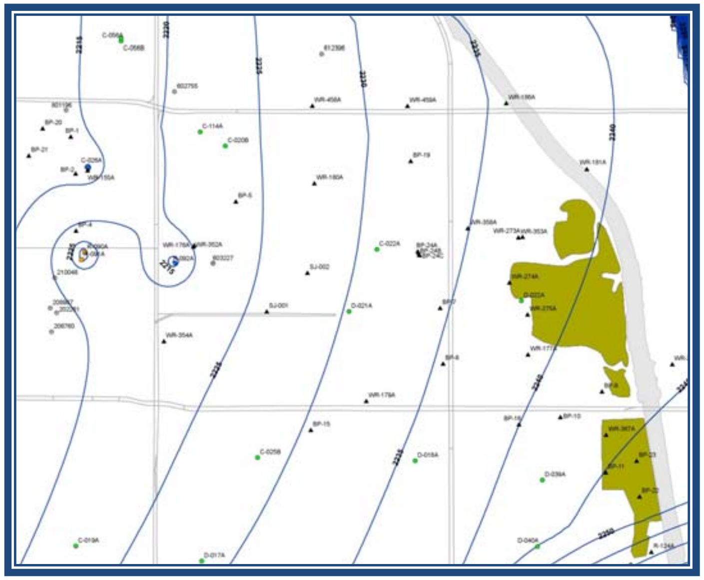

# GROUNDWATER FLOW MODEL DOCUMENTATION REPORT

## For Use in Conducting Feasibility Study

## Broadway-Pantano Water Quality Assurance Revolving Fund Site

***Tucson, Arizona***

***Prepared for:***


**Arizona Department of Environmental Quality**
400 West Congress Street, Suite 433
Tucson, AZ 85701


***Prepared by:***


**Clear Creek Associates, P.L.C.**
221 North Court Avenue, Suite 101
Tucson, AZ 85701


**June 25, 2010**

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REGISTERED GEOLOGIST
CERTIFICATE NO.
33261
MICHAEL L
ALTER
Date Signed 6/25/10
ARIZONA, U.S.A.
EXPIRES 12/31/2010

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| af/yr | acre-feet per year |
| ADEQ | Arizona Department of Environmental Quality |
| ADWR | Arizona Department of Water Resources |
| amsl | above mean sea level |
| AWQS | Arizona Aquifer Water Quality Standard |
| bgs | below ground surface |
| BNL | Broadway North Landfill |
| BSL | Broadway South Landfill |
| CCA | Clear Creek Associates |
| CSM | Conceptual Site Model |
| DCE | *cis*-1,2-Dichloroethene (a.k.a. *cis*-1,2-Dichloroethylene) |
| DO | Dissolved oxygen |
| EPA | United States Environmental Protection Agency |
| FS | Feasibility Study |
| gpm | Gallons per minute |
| Kh | Horizontal hydraulic conductivity |
| Kv | Vertical hydraulic conductivity |
| $n_c$ | Effective porosity |
| $n_t$ | Total porosity |
| MAE | Mean Absolute Error |
| ME | Mean Error |
| MODFLOW | Modular Three-Dimensional Finite Difference Groundwater Flow Model |
| NRC | National Research Council |
| PCE | Tetrachloroethene (a.k.a. tetrachloroethylene) |
| R | Calibration residual |
| RI/FS | Remedial Investigation/Feasibility Study |
| RMS | Root Mean Square Error |
| %RMSE | Percent Root Mean Square Error |
| S | Specific storage |
| Site | Broadway-Pantano Water Quality Assurance Revolving Fund Site |
| Sy | Specific yield |

| | |
|---|---|
| T | Transmissivity |
| TCE | Trichloroethene (a.k.a. trichloroethylene) |
| VC | Vinyl Chloride |
| VOC | Volatile Organic Compounds |
| WCS | Western Containment System |
| WQARF | Water Quality Assurance Revolving Fund |
| μg/L | Micrograms per liter |

# 1.0 INTRODUCTION

The Arizona Department of Environmental Quality (ADEQ) is conducting a Remedial Investigation/Feasibility Study (RI/FS) to address groundwater impacts at the Broadway-Pantano Water Quality Assurance Revolving Fund (WQARF) Site (Site) in Tucson, Arizona. Figure 1 is a Site Location Map. Clear Creek Associates was contracted by ADEQ to construct a groundwater flow and contaminant transport model to use in the RI/FS, specifically to evaluate remedial alternatives as part of the Feasibility Study (FS). This report describes the model development process, starting with a discussion on model objectives, and including sections to describe the Conceptual Site Model (CSM), the various modeling codes that were used, and the construction and calibration of the model.

Model development was completed by Clear Creek Associates with the majority of the work conducted in 2008 and 2010. Numerous meetings were held during construction and calibration of the model to update progress and solicit feedback from key stakeholders. These meetings were attended by ADEQ and other interested parties, including the City of Tucson Water Department, the City of Tucson Environmental Services Department, and Pima County Solid Waste.

A prior groundwater modeling study of the Broadway-Pantano WQARF Site was conducted by URS-Dames & Moore in 1999-2000 for use in developing an interim groundwater containment plan for impacted groundwater in the western portion of the WQARF Site (URS, 2000). The URS-Dames&Moore study relied on a five-layer groundwater flow model and covered most of the Tucson Basin. The study did not include a contaminant transport model. Clear Creek Associates reviewed the prior model for potential use in this study and determined that a new flow model was appropriate, primarily to accommodate revisions to the conceptual site model associated with more recent data (e.g., new monitor wells and observations from operation of the Western Containment System). A new model was also required to allow for refinement of the horizontal and vertical calculation grids and an updated (more current) calibration period, and it accommodates a mass transport model. While not directly used in this study, the original model served as a key reference during development of the new model.

## 1.1 MODELING OBJECTIVES

The primary objective of the groundwater flow and transport model will be to serve as a tool for use in completing the Feasibility Study, during which ADEQ will evaluate various strategies for containing and/or remediating impacted groundwater at the WQARF Site. This objective requires that the model can be used to do the following:

- Simulate the groundwater flow system,
- Evaluate and optimize possible hydraulic containment scenarios subject to various hydraulic stresses,
- Predict future chlorinated volatile organic compound (CVOC) concentrations,
- Identify data gaps – optimize monitoring efforts,
- Compare the effectiveness of remedial strategies, and
- Characterize the uncertainty of and perform analyses to support remedial decisions.
-

## 1.2 MODEL STATUS

As stated above, this report is intended to document the construction and calibration of the model. The report is not intended to present the results of the evaluation of remedial alternatives for the WQARF Site, which will be presented in the FS Report.

The report is presented in accordance with the ASTM Standard Guide for Documenting a Ground-Water Flow Model Application (1995). As such, the document presents the model assumptions and objectives, the conceptual model, code description, model construction, model calibration, and summary.

## 1.3 GENERAL SETTING

The Broadway-Pantano WQARF Site (Site) is located in east-central Tucson, Arizona. The Site is bounded approximately by Speedway Boulevard to the north, Pantano Wash to the east, Calle Madero to the south (south of Broadway Boulevard), and just east of Craycroft Boulevard to the west. Figure 1 is a project location map. The Site is located within the Tucson Basin, a northwest trending structural basin filled with alluvial sediments. Depth to groundwater at the Site ranges from approximately 315 feet below ground surface (bgs) to 370 feet bgs. Groundwater flow is generally to the west-northwest.

The Broadway-Pantano WQARF Site consists of the groundwater containing tetrachloroethene (PCE), trichloroethene (TCE), and vinyl chloride (VC) at concentrations above Arizona Aquifer Water Quality Standards (AWQS). The two known sources of this contamination at the Site are the closed Broadway North Landfill (BNL) and the closed Broadway South Landfill (BSL). Groundwater contamination extends from the BNL west and from the BSL northwest/west approximately 2 ½ miles. The PCE plume is surrounded by City of Tucson municipal water supply wells to the north, west, and south, and private domestic and commercial wells to the southwest and northwest, respectively. Additional information concerning the Site is discussed in Section 2.0 – Conceptual Site Model, which served as the basis for development of the groundwater flow and transport model.

# 2.0 CONCEPTUAL SITE MODEL

This section presents Clear Creek Associates' conceptual site model (CSM) of the hydrologic system in and around the Site. This CSM served as the basis for developing the numerical groundwater flow model that will be used to evaluate remedial alternatives for VOCs in groundwater at the Site.

This CSM was developed based on Clear Creek Associates' review of geologic and hydrologic data from within and around the Site. The data review focused on site-specific hydrogeologic data compiled from reports provided by ADEQ, the City of Tucson, and other sources. Specific data sources included:

- Lithologic and geophysical logs,
- Well construction records,
- Pumping/Aquifer test data,
- Western Containment System (WCS) operating records,
- Water level data (current and historic), and
- Water quality data.

## 2.1 OVERVIEW

A conceptual model is a summary of the site conditions that govern groundwater flow, simplified to present the essence of how the hydrologic system works. The following section, taken from ASTM D 5447-1993 "Application of a Ground-Water Flow Model to a Site-Specific Problem", discusses the objectives and key components of a conceptual groundwater flow model:

*A conceptual model of a groundwater flow and hydrologic system is an interpretation or working description of the characteristics and dynamics of the physical hydrogeologic system. The purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into a set of assumptions and concepts that can be evaluated quantitatively.*

*Development of the conceptual model requires the collection and analysis of hydrogeologic and hydrologic data pertinent to the aquifer system under investigation.*

Some of the more important features of the CSM are described below. The primary features of the groundwater flow system to be considered include:

- Geologic setting, including the spatial and depth variability (e.g., grain size, consolidation) of the basin fill sediments in the WQARF Site area;
- Horizontal and vertical hydraulic gradients, including the Pantano Feature, a steep hydraulic gradient observed east of the WQARF Site;
- The hydraulic characteristics of the aquifer system(s), including horizontal and vertical hydraulic conductivity, specific yield, storage coefficient, and effective porosity;
- Natural aquifer recharge from the Pantano Wash and other streams/washes and associated flood plain alluvium and its potential effect on groundwater flow and contaminant transport;
- Effect of well pumping on groundwater flow and contaminant migration;
- Effect of existing WCS, specifically the operation of extraction and injection wells;

The following sections detail these primary features.

## 2.2 SITE DESCRIPTION

The Broadway Pantano WQARF Site is located in the east-central Tucson basin and is bounded approximately by Speedway Boulevard to the north, Pantano Wash to the east, Calle Madero to the south (south of Broadway Boulevard), and Sahuara Avenue to the west (west of Wilmot Road). The Site consists of the closed BNL, the closed BSL and the associated VOC contaminant plumes.

