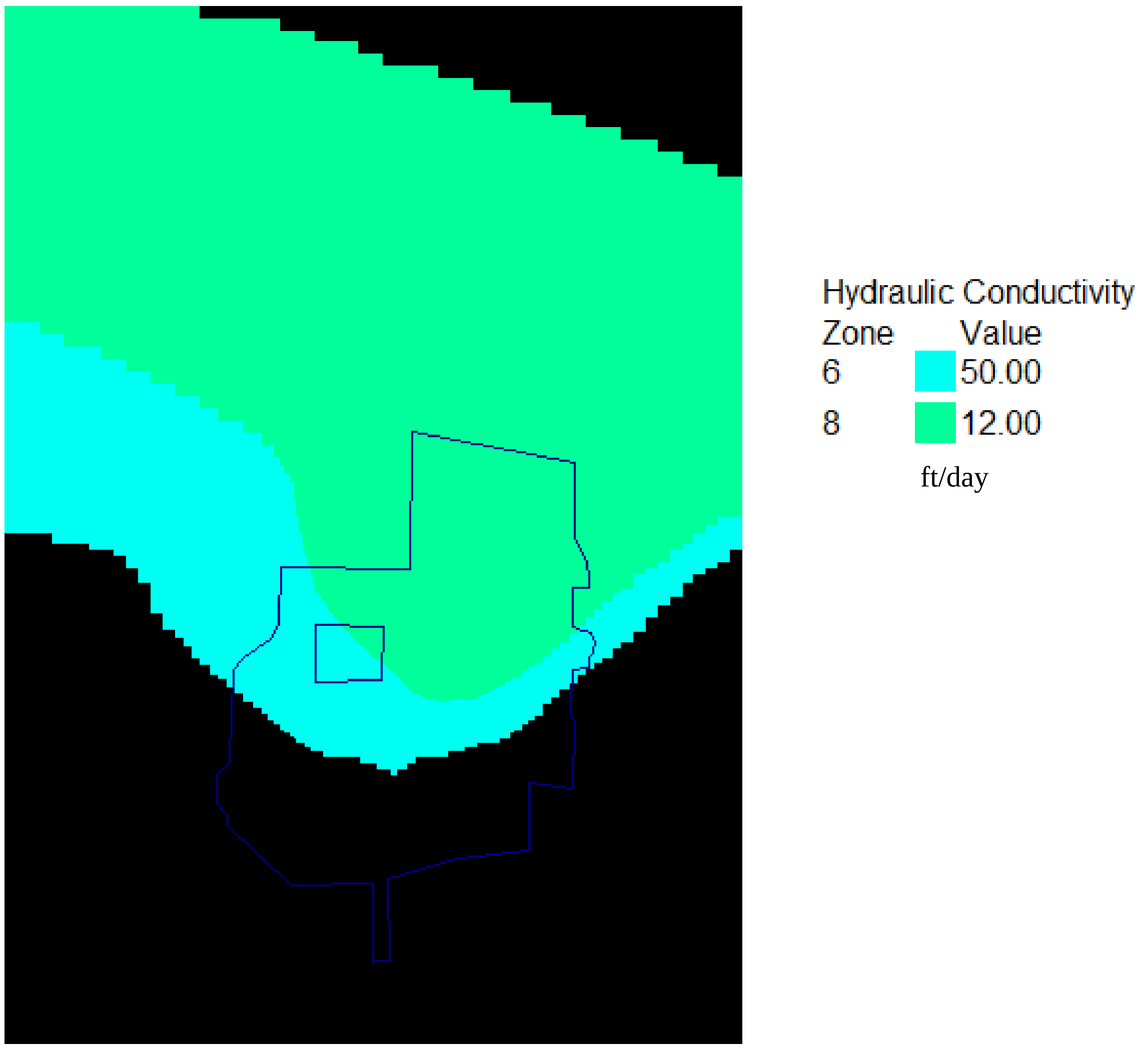


Figure 3.14. Model Layer 4 Hydraulic Conductivity Distribution

3.2.3.2 Recharge Zonation

Recharge to the model consists of infiltration from precipitation (6.6 inches/year) and anthropogenic sources such as leaky waterlines and drainage ditches (maximum of 26.3 inches/year) (Figure 3.15). Areas covered by buildings and pavement were assigned a recharge rate of zero.

3.2.3.3 Other Flow Parameters

Porosity was assigned a value of 30% for all model layers.

3.2.4 Parameter Sensitivities

Model input parameters can be sensitive or insensitive. A sensitive parameter is one that when changed produces measurable differences in the model's calibration statistics. As implied, insensitive parameters are those that when changed produce no or very little change to the model's calibration statistics. PEST, a parameter estimation code, calculates parameter sensitivities as part of the automated calibration process (Doherty 2004). It should be noted that parameter estimation was in its infancy when the PGDP flow model was calibrated, so use of parameter estimation to calibrate the flow model was not expected. A rule of thumb is parameters having sensitivities within two orders of magnitude of the most sensitive parameter can be calibrated uniquely (Hill 1998). Parameters having sensitivities between two and three orders of magnitude less than the most sensitive parameter might be able to be calibrated uniquely. Parameters having sensitivities more than three orders of magnitude less than the most sensitive parameter are incapable of being calibrated uniquely.

Figure 3.16 shows parameter sensitivities for all model input parameters. With respect to the model as configured, only six parameters (shown in green) can be calibrated uniquely. The most sensitive parameter in the model is the hydraulic head assigned to the GHB boundary representing upgradient McNairy through flow (general head boundary head reach 0). The next sensitive parameter is the Ohio River stage (constant head boundary head reach). These parameters are highly sensitive because these parameters control the slope of the RGA potentiometric surface. The next most sensitive parameter is the hydraulic conductivity zone associated with the plumes (Kx zone 14; see Figure 3.13 for RGA hydraulic conductivity distributions). The reason this parameter is sensitive is because this zone contains more targets (targets are the monitoring wells installed at the site to characterize the plume) relative to other zones (the wells were installed to characterize the plume). Following the most permeable RGA hydraulic conductivity zone in sensitivity is creek conductance (river boundary conductance reach 1), which is sensitive because altering conductance changes the volume of water entering or leaving the system, which, in turn, alters the model layer potentiometric surfaces. Recharge from precipitation (recharge zone 2; see Figure 3.15 for recharge zoneations) also is highly sensitive because the recharge zone is the most widely distributed recharge parameter, so small changes to the parameters value cause increases and decreases to predicted water levels. The last of the highly sensitive input parameters is the RGA hydraulic conductivity zone adjacent to the Ohio River (Kx zone 10; see Figure 3.13 for RGA hydraulic conductivity distributions). This parameter is sensitive because the parameter provides resistance to groundwater discharging to the Ohio River. Because of this damming effect, water levels upgradient of this hydraulic conductivity zone rise and decline as the parameters value is decreased and increased, respectively.

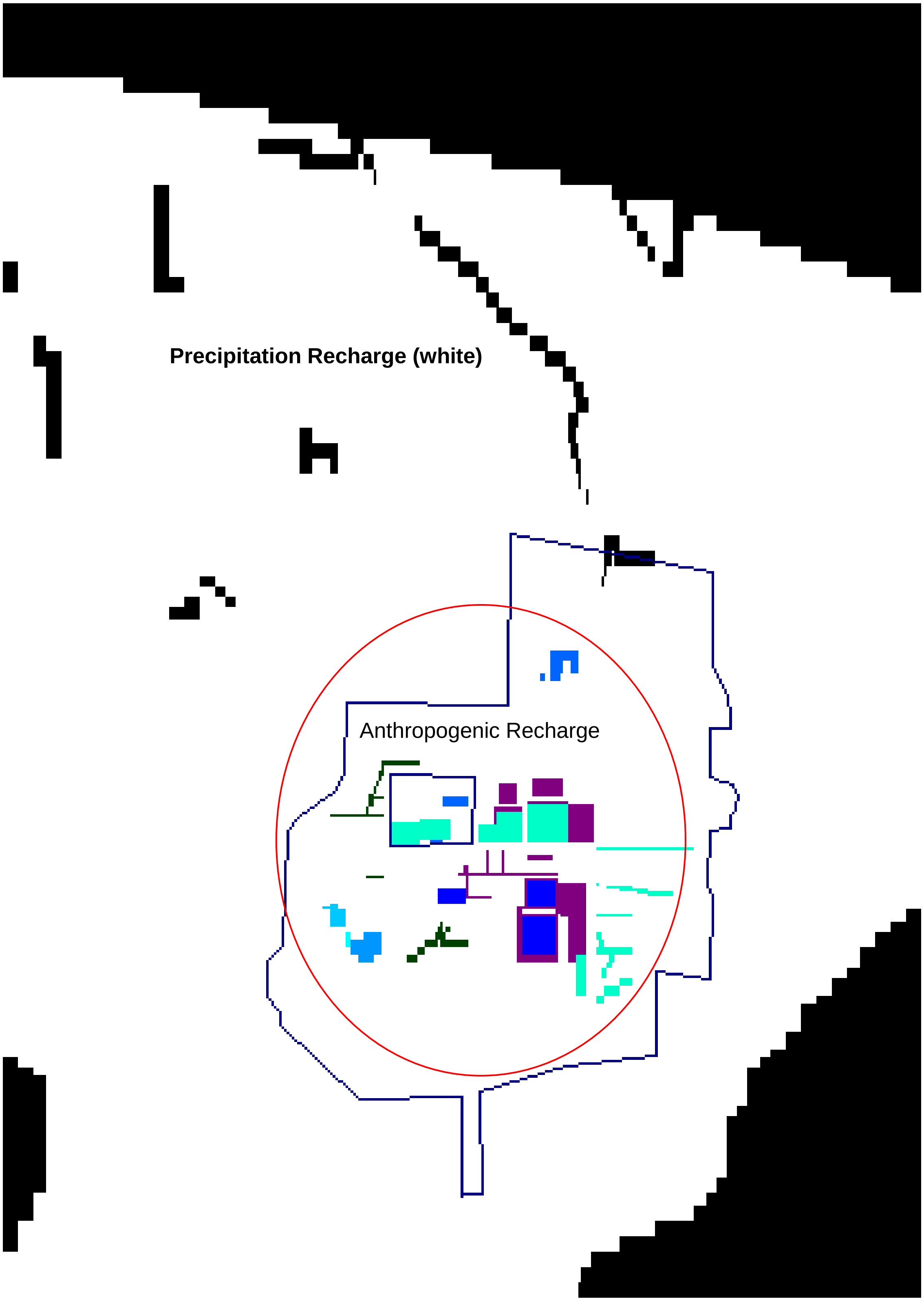


Figure 3.15. Recharge Distribution

Another 11 model input parameters (shown in yellow) are marginally sensitive; that is, it might or might not be possible to find unique parameter values. The remaining model input parameters (shown in red) are insensitive, meaning that it is impossible to find unique parameter values during calibration. It needs to be noted that a parameter's sensitivity is not an indication of the representativeness of the assigned parameter value. All that the sensitivity quantifies is how altering the parameter value changes the model's calibration statistics.

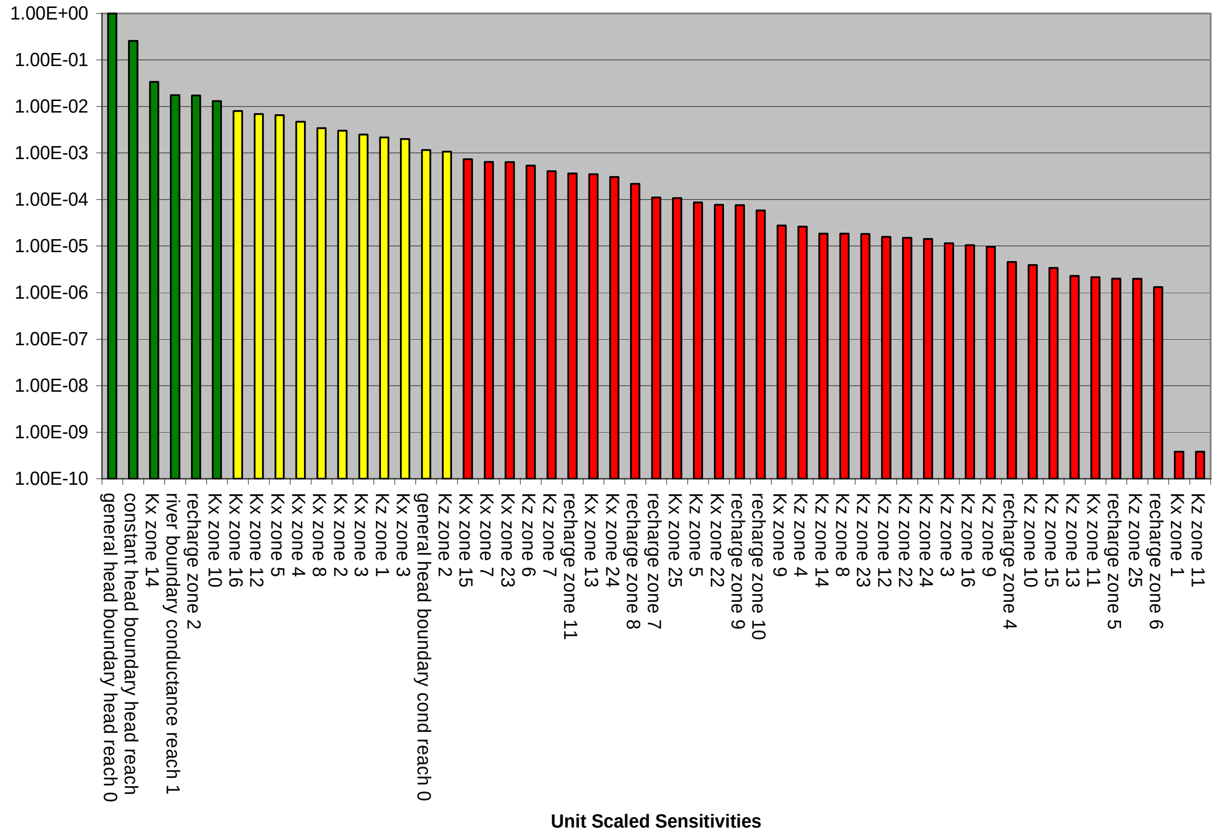


Figure 3.16. Parameter Sensitivities

3.3 MODEL CALIBRATION

Model calibration is primarily 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. Trial-and-error techniques were used to calibrate the existing PGDP flow model. During trial-and-error calibration, the modeler adjusts the distribution and value of model input parameters until an acceptable match is achieved between target and model-predicted water levels. The existing PGDP flow model was calibrated to 79 water level elevation targets representative of October 1992 groundwater levels. Other calibration metrics include matching the conceptualized groundwater mass balance (where and how much water enters and leaves the flow system) and mimicking observed plume flow paths with particle traces. This section describes calibration results for the existing PGDP flow model and includes discussions about the model-predicted potentiometric surfaces, comparison of model-predicted and target water-level elevations, groundwater mass balance evaluation, and predicted plume flow paths.

3.3.1 Model-Predicted Potentiometric Surfaces

Model layer 1 (upper UCRS) model-predicted potentiometric surface is discontinuous due to the presence of many dry cells (Figure 3.17). Dry cells occur when the model-predicted water level elevation is below the bottom elevation of the model layer. Effectively, dry cells are analogous to no flow cells in that there is no flow in or out of the dry cells; however, MODFLOW does allow recharge associated with dry cells to pass vertically through the cell to the next active cell. The presence of dry cells in the model results in longer simulation run times because dry cells are periodically rewetted to give the cells an opportunity to remain saturated during the simulation. Typically, multiple wetting and drying cycles are undertaken before the model converges on a solution.

Model layer 2 (lower UCRS) model-predicted potentiometric surface consists of many concentric groundwater highs and lows, which is a primarily a function of the strong vertical flow component within the layer (Figure 3.18). Calculated vertical groundwater gradients within the UCRS often approach unity, which means that for every foot of elevation decline within the unit, there is a corresponding decline in water level elevation. The strong vertical gradient is caused by the large contrast in UCRS and RGA hydraulic conductivity. Groundwater flow in the UCRS is primarily vertical and in the RGA primarily horizontal. The lower groundwater elevations are associated with areas where water is modeled to move more easily vertically through the UCRS. Conversely, the higher groundwater elevations are locations where there is greater modeled resistance to vertical groundwater movement within the UCRS. Additionally, at locations where there are dry cells in model layer 1, recharge is added directly to model layer 2, which results in mounding. Lastly, mounding in model layer 2 is also associated with the locations of river cells representing the creeks and drainage ditches in model layer 1. The river cells in model layer 1 are contributing water to the model, which causes mounding in model layer 2.

Model layer 3 (RGA) model-predicted potentiometric surface is relatively continuous (absent of the highs and lows shown in model layer 2) and depicts groundwater flow from PGDP toward the Ohio River (Figure 3.19). There is a mound present adjacent to the Ohio River associated with the TVA discharge pond located in model layer 1.

Model layer 4 (McNairy) model-predicted potentiometric surface like the model layer 3 (RGA) potentiometric surface is relatively continuous (Figure 3.20). The same mound caused by leakage from the TVA discharge pond present in model layer 3 is present in model layer 4. Concentric equipotential lines are present in the vicinity of the PGDP suggesting that flow originating from the GHB cells representing upgradient McNairy through flow beneath the plant discharges to other GHB cells located east and west of where water enters the flow system.

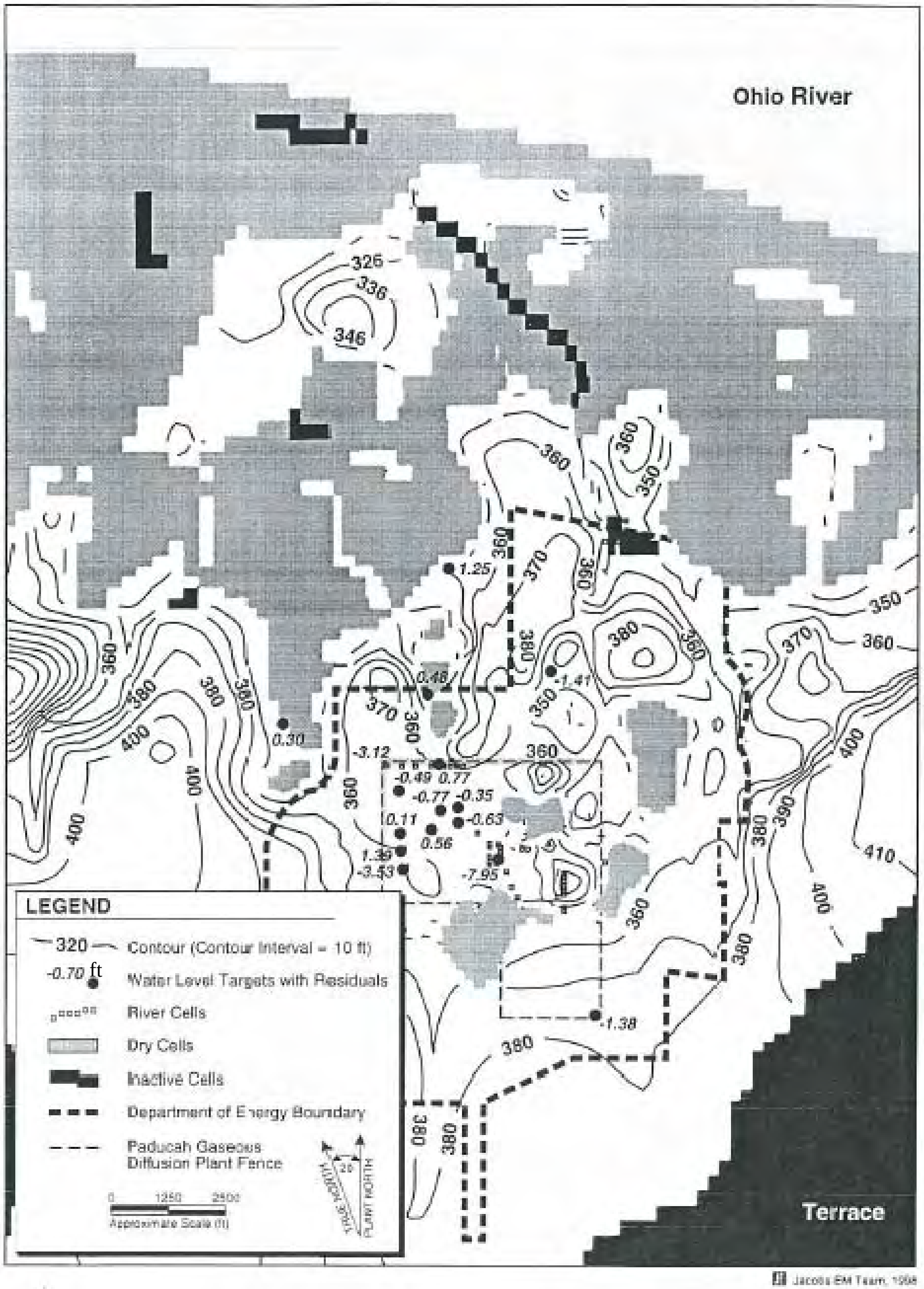


Figure 3.17. Model Layer 1 Predicted Potentiometric Surface

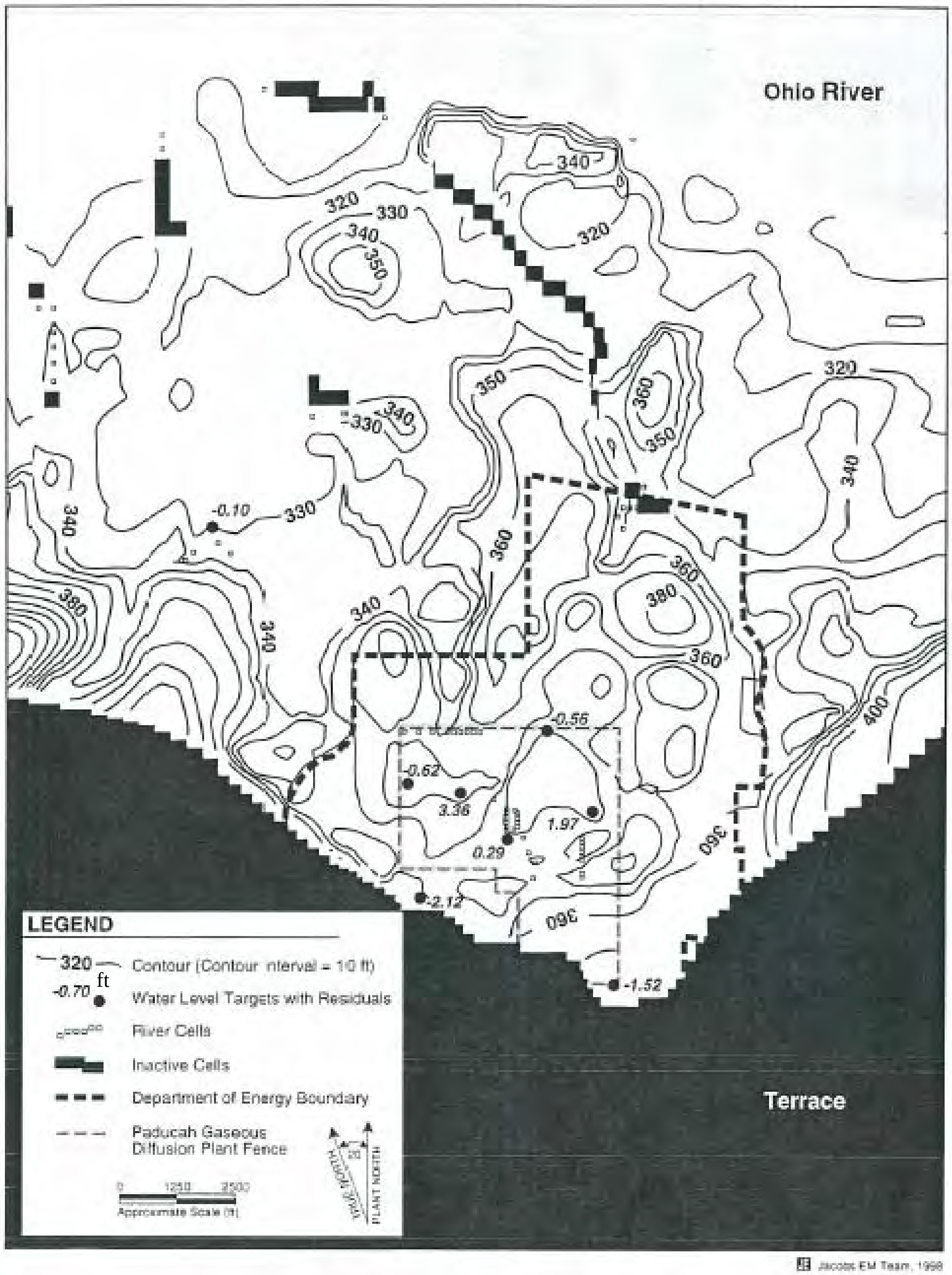


Figure 3.18. Model Layer 2 Predicted Potentiometric Surface

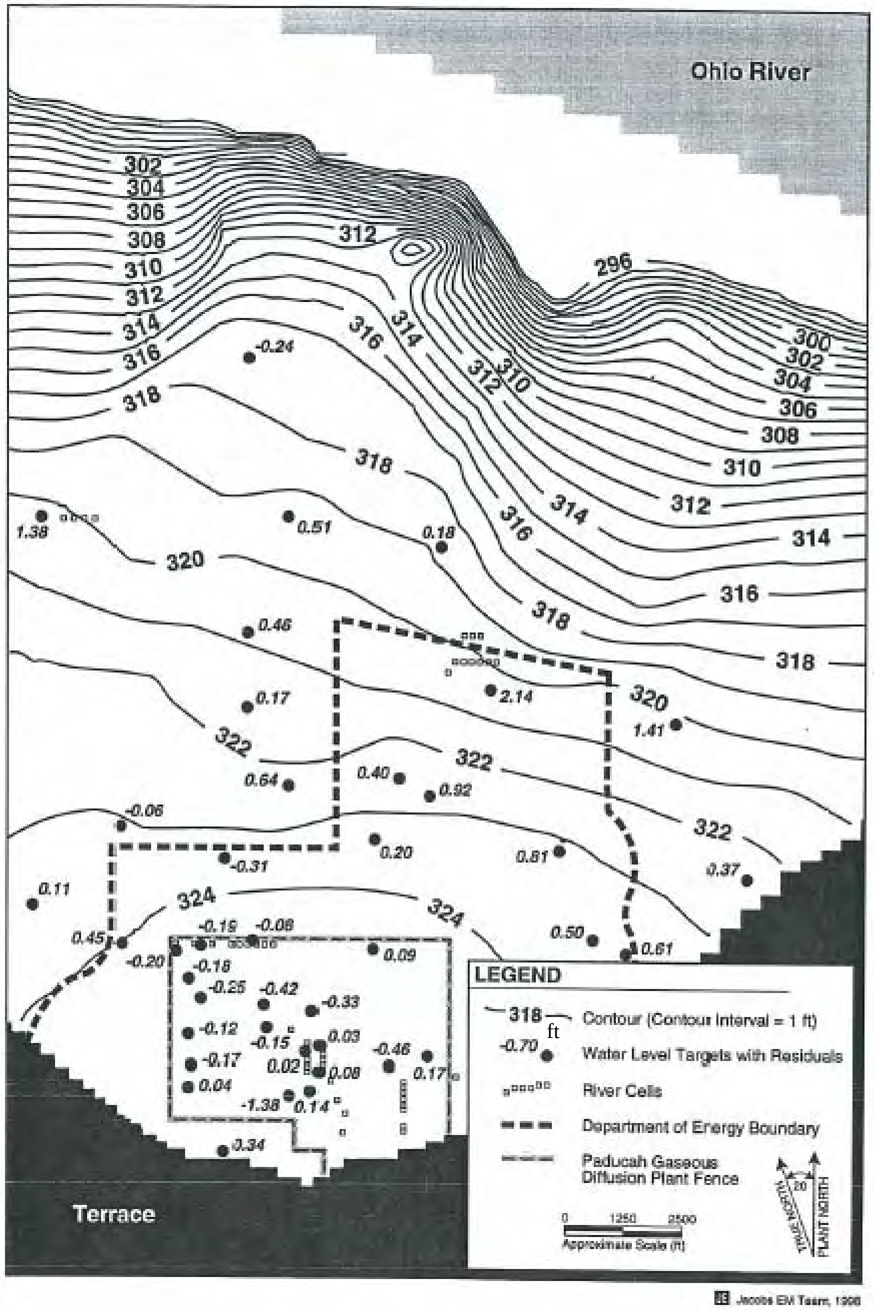


Figure 3.19. Model Layer 3 Predicted Potentiometric Surface

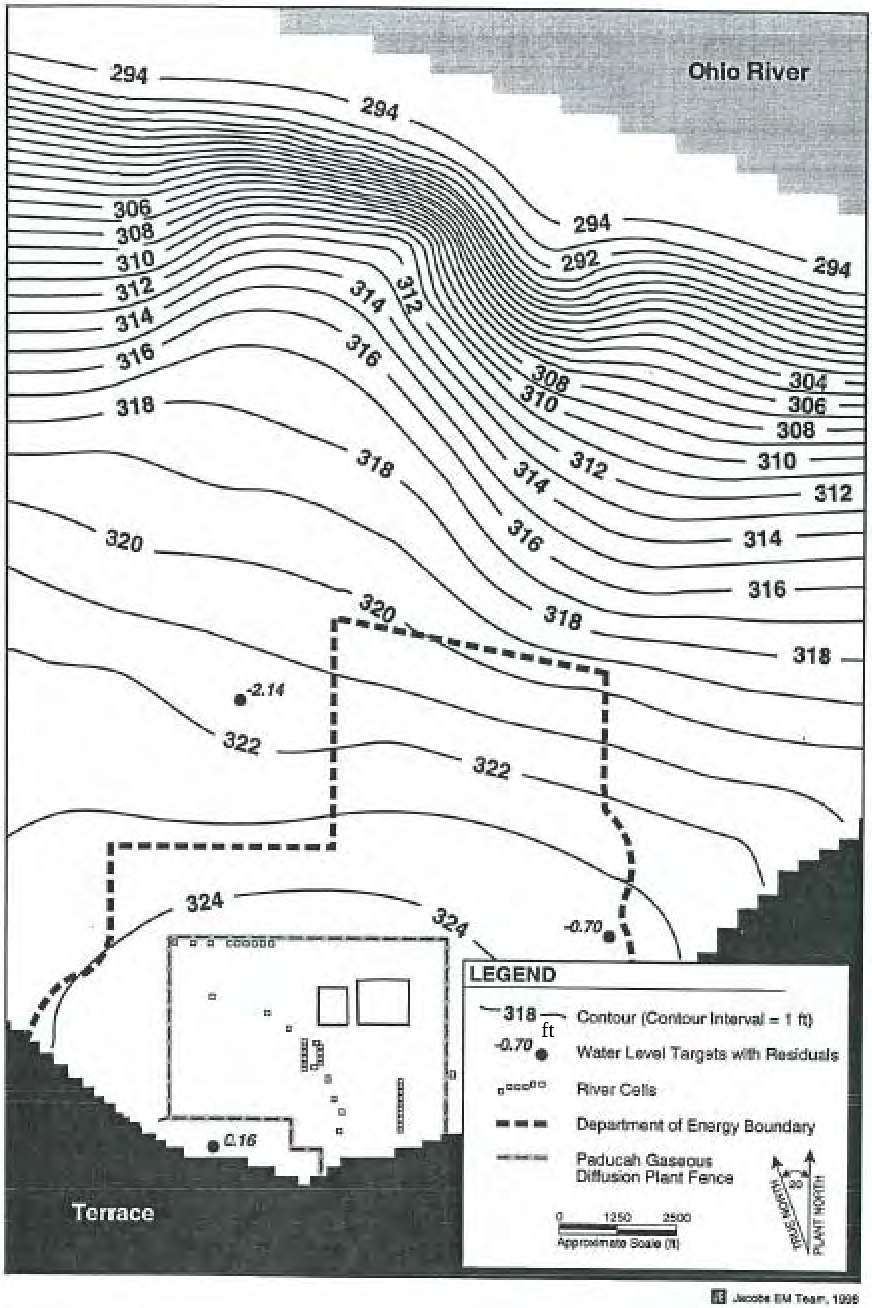


Figure 3.20. Model Layer 4 Predicted Potentiometric Surface

3.3.2 Comparison of Target and Model-Predicted Water Level Elevations

Table 3.2 lists individual target names, target water level elevations, model-predicted water level elevations, and residuals (the difference between the target and model-predicted values). The model is better at matching RGA water levels than UCRS or McNairy water levels (Table 3.3). Sum of the difference squared (SDS), a calibration metric, is calculated by squaring the difference of the measured and modeled water levels and summing the squared differences. Relative to the other model layers, despite having the greatest number of targets, overall, on a per target basis, the RGA contributes less to the SDS relative to the other model layers. The upper UCRS (model layer 1) is the greatest contributor to the SDS, followed by the lower UCRS (model layer 2), followed by the McNairy (model layer 4). A plot of residuals versus target water level elevations supports this assessment showing residuals for model layer 3 (RGA) clustering closer around the zero residual line relative to the other model layers (Figure 3.21).

Table 3.2. Water Level Elevation Targets and Calibration Results

Name	X	Y	Layer	Observed	Computed	Residual
MW-007	10788.54	13243.04	2	361.59	362.21	-0.62
MW-043	16115.5	17847.23	3	323.56	322.64	0.92
MW-052	11295.59	13579.74	3	324.19	324.44	-0.25
MW-054	11060.36	13885.99	3	324.17	324.35	-0.18
MW-063	10751.76	14542.56	3	323.98	324.18	-0.20
MW-064	10752.13	14527.54	1	363.21	366.33	-3.12
MW-065	10752.59	14512.42	3	323.97	324.19	-0.22
MW-069	13644.25	11572.96	2	341.74	342.03	-0.29
MW-071	13614.57	11573.14	3	325.04	324.90	0.14
MW-073	12486.97	12913.31	3	324.51	324.66	-0.15
MW-075	12370.09	12805.14	2	364.92	361.56	3.36
MW-103	11735.36	10146.46	3	325.61	325.27	0.34
MW-104	11390.73	9964.42	2	349.8	351.92	-2.12
MW-106	9548.6	14638.23	3	324.36	323.91	0.45
MW-124	19866.65	14373.68	3	324	323.50	0.50
MW-125	12324.69	19786.58	3	321.71	321.54	0.17
MW-126	19868.99	14383.97	3	323.79	323.48	0.31
MW-127	12323.39	19808.53	1	348.89	347.64	1.25
MW-130	16503.61	7723.28	2	371.9	373.42	-1.52
MW-131	16506.09	7708.36	1	371.98	373.36	-1.38
MW-132	17427.71	19839.65	3	322.8	320.66	2.14
MW-134	9652.5	17216.23	3	322.91	322.97	-0.06
MW-137	16260.75	22798.16	3	319.04	318.86	0.18
MW-142	5825	20177.05	3	322.53	322.07	0.46
MW-143	5831.4	20160.94	2	332.43	332.53	-0.10
MW-144	17217.4	14016.88	3	323.99	324.00	-0.01
MW-147	12318.22	27195.99	3	317.26	317.50	-0.24
MW-149	21227.17	19402.36	3	321.48	320.07	1.41
MW-150	22640.36	15887.1	3	322.93	322.56	0.37
MW-152	17294.86	26783.97	3	313.35	312.44	0.91
MW-154	11769.99	12837.01	1	363.89	363.33	0.56
MW-155	13962.5	11977.9	3	324.94	324.86	0.08
MW-156	13961.8	11943.6	3	324.89	324.86	0.03
MW-157	13961.8	11958.7	1	347.51	355.46	-7.95
MW-158	11030.5	12656.1	3	324.45	324.57	-0.12
MW-159	11050.4	12657.5	3	324.47	324.58	-0.11
MW-160	11041.6	12675.4	1	363.02	362.91	0.11
MW-161	11070.6	11980.6	3	324.5	324.67	-0.17
MW-162	11101.3	11980.5	1	360.27	358.88	1.39
MW-163	15946.5	12246.5	3	324.87	324.70	0.17
MW-164	15953.3	12231.7	2	336.99	335.02	1.97
MW-165	14851.8	14545.6	3	324.61	324.52	0.09

Table 3.2. Water Level Elevation Targets and Calibration Results (Continued)

Name	X	Y	Layer	Observed	Computed	Residual
MW-166	14835.2	14540.6	2	341.56	342.12	-0.56
MW-167	13165	12738.6	1	368.33	365.75	2.58
MW-168	13165	12722.5	3	324.31	324.72	-0.41
MW-169	12429.5	13455.9	3	324.2	324.62	-0.42
MW-170	12429.9	13471.5	1	362.85	363.20	-0.35
MW-171	12569.1	13175.8	1	365.31	364.68	0.63
MW-172	12009.6	13455.1	1	362.68	363.45	-0.77
MW-173	12697.5	14667.6	3	324.39	324.47	-0.08
MW-174	12680.3	14668.5	1	363.84	363.07	0.77
MW-175	13608.4	12219	3	324.82	324.80	0.02
MW-178	13913.9	12431.1	3	324.82	324.79	0.03
MW-179	15471	18275.2	3	323	322.60	0.40
MW-181	14944.7	16754.6	3	323.5	323.30	0.20
MW-182	14960.1	16754.5	1	355.67	357.08	-1.41
MW-184	10600.6	9650	1	359.09	359.09	0.00
MW-185	11385.6	14600.2	3	324.09	324.28	-0.19
MW-187	11133	14611.7	1	363.45	364.16	-0.71
MW-188	10986.7	11590.2	3	324.76	324.72	0.04
MW-189	10989.9	11590	1	354.86	358.39	-3.53
MW-190	11035.9	13885.2	1	366.21	366.70	-0.49
MW-191	20584.9	14247.6	3	323.89	323.28	0.61
MW-193	18503.3	16712.2	3	323.89	323.08	0.81
MW-194	7810	15512.9	3	323.49	323.38	0.11
MW-195	7794.1	15508.4	1	343.93	343.63	0.30
MW-197	11825	16510.4	3	323.14	323.45	-0.31
MW-198	11824.5	16522.1	1	342.99	342.51	0.48
MW-199	7910.9	23737.4	3	321.49	320.11	1.38
MW-200	13163.6	18090.6	3	322.8	322.16	0.64
MW-201	13103.5	23814.7	3	319.87	319.36	0.51
MW-202	12299.5	21260.5	3	321.36	320.90	0.46
MW-203	12972.7	11488.1	3	323.51	324.89	-1.38
MW-205	13627.2	13283.2	3	324.38	324.71	-0.33
MW-206	15063	12142.5	3	324.33	324.79	-0.46
MW-102	11720.18	10144.76	4	325.55	325.39	0.16
MW-121	12309.85	19808.83	4	319.4	321.54	-2.14
MW-122	19863.67	14364.37	4	322.75	323.45	-0.70
MW-140	5808.31	20205.78	4	319.96	322.04	-2.08

* X, Y, Observed, Computed and Residual have units of ft.

Table 3.3. Calibration Summary

Measurement	Layer 1 HU2A	Layer 2 HU2B	Layer 3 RGA	Layer 4 McNairy	Total
Number of Targets	19	8	48	4	79
Percentage of Targets	24	10	61	5	100
Sum of the Difference Squared	102	23	16	10	151
Percentage Sum of the Difference Squared	68	15	11	6	100
Percentage Sum of the Difference Squared/ Percentage of Targets	2.8	1.5	0.2	1.2	1.0

* Sum of Difference squared has units of ft^2.

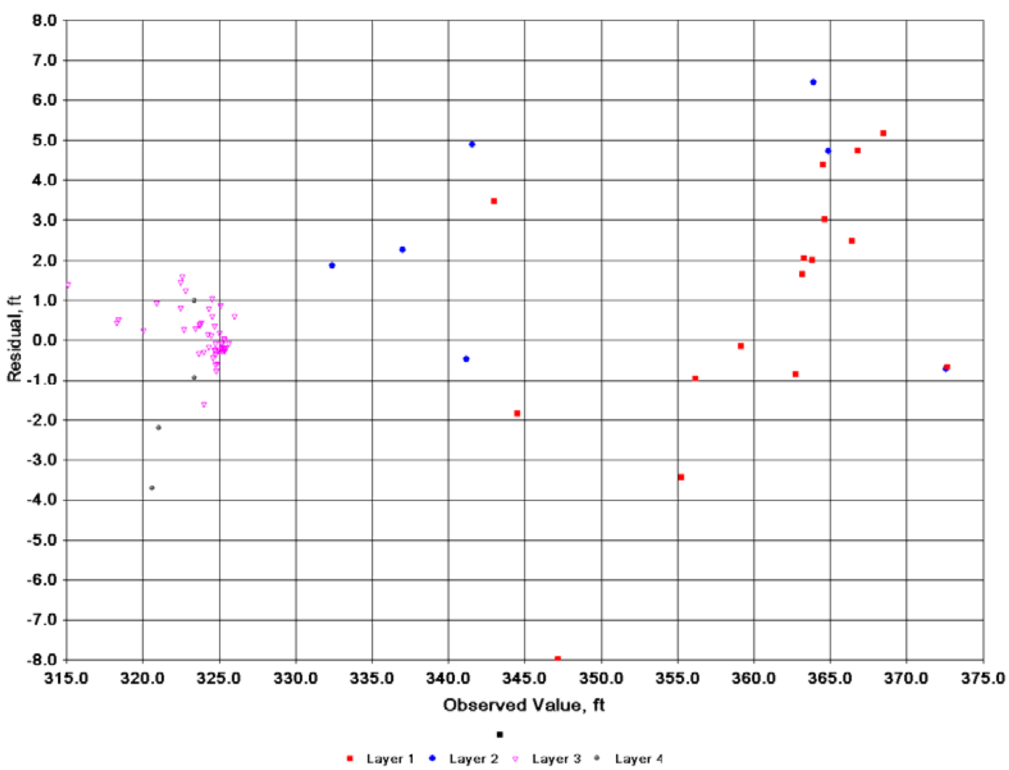


Figure 3.21. Model Residuals Versus Target Water Level Elevations

The reason the model has difficulty matching target water levels in the UCRS is a function of the strong downward vertical hydraulic gradient and layer thickness. The UCRS vertical hydraulic gradients approach unity, meaning for every foot vertically below the water table, the water level elevation declines a corresponding amount. Model layer 1 is configured to represent the upper UCRS. Assume the saturated thickness of the upper UCRS is 20 ft. Based on a unity gradient, the water table potentially will be 20 ft higher than the water level at the bottom of the upper UCRS. Assuming the UCRS targets are evenly distributed vertically, the best calibration will be achieved by matching targets from wells screened near the middle of the vertical section. However, doing so results in poor matches between the model predicted and targets water levels from wells screened at the top and bottom of the UCRS vertical section. The only way to improve UCRS calibration is to subdivide the model layers representing the UCRS into multiple layers so that the well screen elevations from which the water level targets are derived are located closer to the middle of the cell containing the target.

3.3.3 Evaluation of the Predicted Groundwater Mass Balance

The model-predicted water balance, even in the absence of quantitative targets such as stream flow data, provides an indication of the robustness of the model. A groundwater flow model is considered robust if it reasonably matches target water level elevations and produces a water balance that reasonably substantiates the site conceptual model.

The following is a brief summary of the PGDP conceptual model and is what the model-predicted groundwater mass balance will be compared against. At PGDP, recharge from rainfall is believed to be the greatest contributor of water to the flow system. Anthropogenic sources have larger recharge rates relative to rainfall but, because their extent is much less, they contribute less volumetrically than recharge from rainfall. The TVA discharge pond, having a higher water level than the surrounding groundwater levels, recharges the aquifer. Leakage from drainage ditches contributes water to the groundwater flow system. Lastly, upgradient McNairy through flow contributes water to the flow system. Additional information is provided in Section 6.3.2 regarding site features that contribute to anthropogenic recharge.

The primary discharge location for the groundwater flow system is the Ohio River. Given that rivers and streams in Kentucky are generally gaining, groundwater also discharges to Bayou and Little Bayou Creeks.

Metropolis Lake is a window on the water table and, as such, neither contributes nor removes groundwater from the flow system.

Table 3.4 contains the model-predicted groundwater mass balance for the model. As conceptualized, the greatest contributor to the groundwater flow system is recharge from precipitation. Anthropogenic recharge (leaking water lines, cooling towers, drainage ditches) contributes much less water to the flow system relative to recharge from precipitation. Different than conceptualized, the creeks contribute more water to the flow system than they remove. As conceptualized, although relatively minor, the drainage ditches contribute water to the groundwater flow system. The TVA discharge pond contributes water to the groundwater flow system although the magnitude of the contribution may be unrealistically high (20% of the modeled total). The model predicts that Metropolis Lake contributes water to the aquifer (9% of the modeled total); that is contradictory to the conceptual model, which hypothesizes that the lake is a window on the water table and, as such, neither contributes nor removes water from the groundwater flow system. Upgradient McNairy through flow contributes water to the flow system, but, unlike the conceptualization, removes an equal amount of water from the flow system. Lastly, as conceptualized, the majority of groundwater discharge is to the Ohio River.

In summary, the model is not in agreement with the conceptual model with regard to groundwater interaction with the creeks, the direction of groundwater movement across the McNairy upgradient through flow boundary, and the interaction of Metropolis Lake with groundwater. Additionally, the predicted contribution to groundwater (20%) from the TVA discharge pond may be excessive.

Table 3.4. Model-Predicted Groundwater Mass Balance (gpm)

Parameter	In	In %	Out	Out %	Net
Recharge - Rainfall	5,764	39%	0	0%	5,764
Recharge - Anthropogenic	233	2%	0	0%	233
Creeks	4,144	28%	3,035	21%	1,109
Drainage Ditches	41	0%	3	0%	38
TVA Pond	2,888	20%	0	0%	2,888
Metropolis Lake	1,305	9%	0	0%	1,305
McNairy Throughflow	275	2%	278	2%	-3
Ohio River	0	0%	11,037	77%	-11,037
TOTAL	**14,650**	**100%**	**14,354**	**100%**	**296**

3.3.4 Model-Predicted Plume Flow Paths

Particles were placed at the most downgradient extent of the Northeast and Northwest Plumes and migrated backward using MODPATH (Pollack 1994) to assess the model's ability to replicate the plumes flow paths (Figure 3.22). In general, the particles follow the plume flow paths.

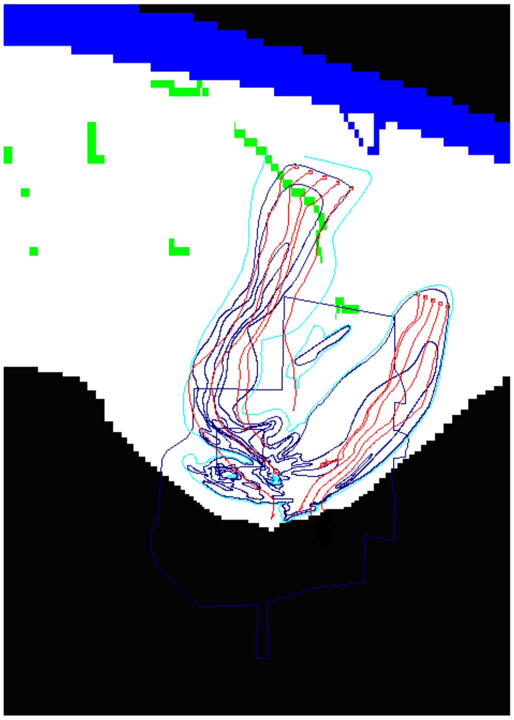


Figure 3.22. Model-Predicted Plume Flow Paths

3.4 TRANSPORT MODEL

The transport model never has been calibrated by adjusting source locations and strength and transport parameters until a reasonable match has been achieved between the model-predicted and observed plume extent and concentration distribution. At the time the model was developed, 20 days were required to simulate transport. Given the excessively long simulation times, it is understandable that the transport model never has been rigorously calibrated. Rather than undergo calibration, the existing plume geometries and concentrations were placed in the model and future migration simulated. As part of the simulation it was assumed that source areas no longer are active. Transport parameters used to simulate trichloroethene (TCE) migration are listed in Table 3.5.

Table 3.5. Transport Parameters

Transport Parameter (TCE)	Value
Distribution Coefficient (K_d)	0.026 cm^3/g
Soil Bulk Density	1.67 g/cm^3
Effective Porosity	0.30
Longitudinal Dispersivity	50 ft
Transverse Dispersivity	5 ft
Vertical Dispersivity	0 ft
Half-Life	9,729 days

3.5 RECOMMENDATIONS

Evaluation of the existing PGDP flow and transport models has identified several items requiring attention in the next round of model configuration and calibration. The following sections make recommendations with regard to model configuration and calibration. Many of the recommendations are general and not specific (i.e., how many model layers) because data evaluation is still ongoing, and experience has shown that changes to model configuration during model calibration often have to be made to achieve better calibration and to overcome numerical issues.

3.5.1 Model Discretization

The current model is discretized vertically into four layers. To replicate vertical flow components in the UCRS, more model layers are needed. Additionally, to capture RGA vertical hydraulic conductivity variations, so contaminant transport can be more accurately simulated, the model layer representing the RGA should be subdivided. Lastly, to capture vertical flow components within the McNairy the model layer representing the McNairy also should be subdivided.

Currently, the model layers honor the UCRS (model layers 1 and 2), RGA (model layer 3), and McNairy (model layer 4) units. To eliminate the dry cells in model layer 1, the model layers should be reoriented essentially to parallel the water table surface. Doing so will result in model layers, particularly the upper few, that contain more than one lithologic unit. The hydraulic conductivity distribution within each layer can be configured to honor expected values within the lithologic units.

Cell size in the current model ranges from 50 by 50 ft to a maximum of 425 by 425 ft. To better simulate contaminant transport and remedial design, it is recommended that the minimum cell size be reduced to 25 by 25 ft. The maximum current cell size also should be reduced, but no specific recommendations regarding cell size are provided. Rather, determination of the maximum cell size should be part of model configuration.

3.5.2 Model Boundaries and Properties

Currently, the Ohio River is simulated using constant head cells. It is recommended that the Ohio River be simulated using drain cells, which, because of the inclusion of a conductance term, offer resistance to flow. Switching to drain cells will eliminate the need of a low conductance zone in the RGA to "dam" groundwater upgradient of the river.

It is recommended that the creek stage be reanalyzed and reconfigured in the model. As currently configured, the creeks contribute more water to the model than they remove, which is in contrast to the conceptual model, which hypothesizes that the creeks receive groundwater discharge.

The gravel pits and Metropolis Lake are surface expressions of the water table. As currently configured in the model (river cells), the features contribute water to the flow system. It is recommended that the gravel pits be removed from the model domain because hydrologically the pits are insignificant and are not located where they influence contaminant migration. Metropolis Lake should be represented using a series of very high hydraulic conductivity cells, which will allow the water table passing through the feature to have a constant elevation.

Attempts should be made to quantify the volume of water discharged to the TVA ponds and that amount should be compared to the model-predicted volume to assess the representativeness of the feature within the model domain.

The various anthropogenic recharge zones should be combined in an attempt to improve anthropogenic recharge sensitivity so that the parameter can be uniquely calibrated.

3.5.3 Flow Model Calibration

It is recommended that model calibration be performed using PEST (Doherty 1999) and PEST-SVD (Doherty 2004) coupled with pilot points PEST (Doherty 1999). Details regarding these codes are found in Section 7.

It is recommended that the more recent water level data be evaluated and a more comprehensive target set be developed for use in calibrating the model.

3.5.4 Transport Model Calibration

The existing PGDP transport model has never undergone calibration. It is recommended that a calibrated transport model be developed that includes source terms. Calibration will involve adding contamination at the source areas and allowing the plumes to expand temporally. Temporal source loading strengths and transport parameters (biodegradation, retardation, etc.) will be adjusted until a reasonable match is obtained between the observed and predicted plumes.

Considerable progress has been made with regard to calibrating transport models in the past few years. PEST now can be used to calibrate source strengths and transport parameters and has the advantage that the code can be run in parallel on a network of computers, which greatly reduces the time to achieve calibration. Another technique that has shown great promise is based on the principles of superposition. Superposition works as follows, assume a single source with an unknown contaminant loading history over 40 years. To determine the loading history, 40 contaminant transport model runs are made with the constant source active for 1 year for years 1 through 40. Each of the simulations generates a pulse of contamination that migrates through the aquifer that, when added to the other simulations, produces a plume. The key to matching known temporal plume geometry is to vary the simulated temporal loading rates, something that is accomplished outside of the model using PEST. The theory also can be extended to determine both spatial (horizontal and vertical) and temporal variations in contaminant loading rates. All that is required is one model run for each potential source location for each year of source area loading. As with PEST, the superposition technique can be performed using a network of computers, which greatly reduces the time necessary to achieve calibration.

Finally, consideration should be given to using RT3D (Clement 1998) to simulate contaminant transport. RT3D is exactly like MT3D (Zeng 1999), the most widely used transport code, except the code can simulate aerobic and anaerobic biodegradation of TCE. It is anticipated that use of RT3D will help confirm the biodegradation rates currently being determined as part of the dissolved plumes study.

