This document entitled DRAFT Groundwater Flow & Solute Transport Modeling Report was prepared by Stantec Consulting Services Inc. ("Stantec") for the account of Tennessee Valley Authority (TVA).

Prepared by

Alexis Harkins, PG
Hydrogeologist

Joel RK Thompson, PG
Senior Hydrogeologist

Reviewed by

John Griggs, PhD, TN PG No. 5966
Senior Principal

John W. Jengo, TN PG No. 5973
Principal

Patrick Dunne
Senior Hydrogeologist

Approved by

Kim Kesler-Arnold, TN PG No. 5969
Vice President
# Table of Contents

**ABBREVIATIONS** .......................................................................................................................... V

1.0  **INTRODUCTION** ....................................................................................................................... 1.1  
1.1  **SITE HISTORY** ......................................................................................................................... 1.1  
1.2  **GROUNDWATER FLOW MODEL OBJECTIVES AND USAGE** .................................................. 1.1  
1.3  **REPORT ORGANIZATION** ........................................................................................................ 1.2  

2.0  **MODEL DEVELOPMENT APPROACH** ....................................................................................... 2.1  
2.1  **HISTORICAL MODEL STUDIES** ............................................................................................... 2.1  

3.0  **DATA COMPILATION** ................................................................................................................ 3.1  

4.0  **HYDROGEOLOGIC CONCEPTUAL SITE MODEL** ......................................................................... 4.1  
4.1  **STUDY AREA DESCRIPTION** .................................................................................................... 4.1  
4.2  **REGIONAL STRATIGRAPHY AND GEOLOGY** .......................................................................... 4.1  
4.3  **SURFACE WATER** .................................................................................................................... 4.2  
4.4  **STUDY AREA HYDROGEOLOGY** ............................................................................................... 4.3  
4.4.1  Fill........................................................................................................................................... 4.3  
4.4.2  Ash Disposal Areas.................................................................................................................... 4.3  
4.4.2.1  Composition...................................................................................................................... 4.4  
4.4.2.2  Extent and Structure.......................................................................................................... 4.4  
4.4.2.3  Hydraulic Properties........................................................................................................... 4.4  
4.4.2.4  Water Quality...................................................................................................................... 4.4  
4.4.2.5  Sluiced Water...................................................................................................................... 4.4  
4.4.3  Alluvial Aquifer ........................................................................................................................ 4.4  
4.4.3.1  Composition...................................................................................................................... 4.4  
4.4.3.2  Extent and Structure.......................................................................................................... 4.5  
4.4.3.3  Hydraulic Properties........................................................................................................... 4.5  
4.4.3.4  Estimated Yields.................................................................................................................. 4.6  
4.4.3.5  Water Quality...................................................................................................................... 4.6  
4.4.3.6  Groundwater Flow.............................................................................................................. 4.7  
4.4.4  Terrace and Loess Deposits....................................................................................................... 4.7  
4.4.4.1  Composition...................................................................................................................... 4.7  
4.4.4.2  Extent and Structure.......................................................................................................... 4.8  
4.4.4.3  Hydraulic Properties........................................................................................................... 4.8  
4.4.4.4  Estimated Yields.................................................................................................................. 4.8  
4.4.4.5  Groundwater Flow.............................................................................................................. 4.8  
4.4.5  Upper Claiborne Confining Unit............................................................................................... 4.8  
4.4.5.1  Composition...................................................................................................................... 4.8  
4.4.5.2  Extent and Structure.......................................................................................................... 4.9  
4.4.5.3  Hydraulic Properties........................................................................................................... 4.9  
4.4.5.4  Estimated Yields.................................................................................................................. 4.9  
4.4.5.5  Groundwater Flow.............................................................................................................. 4.10  
4.5  **THREE DIMENSIONAL LITHOLOGIC MODEL** ........................................................................ 4.10  

5.0  **COMPUTER CODE** .................................................................................................................. 5.1  
5.1  **MODFLOW** ............................................................................................................................. 5.1  

## Draft Groundwater Flow & Solute Transport Modeling Report

### 5.2 MT3DMS

### 6.0 MODEL CONSTRUCTION

#### 6.1 MODEL DISCRETIZATION

- **6.1.1 Horizontal Discretization**
- **6.1.2 Vertical Discretization**

#### 6.2 TIME DISCRETIZATION

#### 6.3 PARAMETER DISTRIBUTION

- **6.3.1 Hydraulic Conductivity**
- **6.3.2 Storage**
- **6.3.3 Recharge**

#### 6.4 BOUNDARY CONDITIONS

- **6.4.1 No Flow**
- **6.4.2 Constant Head**

### 7.0 CALIBRATION

#### 7.1 MODEL CALIBRATION APPROACH

#### 7.2 SELECTION OF CALIBRATION DATA

#### 7.3 CALIBRATION CRITERIA

#### 7.4 CALIBRATION RESULTS

#### 7.5 CONVERGENCE CRITERIA

### 8.0 SENSITIVITY ANALYSIS

#### 8.1 SENSITIVITY APPROACH

#### 8.2 DISCUSSION OF SENSITIVITY

- **8.2.1 Hydraulic Conductivity**
- **8.2.2 Storage**
- **8.2.3 Recharge**

### 9.0 SIMULATIONS

#### 9.1 CALIBRATED MODEL SIMULATION

#### 9.2 SIMULATED SCENARIOS

- **9.2.1 Simulation 1 Impact of Historical Operation of Harsco Well**
- **9.2.2 Solute Transport Scenarios**
  - **9.2.2.1 Scenario 2 Baseline Simulation of Solute Transport East Ash Disposal Area – North Area**
  - **9.2.2.2 Scenario 3 Groundwater Extraction Simulation of Solute Transport East Ash Disposal Area – North Area**
  - **9.2.2.3 Scenario 4 Baseline Simulation of Solute Transport East Ash Disposal Area – South Area**
  - **9.2.2.4 Scenario 5 Groundwater Extraction Simulation of Solute Transport East Ash Disposal Area – South Area**