A draft Remedial Investigation (RI) report for the groundwater VOC contaminant plumes was issued by ADEQ for public comment in Spring 2007 (Secor, 2007). The draft RI report describes the physical characteristics of the Site, including detailed discussions on the sources of contamination at the Site and the nature and extent of groundwater contamination.

## 2.3 STUDY AREA

The term Study Area is used in this report to identify the area that was the focus of the modeling study. Figure 2 shows the location of the Study Area, the Broadway-Pantano WQARF Site, the BNL and BSL, and nearby municipal supply wells. Since the objective of the modeling study is to evaluate contaminant transport and groundwater remedies, the Study Area includes the extent of the VOC plumes (i.e., the extent of PCE at concentrations above 5 micrograms per liter [µg/L]). The Study Area also includes nearby hydrologic features that could affect groundwater flow in the area of the plume. This includes water supply wells and recharge features sufficiently close to the VOC plume to affect groundwater flow direction and/or hydraulic gradient. In the western portion of the WQARF Site, the extent of PCE concentrations above 5 µg/L extends just west of monitor well WR-704A. The Study Area includes the area between WR-704A and private and City of Tucson municipal water supply wells located to the west, such as C-051B. Based on a review of historical pumping records and water level data from WQARF Site wells, the Study Area includes wells and other features located within two miles of the VOC plume. Based on our review, we believe pumpage from individual wells and recharge features outside of the two mile distance would not have the potential to affect groundwater flow in the area of the VOC plume.

## 2.4 GEOLOGY

The Broadway-Pantano WQARF Site is located in the Tucson basin, a Cenozoic extensional basin comprised of sediments derived from the nearby mountain ranges. The upper (more recent) sedimentary deposits consist of relatively undeformed alluvial fan, alluvial plain, and playa deposits (Houser et al., 2004). Deeper (older) sedimentary deposits consist of more consolidated and faulted basin fill.

For this study we relied primarily on a review of lithologic and geophysical logs from City of Tucson supply wells. Figure 3 shows the location of two west-to-east cross sections drawn through the Study Area. The cross sections are presented in Figures 4 and 5. The cross sections show the water table, and depths and screen intervals of production and monitor wells. The lithologic logs for the wells did not indicate the existence of a laterally extensive stratigraphic contact to at least 1,000 feet in depth within the Study Area. Appendix A presents lithologic logs for selected supply well and monitor well boreholes; these logs are provided to demonstrate the general lack of grain-size and clast composition variability in the Study Area (see discussion below). We also reviewed lithologic logs from other supply well and monitoring well boreholes in and around the WQARF Site. Geophysical logs were not collected from the monitor well borings, which were generally drilled to shallower depths than the Tucson Water well boreholes.

The lithologic logs generally indicate similar grain size (sands and gravels) and clast composition (granitic gneiss) from the land surface to total drilled depths. Likewise, the geophysical logs indicate relatively similar geologic conditions (i.e., grain size, density) throughout the total drilled depth. Thin discontinuous clayey beds are noted in some lithologic logs, but do not appear laterally extensive or thick enough to warrant separate hydrostratigraphic designations in the groundwater flow model. An increase in cementation and/or consolidation is suggested by subtle shifts on geophysical logs, particularly the sonic and electric logs. In general, the lithology of saturated sediments within the Study Area appears to be relatively uniform and homogeneous to depths of at least 1,000 feet.

The geology of the Study Area (east Central Tucson basin) is characterized by a thick (greater than 1,000 foot) sequence of alluvial fan deposits that are most likely derived from the Santa Catalina Mountains to the north. The lithologic and geophysical logs do not indicate any mappable geologic contacts within this depth interval. Our conceptual model, however, accommodates possible variations in consolidation and cementation with depth, as possibly indicated in the sonic logs.

## 2.5 AQUIFER SYSTEM

Groundwater in the Study Area occurs in the basin fill sediments (generally unconsolidated alluvial fan deposits), which comprise a regional unconfined aquifer. Important features of the aquifer system are shown on Figure 6. Groundwater flows into the WQARF Site area from the northeast, east, and southeast (see flow arrows on Figure 6). Aquifer recharge sources within the Study Area include Pantano Wash, Rillito Creek, and Tanque Verde Creek, which are ephemeral streams that flow in response to storm events. As such, aquifer recharge within the Study Area varies seasonally and annually. Groundwater flows out of the Study Area to the west. Water is also removed from the aquifer by pumping.

The aquifer system within the Study Area is an important source of water for municipal and private water supply. Figure 7 presents a chart showing total municipal pumping within the Study Area from 1955 through 2007. The vast majority of historical and current pumping in the Study Area is for municipal (City of Tucson) supply, representing greater than 90 to 95 percent of all pumping. Private supply wells comprise the remainer of the total pumping.

City of Tucson wells are operated to meet municipal demand, which varies seasonally and annually. The operation of this portion of the municipal wellfield is also affected by regional water policy decisions. In 1993, the City of Tucson reduced municipal supply well pumping significantly when Central Arizona Project water was directly delivered to customers. Full–scale pumping resumed in 1994. In 2001, the City of Tucson began importing water from the Clearwater Project, which has allowed for a corresponding reduction in municipal pumping from the Tucson Basin.

Arizona Department of Water Resources (ADWR) considers wells that are designed to operate at less than 35 gallons per minute (gpm) as exempt wells, which means the state does not require the well owner to report pumping. As a whole, exempt well pumping is not considered to have a significant effect on groundwater flow in the Study Area.

A typical supply well in the Study Area has a screen interval that extends from the top of the aquifer to depths of approximately 200 to 300 feet below the water table. The total thickness of the basin-fill aquifer in the Study Area is unknown, but it is at least 600 feet based on drilling results. Therefore, most well pumping is from the upper portion of the aquifer.

## 2.6 GROUNDWATER FLOW DIRECTION AND HYDRAULIC GRADIENT

Current and historic groundwater level data were reviewed for wells in the Study Area to evaluate groundwater flow direction and gradient. The water level data set is extensive and includes periodic hand measurements dating as far back as the 1940s and more detailed transducer data sets for the more recent period (generally since 2006).

The depth to groundwater in the Study Area is approximately 315 to 370 feet bgs. Figure 8 presents a water level contour map of the Study Area using data from February 2008. The regional groundwater flow direction in the Study Area is to the west. Water level contours in the Study Area reveal a broad west-northwest trending trough, with groundwater flowing into the Site from the northeast, east, and southeast. The existence of this trough feature is attributed to the general geometry of the Tucson basin, a broad zone of higher aquifer hydraulic conductivities, and a cone of depression caused by historical pumping within the Central Wellfield area. The steeper hydraulic gradients that define the eastern boundaries of the trough are interpreted to correspond to decreased hydraulic conductivities.

Groundwater flow in the western WQARF Site is affected by operation of the WCS, which uses two extraction wells (R-092A and C-026B) and two injection wells (R-090A and R-091A) to contain a portion of the VOC plume. St. Joseph's Hospital operates a private supply well that is located approximately 300 feet east of R-092A. When operating, this well contributes to the overall cone of depression around R-092A. The system has operated since 2003 at overall extraction/injection rates ranging from 800 to 1,100 gpm. Water level data from monitor wells are used to evaluate the performance of the WCS. The data indicate a groundwater mound forms in response to injection at R-090A and R-091A. Likewise, a cone of depression forms in response to pumping at R-092A and C-026B. The effect of the WCS on water level contours is demonstrated on Figure 9, a more detailed water level contour map for the WQARF Site area for February 2008, a time when the WCS was operating.

### 2.6.1 Horizontal Hydraulic Gradient

The horizontal hydraulic gradient ranges from approximately 10 feet per mile (0.0020 ft/ft) in the eastern WQARF Site area to approximately 15 feet per mile (0.0029 ft/ft) farther west. The gradient has varied historically in response to municipal pumping in the Tucson Basin. Figure 10 presents hydrographs for wells C-058A, D-021A, and D-022A. The wells are oriented west to east and spaced approximately ½ mile to 1 ½ miles apart (wells are shown on Figure 2). The difference in water level between the three locations at any one time is an indication of the hydraulic gradient in the east-west direction. In general, the hydraulic gradient across the Site has decreased as wellfield pumping has decreased. The highest gradient values were recorded in the late 1990s, with the gradient in the western portion of the Site at approximately 23 feet per mile (0.0044 ft/ft). The difference in gradient in western and eastern portions of the Study Area is due primarily to the shutdown of water supply wells located near the WQARF Site in the late 1980s.

A steeper hydraulic gradient is observed east of the WQARF Site along a northwest-trending zone (Figure 8). This zone has been identified as the Pantano Feature (Johnson, 1993). The approximate location of the Pantano Feature is shown on the Hydrologic Features Map (Figure 6). The steeper gradient occurs over a narrow (less than 1/4 mile) zone. Water levels recorded in water wells east of this zone are approximately 150 feet higher than west of the zone. The cause of the steeper gradient is generally unknown. From a hydrologic standpoint, the zone effectively represents a boundary between two aquifer systems. Hydrologic stresses east of the zone (e.g., well pumping) are not capable of affecting groundwater flow (direction or gradient) in the WQARF Site.

### 2.6.2 Vertical Hydraulic Gradient

A field investigation was completed in 2003 to evaluate whether vertical groundwater flow was occurring within the Site (Secor, 2004). The investigation relied on temperature and Flovision TM surveys of seven monitoring wells. While the temperature survey suggested vertical flow in six of seven monitor wells, the more reliable Flovision survey indicated measurable vertical groundwater flow at only two locations (BP-2, and C-026A) and non-quantifiable flow at one location (BP-4). The other wells surveyed showed no quantifiable vertical flow. Secor (2004) attributed the downward flow in BP-2 and C-026A to pumping at nearby WCS extraction well C-026B. Likewise, the downward flow in BP-4 could be reflecting the operation of nearby WCS injection wells R-090A and R-091A. The three wells that had interpreted vertical flow have relatively long screen intervals that likely intersect lithologic beds with variable hydraulic properties. While this vertical flow could potentially lead to mixing of water in the well casing, it is not interpreted to a significant potential source of cross contamination at the Site. Recent sampling results for these three monitor wells indicate low or non-detect concentrations of PCE;

therefore, downward gradients in these wells are not contributing to vertical spreading of the VOC plume.