4. DATA EVALUATION AND ANALYSIS

Data evaluation and analysis were undertaken to update, organize, and evaluate existing PGDP field data so that the groundwater flow system could be more readily understood. No new data were collected specifically for this modeling study; however, new data and information was available that was not included in the previous model. Some of the data examined included groundwater and surface water levels, flow directions, horizontal and vertical hydraulic gradients, ambient and anthropogenic recharge rates, pumping test results, lithologic descriptions, well construction information, and plume geometries. Ultimately, the evaluated data were used to define, configure, and constrain the groundwater flow model.

4.1 GEOLOGY

A brief summary of relevant geologic and hydrogeologic information is presented in this section. A more complete description of PGDP hydrogeologic information can be found in the *Ground-Water Conceptual Model for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky* (DOE 1997b).

At PGDP Cretaceous, Tertiary, and Quaternary age sediments overlay Mississippian age carbonate bedrock. The sediments are subdivided into hydrostratigraphic units termed the UCRS and RGA (Figure 4.1). Beneath the UCRS and RGA is the McNairy Flow System (McNairy).

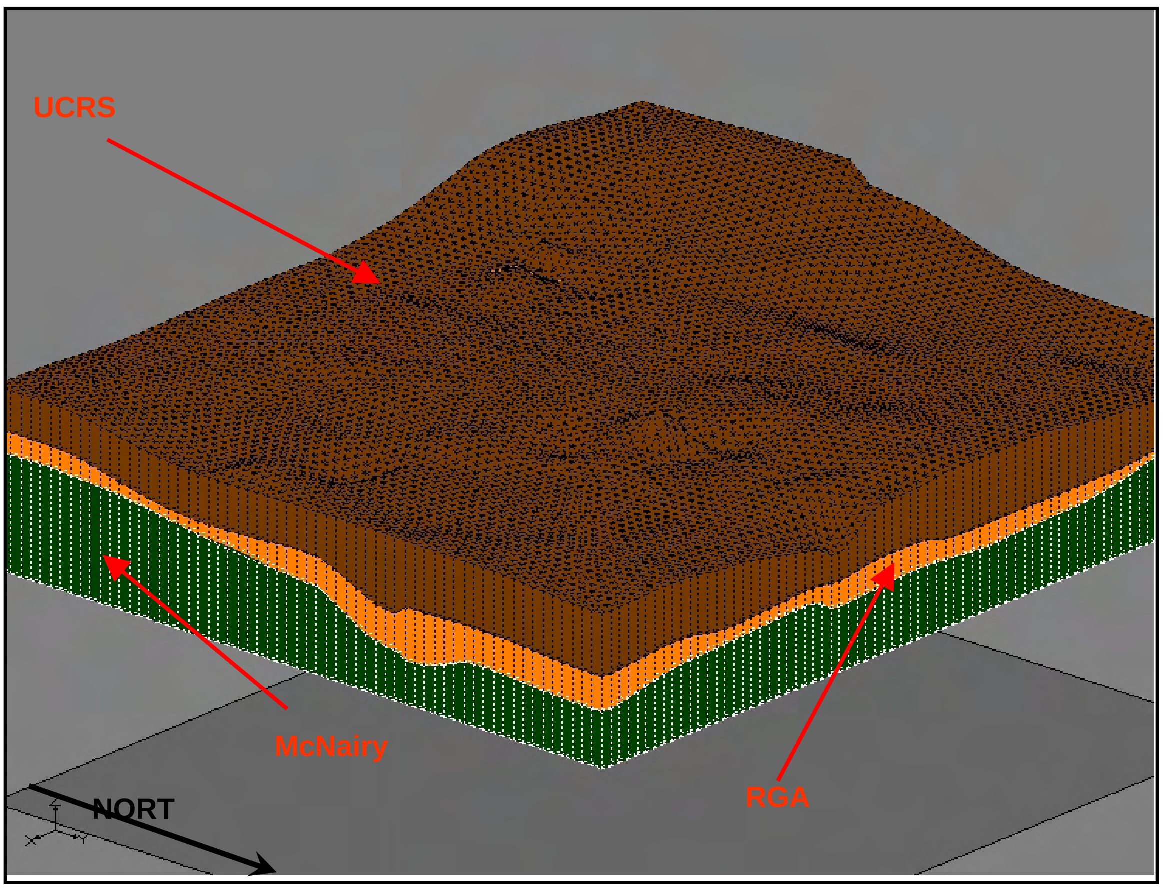


Figure 4.1. PGDP Hydrostratigraphic Units

4.2 WATER LEVEL ELEVATIONS

Water level elevations for the three hydrostratigraphic units were examined to determine expected temporal water level fluctuations and potential target sets for model calibration. The comprehensive PGDP water level database contains water level measurements collected since late 1980s to present. The water level data presented in this section represent a subset of the available data for model calibration. The results of an initial query of the database provided 17,712 records from wells that were included as part of the Environmental Monitoring Program. These data were winnowed to a more manageable dataset of less than 5,000 records (culled dataset) to evaluate for appropriate model calibration targets. The dataset was restricted by eliminating any water levels not measured within three days of other water level measurements and in cases, eliminating water levels collected when the stage of the Ohio River was particularly elevated. Water levels typically are measured on a quarterly basis in selected monitoring wells completed in the UCRS, RGA, and McNairy (Figure 4.2). The date range for Figure 4.2 represents the time frame over which useful data for the site is available prior to the initiation of model revision efforts. Figures of the current monitoring well locations and proposed locations for new monitoring wells are included in Appendix A.

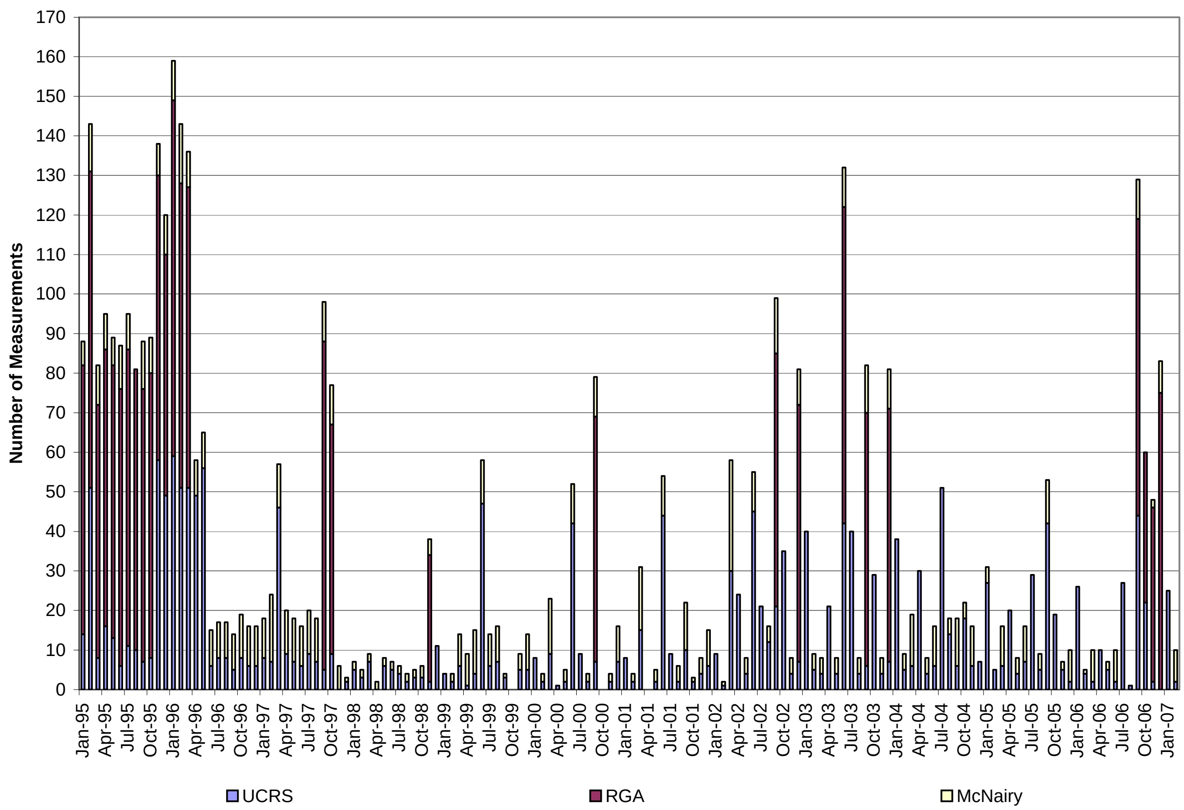


Figure 4.2. Water Level Measurement Frequency

4.2.1 UCRS Water Level Elevations

In the culled dataset, UCRS water levels have been measured in 80 individual wells as many as 133 times [monitoring well (MW)246] and a few as once (MW184) (Table 4.1). Water levels have been measured 10 or more times in 67 of the 80 UCRS wells. The maximum observed water level elevation fluctuation in any well was 19.87 ft in MW237. Of the wells measured 10 or more times, the minimum observed water level elevation fluctuation was 1.84 ft in MW82. In general, the mean and median values are similar, suggesting the absence of extreme minimum and maximum water levels.

4.2.2 RGA Water Level Elevations

In the culled dataset, RGA water levels have been measured in 178 individual wells as many as 28 times (MW58) and as few as once (many wells) (Table 4.2). Water levels have been measured 10 or more times in 79 of the 178 RGA wells. The maximum observed water level elevation fluctuation in any well was 10.61 ft in MW93. Of the wells measured 10 or more times, the minimum observed water level elevation fluctuation was 3.57 ft in MW241. In general, similar to the UCRS water levels, the mean and median RGA values are similar, suggesting the absence of extreme minimum and maximum water levels.

4.2.3 McNairy Water Level Elevations

Eleven monitoring wells at PGDP penetrate the McNairy in the culled dataset, (Table 4.3). Of the 11 McNairy wells, MW102 has been measured the most (170) and PZ114 the least (11) times. The maximum and minimum observed water level fluctuations of 13.24 and 6.97 ft were observed in MW133 and MW140, respectively. As with both UCRS and RGA water levels, the mean and median McNairy values are similar, suggesting the absence of extreme minimum and maximum water levels.

4.3 POTENTIOMETRIC SURFACES AND GROUNDWATER FLOW DIRECTIONS

A concern expressed during preliminary modeling discussions was whether the PGDP groundwater flow system could be represented using a steady-state model or would require a transient model. The definition of a steady-state groundwater flow system is one where there is no change in the volume of groundwater in storage (groundwater in the aquifer matrix). A change in storage occurs every time water levels change and, as evidenced by the discussions in Section 4.2, water levels do fluctuate at PGDP. By definition, the PGDP groundwater flow system is not truly steady state; however, no groundwater flow system is ever truly steady state. If a less arduous definition is adopted based on maintaining groundwater flow directions as water levels fluctuate, it is possible for many flow systems, including PGDP, to be considered steady state. This evaluation focused on characterizing the temporal consistency of PGDP flow directions.

Table 4.1. UCRS Water Level Elevation Statistics (ft amsl)

Well Number	X-Coordinate, ft	Y-Coordinate, ft	# Measurements	Min	Max	Range	Avg	Std	Median
MW246	-7447.70	1345.13	133	353.90	365.38	11.48	359.60	3.24	359.59
MW237	-5196.81	7328.85	129	339.00	358.87	19.87	348.22	4.51	347.44
MW88	-5809.90	-805.09	68	357.99	364.44	6.45	361.49	1.29	361.39
MW85	-5960.21	-804.80	67	358.41	364.81	6.40	361.42	1.52	361.21
MW94	-5979.52	-1028.64	65	359.60	364.02	4.42	361.58	1.23	361.54
MW91	-5660.38	-804.60	64	361.58	364.43	2.85	362.78	0.68	362.81
MW396	-1894.83	3471.98	55	365.82	373.89	8.07	369.95	2.44	369.41
MW371	-2957.43	4576.61	54	339.57	343.89	4.32	341.63	1.19	341.69
MW374	-2497.62	4819.04	53	321.82	336.05	14.23	332.35	3.20	332.88
MW386	-3120.54	3816.45	52	338.08	346.76	8.68	343.72	1.85	344.12
MW393	-1993.08	4571.03	52	330.44	341.80	11.36	340.37	2.11	340.80
MW365	-2383.31	6528.32	51	321.85	330.16	8.31	326.84	2.31	326.02
MW359	-2840.71	6448.02	50	327.21	343.83	16.62	337.19	5.06	338.39
MW362	-2621.41	6477.31	50	328.74	339.28	10.54	336.06	2.44	336.65
MW390	-2713.38	4394.91	50	322.25	329.31	7.06	325.64	1.70	325.26
MW174	-5307.20	1021.20	46	363.81	367.53	3.72	365.70	1.00	365.73
MW186	-6581.30	952.60	46	363.38	367.54	4.16	365.44	1.18	365.55
MW187	-6854.50	964.40	38	362.37	366.93	4.56	365.34	1.22	365.56
MW166	-3152.30	893.30	32	340.12	348.28	8.16	344.73	2.03	344.32
MW96	-4459.50	-2229.19	24	341.25	343.32	2.07	342.16	0.56	342.02
MW368	-2247.27	6134.00	23	322.99	330.96	7.97	327.10	2.42	327.35
MW182	-3027.40	3107.20	22	353.23	362.00	8.77	357.87	2.46	358.09
MW207	-4636.00	-2432.00	19	343.07	345.08	2.01	344.07	0.54	343.88
MW154	-6225.48	-810.29	18	365.12	369.27	4.15	367.41	1.16	367.46
MW180	-2494.20	4627.00	18	338.67	344.29	5.62	341.69	1.83	341.81
MW192	2587.80	600.40	18	321.99	330.14	8.15	325.71	2.82	325.53
PZ278	-2707.60	4985.53	18	340.85	347.52	6.67	344.60	1.67	344.30
MW204	-5014.10	-2148.10	17	331.14	337.89	6.75	334.14	2.16	333.61
MW212	-4171.88	-2041.46	17	339.03	342.43	3.40	349.09	1.02	340.41
MW213	-4290.20	-2233.90	17	336.04	342.11	6.07	339.65	1.32	339.76
MW219	-4481.40	-1917.30	17	340.18	342.57	2.39	341.01	0.82	340.73
MW64	-7235.37	880.24	17	361.61	366.11	4.50	363.86	1.68	364.40
PZ111	-3668.26	-3148.00	17	366.18	374.94	8.76	370.67	2.68	371.19
PZ279	-3171.05	5355.81	17	339.02	345.99	6.97	342.23	2.20	341.61
MW149	3214.11	5754.34	16	321.03	328.92	7.89	324.32	2.23	323.50
MW162	-6886.20	-1666.80	16	359.20	366.22	7.02	362.69	2.02	362.99
MW164	-2034.20	-1415.60	16	337.16	344.70	7.54	339.90	2.51	339.12
MW167	-4822.50	-908.70	16	369.07	371.27	2.20	370.21	0.71	370.21
MW170	-5557.60	-175.80	16	362.42	367.20	4.78	364.85	1.44	365.10
MW171	-5418.40	-471.50	16	365.52	369.93	4.41	368.41	1.30	368.87
MW172	-5977.90	-192.20	16	362.56	367.88	5.32	365.38	1.60	365.53
MW189	-6997.60	-2057.30	16	353.39	361.34	7.95	356.87	2.29	357.39
MW214	-4565.38	-2602.06	16	342.16	344.74	2.58	343.78	0.65	343.80
MW215	-3905.70	-2301.20	16	341.07	345.61	4.54	343.18	1.33	342.79
MW217	-5080.28	-2760.66	16	347.76	350.60	2.84	349.10	0.77	349.32
MW313	-7203.70	-3158.76	16	358.88	362.75	3.87	360.36	1.15	360.19
MW315	-6633.33	-2273.87	16	364.76	369.69	4.93	367.03	1.53	366.79
MW316	-7173.33	-2645.91	16	362.46	365.92	3.46	364.35	1.04	364.70
MW190	-6951.60	237.90	15	364.83	369.99	5.16	367.79	1.50	368.10
MW210	-4321.00	-2536.00	15	355.35	366.49	11.14	363.28	3.24	364.03
MW216	-4452.20	-3235.20	15	333.76	336.61	2.85	335.48	0.74	335.61
MW312	-7017.87	-3231.19	15	353.64	366.69	13.05	361.40	4.78	362.32
PZ74	-6152.39	-826.91	15	354.14	357.33	3.19	355.47	0.93	355.26
MW82	-5510.20	-846.01	14	361.04	362.88	1.84	361.71	0.48	361.70
MW157	-4025.70	-1688.60	13	343.30	351.71	8.41	347.81	2.15	348.06
MW211	-4841.90	-2040.50	13	340.95	345.97	5.02	343.25	1.75	342.78
MW218	-5090.38	-2626.16	13	351.91	356.80	4.89	353.37	1.40	353.31
MW314	-7116.68	-3534.26	13	351.36	365.33	13.97	358.21	5.40	359.11
MW377	-2280.94	5318.27	13	327.83	330.72	2.89	328.37	0.91	328.02
MW83	-5540.13	-846.22	13	363.43	365.33	1.90	364.40	0.65	364.35
MW208	-4704.00	-2298.00	12	342.42	344.91	2.49	343.35	0.75	343.18
MW69	-4343.25	-2074.34	12	324.21	341.81	17.60	330.21	5.95	328.86
MW138	-1734.38	9163.18	11	323.79	332.01	8.22	327.41	2.24	327.29
MW177	-4073.80	-1227.50	11	332.03	335.93	3.90	333.35	1.48	332.69
MW75	-5617.41	-842.16	11	365.34	368.45	3.11	367.02	1.11	367.18
MW160	-6945.90	-971.90	10	362.33	366.80	4.47	364.53	1.67	364.70
MW209	-4769.00	-2600.00	10	343.62	345.92	2.30	344.63	0.69	344.55
MW389	-2913.08	4258.20	9	328.88	330.06	1.18	329.26	0.32	329.19
MW153	-695.33	13122.54	8	315.44	324.33	8.89	318.01	2.96	317.02
MW198	-6163.00	2874.80	7	343.08	352.20	9.12	346.88	3.66	347.94
PZ251	-4817.20	-872.51	7	357.95	359.65	1.70	358.66	0.69	358.29
PZ281	-3160.89	5999.94	7	330.56	336.43	5.87	334.03	1.81	334.35
MW104	-6596.77	-3682.88	6	348.65	350.24	1.59	349.48	0.55	349.36
PZ282	-2379.92	6441.68	6	331.95	333.59	1.64	332.40	0.69	332.01
PZ280	-2199.39	5921.63	4	334.54	334.68	0.14	334.62	0.06	334.64
MW127	-5664.11	6161.23	3	349.21	349.40	0.19	349.33	0.10	349.38
MW128	1883.08	746.17	3	328.00	329.15	1.15	328.73	0.64	329.05
MW143	-12156.05	6513.64	2	332.71	333.69	0.98	333.20	0.69	333.20
MW176	-4380.00	-1444.20	2	325.25	341.01	15.76	333.13	11.14	333.13
MW184	-7386.90	-3997.30	1	359.14	359.14	0.00	359.14		359.14

Table 4.2. RGA Water Level Elevation Statistics (ft amsl)

Well Number	X-Coord	Y-Coord	# Meas	Min	Max	Range	Avg	Std	Median
MW98	-3281.31	7397.46	28	320.40	328.44	8.04	323.57	2.23	322.98
MW200	-4823.90	4443.30	27	321.94	329.80	7.86	325.22	2.23	324.52
MW202	-5688.00	7613.20	27	320.66	328.71	8.05	323.91	2.24	323.42
MW123	-5661.33	6125.60	26	321.21	329.12	7.91	324.55	2.23	324.01
MW126	1881.49	736.67	26	322.37	330.38	8.01	325.80	2.33	325.21
MW134	-8335.00	3568.93	26	322.03	330.46	8.43	325.88	2.43	325.27
MW173	-5290.00	1020.30	26	323.16	330.76	7.60	326.73	2.09	326.22
MW185	-6601.90	952.90	26	322.64	330.44	7.80	326.35	2.14	326.09
MW193	515.80	3064.90	26	322.59	329.94	7.35	325.96	2.17	325.23
MW197	-6162.50	2863.10	26	322.18	330.13	7.95	325.59	2.18	324.94
MW201	-4884.00	10167.40	26	319.23	327.52	8.29	322.52	2.20	321.94
MW63	-7235.74	895.26	26	322.55	330.36	7.81	326.10	2.21	325.81
MW66	-6872.62	978.57	26	321.50	329.48	7.98	325.25	2.22	324.96
MW103	-6252.14	-3500.84	25	324.37	333.02	8.65	327.79	2.26	327.50
MW137	-1726.75	9150.86	25	318.56	326.78	8.22	321.75	2.15	321.09
MW139	-576.59	6189.67	25	321.09	328.66	7.57	324.31	2.15	323.58
MW150	4782.26	2215.00	25	322.29	330.03	7.74	325.72	2.18	325.43
MW152	-692.64	13136.67	25	313.32	323.44	10.12	316.79	2.43	316.18
MW163	-2041.00	-1400.80	25	323.76	330.82	7.06	327.20	1.93	326.69
MW169	-5558.00	-191.40	25	323.19	330.59	7.40	326.70	2.15	326.14
MW188	-7008.80	-2057.10	25	323.65	330.88	7.23	327.21	2.00	326.77
MW191	2597.40	600.30	25	322.44	330.08	7.64	326.05	2.24	325.24
MW194	-10177.50	1865.60	25	323.63	330.81	7.18	326.36	2.13	326.08
MW206	-2924.50	-1504.80	25	323.29	330.37	7.08	326.74	1.95	326.37
MW327	-7100.87	-2559.81	25	323.71	330.96	7.25	327.29	2.01	326.81
MW71	-4372.93	-2074.16	25	323.78	330.94	7.16	327.30	2.06	326.94
MW84	-5975.23	-804.20	25	323.29	330.76	7.47	326.93	2.07	326.51
MW93	-5994.81	-1028.57	25	323.08	333.69	10.61	327.31	2.63	327.12
PZ107	-3681.93	-3571.32	25	325.45	332.90	7.45	329.05	1.91	328.94
PZ117	-3758.80	-3081.60	25	324.26	331.41	7.15	327.78	1.95	327.41
PZ118	-3698.80	-3283.90	25	323.28	331.42	8.14	327.73	2.05	327.43
MW106	-8438.90	990.93	24	322.71	330.60	7.89	326.51	2.25	326.44
MW156	-4025.70	-1703.70	24	323.85	330.97	7.12	327.32	1.99	326.86
MW161	-6916.90	-1666.70	24	323.59	330.98	7.39	327.13	2.03	326.73
MW165	-3135.70	898.30	24	321.00	330.59	9.59	326.64	2.36	326.32
MW168	-4822.50	-924.80	24	323.40	330.83	7.43	326.96	2.08	326.63
MW175	-4379.10	-1428.30	24	323.78	330.98	7.20	327.43	1.95	327.03
MW199	-10076.60	10090.10	24	320.69	329.08	8.39	324.16	2.34	323.78
MW203	-5014.80	-2159.20	24	323.75	331.08	7.33	327.35	2.06	327.02
MW205	-4360.30	-364.10	24	323.19	330.49	7.30	326.67	2.07	326.36
MW226	-5740.41	-1241.06	24	323.93	331.33	7.40	327.64	2.06	327.25
MW99	1842.46	6826.71	24	322.01	328.58	6.57	324.25	2.08	323.79
MW178	-4073.60	-1216.20	23	323.63	330.97	7.34	327.26	2.07	326.80
MW227	-5769.88	-1240.60	21	325.08	331.21	6.13	327.81	1.95	327.57
MW248	-7376.72	1385.42	20	322.18	330.64	8.46	325.81	2.42	325.01
MW236	-5087.79	7919.99	18	320.41	328.34	7.93	323.18	2.08	322.90
MW240	-5195.78	7390.60	18	320.74	328.70	7.96	323.35	2.05	322.91
MW242	-7083.28	1678.98	18	322.50	329.95	7.45	325.47	1.95	325.04
MW243	-7382.03	1681.40	18	322.27	330.14	7.87	325.36	2.10	324.71
MW90	-5675.22	-803.46	18	323.26	330.88	7.62	327.07	2.18	327.28
MW142	-12162.53	6529.75	17	322.90	330.19	7.29	326.03	2.32	325.26

Table 4.2. RGA Water Level Elevation Statistics (ft amsl) (Continued)

Well Number	X-Coord	Y-Coord	# Meas	Min	Max	Range	Avg	Std	Median
MW145	-768.84	383.32	17	324.18	330.68	6.50	326.91	2.17	326.75
MW225	-2634.42	3323.37	17	324.02	330.22	6.20	326.50	2.05	326.47
MW238	-5197.06	7505.64	17	320.55	328.47	7.92	323.05	1.78	322.98
MW249	-7432.45	1357.75	17	322.39	330.45	8.06	325.45	2.25	324.53
MW325	-6100.30	-2090.91	17	324.69	330.95	6.26	327.44	1.99	327.35
MW159	-6937.10	-989.80	16	324.62	330.95	6.33	327.49	1.94	327.45
MW179	-2516.50	4627.90	16	323.36	329.64	6.28	326.02	2.11	325.78
MW181	-3042.80	3107.30	16	323.70	329.99	6.29	326.40	2.09	326.21
MW222	-2563.11	3659.61	16	323.88	330.10	6.22	326.35	2.20	326.24
MW223	-2725.63	3719.99	16	323.87	330.05	6.18	326.28	2.12	326.15
MW224	-2467.33	3627.71	16	323.88	333.18	9.30	326.78	2.69	326.29
MW233	-5530.15	7300.34	16	320.67	328.64	7.97	323.25	1.82	322.99
MW244	-7589.08	1467.50	16	322.28	330.26	7.98	325.17	2.38	324.49
MW250	-7431.78	1396.34	16	322.38	330.40	8.02	325.80	2.45	325.06
MW220	-2822.84	3279.19	15	323.99	330.20	6.21	326.56	2.22	326.45
MW221	-2784.92	3863.68	15	323.81	330.05	6.24	326.43	2.06	326.63
MW245	-7397.55	1119.22	15	322.33	330.15	7.82	324.97	1.90	324.55
MW326	-6185.00	-2430.11	15	324.71	331.06	6.35	327.64	2.05	327.73
MW328	-7337.48	-1962.31	15	324.65	331.11	6.46	327.48	2.12	327.63
MW329	-7347.44	-1419.37	15	324.60	330.97	6.37	327.46	2.14	327.58
MW330	-6636.33	-2206.91	15	324.75	330.94	6.19	328.15	1.97	327.75
PZ109	-3665.80	-3143.30	15	325.91	331.42	5.51	328.47	1.97	328.31
W108	-3698.90	-3132.90	15	325.71	331.43	5.72	328.13	1.92	328.35
MW146	-5684.18	13549.15	12	317.35	325.67	8.32	320.12	2.40	319.41
MW257	-5972.21	442.38	12	322.30	329.70	7.40	325.77	2.07	325.42
MW234	-5188.17	7205.82	11	320.80	328.13	7.33	323.09	1.97	322.71
MW235	-4890.74	7746.42	11	320.43	324.10	3.67	322.46	1.09	322.60
MW241	-5203.79	7346.86	11	320.63	324.20	3.57	322.43	1.03	322.55
MW148	3289.83	5755.06	8	322.83	328.91	6.08	326.25	2.35	326.46
MW341	-3939.16	-1062.27	8	323.11	330.08	6.97	325.83	2.14	325.53
MW342	-4403.56	-1289.51	8	323.16	330.17	7.01	325.89	2.15	325.61
MW343	-4404.16	-1083.87	8	323.19	330.16	6.97	325.86	2.16	325.61
MW380	-5190.31	7205.26	7	321.70	328.54	6.84	323.88	2.30	322.85
MW381	-4892.90	7745.84	7	321.51	328.28	6.77	323.73	2.25	322.94
MW90A	-5688.64	-793.68	7	324.67	330.72	6.05	326.61	2.05	325.93
MW255	-1510.28	-2230.29	6	324.23	330.55	6.32	327.29	2.67	327.32
MW258	-745.65	-1643.25	6	324.76	330.58	5.82	327.65	2.38	328.11
MW125	-5662.81	6139.28	5	321.64	323.83	2.19	322.57	0.88	322.26
MW256	-1596.77	-1896.41	5	324.15	328.91	4.76	326.49	2.12	327.31
MW95A	-5944.19	-1029.96	5	325.36	330.80	5.44	327.17	2.24	325.98
MW158	-6957.00	-991.20	4	325.94	328.58	2.64	326.92	1.21	326.57
MW86	-5945.24	-804.90	4	325.85	330.32	4.47	328.38	2.06	328.68
MW87	-5825.09	-804.98	4	326.32	330.77	4.45	328.84	2.10	329.13
MW89	-5795.14	-804.13	4	325.75	330.77	5.02	328.66	2.30	329.07
MW92	-5645.00	-805.26	4	325.78	330.80	5.02	328.71	2.31	329.12
MW95	-5964.22	-1028.61	4	325.72	330.98	5.26	328.80	2.43	329.25
MW124	1879.15	726.38	3	323.39	324.68	1.29	323.92	0.68	323.68
MW132	-559.79	6192.35	3	322.25	328.70	6.45	324.81	3.42	323.48
MW144	-770.10	369.58	3	324.89	330.12	5.23	326.92	2.81	325.74
MW147	-5669.28	13548.69	3	319.46	323.94	4.48	321.16	2.43	320.09
MW283	599.27	903.26	3	323.29	326.58	3.29	324.64	1.72	324.05

Table 4.2. RGA Water Level Elevation Statistics (ft amsl) (Continued)

Well Number	X-Coord	Y-Coord	# Meas	Min	Max	Range	Avg	Std	Median
MW284	1590.00	913.48	3	323.26	326.61	3.35	324.60	1.77	323.92
MW288	1564.94	679.01	3	323.50	326.81	3.31	324.78	1.78	324.03
MW291	1699.81	968.89	3	323.41	326.72	3.31	324.56	1.87	323.54
MW292	924.03	33.19	3	323.82	327.37	3.55	325.02	2.03	323.88
MW353	-3311.97	2599.30	3	323.86	325.41	1.55	324.68	0.78	324.77
MW67	-6134.48	-755.36	3	325.27	331.08	5.81	327.72	3.01	326.82
MW72	-5880.60	-737.48	3	324.66	330.56	5.90	327.21	3.03	326.41
MW73	-5500.53	-733.99	3	325.00	330.89	5.89	327.55	3.02	326.76
MW77	-5826.08	-1298.11	3	324.24	326.65	2.41	325.31	1.23	325.03
MW79	-5500.02	-845.91	3	324.57	330.47	5.90	327.16	3.02	326.43
MW80	-5500.02	-855.74	3	324.59	330.49	5.90	327.14	3.03	326.34
PZ110	-3741.36	-3168.00	3	325.67	331.22	5.55	327.81	2.99	326.54
MW135	-1520.05	9137.28	2	320.51	326.92	6.41	323.72	4.53	323.72
MW141	-12173.02	6544.69	2	323.12	324.84	1.72	323.98	1.22	323.98
MW260	-1982.18	-786.01	2	327.36	328.66	1.30	328.01	0.92	328.01
MW261	-5979.20	442.19	2	327.34	327.93	0.59	327.64	0.42	327.64
MW293	1802.40	839.01	2	323.55	326.71	3.16	325.13	2.23	325.13
MW294	1790.40	842.77	2	323.49	326.64	3.15	325.07	2.23	325.07
MW409	4855.28	3821.11	2	323.24	325.14	1.90	324.19	1.34	324.19
MW410	5021.19	5549.30	2	320.81	322.96	2.15	321.89	1.52	321.89
MW411	5081.82	8876.15	2	319.50	321.15	1.65	320.33	1.17	320.33
MW414	-6531.28	-1220.85	2	325.37	326.86	1.49	326.12	1.05	326.12
MW415	-6530.80	-1206.59	2	325.45	326.65	1.20	326.05	0.85	326.05
MW416	-6559.06	-1470.47	2	325.69	326.70	1.01	326.20	0.71	326.20
MW417	-6559.24	-1461.40	2	325.65	326.53	0.88	326.09	0.62	326.09
MW418	-1833.99	4418.94	2	324.06	325.71	1.65	324.89	1.17	324.89
MW419	-1833.77	4429.38	2	324.06	325.69	1.63	324.88	1.15	324.88
MW76	-5625.40	-1059.38	2	324.72	326.40	1.68	325.56	1.19	325.56
MW78	-5399.89	-845.82	2	324.54	330.43	5.89	327.49	4.16	327.49
PZ112	-3665.05	-3138.58	2	339.60	342.46	2.86	341.03	2.02	341.03
PZ287	1489.22	608.40	2	323.41	326.85	3.44	325.13	2.43	325.13
PZ289	1629.92	609.65	2	323.44	326.83	3.39	325.14	2.40	325.14
PZ290	1506.70	849.90	2	323.34	326.66	3.32	325.00	2.35	325.00
MW100	4817.00	7167.00	1	322.40	322.40	0.00	322.40		322.40
MW252	4228.40	5717.89	1	329.77	329.77	0.00	329.77		329.77
MW253	3572.22	3669.88	1	330.09	330.09	0.00	330.09		330.09
MW262	-5379.80	-292.32	1	328.75	328.75	0.00	328.75		328.75
MW263	-2760.60	4551.97	1	324.23	324.23	0.00	324.23		324.23
MW264	-2239.65	4639.91	1	324.31	324.31	0.00	324.31		324.31
MW265	-1888.70	4409.76	1	326.98	326.98	0.00	326.98		326.98
MW266	-2259.74	4639.90	1	324.25	324.25	0.00	324.25		324.25
MW267	-2819.73	3264.74	1	324.61	324.61	0.00	324.61		324.61
MW268	-3103.02	6472.48	1	324.61	324.61	0.00	324.61		324.61
MW274	-2205.70	6169.96	1	324.90	324.90	0.00	324.90		324.90
MW276	-3107.19	4470.74	1	329.36	329.36	0.00	329.36		329.36
MW293A	1789.75	843.01	1	323.56	323.56	0.00	323.56		323.56
MW294A	1801.80	839.09	1	323.44	323.44	0.00	323.44		323.44
MW333	-6210.00	-1040.00	1	328.28	328.28	0.00	328.28		328.28
MW337	-6263.08	-849.62	1	327.95	327.95	0.00	327.95		327.95
MW338	-6212.95	-898.02	1	328.01	328.01	0.00	328.01		328.01
MW339	-6468.50	663.20	1	325.34	325.34	0.00	325.34		325.34

Table 4.2. RGA Water Level Elevation Statistics (ft amsl) (Continued)

Well Number	X-Coord	Y-Coord	# Meas	Min	Max	Range	Avg	Std	Median
MW354	-8428.96	-423.07	1	324.09	324.09	0.00	324.09		324.09
MW355	-4327.94	761.55	1	324.23	324.23	0.00	324.23		324.23
MW357	-2829.58	6451.80	1	322.70	322.70	0.00	322.70		322.70
MW358	-2851.93	6444.38	1	322.70	322.70	0.00	322.70		322.70
MW360	-2627.14	6467.64	1	322.68	322.68	0.00	322.68		322.68
MW361	-2617.48	6487.36	1	322.72	322.72	0.00	322.72		322.72
MW363	-2392.05	6521.42	1	322.58	322.58	0.00	322.58		322.58
MW364	-2373.54	6535.89	1	322.57	322.57	0.00	322.57		322.57
MW366	-2246.10	6121.18	1	322.76	322.76	0.00	322.76		322.76
MW367	-2247.09	6145.28	1	322.75	322.75	0.00	322.75		322.75
MW369	-2957.51	4564.73	1	324.01	324.01	0.00	324.01		324.01
MW370	-2957.40	4589.20	1	324.00	324.00	0.00	324.00		324.00
MW372	-2486.89	4817.24	1	324.00	324.00	0.00	324.00		324.00
MW373	-2509.92	4823.14	1	323.99	323.99	0.00	323.99		323.99
MW375	-2907.85	5886.80	1	339.15	339.15	0.00	339.15		339.15
MW384	-3121.20	3828.36	1	324.18	324.18	0.00	324.18		324.18
MW385	-3119.46	3804.81	1	324.17	324.17	0.00	324.17		324.17
MW387	-3073.18	4188.73	1	324.16	324.16	0.00	324.16		324.16
MW388	-3080.77	4197.35	1	324.16	324.16	0.00	324.16		324.16
MW391	-1993.30	4557.92	1	324.26	324.26	0.00	324.26		324.26
MW392	-1994.30	4582.37	1	324.16	324.16	0.00	324.16		324.16
MW394	-1895.64	3460.44	1	324.41	324.41	0.00	324.41		324.41
MW395	-1894.71	3484.23	1	324.37	324.37	0.00	324.37		324.37
MW397	-2509.48	3138.15	1	324.34	324.34	0.00	324.34		324.34
MW68	-4357.96	-2074.15	1	325.13	325.13	0.00	325.13		325.13

Table 4.3. McNairy Water Level Elevation Statistics (ft amsl)

X-Coord	Y-Coord	Well #	# Meas	Min	Max	Range	Avg	Std	Median
-6267	-3503	MW102	170	323.15	333.98	10.83	327.85	2.41	327.76
-1489	-5880	MW120	82	323.22	331.33	8.11	326.88	1.85	326.92
-5678	6162	MW121	85	319.11	328.61	9.50	323.02	1.82	322.7
1876	717	MW122	86	321.56	331.19	9.63	325.54	2.21	325.42
-1716	9125	MW133	86	318.37	331.61	13.24	322.92	2.63	322.68
-12179	6558	MW140	38	321.89	328.86	6.97	324.27	1.82	323.96
-5204	7330	MW239	137	319.93	332.23	12.30	324.86	2.69	324.60
-7446	1360	MW247	143	321.44	333.25	11.81	326.55	2.71	326.54
-1466	863	MW356	22	321.63	331.46	9.83	324.67	2.72	323.47
-3664	-3129	PZ114	11	324.68	333.13	8.45	328.45	3.17	326.75
-3666	-3124	PZ115	67	322.99	333.13	10.14	327.48	2.33	327.40

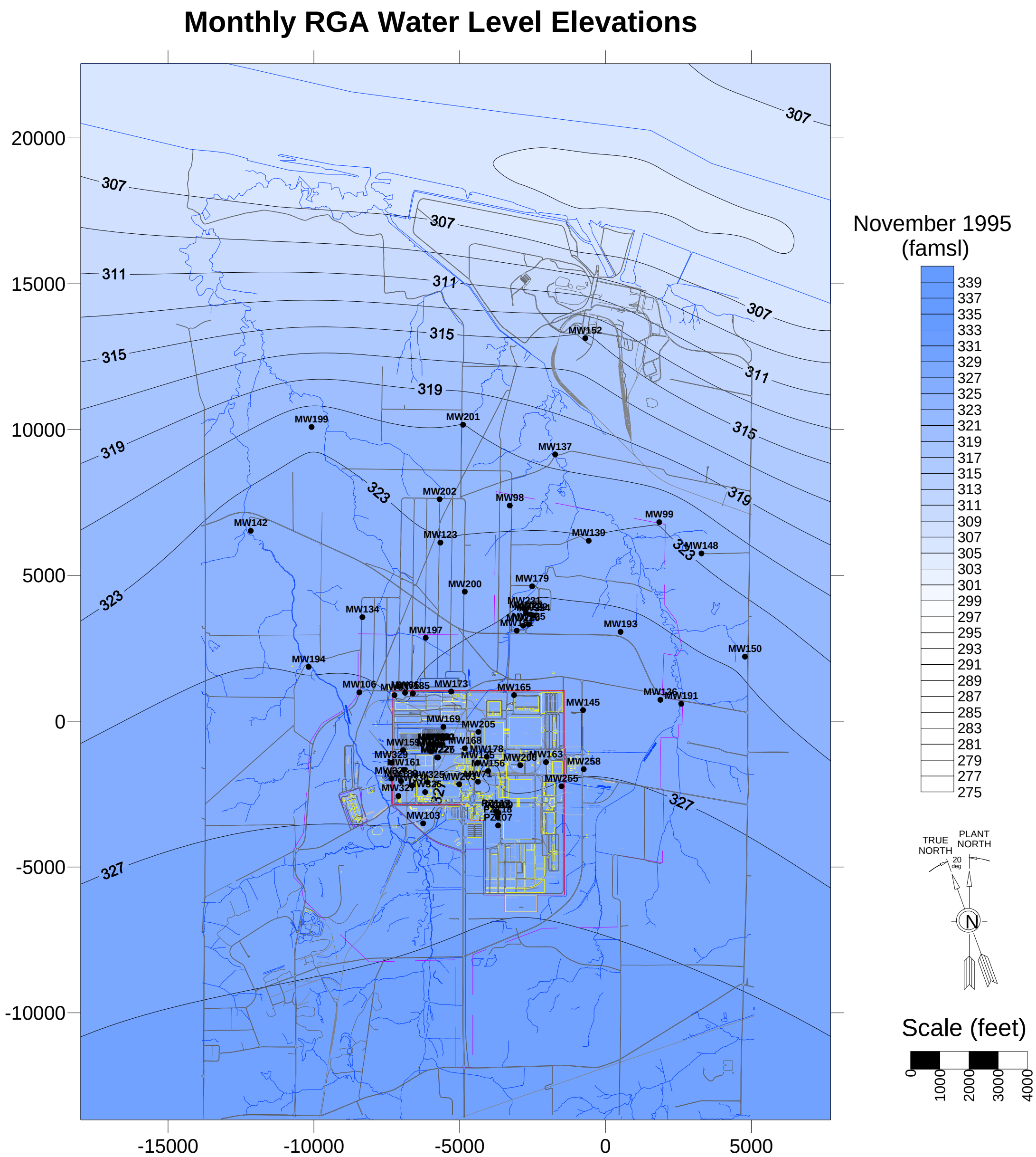
4.3.1 RGA Potentiometric Surfaces

RGA potentiometric surfaces were generated by contouring RGA water level data representing eight different measuring dates between November 1995 and September 2006 (Figure 4.3). All the potentiometric surfaces were created using the standard kriging algorithm in Surfer. Based on the position and orientation of the equipotential lines, it appears groundwater flow changes at PGDP in response to changes in Ohio River stage. It is important to recognize that different sets of water level measurements were used to create the potentiometric surfaces. As illustrated by Figure 4.2, the number of locations varies between measurement events. The difference in locations and the number of locations for these data sets potentially could affect the contoured surfaces. Additionally, a single water level measurement having a significantly different value (+/- a few feet) relative to the surrounding wells will exert considerable influence on how the potentiometric surface is contoured making it appear that flow directions are vastly different between measurement intervals.

4.3.2 RGA Three-Point Analysis

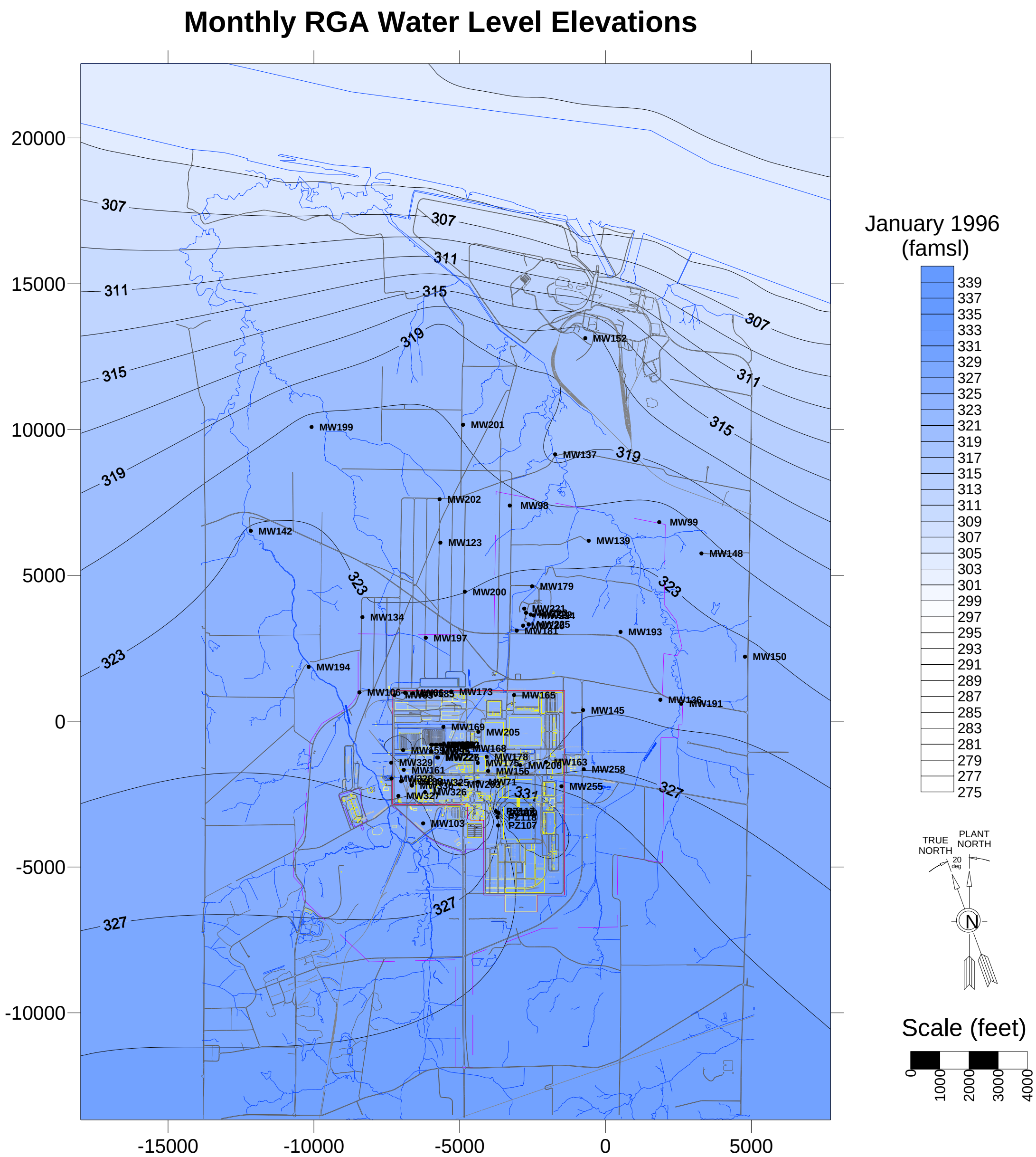
A more quantitative flow direction analysis, relative to potentiometric surface evaluation, was conducted using Visual Three-Point Plus (V3PP), a computer code developed by Oak Ridge National Laboratory (Laase *et al.* 2001). Applying V3PP, the user creates triangles using wells as the vertices, and the algorithm calculates a flow vector (magnitude and direction) based on the measured water levels in the three wells. V3PP was used to evaluate flow directions for nine different measurement periods between February 1995 and September 2006. The same 40 wells were common to all measurement periods except for the September 1997 measurement period, when only 38 wells were used in the analysis. Figure 4.4 shows the predicted flow directions for the nine measurement periods. (NOTE: the measurement periods, with the exception of February 1995, are identical to those used for the potentiometric surface evaluation.) Different than the potentiometric surface evaluation, three-point analysis shows, in general, that the flow patterns between PGDP and the Ohio River remain relatively stable regardless of changes in Ohio River stage.

Three-point analysis shows that flow directions inside the PGDP are variable between measurement periods (Figure 4.4). The variability is attributed to anthropogenic recharge, recharge that is caused or produced by human activity. Some sources of anthropogenic recharge at the PGDP include leaky underground water supply lines, infiltration from storm and outfall ditches, leakage from unlined lagoons, and runoff from building roofs. The variability is attributed to the different time constants associated with the various anthropogenic recharge sources. Leakage from an underground water line is relatively constant compared to infiltration from a drainage ditch which is a function of rainfall. During and immediately after a rainfall event, recharge will occur through the bottom of the drainage ditch. The rest of the time, no recharge will be associated with this feature. Conversely, the water line will continue to leak regardless of weather conditions.