### 10.0 SUMMARY AND CONCLUSIONS

### 11.0 MODEL LIMITATIONS

### 12.0 REFERENCES
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Site Location Map</td>
</tr>
<tr>
<td>1-2</td>
<td>Site Map</td>
</tr>
<tr>
<td>2-1</td>
<td>Historical Model Domain Extents</td>
</tr>
<tr>
<td>4-1</td>
<td>Quaternary Aquifers Map</td>
</tr>
<tr>
<td>4-2</td>
<td>Regional Stratigraphic Cross Section</td>
</tr>
<tr>
<td>4-3</td>
<td>Conceptual Site-Specific Hydrostratigraphic Column</td>
</tr>
<tr>
<td>4-4</td>
<td>Conceptual Site Model Block Diagram</td>
</tr>
<tr>
<td>4-5</td>
<td>Regional Physiographic Province Distribution</td>
</tr>
<tr>
<td>4-6</td>
<td>Mississippi River Bathymetry: 1964 - 2004</td>
</tr>
<tr>
<td>4-7</td>
<td>Subsurface Investigation Location Map</td>
</tr>
<tr>
<td>4-8</td>
<td>Geologic Cross Section Location Map - East Ash Disposal Area</td>
</tr>
<tr>
<td>4-9</td>
<td>Geologic Cross Section A-A’</td>
</tr>
<tr>
<td>4-10</td>
<td>Geologic Cross Section B-B’</td>
</tr>
<tr>
<td>4-11</td>
<td>Geologic Cross Section C-C’</td>
</tr>
<tr>
<td>4-11a</td>
<td>Geologic Cross Section C1-C1’</td>
</tr>
<tr>
<td>4-12</td>
<td>Geologic Cross Section D-D’</td>
</tr>
<tr>
<td>4-12a</td>
<td>Geologic Cross Section D1-D1’</td>
</tr>
<tr>
<td>4-13</td>
<td>Alluvial Aquifer Thickness Maps</td>
</tr>
<tr>
<td>4-14</td>
<td>Base Elevation Map of the Upper Alluvium</td>
</tr>
<tr>
<td>4-15</td>
<td>Site-Specific Hydraulic Conductivity Summary Map</td>
</tr>
<tr>
<td>4-16</td>
<td>Regional Groundwater Contour Map</td>
</tr>
<tr>
<td>4-17</td>
<td>Groundwater Elevation Map in the Upper Alluvium - December 2018</td>
</tr>
<tr>
<td>4-18</td>
<td>Groundwater Elevation Map in the Shallow Zone of the Lower Alluvium - June 2017</td>
</tr>
<tr>
<td>4-19</td>
<td>Groundwater Elevation Map in the Shallow Zone of the Lower Alluvium - September 2017</td>
</tr>
<tr>
<td>4-20</td>
<td>Groundwater Elevation Map in the Shallow Zone of the Lower Alluvium - October 2017</td>
</tr>
<tr>
<td>4-21</td>
<td>Groundwater Elevation Map in the Shallow Zone of the Lower Alluvium - November 2017</td>
</tr>
<tr>
<td>4-22</td>
<td>Groundwater Elevation Map in the Shallow Zone of the Lower Alluvium - December 2018</td>
</tr>
<tr>
<td>4-23</td>
<td>Groundwater Elevation Map in the Intermediate Zone of the Lower Alluvium - September 2017</td>
</tr>
<tr>
<td>4-24</td>
<td>Groundwater Elevation Map in the Intermediate Zone of the Lower Alluvium - October 2017</td>
</tr>
<tr>
<td>4-25</td>
<td>Groundwater Elevation Map in the Intermediate Zone of the Lower Alluvium - November 2017</td>
</tr>
<tr>
<td>4-26</td>
<td>Groundwater Elevation Map in the Intermediate Zone of the Lower Alluvium - December 2018</td>
</tr>
<tr>
<td>4-27</td>
<td>Groundwater Elevation Map in the Deep Zone of the Lower Alluvium - September 2017</td>
</tr>
<tr>
<td>4-28</td>
<td>Groundwater Elevation Map in the Deep Zone of the Lower Alluvium - October 2017</td>
</tr>
<tr>
<td>4-29</td>
<td>Groundwater Elevation Map in the Deep Zone of the Lower Alluvium - November 2017</td>
</tr>
<tr>
<td>4-30</td>
<td>Groundwater Elevation Map in the Deep Zone of the Lower Alluvium - December 2018</td>
</tr>
<tr>
<td>4-31</td>