The results of the 2003 Secor investigation indicated that vertical gradients can occur at the Broadway-Pantano WQARF Site, especially within wells with longer screen intervals located in the vicinity of operating pumping or injection wells. The results also indicated that vertical gradients are not likely to be significant in areas outside the immediate vicinity of operating water supply wells.

Water level elevation data from monitor well cluster BP-24, which includes three wells screened at different levels of the aquifer, were reviewed to analyze vertical hydraulic gradients at that location. The analysis involved comparing water level elevations from two measurement events - January 21, 2008 and June 3, 2008. The results are summarized below:

| Well ID | 1/21/08 Water Level Elevation (ft amsl) | 6/3/08 Water Level Elevation (ft amsl) |
|---|---|---|
| BP-24A | 2232.60 | 2232.09 |
| BP-24B | 2234.14 | 2233.74 |
| BP-24C | 2234.44 | 2234.08 |

In both measurement events, the lowest water level elevations were measured in the shallowest well (BP-24A) and the highest water level elevations were measured in the deepest well (BP-24C). This would indicate an upward vertical hydraulic gradient.

One possible interpretation of the upward gradient is that the shallowest well is better hydraulically connected to the nearest pumping wells (St. Joseph's Hospital private supply well and R-092A).

It is not clear whether the vertical gradients are sufficient to cause significant downward or upward groundwater flow in the natural aquifer system (outside a well borehole), and the overall site data do not indicate any regionally extensive vertical hydraulic gradient. However, water level data and flow-profiling results do indicate that localized vertical gradients are possible, especially around active wells.

## 2.7 AQUIFER PARAMETERS

Step drawdown and constant discharge pumping tests have been performed on many Study Area water supply wells (CH2M Hill, 1988; Errol L. Montgomery & Associates, 1991; Errol L. Montgomery, 1992; URS, 2002). To support this study, Clear Creek Associates re-analyzed selected aquifer tests completed on nearby Tucson Water supply wells. Hydrologic data, including test date, duration, pumping rate, and maximum drawdown, for the re-analyzed pumping tests are summarized in Table 1. Aquifer transmissivity (T) based on the single well tests ranges from approximately 5,400 to 394,000 gallons per day per foot (gpd/ft) (700 to 53,000 $ft^2$/day). Horizontal hydraulic conductivity (Kh) values were estimated using the calculated aquifer transmissivity and the difference between the static water level and the total well depth (saturated thickness). Kh values ranges from 1 to 170 feet per day (ft/day). Figure 11 shows estimated Kh values for wells in the Study Area. Note that many of the estimated values shown on this map are from tests conducted in the 1970s and 1980s. There have been considerable water level declines in the area of some of these wells and the conductivity values shown on the map may not be representative of current conditions. Representative Kh values in the Study Area are approximately 20 to 120 ft/day. Lower T and Kh values are observed south of the WQARF Site.

For some wells, such as well C-046B, tests were conducted at different time periods. At C-046B, aquifer T decreased over the three tests. This decrease is interpreted to be caused by decreasing water levels (the water table dropped 71 feet over the 18 year period), and a corresponding decrease in the saturated thickness of the aquifer. The calculated Kh did not vary significantly between the three tests (Kh = 40 to 45 ft/day).

One limitation to the aquifer testing data set is that all previous tests were conducted on wells that are screened from above the water table to depths generally greater than 200 feet. This makes it impossible to resolve variations in Kh with depth. The data set is particularly deficient when it comes to the lower portions of the aquifer system (i.e., below 100 feet below the water table).

To address this data gap, Clear Creek coordinated a series of aquifer tests on three 5-inch monitoring wells constructed with screen intervals at different depths. The three monitoring wells, BP-24A, B, and C, are located within the VOC plume approximately 2,000 feet west of the BNL. Eight-hour constant discharge pumping tests were conducted on BP-24B, middle screen interval, and BP-24C, deeper screen interval. A pumping test was attempted at BP-24A, but was not completed due to the limited available drawdown (less than 20 feet). Recovery monitoring was conducted following the completion of the pumping at each well. Transducers recorded water levels in the pumping well and both observation wells during each test. Details concerning the pumping tests are summarized in a letter report to ADEQ dated September 8, 2008 (CCA, 2008). The key results of the aquifer testing at BP-24 are summarized below:

- The specific capacity value was slightly lower in BP-24C (3 gpm/ft) than BP-24B (5 gpm/ft); however this relatively small difference is interpreted to be caused by well efficiency differences, not different aquifer conditions.

- Pumping at each monitoring well caused drawdown in each of the observation wells. Pumping BP-24B resulted in 0.3 feet and 1.6 feet of drawdown in BP-24A and BP-24C, respectively. Pumping BP-24C resulted in 0.1 feet and 1.9 feet of drawdown in BP-24A and BP-24B, respectively. Both tests indicated greater drawdown responses in the middle and deep monitoring wells than the shallow monitoring well. We interpret this to reflect the presence of a thin clay bed between the middle (BP-24B) and upper (BP-24A) monitoring wells.

- Aquifer T and Kh were estimated based on the recovery data from each of the pumped monitoring wells. Theis recovery plots are presented in the letter report. The T and Kh estimates for BP-24B, representing the interval from 50 to 70 feet below the water table, were 1,500 $ft^2$/day and 76 ft/day, respectively. The T and Kh estimates for BP-24C, representing the interval from 105 to 125 feet below water table, were 4,700 $ft^2$/day and 235 ft/day, respectively. These results indicate Kh is likely variable in the depth intervals considered important for this study (upper 200 feet of the aquifer). It also indicates aquifer tests of wells with longer screen intervals should be analyzed with the understanding the results represent average conditions, and variable Kh values are probable.

Most studies assume that hydraulic conductivity decreases with depth due to increased cementation and consolidation. In this Study Area there is no direct hydraulic conductivity data for the aquifer below approximately 550 feet bgs and lithologic logs indicate very little grain size and clast composition variability with depth. However, there are a couple ‘lines of evidence’ that suggest hydraulic conductivity decreases with depth. These include:

- **Increased travel-time velocities on down-hole acoustic (sonic) logs**, indicating increases in material density.
- **Decreasing specific capacities over time in water supply wells.** This could be attributed to deteriorating well conditions, like plugging of screen openings. However, we believe the overall decrease in specific capacity in most Study Area supply wells over time is attributed to the gradual dewatering of the more productive (higher conductivity) shallower aquifer.

Aquifer testing data indicate that Kh varies both laterally and vertically within the Study Area reflecting subtle variations in grain size, sorting, and degrees of cementation and consolidation. Of particular interest for this study are changes in Kh with depth. There are limited data available to discern such changes; however, vertical variations in Kh could affect hydraulic capture and contaminant transport predictions.

Over the past two years, ADEQ has installed and monitored transducers in observation wells located around the WQARF Site. The data from these wells is used to prepare water level contour maps and to evaluate the water level response to WCS operations. Transducers are set to record water levels every two hours. The WCS was shut down on September 17, 2006 due to a pipeline break. The system was restarted on April 25, 2007 and operated fairly continuously through the following summer. The transducer data set recorded the aquifer response to this shut down/restart event.

This modeling study included a more detailed analysis of the WCS shut-down and restart events. Matching the aquifer response recorded by the observation well transducers was a primary component of the model calibration process (Section 4.1.6.1 – Calibration Targets and Goals).

Vertical hydraulic conductivity (Kv) is assumed to be less than Kh. The initial CSM assumed a Kh:Kv ratio of 50:1 based on the analysis of constant discharge tests conducted on the new WCS extraction/injection wells (URS, 2002).

Aquifer specific yield (Sy) and storage coefficient were estimated by URS (2002) based on detailed analyses of aquifer tests completed on WCS wells R-090A, R-091A, and R-092A. URS' analysis relied on observation well data to estimate specific yield and storage. Sy ranged from 0.005 to 0.07. Estimates of Sy from regional studies of the Tucson Basin range from 0.03 to 0.25 with average values between 0.12 and 0.15 (Anderson, 1972; Davidson, 1973; Hanson and Benedict, 1994). Storage coefficient estimates from the URS (2002) analysis ranged from 0.0001 to 0.005.

## 2.8 OCCURRENCE AND DISTRIBUTION OF CONTAMINANTS

The contaminants that are present, or have been present, in groundwater at the Site at concentrations exceeding their respective AWQS include PCE, TCE, and VC (Secor, 2007). The BNL and BSL are interpreted as the primary sources of groundwater contamination at the WQARF Site (Secor, 2007). Groundwater containing PCE at concentrations above the AWQS of 5 µg/L occurs over two miles west of the BNL, with the end of the contaminant plume located just east of Craycroft Road[1]. PCE concentrations in the middle of the VOC plume have

[1] The western extent of the PCE plume is interpreted between monitor well WR-704A, located just east of Craycroft Road, and municipal supply well C-051B, located approximately ¼ mile west of Craycroft Road. Recent water chemistry results from WR-704A indicate that PCE concentrations increased from below 5 µg/L to above 5 µg/L in the first quarter of 2010, suggesting the western extent of the PCE plume was in the vicinity of WR-704A at this time.

decreased in response to the operation of the WCS; concentrations in this area are now below the AWQS. The vertical extent of the VOC plume is limited to the upper 50 to 100 feet of the aquifer based on sampling results from monitor wells west of the BNL. Based on relative concentrations and the distribution in the aquifer, PCE presents the greatest concern at the WQARF Site. Other plumes of contaminants of concern at the Site are well within the margins of the PCE plume and are limited to the immediate area of the BNL and BSL. Figure 12 shows the extent of the PCE plume in April 2007.

## 3.0 COMPUTER CODE DESCRIPTION

The Modular Three-Dimensional Finite Difference Groundwater Flow Model (MODFLOW) was the selected model code for the Broadway-Pantano WQARF Site modeling study. MODFLOW is a numerical groundwater flow engine that was developed by the United States Geological Survey (McDonald and Harbaugh, 1988; Harbaugh and others, 2000). This study uses MODFLOW-2000, the most recently released version (Harbaugh and others, 2000).

The MODFLOW code was selected for this study because it addresses the primary groundwater flow modeling objectives, such as three-dimensional groundwater flow, spatial variability of hydrologic parameters, and time-varying hydraulic stresses such as pumping wells. The MODFLOW code is widely used and is accepted as a valid model for simulating groundwater flow.

Contaminant transport at the Site was simulated using the modeling application RT3D, which was developed for the Battelle Memorial Institute, Pacific Northwest National Laboratory (Clement and Johnson, 2002). RT3D is a program for simulating reactive multi-species mass transport in three-dimensional groundwater aquifers. The original program was released to the public domain in 1997. This study used Version 2.5, which was released to the public domain in 2002.