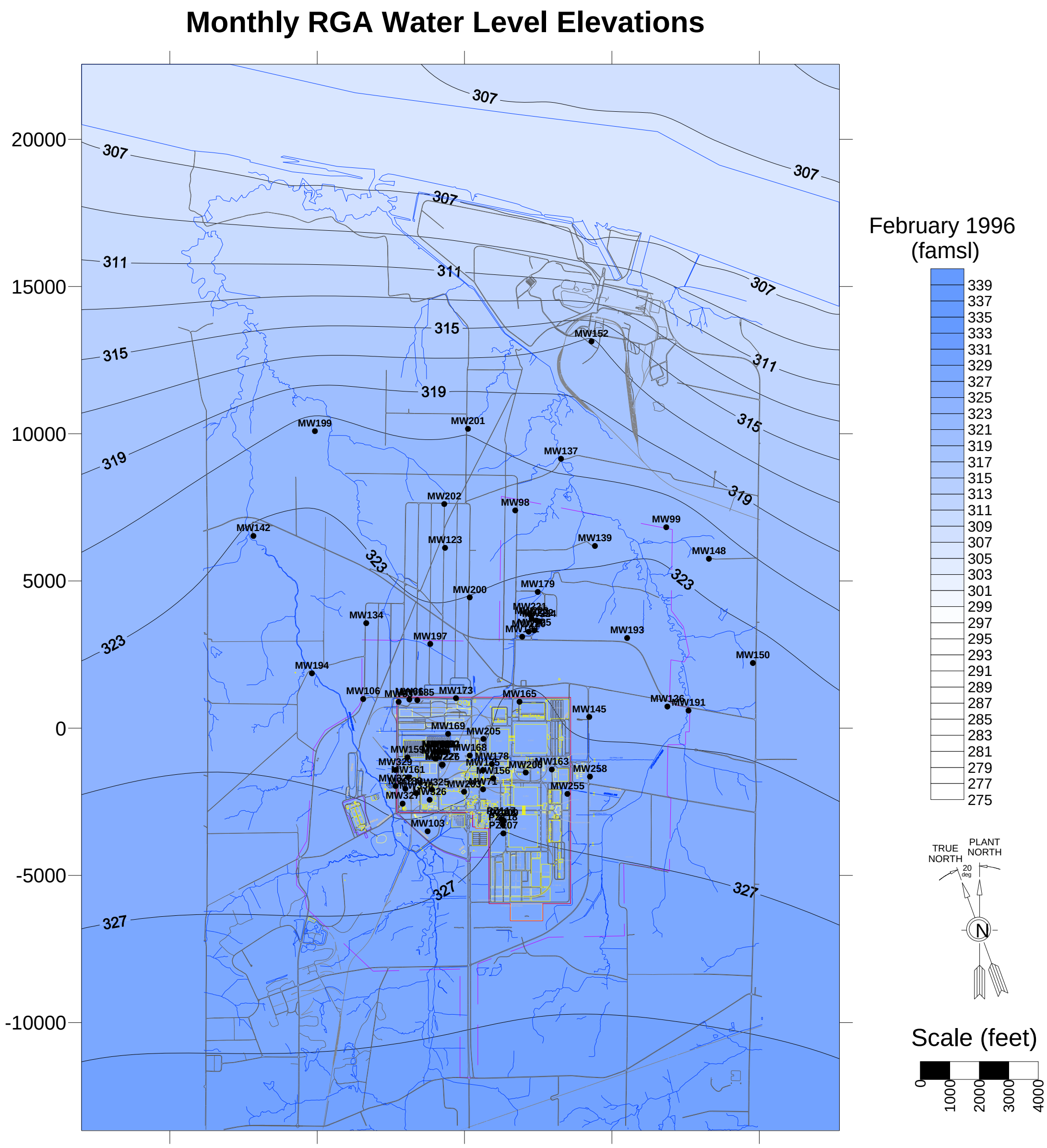
November 1995, Ohio River Stage = 297.4 ft

Figure 4.3. RGA Potentiometric Surfaces



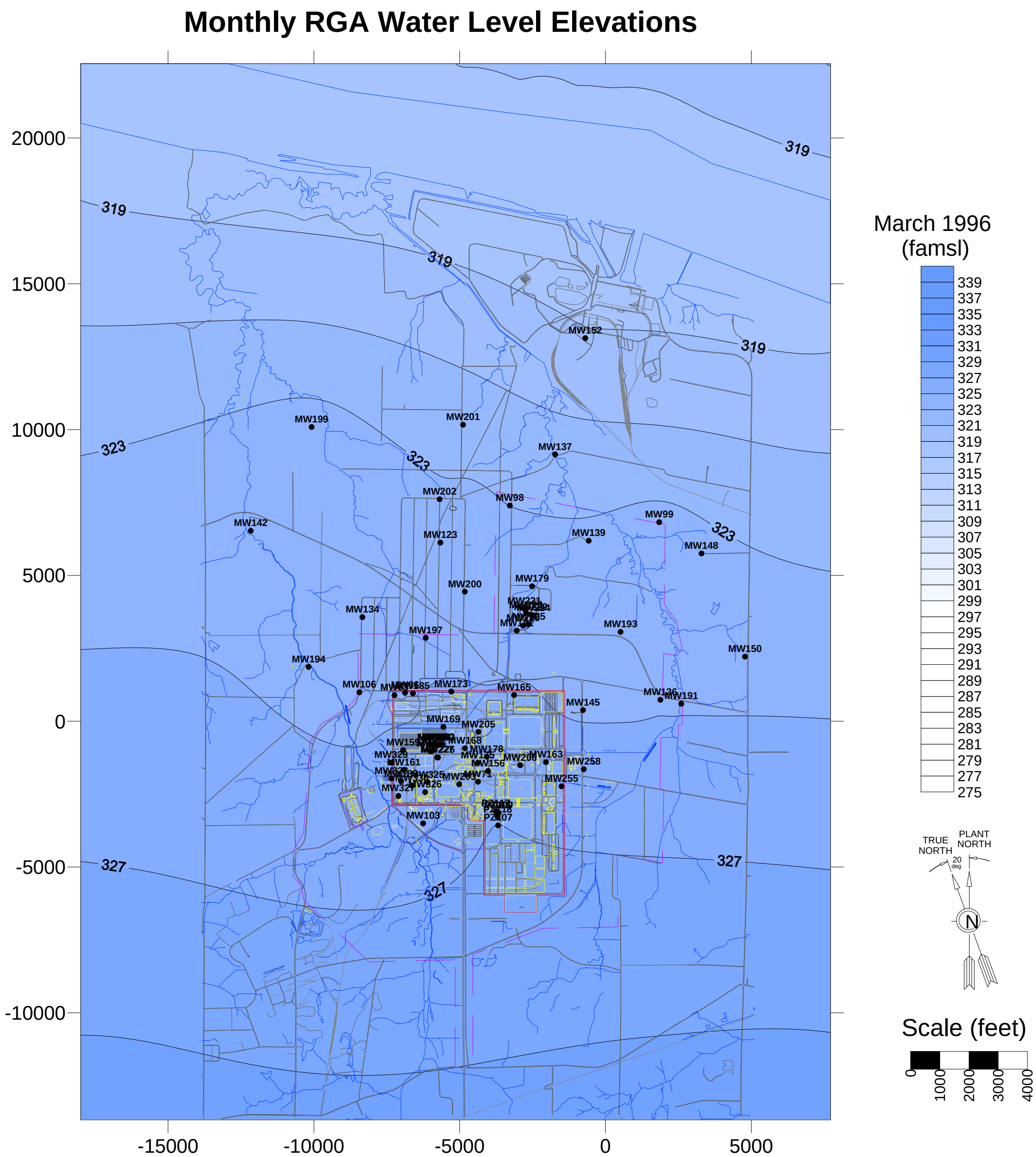
January 1996, Ohio River Stage = 304.5 ft

Figure 4.3. RGA Potentiometric Surfaces (Continued)



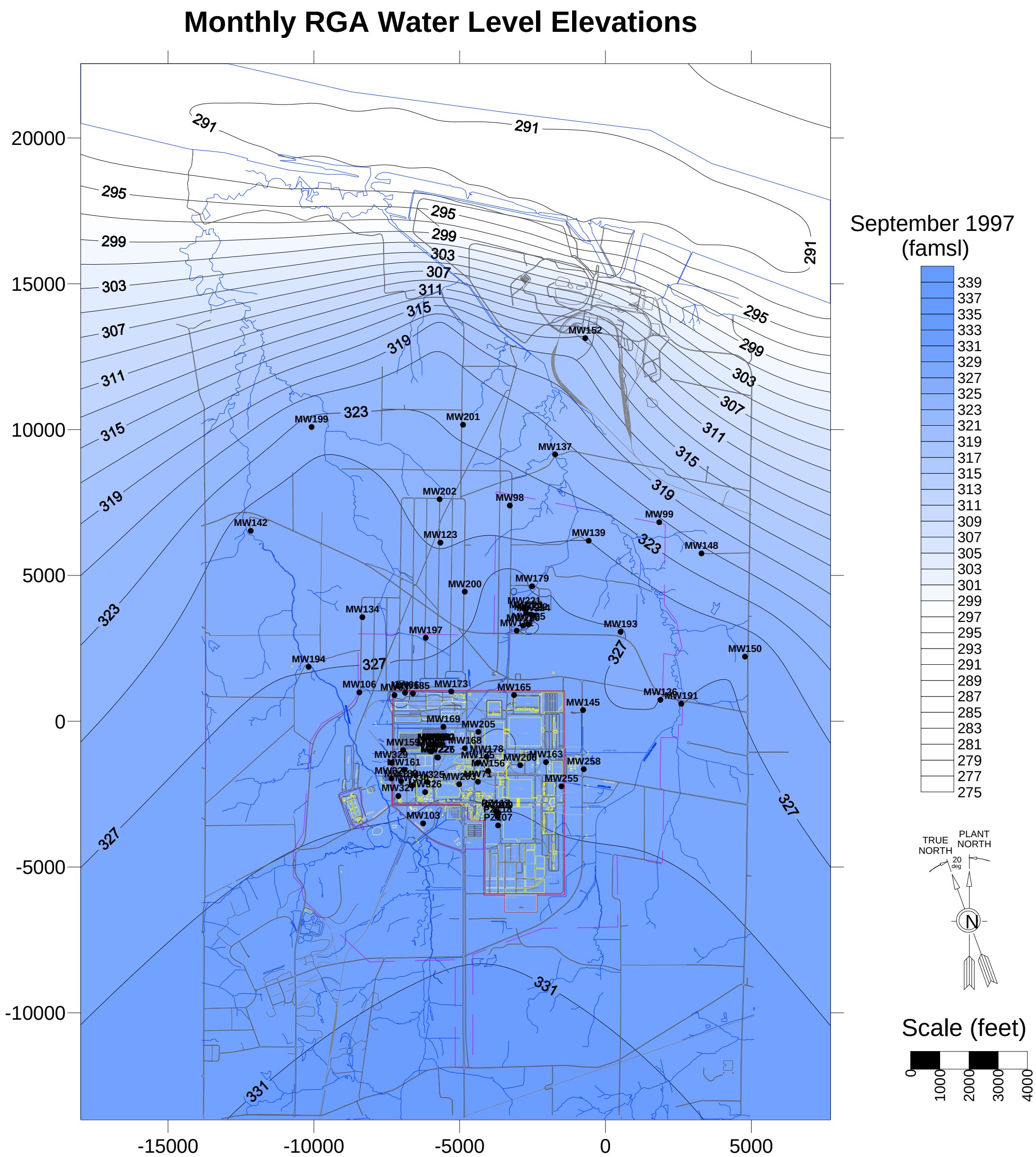
February 1996, Ohio River Stage = 306.6 ft

Figure 4.3. RGA Potentiometric Surfaces (Continued)



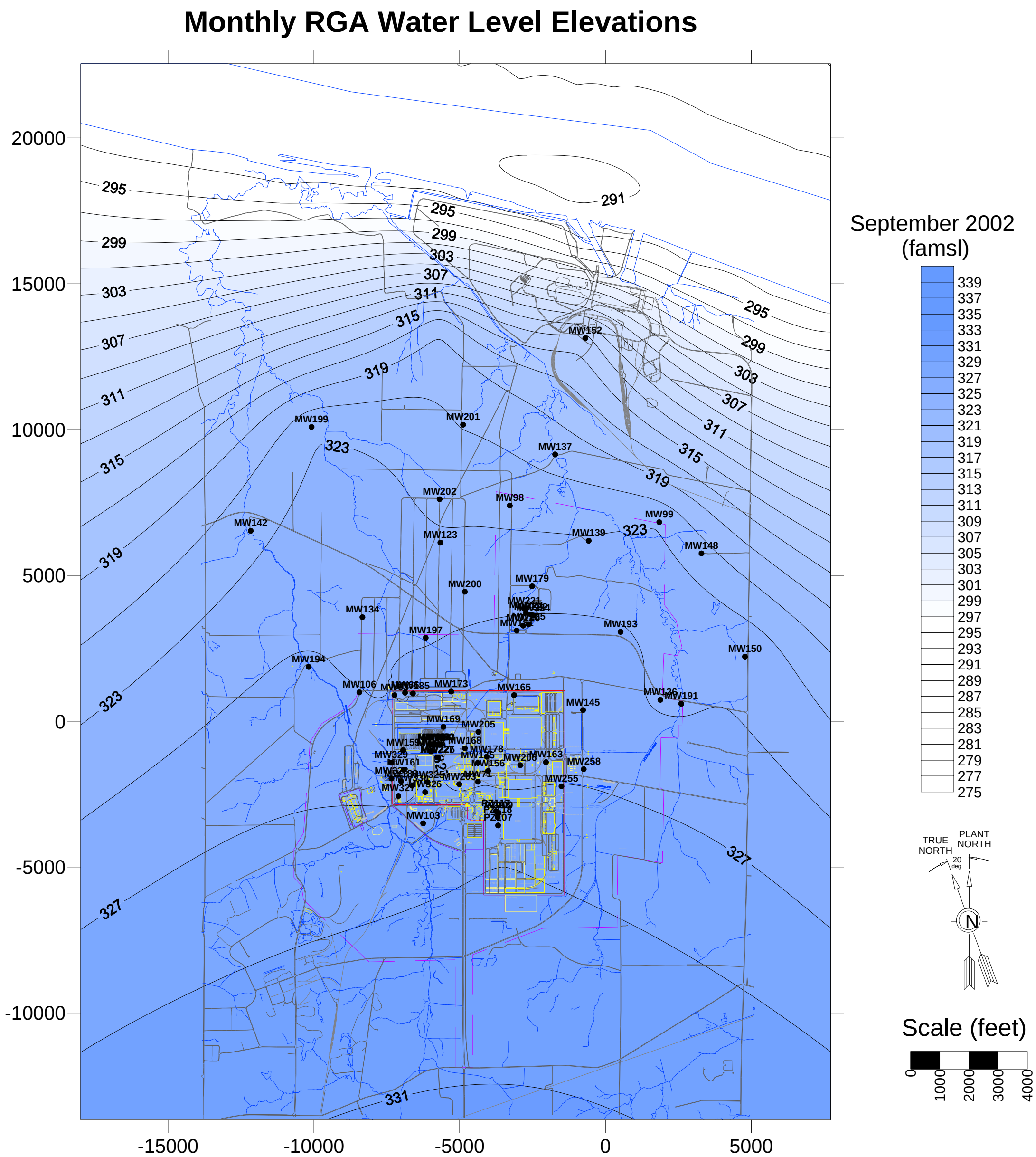
March 1996, Ohio River Stage = 318.1 ft

Figure 4.3. RGA Potentiometric Surfaces (Continued)



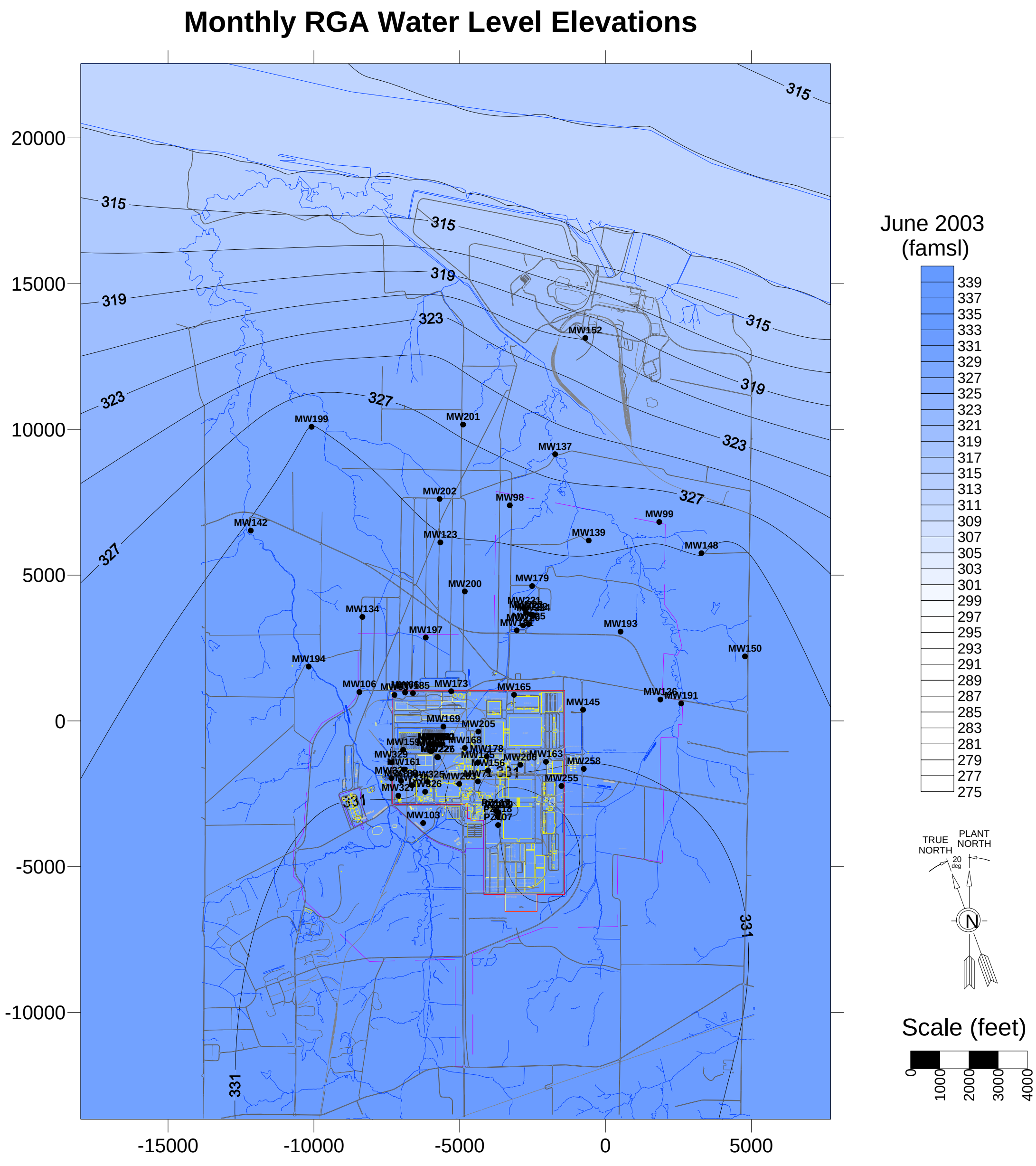
September 1997, Ohio River Stage = 291.4 ft

Figure 4.3. RGA Potentiometric Surfaces (Continued)



September 2002, Ohio River Stage = 292.1 ft

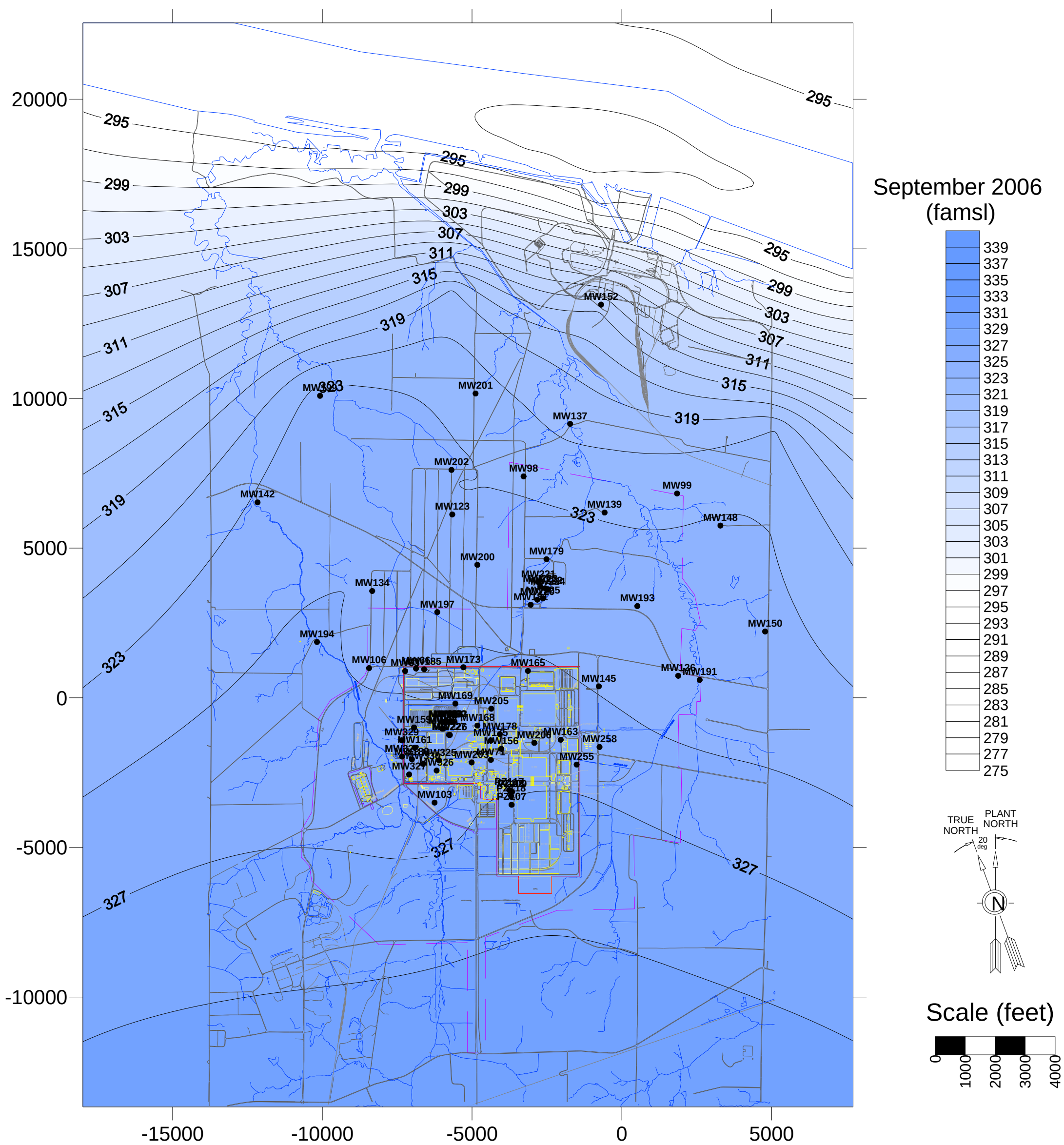
Figure 4.3. RGA Potentiometric Surfaces (Continued)



June 2003, Ohio River Stage = 312.9 ft

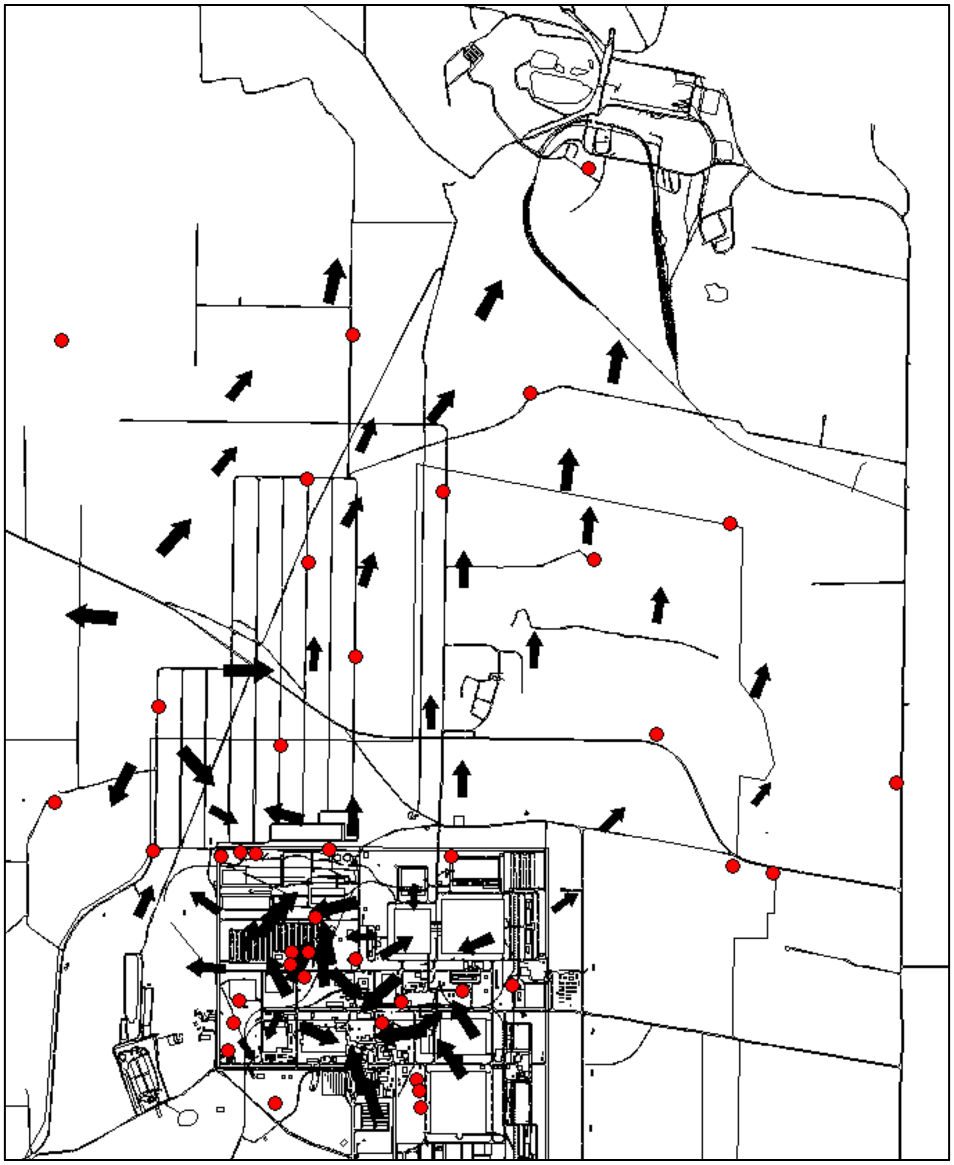
Figure 4.3. RGA Potentiometric Surfaces (Continued)

Monthly RGA Water Level Elevations



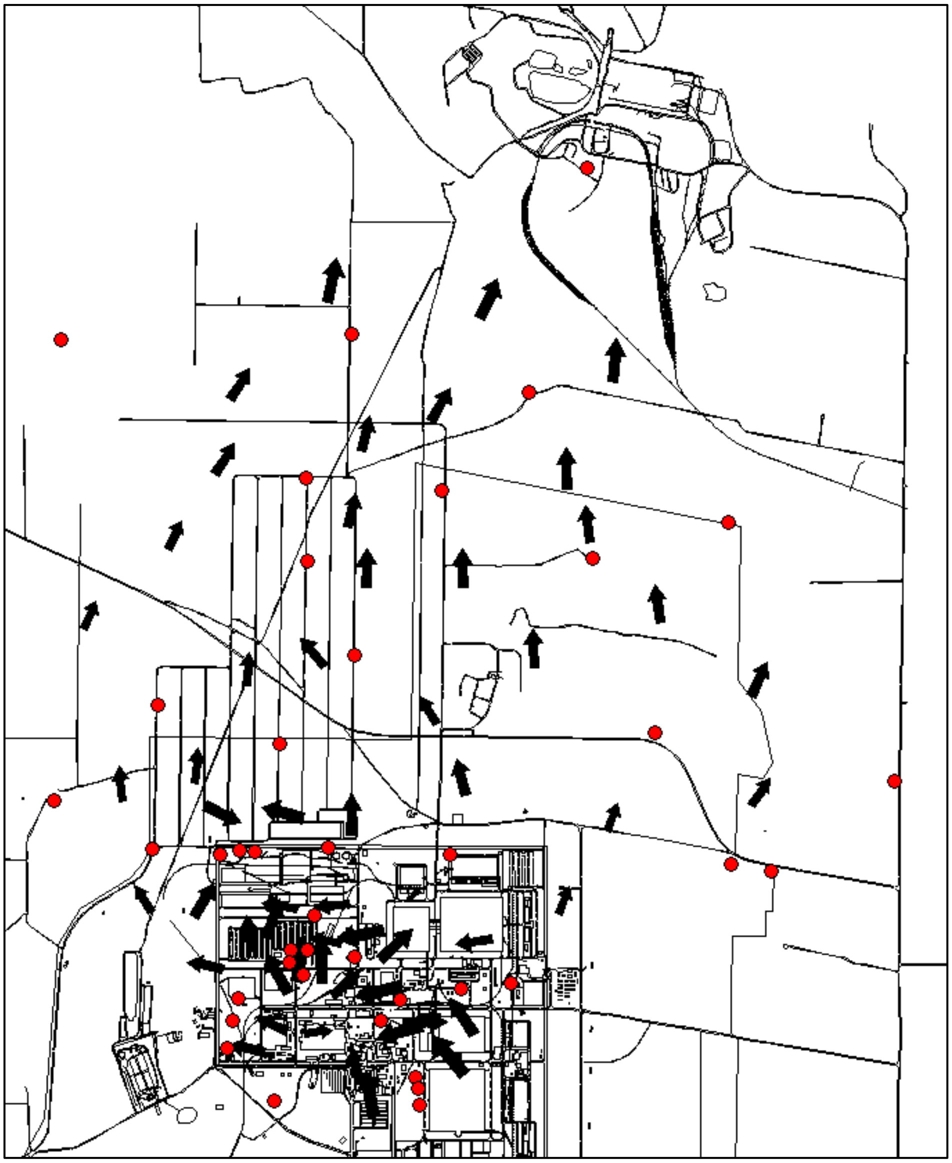
September 2006, Ohio River Stage = 293.8 ft

Figure 4.3. RGA Potentiometric Surfaces (Continued)



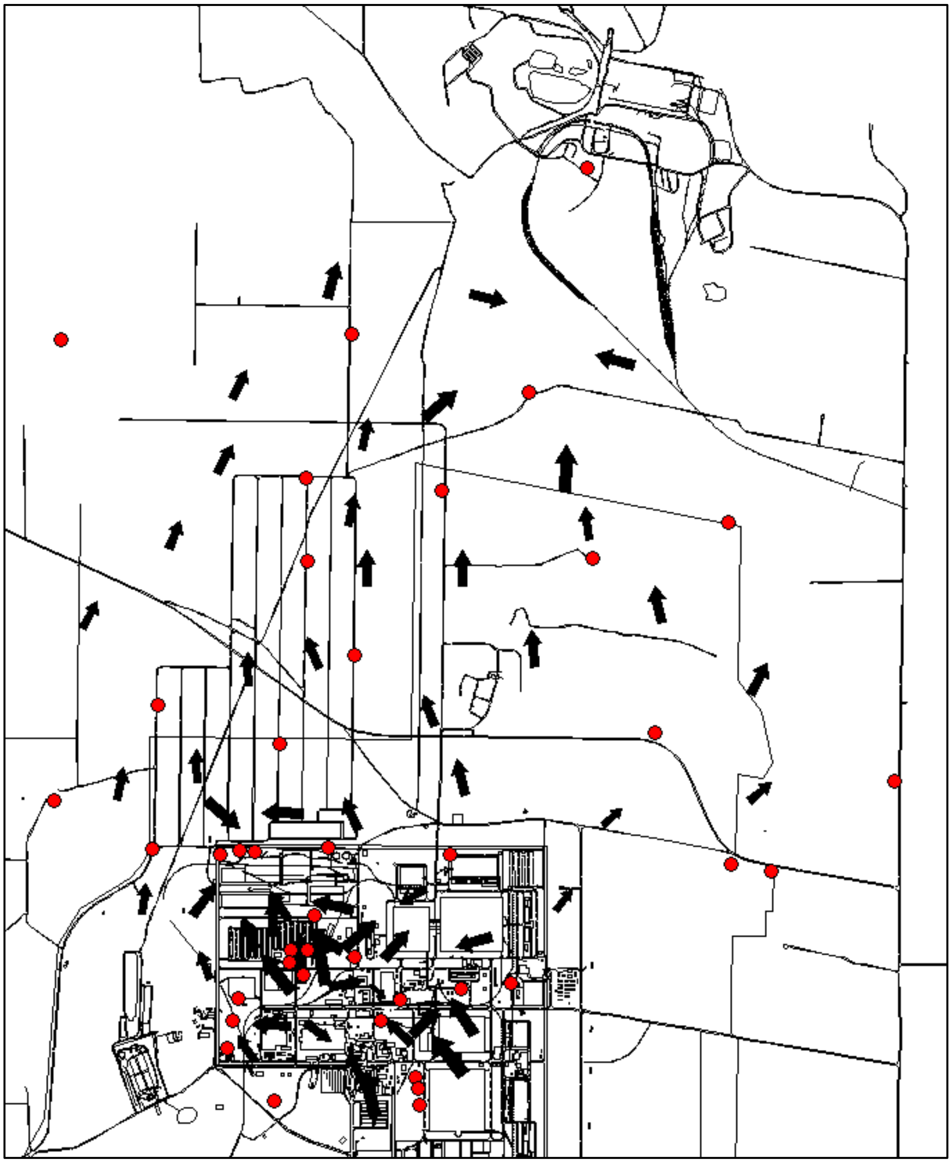
February 1995

Figure 4.4. RGA Three-Point Flow Directions



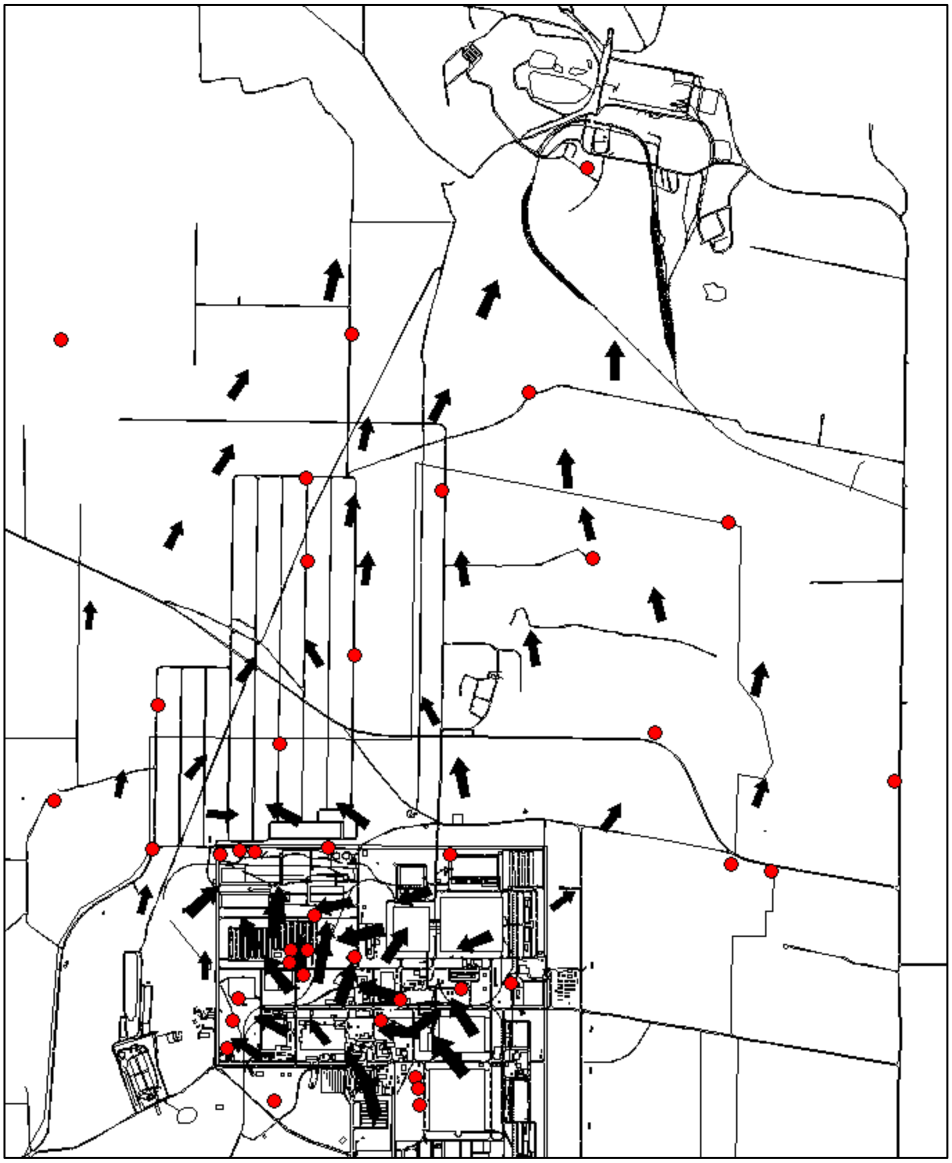
November 1995

Figure 4.4. RGA Three-Point Flow Directions (Continued)



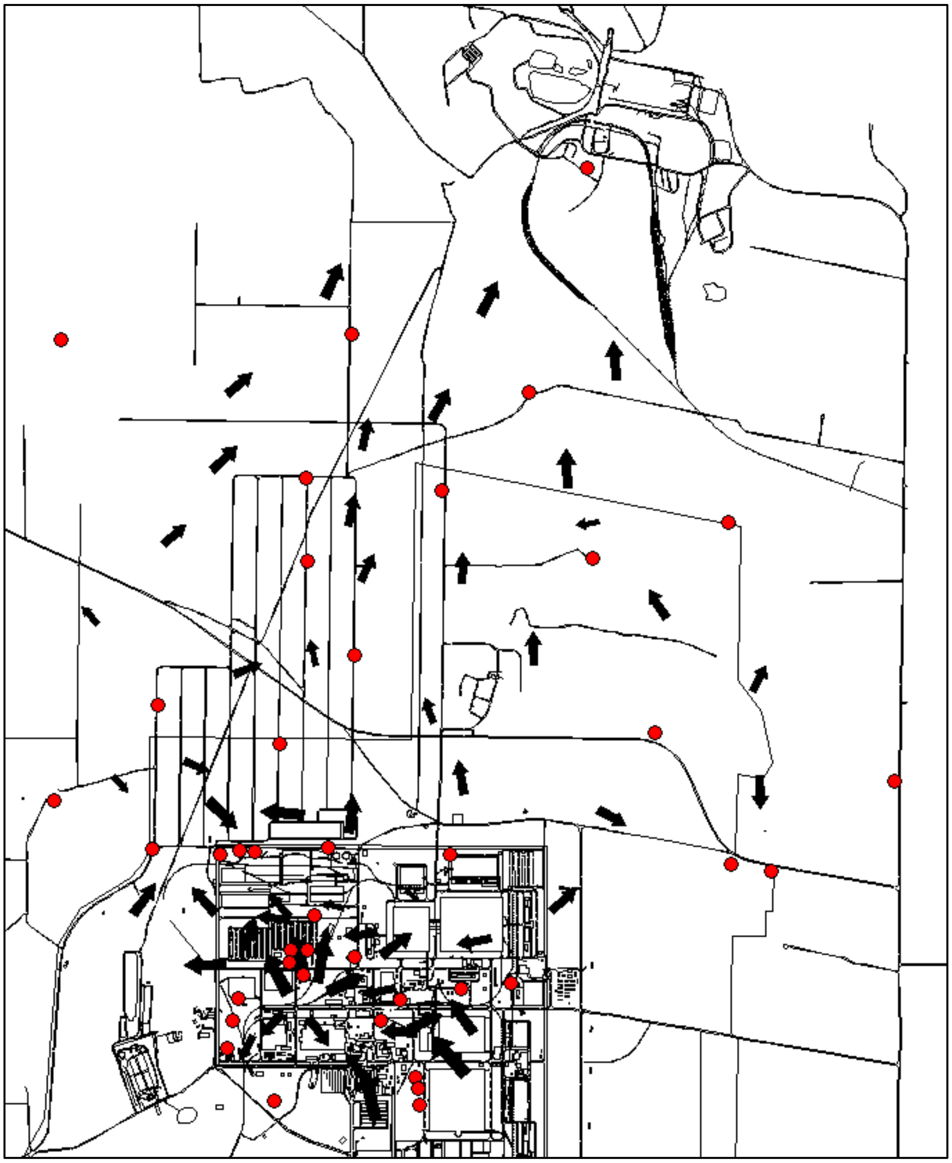
January 1996

Figure 4.4. RGA Three-Point Flow Directions (Continued)



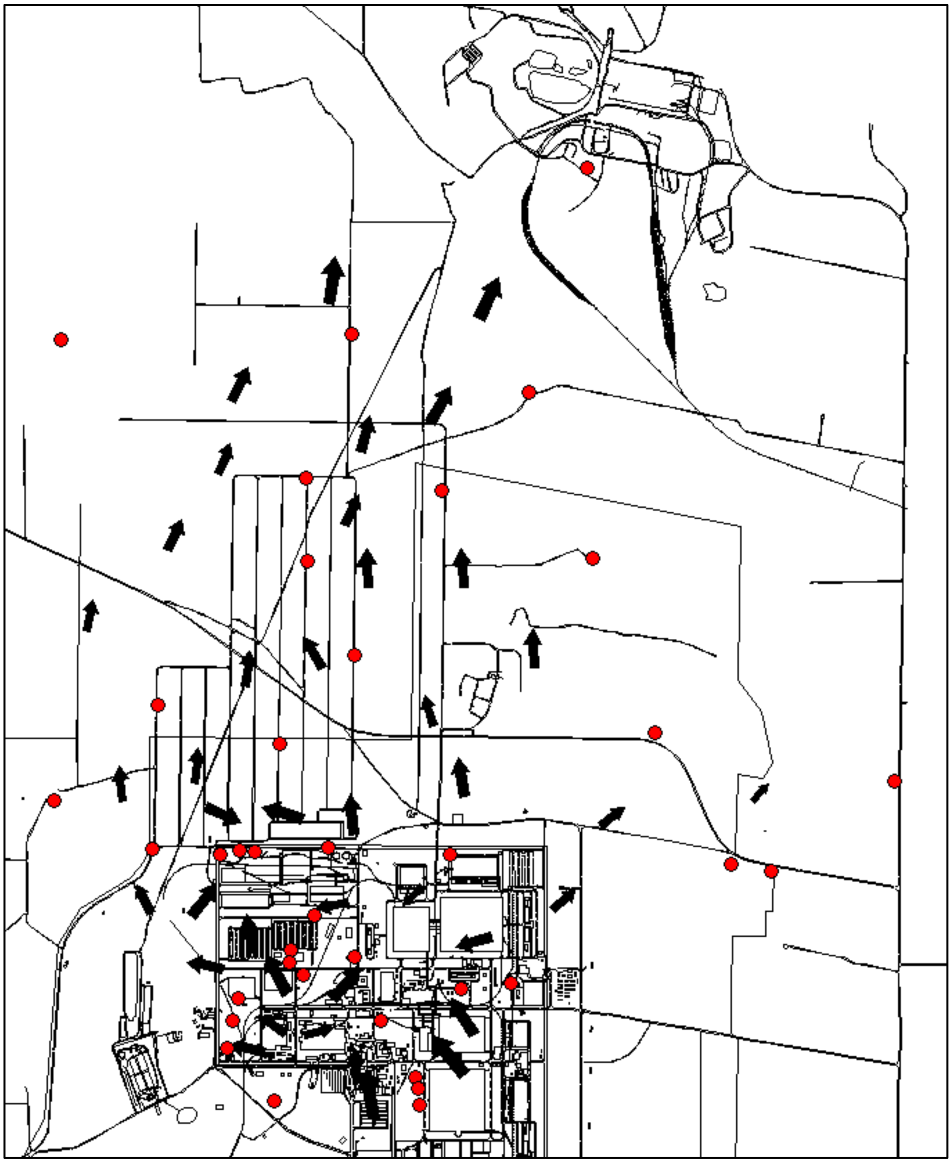
February 1996

Figure 4.4. RGA Three-Point Flow Directions (Continued)



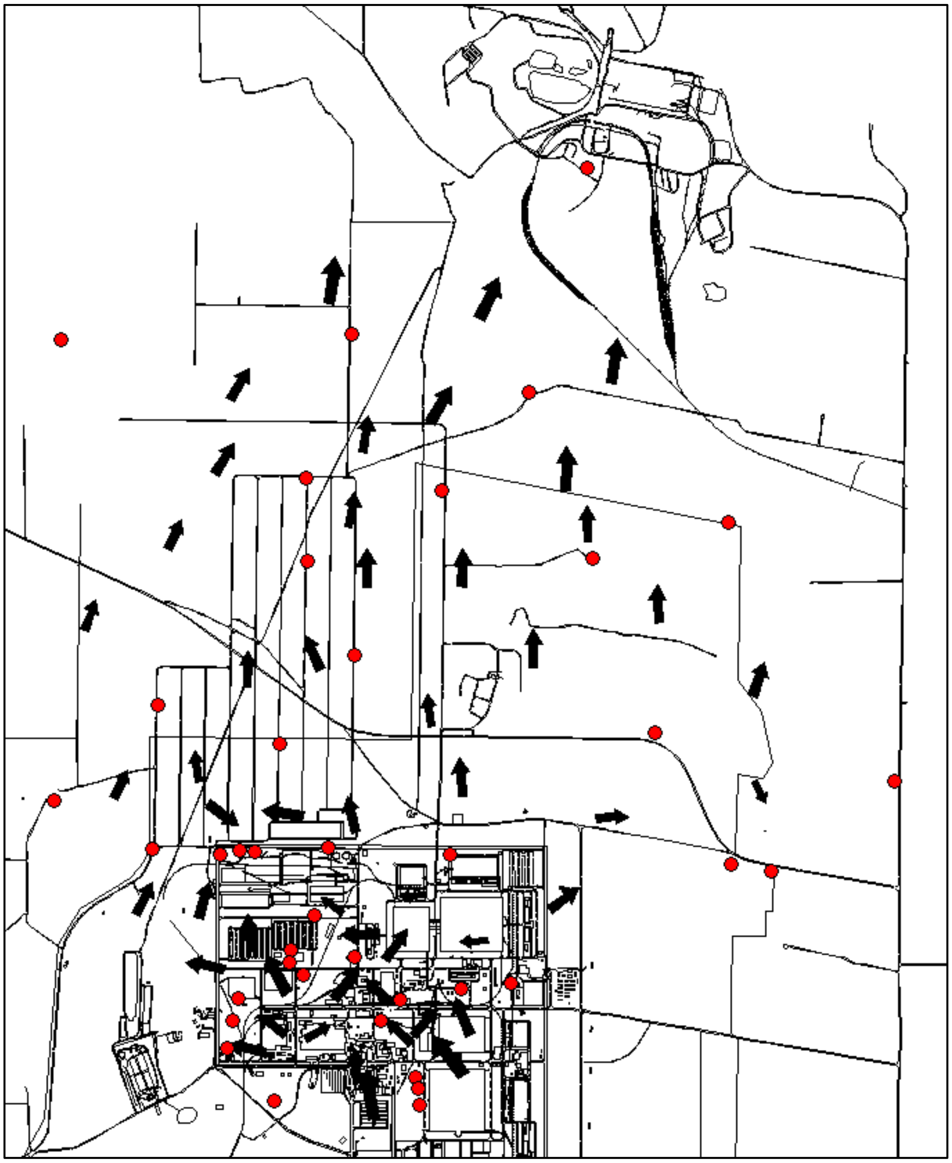
March 1996

Figure 4.4. RGA Three-Point Flow Directions (Continued)



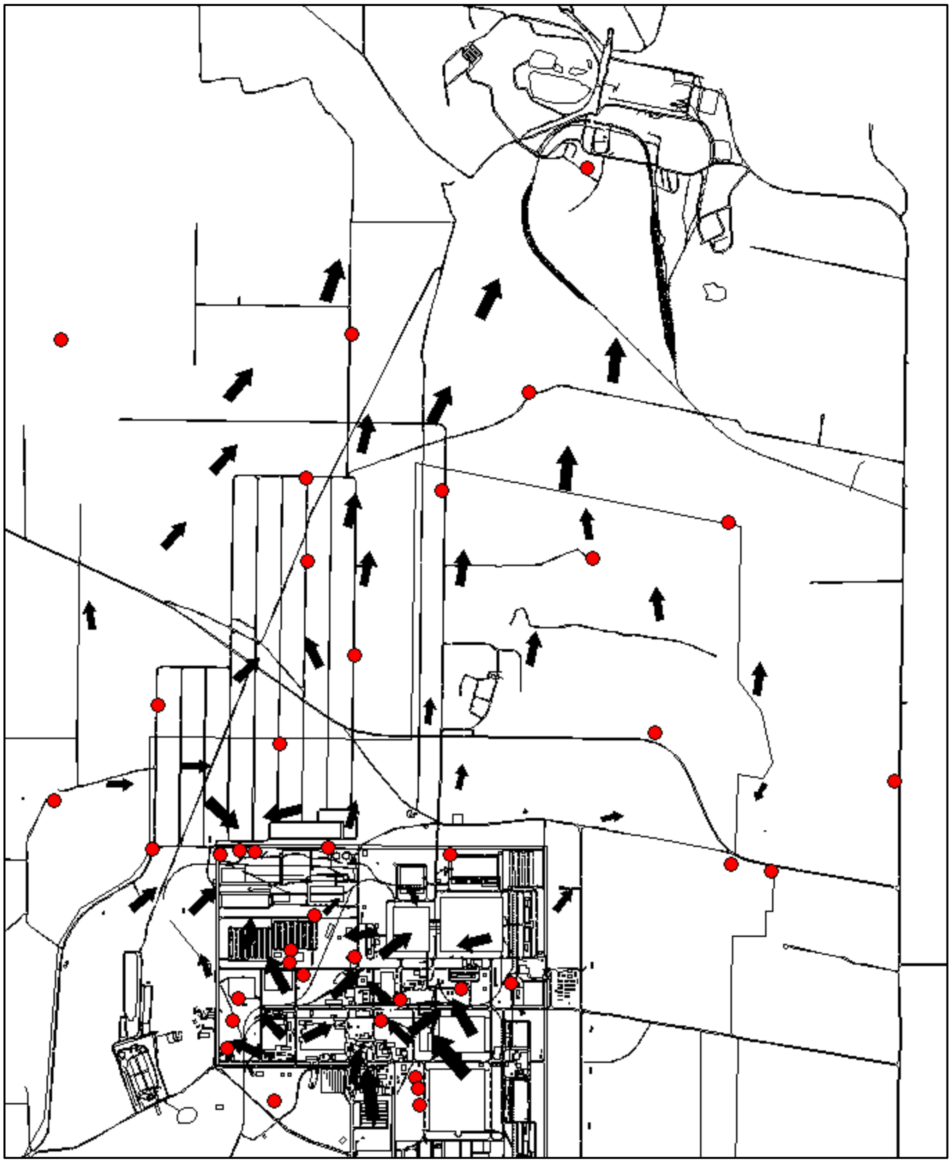
September 1997

Figure 4.4. RGA Three-Point Flow Directions (Continued)



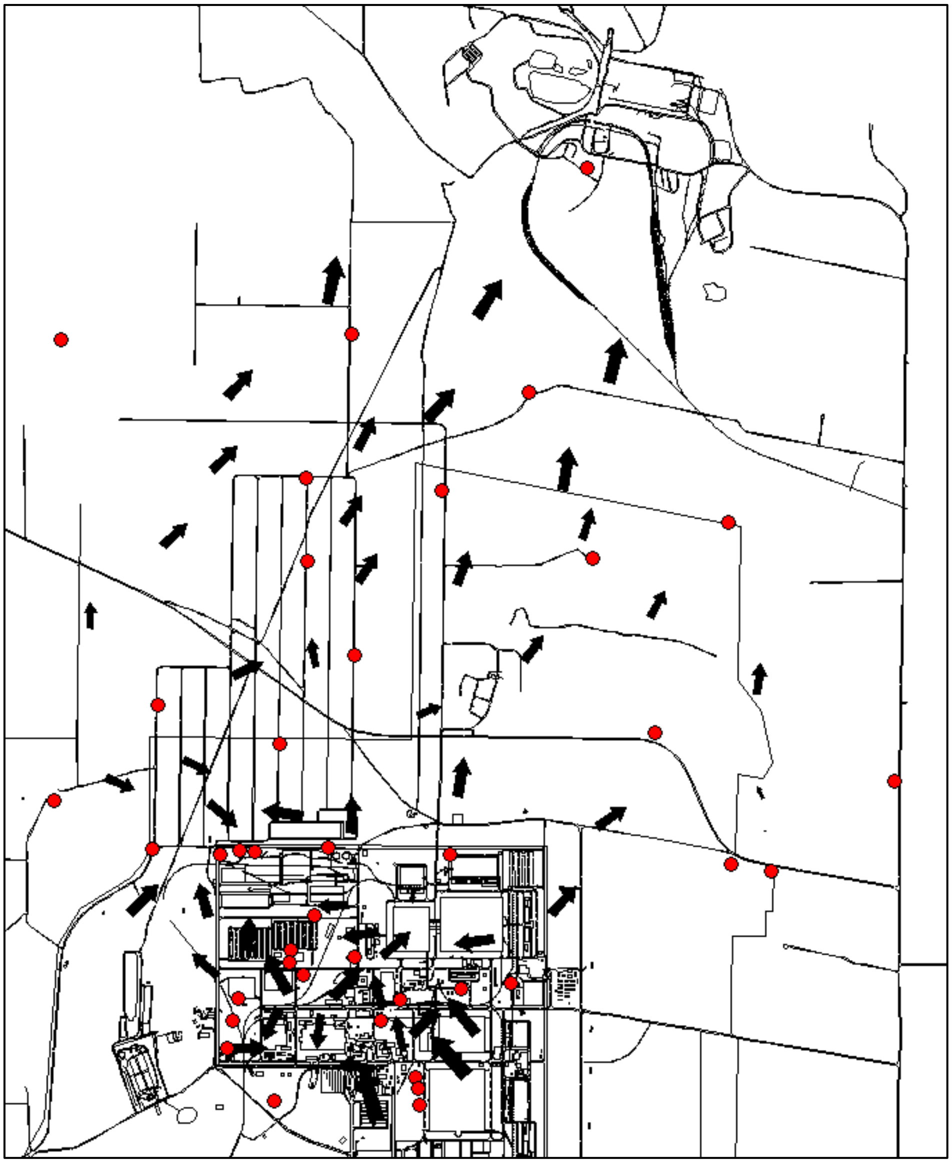
September 2002

Figure 4.4. RGA Three-Point Flow Directions (Continued)



July 2003

Figure 4.4. RGA Three-Point Flow Directions (Continued)



September 2006

Figure 4.4. RGA Three-Point Flow Directions (Continued)

Using an example of the V3PP code, consider three hypothetical wells. The first is located in a grassy area, the second adjacent to a leaky underground water line, and the third next to a drainage ditch. The well located in a grassy area has water levels that respond to rainfall events. The well located adjacent to the water line has water levels that are always elevated as a result of the leak, but also move up and down in response to rainfall events. Similar to the first two wells, the well located adjacent to the drainage ditch has water levels that respond to rainfall events; only the response is magnified because the ditch concentrates rainfall infiltration. Three point analysis conducted using water levels from these three wells would produce different flow directions depending on the proximity of the measurement period to a rainfall event. While this hypothetical scenario focused on water level perturbations resulting from rainfall, it is not hard to envision changes in plant activity influencing PGDP flow directions. For example, during hot weather, more water potentially could be run through the cooling towers relative to cold weather conditions resulting in more leakage during warm weather than cold weather. Additionally, the PGDP uses more water during the fall and winter when production is increased to take advantage of lower power rates, resulting in more potential leakage during that period. Thus, changes in flow directions at industrial facilities are to be expected.

4.3.3 Plume Paths

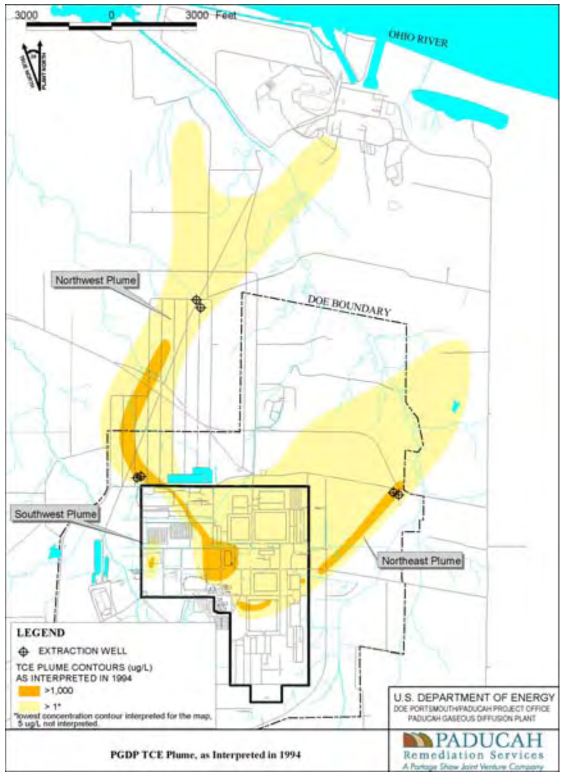
The ultimate arbitrator of groundwater flow directions is the contaminant plumes. While the three-point calculated flow vectors show the short-term variability in groundwater flow directions, plume orientation represents the long-term average flow directions. While the absolute concentrations (especially within the PGDP) within PGDP TCE plumes have changed with time, the plumes' location and extent have remained relatively constant with time (Figure 4.5). Based on consistent plume geometries (constructed using between 120 and 140 measurement locations), it appears that the long-term PGDP flow directions are relatively stable, suggesting that the groundwater flow system can be considered steady state.