<td>Subsurface Data Locations applied to the 3D EVS Lithologic Model</td>
</tr>
<tr>
<td>4-32</td>
<td>3D EVS Cross Section C1-C1’ within the Upper Alluvium</td>
</tr>
<tr>
<td>4-33</td>
<td>3D EVS Cross Section D1-D1’ within the Upper Alluvium</td>
</tr>
<tr>
<td>6-1</td>
<td>Model Domain Map</td>
</tr>
<tr>
<td>6-2</td>
<td>Model Grid Extent Map</td>
</tr>
<tr>
<td>6-3a</td>
<td>Elevation of the Top of the Model (Ground Surface)</td>
</tr>
<tr>
<td>6-3b</td>
<td>Elevation of the Tops of Layers 2 - 5 (Upper Alluvium)</td>
</tr>
<tr>
<td>6-3c</td>
<td>Elevation of the Tops of Layers 6 - 8 and the Bottom of the Model (Lower Alluvium &amp; Upper Claiborne Confining Unit)</td>
</tr>
<tr>
<td>6-4</td>
<td>Model Layer and Conceptual Regional Cross Section Comparison</td>
</tr>
<tr>
<td>6-5</td>
<td>Time Discretization Based on Lake McKellar Hydrographs</td>
</tr>
<tr>
<td>6-6a</td>
<td>Hydraulic Conductivity and Specific Storage/Yield Zone Distribution within the Model (Layers 1-4)</td>
</tr>
<tr>
<td>6-6b</td>
<td>Hydraulic Conductivity and Specific Storage/Yield Zone Distribution within the Model (Layers 5-8)</td>
</tr>
<tr>
<td>6-7</td>
<td>Recharge Zone Distribution within the Model</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>6-8</td>
<td>Model Boundary Conditions</td>
</tr>
<tr>
<td>7-1</td>
<td>Calibration Target Location map</td>
</tr>
<tr>
<td>7-2</td>
<td>Calibration Results – North Area</td>
</tr>
<tr>
<td>7-3</td>
<td>Calibration Results – South Area</td>
</tr>
<tr>
<td>7-4</td>
<td>Observed Versus Simulated Calibration Chart</td>
</tr>
<tr>
<td>9-1a</td>
<td>Simulated Potentiometric Surfaces - Upper Alluvium</td>
</tr>
<tr>
<td>9-1b</td>
<td>Simulated Potentiometric Surfaces at the East Ash Disposal Area – Upper Alluvium</td>
</tr>
<tr>
<td>9-1c</td>
<td>Simulated Potentiometric Surfaces - Lower Alluvium</td>
</tr>
<tr>
<td>9-1d</td>
<td>Simulated Potentiometric Surfaces at the East Ash Disposal Area – Lower Alluvium</td>
</tr>
<tr>
<td>9-2a</td>
<td>Simulated Velocity Vectors - Upper Alluvium</td>
</tr>
<tr>
<td>9-2b</td>
<td>Simulated Velocity Vectors at the East Ash Disposal Area – Upper Alluvium</td>
</tr>
<tr>
<td>9-2c</td>
<td>Simulated Velocity Vectors - Lower Alluvium</td>
</tr>
<tr>
<td>9-2d</td>
<td>Simulated Velocity Vectors at the East Ash Disposal Area – Lower Alluvium</td>
</tr>
<tr>
<td>9-3a</td>
<td>Simulated Groundwater Velocity - Upper Alluvium</td>
</tr>
<tr>
<td>9-3b</td>
<td>Simulated Groundwater Velocity - Lower Alluvium</td>
</tr>
<tr>
<td>9-4</td>
<td>Harsco Well Drawdown Distribution</td>
</tr>
<tr>
<td>9-5a</td>
<td>Scenario 2 Arsenic Distribution – Layer 3</td>
</tr>
<tr>
<td>9-5b</td>
<td>Scenario 2 Arsenic Distribution – Layer 4</td>
</tr>
<tr>
<td>9-6a</td>
<td>Scenario 3 Arsenic Distribution – Layer 3</td>
</tr>
<tr>
<td>9-6b</td>
<td>Scenario 3 Arsenic Distribution – Layer 4</td>
</tr>
<tr>
<td>9-7a</td>
<td>Scenario 4 Arsenic Distribution – Layer 3</td>
</tr>
<tr>
<td>9-7b</td>
<td>Scenario 4 Arsenic Distribution – Layer 4</td>
</tr>
<tr>
<td>9-8a</td>
<td>Scenario 5 Arsenic Distribution – Layer 3</td>
</tr>
<tr>
<td>9-8b</td>
<td>Scenario 5 Arsenic Distribution – Layer 4</td>
</tr>
</tbody>
</table>
List of Tables