The RT3D code was selected for this study because it allows for simulating the processes of advection, dispersion, sequential biodegradation reactions, and sorption, all of which are factors that affect plume migration at the Broadway-Pantano WQARF Site.

Clear Creek Associates used the Visual MODFLOW modeling application to construct the model and evaluate results. Visual MODFLOW supports the numerical engines introduced above and allows for two-dimensional and three-dimensional visualization of model input parameters and results. Visual MODFLOW is distributed by Waterloo Hydrogeologic, Inc. The Broadway-Pantano WQARF Site modeling study used Version 2009.1.

# 4.0 MODEL CONSTRUCTION

## 4.1 GROUNDWATER FLOW MODEL

The Broadway-Pantano WQARF Site groundwater flow model was constructed using Visual MODFLOW, version 2009.1. Visual MODFLOW allows for use of a World Coordinate system, allowing site features, such as pumping wells, to be directly imported and represented at actual locations. The Broadway-Pantano WQARF Site model uses the Arizona State Plane, NAD 83, coordinate system. Hydraulic parameters and other model features were assigned according to the discussions presented in this section.

### 4.1.1 Model Domain

The Broadway-Pantano WQARF Site groundwater flow model domain includes approximately 56 square miles of the Tucson basin (Figure 13). The domain extends approximately from Country Club Road on the west to Harrison Road on the east, and from Escalante Road on the south to River Road on the north. The domain boundaries are positioned at least two miles from the WQARF Site in all directions and encompass the full Study Area described in Section 2.3 – Study Area.

The model domain is oriented east-west, roughly parallel to the primary regional groundwater flow direction in the WQARF Site area.

The horizontal model grid contains 150 rows and 213 columns for a total of 31,950 cells per layer. With a total of six layers (see below), the model contains 191,700 calculation cells. The model-grid is shown in Figure 14. The cell dimensions range from 500 by 500 feet near the edges of the model to 100 by 100 feet in the area of the WQARF Site. The maximum horizontal aspect ratio, which is the ratio of the lengths of the cell sides, ranges from 1:1 to 5:1.

Six constant-thickness model layers are used to simulate the aquifer system (Figure 15). The land surface represents the top of the uppermost model layer. Land surface elevations were assigned using 30m Digital Elevation Model files for the Tucson Basin. The bottom of layer 1, the uppermost model layer, is 400 feet below the land surface throughout the model domain. Note that much of layer 1 is unsaturated. In the area of the WQARF Site the water table is at a depth of 315 to 370 feet bgs, corresponding to a 30 to 85 foot saturated thickness of layer 1. Layers 2 through 4 are each 50 feet thick. Layers 5 and 6 are 250 feet think each. Layer thicknesses were assigned to allow simulation of key components of the CSM, such as the vertical extent of contamination. The model layer thicknesses were also assigned to be generally consistent with the horizontal grid spacing used in the area of the WQARF Site. The ratio of horizontal to vertical grid dimensions in the WQARF Site area is an acceptable 2:1 ratio (100x 100 horizontal spacing and 50 to 250 foot thick model layers. The bottom of the model is 1,050 feet bgs throughout the entire model domain.

### 4.1.2 Hydraulic Parameters

Hydraulic parameters were initially assigned to be consistent with the CSM, primarily relying on the aquifer testing results for municipal supply wells located around the model domain. Values were assigned for horizontal hydraulic conductivity (Kh), vertical hydraulic conductivity (Kv), specific yield (Sy), specific storage (S), effective porosity ($n_e$) and total porosity ($n_t$). These parameters were varied during model calibration to achieve the best fit to observed hydraulic patterns, including head elevations, hydraulic gradients, flow directions, and responses to hydraulic stresses such as pumping or injection well operations. Particular emphasis was placed on matching the hydrologic response of the aquifer system to the operation of the WCS. This exercise involved numerous model iterations to identify the value and distribution of hydraulic parameters necessary to match the observed responses in monitor wells located around the WCS. The final hydraulic parameter values are within the ranges of estimates described in the CSM. Figure 16 presents the final Kh and Kv values for model layers 1 and 2. Figure 17 presents the final Kh and Kv values for model layers 3 and 4. Figure 18 presents the final Kh and Kv values for model layers 5 and 6. Figure 19 presents the final Sy, S, $n_e$, and $n_t$ values for model layers 1 through 4. Figure 20 presents the final Sy, S, $n_e$, and $n_t$, values for model layers 5 and 6.

Important observations regarding the final distribution of hydraulic parameters are presented below:

- Kh values for model layers 1 through 4, representing the aquifer system to a depth of 550 feet bgs, ranges from 2 to 160 ft/day, with the exception of the Pantano Feature, which is

0.1 ft/day. Below this depth, corresponding to model layers 5 and 6 (550 to 1,050 feet bgs), the final Kh value of 0.5 ft/day was assigned.

- The ratio of horizontal to vertical hydraulic conductivity (Kh:Kv) ranges from 10:1 to 50:1, with the greater Kh:Kv ratios corresponding to the lower Kh values. The assumption being that the lower Kh values reflect greater percentages of fines (e.g., silt and clay), which, due to stratification, would have a more pronounced effect on vertical rather than horizontal flow.

- Kh values in the Broadway-Pantano WQARF Site area were assigned to match aquifer responses to WCS operations. The final Kh value of 35 ft/day (layers 1 through 4) was shown with numerous model runs to provide the best match to the observation well data set, including transducer data available for many monitor wells (e.g., BP-2 and BP-4).

- The Pantano Feature, which is discussed in Section 2.6, is simulated with a Kh value of 0.1 ft/day assigned to all model layers (Figures 16 through 18).

- Sy values range from 0.1 to 0.14 for the upper four model layers. Specific storage values range from $2.0 \times 10^{-6}$ to $2.0 \times 10^{-5}$, corresponding to storage coefficients ranging from 0.0005 to 0.001.

### 4.1.3 Sources and Sinks

Local and regional water sources and sinks simulated in the groundwater flow model are described in this section. Simulated water sources, features that add water to the system, include stream-channel recharge and aquifer injection wells. Simulated water sinks, features that remove water from the system, include private and municipal supply wells.

#### 4.1.3.1 Stream-Channel Recharge

Natural stream-channel recharge is simulated in the Broadway-Pantano WQARF Site groundwater model. Recharge is applied to cells representing the Rillito Creek-Tanque Verde Creek drainage and the Pantano Wash. Figure 21 shows the distribution of recharge cells in the Broadway-Pantano WQARF Site model domain. Stream channel recharge values were initially assigned based on estimates by Osterkamp (1973) and previous modeling studies (e.g., Hanson & Benedict, 1994). The recharge values were adjusted during model development to achieve calibration. The final stream channel recharge values used in the model are summarized below:

- Rillito/Tanque Verde drainage – Recharge values ranged from 29.7 to 118.8 inches per year (in/yr), which translates to annual recharge rates of approximately 150 to 600 acre-feet per mile, or 1,125 to 4,500 total acre-feet per year (af/yr) for the entire Rillito/Tanque Verde system within the model domain (approximately 7 ½ miles).

- Pantano Wash – Recharge values ranged from 2.5 to 9.9 in/yr, which translates to annual recharge rates of approximately 13 to 50 acre-feet per mile, or 100 to 400 total af/yr for the entire Pantano Wash system within the model domain (approximately 8 miles).

Stream-channel recharge was simulated in the model calibration runs at the rates discussed above. Lower recharge rates, representing ¼ of the normal recharge rates, were assigned to simulate drought conditions that persisted from the mid-1990s.

#### 4.1.3.2 Aquifer-Injection Wells

Direct injection of water into the aquifer system in the area of the Broadway-Pantano WQARF Site has been conducted at select locations at rates sufficient to affect hydraulic gradients and water chemistry; therefore, it was necessary to simulate these injection events in the groundwater flow model. The following injection events were simulated:

- Tucson Water Injection Well Program – 1993 – The City of Tucson conducted an aquifer injection well program that involved injecting water in ten wells: C-110A, C-108A, C-109A, C-056A, C-048A, C-049A, C-052A, C-050A, C-051B, C-046A, C-058A, and C-026A. All of these wells are located in the groundwater flow model domain. The total volume of water injected in the 10 wells was 2,348 acre-feet in the year 1993.

- Western Containment System – Re-injection Wells – Since March 23, 2003 – The Broadway-Pantano WQARF Site Western Containment System (WCS) uses two wells, R-090A and R-091A, to inject treated water. The two wells are located in the southwest area of the WQARF Site. Injection rates have varied since the WCS began operating in March 2003, with individual well injection rates ranging from 325 to 645 gpm.

The injection of water at individual wells is simulated in the groundwater flow model consistent with actual injection records.[2] For example, the operation of WCS injection well R-090A is simulated in accordance with the operation schedules indicated in the quarterly monitoring records for the WCS. Individual injection wells are simulated with screen intervals consistent with actual construction records.

#### 4.1.3.3 Well Pumping

Groundwater pumping represents the primary hydraulic sink in the modeled area. There are hundreds of water supply wells located within the model domain. Historical pumping from these wells represents both a regional hydraulic stress (total water table declines of greater than 150 feet have occurred since large-scale water resources development began in the 1940s) and a local hydraulic stress, with pumping from individual wells capable of altering nearby groundwater flow directions and hydraulic gradients. Pumping in the groundwater flow model was simulated using two methods depending on the time period being simulated.

**Ramp-up Simulation Period (1940 to 1990)**

For the period from 1940 to 1990, pumping was assigned within the model domain only to simulate the regional hydraulic effect, specifically the regional decline in the water table. This was accomplished by estimating the total groundwater pumping and distributing the pumping to ten specified locations around the domain. The locations of the ten ramp-up simulation wells are shown on Figure 22. The locations do not correspond directly to actual pumping wells; instead

[2] Individual well recharge rates were not available for the 1993 Tucson Water Injection Well Program; therefore, injection rates were assigned by dividing the total injected volume (2,348 acre-feet) by the number of injection wells in the program (10).

the wells were spread throughout the model domain. The total pumping assigned to the ramp-up period varied as follows:

- 1940 to 1970 – 10,000 af/yr
- 1970 to 1980 – 20,000 af/yr
- 1980 to 1990 – 35,000 af/yr

This approach was used because i) pumping records are not available for all wells for this period, and ii) the focus of the model calibration was on the more recent period from 1990 to 2007.