4.4 HORIZONTAL AND VERTICAL HYDRAULIC GRADIENTS

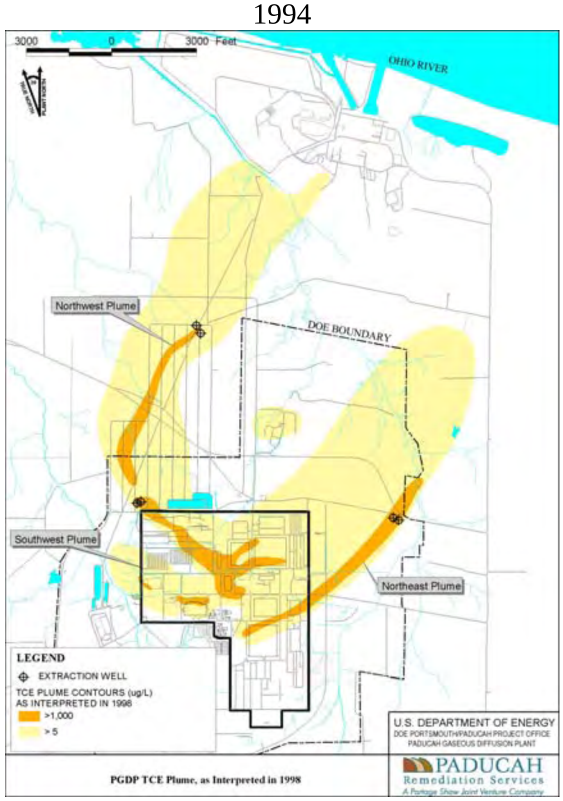
Hydraulic gradients provide an indication of the potential for flow in the horizontal and vertical directions. Horizontal gradients were calculated for the RGA and McNairy and were coupled with bulk hydraulic conductivity and aquifer geometries to estimate potential groundwater through flow volumes (Section 4.10). Vertical hydraulic gradients were calculated between the UCRS and RGA and between the RGA and McNairy to evaluate the potential for flow between the hydrostratigraphic units.

4.4.1 RGA Horizontal Hydraulic Gradients

In addition to determining flow directions, V3PP calculates horizontal hydraulic gradients based on the water levels at the triangle vertices (Table 4.4). Based on the average horizontal hydraulic gradient calculated for the nine measurement periods for each triangle, RGA horizontal hydraulic gradients range between 1.84×10^{-4} and 2.98×10^{-3} ft/ft and have average and median values of 7.81×10^{-4} and 4.4×10^{-4} ft/ft, respectively. Because of the inclusion in the data set of some localized relatively high horizontal hydraulic gradients associated with PGDP anthropogenic influences, the median horizontal hydraulic gradient is thought to be more representative than the average horizontal hydraulic gradient. In layman's terms, based on the median horizontal hydraulic gradient, RGA water levels decline approximately 0.5 ft for every 1,000 ft traveled in the direction of the Ohio River.

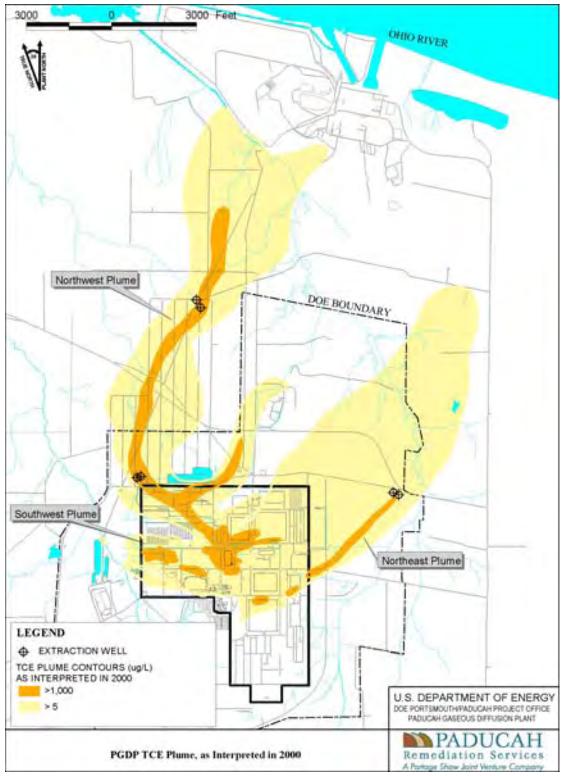


1994

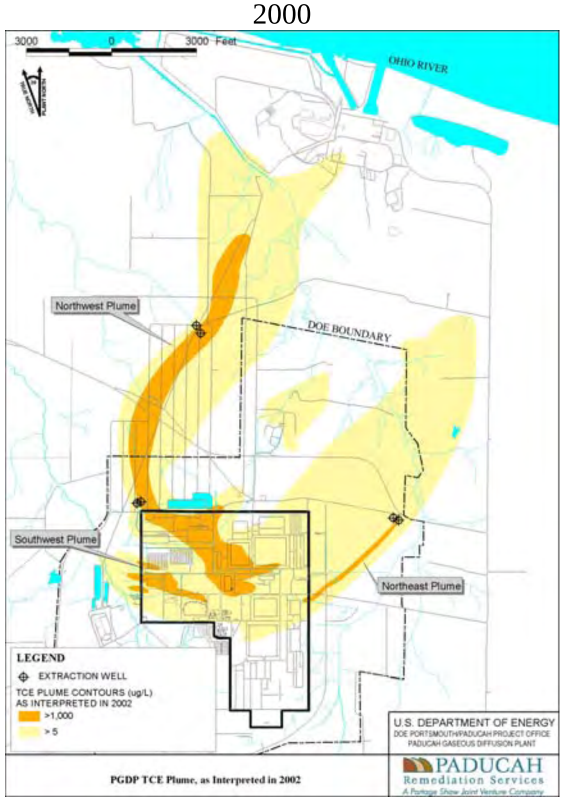


1998

Figure 4.5. TCE Temporal Plume Configuration

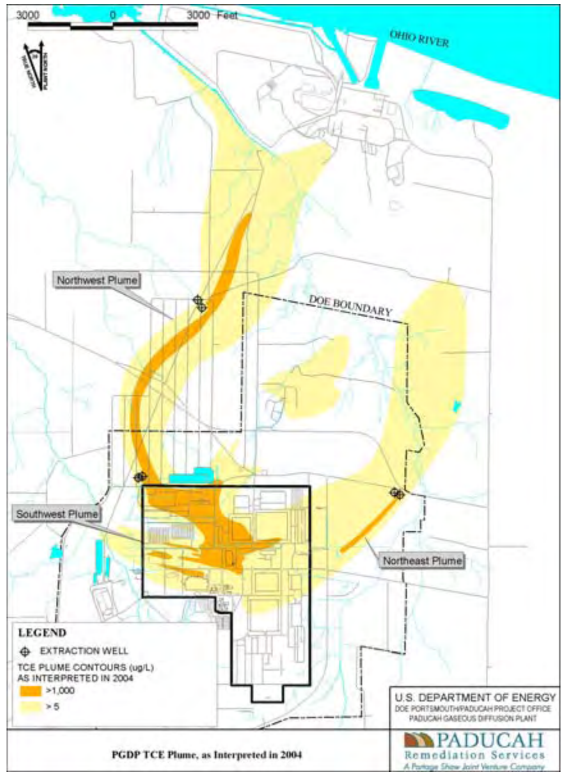


2000

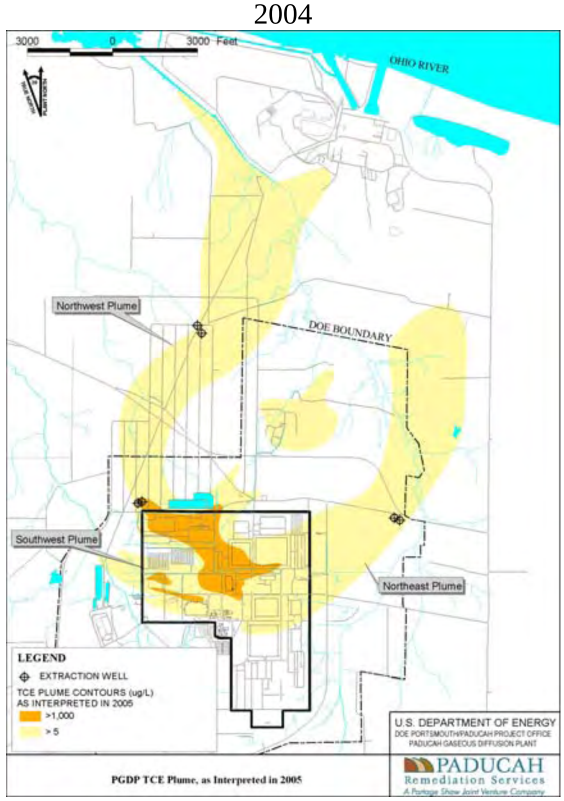


2002

Figure 4.5. TCE Temporal Plume Configuration (Continued)



2004



2005

Figure 4.5. TCE Temporal Plume Configuration (Continued)

Table 4.4. RGA Horizontal Hydraulic Gradients

Triangle	Well1	Well2	Well3	Feb-95	Nov-95	Jan-96	Feb-96	Mar-96	Sep-97	Sep-03	Jun-03	Sep-06	Average	STD	Max	Min	Range
35	PZ117	MW71	MW156	3.62E-03	2.04E-03	4.40E-04	9.78E-04	6.06E-04		4.40E-04	3.52E-04	3.57E-04	1.10E-03	1.16E-03	3.62E-03	3.52E-04	3.27E-03
33	MW163	PZ107	PZ117	1.58E-03	2.58E-03	2.56E-03	2.81E-03	3.11E-03	2.81E-03	3.00E-03	4.01E-03	4.34E-03	2.98E-03	8.14E-04	4.34E-03	1.58E-03	2.77E-03
39	MW168	MW71	MW156	2.77E-03	2.09E-03	8.98E-05	1.40E-03	4.82E-04		5.39E-04	2.69E-04	4.06E-04	1.01E-03	9.77E-04	2.77E-03	8.98E-05	2.68E-03
15	MW134	MW199	MW194	2.77E-03	3.04E-04	2.92E-04	2.19E-04	1.34E-04	3.46E-04	3.52E-04	2.09E-04	1.70E-04	5.33E-04	8.43E-04	2.77E-03	1.34E-04	2.64E-03
13	MW197	MW106	MW134	2.53E-03	4.67E-04	3.51E-04	2.42E-04	2.20E-04	4.67E-04	3.14E-04	1.82E-04	2.67E-04	5.60E-04	7.47E-04	2.53E-03	1.82E-04	2.35E-03
34	PZ107	MW103	PZ117	1.43E-03	2.22E-03	2.22E-03	2.44E-03	2.63E-03	2.42E-03	2.62E-03	3.43E-03	3.66E-03	2.56E-03	6.63E-04	3.66E-03	1.43E-03	2.23E-03
37	MW156	MW168	MW173	2.63E-04	1.95E-03	9.93E-04	2.36E-03	4.29E-04		7.88E-04	4.29E-04	5.97E-04	9.76E-04	7.70E-04	2.36E-03	2.63E-04	2.10E-03
12	MW197	MW134	MW123	2.31E-03	3.95E-04	3.71E-04	2.74E-04	2.89E-04		4.88E-04	3.78E-04	3.68E-04	6.09E-04	6.89E-04	2.31E-03	2.74E-04	2.03E-03
38	MW168	MW169	MW173	2.13E-03	4.73E-04	1.03E-03	7.36E-04	1.14E-04	3.68E-04	1.94E-03	9.55E-05	2.91E-04	6.03E-04	6.47E-04	2.13E-03	9.55E-05	2.03E-03
14	MW106	MW194	MW134	2.00E-03	4.71E-04	3.52E-04	1.96E-04	1.10E-04	4.71E-04	3.40E-04	1.69E-04	3.09E-04	4.91E-04	5.80E-04	2.00E-03	1.10E-04	1.89E-03
5	MW152	MW201	MW199	1.53E-03	1.51E-03	5.66E-04	9.54E-04	6.90E-04	2.02E-03	2.03E-03	1.35E-03	1.94E-03	1.40E-03	5.59E-04	2.03E-03	5.66E-04	1.46E-03
10	MW123	MW134	MW199	1.68E-03	3.16E-04	2.64E-04	2.84E-04	2.71E-04		3.74E-04	3.80E-04	3.51E-04	4.90E-04	4.84E-04	1.68E-03	2.64E-04	1.42E-03
44	MW90	MW169	MW63	1.57E-03	5.40E-04	4.40E-04	6.64E-04	2.60E-04					6.94E-04	5.10E-04	1.57E-03	2.60E-04	1.31E-03
48	MW84	MW161	MW226	1.21E-03	1.62E-03	2.25E-03	1.42E-03	1.82E-03	1.61E-03	1.61E-03	1.01E-03	1.62E-03	1.57E-03	3.54E-04	2.25E-03	1.01E-03	1.25E-03
42	MW168	MW169	MW90	1.39E-03	3.49E-04	8.89E-04	6.43E-04	1.61E-04					6.86E-04	4.81E-04	1.39E-03	1.61E-04	1.23E-03
36	MW71	PZ117	MW103	1.57E-03	5.33E-04	4.26E-04	5.96E-04	3.41E-04	4.74E-04	4.74E-04	4.57E-04	4.75E-04	5.94E-04	3.71E-04	1.57E-03	3.41E-04	1.23E-03
47	MW84	MW90	MW63	1.40E-03	9.52E-04	5.87E-04	7.05E-04	3.37E-04					7.95E-04	4.02E-04	1.40E-03	3.37E-04	1.06E-03
43	MW90	MW168	MW226	2.09E-03	2.07E-03	2.62E-03	1.58E-03	1.81E-03					2.03E-03	3.88E-04	2.62E-03	1.58E-03	1.04E-03
1	MW152	MW201	MW137	1.24E-03	1.26E-03	6.66E-04	8.13E-04	6.75E-04	1.58E-03	1.59E-03	1.26E-03	1.52E-03	1.18E-03	3.73E-04	1.59E-03	6.66E-04	9.23E-04
6	MW99	MW98	MW137	1.01E-03	9.93E-04	1.64E-03	7.35E-04	7.18E-04					1.02E-03	3.73E-04	1.64E-03	7.18E-04	9.20E-04
46	MW226	MW84	MW90	2.15E-03	2.03E-03	2.51E-03	1.60E-03	1.91E-03					2.04E-03	3.35E-04	2.51E-03	1.60E-03	9.14E-04
2	MW152	MW99	MW137	1.19E-03	1.25E-03	8.59E-04	8.26E-04	6.94E-04		1.56E-03	1.26E-03	1.43E-03	1.13E-03	3.09E-04	1.56E-03	6.94E-04	8.68E-04
52	MW327	MW106	MW161	7.73E-04	5.43E-04	2.64E-04	2.24E-04	9.64E-04	5.92E-04	7.40E-04	1.32E-04	4.50E-04	5.20E-04	2.79E-04	9.64E-04	1.32E-04	8.33E-04
41	MW226	MW71	MW103	1.07E-03	2.43E-04	3.14E-04	2.68E-04	4.70E-04	2.74E-04	2.57E-04	3.46E-04	4.35E-04	4.08E-04	2.60E-04	1.07E-03	2.43E-04	8.27E-04
51	MW161	MW327	MW103	1.59E-04	5.88E-04	3.18E-04	5.68E-04	2.28E-04	5.88E-04	6.86E-04	5.19E-04	9.70E-04	5.14E-04	2.49E-04	9.70E-04	1.59E-04	8.11E-04
26	MW173	MW165	MW197	6.70E-04	9.81E-04	4.90E-04	6.11E-04	6.97E-04	8.30E-04	5.99E-04	1.98E-04	6.14E-04	6.32E-04	2.17E-04	9.81E-04	1.98E-04	7.83E-04
31	MW156	MW173	MW206	6.80E-04	1.38E-03	6.78E-04	8.99E-04	6.04E-04		6.18E-04	6.94E-04	6.21E-04	7.72E-04	2.64E-04	1.38E-03	6.04E-04	7.80E-04
24	MW106	MW66	MW197	2.95E-04	8.59E-04	1.07E-03	3.19E-04	8.80E-04	7.68E-04	7.13E-04	1.04E-03	5.84E-04	7.25E-04	2.81E-04	1.07E-03	2.95E-04	7.76E-04
54	MW201	MW137	MW98	8.13E-04	7.42E-04	1.29E-03	5.27E-04	5.21E-04		9.96E-04	1.01E-03	1.02E-03	8.65E-04	2.66E-04	1.29E-03	5.21E-04	7.70E-04
40	MW71	MW168	MW226	1.08E-03	6.74E-04	4.17E-04	1.17E-03	8.32E-04	1.07E-03	9.75E-04	6.74E-04	9.34E-04	8.69E-04	2.43E-04	1.17E-03	4.17E-04	7.53E-04
23	MW165	MW193	MW197	5.84E-04	7.06E-04	5.70E-04	8.86E-04	4.53E-04	7.80E-04	7.15E-04	1.44E-04	7.66E-04	6.23E-04	2.22E-04	8.86E-04	1.44E-04	7.43E-04
53	MW327	MW106	MW194	4.67E-04	2.97E-04	2.96E-04	2.61E-04	5.87E-04	3.18E-04	5.84E-04	3.93E-04	9.69E-04	4.63E-04	2.26E-04	9.69E-04	2.61E-04	7.08E-04
25	MW66	MW173	MW197	8.68E-04	1.33E-03	1.08E-03	6.62E-04	1.21E-03	1.14E-03	1.03E-03	7.10E-04	9.63E-04	9.98E-04	2.22E-04	1.33E-03	6.62E-04	6.66E-04
32	PZ117	MW163	MW206	1.27E-03	1.21E-03	1.27E-03	1.27E-03	9.66E-04	1.27E-03	8.66E-04	1.15E-03	1.51E-03	1.20E-03	1.89E-04	1.51E-03	8.66E-04	6.47E-04
30	PZ117	MW206	MW156	6.91E-04	1.18E-03	6.48E-04	6.91E-04	5.57E-04		5.75E-04	6.91E-04	6.48E-04	7.10E-04	1.97E-04	1.18E-03	5.57E-04	6.22E-04
50	MW161	MW106	MW63	4.74E-04	7.40E-04	6.36E-04	9.57E-04	4.66E-04	1.05E-03	7.26E-04	5.08E-04	4.34E-04	6.65E-04	2.22E-04	1.05E-03	4.34E-04	6.13E-04
28	MW163	MW206	MW165	5.82E-04	5.63E-04	5.72E-04	5.82E-04	4.51E-04	5.72E-04	2.25E-04	4.55E-04	7.87E-04	5.32E-04	1.50E-04	7.87E-04	2.25E-04	5.62E-04
45	MW226	MW161	MW103	2.22E-04	4.44E-04	7.82E-04	6.10E-04	3.55E-04	3.90E-04	4.31E-04	3.93E-04	4.44E-04	4.52E-04	1.60E-04	7.82E-04	2.22E-04	5.60E-04
29	MW206	MW165	MW173	1.68E-04	6.72E-05	2.81E-04	5.64E-04	5.82E-05	2.02E-04	1.87E-04	8.99E-05	4.19E-05	1.84E-04	1.63E-04	5.64E-04	4.19E-05	5.22E-04
7	MW98	MW139	MW99	6.06E-04	5.90E-04	3.75E-04	3.77E-04	1.21E-04					4.14E-04	1.98E-04	6.06E-04	1.21E-04	4.85E-04
18	MW139	MW193	MW99	5.11E-04	7.38E-04	6.11E-04	4.85E-04	3.74E-04		6.27E-04	3.69E-04	2.81E-04	4.99E-04	1.54E-04	7.38E-04	2.81E-04	4.57E-04
27	MW165	MW163	MW126	2.48E-04	2.32E-04	1.92E-04	2.25E-04	4.14E-04	2.98E-04	4.29E-04	1.72E-04	6.17E-04	3.14E-04	1.45E-04	6.17E-04	1.72E-04	4.45E-04
11	MW123	MW200	MW197	3.66E-04	6.03E-04	4.27E-04	3.21E-04	1.64E-04		5.85E-04	3.73E-04	2.23E-04	3.83E-04	1.56E-04	6.03E-04	1.64E-04	4.40E-04
20	MW193	MW150	MW99	5.02E-04	6.55E-04	5.34E-04	4.01E-04	2.29E-04		5.77E-04	3.33E-04	2.83E-04	4.39E-04	1.51E-04	6.55E-04	2.29E-04	4.27E-04
16	MW98	MW200	MW123	4.55E-04	6.66E-04	4.75E-04	3.84E-04	2.70E-04	6.97E-04	6.49E-04	4.70E-04	4.22E-04	4.98E-04	1.43E-04	6.97E-04	2.70E-04	4.26E-04
19	MW193	MW139	MW200	4.85E-04	7.52E-04	6.21E-04	4.90E-04	3.79E-04	6.61E-04	6.46E-04	4.24E-04	3.28E-04	5.32E-04	1.44E-04	7.52E-04	3.28E-04	4.24E-04
49	MW84	MW63	MW161	3.51E-04	5.82E-04	4.85E-04	5.76E-04	4.38E-04	7.37E-04	6.59E-04	3.17E-04	4.34E-04	5.09E-04	1.40E-04	7.37E-04	3.17E-04	4.20E-04
4	MW201	MW199	MW202	5.57E-04	5.44E-04	3.44E-04	3.86E-04	3.98E-04	6.80E-04	6.15E-04	7.60E-04	6.18E-04	5.45E-04	1.42E-04	7.60E-04	3.44E-04	4.16E-04
17	MW139	MW200	MW98	5.06E-04	6.90E-04	4.78E-04	4.43E-04	2.95E-04	7.08E-04	6.32E-04	4.79E-04	4.24E-04	5.17E-04	1.35E-04	7.08E-04	2.95E-04	4.13E-04
22	MW126	MW165	MW193	2.92E-04	2.39E-04	1.69E-04	3.39E-04	3.40E-04	2.85E-04	3.41E-04	1.01E-04	4.96E-04	2.89E-04	1.13E-04	4.96E-04	1.01E-04	3.94E-04
3	MW201	MW202	MW98	5.26E-04	5.24E-04	3.38E-04	3.76E-04	3.38E-04	6.73E-04	6.04E-04	7.13E-04	5.67E-04	5.17E-04	1.40E-04	7.13E-04	3.38E-04	3.76E-04
21	MW150	MW126	MW193	2.03E-04	3.78E-04	2.51E-04	2.44E-04	3.42E-04	1.31E-04	1.48E-04	7.37E-05	3.71E-05	2.01E-04	1.15E-04	3.78E-04	3.71E-05	3.40E-04
55	MW200	MW197	MW193	3.90E-04	3.23E-04	3.87E-04	2.85E-04	1.93E-04		3.68E-04	1.71E-04	1.61E-04	2.85E-04	9.75E-05	3.90E-04	1.61E-04	2.29E-04
9	MW123	MW202	MW199	4.44E-04	5.71E-04	3.90E-04	4.02E-04	4.92E-04					4.60E-04	7.38E-05	5.71E-04	3.90E-04	1.81E-04
8	MW98	MW123	MW202	3.92E-04	4.89E-04	3.45E-04	3.45E-04	3.45E-04					3.83E-04	6.27E-05	4.89E-04	3.45E-04	1.44E-04

4.4.2 McNairy Horizontal Hydraulic Gradients

V3PP also was used to calculate flow directions and horizontal hydraulic gradients in the McNairy (Table 4.5). Based on the average horizontal hydraulic gradient calculated for the nine measurement periods for each triangle, McNairy horizontal hydraulic gradients range between 2.33×10^{-4} and 7.49×10-^{4} ft/ft and average 5.15×10^{-4} ft/ft. The calculated McNairy average horizontal hydraulic gradient (5.15×10^{-4} ft/ft) is very similar to that calculated median RGA horizontal hydraulic gradient (4.40×10^{-4} ft/ft). In general, water levels in the McNairy decline approximately 0.5 ft for every 1,000 ft traveled in the direction of the Ohio River.

4.4.3 UCRS/RGA Vertical Hydraulic Gradients

Vertical hydraulic gradient calculations were performed using UCRS and RGA well pairs (Table 4.6). Review of the water level records show that water levels are rarely measured in both the UCRS and RGA well pairs at the same time. Based on a limited number of water level measurements, the average UCRS/RGA vertical hydraulic gradient is 0.53 ft/ft downward. Generally, groundwater levels decline on average approximately 0.5 ft for every 1 ft distance below the water table. The strong vertical gradient indicates that groundwater flow in the UCRS is primarily downward. In essence, the UCRS acts as a transmitter and conveys recharge vertically, straight down from the water table to the RGA.

4.4.4 RGA/McNairy Vertical Hydraulic Gradients

Vertical hydraulic gradient calculations were performed using RGA and McNairy well pairs (Table 4.7). RGA/McNairy vertical hydraulic gradients average 0.0073 ft/ft downward, which is considerable less than the average UCRS/RGA vertical hydraulic gradient of 0.53 ft/ft downward. The large difference in vertical hydraulic gradients suggests that the potential for groundwater to move between the RGA and McNairy is much less than the potential for groundwater to move between the UCRS and RGA.

Table 4.5. McNairy Horizontal Hydraulic Gradients

Name	Well1	Well2	Well3	Feb-95	Nov-95	Jan-96	Mar-96	Sep-02	Jun-03	Sep-06	Average	STD	Max	Min	Range
3	PZ115	MW133	MW121	7.19E-04	5.39E-04	4.31E-04	2.91E-04	9.21E-04	5.42E-04	5.36E-04	5.68E-04	2.02E-04	9.21E-04	2.91E-04	6.30E-04
2	PZ115	MW121	MW102	4.24E-04	5.49E-04	3.06E-04	2.69E-04	8.38E-04	6.04E-04	5.65E-04	5.08E-04	1.95E-04	8.38E-04	2.69E-04	5.69E-04
4	MW120	PZ115	MW133	8.65E-04	9.39E-04	5.37E-04	4.51E-04	7.85E-04	9.43E-04	7.26E-04	7.49E-04	1.93E-04	9.43E-04	4.51E-04	4.92E-04
1	PZ115	MW120	MW102	7.92E-05	2.32E-04	4.39E-05	5.80E-05	3.14E-04	4.88E-04	4.15E-04	2.33E-04	1.80E-04	4.88E-04	4.39E-05	4.45E-04

Table 4.6. UCRS/RGA Vertical Hydraulic Gradients

UCRS Well	RGA Well	Average Vertical Gradient, ft/ft	# Measurements
MW174	MW173	1.23	10
MW246	MW249	0.60	8
MW187	MW185	0.88	6
MW166	MW165	0.61	4
MW192	MW191	0.05	3
MW162	MW161	0.57	2
MW164	MW163	0.22	2
MW167	MW168	1.02	2
MW170	MW169	0.94	2
MW177	MW178	0.25	2
MW189	MW188	0.60	2
MW315	MW330	0.68	2
MW316	MW227	0.70	2
MW64	MW63	1.09	2
MW88	MW89	0.63	2
MW91	MW92	0.70	2
MW138	MW137	0.36	1
MW143	MW142	0.23	1
MW153	MW152	0.00	1
MW157	MW156	0.62	1
MW180	MW179	0.45	1
MW182	MW181	0.77	1
MW204	MW203	0.29	1
MW359	MW358	0.28	1
MW362	MW361	0.42	1
MW365	MW363	0.12	1
MW368	MW366	0.14	1
MW371	MW370	0.45	1
MW374	MW373	0.24	1
MW386	MW385	0.00	1
MW393	MW391	0.58	1
MW396	MW395	1.10	1
PZ111	PZ110	0.80	1
Average		0.53	

Table 4.7. RGA/McNairy Vertical Hydraulic Gradients

McNairy Well	RGA Well	Average Vertical Gradient, ft/ft	# Measurements
121	123	0.0134	23
247	248	0.0016	19
102	103	0.0003	25
115	118	0.0139	25
Average		0.0073	

4.5 HYDRAULIC PROPERTIES

Hydraulic conductivity is a measure of the porous media's resistance to groundwater flow. Hydraulic conductivity of the three PGDP hydrostratigraphic units has been measured via pumping, slug, and laboratory permeameter test. The following is a summary of those results.

4.5.1 UCRS Hydraulic Properties

Slug testing has been used to measure hydraulic conductivity in 20 UCRS monitoring wells (Table 4.8). Testing was conducted in some of the wells more than once. Based on the slug test results, UCRS horizontal hydraulic conductivity is quite variable and ranges between 2.9×10^{-5} and 1.96 ft/day, with an average value of 0.28 ft/day.

Laboratory permeameter tests were conducted on soil cores collected from the UCRS (Table 4.8). Permeameter tests measure vertical hydraulic conductivity. Similar to the slug tests results, permeameter results suggest UCRS vertical hydraulic conductivity is quite variable and ranges between 3.34×10^{-4} and 1.50×10^{-1} ft/day, with an average value of 2.62×10^{-2} ft/day. Comparison of the average UCRS horizontal and vertical hydraulic conductivities suggests an anisotropy ratio (K_x/K_z) of approximately 10:1.

Table 4.8. UCRS Hydraulic Conductivities

Slug Tests

Well ID	Hyd. Cond. (cm/sec)	Hyd. Cond. (ft/d)
MW64	3.56E-07	1.01E-03
MW82	1.08E-06	3.06E-03
MW83	2.22E-06	6.29E-03
MW127	2.11E-07	5.98E-04
MW128	7.22E-07	2.05E-03
MW131	5.90E-05	1.67E-01
MW131	5.20E-05	1.47E-01
MW157	2.47E-05	7.00E-02
MW160	5.41E-06	1.53E-02
MW160	8.45E-05	2.40E-01
MW162	4.30E-05	1.22E-01
MW162	2.86E-05	8.11E-02
MW164	6.54E-04	1.85E+00
MW166	1.02E-08	2.89E-05
MW167	3.65E-05	1.03E-01
MW167	3.64E-05	1.03E-01
MW170	1.63E-07	4.62E-04
MW170	9.93E-05	2.81E-01
MW177	2.81E-04	7.97E-01
MW189	4.27E-05	1.21E-01
MW189	4.27E-05	1.21E-01
MW190	1.16E-05	3.29E-02
MW190	1.24E-05	3.51E-02
MW192	1.95E-05	5.53E-02
MW192	3.75E-05	1.06E-01
MW195	6.31E-04	1.79E+00
MW195	6.93E-04	1.96E+00
MW198	7.45E-07	2.11E-03
MW204	3.01E-05	8.53E-02
MW204	3.78E-05	1.07E-01
Average	9.89E-05	2.80E-01

Permeameter Tests

Soil Boring	Hyd. Cond. (cm/sec)	Hyd. Cond. (ft/d)
GB-04S	1.18E-07	3.34E-04
GB-06S	1.55E-05	4.39E-02
GB-09S	9.88E-08	2.80E-04
GB-12S	2.13E-07	6.04E-04
GB-14S	1.19E-05	3.37E-02
GB-16S	2.08E-06	5.90E-03
GB-20S	5.30E-05	1.50E-01
GB-21S	1.66E-07	4.71E-04
GB-25S	2.26E-07	6.41E-04
Average	9.26E-06	2.62E-02

4.5.2 RGA Hydraulic Properties

Six RGA pumping tests have been conducted and have produced hydraulic conductivity estimates ranging between approximately 100 and 3,600 ft/day (Figure 4.6) (CH2M HILL 1992; LMES 1996a and 1996b; LMES 1997; Terran 1990; Terran 1992). The lowest measured RGA hydraulic conductivity is beneath PGDP. The highest measured value is between PGDP and the Ohio River. It is reasonable to assume that RGA horizontal hydraulic conductivities exist that are lower and higher than those measured. Thus it was assumed that RGA hydraulic conductivity ranges between 50 and 5,000 ft/day.

Alternatively, the bulk RGA hydraulic conductivity can be estimated by assuming all recharge from all sources reaches the RGA (Section 4.10). Using Darcy's Law with equation inputs for discharge, hydraulic gradient, RGA aquifer thickness, and Ohio River length of between 313,210 and 906,411 ft^3/day, 4.4×10^{-4} ft/ft, 35 ft, and 28,535 ft, respectively, yields hydraulic conductivity estimates between 713 and 2,063 ft/day.

RGA vertical hydraulic conductivity has never been measured, but is assumed to be one-tenth of horizontal hydraulic conductivity, a similar ratio as observed in the UCRS.

RGA porosity is assumed to be 0.30.

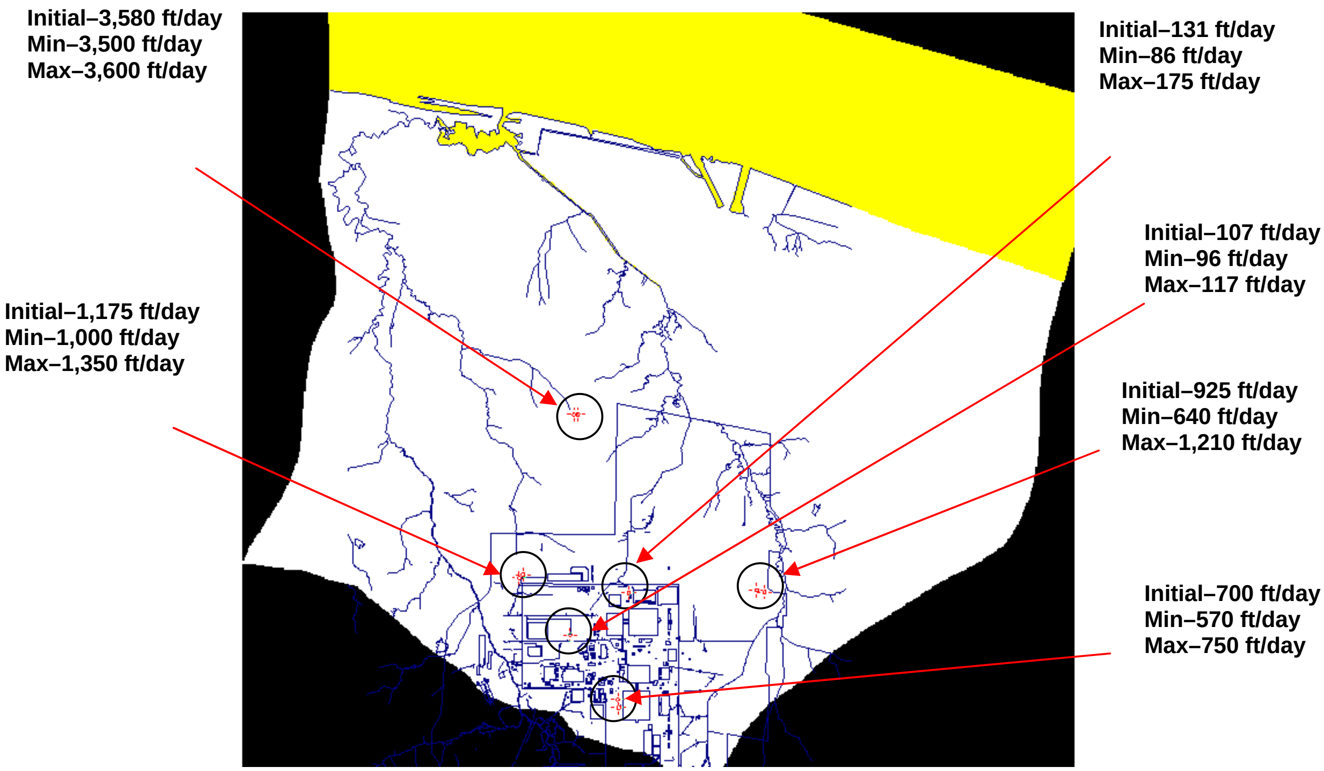


Figure 4.6. RGA Pumping Test Locations and Results

4.5.3 McNairy Hydraulic Conductivity

Slug testing has been used to measure hydraulic conductivity in three McNairy monitoring wells (Table 4.9) (CH2M HILL 1991). Based on limited slug test results, McNairy horizontal hydraulic conductivity ranges between 0.08 and 0.55 ft/day, with an average value of 0.30 ft/day. (NOTE: the measurements are at least three orders of magnitude less than the RGA hydraulic conductivity measurements.)

Laboratory permeameter tests were conducted on cores collected from the McNairy (Table 4.9) (LMES 1996c). Permeameter test measure vertical hydraulic conductivity. The results suggest McNairy vertical hydraulic conductivity is potentially quite variable and ranges between 7.80×10^{-4} and 1.34×10^{-1} ft/day, with an average value of 1.77×10^{-2} ft/day. Comparison of the average McNairy horizontal and vertical hydraulic conductivities suggests an anisotropy ratio (K_x/K_z) of approximately 17:1.

Table 4.9. McNairy Hydraulic Conductivities

Slug Tests			Permeameter Tests		
Well ID	**Hydraulic Conductivity (cm/s)**	**Hydraulic Conductivity (ft/d)**	**Soil Boring**	**Hydraulic Conductivity (cm/s)**	**Hydraulic Conductivity (ft/d)**
MW120	1.93e-4	5.47e-1	GB-01D	2.75e-7	7.80e-4
MW120	1.84e-4	5.22e-1	GB-01D	3.67e-7	1.04e-3
MW121	3.41e-5	9.67e-2	GB-02D	4.09e-8	1.16e-4
MW121	2.88e-5	8.16e-2	GB-02D	7.25e-8	2.06e-4
MW122	9.60e-5	2.72e-1	GB-03D	4.66e-6	1.32e-2
MW122	9.69e-5	2.75e-1	GB-03D	2.67e-6	7.57e-3
			GB-04D	4.71e-5	1.34e-1
			GB-04D	4.12e-6	1.17e-2
			GB-05D	1.25e-6	3.54e-3
			GB-05D	2.05e-6	5.81e-3
Arithmetic Mean	1.05e-4	2.99e-1	Arithmetic Mean	6.26e-6	1.77e-2
Geometric Mean	8.29e-5	2.35e-1	Geometric Mean	1.06e-6	2.99e-3

4.6 RECHARGE

Both precipitation and anthropogenic sources contribute recharge to groundwater at and in the vicinity of PGDP. The following sections attempt to quantify potential recharge rates from these sources.

4.6.1 Recharge from Precipitation

Thornthwaite analysis (Thornthwaite and Mather 1957), which is based on monthly precipitation and potential evaporation rates, was used to estimate recharge from precipitation at the PGDP (Table 4.10). The calculations estimate that recharge from precipitation ranges from 2.64 to 7.64 inches/year.

Calculations involving RGA water level fluctuations estimate recharge from precipitation to be 5.7 inches/year (Moore 1996).

Table 4.10. Thornthwaite Recharge Calculations

Paducah, Kentucky

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean Monthly Air Temperature, F	36.60	38.50	46.50	56.50	65.80	75.30	78.50	76.80	70.00	59.30	45.90	37.30	
Heat Index	0.36	0.60	2.06	4.55	7.42	10.78	12.01	11.33	8.85	5.37	1.93	0.44	65.70
Unadjusted Potential Evaporation, in.	0.00	0.01	0.03	0.06	0.11	0.15	0.17	0.16	0.13	0.07	0.03	0.00	
Evaporation Adjustment Values	25.50	25.20	30.90	33.00	36.90	37.20	37.50	35.10	31.20	28.80	25.20	24.90	
Adjusted Potential Evaporation, in.	0.00	0.25	0.93	1.98	4.06	5.58	6.38	5.62	4.06	2.02	0.76	0.00	
Monthly Precipitation, in.	5.00	3.90	5.28	4.38	4.02	3.70	3.03	3.30	3.36	2.75	3.72	3.55	45.99
Precipitation - Adj. Potential Evap., in.	5.00	3.65	4.35	2.40	-0.04	-1.88	-3.35	-2.32	-0.70	0.73	2.96	3.55	
Available for Recharge and Runoff, in.	5.00	3.65	4.35	2.40	0.00	0.00	0.00	0.00	0.00	0.73	2.96	3.55	22.64

Available for Recharge and Runoff, in/yr	22.64		22.64
- Runoff, in/yr	20	to	15
= Recharge, in/yr	2.64	to	7.64

4.6.2 Anthropogenic Recharge

There are a number of man-made features at PGDP that potentially contribute recharge to the groundwater system. These features include leaky underground water supply lines, cooling towers, infiltration from storm and outfall ditches, leakage from unlined lagoons, and runoff from building roofs. The building roof drains are unique in that runoff from the building roof is collected and routed to gravel beds located beneath the buildings. While the anthropogenic features that potentially contribute recharge to groundwater have been identified, recharge rates from these features have not been quantified. In truth, such a task would be Herculean and rife with uncertainty.

While individual feature anthropogenic recharge rates have not been determined, the bulk recharge rate for the PGDP has been estimated based on RGA water level fluctuations to be 4.1 inches/year, which is less than recharge from precipitation (Moore 1996).

In 2006, average PGDP water usage from all sources was 9,097 gpm. Typically, municipal water supply systems lose approximately 19% of the water transmitted in the pipe lines (Jowitt and Xu 1990). Assuming similar losses at PGDP, anthropogenic recharge associated with leaky utility lines could be 1,728 gal/minute (332,640 ft^3/day). PGDP occupies an area of approximately 31 million ft^2. Dividing the estimated leakage rate from the utilities by the area occupied by PGDP produces a recharge estimate of approximately 48 inches/year, which is an order of magnitude greater than the previous estimate of 4.1 inches/year. It should be noted that it is likely that not all of the leakage reaches the water table and some is lost to evapotranspiration. The uncertainty serves to illustrate the difficulty in estimating anthropogenic recharge rates.

4.7 MONITORING AND EXTRACTION WELLS

Three-hundred sixty-four monitoring wells, 44 piezometers, and six extraction wells have been installed at PGDP and surrounding areas since the start of PGDP characterization activities. Of the 408 monitoring wells/piezometers, 112 monitoring wells have been abandoned. Relevant construction details and extraction rates are presented in the following sections.

4.7.1 Monitoring Wells

Table 4.11 lists survey coordinates, top of casing, and screen elevations for all the PGDP monitoring wells. This information will be used to assign monitoring well and associated water level target information to the various model layers. The information presented is exactly as it was provided from the data base. No effort was made to identify which monitoring wells correspond to which hydrostratigraphic unit. The target importation routine in Groundwater Vistas will determine which wells get assigned to which model layer, based on the middle of the screen elevations. Finally, well construction information was not available for all wells listed in the data base.

Table 4.11. Monitoring Well Construction Details

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW7	-7198.96	-404.26	373.00	358.50	338.50	348.50
MW12	-8473.05	-67.26	368.40	318.40	308.40	313.40
MW16	-2899.11	3088.57	373.20	355.70	335.70	345.70
MW17	-2811.66	4149.22	376.00	335.00	315.00	325.00
MW18	-2354.58	4213.97	405.40	367.40	347.40	357.40
MW19	-2964.46	4470.12	364.40	328.40	318.40	323.40
MW20	-6552.80	4889.55	363.80	Residential well converted to monitoring well, no well construction data		
MW21	-4896.71	1749.85	371.80	322.80	312.80	317.80
MW22	-6219.97	1525.18	369.70	321.70	311.70	316.70
MW23	-7404.75	-3761.50	373.60	334.90	332.40	333.65
MW24	-7568.92	-4011.94	375.70	338.70	336.20	337.45
MW25	-7727.23	-3607.34	376.70	353.20	350.70	351.95
MW26	-7865.40	-3612.29	379.83	337.23	334.93	336.08
MW27	-8203.62	-3831.51	378.79	333.29	330.59	331.94
MW38	-2946.04	3731.86	384.03	319.03	314.03	316.53
MW39	-2947.05	3947.77	381.06	315.06	310.06	312.56
MW40	-2940.30	3961.19	381.46	286.46	281.46	283.96
MW41	-2871.23	4087.52	378.22	313.22	308.22	310.72
MW42	-2391.85	4539.32	362.62	318.92	313.92	316.42
MW43	-1872.00	4199.93	373.39	306.39	301.39	303.89
MW44	-2259.00	3848.04	402.73	311.73	306.73	309.23
MW46	-5881.63	-1069.22	376.82	308.82	298.82	303.82
MW47	-5871.99	-1070.29	377.88	346.68	344.18	345.43
MW48	-6197.46	-1060.99	377.75	309.75	299.75	304.75
MW49	-6190.56	-1061.97	378.42	344.32	341.82	343.07
MW50	-6322.26	-974.47	374.45	312.45	302.45	307.45
MW51	-6325.50	-883.14	373.85	312.85	302.85	307.85
MW52	-6691.91	-67.56	372.31	313.31	304.31	308.81
MW53	-6501.71	240.33	375.25	313.25	303.25	308.25
MW54	-6927.14	238.69	374.10	310.10	300.10	305.10
MW57	-6194.01	-810.89	371.18	342.18	332.18	337.18
MW58	-6204.00	-810.00	375.07	358.57	356.57	357.57
MW63	-7235.74	895.26	369.90	311.40	306.40	308.90
MW64	-7235.37	880.24	372.60	344.80	339.80	342.30
MW65	-7234.91	865.12	370.62	284.42	279.42	281.92
MW66	-6872.62	978.57	368.37	313.17	308.17	310.67
MW67	-6134.48	-755.36	372.30	307.00	302.00	304.50
MW68	-4357.96	-2074.15	376.84	279.44	274.44	276.94
MW69	-4343.25	-2074.34	377.00	343.70	338.70	341.20
MW70	-4327.95	-2074.66	377.36	312.36	307.06	309.71

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW71	-4372.93	-2074.16	376.96	309.86	304.86	307.36
PZ74	-6152.39	-826.91	372.35	340.75	330.35	335.55
MW79	-5500.02	-845.91	373.66	309.46	288.46	298.96
MW84	-5975.23	-804.20	372.14	306.67	296.27	301.47
MW85	-5960.21	-804.80	372.36	342.62	332.22	337.42
MW86	-5945.24	-804.90	372.70	297.53	287.13	292.33
MW87	-5825.09	-804.98	372.70	308.82	298.42	303.62
MW88	-5809.90	-805.09	372.68	343.41	338.41	340.91
MW89	-5795.14	-804.13	372.69	294.94	284.54	289.74
MW90	-5675.22	-803.46	371.40	307.59	297.19	302.39
MW90A	-5688.64	-793.68	372.41	310.41	300.41	305.41
MW91	-5660.38	-804.60	371.45	342.84	337.84	340.34
MW92	-5645.00	-805.26	371.63	292.75	282.35	287.55
MW93	-5994.81	-1028.57	374.69	305.19	294.79	299.99
MW94	-5979.52	-1028.64	374.80	346.14	335.74	340.94
MW95	-5964.22	-1028.61	374.80	296.98	286.58	291.78
MW95A	-5944.19	-1029.96	375.51	297.51	287.51	292.51
MW96	-4459.50	-2229.19	375.78	347.78	337.78	342.78
MW97	-8417.89	3515.64	367.42	312.42	302.42	307.42
MW98	-3281.31	7397.46	367.50	303.00	293.00	298.00
MW99	1842.46	6826.71	366.51	304.51	294.51	299.51
PZ101	1374.61	-2413.82	371.51	334.51	324.51	329.51
MW102	-6267.32	-3502.54	382.14	246.14	236.14	241.14
MW103	-6252.14	-3500.84	382.42	302.92	292.92	297.92
MW104	-6596.77	-3682.88	372.02	327.52	317.52	322.52
MW106	-8438.90	990.93	366.29	304.29	294.29	299.29
PZ107	-3681.93	-3571.32	383.17	320.67	310.67	315.67
W108	-3698.90	-3132.90	383.25	316.25	286.25	301.25
PZ109	-3665.80	-3143.30	383.12	307.12	297.12	302.12
PZ110	-3741.36	-3168.00	383.59	309.59	299.59	304.59
PZ111	-3668.26	-3148.00	383.19	358.19	353.19	355.69
PZ114	-3664.40	-3128.90	383.14	277.64	276.64	277.14
PZ115	-3665.70	-3123.50	383.05	271.05	270.05	270.55
PZ117	-3758.80	-3081.60	383.85	308.35	298.35	303.35
PZ118	-3698.80	-3283.90	383.15	307.15	297.15	302.15
MW120	-1489.08	-5880.16	384.08	224.08	214.08	219.08
MW121	-5677.65	6161.53	372.41	172.41	162.41	167.41
MW122	1876.17	717.07	362.89	214.89	204.89	209.89
MW123	-5661.33	6125.60	372.74	309.74	299.74	304.74
MW124	1879.15	726.38	362.65	279.65	269.65	274.65

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW125	-5662.81	6139.28	372.67	294.67	284.67	289.67
MW126	1881.49	736.67	362.57	307.57	297.57	302.57
MW127	-5664.11	6161.23	372.43	343.43	333.43	338.43
MW128	1883.08	746.17	362.58	329.58	319.58	324.58
MW129	-1485.42	-5912.73	383.80	339.30	334.30	336.80
MW130	-1483.89	-5924.02	383.86	349.36	344.36	346.86
MW131	-1481.41	-5938.94	383.64	363.64	353.64	358.64
MW132	-559.79	6192.35	360.61	285.61	275.61	280.61
MW133	-1715.66	9124.70	334.70	254.70	244.70	249.70
MW134	-8335.00	3568.93	365.96	280.96	270.96	275.96
MW135	-1520.05	9137.28	333.50	292.50	282.50	287.50
MW137	-1726.75	9150.86	333.20	299.20	294.20	296.70
MW138	-1734.38	9163.18	333.20	323.20	313.20	318.20
MW139	-576.59	6189.67	360.97	303.97	293.97	298.97
MW140	-12179.19	6558.48	341.83	205.83	195.83	200.83
MW141	-12173.02	6544.69	342.51	274.51	264.51	269.51
MW142	-12162.53	6529.75	342.72	300.72	290.72	295.72
MW143	-12156.05	6513.64	342.84	332.84	322.84	327.84
MW144	-770.10	369.58	378.01	273.01	263.01	268.01
MW145	-768.84	383.32	378.06	293.06	283.06	288.06
MW146	-5684.18	13549.15	350.35	293.35	283.35	288.35
MW147	-5669.28	13548.69	351.08	306.08	296.08	301.08
MW148	3289.83	5755.06	371.08	311.08	281.08	296.08
MW149	3214.11	5754.34	371.30	321.30	311.30	316.30
MW150	4782.26	2215.00	374.44	309.44	279.44	294.44
MW151	4208.20	-613.57	380.40	344.40	324.40	334.40
MW152	-692.64	13136.67	351.61	306.61	276.61	291.61
MW153	-695.33	13122.54	351.43	326.43	316.43	321.43
MW154	-6225.48	-810.29	371.80	355.30	353.30	354.30
MW155	-4025.00	-1669.40	379.13	292.13	287.13	289.63
MW156	-4025.70	-1703.70	379.55	316.55	309.55	313.05
MW157	-4025.70	-1688.60	379.10	349.10	344.10	346.60
MW158	-6957.00	-991.20	371.51	269.51	263.51	266.51
MW159	-6937.10	-989.80	371.96	308.96	303.96	306.46
MW160	-6945.90	-971.90	371.35	351.35	346.35	348.85
MW161	-6916.90	-1666.70	371.66	293.66	288.66	291.16
MW162	-6886.20	-1666.80	371.70	353.70	347.70	350.70
MW163	-2041.00	-1400.80	383.77	289.77	284.77	287.27
MW164	-2034.20	-1415.60	383.59	341.59	336.59	339.09
MW165	-3135.70	898.30	378.22	315.22	310.22	312.72

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW166	-3152.30	893.30	378.16	345.16	340.16	342.66
MW167	-4822.50	-908.70	374.86	353.86	348.86	351.36
MW168	-4822.50	-924.80	374.90	311.90	306.90	309.40
MW169	-5558.00	-191.40	370.39	305.39	300.39	302.89
MW170	-5557.60	-175.80	370.85	345.85	340.85	343.35
MW171	-5418.40	-471.50	372.82	354.82	349.82	352.32
MW172	-5977.90	-192.20	370.88	349.08	344.08	346.58
MW173	-5290.00	1020.30	371.43	318.43	313.43	315.93
MW174	-5307.20	1021.20	371.56	348.56	343.56	346.06
MW175	-4379.10	-1428.30	378.60	303.60	298.60	301.10
MW176	-4380.00	-1444.20	378.84	346.34	341.34	343.84
MW177	-4073.80	-1227.50	377.39	337.89	332.89	335.39
MW178	-4073.60	-1216.20	376.81	314.31	309.31	311.81
MW179	-2516.50	4627.90	356.79	304.79	299.79	302.29
MW180	-2494.20	4627.00	355.74	333.74	328.74	331.24
MW181	-3042.80	3107.30	368.76	316.76	311.76	314.26
MW182	-3027.40	3107.20	368.85	353.85	348.85	351.35
MW184	-7386.90	-3997.30	371.01	360.51	358.01	359.26
MW185	-6601.90	952.90	371.78	303.78	298.78	301.28
MW186	-6581.30	952.60	371.88	353.88	348.88	351.38
MW187	-6854.50	964.40	370.20	348.70	343.70	346.20
MW188	-7008.80	-2057.10	371.69	301.69	296.69	299.19
MW189	-6997.60	-2057.30	372.36	349.86	344.86	347.36
MW190	-6951.60	237.90	371.10	353.60	348.60	351.10
MW191	2597.40	600.30	357.12	302.12	297.12	299.62
MW192	2587.80	600.40	356.90	318.90	313.90	316.40
MW193	515.80	3064.90	366.24	308.24	303.24	305.74
MW194	-10177.50	1865.60	353.76	306.86	301.86	304.36
MW195	-10193.40	1861.10	354.03	348.03	343.03	345.53
MW196	-4977.80	-7987.30	387.47	365.57	360.57	363.07
MW197	-6162.50	2863.10	366.54	308.54	303.54	306.04
MW198	-6163.00	2874.80	366.61	348.61	343.61	346.11
MW199	-10076.60	10090.10	353.87	296.87	291.87	294.37
MW200	-4823.90	4443.30	377.11	303.11	298.11	300.61
MW201	-4884.00	10167.40	364.51	302.01	297.01	299.51
MW202	-5688.00	7613.20	370.53	293.53	287.53	290.53
MW203	-5014.80	-2159.20	374.95	303.95	298.95	301.45
MW204	-5014.10	-2148.10	374.84	325.34	320.44	322.89
MW205	-4360.30	-364.10	377.22	312.22	307.22	309.72
MW206	-2924.50	-1504.80	382.36	315.36	305.36	310.36