4-1 Monitoring Well Summary
4-2 Soil Boring and Cone Penetration Testing Summary
4-3 Upper and Lower Alluvium Distribution Summary
4-4 Summary of Literature Referenced Hydraulic Properties
4-5 Summary of Slug Testing Hydraulic Conductivity Test Results by Well
4-6 Summary of Step-Drawdown Test Aquifer Analysis
4-7 Summary of Constant Rate Test Aquifer Analysis
4-8 Alluvial Aquifer Horizontal Hydraulic Gradients
4-9a Alluvial Aquifer Vertical Hydraulic Gradients in Co-Located Monitoring Wells: Upper and Lower Alluvium
4-9b Alluvial Aquifer Vertical Hydraulic Gradients in Co-Located Monitoring Wells: Shallow, Intermediate and Deep Zones of the Lower Alluvium
6-1 Laboratory Permeability Test Results
6-2 Summary of Hydraulic Conductivity Applied to the Model
6-3 Summary of Specific Storage and Specific Yield Values Applied to the Model
6-4 Average Biweekly Precipitation and the Model Applied Recharge Summary
6-5 Transient Constant Head Applied to the Mississippi River and Lake McKellar
9-1 Summary of Groundwater Transport Parameters

List of Appendices

Appendix A  Transducer Data Hydrographs
Appendix B  Boring Logs
Appendix C  Calibration Hydrographs
## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVS</td>
<td>Earth Volumetric Studio</td>
</tr>
<tr>
<td>ACC</td>
<td>Allen Combined Cycle Plant</td>
</tr>
<tr>
<td>ALF</td>
<td>Allen Fossil Plant</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>CAESER</td>
<td>Center for Applied Earth Science and Engineering Research</td>
</tr>
<tr>
<td>CCR</td>
<td>coal combustion residual</td>
</tr>
<tr>
<td>CSM</td>
<td>conceptual site model</td>
</tr>
<tr>
<td>COCs</td>
<td>contaminants of concern</td>
</tr>
<tr>
<td>CPT</td>
<td>Cone Penetration Test</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>EW</td>
<td>extraction well</td>
</tr>
<tr>
<td>ft</td>
<td>feet</td>
</tr>
<tr>
<td>ft/ft</td>
<td>feet per foot</td>
</tr>
<tr>
<td>ft/day</td>
<td>feet per day</td>
</tr>
<tr>
<td>ft²/day</td>
<td>square feet per day</td>
</tr>
<tr>
<td>gpm</td>
<td>gallons per minute</td>
</tr>
<tr>
<td>Kh</td>
<td>horizontal hydraulic conductivity</td>
</tr>
<tr>
<td>Kv</td>
<td>vertical hydraulic conductivity</td>
</tr>
<tr>
<td>MCLs</td>
<td>maximum contaminant levels</td>
</tr>
<tr>
<td>MERAS</td>
<td>Mississippi River Valley Alluvial Aquifer System</td>
</tr>
<tr>
<td>µg/L</td>
<td>micrograms per Liter</td>
</tr>
<tr>
<td>MLGW</td>
<td>Memphis Light, Gas and Water Division</td>
</tr>
<tr>
<td>NGVD29</td>
<td>National Geodetic Vertical Datum of 1929</td>
</tr>
<tr>
<td>PMW</td>
<td>performance monitoring well</td>
</tr>
<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
</tr>
<tr>
<td>USACE</td>
<td>United States Army Corps of Engineers</td>
</tr>
<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
</tbody>
</table>
INTRODUCTION

The Tennessee Valley Authority (TVA) developed a groundwater flow and transport model (the Model) for the Allen Fossil Plant (ALF) in Memphis, Tennessee. The location of the ALF and its surroundings is presented in Figure 1-1. The Model was developed to support specific proposed remedial actions focused on the East Ash Disposal Area, which was used to manage coal combustion residuals (CCR) while the ALF was operational, and to be used to support a comprehensive regional groundwater flow framework for future projects that require modeling support.

This report presents the findings and results of groundwater modeling activities performed to meet the objectives described above based on available data at the time of construction of the Model. Future updates to the Model are anticipated as additional data are obtained.

SITE HISTORY

The Site is defined as the area inclusive of the property boundary and the area within it; the Allen Combined Cycle Plant (the ACC); the East and West Ash Disposal Areas; and the subsurface investigation and monitoring well locations. The ALF was constructed in 1959 by Memphis Light, Gas and Water Division (MLGW) and consisted of three coal-fired electric generating units. TVA began operating ALF in 1965, and the East and West Ash Disposal Areas were used to manage CCR. By 1993, the West Ash Disposal Area no longer received sluiced ash, and by 2015 the area was retrofitted to no longer receive flows or impound water. The East Ash Disposal Area ceased receiving CCR in 2018 and ceased receiving all types of flows in 2019. A facility location map and detailed site map have been included as Figures 1-1 and 1-2.

GROUNDWATER FLOW MODEL OBJECTIVES AND USAGE

The overall objective of the modeling activities is to create a quantitative tool capable of predicting groundwater flow and potential CCR constituents of concern (COC) transport under varying conditions to evaluate groundwater management scenarios, solute fate and transport, and remedial strategies, as needed. The specific objectives of the modeling activities are summarized below:

- Develop and calibrate a numerical groundwater flow model of ALF using site-specific and regional hydrogeologic and hydrologic properties. The Model was constructed to:
  - Incorporate the entire approximately 500-acre ALF property including the East Area and West Ash disposal areas;
  - Include the subsurface heterogeneity noted in the Alluvial aquifer during previous investigation activities;
  - Capture observed patterns of groundwater flow direction and velocity in the Alluvial aquifer; and...
Introduction
July 12, 2019

- Include simulation of relevant features including interaction between Lake McKellar and the Alluvial aquifer.

- Link the groundwater flow model with a contaminant transport model to evaluate the fate and solute transport of COCs.

- Provide a framework for predictive modeling including:
  - Performance of interim hydraulic capture system; and
  - Influence of ash disposal area closure activities (i.e., dewatering) on the hydraulic system and fate and transport of COCs.