**1990 to 2007 Simulation Period**

For the period 1990 to 2007, pumping values were assigned to individual wells within the model domain. Pumping rates were assigned to 85 City of Tucson supply wells and 76 private (non-City of Tucson) supply wells during this period. Figure 23 shows the location of simulated municipal and private pumping wells located within the model domain. Despite the similarity in the number of municipal and private wells within the domain, City of Tucson municipal pumpage accounted for over 92 percent of total pumpage for the simulation period 1990 to 2007. Figure 24 presents the simulated pumping rates for the entire model domain by stress period. Simulated rates for individual pumping wells are presented in Appendix B. Private well pumping rates were assigned on an annual basis and are based on the annual reported pumpage indicated in ADWR's pumping records. City of Tucson supply well pumping rates were assigned on either a quarterly or annual basis and were based on reported monthly pumpage volumes listed in the City of Tucson Water Department Well Database (TW_WellDB.mdb; October 2008). Pumping rates for WCS extraction wells were assigned based on actual operating records as indicated in the quarterly operating reports prepared by URS and submitted to ADEQ.

Well locations and screen intervals for City of Tucson supply wells were assigned to the model based on survey coordinates and actual screen depths recorded in the Tucson Water database. Private supply wells were simulated with 400 foot screen intervals with the top of screen at an elevation of 2300 feet and a bottom of screen elevation of 1900 feet[3]. This interval represents the upper portion of the aquifer system in most of the model domain, including the water table. Note that in wells with screened intervals spanning multiple layers, MODFLOW will reduce the pumping rate when a layer goes dry. This of course, is not what actually happens as most wells are capable of sustaining pumping rates even as water levels decline. To sustain pumping rates at actual observed rates, the model assigned screen intervals were placed at deeper levels in areas where the upper model layers were shown to go dry. Note this was not necessary in the immediate area of the Broadway-Pantano WQARF Site as the uppermost layer remained saturated during the simulation periods.

#### 4.1.4 Boundary Conditions

A model boundary is the interface between the model calculation cells and the area outside the model (Spitz and Moreno, 1996). Boundaries occur at the edges of the model domain and at other locations where external influences are represented (e.g., recharge boundaries). As shown in Figure 21, the Broadway-Pantano WQARF Site flow model includes the following types of hydrologic boundaries:

**No-flow boundaries** include groundwater divides, boundaries that are parallel to flow lines, and bedrock areas. No-flow boundaries in the Broadway-Pantano WQARF Site model include i) short segments of the northwestern and southwestern model edges, where flow into and out of the model is assumed to be negligible due to parallel flow paths, and ii) the bottom of the model (i.e., the base of Layer 6 at 1,050 feet bgs).

**Constant-head and time-varying constant heads.** A constant-head boundary specifies the hydraulic head that the model will use to calculate flow into or out of the model. Constant-head boundaries are assigned along most of the periphery of the model domain. The constant-head boundaries assist in establishing the hydraulic gradient across the model domain. The hydraulic

[3] Construction details are not available, or are not reliable, for most private wells.

head values used for boundaries varied laterally based on the extrapolation of water levels in nearby observation wells, including D-038A (east), C-085A (east), B-046A (west), GB-001A (west), C-086A (north), D-027A (northeast). Regional changes in head elevations outside the model domain are simulated in the transient calibration using time-varying constant heads, which allow decline or rise rates to be applied to the boundary cells. For the Broadway-Pantano groundwater flow model, water levels have generally declined during the simulation period. The rate of decline varies depending on location within the basin, which affects regional hydraulic gradients. Decline rates assigned to the Broadway-Pantano model were based on the analysis of hydrographs for wells listed above. Decline rates are listed below (reference hydrograph in parentheses):

- Northern boundary - 0 feet per year (C-086A)
- Eastern boundary – 1 ½ feet per year (D-027A)
- Western Boundary – 3 feet per year (B-046A and B-047A)

Time-varying constant-head boundaries were specified for model edge cells for all six model layers. Simulated flow into and out of the model domain is calculated by the model based on aquifer hydraulic conductivity, hydraulic gradients, and the width and thickness of the model boundaries.

**Recharge boundaries**, such as stream channel and mountain-front recharge, are represented as constant flux boundaries in the model. Recharge boundaries in the Broadway-Pantano WQARF Site model include natural recharge in the Tanque Verde/Rillito Creek and Pantano Wash channels. Mountain-front recharge was not included in the model as the model boundaries do not extend to the margins of the basin. While not directly simulated, mountain-front recharge is not precluded from the model domain water balance, since flux into the model from upgradient sources (which would include mountain-front recharge) is simulated at the model boundaries. Figure 21 shows the recharge boundary locations assigned to the Broadway Pantano WQARF Site model. A discussion of stream-channel recharge is presented in Section 4.1.3.1 – Stream-Channel Recharge.

### 4.1.5 Numerical Parameters

The Broadway-Pantano WQARF Site groundwater flow modeling study used the WHS Solver for Visual MODFLOW (Waterloo Hydrogeologic, 2005). The WHS Solver is an iterative solver that uses a two-tier approach to a solution at each model time step. The following solver parameters were specified:

- Head change criterion – 0.01 ft
- Residual criterion – 0.01 ft
- Damping factor – 1
- Relative residual criterion – 0
- Factorization Level – 0

The transport model, described in Section 4.2, specified the following transport solution parameters/methods:

- Generalized conjugate gradient solver – Jacobi preconditioner – Relative convergence criterion = 0.0001 – Initial step size = 30 days – Multiplier 1.2
- Advection term solver – Upstream Finite Difference
- Courant number – 0.75

### 4.1.6 Calibration

Model calibration is the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulation and observations of the groundwater flow system. Specific calibration objectives for this modeling application described below in Section 4.1.6.1 – Calibration Targets and Goals.

The Broadway-Pantano WQARF Site groundwater flow model was calibrated to historical groundwater flow conditions. The calibration process involved an initial steady-state run followed by two transient period simulations, the first to simulate the period from 1940 to 1990 and the second to simulate the period from 1990 through 2007. The following sections describe the tasks completed to demonstrate model calibration. Digital files for the Broadway-Pantano WQARF Site calibration simulation are included with this report. The following sections provide a comparison of calibration simulation results and historical conditions.

#### 4.1.6.1 Calibration Targets and Goals

The purpose of model calibration is to obtain reasonable estimates for uncertain model input data, such that model predictions match observed data to the highest degree possible given the intended use of the model. The calibration approach for this study involved:

- Varying the values of uncertain input data within reasonable ranges to achieve the best correspondence between observed water levels and predicted heads.

- Minimizing the difference between predicted heads and observed water levels, or residuals. Statistical correlations were generated for each alternate set of input data.

- Judging the model accuracy using statistical analysis. For flow calibration, the variance of the residuals of the calibrated flow model should be less than 10 percent of the change in hydraulic head across the model domain or area of most importance. Statistical analyses in this study were conducted using both a regional (model domain-wide) observation well data set and a more focused observation well data set in and around the Broadway-Pantano WQARF Site. The 10-percent residual difference criteria described above was applied to both calibration data sets. For the domain-wide data set, the change in head (across the full model domain) is approximately 340 feet (in year 2007); so the variation between observed water levels and predicted heads should be less than about 34 feet. In the case of the WQARF Site area data set, the change in head across the WQARF Site is approximately 55 feet; so the residuals should be less than about 5.5 feet in this data set.

Calibration targets and goals were developed to provide the greatest level in confidence in using the model for its intended purpose, which is to evaluate remedial alternatives for the VOC groundwater plume. Since the FS will likely require an evaluation of various pumping and hydraulic containment alternatives, it is necessary for the model to accurately simulate the hydraulic response of the aquifer to local hydraulic stresses, such as the operation of pumping and injection wells in the immediate area of the WQARF Site. The following calibration targets reflect these calibration objectives:

- Simulate regional hydraulic stresses and regional gradients throughout model domain for the ramp-up period (1940 to 1990).

- Simulate regional hydraulic stresses and regional gradients throughout the model domain for the period 1990 through 2007.

- Simulate local hydraulic stresses and local gradients for the period 1990 through 2007. Note this requires simulation of regional stresses discussed above, and also local stresses such as the operation of the WCS and surrounding pumping wells.

- Precisely simulate the response of the aquifer system to local hydraulic stresses for the period 1990 to 2007. Considerable field data is available to evaluate the response of the aquifer to hydraulic stresses in the immediate area of the WQARF Site. Of particular interest is a transducer data set that includes water levels for numerous WQARF Site monitor wells for periods corresponding to operations of the WCS. The transducer data set captures WCS shutdown and restart events, providing a direct indication of the hydraulic response of the aquifer system to local hydraulic stresses. Precise simulation of these responses with the groundwater flow model was identified as a primary goal of the model calibration process. Hydrographs plotting the transducer data set and model predicted head elevations are the primary tool for assessing this calibration goal.

#### 4.1.6.2 Steady-State Simulation

A steady-state simulation was developed as a starting point to begin the transient-state calibration simulation, described below. The steady-state simulation was used to establish initial conditions for the transient-state simulation, the primary calibration mechanism. The steady-state simulation represents conditions within the model domain before large-scale groundwater withdrawals and other non-natural hydraulic stresses (e.g., groundwater injection). The year 1940 was chosen as the starting point for the transient simulation because, at that time, pumping in the Tucson Basin had not yet had an appreciable influence on groundwater levels, yet there were enough wells in the basin to provide water level elevation data from which to interpret regional flow directions. The steady state model was run without pumping in the model domain. Figure 25 presents the predicted head elevation contours for the steady state simulation. The predicted heads from the steady-state simulation served as the initial heads in the transient simulation.

#### 4.1.6.3 Transient-State Calibration Simulation

Calibration of the groundwater flow model relied primarily on a transient-state model simulation of conditions from 1940 through 2007, a period of 68 years. The transient-state simulation included a 50-year ramp-up period (1940 through 1989) and an 18-year calibration period (1990 through 2007). The ramp-up period was subdivided into three time intervals to approximate the step-like increase in groundwater pumpage within Tucson Basin (Figure 7). The 18-year calibration period was subdivided into 36 time intervals to simulate important changes in hydraulic stresses in the model, including those that pertain to calibration targets and goals, such as operational shut-down and restart events in the WCS. Input assumptions such as constant-head boundary elevations, pumping rates, and recharge rates were adjusted, as needed for each time interval. Table 2 lists and describes the simulation time intervals simulated in the transient-state calibration simulation.