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW207	-4636.00	-2432.00	376.24	347.24	337.24	342.24
MW208	-4704.00	-2298.00	375.98	343.98	334.48	339.23
MW209	-4769.00	-2600.00	376.12	348.12	338.12	343.12
MW212	-4171.88	-2041.46	376.64	343.64	333.64	338.64
MW213	-4290.20	-2233.90	377.92	340.92	330.92	335.92
MW214	-4565.38	-2602.06	376.16	348.16	338.16	343.16
MW215	-3905.70	-2301.20	380.79	346.79	336.79	341.79
MW216	-4452.20	-3235.20	377.32	331.32	321.32	326.32
MW217	-5080.28	-2760.66	375.46	335.96	325.96	330.96
MW218	-5090.38	-2626.16	372.32	343.32	333.32	338.32
MW219	-4481.40	-1917.30	377.79	343.29	333.29	338.29
MW220	-2822.84	3279.19	379.10	320.10	310.10	315.10
MW221	-2784.92	3863.68	388.26	314.26	304.26	309.26
MW222	-2563.11	3659.61	392.27	323.97	313.97	318.97
MW223	-2725.63	3719.99	391.37	318.97	308.97	313.97
MW224	-2467.33	3627.71	392.41	320.41	310.41	315.41
MW225	-2634.42	3323.37	383.14	315.14	305.14	310.14
MW226	-5740.41	-1241.06	375.90	297.00	287.00	292.00
MW227	-5769.88	-1240.60	375.95	311.45	301.45	306.45
MW233	-5530.15	7300.34	370.21	300.99	290.99	295.99
MW234	-5188.17	7205.82	368.55	299.25	289.25	294.25
MW235	-4890.74	7746.42	369.99	301.89	291.89	296.89
MW236	-5087.79	7919.99	369.28	299.78	289.78	294.78
MW237	-5196.81	7328.85	367.00	341.62	331.62	336.62
MW238	-5197.06	7505.64	370.57	300.74	290.74	295.74
MW239	-5203.65	7330.40	370.06	223.18	213.18	218.18
MW240	-5195.78	7390.60	370.20	300.54	290.54	295.54
MW241	-5203.79	7346.86	369.67	303.16	293.16	298.16
MW241A	7346.16	-5205.82	369.19			
MW242	-7083.28	1678.98	369.61	304.51	294.51	299.51
MW243	-7382.03	1681.40	368.14	303.01	293.01	298.01
MW244	-7589.08	1467.50	366.23	301.93	291.93	296.93
MW245	-7397.55	1119.22	369.20	304.62	294.62	299.62
MW246	-7447.70	1345.13	367.05	351.68	341.68	346.68
MW247	-7445.70	1360.15	366.85	231.60	221.60	226.60
MW248	-7376.72	1385.42	368.51	302.70	292.70	297.70
MW249	-7432.45	1357.75	367.04	301.57	291.57	296.57
MW250	-7431.78	1396.34	367.77	304.00	294.00	299.00
MW252	4228.40	5717.89	371.99	287.79	283.09	285.44
MW253	3572.22	3669.88	364.30	273.10	268.40	270.75

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW255	-1510.28	-2230.29	380.96	289.96	285.26	287.61
MW256	-1596.77	-1896.41	382.06	281.86	277.16	279.51
MW257	-5972.21	442.38	370.28	299.08	294.38	296.73
MW258	-745.65	-1643.25	381.15	291.95	287.25	289.60
MW260	-1982.18	-786.01	381.00	287.80	283.10	285.45
MW261	-5979.20	442.19	370.31	280.31	275.61	277.96
MW262	-5379.80	-292.32	371.40	281.20	276.50	278.85
MW263	-2760.60	4551.97	357.54	308.38	298.58	303.48
MW264	-2239.65	4639.91	362.97	317.47	307.77	312.62
MW265	-1888.70	4409.76	366.17	305.67	295.87	300.77
MW266	-2259.74	4639.90	362.87	296.27	286.27	291.27
MW267	-2819.73	3264.74	378.49	303.49	293.49	298.49
MW268	-3103.02	6472.48	368.47	311.27	301.57	306.42
MW269	-3112.98	6472.67	368.32	299.12	289.42	294.27
MW270	-2713.10	6513.51	366.35	311.15	301.45	306.30
MW271	-2703.28	6514.58	368.78	305.58	295.88	300.73
MW272	-2253.88	6598.45	363.48	309.68	299.98	304.83
MW273	-2244.57	6598.12	363.31	297.01	287.31	292.16
MW274	-2205.70	6169.96	365.90	310.70	301.00	305.85
MW275	-2195.97	6171.00	365.74	294.54	284.84	289.69
MW276	-3107.19	4470.74	359.97	310.77	301.07	305.92
MW277	-3117.11	4469.60	360.28	298.58	288.88	293.73
PZ278	-2707.60	4985.53	364.98			
PZ279	-3171.05	5355.81	372.35			
PZ280	-2199.39	5921.63	365.65			
PZ281	-3160.89	5999.94	369.85			
PZ282	-2379.92	6441.68	366.86			
MW283	599.27	903.26	367.04	298.04	288.04	293.04
MW284	1590.00	913.48	367.86	285.86	275.86	280.86
PZ287	1489.22	608.40	368.90	286.00	276.00	281.00
MW288	1564.94	679.01	368.10	290.10	280.10	285.10
PZ289	1629.92	609.65	368.66	288.66	278.66	283.66
MW291	1699.81	968.89	367.59	297.59	287.59	292.59
MW292	924.03	33.19	373.10	286.10	276.10	281.10
MW293	1802.40	839.01	363.48	299.48	289.48	294.48
MW293A	1789.75	843.01	369.19			
MW294	1790.40	842.77	363.48	282.98	272.98	277.98
MW294A	1801.80	839.09	369.19			
MW300	-7898.27	-4203.55	369.39	362.39	357.39	359.89
MW301	-7582.70	-4128.06	372.18	364.18	359.18	361.68

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW302	-8066.64	-3714.20	380.84	365.64	360.64	363.14
MW303	-7461.23	-3559.90	365.02	353.22	348.22	350.72
MW304	-6118.82	-2158.69	373.27	357.37	347.37	352.37
MW305	-9121.68	-6929.79	413.19	397.19	387.19	392.19
MW306	-8795.67	-6517.76	419.30	404.30	394.30	399.30
MW307	-8785.40	-6208.05	415.00	392.00	382.00	387.00
MW308	-9226.32	-6479.71	415.75	397.25	387.25	392.25
MW309	-9059.28	-4925.20	377.74	363.64	353.64	358.64
MW310	-9158.54	-5074.47	386.57	369.57	359.57	364.57
MW311	-8963.36	-5293.58	392.67	373.67	363.67	368.67
MW312	-7017.87	-3231.19	367.40	360.40	350.40	355.40
MW313	-7203.70	-3158.76	368.69	358.19	348.19	353.19
MW314	-7116.68	-3534.26	367.98	360.98	350.98	355.98
MW315	-6633.33	-2273.87	375.26	360.81	350.81	355.81
MW316	-7173.33	-2645.91	369.30	361.70	351.70	356.70
MW317	-8399.05	-3377.36	385.84	371.54	361.54	366.54
MW318	-8589.42	-3378.00	387.10	373.90	363.90	368.90
MW325	-6100.30	-2090.91	372.95	294.25	289.25	291.75
MW326	-6185.00	-2430.11	373.32	289.82	284.82	287.32
MW327	-7100.87	-2559.81	369.68	288.68	283.68	286.18
MW328	-7337.48	-1962.31	365.73	304.98	299.98	302.48
MW329	-7347.44	-1419.37	373.25	307.75	302.75	305.25
MW330	-6636.33	-2206.91	374.45	301.95	296.95	299.45
MW344	-7450.36	-3566.69	366.14	311.14	301.52	306.33
MW345	-2955.33	1132.87	378.11	50.61	40.61	45.61
MW346	-3100.07	3210.08	365.90	70.90	60.90	65.90
MW347	-4713.07	1116.83	371.78	36.78	26.78	31.78
MW352	-530.83	-1189.73	381.12	283.62	278.62	281.12
MW353	-3311.97	2599.30	371.97	304.47	299.47	301.97
MW354	-8428.96	-423.07	370.85	305.85	300.85	303.35
MW355	-4327.94	761.55	375.40	290.40	285.40	287.90
MW356	-1466.38	863.45	379.86	261.86	256.86	259.36
MW357	-2829.58	6451.80	366.86	314.16	304.16	309.16
MW358	-2851.93	6444.38	366.62	295.12	285.12	290.12
MW359	-2840.71	6448.02	366.65	337.65	327.65	332.65
MW360	-2627.14	6467.64	360.03	320.03	310.03	315.03
MW361	-2617.48	6487.36	359.46	304.46	294.46	299.46
MW362	-2621.41	6477.31	359.63	339.13	329.13	334.13
MW363	-2392.05	6521.42	366.25	311.25	301.25	306.25
MW364	-2373.54	6535.89	365.95	292.95	282.95	287.95

Table 4.11. Monitoring Well Construction Details (Continued)

Well	X-Coordinate, ft	Y-Coordinate, ft	Ground Elevation, ft	Top Screen Elevation, ft	Bottom Screen Elevation, ft	Middle Screen Elevation, ft
MW365	-2383.31	6528.32	366.00	334.00	324.00	329.00
MW366	-2246.10	6121.18	366.87	313.87	303.87	308.87
MW367	-2247.09	6145.28	367.37	294.37	284.37	289.37
MW368	-2247.27	6134.00	367.07	334.07	324.07	329.07
MW369	-2957.51	4564.73	362.02	320.52	310.52	315.52
MW370	-2957.40	4589.20	362.95	301.95	291.95	296.95
MW371	-2957.43	4576.61	362.56	340.96	330.96	335.96
MW372	-2486.89	4817.24	357.33	310.83	300.83	305.83
MW373	-2509.92	4823.14	357.72	297.72	287.72	292.72
MW374	-2497.62	4819.04	357.53	332.53	322.53	327.53
MW375	-2907.85	5886.80	368.73	326.73	316.73	321.73
MW384	-3121.20	3828.36	363.07	313.07	303.07	308.07
MW385	-3119.46	3804.81	363.18	296.98	286.98	291.98
MW386	-3120.54	3816.45	363.11	343.11	333.11	338.11
MW387	-3073.18	4188.73	361.46	314.06	304.06	309.06
MW388	-3080.77	4197.35	360.98	300.78	290.78	295.78
MW389	-2913.08	4258.20	361.92	341.72	331.72	336.72
MW390	-2713.38	4394.91	358.23	330.43	320.43	325.43
MW391	-1993.30	4557.92	364.39	307.19	297.19	302.19
MW392	-1994.30	4582.37	363.73	282.53	272.53	277.53
MW393	-1993.08	4571.03	364.25	336.25	326.25	331.25
MW394	-1895.64	3460.44	376.57	311.57	301.57	306.57
MW395	-1894.71	3484.23	377.50	304.50	294.50	299.50
MW396	-1894.83	3471.98	376.77	343.17	333.17	338.17
MW397	-2509.48	3138.15	385.00	300.00	290.00	295.00
MW405	-4116.32	-1686.57	378.38			
MW406	-4076.55	-1700.83	378.24			
MW407	-4081.78	-1716.10	378.48			
MW408	-4071.66	-1737.92	378.08			
MW414	-6531.28	-1220.85	371.56			
MW415	-6530.80	-1206.59	371.63			
MW416	-6559.06	-1470.47	375.22			
MW417	-6559.24	-1461.40	375.01			
MW418	-1833.99	4418.94	364.25			
MW419	-1833.77	4429.38	364.08			

4.7.2 Extraction Wells

Six extraction wells are operational at PGDP and were installed to capture groundwater contamination (Figure 4.7). The extraction wells were installed between 1995 and 1997 and have pumping rates ranging from 30 to 105 gpm.

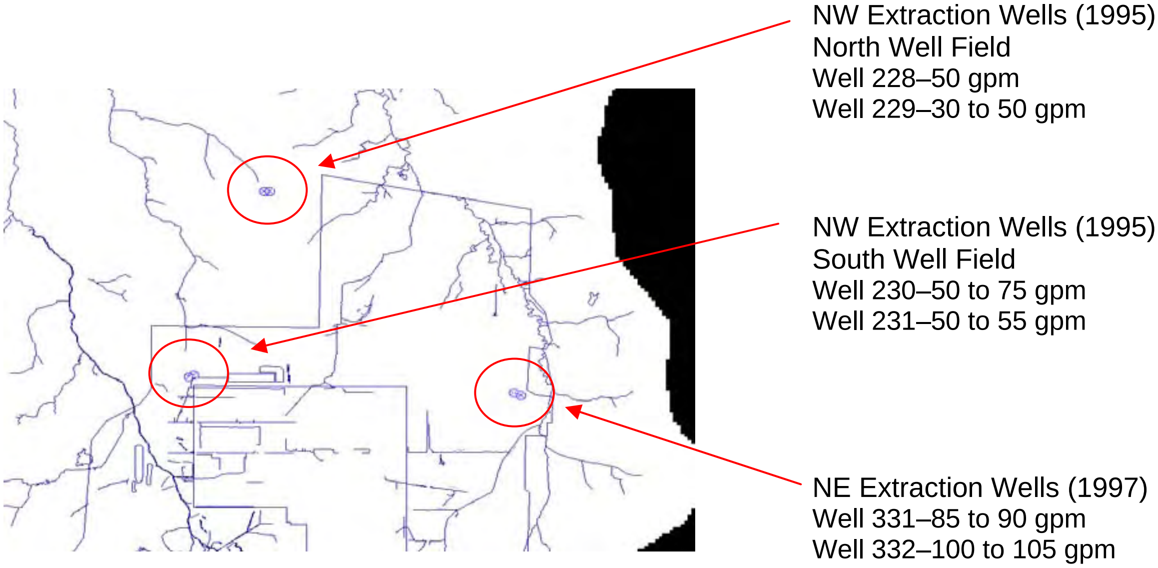


Figure 4.7. Extraction Well Locations and Pumping Rates

4.8 SURFACE WATER STAGE AND DISCHARGE

PGDP is located within the watersheds of the Ohio River, Little Bayou Creek, and Bayou Creek (Figure 4.8). In addition to the river and creeks, Metropolis Lake and a TVA slurry pond also are located within the watershed. The following sections present stage and discharge information, when known, for these surface water boundaries.

4.8.1 Ohio River

Ohio River stage corresponding to the water level measurement collection periods shown in Figure 4.2 ranges from approximately 290 to 325 ft (http://waterdata.usgs.gov/) and averages 303 ft (Figure 4.8). It should be noted that Olmstead Dam is scheduled to be installed down river of PGDP and, once operational, may alter Ohio River stage from the historic values. Lastly, the Ohio River has been engineered to benefit transportation and for flood control and the river stage is controlled by a series of dams along the length of the river. The length of the Ohio River within the PGDP hydrologic basin is approximately 28,535 ft.

Using Darcy's Law, with equation output of volume and with equation input for hydraulic conductivity, hydraulic gradient, RGA aquifer thickness, and Ohio River length of between 100 and 3,600 ft/day,

4.4×10^{-4} ft/ft, 35 and 28,535 ft, respectively, the equation yields a range of groundwater discharge to the Ohio River between 228 and 8,218 gpm, with a middle value of 4,223 gpm.

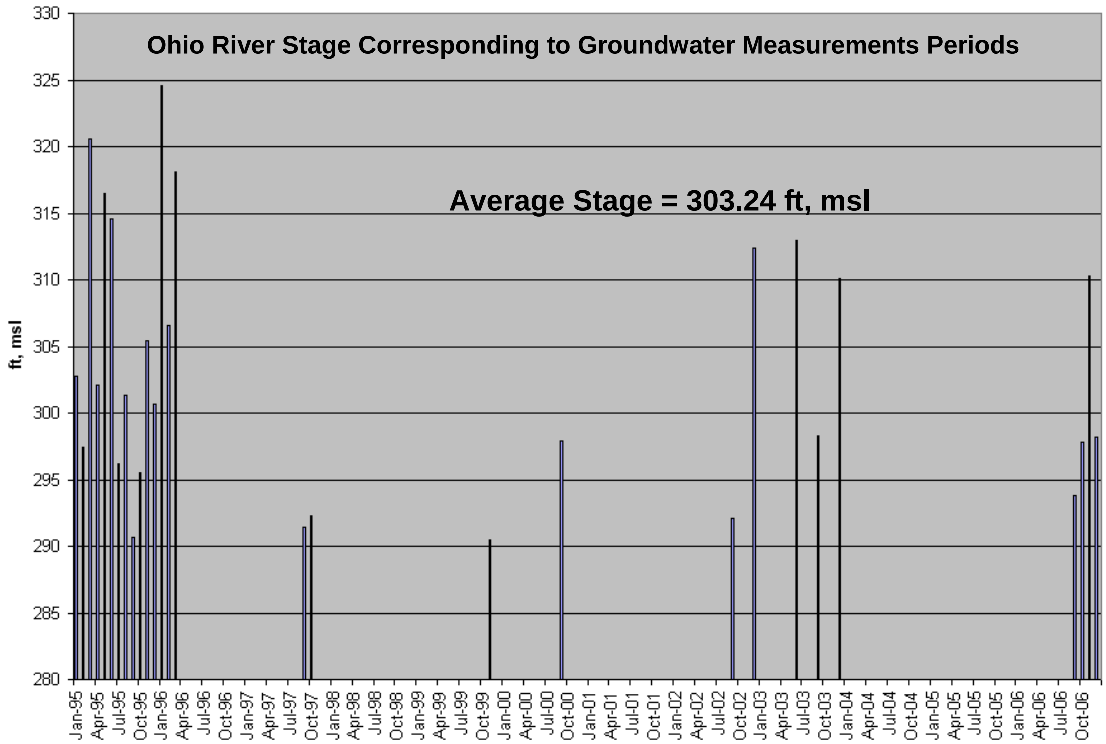


Figure 4.8. Ohio River Stage Fluctuations

4.8.2 Bayou and Little Bayou Creeks

Bayou and Little Bayou Creeks are located west and east of PGDP, respectively (Figure 4.9). The creeks receive permitted discharge from the facility. Flows typically are measured after precipitation events and are not representative of "typical" flow conditions. Additionally, the reported flows are representative of creek flow rates and cannot be correlated to potential groundwater recharge and discharge rates. The creeks were gauged once in 1989 (Evaldi and McClain 1989) and reported the upper sections of Bayou and Little Bayou Creek contribute 606 and 471 gpm to groundwater, respectively. The same study reported that groundwater discharge to the lower sections of Bayou and Little Bayou Creeks to be 404 and 0 gpm, respectively. Given that these values represent a single measurement period, there is considerable uncertainty associated with these measurements.

The University of Kentucky also performed studies on Little Bayou Creek, which focused primarily on the area surrounding the seeps (LaSage 2004). Study results found that groundwater discharge was variable in correspondence to adjacent groundwater levels and ranged between 56 and 302 gpm.

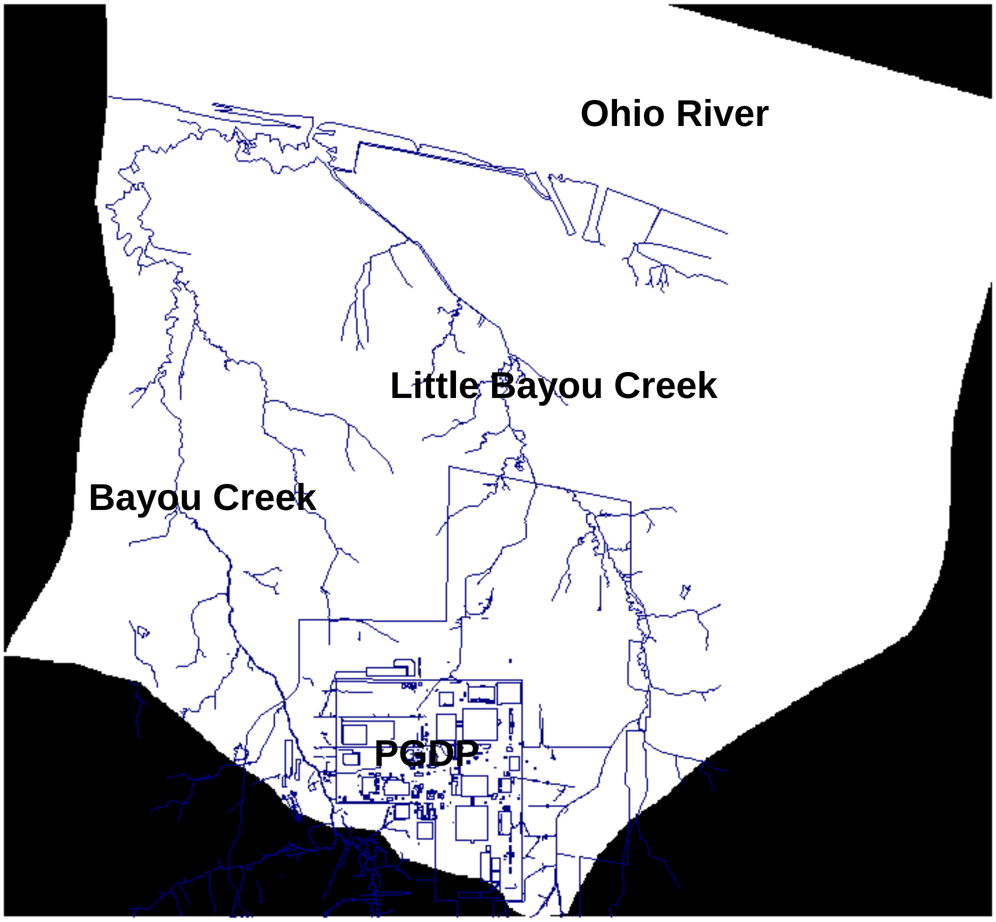


Figure 4.9. Location of Bayou and Little Bayou Creeks

4.8.3 Metropolis Lake

Metropolis Lake is a surface water feature that represents the intersection of land surface and the water table. As such, Metropolis Lake is both a groundwater recharge and discharge location. The recharge and discharge components equal so the lake's contribution to the groundwater flow system is neutral.

4.8.4 TVA Slurry Pond

Adjacent to the Ohio River on TVA property, TVA operates a slurry pond that has a pond stage higher than adjacent groundwater levels. Based on the head difference, the pond contributes groundwater to the groundwater flow system. TVA data shows water entering and exiting the pond is measured to the nearest 100,000 gpd. The imprecise nature of the flow measurements precludes determination of the volume of water lost to groundwater through the bottom of the pond.

4.9 EXTENT OF THE HYDROLOGIC BASIN

In general, groundwater divides for unconfined aquifers correspond with surface water divides. Following this adage, surface elevation contours were examined to determine the lateral extent of the model domain (Figure 4.10). The basin extent to the south can be defined by either a surface water divide (if the Terrace

Gravel is included in the model) or the northern extent of the Porters Creek Clay (which is considered impermeable relative to adjacent lithologies) if the Terrace Gravel is excluded from the model. Given that there is minimal hydrologic data available for the Terrace Gravel and there are no waste units located on the Terrace, the most logical southern basin boundary is the northern extent of the Porters Creek Clay. The northern end of the basin is defined by the Ohio River. The hydrologic basin, as shown, covers an area of approximately 18.6 square miles (5.2×10^8 ft^2).

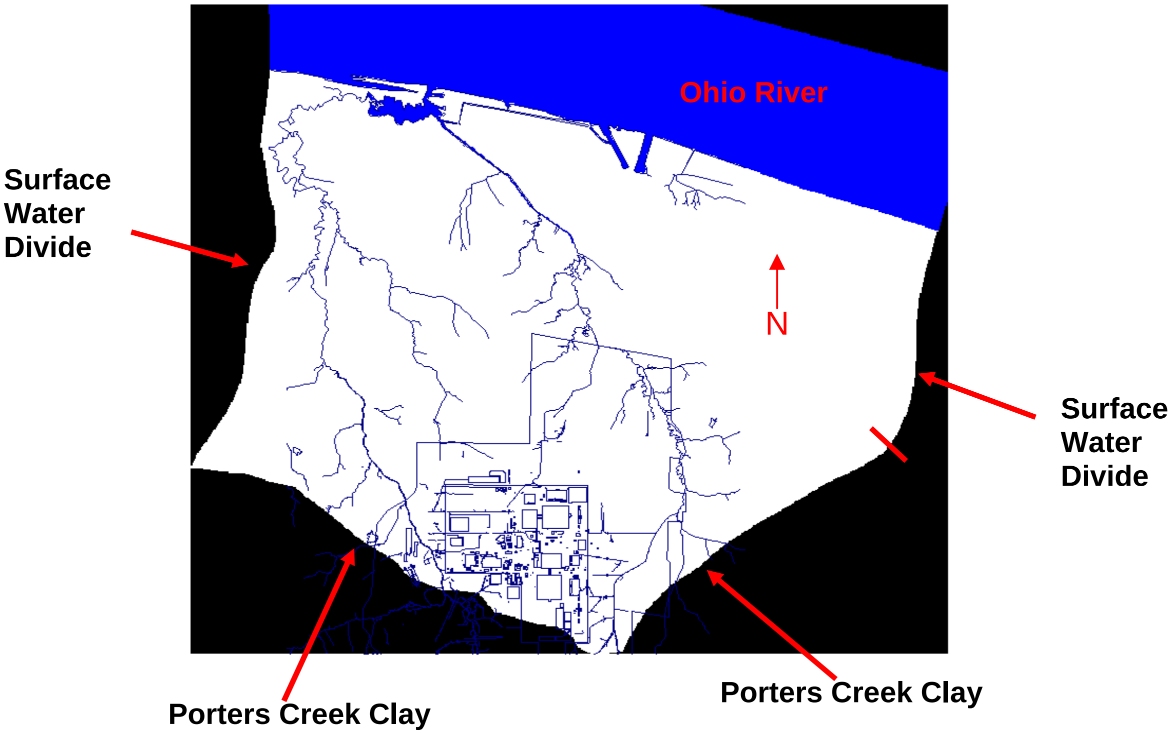


Figure 4.10. Extent of the PGDP Hydrologic Basin

4.10 PGDP WATER BALANCE

Water balances bound the expected ranges of recharge and discharge rates within a hydrologic basin. The calculated recharge and discharge range provide a quantitative assessment of where water enters and leaves the groundwater flow system, and these are used to constrain and assess the accuracy of the calibrated groundwater flow model.

Recharge from precipitation is the dominant recharge mechanism for the PGDP hydrologic basin and ranges between 1,625 and 4,700 gpm (Table 4.12). The range was calculated by multiplying the expected range of recharge rates (2.64 to 7.64 inches/year) by the area of the model domain (5.2×10^8 ft^2). Anthropogenic recharge is virtually impossible to measure directly, but has been calculated to be between 148 and 1,728 gpm. The minimum anthropogenic recharge rate was calculated by multiplying 4.1 inches/year (the estimated PGDP recharge rate) by the surface area of the PGDP (332,640 ft^3/day). Recharge from Bayou and Little Bayou Creeks is estimated to be 1,077 gpm based on one-time gauging measurements. The TVA Pond also recharges groundwater, but the amount is unknown.

Between 405 and 14,587 gpm of groundwater discharges to the Ohio River (Table 4.12). Groundwater discharge to Bayou and Little Bayou Creeks, based on one-time gauging measurements, is 404 gpm. The total groundwater discharge rate within the PGDP hydrologic basin ranges between 809 and 14,991 gpm.

Table 4.12. PGDP Water Balance, gpm

Rate, gpm	In	Out
Recharge from Precipitation	1,625 - 4,700	
Bayou and Little Bayou Creeks	1,077	404
Anthropogenic Recharge	148 - 1,728	
Ohio River		405 - 14,587
McNairy Through Flow		3
RGA to McNairy		349
TOTAL	3,625 - 9,685	1,161 - 15,343

The water balance focuses on water entering and leaving the RGA. Also of interest is McNairy, specifically in relation to the RGA. The volume of water flowing through the McNairy can be estimated using Darcy's Law with equation output of volume and with equation input for hydraulic conductivity, hydraulic gradient, McNairy aquifer thickness, and Ohio River length of 0.3 ft/day, 5.15×10^{-4} ft/ft, 120, and 28,535 ft, respectively, the equation yields a groundwater discharge through flow rate to the Ohio River of approximately 3 gpm. (NOTE: the estimated through flow rate is much less than the estimated RGA through flow rate [middle value is 4,223 gpm]). Based on the Ohio River being a regional groundwater discharge feature, McNairy through flow is believed to ultimately discharge to the Ohio River.

In addition to groundwater flowing through the McNairy, there is hydraulic interaction between the RGA and McNairy. Again, the volume of water entering the McNairy from the RGA can be estimated using Darcy's Law with equation inputs for hydraulic conductivity, vertical hydraulic gradient and cross-sectional area of 1.77×10^{-2} ft/day, 7.3×10^{-3} ft/ft, and 5.2×10^{8} ft^{2}, respectively, yields a groundwater discharge rate of approximately 349 gpm. Again, this value is considerably less than the total volume of RGA through flow (middle value is 4,223 gpm). Additionally, it should be noted that the RGA/McNairy vertical gradient measurements were collected from well pairs located in the vicinity of PGDP. Due to the Ohio River being a regional discharge point, well pairs closer to the Ohio River might have shown a vertical hydraulic gradient reversal (water moving from the McNairy to the RGA). Thus, it is likely that the cumulative volume of groundwater entering the McNairy from the RGA is less than 349 gpm. Again, based on the Ohio River's being a regional groundwater discharge feature, all groundwater within the McNairy is believed ultimately to discharge to the Ohio River.

In summary, total contribution to the PGDP groundwater flow system from these features ranges between 3,625 and 9,685 gpm. Total groundwater flow system discharge is estimated to be between 1,161 and 15,343 gpm. The discrepancy between the estimated inflow and outflow volumes seems problematic; however, the discrepancy is typical and serves to illustrate the uncertainty in mass balance estimates.

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5. CONCEPTUAL MODEL

A hydrological conceptual model is a description of how, where, and in what quantities water enters the groundwater flow system and the factors controlling groundwater movement between inflow and outflow locations. The conceptual model is derived from site-specific data and is intended to force condensation of concepts and ideas about the flow system into a series of statements that will guide model configuration and calibration. The following, based on the data presented in Section 4, is the PGDP conceptual model.

With regard to steady-state or transient groundwater flow conditions:

- Three-point vector analysis shows that RGA groundwater flow directions between PGDP and the Ohio River remain relatively constant overtime regardless of river stage. This assessment is supported by the temporal consistency of the PGDP plumes.

- The same three-point analysis shows that groundwater flow directions beneath PGDP are variable as a result of differing anthropogenic recharge time constants. Despite flow direction variability, plume orientation at the PGDP remains relatively constant, suggesting “average” flow conditions do exist.

- In summary, the PGDP groundwater flow system can be considered steady state.

Groundwater flow is as follows:

- Strong downward vertical hydraulic gradients between the UCRS and RGA indicate that groundwater movement in the UCRS is primarily vertical. Simplistically, the UCRS conveys recharge at land surface to the RGA.

- Mass balance assessment indicates that the RGA conveys significantly more groundwater than the McNairy downgradient in the direction of the Ohio River.

- Vertical hydraulic gradient and mass balance evaluation indicates that there is vertical movement of groundwater between the RGA and McNairy, but the volume of groundwater moving between the two units is much less relative to the volume of groundwater moving horizontally in the RGA.

- In summary, the RGA is the primary conveyor of groundwater from PGDP to the Ohio River.

Recharge:

- The biggest source of recharge within the PGDP basin is rainfall and likely ranges between 2.64 and 7.64 inches/year.

- The upper portions of Little Bayou and Bayou Creeks lose water to the groundwater flow system. The volume contributed to the groundwater flow system is much less than that derived from precipitation.

- Anthropogenic recharge from leaking underground water supply lines, runoff from building roofs, infiltration from lagoons, and seepage through ditch and outfalls contribute recharge to groundwater. While very important in controlling plume migration, the volume of recharge contributed to the groundwater flow system from these sources is much less relative to that contributed by precipitation.

Additionally, while underground water supply lines are known to leak, the location of the leaks is not known.

- In summary, precipitation is the dominant recharge provider in the PGDP basin, and characterizing anthropogenic recharge locations and rates is problematic.

Groundwater discharge is as follows:

- The majority of groundwater within the PGDP basin discharges to the Ohio River.

- Groundwater also discharges to the lower portions of Bayou and Little Bayou Creeks.

With respect to hydraulic conductivity these apply:

- Pumping tests predict RGA horizontal hydraulic conductivity to range between 100 and 3,600 ft/day. Bulk hydraulic conductivities, based on the assumption that all recharge enters the RGA, predict bulk RGA hydraulic conductivity to range between 713 and 2,063 ft/day.

- The average horizontal UCRS hydraulic conductivity derived from slug testing is 0.28 ft/day. Permeameter testing yielded an average UCRS vertical hydraulic conductivity of 0.03 ft/day.

- Slug and permeameter testing yielded average McNairy horizontal and vertical hydraulic conductivities of 0.30 and 0.02 ft/day, respectively.

- In summary, RGA hydraulic conductivity is much greater relative to either the UCRS or McNairy hydraulic conductivity.

Finally, with respect to the PGDP hydrologic basin groundwater mass balance:

- Estimated cumulative groundwater recharge ranges between 3,625 and 9,685 gpm.

- Estimated cumulative groundwater discharge ranges between 1,161 and 15,434 gpm.

6. 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 and pumping wells. 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 PGDP conceptual model into a groundwater flow model.

After evaluating site-specific data and reviewing the site-conceptual model, it was decided to simulate only the RGA with the model. The rationale for excluding the UCRS and McNairy from the modeling domain is that groundwater flow within the UCRS is primarily vertical and the unit is, for all practical purposes, only a conduit for recharge to reach the RGA, and that the volumes of groundwater flowing through the McNairy are much less than the volume of water flowing through the RGA.

Additionally, the interaction between the RGA and McNairy will be evaluated using a cross-sectional model to be constructed separate from this modeling effort. The model domain will include both sides of the Ohio River and will be used, among other things, to assess the potential for contaminant migration beneath the river in response to pumping on the Illinois side of the river.

6.1 MODEL DISCRETIZATION

The model used for this study was discretized into three model layers and consists of 582 rows and 627 columns with a constant width of 50 ft. Constant cell size dimensions were used to ensure that future versions of the model could simulate contaminant transport and be used for remedial design evaluation anywhere within the model domain. It needs to be noted that the 50 by 50-ft cell size is bigger than the 25 by 25-ft cell size typically used for contaminant transport and remedial design; however, use of 25 by 25-ft cells everywhere in the model proved unwieldy with regard to computer memory requirements, so the larger cell size was adopted. It is unlikely that the 50 by 50-ft cells will have any impact on the groundwater flow simulations because horizontally RGA water levels minimally change over that distance. If the 50 by 50-ft cell size proves problematic during future transport and remedial design simulations, telescopic mesh refinement (TMR) models having finer grid cells can be cut from the regional model and used to improve prediction capabilities. TMR models use the heads or fluxes predicted by the larger model as boundary conditions along the edges of the smaller more refined (with respect to cell dimensions) model. Additionally, the TMR model preserves the hydraulic property and boundary condition distributions with the larger model domain. As a result, the smaller TMR model matches the larger model predicted groundwater flow patterns and rates within the extracted portion of the model domain.

The top elevation of model layer 1 corresponds to the top of the RGA, and the bottom of model layer 3 corresponds to the top of the McNairy. Water quality results show that dissolved contamination tends to migrate downwards toward the bottom of the RGA with distance away from PGDP. The RGA was divided into three layers of equal thickness to allow future versions of the transport model to more accurately simulate the observed vertical movement of dissolved contamination within the RGA.

6.2 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 the Ohio River. Bayou Creek, located within the edges of the model domain, is an interior model boundary. While technically boundary conditions, recharge is viewed as a parameter (analogous to hydraulic conductivity) within the modeling community and, as such, will be discussed in Section 6.3.

External boundaries are located in model layers 1 through 3 (Figure 6.1). The Ohio River is simulated using drain cells. Simplistically, drain boundary cells have head and conductance components that control the amount of water entering the cell. If adjacent groundwater levels are higher than the specified river cell head value, then water enters the drain cell. Conversely, if groundwater levels are lower than the specified drain cell head value, then water does not enter the drain cell. The drain cell conductance, which represents the silt layer at the bottom of river, provides resistance to flow in and out of the drain cells. Given that Ohio River is a regional discharge feature, it is unlikely that the river recharges groundwater. The Ohio River was assigned a river stage of 297 ft based on the measured Ohio River stage that corresponds to the date that the water level elevations used for calibration were measured. The “best” conductance value was determined during model calibration.

The black areas shown in Figure 6.1 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 eastern and western edge of the model domain represent portions of the flow system on the other side of a groundwater divide. The flow area north of the Ohio River is hydraulically similar to the active portion of the model across the feature to the west; however, the Ohio River is a regional groundwater discharge feature and as such hydraulically isolates groundwater flow on either side of the surface water feature. Because the north side of the river is not part of the PGDP flow system, the area was assigned no-flow cells.

The bottom of model layer 3 corresponds to the top of the McNairy. It is recognized that groundwater flow does occur in the McNairy; however the velocities and volumes are significantly less than those of the RGA. Because of the minimal water transmission capabilities, the McNairy was excluded from the model.

Bayou Creek and Little Bayou Creek (internal model boundaries) were simulated using recharge cells and, while these features are technically boundary conditions, because they were simulated using recharge cells, the creeks will be discussed in Section 6.3.

Metropolis Lake was configured in model layer 1 by assigning a hydraulic conductivity value of 50,000 ft/day to the area corresponding to the lake. Use of a high hydraulic conductivity value results in a near horizontal water table (lake surface) in the feature that can move up and down during the calibration process and remain neutral with respect to the groundwater mass balance.

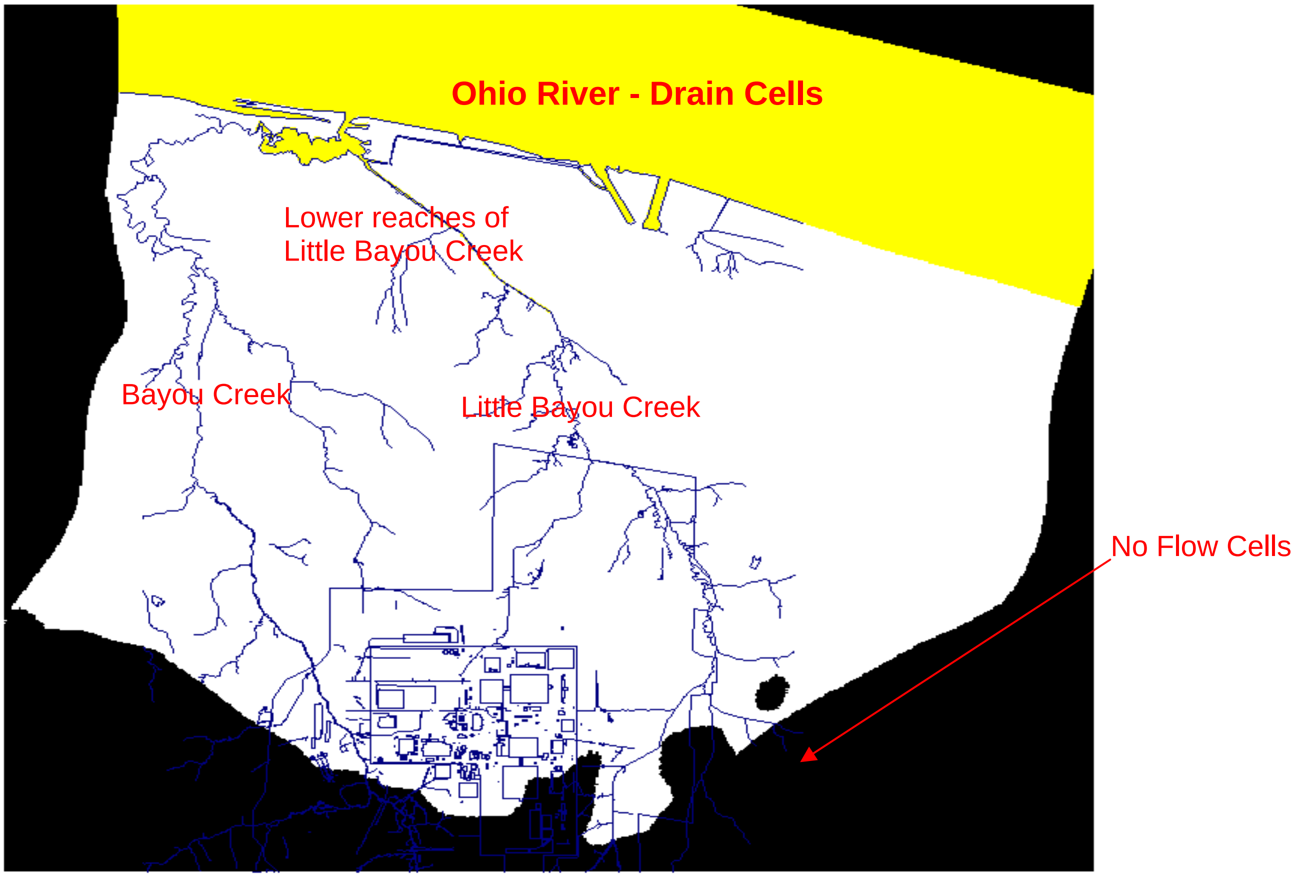


Figure 6.1. Model Boundaries

6.3 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.

6.3.1 Hydraulic Conductivity Zonation

Horizontal and vertical hydraulic conductivity distribution within the model domain was determined using pilot-points (Doherty 2004). 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 regression 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. For this application, the horizontal to vertical hydraulic conductivity ratio was assumed constant at 10:1.

Pilot points can be assigned locations and initial hydraulic conductivity values corresponding to well location and aquifer test results, respectively. For this application, pilot points were located where pumping tests had been conducted and assigned initial, minimum, and maximum hydraulic conductivity values corresponding to the pumping test results (Figure 6.2).

Pilot points also were used to determine horizontal and vertical hydraulic conductivity distribution in model layers 1 through 3 at locations absent of pumping test results (Figure 6.3). Greater pilot point density was used at PGDP and within the groundwater plumes 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 750 ft/day and constrained to minimum and maximum values of 50 and 5,000 ft/day. Initial vertical hydraulic conductivities were assumed to be one-tenth of the initial horizontal hydraulic conductivity estimates.

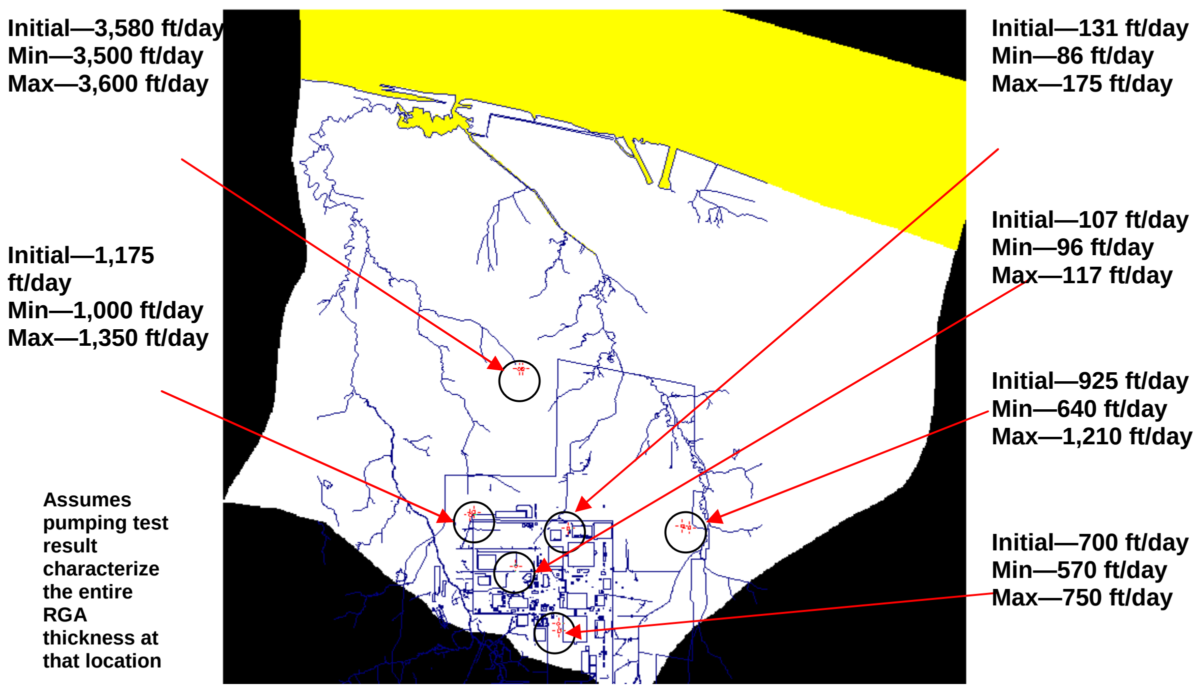


Figure 6.2. Pumping Test Pilot Point Locations

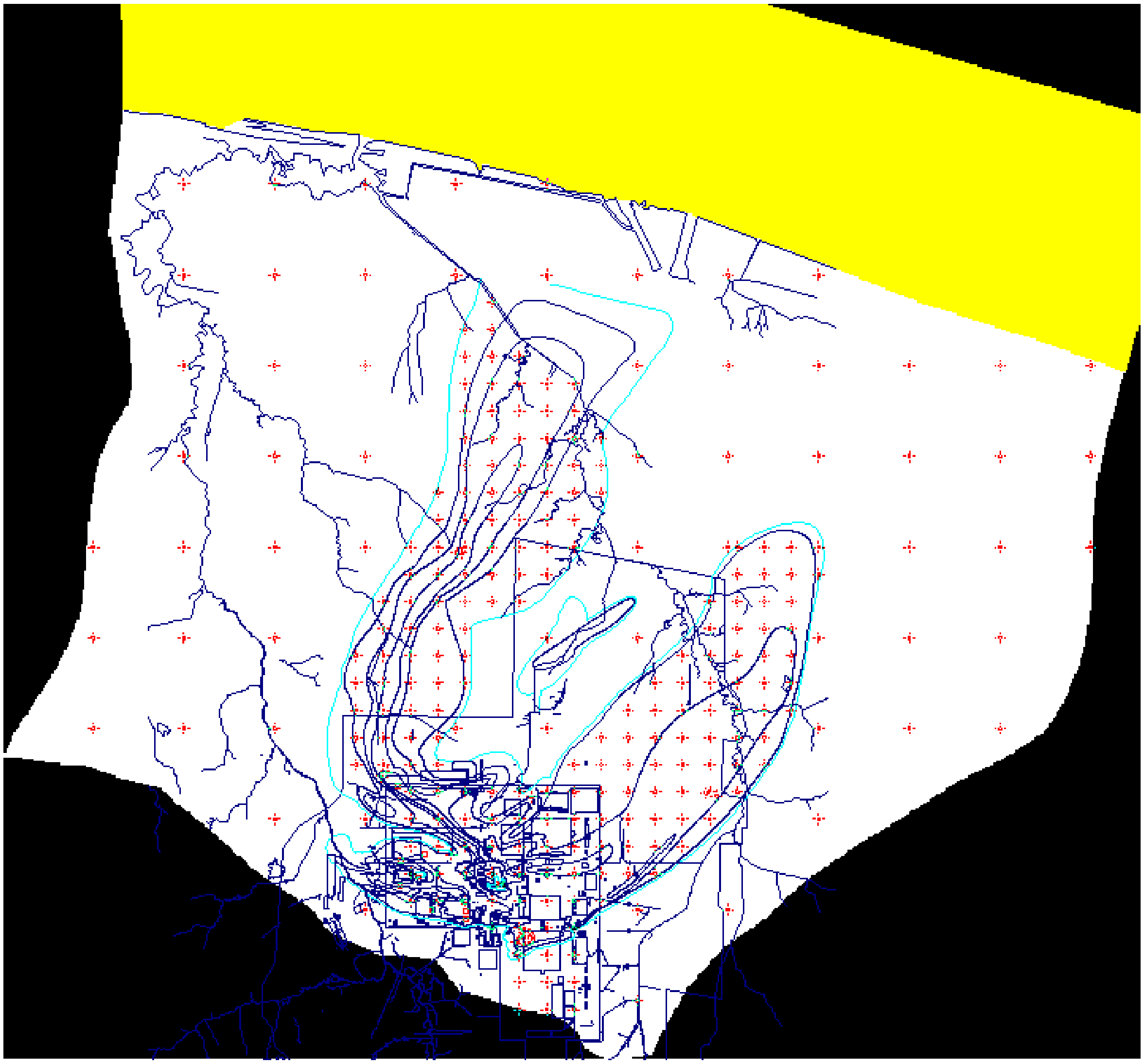


Figure 6.3. Model Layers 1 Through 3 Pilot Point Locations

6.3.2 Recharge Zonation

Both recharge from precipitation and anthropogenic recharge are represented in the model. Additionally, creek recharge and discharge are represented in the model using recharge cells. To remove water from the modeling domain, the recharge cells are assigned negative recharge.

Recharge associated from precipitation was assigned to all cells except those containing surface water and anthropogenic features (Figure 6.4). The cells representing the Ohio River were assigned a zero recharge rate. This was done because water falling on the Ohio River does not enter the groundwater flow system. Recharge from precipitation was assigned an initial value of 5.14 inches/year and minimum and maximum allowable values of 2.64 and 7.64 inches/year.