1.3 REPORT ORGANIZATION

This report is organized into twelve chapters, including this introductory chapter. Chapter 2 presents the model development approach, Chapter 3 summarizes the data compiled for the development of the model, and Chapter 4 presents the conceptual site model (CSM) for ALF. The numerical code selected to prepare the groundwater model is described in Chapter 5, with the model construction, calibration, and sensitivity analysis presented in Chapters 6, 7, and 8, respectively. Predictive simulations conducted with the model are summarized in Chapter 9, conclusions and recommendations are presented in Chapter 10, and limitations of the modelling are presented in Chapter 11. Cited references are presented in Chapter 12.
2.0 MODEL DEVELOPMENT APPROACH

The Model has been developed in general accordance with American Society for Testing and Materials (ASTM) Standard Guide for Application of a Numerical Groundwater Flow Model to a Site-Specific Problem (ASTM, 2017) and was designed to be consistent with the objectives outlined above.

The modeling approach was to develop a sub-watershed scale transient groundwater flow model of the Alluvial aquifer and couple the flow model with transport models to evaluate potential migration of COCs in groundwater. Although available hydrogeologic data is primarily available within the limits of the ALF property, the sub-watershed scale was selected to accommodate naturally occurring boundary conditions located, where possible, distal to the primary areas of concern (i.e., the East Ash Disposal Area and the West Ash Disposal Area). A transient model was selected to evaluate the overarching objective of simulating time-varying groundwater and surface water stresses and responses resulting from seasonal and precipitation related groundwater-surface water interactions.

The objectives are focused on understanding the hydrogeologic system and potential fate and transport of COCs associated with the storage of CCR. Because CCR material is present in disposal areas near the ground surface, the model was more finely discretized in the upper portion of the Alluvial aquifer. However, the full thickness of the Alluvial aquifer was included to allow for simulation of the integrated groundwater-surface water flow system. Other numerical models completed in the area have included portions of the aquifers underlying the Alluvial aquifer (Section 2.1); however, these models were completed for different objectives and were not suitable to evaluate the site at the scale necessary for this study. The vertical extent of the Model was limited to the Alluvial aquifer to concentrate on the area of concern. Finally, the flow model was used to evaluate groundwater flow paths and velocity and was coupled with a contaminant transport model to evaluate COC distribution as a result of advection, dispersion, and partitioning in the subsurface.

To accomplish the approach outlined above, the Model was constructed using the three-dimensional finite-difference MODFLOW2005 computer code developed by the United States Geological Survey (USGS) (Langevin et. al, 2017) coupled with a modular 3-D multi-species transport model (MT3DMS) for simulation of advection, dispersion, and chemical reactions of constituents in the groundwater system (Zheng and Wang, 1999). These programs were selected because they are thoroughly documented, widely used by consultants, government agencies, and researchers (including several projects that include or are adjacent to the study area) and are consistently accepted by regulatory agencies.

2.1 HISTORICAL MODEL STUDIES

The following modeling studies have been completed in or proximal to the study area:

evaluate the potential for leakage between the principal aquifers and assist in managing groundwater resources (Brahana and Broshears, 2001).

- **Recalibration of a Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer of Northeastern Arkansas, 1918-1998, with Simulations of Water Levels Caused by Projected Ground-Water Withdrawals through 2049:** U.S. Geological Survey Water-Resources Investigations Report 03-4109 prepared in cooperation with the Arkansas Soil and Water Conservation Commission and the United States Army Corps of Engineers (USACE), Memphis District. A groundwater flow model of the Mississippi River Valley Alluvial Aquifer of Northeastern Arkansas (bordering the study area) used to evaluate the impact of increasing pumping form the Alluvial aquifer (Reed, 2003).

- **The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment:** U.S. Geological Survey Scientific Investigations Report 2009-5172. The USGS Mississippi Embayment Regional Aquifer System (MERAS) groundwater-flow model was developed as a tool to estimate available groundwater within the Mississippi embayment aquifer system (Clark and Hart, 2009).

- **Preliminary Evaluation of the Hydrogeology and Groundwater Quality of the Mississippi River Valley Alluvial Aquifer and Memphis Aquifer at the Tennessee Valley Authority Allen Power Plants, Memphis, Shelby County, Tennessee:** U.S. Geological Survey Open-File Report 2018-1097 prepared for the Tennessee Valley Authority in cooperation with the University of Memphis, Center for Applied Earth Science and Engineering Research [CAESER]. The MERAS groundwater-flow model was used to evaluate the potential influence of operation of Allen Combined Cycle (ACC) plant extraction wells on the Memphis aquifer over a 30-year simulation period (Carmichael, et al., 2018).

- **Application of Numerical Tools to Investigate a Leaky Aquitard beneath Urban Well Fields.** A groundwater flow model built to evaluate potential leakage through the aquitard overlying the Memphis aquifer that incorporates nine active MLGW well fields within the Memphis area (Jazaei, et al. 2018).

These models were reviewed during the development of the hydrogeologic CSM and planning for the Model construction phase. The Model was developed based in part on the parameters and model design used within these models for the areas outside of ALF. **Figure 2-1** presents the ALF model domain within the above historical model domains.
3.0 DATA COMPILATION

Development of the Model required the collection and analysis of hydrogeologic and hydrologic data pertinent to the characterization of the model study area. The study area includes the ALF property and the surrounding areas that are relevant to simulate groundwater flow within the model domain. The model study area is expanded to include the alluvial floodplain on which the ALF property sits, and a portion of the loess covered uplands east of the alluvial flood plain.