Simulation time in MODFLOW is divided into stress periods. A stress period is defined as a time period in which dynamic stresses, such as pumping rates, are held constant. Stress periods are, in turn, divided into time steps. The modeler defines the number of time steps, and the time step multiplier, or ratio of the length of each time step to that of the preceding time step. For this study each stress period was divided into either 5 or 10 time steps depending on the length of the stress period. Using these terms, Visual MODFLOW calculates the length of each time step in a stress period. Head elevations are recorded at the end of each time step. These predicted head elevations were compared with measured water levels at selected observation wells. The following comparison methods were used to assess the calibration of the transient simulation runs:

- Scatter-graphs of predicted heads vs. observed water levels
- Statistical analysis
- Residual distribution maps
- Hydrographs
- Head elevation and water level contour maps
- Mass balance

#### *4.1.6.3.1 Transient-State Calibration Data Sets*

The transient simulation was calibrated to three primary data sets:

- 1990 Full Model Domain Data Set – This set includes 61 observation wells with reported and reliable late 1989 or early 1990 water level measurements. The observations wells are located throughout the model domain. Figure 26 shows the locations of observation wells used in the 1990 full model domain data set.

- 2007 Full Model Domain Data Set – This data set includes 205 observation wells with reported and reliable late 2007 or early 2008 water level measurements. The observation wells are located throughout the model domain. Figure 27 shows the locations of observation wells used in the 2007 full model domain data set.

- 2007 WQARF Site Area Data Set – This data set includes 33 observation wells with reported and reliable late 2007 or early 2008 water level measurements. The observation wells are located in and around the Broadway-Pantano WQARF Site. Figure 28 shows the locations of observation wells used in the 2007 WQARF Site area data set.

#### *4.1.6.3.2 Transient Simulation Results*

The overall performance of the transient-state simulation was assessed by reviewing the final model predicted head elevation contours and hydraulic gradients, both from a regional perspective and a more detailed assessment in the WQARF Site area.

Figure 29 shows the December 2007 model predicted head elevation contours for the full model domain. The contours show that the model has simulated the key regional hydraulic features, including:

- the regional westerly flow direction is simulated with water entering the model domain through the northeast, east, and southeast boundaries and exits the domain along the western boundary.

- the basin-scale hydraulic trough evident in the central portion of the model domain is simulated in the correct area and orientation. The simulation of the flow of water into this area from the northeast, east, and southeast matches observed conditions.

- the Pantano Feature (described in Section 2.6.1) is simulated in the correct location and the simulated magnitude of head drop across the feature matches observed conditions (simulated drop is over 150 feet).

- the overall hydraulic gradient across the model domain is accurately simulated.

- steeper hydraulic gradients are observed along the northern and southern model areas, providing an acceptable match to observed conditions.

Figure 30 shows the December 2007 model predicted head elevation contours for the immediate area around the Broadway-Pantano WQARF Site. A smaller contour interval of 5 feet is used in this map to illustrate more local hydrologic features, such as cones of depressions around pumping wells. The model predicted contours in WQARF Site area demonstrate that the calibrated model simulates key local hydraulic features, including:

- Hydraulic gradients and flow directions in all areas of the WQARF Site are simulated by the model and match interpreted conditions. Predicted flow directions in the areas of the BNL and BSL are to the northwest, matching observed trends. Predicted flow directions north of the WQARF Site are to the southwest and west, also matching observed trends.

- Cones of depression are observed around pumping wells R-092A and C-026B. The simulated extent and magnitude of the depressions correlate well with observed conditions.

- A water table mound is predicted around injection wells R-090A and R-091A. The model simulated location and magnitude of the mound correlate well with observed condition.

#### *4.1.6.3.3 Scatter Graphs of Predicted Head Elevations vs. Observed Water Levels*

Scatter graphs of predicted head elevations vs. measured water levels provide a simple, easy-to-review method of evaluating the calibration of each run. These graphs represent a snapshot in time of the comparison between the values calculated by the model (Y-axis), and the values observed or measured in the field (X-axis). Figures 31, 32, and 33 present scatter graphs for each of the three model calibration data sets. A straight 45 degree line drawn on each graph indicates where X=Y, or the hypothetical situation where all predicted heads match observed water levels. This represents an ideal calibration scenario, but it is not likely to happen in many real-life situations. If the data points appear above the X=Y line, then the calculated values are larger than the observed values. If the data points are under the X=Y line, then the calculated values are less than the observed values.

#### 4.1.6.3.4 Statistical Analysis

Calibration statistics reported for each transient simulation run included the following measures:

Mean error, ME:

$$ME = \sum_{i=1}^{n} \frac{\{P_i - O_i\}}{n}$$

Mean absolute error, MAE:

$$MAE = \sum_{i=1}^{n} \frac{\{|P_i - O_i|\}}{n}$$

Percent root mean square error, %RMSE:

$$\% RMSE = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{1/2} \left[\frac{100}{\mathrm{MAX}(O_i) - \mathrm{MIN}(O_i)}\right]$$

Correlation coefficient, R:

$$R = \left(\frac{CoVp,o}{\sigma_p \sigma_o}\right)$$

| | | |
|---|---|---|
| where: $O$ | = | $i^{th}$ observed value, |
| $\bar{o}$ | = | mean of observed values, |
| $P_i$ | = | $i^{th}$ predicted value, |
| $\bar{p}$ | = | mean of predicted values, |
| $n$ | = | number of pairs of values, |
| MIN ($O_i$) | = | minimum of observed values |
| MAX ($O_i$) | = | maximum of observed values |
| $CoVp,o$ | = | $[\Sigma (P - \bar{p})(O - \bar{o})]/[n - 1]$, |

ME, MAE, and %RMSE equal zero for perfect predictions (i.e., predicted minus observed equals 0 feet). The correlation coefficient equals one for perfect predictions, and should be greater than

0.7. For flow calibration, the variance of the residuals of the calibrated flow model should be less than 10 percent of the change in hydraulic head across the model domain (i.e., % RMSE should be less than 10 percent). In this case, the change in water levels across the model domain is about 340 feet, so the variation between observed and predicted heads should be less than about 34 feet (i.e., root mean square error (RMS) should be less than 34 feet).

The quantitative measures for the calibrated transient simulation are presented below according to data set:

***1990 Full Model Domain Data Set***

- Number of points – 61
- Minimum Residual = -0.061 feet (GL-001A)
- Maximum Residual = 50.27 (C-091A)
- ME = -0.7 feet
- MAE = 11.5 feet
- RMS = 15.1 feet
- %RMSE = 5.2%
- Correlation Coefficient = 0.99

For the 1990 data set, model predicted heads matched observed water levels on average within 15.1 feet (RMS), which is 5.2 percent of the total decline of observed levels in the model domain. Based on this analysis, the ramp-up period of the transient calibration provided an acceptable simulation of actual water level elevations, and therefore water table declines. The statistical analysis also shows the model predicted 1990 heads represent an appropriate and accurate starting point for the 1990-2007 calibration run.

***2007 Full Model Domain Data Set***

- Number of points – 205
- Minimum Residual = 0.0 feet (D-052A)

- Maximum Residual = -87.3 (PR-05)
- ME = -4.6 feet
- MAE = 13.2 feet
- RMS = 21.1 feet
- %RMSE = 6.2%
- Correlation Coefficient = 0.97

For the 2007 full model domain data set, model predicted heads matched observed water levels on average within 21.2 feet (RMS), which is 6.2 percent of the total range of observed levels in the model domain. Based on this analysis, the calibrated model provides an adequate simulation of the regional hydraulic stresses within the model domain.

***2007 WQARF Site Area Data Set***

- Number of points – 33
- Minimum Residual = 0.0 feet (BP-21A)
- Maximum Residual = 8.1 (C-048B)
- ME = 1.4 feet
- MAE = 2.3 feet
- RMS = 3.0 feet
- %RMSE = 5.3%
- Correlation Coefficient = 0.99

For the 2007 WQARF Site area data set, model predicted heads matched observed water levels on average within 3 feet (RMS), which is 5.3 percent of the total range of observed levels in the model domain. These low residual values yield a strong statistical correlation, but also indicate the model is capable of accurately simulating the effect of local hydraulic stresses in the area of most interest to this study. Based on this statistical analysis, the model is well calibrated in the WQARF Site area.

#### *4.1.6.3.5 Residual Distribution Maps*

Head residual maps depict the spatial variation in model predicted heads and observed water levels. Figures 34 and 35 present the head residuals for the full domain and WQARF Site area data sets, respectively. The size of the bubble is proportional to the magnitude of difference between the predicted and observed water levels. Red bubbles indicate areas where the model predicted heads are lower than observed water levels. Blue bubbles indicate areas where the model predicted heads are higher than observed water levels. Figure 35 shows that predicted heads are generally within about 3 feet in the area of the Broadway-Pantano WQARF Site.

#### *4.1.6.3.6 Hydrographs*

An objective of the model calibration process was to accurately simulate the aquifer response to local hydraulic stresses in the area of the WQARF Site. Examples of hydraulic stresses simulated in the transient-state calibration simulation include

- the partial shutdown of the City of Tucson municipal supply well pumping in the Tucson Basin in 1993,
- the injection of water in 10 City of Tucson wells in 1993,
- the operation of the WCS beginning in 2003,
- and the short-duration restart of selected City of Tucson 'Last-On First-Off' wells in 2006.

The hydrologic impact of these and other stresses is represented in the observation well data set used in the transient calibration modeling study. The observation well data set includes over 8,000 water level measurements from more than 200 observation wells. These data were used to develop hydrographs for selected wells within the model domain that were then compared with model predicted head elevation hydrographs. During the calibration process, predicted versus observed hydrographs were developed for numerous observation wells, selected examples are included in Appendix C. In general, the hydrographs demonstrate the model is capable of matching groundwater trends (both declines and rises) in most areas of the model domain, with a very strong correlation observed in wells in and around the Broadway-Pantano WQARF Site.

The calibration focused heavily on monitor wells in the immediate vicinity of WCS pumping/injection wells. A specific calibration target was to match the water level responses in monitor wells BP-2 and BP-4, which are located near WCS extraction well C-026B and injection wells R-090A and R-091A, respectively. Transducers installed in these two wells recorded daily water levels and captured the aquifer response to a 2006 shutdown of the WCS. All pumping and injection was stopped on September 17, 2006 and the system was restarted on April 25, 2007. The hydrographs from BP-2 and BP-4, shown on Figure 36, show a distinctive response curve to the shutdown and restart of the system. Water levels in BP-2, which is closest to extraction well C-026B, responded to the shutdown by abruptly rising over two feet. Water levels in BP-4, which is closest to injection wells R-090A and R-091A, responded to the shutdown by dropping over four feet. Numerous model runs were completed to achieve an acceptable correlation between the model predicted responses in these wells and the actual responses recorded in the transducer data set. Figures 37 and 38 present graphs comparing the model predicted head elevations and transducer water levels for the period that includes the 2006-2007 WCS shutdown and restart events. The graphs show a strong correlation between the predicted and observed heads in these locations and indicate the model is capable of simulating the aquifer response to local hydraulic stresses. Specifically, this analysis (along with the results of the Sensitivity Analysis, described below) supports the assignment of hydraulic parameters in this portion of the model domain.