Anthropogenic recharge is difficult to simulate because, while underground water lines are known to leak, the location of the leaks are difficult to locate. To overcome this difficulty, underground water supply lines at the PGDP were simulated using a checkerboard pattern of recharge cells (Figure 6.5). The

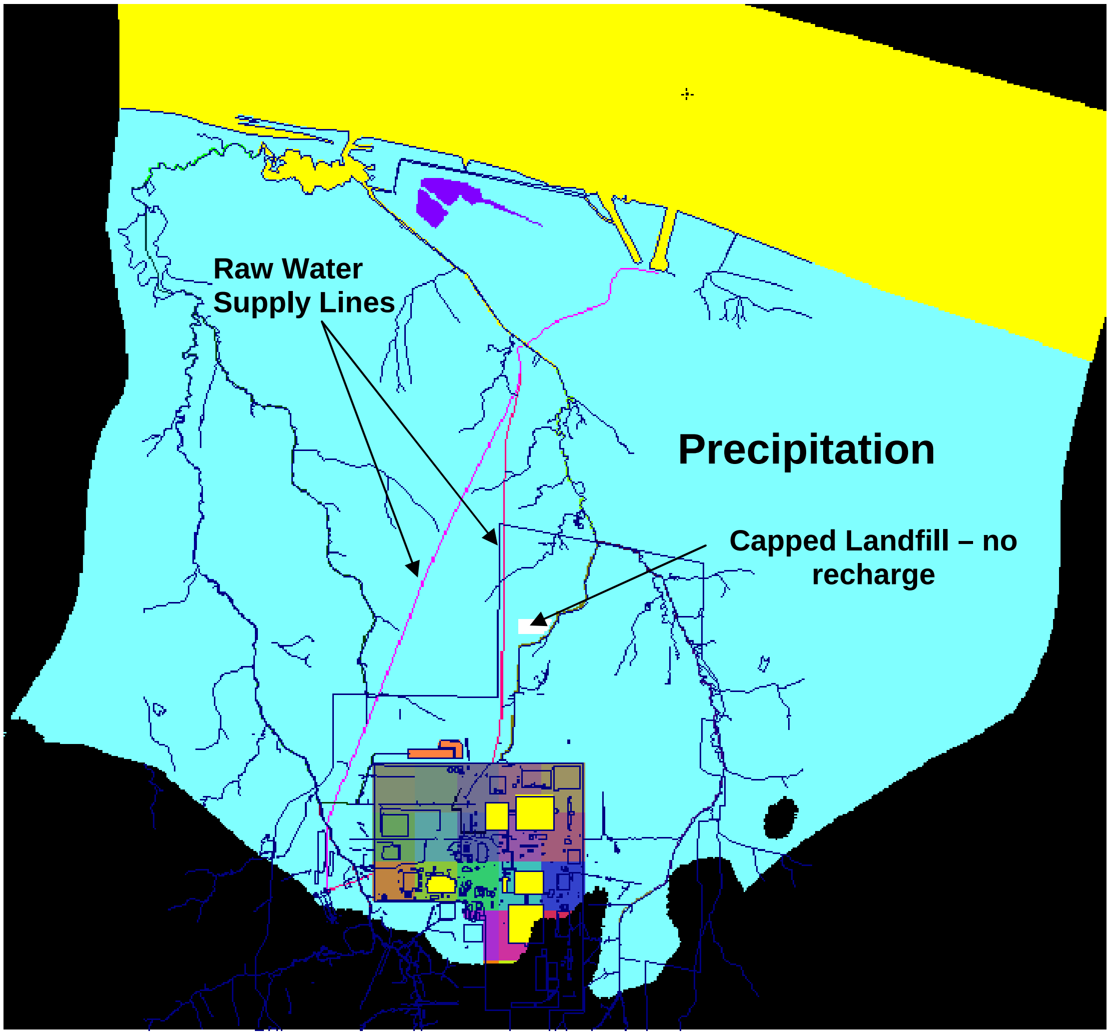


Figure 6.4. Recharge from Precipitation (Light Blue)

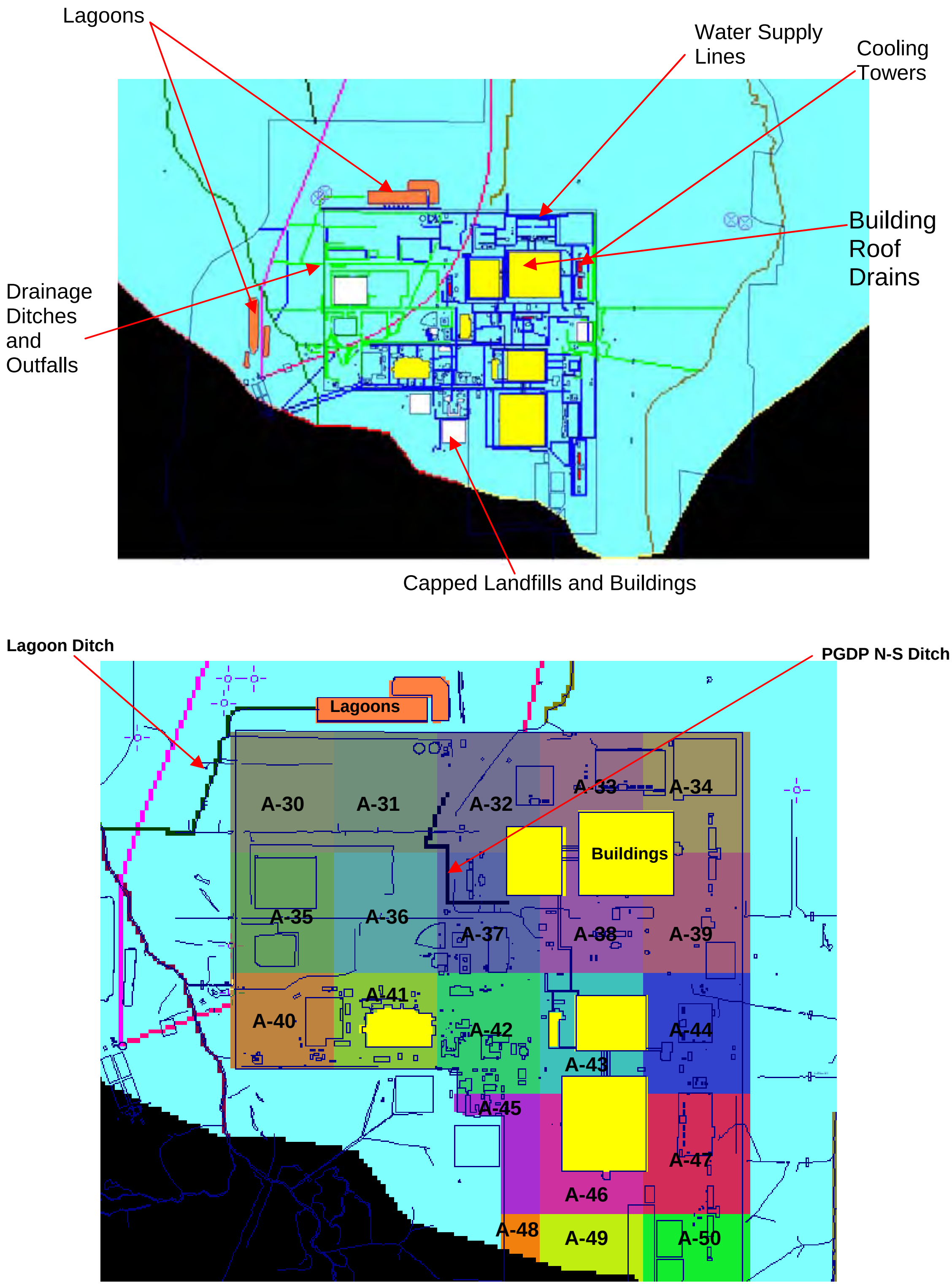


Figure 6.5. Anthropogenic Recharge

checkerboard pattern was adopted so that the bulk anthropogenic recharge rates representing recharge rates from leaky underground utilities, rainfall infiltration, and the absence of recharge (pavement and capped landfills) within individual checkerboard squares could be calculated rather than trying to estimate leakage from the individual components as a whole. For identification purposes, the anthropogenic recharge squares were assigned names between A-30 and A-50. Other anthropogenic features simulated include a lagoon, building roof drains, the lagoon ditch, and the PGDP North-South Diversion Ditch. Recharge from these features was assumed to between 1×10^{-6} and 2.62×10^{-2} ft/day and was assigned initial values somewhere between the extreme values. The maximum recharge rate corresponds to the maximum possible flux through the UCRS, assuming a vertical hydraulic conductivity of 2.62×10^{-2} ft/day and a vertical hydraulic gradient of unity.

Given the absence of data regarding the TVA Pond, the feature was assigned a recharge rate of 1.59×10^{-2} ft/day (Figure 6.6). Recharge from the pond was assumed constant and was not adjusted during model calibration. The TVA Pond recharge rate was assigned based on simulation results from numerous model runs conducted during this modeling effort prior to the final calibration effort. The objective of the simulations was to achieve reasonable mounding in the vicinity of the feature without dominating groundwater flow pattern in the area (i.e., force the Northwest Plume away from its observed location).

Anthropogenic recharge associated with the raw water supply lines extending from the Ohio River to the PGDP was not simulated in the model (Figure 6.6). Model runs conducted prior to the final calibration effort showed these features to be insensitive, meaning it was impossible to determine unique calibrated recharge values for the features. Portions of the model domain containing these features were assigned recharge rates corresponding to precipitation recharge.

Similarly, model runs conducted prior to the final calibration showed that anthropogenic leakage from the settling ponds was insensitive and could not be robustly estimated.

Finally, Bayou and Little Bayou Creeks were divided into four sections labeled very upper, upper, middle, and lower Bayou and Little Bayou Creeks (Figure 6.7). The very upper, upper, and middle creek sections were assigned minimum and maximum recharge values of 1×10^{-6} and 2.62×10^{-2} ft/day, respectively. Initial recharge values for the creek sections were between these values. The lower creek sections correspond to gaining sections of Bayou and Little Bayou Creeks and were assigned minimum negative recharge rates ranging between -1×10^{0} and -1×10^{-6} ft/day, respectively. Initial recharge values for both lower creek sections were between the two extremes.

It should be noted that Bayou Creek does extend further to the south, outside the model domain. This portion of the creek overlies the Porters Creek Clay and, as such, is hydraulically isolated from the RGA and was not included in the model.

6.3.3 Other Parameters

Porosity within the model domain was assigned a value of 30%.

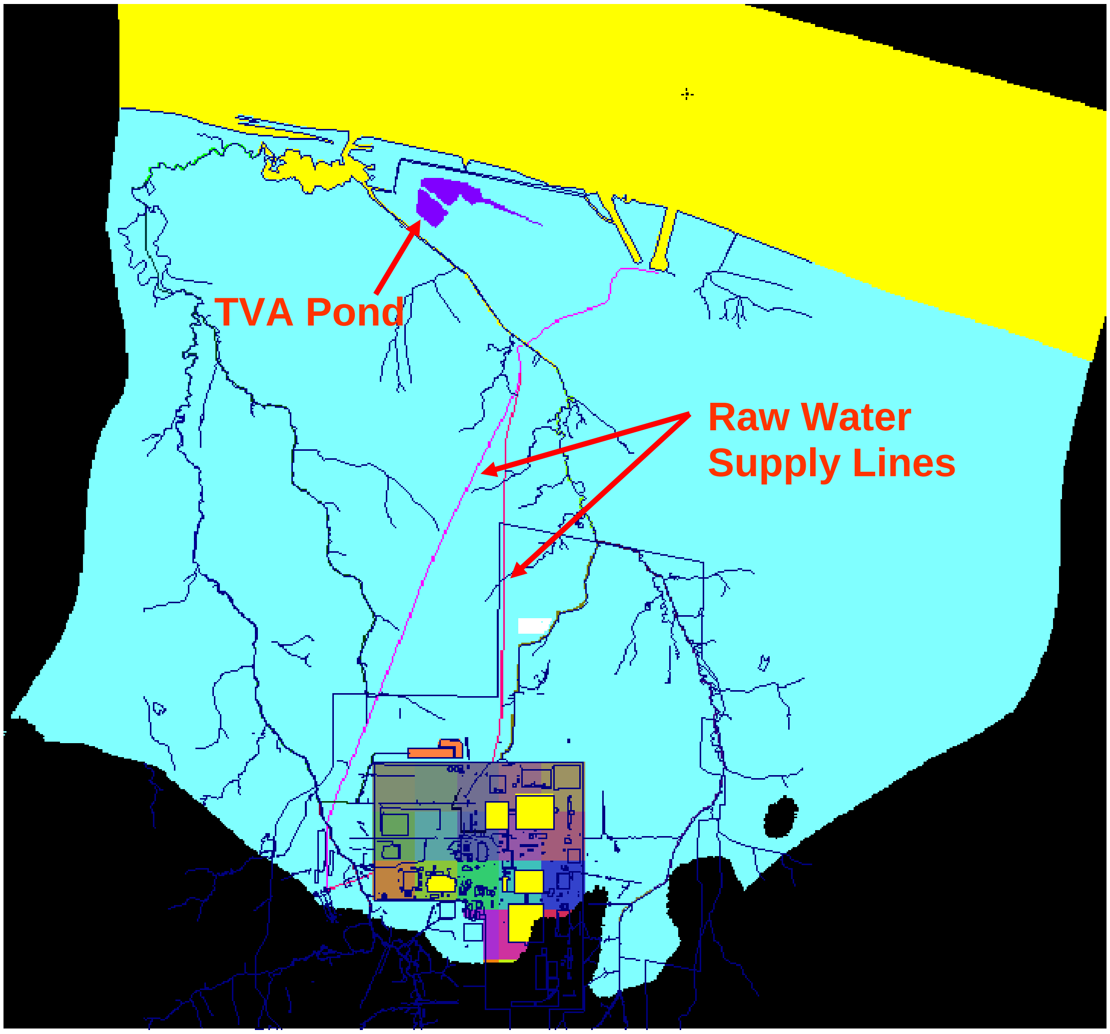


Figure 6.6. Other Anthropogenic Recharge Features

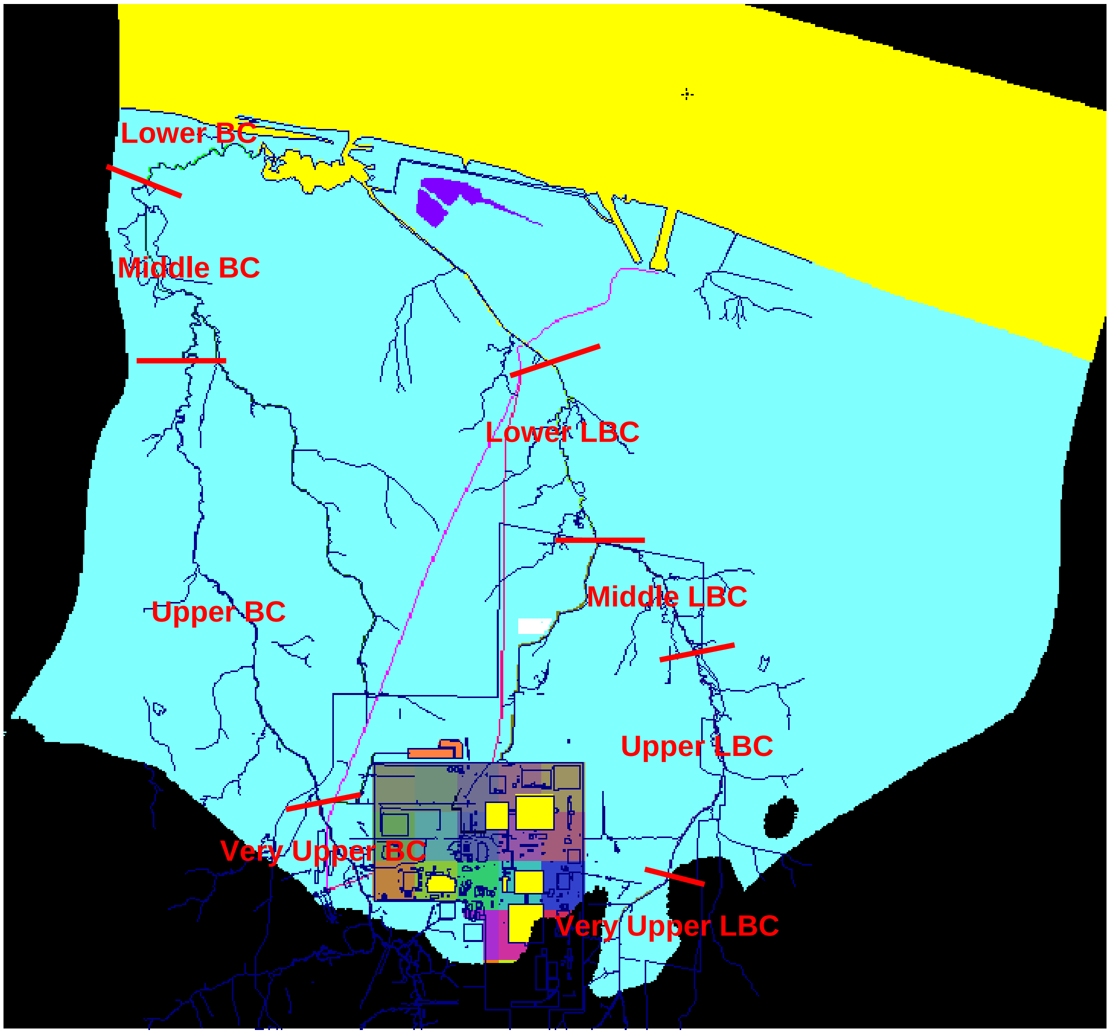


Figure 6.7. Bayou and Little Bayou Creeks

7. 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 developed, is a parameter estimation code that automatically 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 856 model runs and as many as 30 iterations to achieve calibration resulting in a total run time of more than five 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 and that translates to faster simulation times.

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 results in a non-biased answer for a given model configuration. The estimated parameters always will 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.

7.1 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 typically are less available, but also are used to evaluate model calibration. Parameter values themselves, such as hydraulic conductivity derived from pumping tests, can be used as calibration targets too. Finally, plume flow paths 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.

7.1.1 Water Level Elevation Targets

Water level elevations measured in February 1995 were used as calibration targets. This measurement period was selected based on the large number of wells measured and because the measurement period was prior to initiating pumping of the extraction wells (August 1995). In total, 76 water level elevation targets were used to calibrate the model. Forty-four of the targets were located in model layer 1, 20 in model layer 2, and 12 in model layer 3 (Figure 7.1). Target values are listed in Table 7.1.

Most of the water level targets are located within the PGDP plant boundary (42). Eight and 10 targets are located within the Northeast and Northwest Plumes, respectively. The remaining 16 water level targets are located outside of the PGDP plant boundary and the Northeast and Northwest Plumes.

Model Layer 1

Model Layer 2

Model Layer 3

Figure 7.1. Location of Water Level Elevation Targets

Table 7.1. Water Level Elevation Targets

Name	Model Layer	Target, ft amsl	Location	Name	Model Layer	Target, ft amsl	Location
MW126	1	325.29	Northeast Plume	MW169	1	325.22	PGDP
MW145	1	325.68	Northeast Plume	MW173	1	326.28	PGDP
MW193	1	325.10	Northeast Plume	MW178	1	326.65	PGDP
MW99	1	323.14	Northeast Plume	MW185	1	326.18	PGDP
PZ107	1	327.72	Northeast Plume	MW188	1	326.70	PGDP
MW148	2	323.59	Northeast Plume	MW205	1	325.15	PGDP
MW144	3	325.74	Northeast Plume	MW206	1	325.89	PGDP
MW163	3	326.35	Northeast Plume	MW227	1	326.97	PGDP
MW106	1	325.41	Northwest Plume	MW328	1	326.07	PGDP
MW123	1	323.85	Northwest Plume	MW329	1	326.12	PGDP
MW197	1	325.06	Northwest Plume	MW330	1	326.87	PGDP
MW201	1	322.00	Northwest Plume	MW63	1	325.88	PGDP
MW137	2	321.09	Northwest Plume	MW66	1	324.97	PGDP
MW152	2	316.18	Northwest Plume	MW67	1	326.82	PGDP
MW202	2	323.42	Northwest Plume	MW71	1	325.24	PGDP
MW98	2	322.97	Northwest Plume	MW84	1	326.34	PGDP
MW125	3	323.83	Northwest Plume	MW87	1	326.32	PGDP
MW134	3	330.07	Northwest Plume	MW90	1	326.02	PGDP
MW139	1	323.58	Outside PGDP and Plumes	PZ107	1	327.72	PGDP
MW147	1	320.09	Outside PGDP and Plumes	PZ110	1	326.54	PGDP
MW179	1	324.65	Outside PGDP and Plumes	PZ117	1	327.03	PGDP
MW181	1	324.96	Outside PGDP and Plumes	MW161	2	326.65	PGDP
MW191	1	325.24	Outside PGDP and Plumes	MW175	2	326.71	PGDP
MW194	1	325.39	Outside PGDP and Plumes	MW325	2	325.64	PGDP
MW222	1	324.59	Outside PGDP and Plumes	MW326	2	326.76	PGDP
MW223	1	324.59	Outside PGDP and Plumes	MW327	2	326.62	PGDP
MW224	1	325.74	Outside PGDP and Plumes	MW79	2	326.43	PGDP
MW225	1	324.81	Outside PGDP and Plumes	MW93	2	326.32	PGDP
MW142	2	325.26	Outside PGDP and Plumes	PZ109	2	326.56	PGDP
MW150	2	324.69	Outside PGDP and Plumes	PZ118	2	326.31	PGDP
MW199	2	323.77	Outside PGDP and Plumes	W108	2	326.82	PGDP
MW200	2	324.52	Outside PGDP and Plumes	MW158	3	327.03	PGDP
MW327	2	326.62	Outside PGDP and Plumes	MW163	3	326.35	PGDP
MW132	3	323.48	Outside PGDP and Plumes	MW226	3	326.94	PGDP
MW156	1	326.62	PGDP	MW86	3	325.85	PGDP
MW159	1	326.50	PGDP	MW89	3	325.75	PGDP
MW165	1	326.30	PGDP	MW92	3	325.78	PGDP
MW168	1	326.37	PGDP	MW95	3	325.72	PGDP

7.1.2 Flux Targets

An Ohio River flux target of 4,837 gpm was assigned to the drain cells representing the river in the model domain. The flux target is representative of expected groundwater discharge to the Ohio River (groundwater discharge plus leakage from TVA Pond). Flux measurements are at a different scale than water level measurements. For example, a 1-ft difference in water levels represents a different degree of accuracy than a measured and modeled flux difference of 1 gpm (a model-predicted Ohio River groundwater discharge of 4,838 gpm would be considered an exact match to the measured value of 4,837 gpm). Based on experience, matching the flux target within a value of 100 gpm would be considered a good match. Model calibration is evaluated by the closeness of the match between measured and model-predicted values and typically is expressed as the SDS. Squaring is performed to nullify the effects of adding negative and positive numbers together when assessing calibration. For example, suppose the model predicts two water levels that differ from the measured values by -5 ft and +5 ft. Summing the two values produces a zero value, which is the same value that is obtained by summing two residuals (the difference between measured and model-predicted values) together that exactly match the target value. To provide a more accurate measurement of calibration, the individual residuals are squared and then added together (SDS). For the above example, adding the differences squared together of two residuals (-5 ft and +5 ft) produces a SDS of 50 ft^2, which is vastly different from the SDS (0 ft^2) of two model-predicted values that exactly match the measured values. Now consider an Ohio River groundwater flux prediction that differs by 100 ft^3/day. Squaring difference results in a value of 10,000 being added to the calibration statistic. There are 76 water level targets that are used to calibrate the model. Each of the water level targets would need to be off by more than 11 ft to equal the contribution that a 100 ft^3/day Ohio River groundwater flux model-predicted and measured difference would contribute to the overall model calibration statistics. To keep the flux target from dominating the calibration, the target was assigned a weight of 7.55×10^{-6}, which, when multiplied by the difference between the predicted and target flux values, produced a weighted target difference of between five and seven if the predicted flux value (ft^3/d) reaches either the minimum (43,890 ft^3/day, 228 gpm) or maximum (1,581,965 ft^3/day, 8,218 gpm) extreme calculated values. Selection of a weighted difference of between five and seven is entirely arbitrary and is based on professional judgment.

7.1.3 Angle Targets

A previous model iteration from this calibration effort matched the northeast, northwest, and southwest plume trajectories for a uniform hydraulic conductivity distribution. The plume trajectory match was achieved with no regard to matching pumping test hydraulic conductivity estimates, water level targets, or reasonable anthropogenic recharge rates. The sole purpose of the simulation was to match plume trajectories, which were used to help calibrate the final model.

Groundwater Vistas, the pre- and post-processing modeling software used during the modeling effort, calculates angle targets based on three user-specified water level elevation targets. To utilize the plume trajectories predicted by the previous model, targets were added every fifth row and column and assigned the model-predicted water levels at those locations as targets (Figure 7.2). As a result, 1,704 angle targets were created using the water level targets as the triangle vertices. As stated in the previous paragraph, no effort was made to match known water level elevations during the simulation effort, only plume flow paths. To keep the target water level elevations from entering into the regression analysis, the water level targets at the triangle vertices were assigned weights of zero; however, the angle targets associated with the triangles are not influenced by the zero water level target weights and do influence the calibration analysis.

Similar to the flux measurement scale issue, because of the sheer number of angle targets relative to the number of water level elevation targets, the angle targets potentially could dominate the calibration and bias the calibration results. For example, assume each of the angle targets is off by two degrees. The contribution of the angle targets to the SDS would be 6,816, which is equivalent to each of the 76 model water level predictions to be off by 19.5 ft. To keep the angle targets from dominating the regression analysis, a global weight of 0.01 was assigned to the angle targets. This means if the angle SDS is 6,816, then a value of 68.16 would be added to the calibration statistics.

7.1.4 Pilot Point Targets

Pilot points were assigned to model layers 1 through 3 as shown in Figures 6.2 and 6.3. During the automated calibration process, horizontal hydraulic conductivity was estimated at each pilot point. 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). To keep the initial and predicted value differences from dominating the regression analysis, a weight is calculated after each parameter estimation iteration and the weight is multiplied by the difference between the model-predicted and initial hydraulic conductivity values so the differences results in a near zero contribution to the regression analysis.

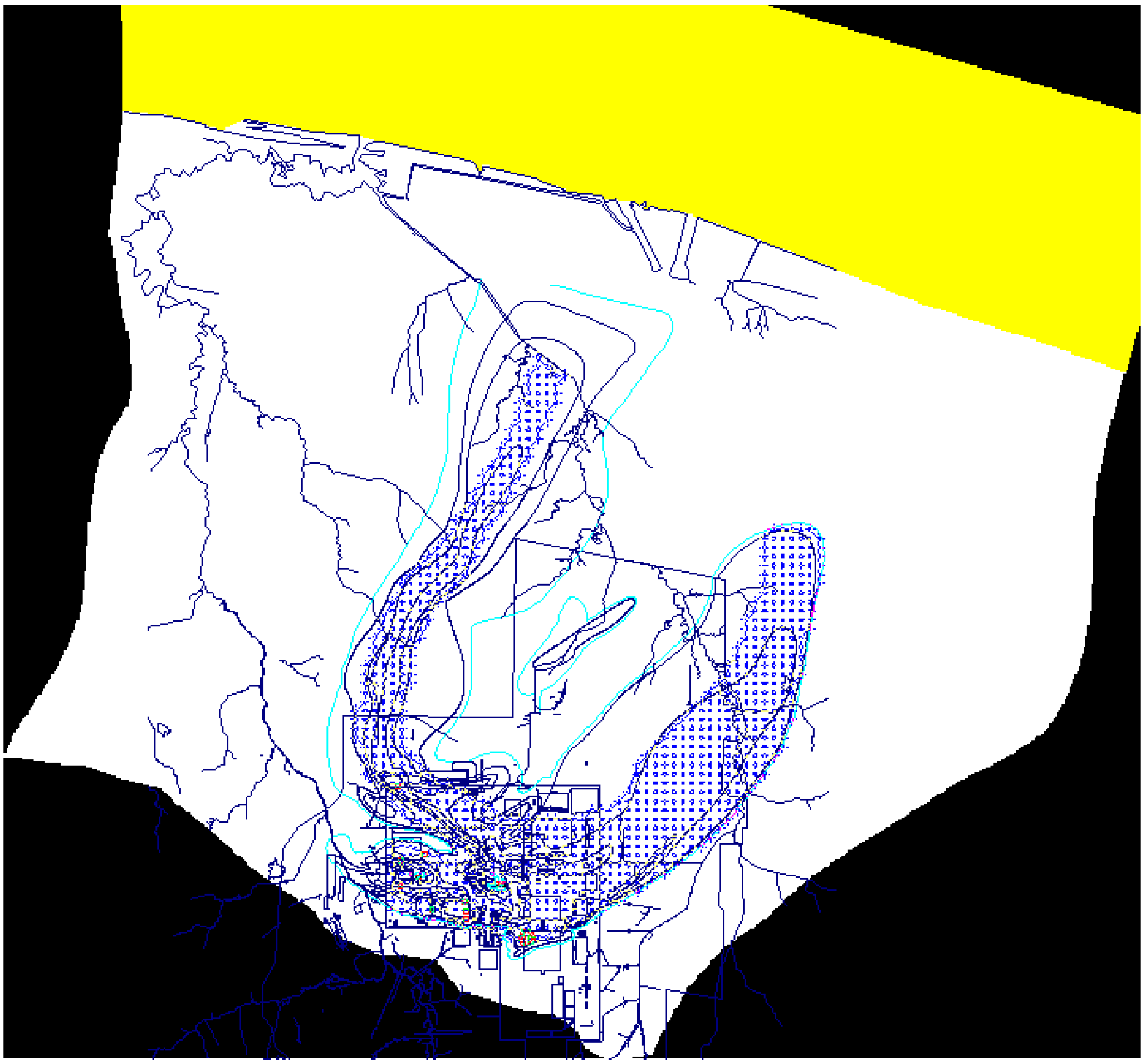


Figure 7.2. Location of Angle Targets

7.1.5 Initial Parameter Sensitivities

Using parameter estimation, it is possible to robustly estimate parameter values having sensitivities within two orders of magnitude of the most sensitive parameter (Hill 1998). It may or may not be possible to robustly estimate parameter values for those parameters having sensitivities within two to three orders of magnitude of the most sensitive parameter. Sensitivities more than three orders of magnitude less sensitive than the most sensitive parameter cannot be robustly estimated.

Before utilizing parameter estimation to calibrate a model, initial parameter sensitivities should be determined to see if any of the parameters are too insensitive to estimate. Figure 7.3 shows the relative composite scaled sensitivities of the ten most sensitive parameters, the most sensitive pilot point, and the 10 least sensitive parameters. (NOTE: all the parameter sensitivities are within two orders of magnitude of the most sensitive parameter indicating that it is possible to robustly estimate values for all the model parameters.)

Initial hydraulic conductivity pilot point sensitivities for model layers 1 through 3 relative to the most sensitive pilot point are shown in Figure 7.4. Note that all the pilot point sensitivities are within an order of magnitude of one other, indicating that unique hydraulic conductivities can be estimated for each pilot point.

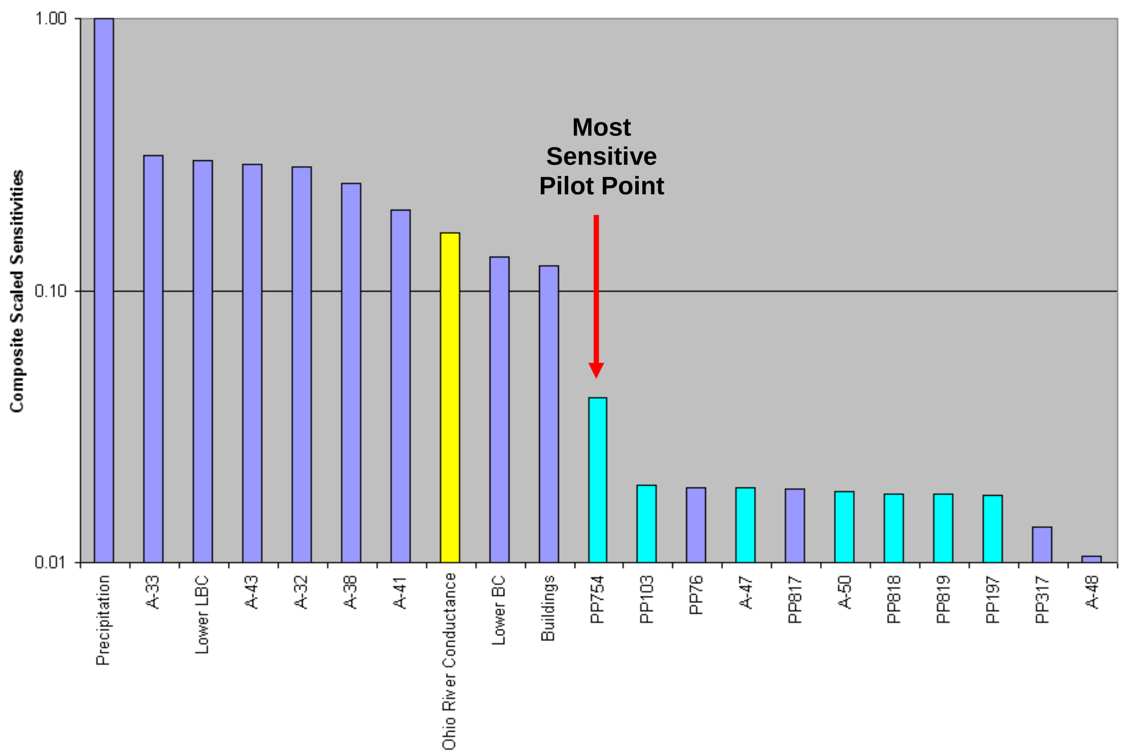


Figure 7.3. Initial Parameter Sensitivities

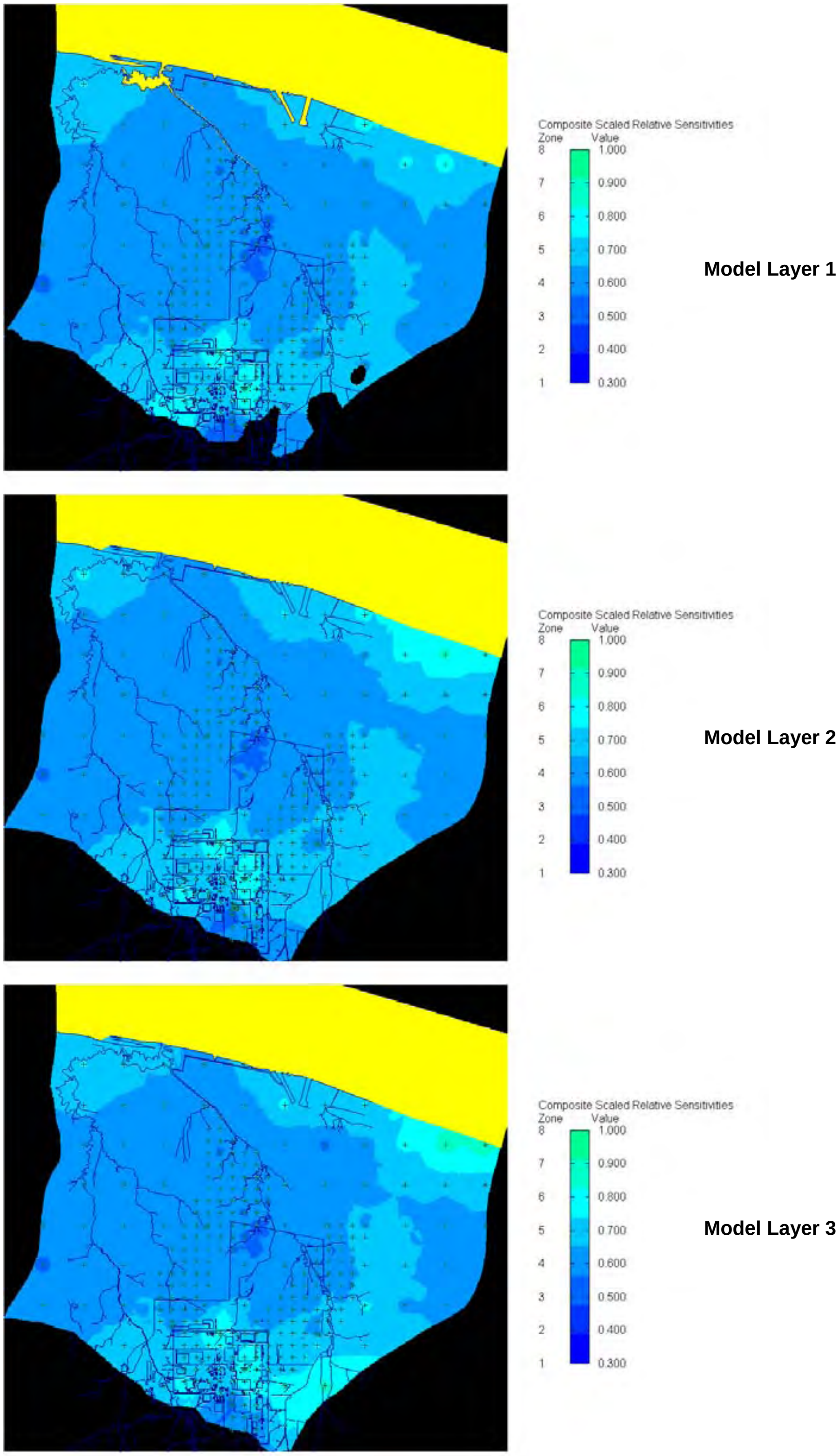


Figure 7.4. Initial Pilot Point Sensitivities

7.2 CALIBRATION RESULTS

The calibration results with respect to predicted hydraulic conductivity distributions, estimated recharge rates, target agreement, and plume flow paths are discussed in the following sections.

7.2.1 Estimated Hydraulic Conductivity Values

The estimated horizontal hydraulic conductivity distributions for model layers 1 through 3 are shown in Figures 7.5 through 7.7. Predicted pilot point hydraulic conductivity values range between 50 and 5,000 ft/day and average 1,906 ft/day (Table 7.2). Higher hydraulic conductivities are predicted east and west of PGDP in all three model layers. Additionally, higher hydraulic conductivities extend toward the north to the Ohio River. Lower hydraulic conductivities are located beneath the PGDP.

Transmissivity is a water supply term used to describe the permeability of a thickness of sediments. The transmissivity of the PGDP hydraulic basin was calculated by multiplying the layer predicted hydraulic conductivity values by the layer thickness and then summing the individual transmissivities of the three layers (Figure 7.8). A zone of higher transmissivity is predicted west of PGDP. Lower transmissivity areas are located along the Ohio River and in isolated areas beneath PGDP.

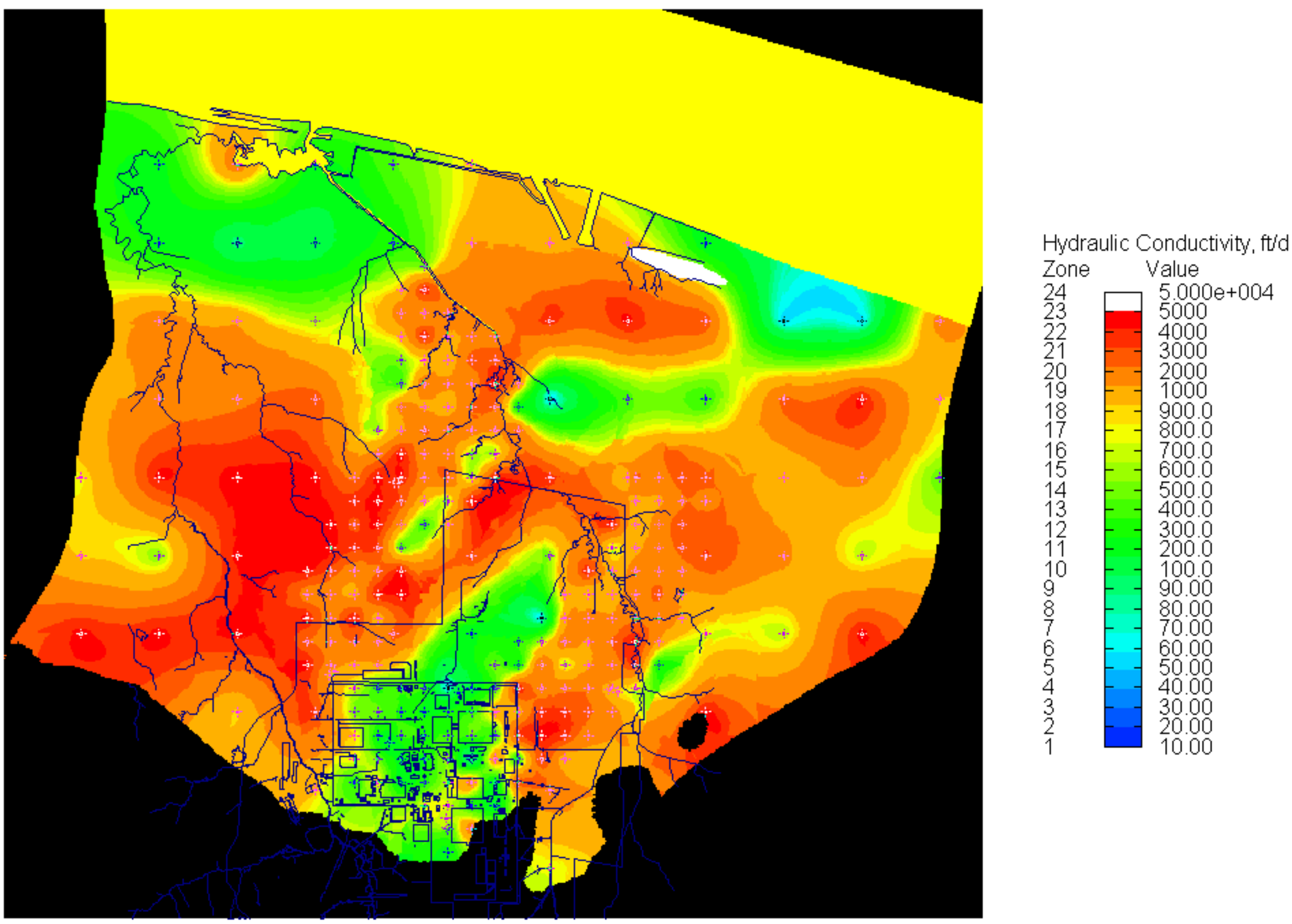


Figure 7.5. Model Layer 1 Predicted Hydraulic Conductivity Distribution

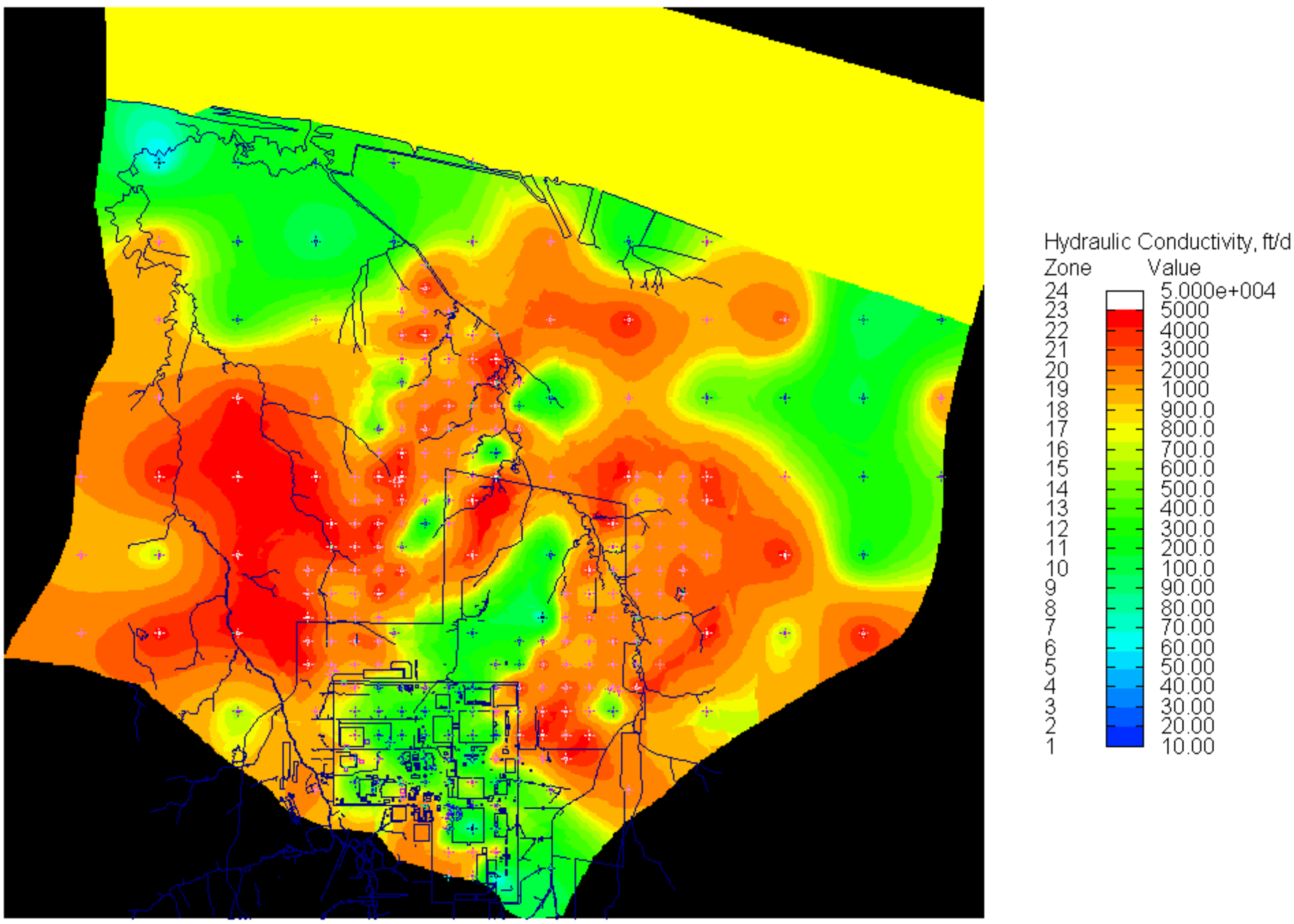


Figure 7.6. Model Layer 2 Predicted Hydraulic Conductivity Distribution

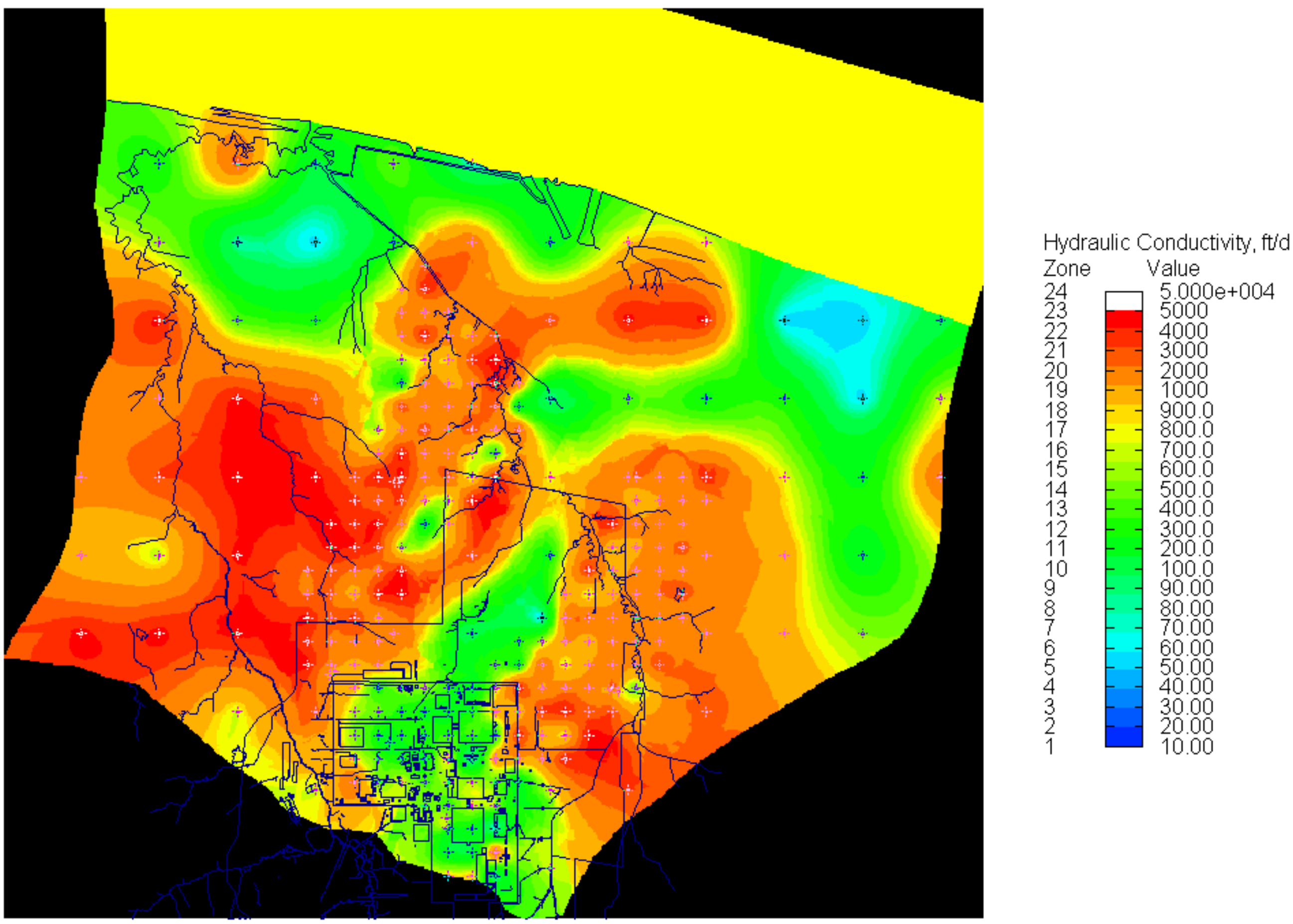


Figure 7.7. Model Layer 3 Predicted Hydraulic Conductivity Distribution

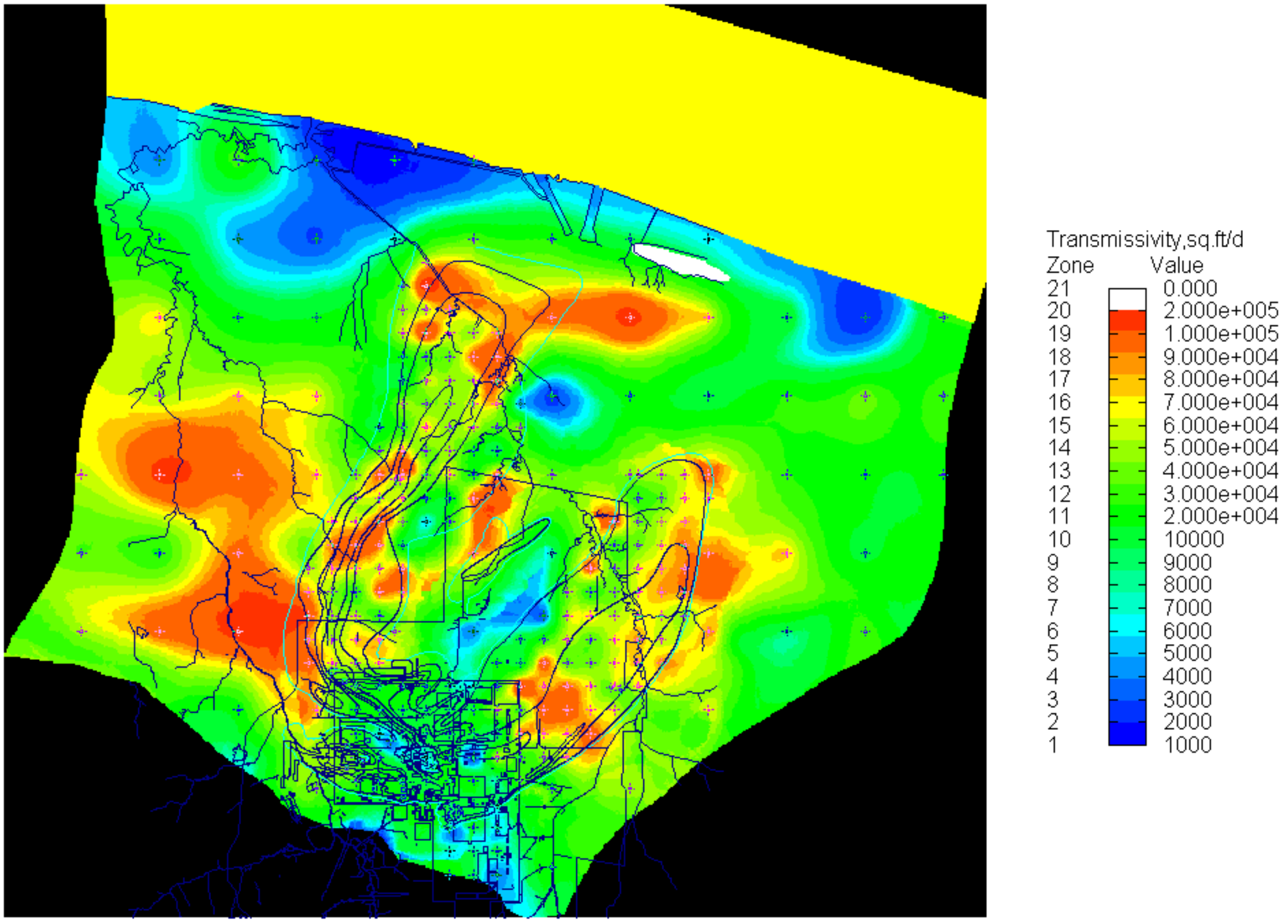


Figure 7.8. PGDP Plant Model-Predicted Transmissivity

Table 7.2. Pilot Point Hydraulic Conductivity Statistics

Hydraulic Conductivity, ft/d	All Layers	Layer 1	Layer 2	Layer 3
Average	1906	1947	1874	1899
Median	1497	1531	1379	1535
Standard Deviation	1582	1576	1583	1590
Maximum	5000	5000	5000	5000
Minimum	50	50	50	50
Range	4950	4950	4950	4950

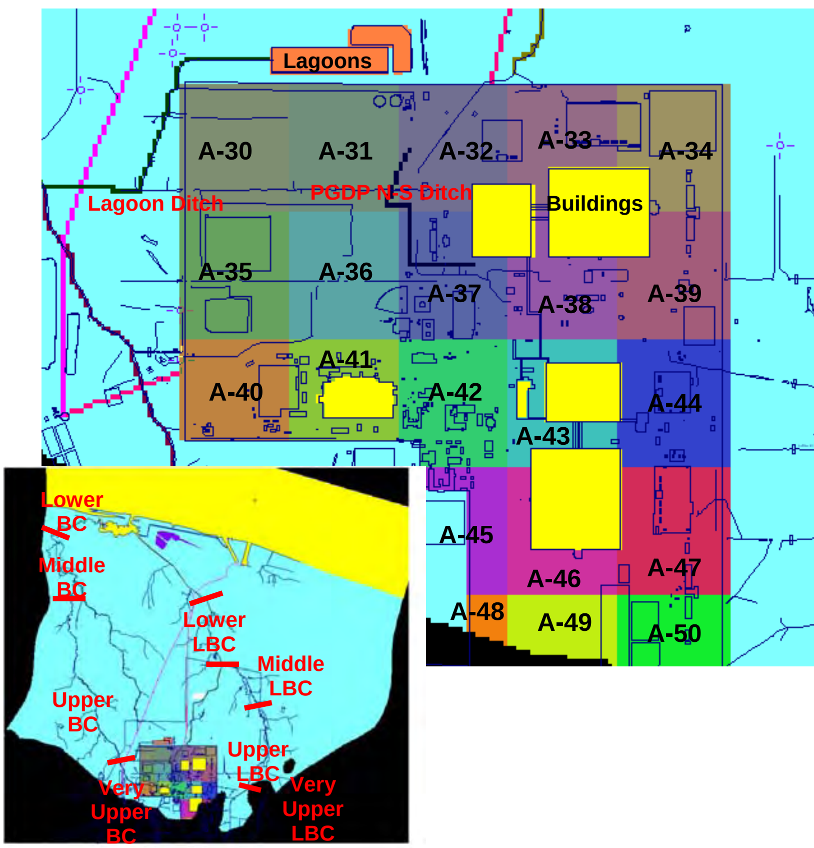
7.2.2 Estimated Recharge Values

Estimated recharge values are presented in Figure 7.9. The estimated recharge rate from precipitation is estimated to be 7.44 inches/year. Recharge associated with building roof runoff routed to gravel beds beneath the building is estimated to be 18.60 inches/year. Additionally, a significant recharge rate is predicted for the lagoon.