The data compilation task was necessary to provide the basis for constructing model input files. Available data pertinent to the development of the hydrogeologic CSM, construction of the groundwater flow model and definition of the predictive simulations was assembled, compiled, reviewed, evaluated, and reduced into a usable format.

As discussed in Section 2.1, the study area has been the subject of several previous modeling studies. In addition to these studies, a review of data was completed to develop the hydrogeologic conceptual model and assist in construction and simulation of the groundwater flow model. Data compiled for incorporation into the groundwater flow model included:

- Stratigraphic data including: 113 soil borings, 32 cone penetration testing (CPT), 68 monitoring well and extraction well lithologic logs and associated well construction details.
- Geologic and topographic maps including:
  - Surficial Geologic Map of the Southwest Memphis Quadrangle, Shelby County, Tennessee, and Crittenden County, Arkansas (Moore and Diehl, 2004);
  - Fletcher Lake Quadrangle Arkansas-Tennessee (2014), USGS 7.5-Minute Series; and
  - Tennessee Geologic Map (USGS, 2005).
- Key publications pertaining to hydrogeologic features and boundaries, including faults, geology, and streams.
- Historical groundwater level data for piezometers and monitoring wells.
- Aquifer testing results.
- Groundwater quality sampling results for extraction wells and monitoring wells.
- Precipitation data from the National Oceanic & Atmospheric Administration’s (NOAA) Memphis International Airport, TN US USQ00013893 Station.
- Stream flow data from USGS stream gauge number 07032000 Mississippi River at Memphis, Tennessee and on-site river gauge operated by TVA.

The data reviewed and compiled is explained in more detail in subsequent sections of this report.
4.0 Hydrogeologic Conceptual Site Model

4.1 STUDY AREA DESCRIPTION

ALF is a TVA retired coal-fired power plant located in Shelby County in the southwest corner of the City of Memphis, Tennessee (Figure 1-1). ALF is located on the southern shore of Lake McKellar, on the eastern bank of the Mississippi River, and adjacent to a USACE flood-control levee. The local topography is relatively level except for the USACE levee and the CCR disposal area dikes, which rise approximately 20 to 25 feet (ft) above the surrounding land. ALF contains two ash disposal areas, the East Ash Disposal Area and West Ash Disposal Area (Figure 1-2). The surface area of the East Ash Disposal Area is approximately 80 acres and is located east of the former coal yard and power plant. The surface area of the West Ash Disposal Area is approximately 18 acres and is located west of the powerhouse. The study area is defined by the Model domain and pertinent regions extending beyond the Model domain. The study area includes the Horn Lake Cutoff water diversion channel and uplands to the east, and the Mississippi River valley to the west and south.

4.2 REGIONAL STRATIGRAPHY AND GEOLOGY

Groundwater modeling efforts have focused on the near surface hydrogeologic units most likely to be influenced by operations at ALF. These units include the Mississippi River Valley Alluvial Aquifer (Alluvial aquifer), which is divided into the upper alluvium and the lower alluvium, loess deposits, terrace deposits, and the upper Claiborne confining unit. A generalized geologic map and regional cross-section adapted from the USGS Professional Paper 448-E (Bowell, et al., 1968) is included as Figures 4-1 and 4-2, respectively, to provide a regional perspective of the stratigraphy and depositional environment. A conceptual cross-section and stratigraphic column illustrating the stratigraphy distribution within the model layers and a conceptual block model diagram are presented as Figures 4-3 and 4-4.

ALF lies within the Mississippi Alluvial Plain, which is adjacent to the western boundary of the East Gulf Coastal Plain of the Coastal Plain physiographic province (Figure 4-1). The Mississippi Alluvial Plain is relatively flat with alluvial deposition features, and the East Gulf Coastal Plain is characterized by loess covered hills and bluffs (Parks, 1990).

ALF is in the north-central part of the Mississippi Embayment geological depositional environment. The Mississippi Embayment is a geologic basin filled with 3,000 ft or more of Cretaceous to Recent age sediments deposited primarily in an ancestral Coastal Plain setting. The sedimentary sequence is dominated by unconsolidated sand, silt, and clay with minor lignite (Hosman and Weiss, 1991).

Regional fault zones have been identified to have northeast-southwest and northwest-southeast trends (Kingsbury and Parks, 1993). Vertical displacement ranging from 50 to 150 ft has been identified in the Memphis aquifer and its underlying Fort Pillow aquifer (Kingsbury and Parks, 1993).

The terrace deposits (also referred to as fluvial deposits in some literature references) are alluvial deposits which overlie the upper Claiborne confining unit in the uplands east of the Mississippi Alluvial
Plain and were deposited during the Pleistocene. Loess overlies the terrace deposits and primarily consist of wind-blown silt, silty clay, and some sand derived from alluvium deposited within the valley (Waldron, et al., 2011; Leighton & Willman, 1950).

The alluvium of the Alluvial aquifer was deposited during the Quaternary within the Mississippi Alluvial Plain. The alluvium can be separated into two general units, the upper alluvium and the lower alluvium, both primarily derived from reworked older Pleistocene deposits (Bowell, et al., 1968). The upper alluvium deposits generally consist of silty sand with intervals of silts and clays that reflect the meandering river depositional environment. The lower alluvium consists of sand and gravel deposited by the higher energy glacial meltwater river system.