#### *4.1.6.3.7 Mass Balance*

The cumulative flow mass balance for the model (inflow to the model versus outflow from the model) is less than 0.01 percent of the total cumulative volumetric flow for the transient-state simulation and less than 0.5 percent for all individual stress periods. These errors are well within acceptable limits.

### 4.1.7 Sensitivity Analysis

A sensitivity analysis is a quantitative method for determining the effect of parameter variation on model results. The purpose of conducting a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (ASTM D 5447, 1993).

Clear Creek Associates conducted sensitivity analyses for horizontal hydraulic conductivity, ratio of Kh to Kv, specific yield, specific storage, and recharge rates. Input values for these parameters were varied within reasonable ranges and the resulting heads were compared to the heads calculated from the calibrated model (statistical analysis). Sensitivity was also assessed based on the effect of the modification on the simulated response to the 2006 WCS shutdown event. This was judged by recording the model predicted response in monitor wells BP-2 and BP-4. For example, the calibrated model (which matched observed conditions) predicted a 2.4 foot rise in heads in BP-2 and a 4.5 foot decline in BP-4.

Table 3 summarizes the results of the sensitivity analyses. The sensitivity analysis showed the model to be most sensitive to variations in hydraulic conductivity, particularly within the Broadway-Pantano WQARF Site area. The sensitivity analysis results support the finding that the hydraulic conductivity values used in the calibrated groundwater flow model provide the best match to the observed water level responses to the 2006 WCS shutdown. The sensitivity analysis results show that model predictions are not as sensitive to variations of other parameters within reasonable ranges of values.

## 4.2 TRANSPORT MODEL

Contaminant mass transport was investigated using a mass transport numerical model linked to the groundwater flow model. The transport model was used to simulate the recent migration of the Broadway-Pantano Site PCE plume. The purpose of the transport model is to serve as an analytical tool for the FS, primarily to allow for the evaluation of various remedial scenarios on contaminant concentrations (e.g., predictions of plume migration and cleanup times). A detailed calibration of the transport model was neither possible nor attempted, due to the lack of information regarding the timing and magnitude of various contaminant sources and the fact that limited water quality data are available for much of the time of plume development. The approach taken in this study was to i) assign contaminant concentrations based on actual data from 2003, and ii) attempt to simulate the more recent migration of the existing contaminant plume beginning in 2003 and continuing through 2007. The results of this simulation will serve as the initial concentrations for future predictive simulations to be conducted during the FS.

### 4.2.1 Mass Transport Input Assumptions

The program RT3D was used to simulate mass transport at the Broadway-Pantano WQARF Site. RT3D uses the finite-difference approach to solve the three-dimensional advective-dispersive-reactive equation. RT3D interfaces directly with MODFLOW-2000 for the head solution. This project uses RT3D Version 2.5 (Clement and Johnson, 2002).

#### 4.2.1.1 Advection

Advection is the mass transport caused by the bulk movement of flowing groundwater (Spitz and Moreno, 1996). Since advective transport is directly related to groundwater flow, the factors that influence groundwater flow, such as hydraulic gradient, hydraulic conductivity, and porosity are the primary factors that affect advective transport. Advective transport velocity is proportional to hydraulic gradient and hydraulic conductivity and inversely proportional to the effective porosity of the sediments. The simulation of advection in the Broadway-Pantano WQARF Site model relies on the output results from the groundwater flow model.

#### 4.2.1.2 Dispersion

Dispersion is the process by which solutes (e.g., contaminants) spread within and transverse to the main flow (advection) direction. Mixing caused by fluids moving at varying velocities within and between soil particles, and fluids traveling different pathways among soil particles, serves to disperse contaminants within the aquifer. The effects of dispersion are amplified as groundwater velocity increases. The spreading of the contaminant in the direction of the bulk flow is known as longitudinal dispersion. Spreading in the directions perpendicular to the flow is called transverse dispersion. Longitudinal dispersion is normally much stronger than transverse dispersion. This study used a longitudinal dispersivity of 10 feet and a ratio of longitudinal to transverse dispersivity of 0.25. These values provided the best match to observed plume characteristics (e.g., long and thin plume with sharp concentration gradients at plume boundaries), and are within published values (Spitz and Moreno, 1996).

#### 4.2.1.3 Sorption

Sorption refers to the adhesion of molecules or ions to the grain surface in the aquifer (Spitz and Moreno, 1996). Compounds less likely to sorb to soil or organic particulates remain in the aqueous phase and migrate with groundwater flow. Where sorption does occur, it slows the rate of contaminant migration relative to groundwater movement, as the contaminant interacts with surrounding soil and organic matter particulates. The degree of sorption for any chemical compound in the groundwater is determined by its chemical properties and structure. The organic carbon-water partitioning coefficient ($K_{oc}$) quantifies this compound-specific relationship. The $K_{oc}$ values for PCE, TCE, *cis*-1,2-Dichloroethene (DCE), and VC were obtained from US EPA (1990). The $K_{oc}$ is used by RT3D to calculate the soil-water distribution ratio ($K_d$), yielding a compound-specific value according to the following equation:

$$K_d = f_{oc}K_{oc}$$

where:

$f_{oc}$ = fraction organic carbon

The value for $f_{oc}$ used in the model was 0.0003, based on regional studies, which consistently yield low $f_{oc}$ values.

RT3D Version 2.5 includes several options for modeling sorption, including linear and non-linear sorption. Sorption is incorporated in the model through the use of the retardation factor, R. The retardation factor quantifies the rate of travel of the contaminant through the aquifer relative to groundwater velocity. This study assumed that sorption was linear and, therefore, governed by the equation:

$$R = 1+(\rho/\theta)K_d$$

Where:

R = retardation factor

ρ = dry bulk density

θ = porosity

$K_d$ = soil-water distribution ratio

The values for porosity and dry bulk density used in this study were based on published values and on values obtained from analysis of *In situ* soil samples collected during the BP-24C monitor well installation.[4]

#### 4.2.1.4 Reactions/Sequential Decay

RT3D Version 2.5 includes seven pre-programmed general reaction packages. This study used the built-in model for PCE/TCE degradation, which simulates aerobic and anaerobic degradation of chlorinated solvents. The model includes six mobile components (PCE, TCE, DCE, VC, ethane, and chloride) and allows the user to specify nine reaction constants. The reaction parameters are presented below along with the reaction rates used in this study:

RC1, Anaerobic reaction rate for PCE – 0.22 1/yr

RC2, Anaerobic reaction rate for TCE – 0.26 1/yr

RC3, Aerobic decay rate for TCE – 0 1/yr

RC4, Anaerobic reaction rate for DCE – 0.91 1/yr

RC5, Aerobic decay rate for DCE – 29.2 1/yr

RC6, Anaerobic reaction rate for VC – 1.1 1/yr

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[4] See Table 3 of the report titled *Groundwater Monitoring Well Installation Activities—BP-24 Well Cluster & Monitoring Well BP-25*, dated August 21, 2008, prepared by Stantec for ADEQ (2008).

RC7, Aerobic decay rate for VC – 4.38 1/yr

RC8, Anaerobic reaction rate for Ethane – 0 1/yr

RC9, Aerobic decay rate for Ethane – 0 1/yr

The anaerobic reaction rates for PCE and TCE were calculated using a 1st order rate estimation (Wiedemeier et al., 1996), that involved an analysis of VOC concentrations in monitor wells downgradient of the landfill site. Aerobic decay rates for PCE and TCE were not specified in the model, as aerobic decay of PCE has not been demonstrated in field studies (NRC, 2000) and aerobic decay of TCE is generally limited to processes which are not likely at this Site (i.e., biodegradation via cometabolism). Aerobic reaction rates for DCE and VC were based on published estimates. As ethane is an innocuous compound, neither anaerobic nor aerobic reaction rates were specified in the model.

Clear Creek Associates reviewed past dissolved oxygen (DO) data to interpret the extent of anaerobic conditions at the Broadway-Pantano WQARF Site. The amount of oxygen in an aquifer greatly influences the redox potential, dictating the types of biodegradation that can be expected to occur. EPA guidance (1998) suggests that when DO concentrations are less than 1 mg/L, anaerobic degradation reactions dominate. At oxygen concentrations greater than 2.0 mg/L, anaerobic reactions are typically inhibited except in limited anaerobic "pockets" or micro-environments of the subsurface. In this study definitive anaerobic conditions were assumed at DO less than 1.0 mg/L. This study also considered slightly higher DO values if daughter products were also observed (e.g., DCE, VC). This assumption is justified because the quality of the DO data set for the Site is limited due to the typical sampling method (no flow-through cells), which likely resulted in some increased DO values in selected wells. Regardless, the ultimate distribution of anaerobic conditions in this study is limited to the immediate area of the BNL. Low or non-detect concentrations of PCE daughter products DCE and VC in BSL monitor wells indicate that biodegradation under anaerobic conditions is limited in the area of the BSL; therefore, anaerobic conditions were not assigned to the BSL. Figure 39 presents the interpreted extent of anaerobic conditions. Anaerobic reaction rates are used within these areas and aerobic decay rates are used in all other areas of the transport model.

#### 4.2.1.5 Transport Boundary Conditions

Boundaries are also important considerations in the transport simulations. The Broadway-Pantano WQARF Site transport model included the following transport boundaries: inactive cells and constant concentration cells. Figure 40 shows boundaries simulated in the transport model. The transport model focused on the area in and around the Broadway-Pantano WQARF Site. Cells located outside of this area are inactive for transport calculations. Model layers 5 and 6, which comprise the interval from 550 to 1,050 feet bgs, are also inactive for transport calculations. This is justified by the observation that VOC impacts at the Site are limited to the upper 100 feet of the aquifer (approximately 450 feet bgs). Excluding inactive transport cells, the transport model encompasses 12 square miles in the area of the Broadway-Pantano WQARF Site.