The predicted recharge rate for the upper reach of Bayou Creek is greater than that predicted for the very upper reach of the creek. Conceptually this makes sense as the PGDP discharges permitted process water to the upper reach of Bayou Creek. Recharge rates decline in the middle reach of Bayou Creek. The lower portion of Bayou Creek is a gaining section as denoted by the negative recharge rate and, as such, removes groundwater from the flow system.

Predicted recharge rates for Little Bayou Creek are greatest for the very upper reaches and decline in value downstream. Conceptually, this makes sense as the Terrace Gravel, located south of the PGDP, is isolated from the RGA by the Porters Creek Clay. A likely discharge location for Terrace Gravel groundwater is Little Bayou Creek. The lower portion of Little Bayou Creek is a groundwater sink as denoted by the negative recharge rate and removes groundwater from the flow system.

Predicted recharge rates for the anthropogenic recharge squares range in value from 0 to 114.83 inches/year. The maximum anthropogenic rate is bounded based on Darcy calculations that used a unity vertical hydraulic gradient and average UCRS vertical hydraulic conductivity. The maximum anthropogenic recharge rate is based on the higher predicted recharge rates are associated with A-43, A-32, A-34, and A-45 squares. Zero recharge is predicted for A-36 through A-38 squares. It should be noted that there are no available data to confirm the validity of the anthropogenic recharge rate predictions other than these are the values that best matched the target water levels and produced the best plume trajectories.



Parameter	In/yr	Ratio
Precipitation	7.44	1.00
Buildings	18.60	2.50
Lagoon	114.83	15.45
Lagoon Ditch	88.18	11.86
PGDP N-S Ditch	11.59	1.56
Very Upper BC	24.53	3.30
Upper BC	148.55	19.98
Middle BC	18.32	2.46
Lower BC	-986.18	-132.64
Tributary BC	6.94	0.93
Very Upper LBC	148.89	20.03
Upper LBC	40.77	5.48
Middle LBC	2.64	0.35
Lower LBC	-938.91	-126.28
Tributary LBC	41.69	5.61
A-30	25.60	3.44
A-31	4.33	0.58
A-32	71.38	9.60
A-33	17.23	2.32
A-34	65.09	8.75
A-35	9.53	1.28
A-36	0.00	0.00
A-37	0.00	0.00
A-38	0.00	0.00
A-39	41.50	5.58
A-40	0.23	0.03
A-41	2.79	0.38
A-42	6.37	0.86
A-43	114.83	15.45
A-44	12.43	1.67
A-45	55.45	7.46
A-46	1.65	0.22
A-47	0.03	0.00
A-48	0.02	0.00
A-49	0.23	0.03
A-50	0.05	0.01

Figure 7.9. Model-Predicted Recharge Values

7.2.3 Estimated Mass Balance

The model-predicted mass balance is summarized in Tables 7.3 and 7.4. The greatest source (~79%) of recharge to the PGDP hydrologic basin is from precipitation. Anthropogenic recharge contributes approximately 16% and the creeks approximately 3% of the inflow to the hydrologic basin. The majority of groundwater within the PGDP hydrologic basin discharges to the Ohio River (~88%), with the remaining groundwater discharging to the lower reaches of Bayou and Little Bayou Creeks.

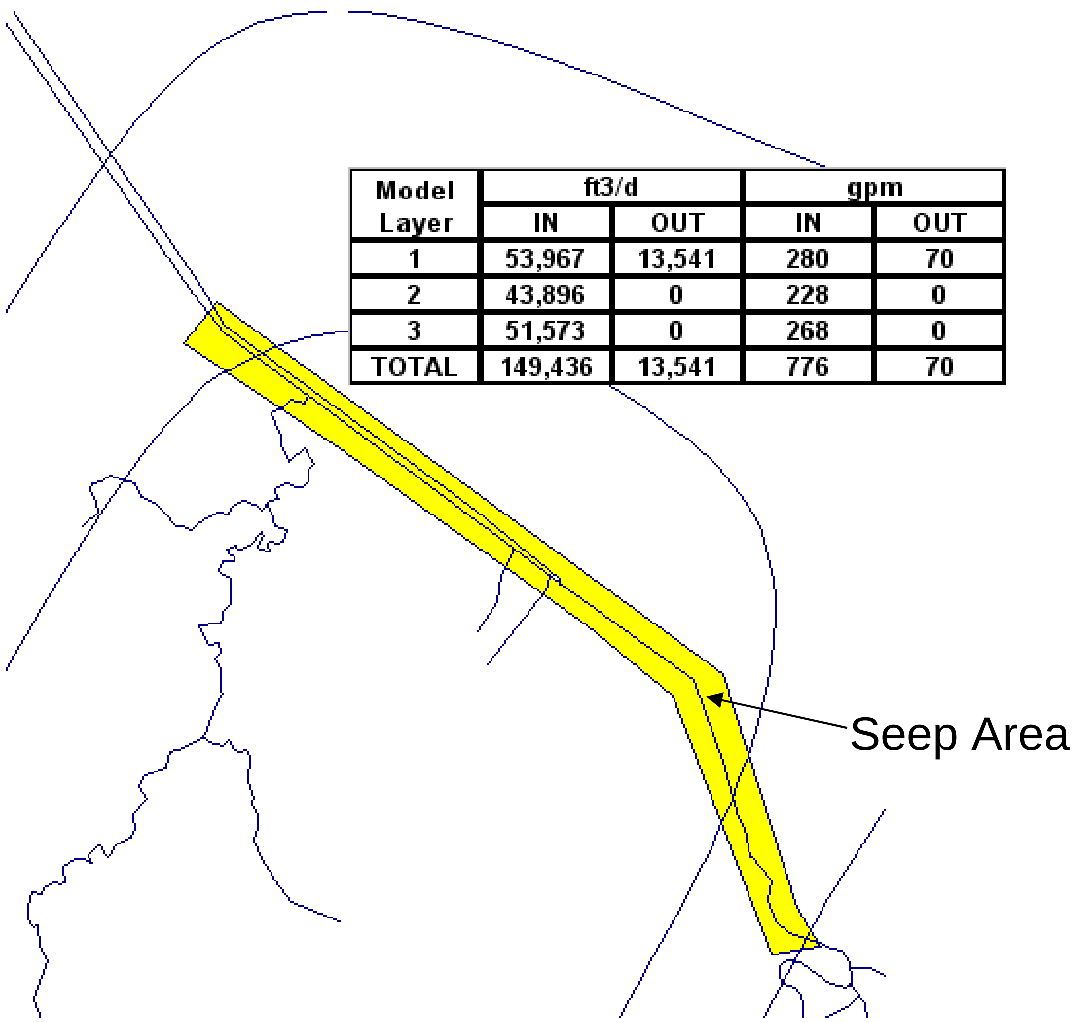
Table 7.3. Model-Predicted Mass Balance

Parameter	ft^3/d		GPM		Percentage	
	In	Out	In	Out	In	Out
TOTAL	**1,036,455**	**1,038,541**	**5,384**	**5,395**	**100.00%**	**100.00%**
Precipitation	815,208		4,235		78.65%	
Buildings	15,659		81		1.51%	
Lagoon	16,113		84		1.55%	
Lagoon Ditch	3,621		19		0.35%	
PGDP N-S Ditch	304		2		0.03%	
Very Upper BC	1,021		5		0.10%	
Upper BC	7,965		41		0.77%	
Middle BC	10,153		53		0.98%	
Lower BC		66,375	0	345	0	6.39%
Tributary BC	1,014		5		0.10%	
Very Upper LBC	7,049		37		0.68%	
Upper LBC	3,581		19		0.35%	
Middle LBC	146		1		0.01%	
Lower LBC		59,981	0	312	0	5.78%
Tributary LBC	4,304		22		0.42%	
A-30	9,812		51		0.95%	
A-31	1,633		8		0.16%	
A-32	25,038		130		2.42%	
A-33	4,777		25		0.46%	
A-34	23,390		122		2.26%	
A-35	3,651		19		0.35%	
A-36	2		0		0.00%	
A-37	1		0		0.00%	
A-38	1		0		0.00%	
A-39	14,912		77		1.44%	
A-40	70		0		0.01%	
A-41	629		3		0.06%	
A-42	2,331		12		0.22%	
A-43	24,235		126		2.34%	
A-44	4,841		25		0.47%	
A-45	9,647		50		0.93%	
A-46	311		2		0.03%	
A-47	12		0		0.00%	
A-48	1		0		0.00%	
A-49	42		0		0.00%	
A-50	18		0		0.00%	
TVA Pond	24,963		130		2.41%	
Ohio River		912,185		4,739		87.83%

Table 7.4. Model-Predicted Mass Balance Summary

Parameter	ft³/d		GPM		Percentage	
	In	Out	In	Out	In	Out
TOTAL	**1,036,455**	**1,038,541**	**5,384**	**5,395**	**100.00%**	**100.00%**
Precipitation	815,208		4,235		78.65%	
Anthropogenic Recharge	161,051		837		15.54%	
TVA Pond	24,963		130		2.41%	
Creeks	35,233	126,356	183	656	3.40%	12.17%
Ohio River		912,185		4,739		87.83%

Model-predicted discharge in the area of the seeps, located at the toe of the Northwest Plume, is 70 gpm, which represents 9.5% of the total volume of groundwater (776 gpm) flowing through the area (Figure 7.10).



Model Layer	ft3/d		gpm	
	IN	OUT	IN	OUT
1	53,967	13,541	280	70
2	43,896	0	228	0
3	51,573	0	268	0
TOTAL	149,436	13,541	776	70

Figure 7.10. Model-Predicted Seep Discharge

7.2.4 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 model results in sum of the difference squared of 63.1 ft^2 (Table 7.5). Figure 7.11 is a plot of target residuals versus target water levels. The majority of the model-predicted water levels are within +/- 1 ft of the target values; however, some of the model-predicted water levels are over or under predicted by as much as 5 ft (Table 7.6). It should be noted that post-calibration evaluation of the target water level values shows that the recorded water level for MW-134 could be in error by as much as 5 ft. In general, the majority of predicted water levels are within +/- 1 ft of the target value.

Table 7.5. Water Level Target Calibration Statistics

Number of Targets		76
Sum of Squares		63.10
Residual Mean		-0.02
Res. Std. Dev.		0.91
Abs. Res. Mean		0.58
Min. Residual		-2.18
Max. Residual		5.12
Range in Target Values		13.89
Std. Dev./Range		0.07

* Units in ft

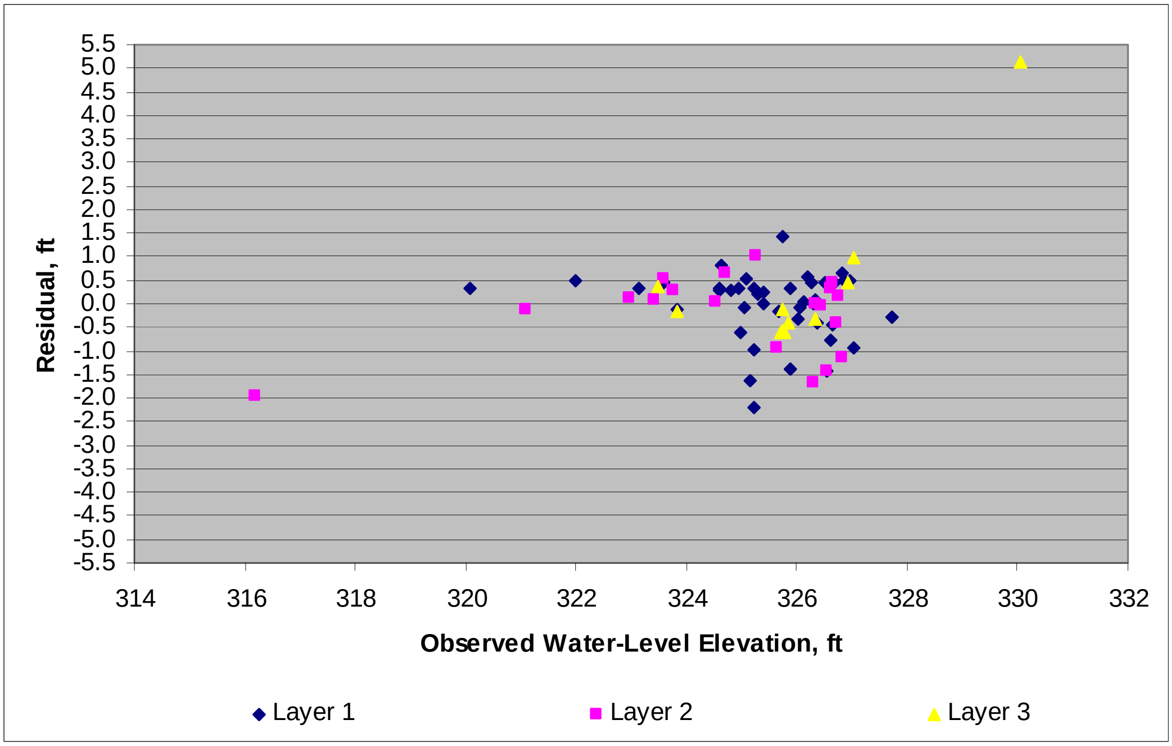


Figure 7.11. Residual Distributions

Table 7.6. Comparison of Model-Predicted and Target Water Level Elevations

Name	Area	Layer	Observed	Computed	Residual	Name	Area	Layer	Observed	Computed	Residual
MW139	Outside	1	323.58	323.12	0.46	MW169	PGDP	1	325.22	326.21	-0.99
MW147	Outside	1	320.09	319.78	0.31	MW173	PGDP	1	326.28	325.84	0.44
MW179	Outside	1	324.65	323.82	0.83	MW178	PGDP	1	326.65	327.11	-0.46
MW181	Outside	1	324.96	324.65	0.31	MW185	PGDP	1	326.18	325.61	0.57
MW191	Outside	1	325.24	324.93	0.31	MW188	PGDP	1	326.70	326.25	0.45
MW194	Outside	1	325.39	325.13	0.26	MW205	PGDP	1	325.15	326.77	-1.62
MW222	Outside	1	324.59	324.29	0.30	MW206	PGDP	1	325.89	327.27	-1.38
MW223	Outside	1	324.59	324.27	0.32	MW227	PGDP	1	326.97	326.49	0.48
MW224	Outside	1	325.74	324.31	1.43	MW328	PGDP	1	326.07	326.17	-0.10
MW225	Outside	1	324.81	324.51	0.30	MW329	PGDP	1	326.12	326.08	0.04
MW142	Outside	2	325.26	324.25	1.01	MW330	PGDP	1	326.87	326.37	0.50
MW150	Outside	2	324.69	324.03	0.66	MW63	PGDP	1	325.88	325.55	0.33
MW199	Outside	2	323.77	323.48	0.29	MW66	PGDP	1	324.97	325.57	-0.60
MW200	Outside	2	324.52	324.48	0.04	MW67	PGDP	1	326.82	326.19	0.63
MW327	Outside	2	326.62	326.31	0.31	MW71	PGDP	1	325.24	327.42	-2.18
MW132	Outside	3	323.48	323.12	0.36	MW84	PGDP	1	326.34	326.25	0.09
MW106	NW Plume	1	325.41	325.41	0.00	MW87	PGDP	1	326.32	326.30	0.02
MW123	NW Plume	1	323.85	323.98	-0.13	MW90	PGDP	1	326.02	326.36	-0.34
MW197	NW Plume	1	325.06	325.13	-0.07	PZ107	PGDP	1	327.72	328.02	-0.30
MW201	NW Plume	1	322.00	321.51	0.49	PZ110	PGDP	1	326.54	327.96	-1.42
MW137	NW Plume	2	321.09	321.23	-0.14	PZ117	PGDP	1	327.03	327.95	-0.92
MW152	NW Plume	2	316.18	318.13	-1.95	MW161	PGDP	2	326.65	326.21	0.44
MW202	NW Plume	2	323.42	323.36	0.06	MW175	PGDP	2	326.71	327.13	-0.42
MW98	NW Plume	2	322.97	322.86	0.11	MW325	PGDP	2	325.64	326.56	-0.92
MW125	NW Plume	3	323.83	323.98	-0.15	MW326	PGDP	2	326.76	326.61	0.15
MW134	NW Plume	3	330.07	324.95	5.12	MW327	PGDP	2	326.62	326.31	0.31
MW126	NE Plume	1	325.29	325.10	0.19	MW79	PGDP	2	326.43	326.47	-0.04
MW145	NE Plume	1	325.68	325.85	-0.17	MW93	PGDP	2	326.32	326.32	0.00
MW193	NE Plume	1	325.10	324.56	0.54	PZ109	PGDP	2	326.56	327.98	-1.42
MW99	NE Plume	1	323.14	322.83	0.31	PZ118	PGDP	2	326.31	327.98	-1.67
PZ107	NE Plume	1	327.72	328.02	-0.30	W108	PGDP	2	326.82	327.97	-1.15
MW148	NE Plume	2	323.59	323.04	0.55	MW158	PGDP	3	327.03	326.07	0.96
MW144	NE Plume	3	325.74	325.85	-0.11	MW163	PGDP	3	326.35	326.67	-0.32
MW163	NE Plume	3	326.35	326.67	-0.32	MW226	PGDP	3	326.94	326.50	0.44
MW156	PGDP	1	326.62	327.38	-0.76	MW86	PGDP	3	325.85	326.26	-0.41
MW159	PGDP	1	326.50	326.07	0.43	MW89	PGDP	3	325.75	326.31	-0.56
MW165	PGDP	1	326.30	326.29	0.01	MW92	PGDP	3	325.78	326.37	-0.59
MW168	PGDP	1	326.37	326.76	-0.39	MW95	PGDP	3	325.72	326.34	-0.62

Figures 7.12 through 7.14 show the distribution of the target residuals within the model domain for model layers 1 through 3; the bigger the residual circle, the bigger the target residual.

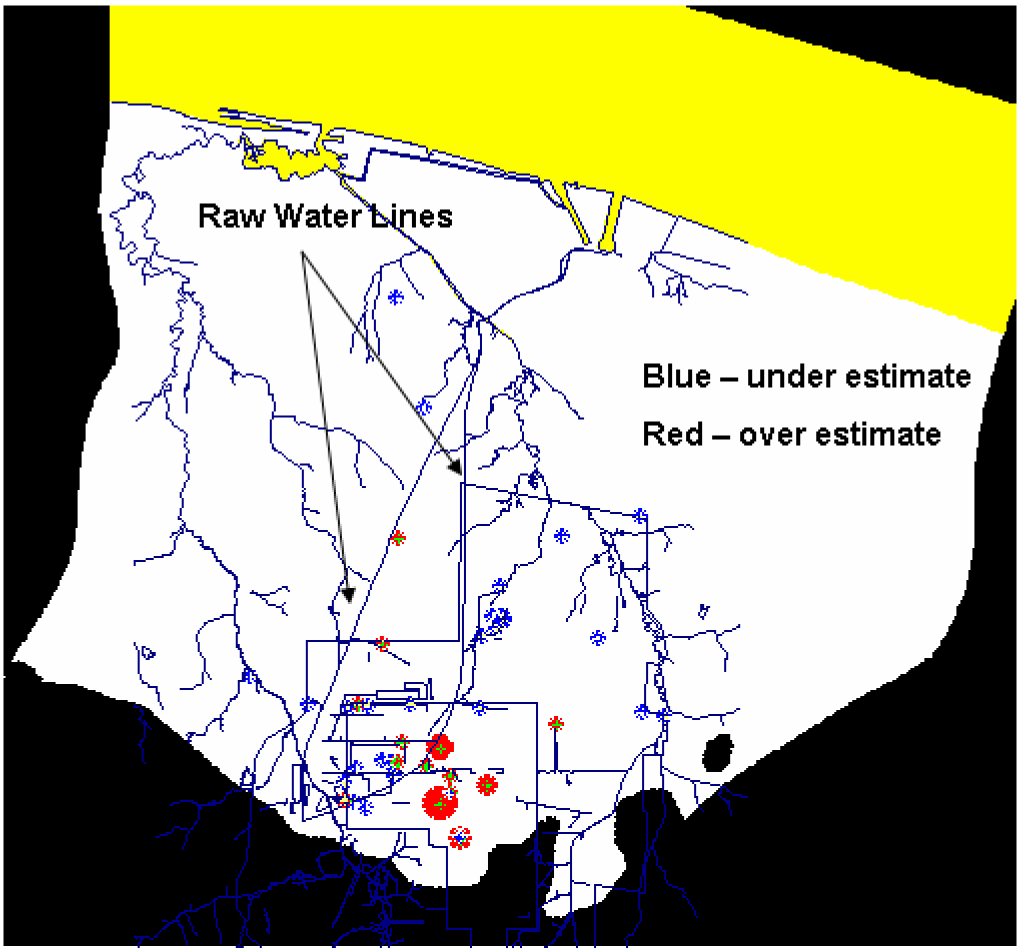


Figure 7.12. Model Layer 1 Residual Distribution

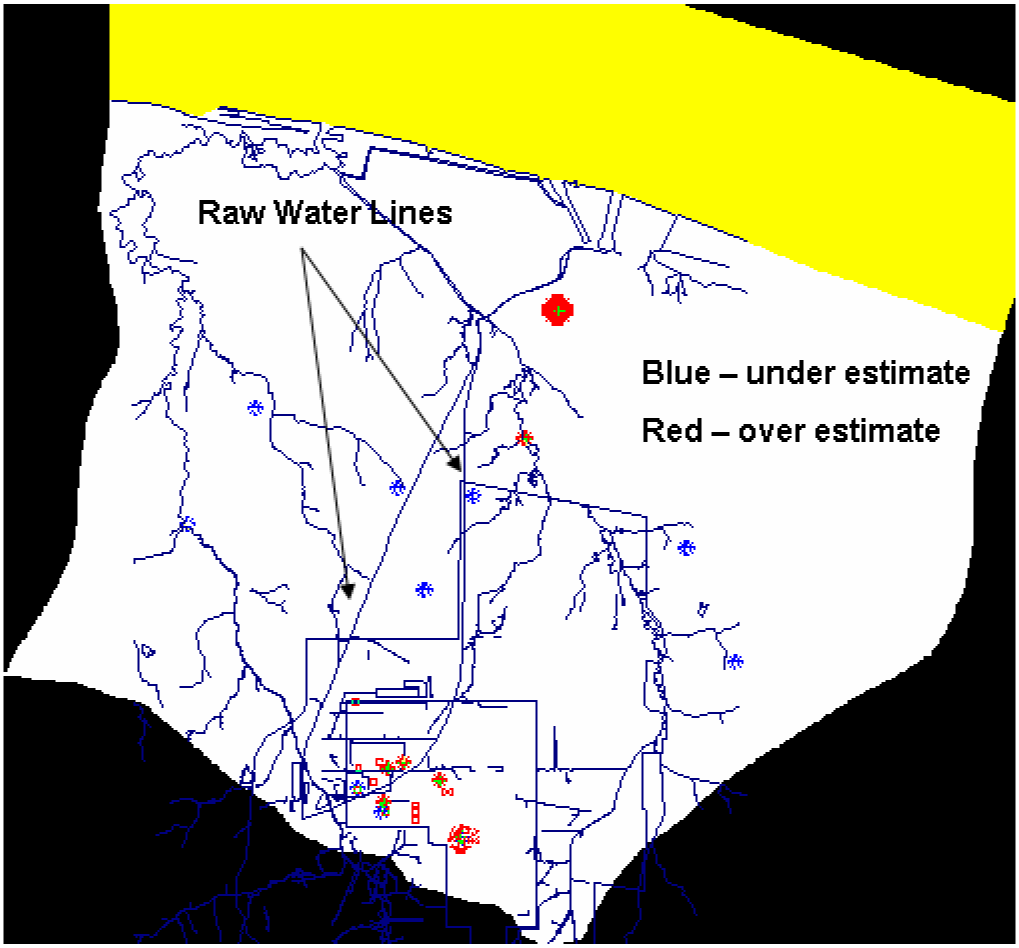


Figure 7.13. Model Layer 2 Residual Distribution

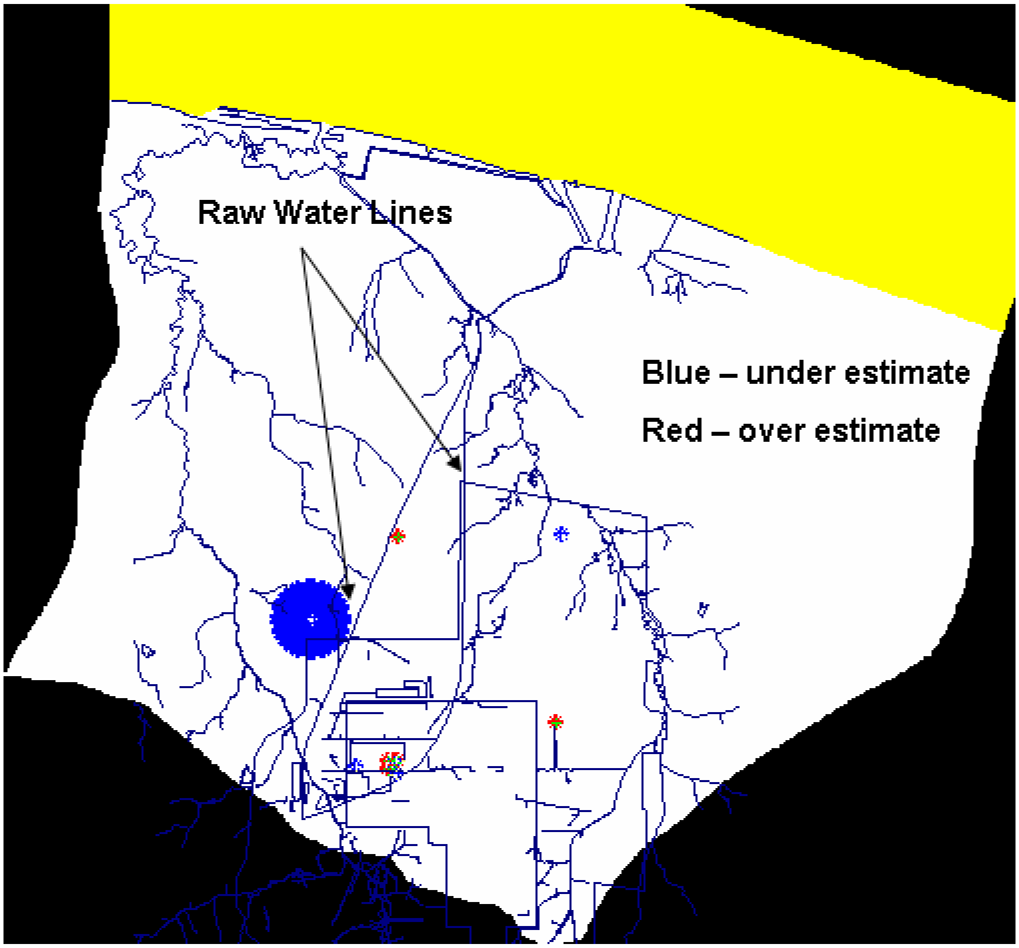


Figure 7.14. Model Layer 3 Residual Distribution

Model-predicted potentiometric surfaces for model-layers 1 through 3 are shown in Figures 7.15 through 7.17. The purple shown in Figure 7.15 represents dry cells, which result when the predicted water level elevation drops below the bottom the model layer. The model cells below these cells in model layers 2 and 3 are saturated. All model layers show mounding at the PGDP resulting from anthropogenic recharge.

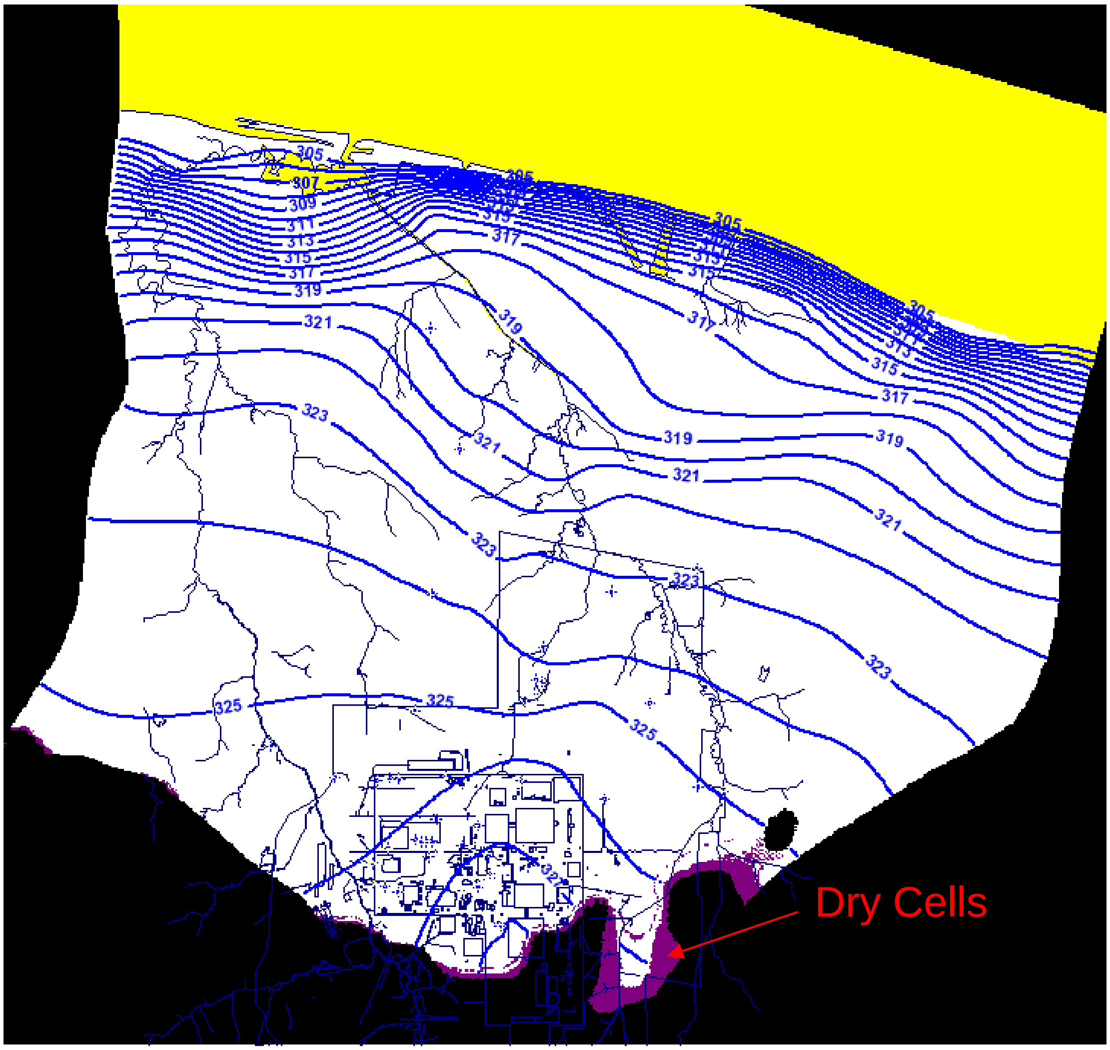


Figure 7.15. Model Layer 1 Model-Predicted Potentiometric Surface

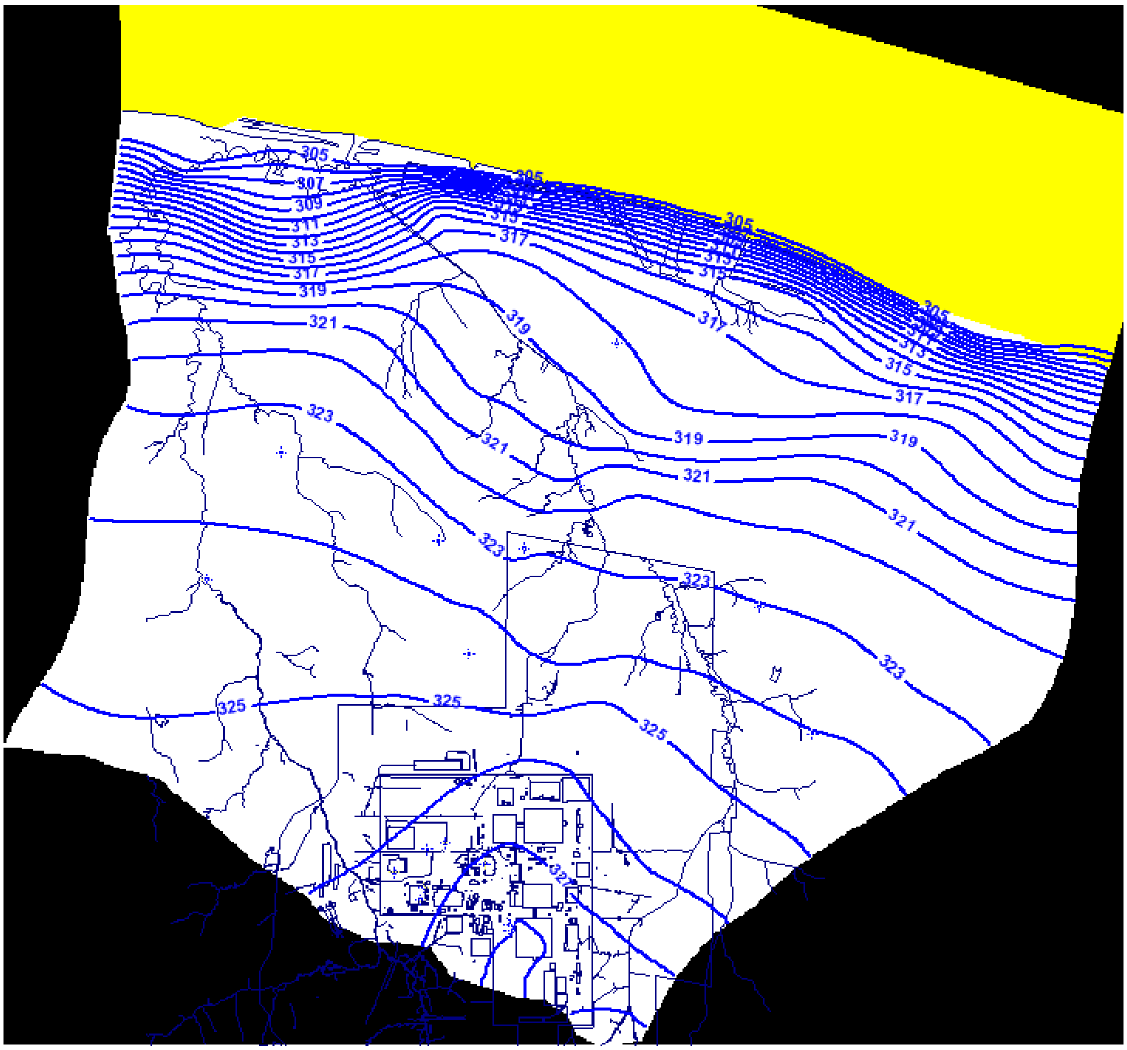


Figure 7.16. Model Layer 2 Model-Predicted Potentiometric Surface

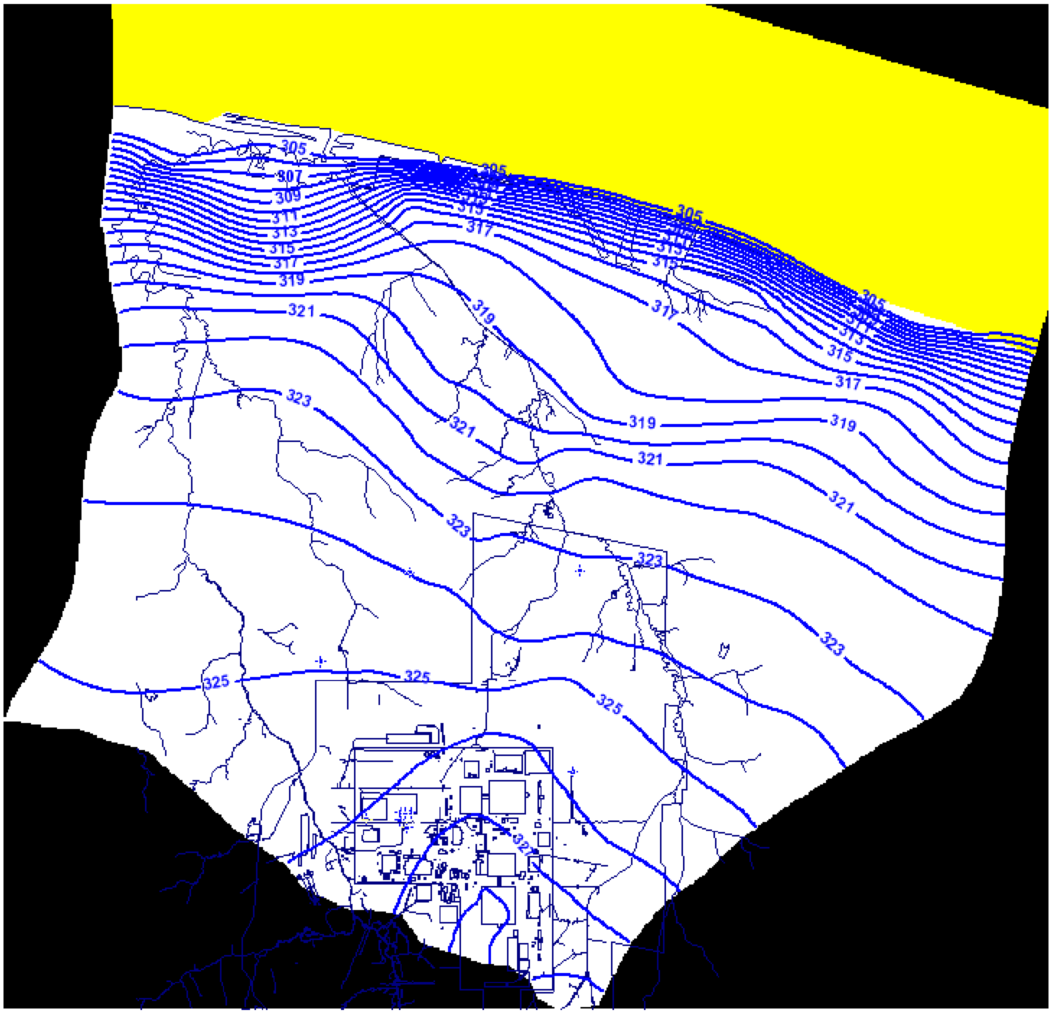


Figure 7.17. Model Layer 3 Model-Predicted Potentiometric Surface

7.2.5 Model-Predicted Ohio River Discharge

The model-predicts a groundwater discharge rate to the Ohio River of 4,739 gpm, which is very similar to the target discharge rate of 4,837 gpm.

7.2.6 Model-Predicted Plume Flow Paths

Particles were placed within the model domain in model layers 1 through 3 at locations corresponding to known and possible source areas and allowed to migrate with the predicted groundwater flow fields (Figure 7.18). 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 the model reasonably replicates the Northeast, Northwest, and Southwest Plumes flow paths.

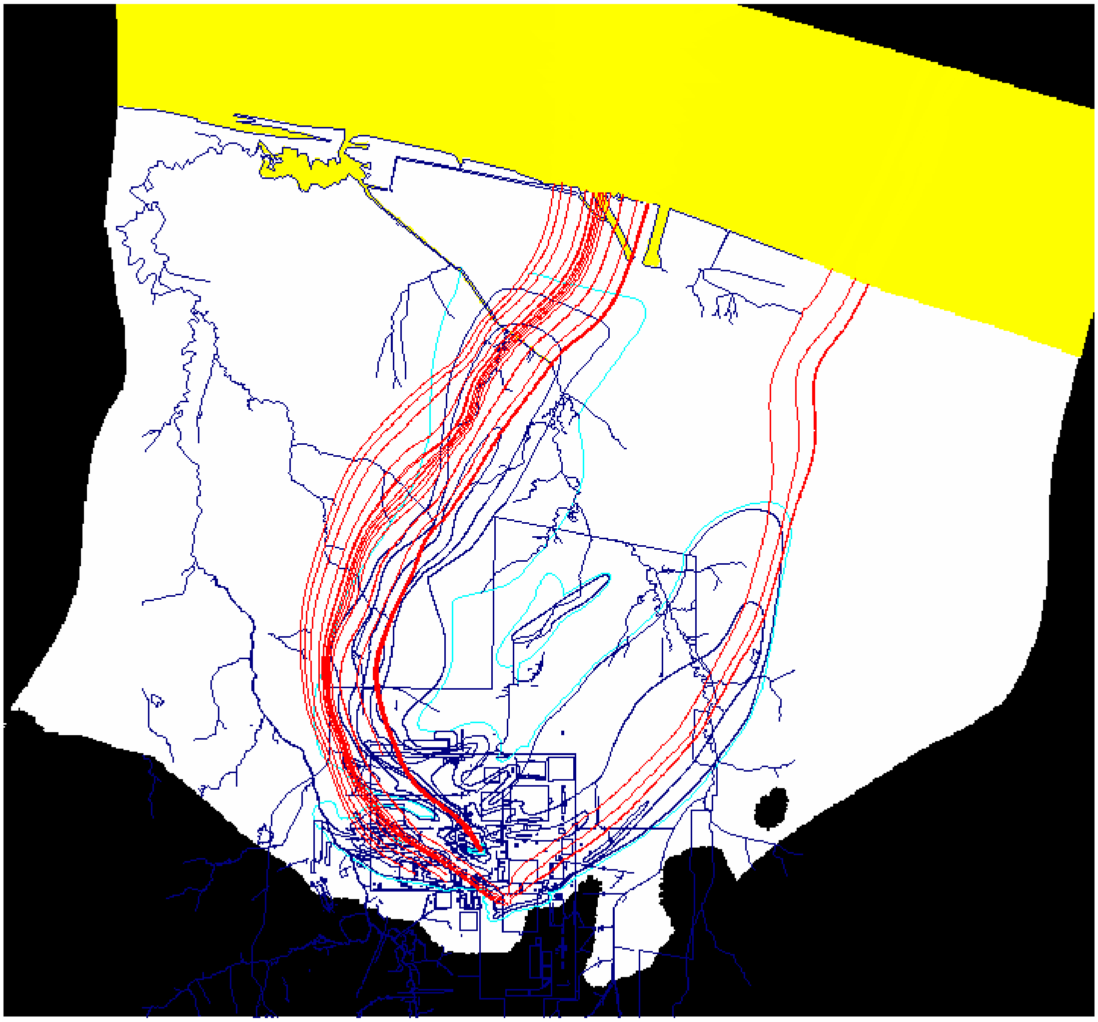


Figure 7.18. Model-Predicted Plume Flow Paths

7.2.7 Angle Targets

Calibration statistics for the 1,704 angle targets are presented in Figure 7.19. The absolute mean error for all angle targets is less than 2 degrees. Additionally, the majority of the predicted angles are within +/- 1 degree of the target value.

Number of Targets	1704
Mean	-0.24
Standard Deviation	2.70
Absolute Mean	1.83
Minimum	-18.84
Maximum	15.62

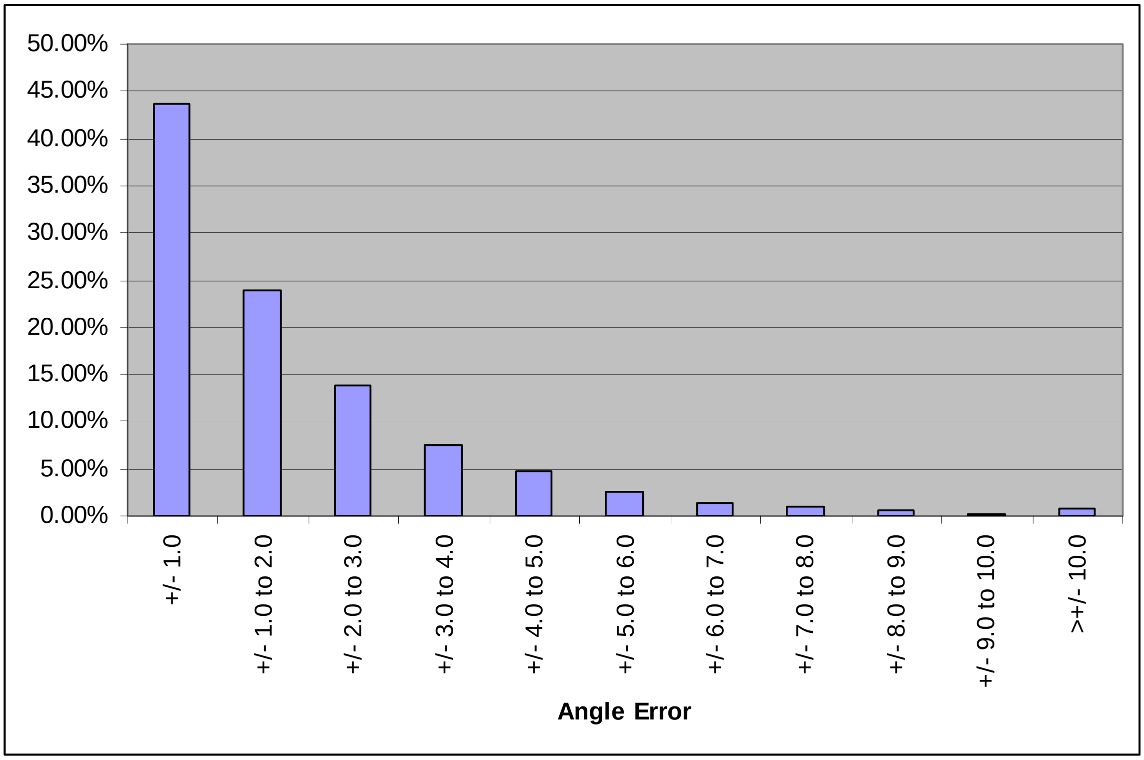


Figure 7.19. Angle Target Calibration Statistics

7.2.8 Final Parameter Sensitivities

PEST calculates sensitivities for all estimated parameters for each iteration of the parameter estimation process. Parameter sensitivities change during the calibration process, and it is important to check the final parameter sensitivities to insure that all the parameter estimates are robust. 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). It may or may not be possible to estimate parameters that are between two and three orders of magnitude less sensitive than the most sensitive parameter. Parameters three orders of magnitude less sensitive than the most sensitive parameter cannot be estimated.

Figure 7.20 shows the final relative composite scaled sensitivities of the 10 most sensitive parameters, the most sensitive pilot point, and the 10 least sensitive parameters. (NOTE: with the exception of the four least sensitive parameters, all the parameter sensitivities are within two orders of magnitude of the most sensitive parameter, indicating that these parameters can be estimated robustly.) The four least sensitivities parameters have sensitivities within two to three orders of magnitude of the most sensitive parameter, indicating that a robust estimation of these parameters is uncertain.

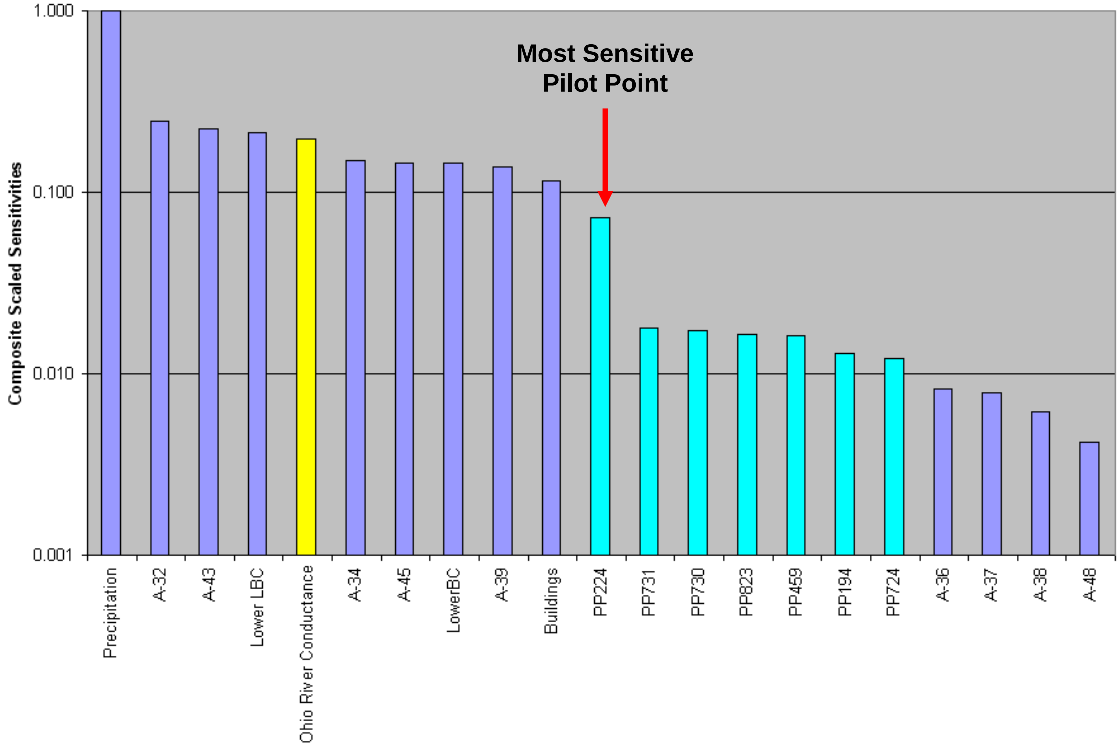


Figure 7.20. Final Parameter Sensitivities

Final hydraulic conductivity pilot point sensitivities for model layers 1 through 3 relative to the most sensitive pilot point are shown in Figure 7.21. (NOTE: all the pilot point sensitivities are within an order of magnitude of one another, indicating that robust hydraulic conductivities can be estimated for each pilot point.)

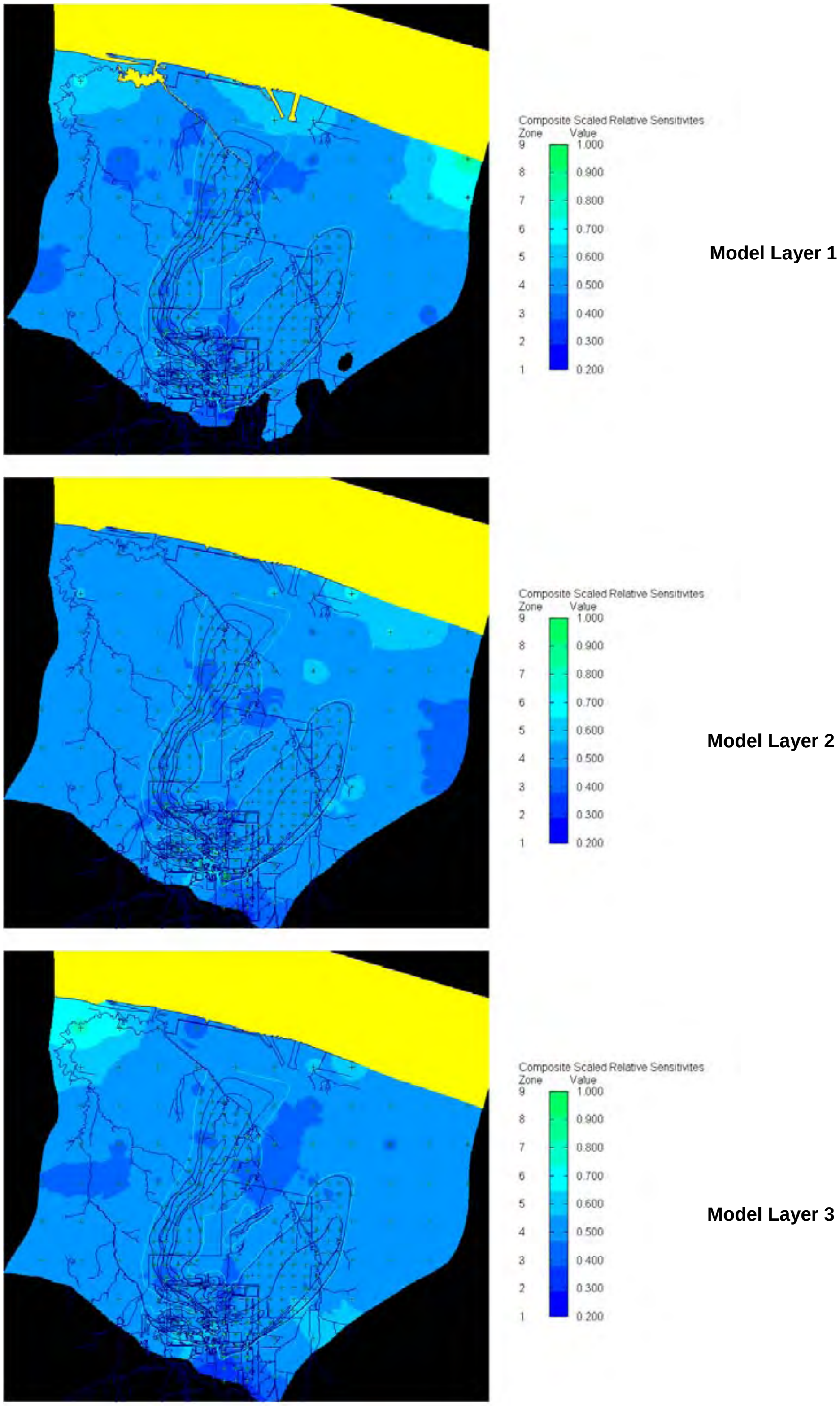


Figure 7.21. Final Pilot Point Sensitivities

7.2.9 Plume Flow Path Sensitivity Analysis

This sensitivity analysis was performed to determine how individual 25% increases and decreases in the calibrated values of the 10 most sensitive parameters (based on the final PEST sensitivities, Figure 7.20) influence predicted plume flow paths as defined by particle traces. The 25% manipulation range was selected in recognition that, over the long-term (the plumes' time scale), parameter fluctuations are not expected to be as extreme as might occur short-term. In addition, a sensitivity analysis was performed to determine how changes in Ohio River stage influence predicted plume flow paths.