4.3 SURFACE WATER

Hydrology within the study area is influenced by natural surface water drainage systems and anthropogenic features. ALF lies within the Mississippi River alluvial plain and the hydrogeological system within the study area is dominated by the Mississippi River. The Mississippi River at the mouth of Lake McKellar drains 932,700 square miles at an average flow rate of 360,000 cubic ft per second (DOE, 1981). The bathymetry mapped by the USACE of the Mississippi River west of the Site displays the deepest part of the river (approximately 40 to 60 ft below Low Water River Plane) at the eastern boundary of the study area, south of where Lake McKellar intersects the Mississippi River (USACE, 2016). Figure 4-6 presents the USACE’s bathymetry maps of the Mississippi River adjacent to the study area (approximately river mile marker 724 to 726) from 1964 through 2004.

Lake McKellar is a constructed cut-off meander of the Mississippi River and was formerly known as the Tennessee Chute located along the northern boundary of ALF. The lake was created as a deep-water harbor for the City of Memphis in 1948 when USACE began construction of a levee connecting President’s Island to the mainland. The southern and eastern shores of President’s Island have been developed as an industrial area. The mouth of Lake McKellar meets the Mississippi River at approximately mile marker 725.5. The lake is approximately seven miles long and receives drainage from approximately 182, 13 and 4 square miles from Nonconnah Creek, Cypress Creek and miscellaneous small streams and runoff, respectively. Lake McKellar has an average yearly discharge of approximately 302 ft per second into the Mississippi River (DOE, 1981).

The Mississippi River’s elevations fluctuated up to approximately 46 ft at the West Memphis USGS gaging station between October 2014 and December 2018 (USGS stream gauge number 07032000 Mississippi River at Memphis, Tennessee). Water levels in Lake McKellar displayed up to 43 ft of elevation fluctuation between September 2017 and December 2018 with elevations ranging from 175 to 219 ft. A hydrograph of Lake McKellar stage data collected at ALF is included in Appendix A.

As the water level in the Mississippi River or Lake McKellar rises as a result of precipitation, rapid snow melt, or release of water from reservoirs up stream, it becomes higher than the surrounding groundwater. The hydraulic pressure gradient causes water to move from the surface water into the banks where it is temporarily stored. This process is termed bank storage. During high water events, surface water is pushed into the bank and becomes groundwater. When the river level subsides, the water that flowed
into the bank reverses flow back into the river. The interaction between surface water and groundwater can influence groundwater quantity, flow direction, and chemistry.

The upland loess hills are characterized by a network of small streams that are tributaries of the Mississippi River, Lake McKellar and the Horn Lake Cutoff (Moore and Diehl, 2004). The Horn Lake Cutoff is a water control feature that lies north and west of the uplands, discharging into Horn Lake located south and west of the Site.

4.4 STUDY AREA HYDROGEOLOGY

Various subsurface investigations have been conducted at ALF to characterize the geology, evaluate slope stability of dikes, monitor groundwater elevations and quality, evaluate potential water supplies, and develop remedial alternatives for groundwater impacts. Figure 4-3 displays monitoring well, extraction well, soil boring and CPT locations at ALF. Tables 4-1 and 4-2 provide a summary of monitoring well and subsurface boring construction details. The stratigraphy at the Site (Figures 4-2 and 4-3) consists of the following units listed generally in order of increasing depth and corresponding age of deposition from recent to Eocene:

- Fill
- Ash disposal areas
- Alluvial aquifer
  - upper alluvium
  - lower alluvium
- Loess
- Terrace deposits
- Upper Claiborne confining unit

These stratigraphic units define the vertical extent of the model and are discussed in greater detail in the following sections. Older stratigraphic units underlying the upper Claiborne confining unit were briefly covered in Section 4.2. However, the focus of the model is limited to groundwater flow systems that are key to understanding COCs in groundwater and how current and future activities at ALF may influence groundwater.

4.4.1 Fill

Fill is locally present beneath areas of Site, specifically in areas that have been developed. The fill generally consists of alluvium dredged from Lake McKellar and materials from cut and fill excavations from the surrounding floodplain. The fill can range in thickness from a few feet to tens of feet beneath industrial areas in the river floodplain (Stantec, 2019b).

4.4.2 Ash Disposal Areas

The following sections will briefly describe the ash disposed at the Site. More detailed documentation on the ash disposal areas at the Site can be reviewed at TVA’s public environmental stewardship website for the ALF CCR (TVA, 2018).
4.4.2.1 Composition

The ash disposal areas have been used for storage of fly ash, bottom ash and boiler slag from coal burning at the Site ALF (Stantec, 2016).

4.4.2.2 Extent and Structure

Two ash disposal areas are located at the Site, the West Ash Disposal Area and East Ash Disposal Area. The surface area of the East Ash Disposal Area is approximately 80 acres and is located east of the former coal yard and non-operational power plant. The surface area of the West Ash Disposal Area is approximately 18 acres and is located west of the powerhouse. The bottom of the both ash areas is approximately 210 ft in the National Geodetic Vertical Datum of 1929 (ft NGVD29) and generally flat (Triad, 2017). Both areas are shown in Figure 1-2.

4.4.2.3 Hydraulic Properties

Laboratory permeameter tests of soil samples collected at ALF indicated a vertical hydraulic conductivity (Kv) of hydraulically emplaced ash of 0.085 feet per day (ft/day) (Stantec, 2011). Heyman et al. (2017) estimate that the hydraulic conductivity of CCR can range from $2.83 \times 10^{-3}$ ft/day (fly ash) to 28.4 ft/day (bottom ash).