The BNL and BSL are simulated using constant concentration cells in the transport simulation. Figure 40 shows the location of the constant concentration cells at each landfill. PCE concentrations were held constant throughout the transient simulation at 150 micrograms per liter (µg/L) and 40 µg/L for the BNL and BSL, respectively.

Other boundary related assumptions used in the transport model include:

- Although both PCE and TCE were disposed of at the BNL, PCE is the primary threat to groundwater receptors. To simplify the modeling process, the transport model focused on simulating PCE fate and transport.

- Constant-concentration cells are assigned at the BNL and BSL to simulate source area PCE concentrations. TCE, DCE, and VC are not simulated with constant concentration cells; however, the model does simulate the transport of TCE, DCE, and VC since these contaminants are generated in the model through the reductive dechlorination of PCE.

- The vertical extent of the PCE source is limited to the uppermost saturated model layer, which is approximately 60 feet thick in the source area (Layer 1).

- The initial (background) concentration of VOCs outside of source areas is 0 µg/L. The same assumption (0 µg/L) was made for recharge boundaries (natural and artificial).

Due to a lack of data, this study did not simulate the initiation of impacts to the groundwater system. Rather, initial concentrations are specified for 2003 based on sampling results and the interpreted extent of contaminants in the groundwater system. Figure 41 presents the initital (2003) PCE concentrations assigned to the transport model.

#### 4.2.1.6 2003-2007 Transport Simulation

Mass transport was simulated for the period 2003 through 2007 by running RT3D in conjunction with the MODFLOW model. Constant concentrations of PCE were assigned to the uppermost saturated model layer beneath the two landfills as described above. Initial concentrations were assigned based on the interpreted 2003 PCE plume.

Figure 42 presents the model simulated PCE, TCE, and VC plumes for December 2007. The model predicted distribution of VOC concentrations in the Broadway-Pantano WQARF Site correlates well with 2007/2008 VOC water sampling results (SECOR, 2008). The vertical extent of impacts at the Broadway-Pantano WQARF Site is monitored at the BP-24 Site, which includes three monitor wells with screen intervals at different aquifer levels. Data from these locations consistently show that VOC impacts at the WQARF Site are limited to the upper 50 to 100 feet of the aquifer. Model predicted PCE concentrations from the layers that correspond to the screened intervals of these two wells were compared against actual sampling results from April 2008:

BP-24A (screen interval 0 to 20 feet below water table)

Jan 2008 PCE Concentration from sample – 31/33 μg/L

Dec 2007 Model Predicted PCE Concentration – 30 μg/L

BP-24B (screen interval 50 to 70 feet below water table)

Dec 2008 PCE Concentration from sample – 9.4/7.8 μg/L

Dec 2007 Model Predicted PCE Concentration – 10.2 μg/L

BP-24C (screen interval 105 to 125 feet below water table)

Dec 2008 PCE Concentration from sample – <1.0/<1.0 μg/L

Dec 2007 Model Predicted PCE Concentration – 0.04 µg/L

These results show that in the middle of the Broadway-Pantano PCE plume, the model accurately simulated the vertical extent of contamination.

The 2003-2007 transport simulation accomplished the objective of developing a reasonable numerical representation of the 2007 Broadway-Pantano PCE plume. The distribution and model predicted concentrations of VOCs at the WQARF Site compare favorably to interpreted conditions and the simulation shows the plume is responsive to local hydraulic stresses (e.g., WCS operations) in accordance with concentration trends indicated by sampling results. Based on these results, the transport model is considered an appropriate analytical tool, which, when used with the groundwater flow model will allow for an assessment of the remedial scenarios currently envisioned to be evaluated during the FS.

### 4.3 MODEL LIMITATIONS

The use of a groundwater flow or contaminant transport model requires recognition of the limitations of the model, both with respect to the construction and interpretation of the hydrogeologic system and the mathematical assumptions incorporated in the model code. The model must be used with the understanding that it portrays the present understanding of the hydrogeologic system, typically summarized as the current Conceptual Site Model. Adjustments to the model may be required if more detailed information is obtained that modifies the conceptual understanding of the Site, or if the objectives and purpose of the models are changed.

These models (groundwater flow and mass transport) were specifically developed for use in evaluating remedial alternatives for the Broadway-Pantano WQARF Site. However, the model domain boundaries extend beyond the Study Area boundaries (See Section 2.3 – Study Area). This was necessary to ensure that model boundaries do not influence model predictions. While the calibration of the overall model relied on multiple calibration data sets, including a domain-wide observation well data set, the calibration focused primarily on the area in and around the WQARF Site. The model is not intended for use in evaluating flow or transport concerns outside the Broadway-Pantano WQARF Site Study Area. Model predictions in areas outside the

Broadway-Pantano WQARF Site Study Area should be used with caution. This includes areas along the model boundaries and areas east of the Pantano Feature (Figure 6).

The transport model should be used with the understanding that a detailed calibration of the mass transport model was not conducted. There is limited data concerning the history and development of the Broadway-Pantano WQARF Site VOC plume. The lack of data, particularly during the early development of the plume, makes it impossible to precisely simulate the formation and development of the plume. The transport model was developed by simulating the recent migration and distribution of PCE at the WQARF Site, focusing on the five year period from 2003 through 2007. Confidence in the transport model relies on the model simulated distribution of PCE and the response of the PCE plume to operations of the WCS during this period.

Other factors with limited existing data that could potentially influence model predictions include:

#### 4.3.1 Recent Aquifer Test Data

There are limited recent aquifer test data for the Broadway-Pantano WQARF Site. Most tests were conducted over 25 years ago. Water levels have declined substantially in the area over this time, and the results from the older tests may no longer be representative. Because of this, the groundwater flow model relied more heavily on the model's ability to accurately simulate the response of the aquifer to other hydraulic stresses. For example, the calibration relied heavily on the simulation of the response of the aquifer to operation of the WCS.

#### 4.3.2 Hydraulic Parameters of Deeper Portions of the Aquifer

There are limited data concerning hydraulic parameters in the deeper portion of the Tucson Basin aquifer system (below ~200 feet below the water). Most aquifer tests have been conducted on wells with long screen intervals that extend from above the water table. This makes it impossible to calculate hydraulic parameters for the deeper portions of the aquifer. This study assumed that hydraulic conductivity values are relatively lower in the deeper portions of the aquifer. This assumption is consistent with prior modeling studies (e.g., URS, 2000) and is reasonable based on increased compaction of sediments at depth in the basin.

### 4.3.3 Mass Transport Biodegredation

The mass transport model simulates the effect of PCE biodegradation. However, there are limited site-specific data concerning decay constants for the Broadway-Pantano WQARF Site. This information could affect future fate and transport predictions, such as estimates of clean up times. This study relied on reasonable estimates based on site-specific field data, the distribution of VOCs at the Site, literature values, and estimates from similar sites. It should be noted that biodegradation of PCE was only simulated in the immediate vicinity of the BNL, where anaerobic conditions are strongly indicated by field data. PCE biodegradation is not simulated outside this area, which limits the potential influence of biodegradation rates on PCE fate and transport. Regardless, consideration should be given during the FS of the sensitivity of future transport simulations to biodegradation effects.

# 5.0 SUMMARY

A groundwater flow model and an associated mass transport model have been developed for use in evaluating remedial alternatives for VOC impacted groundwater at the Broadway-Pantano WQARF Site. The groundwater flow model was constructed based on a conceptual model of the hydrogeologic system that is based heavily on site-specific data collected from within and around the WQARF Site. The flow model simulates key local hydrologic stresses, such as individual pumping and injection wells, which can influence groundwater flow directions and hydraulic gradients. The groundwater flow model was calibrated to historic conditions. The calibration focused on matching observed groundwater flow patterns, water levels, and trends over the past 18 years, for which abundant site-specific hydrologic data are available. The final calibration of the groundwater flow model was demonstrated through a robust statistical analysis and a more qualitative review of the model's capacity to simulate the complex groundwater flow patterns in the area of the Broadway-Pantano WQARF Site. This includes simulating the response of the aquifer to the operation of the WCS, which relies on two pumping wells and two injection wells to provide hydraulic containment of a portion of the PCE plume. The final results, demonstrated in map view (Figure 30) and in hydrographs, such as BP-2 and BP-4 (Figures 37 and 38), indicate the model accurately simulates these local stresses. It is anticipated that remedial alternatives to be considered in the FS will require the simulation of features like the extraction and injection wells used in the current WCS. The model's capacity to accurately simulate the existing WCS provides a high degree of confidence in the future application of the model for its intended purpose.

A mass transport model was developed to run in conjunction with the groundwater flow model. The purpose of the mass transport model is to serve as another analytical tool for the FS, primarily to evaluate the effect of various remedial scenarios on contaminant concentrations (e.g., predictions of plume migration and cleanup times). The program RT3D was used to simulate mass transport. The approach taken in this study was to i) assign contaminant concentrations based on actual data from 2003, and ii) attempt to simulate the more recent migration of the existing contaminant plume beginning in 2003 and continuing through 2007. The 2003-2007 transport simulation accomplished the objective of developing a reasonable numerical representation of the 2007 Broadway-Pantano PCE plume. The distribution and model-predicted concentrations of VOCs at the WQARF Site compare favorably to interpreted conditions, and the simulation shows the plume is responsive to local hydraulic stresses (e.g., WCS operations). Based on these results, the transport model is considered an appropriate analytical tool, which, when used with the groundwater flow model, will allow for an assessment of the remedial scenarios currently envisioned to be evaluated during the FS.

Overall, the Broadway-Pantano groundwater flow and contaminant transport model is an appropriate analytical tool that ADEQ can use to evaluate remedy alternatives for groundwater VOC impacts. Used together, the flow and mass transport models are capable of simulating the effect of the following potential remedy options:

1. Containment and remediation pumping – this includes pumping from existing wells (e.g., municipal supply wells) or simulating the effect of new wells. The transport model can be used to predict future PCE, TCE, VC, and DCE concentrations from wells, which would be needed for the evaluation of treatment alternatives.

2. Injection wells – the flow model allows for the simulation of existing and/or new injection wells.

3. Natural attenuation – the flow and transport models allow for future prediction of natural attenuation of the VOC plume.

4. Enhanced bioremediation – the RT3D v2.5 program allows for the modeler to vary the decay rates for PCE, TCE, DCE, and VC. This allows for an assessment of the effects of establishing more aggressive decay rates, such as what would be expected in an enhanced bioremediation scenario.

Preliminary future simulations have been constructed and run using the Broadway-Pantano flow and mass transport models. The results of the future simulations have been presented to key stakeholders to demonstrate the model is an appropriate and capable tool for its intended use.

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