Simulated increases and decreases in precipitation recharge cause the Northwest Plume to shift minimally east and west relative to the observed plume centroid (Figure 7.22). Increases in precipitation recharge minimally influence the simulated Northeast Plume trajectory. Decreases in precipitation recharge results in a narrowing of the Northeast Plume particle traces and minimally changes the plume trajectory. Perturbing the A-32 anthropogenic recharge zone (Figure 7.9) has minimal effect on the Northeast and Northwest Plumes trajectories (Figure 7.23). Increases and decreases in recharge from the A-43 anthropogenic recharge zone (Figure 7.9) minimally influence the Northwest Plume trajectory (Figure 7.24). However, increases in the A-43 anthropogenic recharge rate causes a narrowing of the Northeast Plume traces relative to the calibrated and reduced recharge scenarios. Increases and decreases in groundwater discharge to lower Little Bayou Creek cause the simulated Northwest Plume trajectory to shift minimally relative to the calibrated plume trajectory (Figure 7.25). Changes in groundwater discharge to lower Little Bayou Creek appear to have no influence on the simulated Northeast Plume trajectory.

Changes in the hydraulic conductivity (conductance) of the Ohio River bottom sediments do not influence Northeast and Northwest Plumes trajectories. This fact begs the question as to why the hydraulic conductivity of the Ohio River bottom sediments was deemed sensitive by PEST. PEST sensitivities are determined based on the response of all target types. The model was calibrated using a combination of head, flux, and angle targets. The hydraulic conductivity of the Ohio River bottom sediments has no effect on plume trajectories or the amount of groundwater entering the river (what comes in must go out), but does greatly influence the shape of the water table (head targets), which explains the extreme sensitivity.

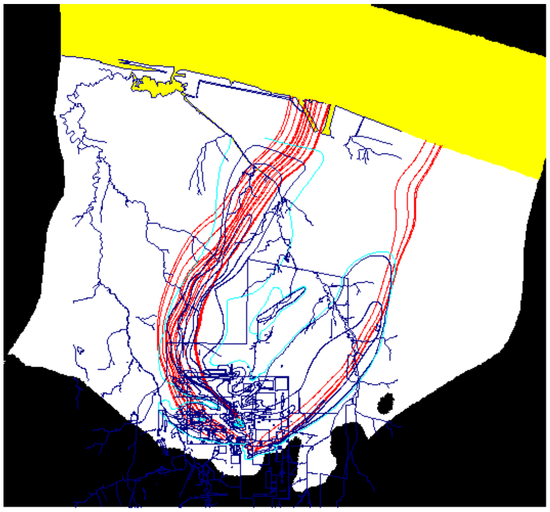
Similar to most of the other sensitive parameters, changes to the A-34 and A-45 anthropogenic recharge zones (Figure 7.9), groundwater discharge rates to Lower Bayou Creek, and A-39 anthropogenic recharge zone minimally influence simulated Northeast and Northwest Plumes trajectories (Figures 7.26 through 7.30).

Changes to the building (Figure 7.9) recharge rate minimally influence the simulated trajectory of the Northwest Plume (Figure 7.31); however, changes to this parameter do influence the trajectories of the particle traces representing the Northeast Plume. Higher recharge rates result in a widening of the particle traces relative to either the calibrated or low recharge simulations. This fact may explain why there is a larger low concentration area along the northern edge relative to the southern edge of the Northeast Plume. Rainfall events, due to increased infiltration under the buildings, cause a widening of the Northeast Plume in the northerly direction. As infiltration decreases with time, the plume narrows and migrates in the area of higher observed concentrations. Given that there are more dry than rainy days, the plume has a greater tendency to migrate in the manner characterized by the calibrated and low recharge simulations than as characterized by the high recharge simulation.

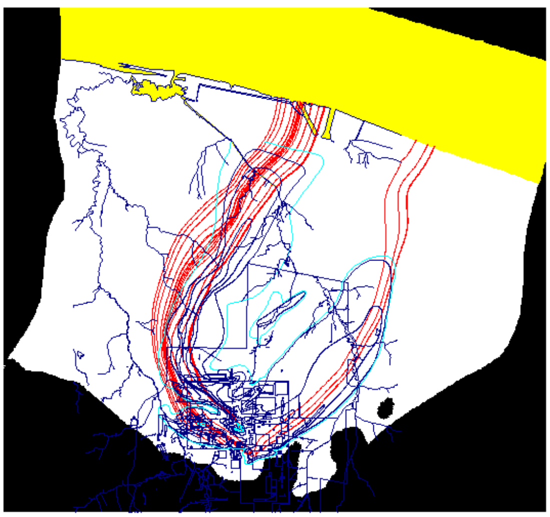
A sensitivity analysis also was performed to determine how simulated changes in Ohio River stage influence simulated plume trajectories (Figure 7.32). Unlike the other parameters, the minimum and maximum stage values do not correspond to 25% increases and decreases, rather the minimum and maximum values correspond to the lowest observed (290 ft) and the 90^{th} percentile (320 ft) stages. The simulated results show that changes in the Ohio River stage minimally influence the particle traces representing the Northwest

Plume. Changing Ohio River stage, similar to varying building recharge rates, widens and narrows the particle traces representing the Northeast Plume.

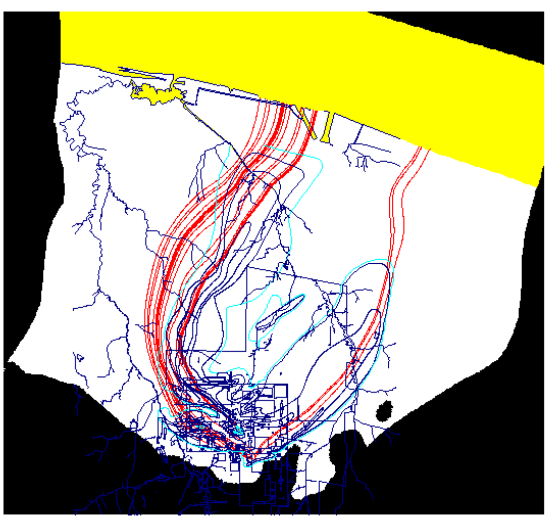
In summary, while increases and decreases in parameter values do influence simulated plume trajectories, the particle traces do not deviate from the observed locations of the Northeast and Northwest Plumes. This suggests that, while groundwater water levels and the Ohio River fluctuate in response to varying precipitation, and groundwater water levels fluctuate in response to varying anthropogenic recharge rates, the overall long-term PGDP groundwater basin flow directions remain relatively constant. The hypothesis is supported by the temporally constant Northeast and Northwest Plumes geometries (Figure 4.3).



Plus 25% = 9.30 inches/year

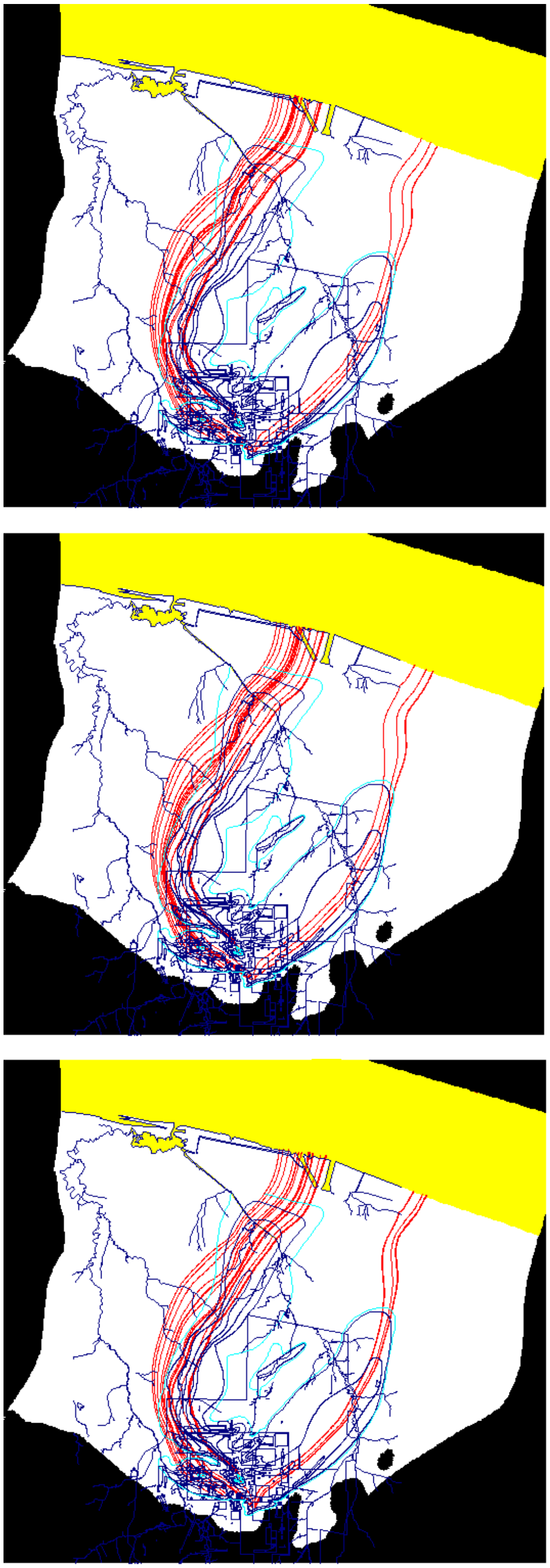


Calibrated Value = 7.44 inches/year



Minus 25% = 5.58 inches/year

Figure 7.22. Particle Trace Sensitivity to Precipitation Recharge

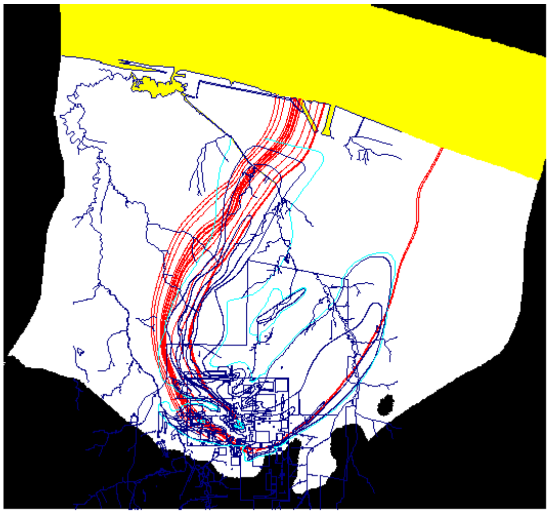


Plus 25% = 89.23 inches/year

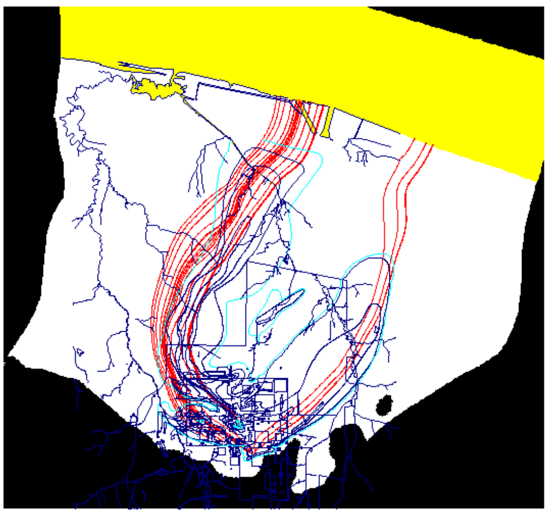
Calibrated Value = 71.38 inches/year

Minus 25% = 53.54 inches/year

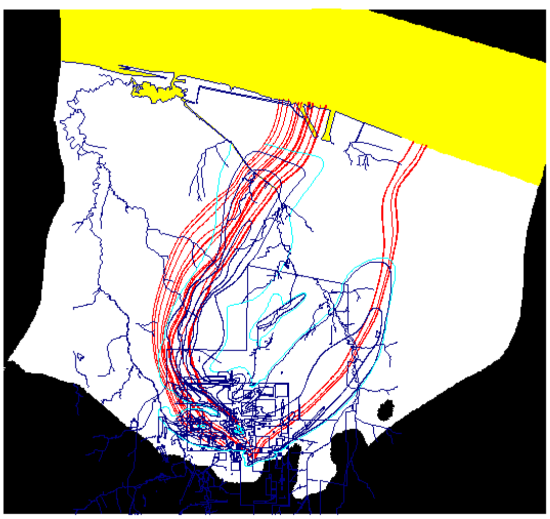
Figure 7.23. Particle Trace Sensitivity to A-32 Anthropogenic Recharge Area



Plus 25% = 143.54 inches/year

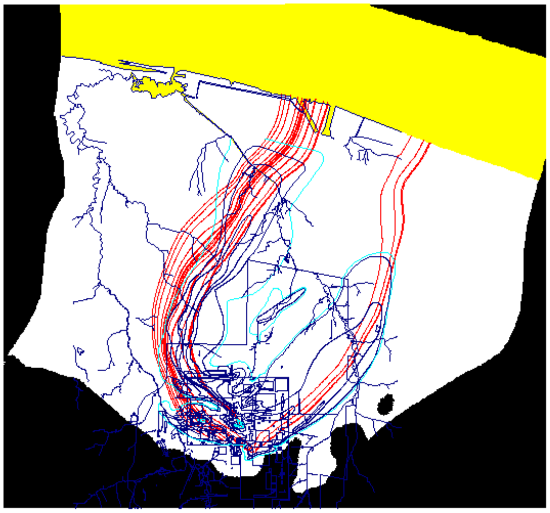


Calibrated Value = 114.83 inches/year

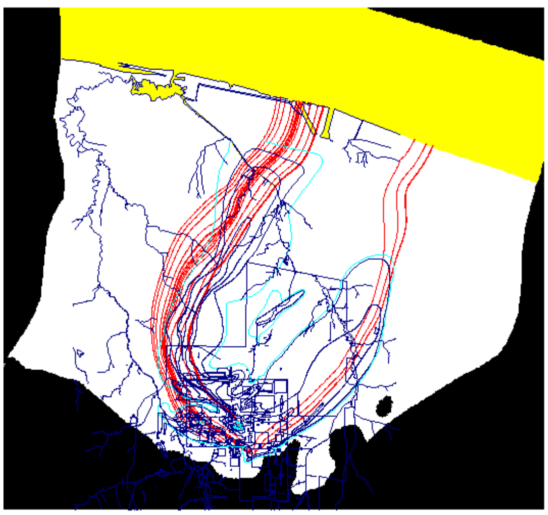


Minus 25% = 86.12 inches/year

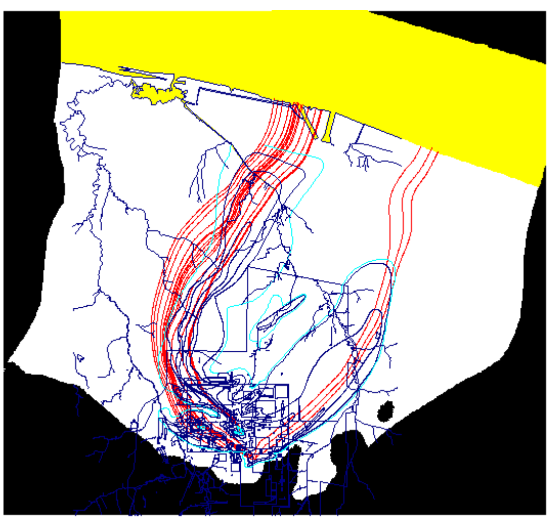
Figure 7.24. Particle Trace Sensitivity to A-43 Anthropogenic Recharge Area



Plus 25% = 390 gpm

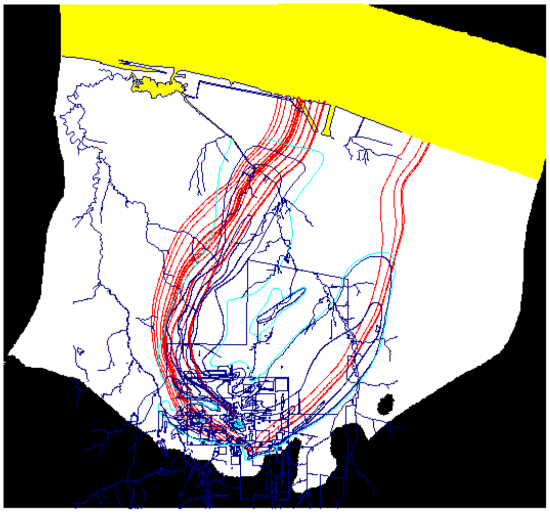


Calibrated Value = 312 gpm

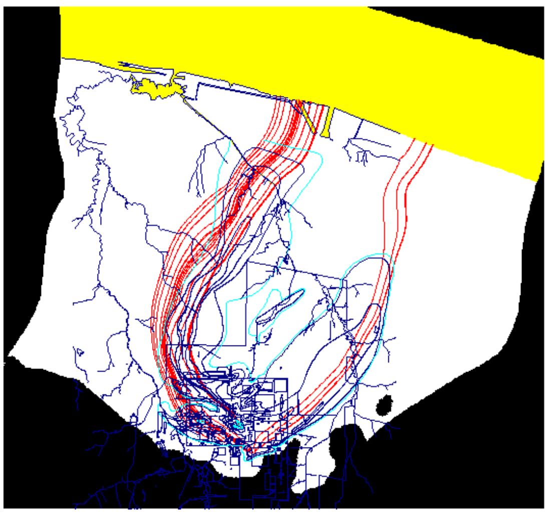


Minus 25% = 234 gpm

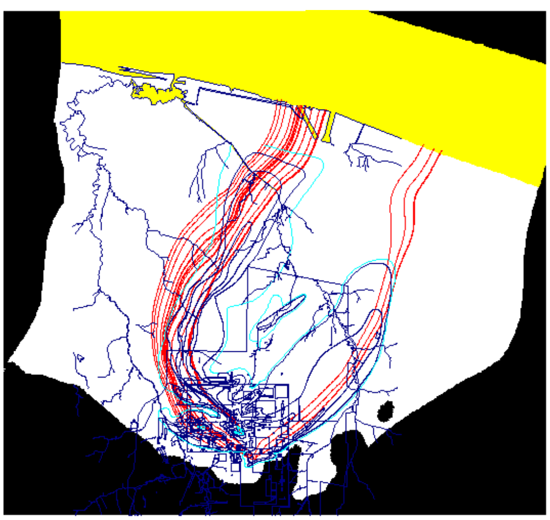
Figure 7.25. Particle Trace Sensitivity to Lower Little Bayou Creek Discharge



Plus 25% = $7.62{\times}10^{-3}$ ft/day

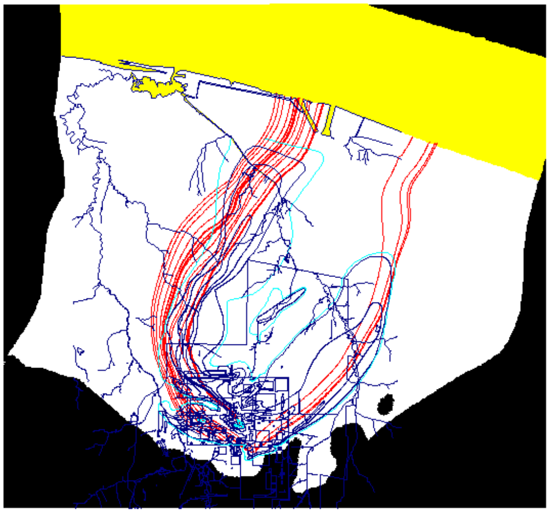


Calibrated Value = $6.10{\times}10^{-3}$ ft/day

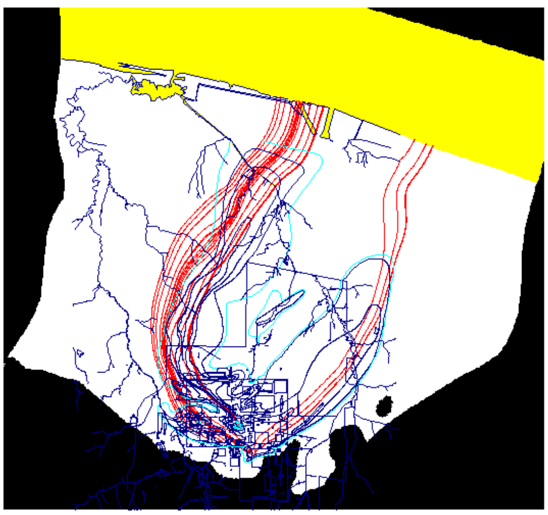


Minus 25% = $4.58{\times}10^{-3}$ ft/day

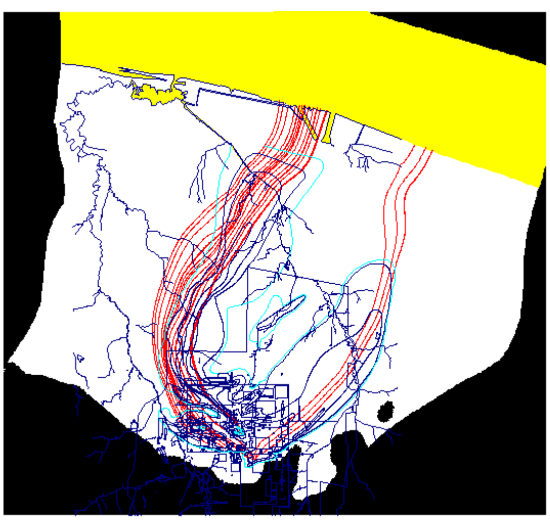
Figure 7.26. Particle Trace Sensitivity to the Ohio River Bottom Sediment Hydraulic Conductivity



Plus 25% = 81.36 inches/year

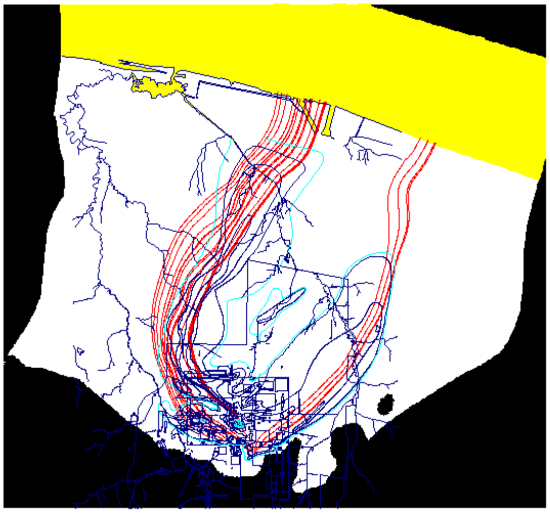


Calibrated Value = 65.09 inches/year

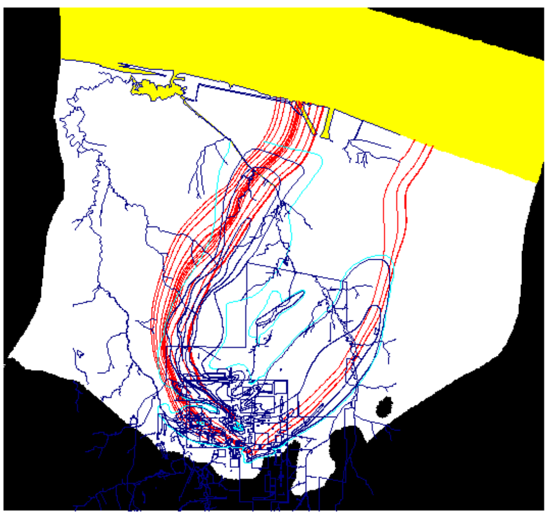


Minus 25% = 48.82 inches/year

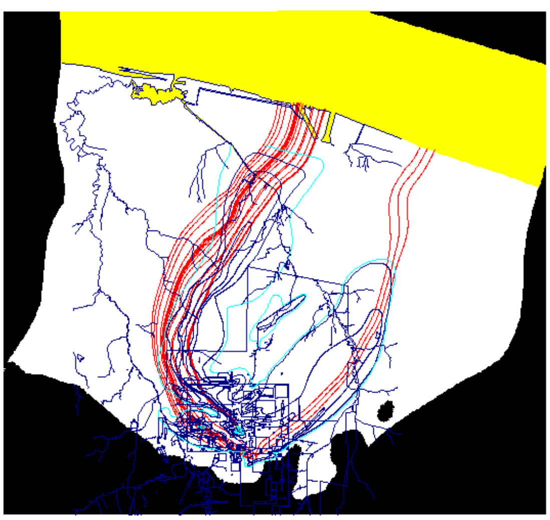
Figure 7.27. Particle Trace Sensitivity to A-34 Anthropogenic Recharge Area



Plus 25% = 69.31 inches/year

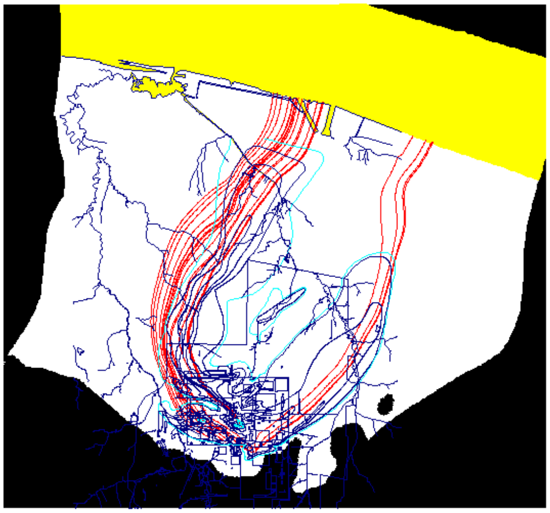


Calibrated Value = 55.45 inches/year

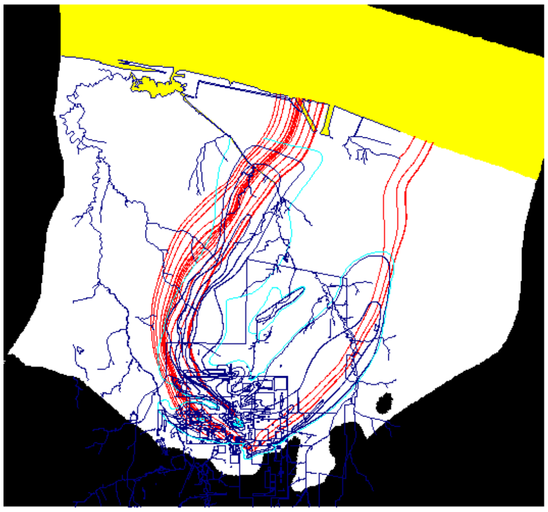


Minus 25% = 41.59 inches/year

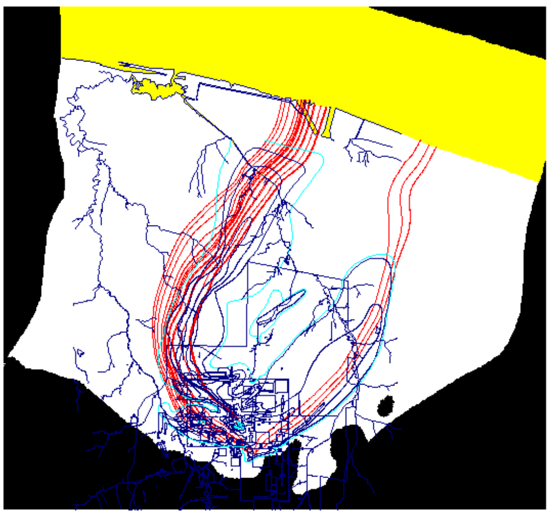
Figure 7.28. Particle Trace Sensitivity to A-45 Anthropogenic Recharge Area



Plus 25% = 431 gpm

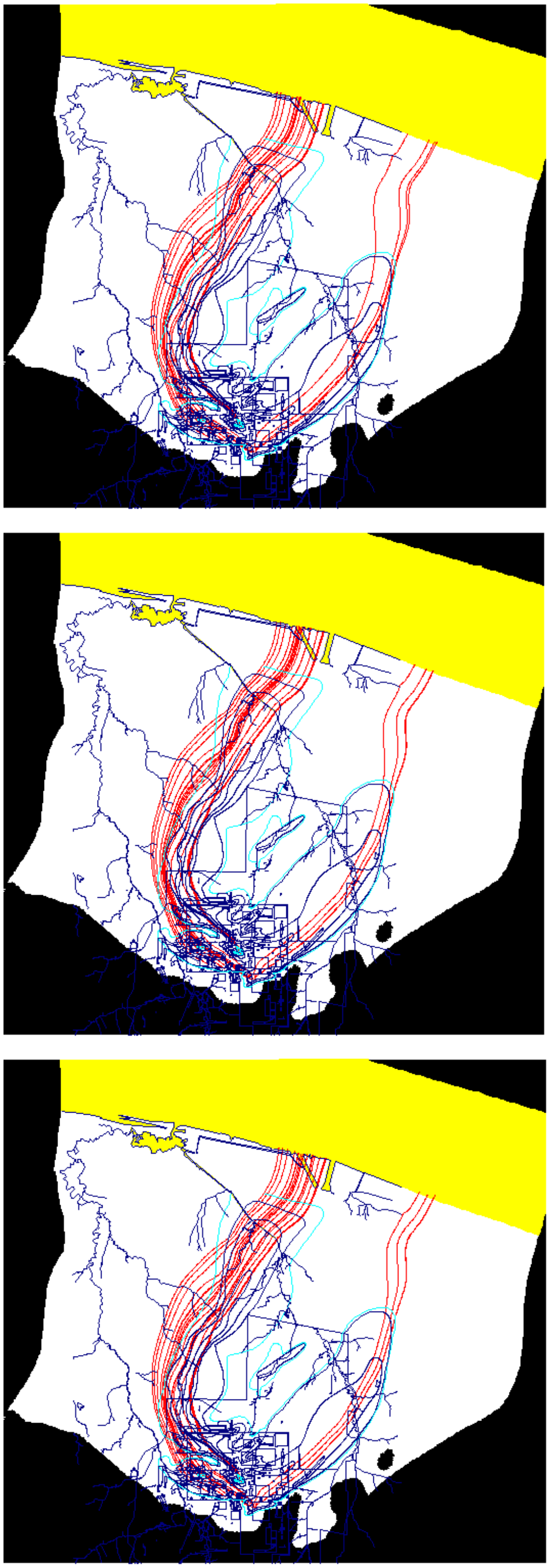


Calibrated Value = 345 gpm



Minus 25% = 259 gpm

Figure 7.29. Particle Trace Sensitivity to Lower Bayou Creek Discharge

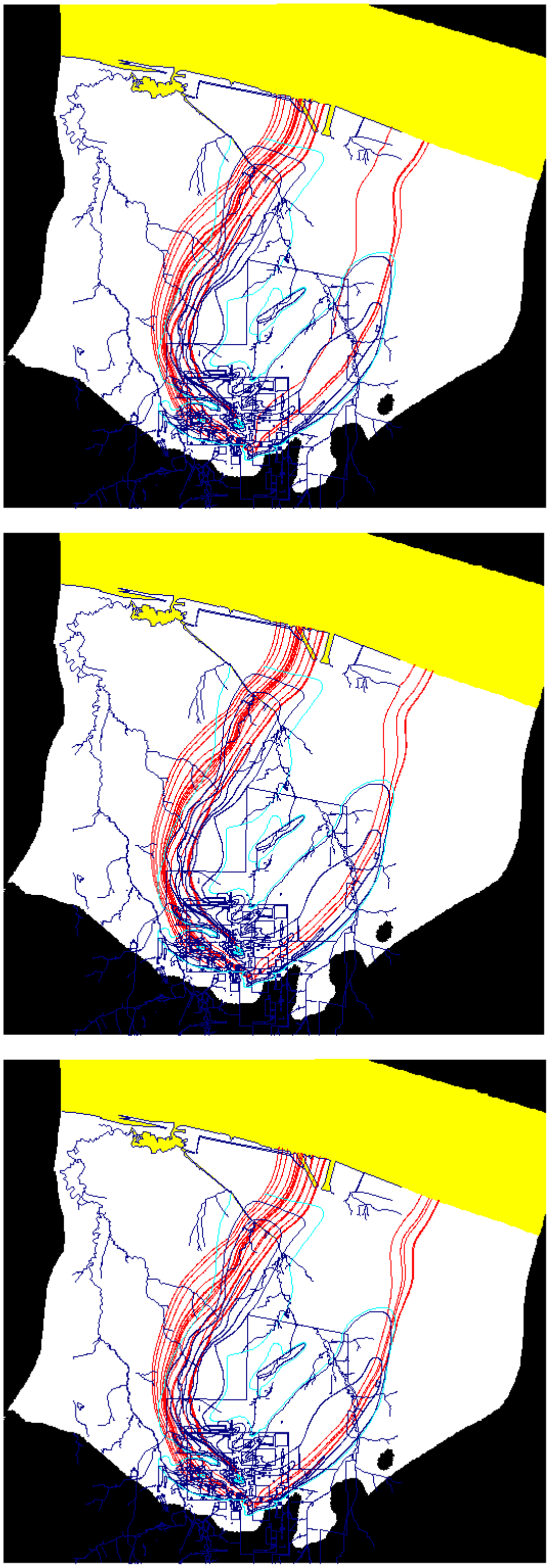


Plus 25% =51.88 inches/year

Calibrated Value = 41.50 inches/year

Minus 25% = 31.13 inches/year

Figure 7.30. Particle Trace Sensitivity to A-39 Anthropogenic Recharge Area

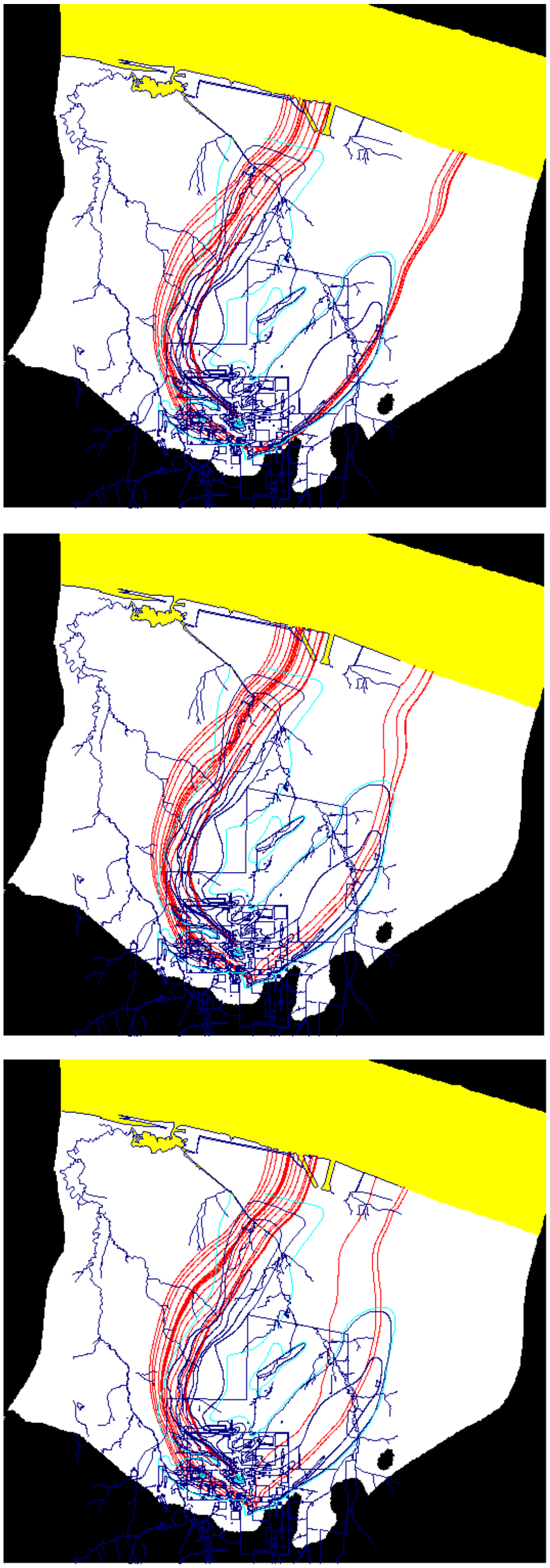


Plus 25% = 23.25 inches/year

Calibrated Value = 18.60 inches/year

Minus 25% = 13.95 inches/year

Figure 7.31. Particle Trace Sensitivity to Building Recharge



90th Percentile = 320 ft

Calibrated Value = 297 ft

Minimum = 290 ft

Figure 7.32. Particle Trace Sensitivity to Ohio River Stage

7.3 MODEL VERIFICATION

The flow model was verified by simulating extraction well operation. The model results were compared against September 2000 water level elevation measurements to verify that the model could reasonably match observed conditions under different conditions (i.e., pumping). The September 2000 data set was selected because the Ohio River stage on that date was similar to the Ohio River stage used to calibrate the model.

Figure 7.33 shows the residual distribution for the verification simulation. The scatter of the data suggests that there is some bias toward over-predicting water level elevations; however, the majority of the predicted water level elevations are within plus or minus one foot. Calibration statistics are as follows: sum of difference squared—45.6 ft^2, absolute residual mean—0.09 ft, and residual mean—0.37 ft.

Just as important as matching water levels is how the model simulates plume trajectories. Figure 7.34 shows particle traces from source areas when the extraction wells are operational. The results demonstrate partial capture at the extraction wells. Contamination bypassing the extraction wells follows known plume trajectories, which suggests that the model is capable of simulating extraction well pumping.

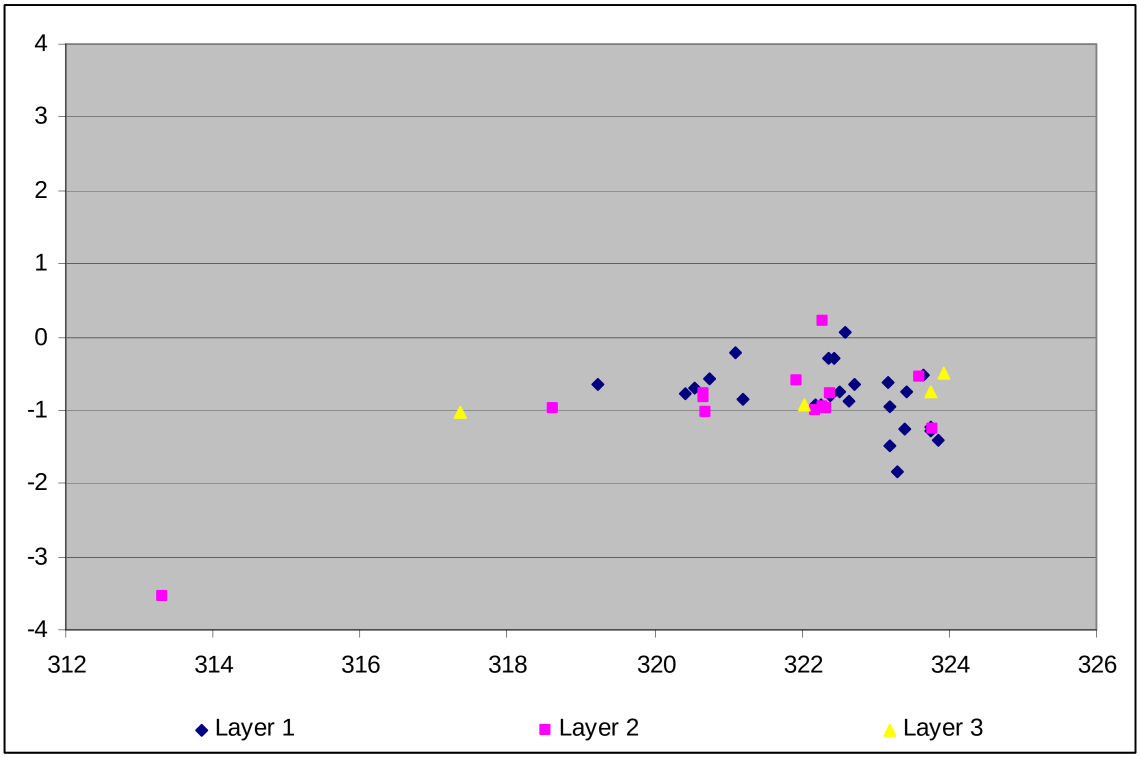


Figure 7.33. Verification Calibration Results

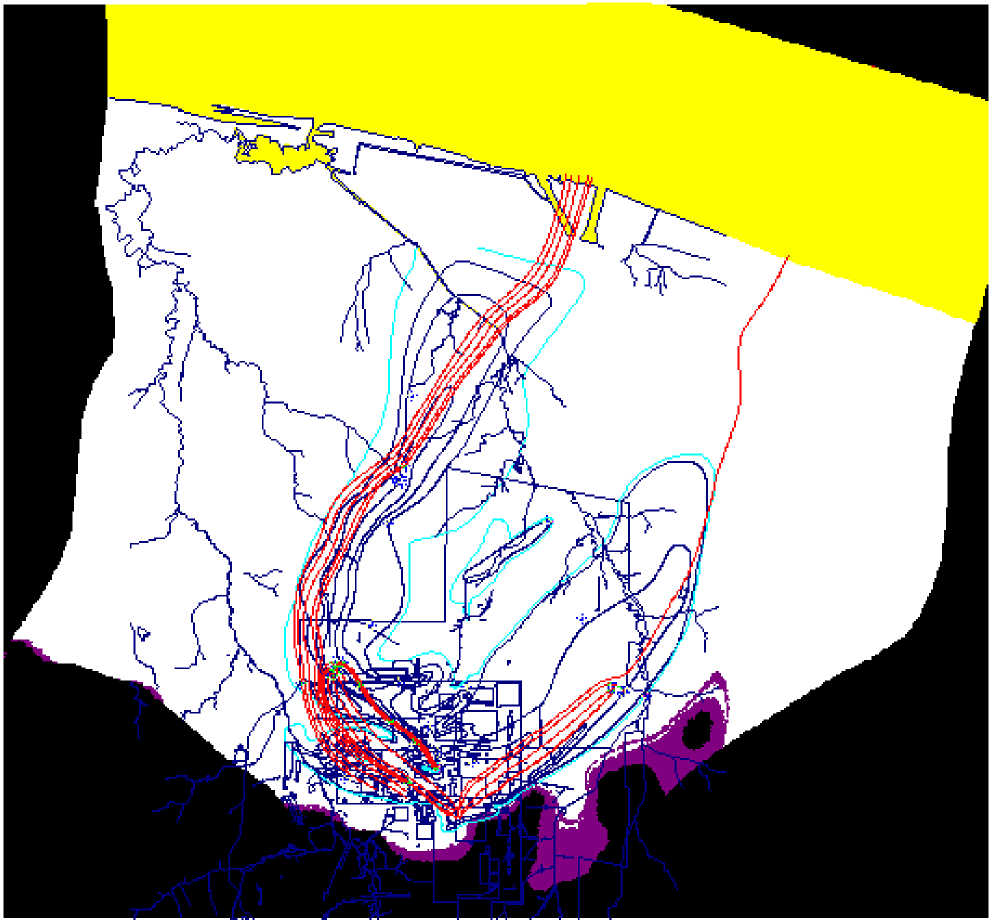


Figure 7.34. Verification Particle Traces

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8. CALIBRATED FLOW MODEL EVALUATION

For a groundwater flow model to be considered representative, the model needs to reasonably match calibration targets, reproduce the estimated site water balance, mimic observed plume trajectories, and be faithful to the conceptual model. Even if good agreements are achieved, the model still may be lacking in some aspects because all models are an approximation of the real world and require assumptions for construction and simulation and, as such, never will exactly mimic actual conditions. Part of any modeling exercise is to evaluate how the modeling assumptions potentially influence the predictions and attempt to quantify that uncertainty. Finally, the calibrated model needs to be capable of satisfying the modeling objectives, or why develop a model? This section evaluates the model with respect to matching observed conditions, uncertainty and the ability to satisfy the modeling objectives. Lastly, recommendations are made regarding the need for additional data collection and modeling that may lessen some of these uncertainties. Additional discussion of model uncertainty and options for additional data collection is included in Appendix B.

8.1 CALIBRATION EVALUATION

The model reasonably matches target water level elevations. In addition, based on particle traces, the model reasonably reproduces the Northeast, Northwest, and Southwest Plumes flow paths. Overall this flow model honors the conceptual model with respect to recharge and discharge rates, relative recharge and discharge volumes and the predicted range of RGA hydraulic conductivities. Also, the predicted RGA bulk hydraulic conductivity, as evidenced by the average pilot point hydraulic conductivity (1,906 ft/day), is within the expected range of bulk RGA hydraulic conductivity (713 to 2,063 ft/day). A verification simulation shows that the model is capable of reasonably matching groundwater water levels and plume flow paths when the six PGDP extraction wells are operational. In summary, the model makes sense when compared to what is known about the PGDP hydrogeology and basin groundwater flow patterns.

Additionally, final PEST sensitivities show that it is possible through calibration to obtain robust parameter values for 852 of the 856 model input parameters. The four remaining input parameters have sensitivities that indicate that it should be possible to obtain robust parameter values through calibration. In summary the calibrated model input parameters are robust.

8.2 UNCERTAINTY EVALUATION

Major assumptions made during model development include the assessment that the PGDP groundwater flow system can be approximated as steady state rather than transient, and that the UCRS and McNairy can be excluded from the flow model and the model will still be representative of groundwater flow within the aquifer in the PGDP basin.

With regard to steady state versus transient conditions, data evaluation performed as part of the modeling exercise shows that while groundwater elevations and Ohio River stage temporally vary, flow directions are generally temporally consistent. The best evidence for temporally consistent flow directions are the Northeast and Northwest Plumes, which have maintained the same basic configuration and concentrations since first characterized. A plume flow path sensitivity analysis conducted by systematically varying the ten most sensitive modeling input parameters and Ohio River stage showed that changing these input parameters within reasonable values results in plume flow paths that travel within the documented plume flow paths. Thus, the steady-state, model-predicted plume flow paths are representative of hydrologic conditions different than the calibrated flow model. In summary, the steady-state assumption is reasonable and is not likely to introduce significant uncertainty into future contaminant transport simulations and remedial design evaluations.

Data evaluation demonstrated that the UCRS primarily conveys recharge at land surface, some of which becomes contaminated, downward vertically to the RGA. Of interest is how excluding the UCRS from the modeling domain will impact the ability of the model to predict the effects of UCRS cleanup on RGA water quality. Excluding the UCRS from the model will have no impact on the model's usefulness in assessing UCRS remedial strategies.

Excluding the McNairy from the model does not allow for evaluation of the potential for contaminant migration in the formation, particularly whether it is possible for contamination to migrate under the Ohio River toward the Metropolis water supply well field. To address this uncertainty, a cross-sectional model will be constructed and used to evaluate contaminant migration potential.

9. RECOMMENDATIONS

The first action of the Modeling Discussion Group was to determine the modeling objectives (i.e., what did the group want to use the model for?). It is fitting at the close of the recalibration exercise that the objectives be revisited to insure that the updated groundwater flow model is capable of satisfying them. Note that this report summarizes the flow model recalibration effort. A companion report will be published later that will document the transport model calibration, which still is ongoing. Additional objectives related to that effort are provided at the end of this section.

Initial modeling group discussions determined that the purpose and or objectives of PGDP groundwater flow model were as follows:

- Optimization of remedial actions
- Feasibility study support/evaluate remediation scheme
- Public communication
- Conceptual model evaluation
- Evaluate changing plant water usage
- Identify potential data gaps
- Evaluate influence of changing Ohio River stage on groundwater flow patterns
- Develop cleanup goals
- CERCLA cell project support
- Support evaluation of dissolved phase plume potential remedies
- Support Burial Grounds Operable Unit remedial evaluations for UCRS and RGA as follows:
  - Excavation
  - Capping
  - Secondary treatment
  - Barriers
- Support UCRS evaluation of C-720 and SWMU 1 remediation.

In general, the updated flow model is capable of satisfying the listed objectives. Some of the objectives, such as the applicability of geo-siphon technology, may require model modification before assessment can be completed. The need for model modification will be predicated on site-specific data such as the depth of influence of Little Bayou Creek and hydraulic conductivity. An exception is CERCLA cell project support. There are multiple disposal cell locations under consideration, some of which are outside of the current model domain.

With regard to the Groundwater Flow Model the following recommendations are made:

- As additional data are collected during upcoming characterization efforts and as part of remedial design and implementation, the new information is compared against the model input parameters and predictions to insure the model remains representative. If differences are observed, the Groundwater Flow Model should be updated to reflect the new information.

- Additionally it is recommended that as work plans are being developed for upcoming Remedial Investigations and Feasibility Studies that the data gaps (i.e., minimal characterization at the Little Bayou seeps) identified in this modeling report be revisited and addressed if possible during the data collection and evaluation phases of those projects.

- It is recommended that periodic comprehensive water level measurements be collected from PGDP and nearby wells to insure a comprehensive data set is available for the next model calibration effort.

Along with supporting some of the same objectives as the PGDP groundwater flow model, the objectives of the upcoming PGDP transport model will include, but are not necessarily limited to, the following:

- Degradation use/evaluate monitored natural attenuation
- Multi-component/analytes
- Support C-400 electrical resistance heating evaluation

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APPENDIX A

CURRENT MONITORING LOCATIONS—2008 AND PROPOSED LOCATIONS; ENVIRONMENTAL MONITORING SYSTEM UPGRADE

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APPENDIX B

MODEL UNCERTAINTIES AND LIMITATIONS

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APPENDIX B: MODEL UNCERTAINTIES AND LIMITATIONS

The updated groundwater flow model presented in this report was developed by a modeling discussion group consisting of personnel from the U.S. Department of Energy (DOE), U. S. Environmental Protection Agency (EPA), Kentucky Department for Environmental Protection (KDEP), University of Kentucky (UK), Paducah Remediation Services, LLC, (PRS), Science Applications International Corporation (SAIC), Performance Results Corporation (PRC), and Portage Environmental (Portage). During the model development process, a number of items were identified as potentially affecting the model uncertainty and warranting consideration during planning of future data collection efforts. A more complete discussion of model uncertainties is provided in Section 13 of the *2008 Update of the Paducah Gaseous Diffusion Plant Sitewide Groundwater Flow Model* report. In some instances, additional data collection may mitigate some of these uncertainties, while not totally eliminating them. It is recognized that it may not be possible to address all these issues; however, the working group thought it important to document the group's discussions to provide continuity for future model updates.

Regarding use of the groundwater model for specific project needs, aside from satisfying those applications specified in Section 14 of the *2008 Update of the Paducah Gaseous Diffusion Plant Sitewide Groundwater Flow Model* report, limits on the application of the model for site or project-specific requirements and determinations of the appropriate use of the model should be made by appropriate project personnel on a case-by-case basis.

These are the data needs identified by the modeling group to be considered for future model revision.

TVA monitoring wells and site processes:

- TVA provided historic groundwater levels from their wells for use in calibrating the groundwater flow model. Use of those measurements proved problematic as the TVA groundwater measurements were out of sync with the PGDP groundwater measurements. It was hypothesized that perhaps TVA used a different survey datum than PGDP, which resulted in the discrepancy. One potential solution identified by the group was to survey the TVA wells using the PGDP well datum.

- The TVA site has a number of slurry ponds that likely interact with groundwater. At present, inflow and outflow to the ponds is measured in 100,000 gpm increments, a measurement too crude to characterize pond losses to groundwater. The group discussed working more closely with TVA to try to better understand and characterize TVA processes that impact groundwater.

New PGDP monitoring wells:

- Approximately 69 new PGDP monitoring wells are scheduled to be installed at the site in late 2009 and early 2010, groundwater chemistry and lithologic and hydraulic data from these wells and associated installation activity will provide new information that should be incorporated as part of the next model iteration.

Additional aquifer tests:

- Aquifer testing (pumping tests and/or slug tests) may help confirm the model's calibrated hydraulic conductivity distribution.

Routine comprehensive groundwater level measurement events:

- Comprehensive time synchronous groundwater level measurements should be collected from wells (TVA, Cabellec, etc.) within the groundwater model flow domain on a routine basis to capture seasonal effects. The water level measurements should be synoptic, collected over a relatively short duration, ideally within more than a few days. These measurements then can be used as calibration targets for the next model iteration.

Anthropogenic recharge refinement:

- It is recognized that this is a difficult task, but efforts should be made when possible to develop a better understanding of anthropogenic recharge locations and rates.

- Examine existing datum anomalies in the water level dataset (groundwater level anomalies) and identify and address other apparent anomalies in the PGDP physical database (incomplete construction information, etc.).

Creek/groundwater interaction:

- The volumetric rates at which water enters and exits streams can be very important for model calibration. Efforts should be made to gage flows in Bayou and Little Bayou Creeks to determine where and in what quantities water enters and exits the creeks.

- The relationship between creek stage and adjacent groundwater levels should be characterized by installation of well clusters adjacent to the creeks.

C-746-S&T and U-Landfills:

- Data specific to the C-746-S&T- and U-Landfills should be utilized during the next model iteration.

RGA/Terrace Gravel groundwater relationship:

The groundwater relationship between the RGA and the Terrace Gravel is poorly understood; specifically, does Terrace Gravel groundwater discharge to the RGA or to creeks located on the Terrace? Data collected during future PGDP projects should be evaluated to better characterize RGA/Terrace Gravel groundwater interaction.