Heyman et al. (2017) suggest that the specific yield of CCR is typically in the range of 5-35% for fly ash and 20-30% for bottom ash. Total porosity typically ranges from 40-50%.

4.4.2.4 Water Quality

Both ash disposal areas were used to dispose of various ash materials. The West Ash Disposal Area has not received CCR since 1992 and is not subject to the Federal CCR Rule. The East Ash Disposal Area had been the primary unit to receive CCR until 2018 when disposal activities ceased.

4.4.2.5 Sluiced Water

The sluiced water in the East Ash Disposal Area is maintained at a surface elevation between 225 and 226 ft NGVD29.

4.4.3 Alluvial Aquifer

4.4.3.1 Composition

Regionally, the Alluvial aquifer is composed of sand, gravel, silt and clay. The deposits consist of fine sand, silt and clay in the upper portion of the unit and sand and gravel in the lower portion of the unit (Parks, 1990).

The upper portion of the Alluvial aquifer consists predominantly of overbank deposits on the flood plain of the Mississippi River. The fine-grained deposits are not uniformly distributed through the upper Alluvial aquifer and generally act as a heterogenous leaky confining unit. A clay interval described as silty clay
with interbedded very fine-grained sand underlies the overbank deposits and has been identified by Carmichael, et al. (2018) as the blue clay interval. The blue clay interval was likely deposited by a shallow lake environment resulting from an oxbow lake during the Pleistocene epoch (Carmichael, et al., 2018). The blue clay interval generally represents the lower limit of the fine-grained sediment zone in the alluvium. While the presence, depth and thickness of blue clay is variable across the investigated area, the presence of interbedded fine-grained sediments in the upper portion of the alluvium is pervasive.

The lower portion of the Alluvial aquifer consists of fine to coarse-grained sand and gravel deposits with minor lenses of silt and lignite interspersed throughout the sediment column. In general, the sediments fine upward from gravel to sand to silty sand and minor interbedded silt intervals. As described in Section 4.2, these deposits are believed to have originated as glacial valley-train transported to and deposited within the Mississippi River Valley (Carmichael, et al., 2018). Site-specific data collected through boring advancement and monitoring well installation indicate Alluvial aquifer deposits consisting of fine- to medium-grained silty sand with intervals of clayey silty sand, clayey sand, sandy silt, clayey silt and silty clay in the alluvium underlain by fine- to coarse-grained sand with trace to common fine- to coarse-grained gravel in the Lower alluvium. The lithology observed during subsurface investigations at ALF are displayed on cross-sections included as Figures 4-8 through 4-12a. Boring logs recording subsurface observations are included as Appendix B.

4.4.3.2 Extent and Structure

The Alluvial aquifer is consistently present beneath the Site and overlies the upper Claiborne confining unit within the Mississippi Alluvial Plain. The Alluvial aquifer does not extend past the boundary between the Mississippi Alluvial Plain and the Coastal Plain that is roughly defined by the uplands south and east of the Site (Parks, et al., 1995).

The average regional thickness of the Alluvial aquifer is approximately 100 ft with maximum thicknesses up to 250 ft (Boswell, et al., 1968). Site-specific data collected at the Site indicated that the thickness of this unit ranges from 111 to 225 ft, with the thickest part of the unit observed in borings PMW-11C and ALF-212C along the southeastern margin of the East Ash Disposal Area. Observed thicknesses of the upper alluvium and lower alluvium have been presented in Figure 4-13 and tabulated in Table 4-3.

Stantec reviewed 223 historical and recent subsurface logs for borings, CPT and wells completed at the Site and identified 56 unique locations that reached the bottom of the upper alluvium and 26 borings that reached the bottom of the lower alluvium. The bottom of the upper alluvium is presented in Figure 4-14. Boring Logs are included in Appendix B.

4.4.3.3 Hydraulic Properties

Groundwater in the Alluvial aquifer is present under unconfined to leaky confined conditions with variable saturated thickness. The saturated thickness is dependent on the water table elevation which fluctuates along with the Mississippi River and Lake McKellar stage and with recharge from precipitation.

Regionally, the Alluvial aquifer has a horizontal hydraulic conductivity (Kh) ranging between 3.28 and 992 ft/day and a Kv ranging between 8.5x10⁻⁶ and 2.29 ft/day according to published sources (see Table 4-4).
The Alluvial aquifer portion of the MERAS model proximal to the Site (MERAS Layer 1) was assigned a hydraulic conductivity of 166.7 ft/day and a specific storage of $4.03 \times 10^{-3}$ ft$^{-1}$ (Clark and Hart, 2009). Estimates of transmissivity within the Alluvial aquifer range from 8,500 to 50,000 ft/day and estimates of storage coefficients in deeper portions of the Alluvial aquifer range from $1.0 \times 10^{-4}$ to $4.0 \times 10^{-2}$ (Brahana and Broshears, 2001).

Single well rising head aquifer testing (slug testing) was completed at 32 monitoring wells to estimate hydraulic conductivity of the Alluvial aquifer (Stantec, 2019b). A summary of the slug test analyses results by well is in Table 4-3 and a figure summarizing the average hydraulic conductivity at each location is presented in Figure 4-1.

In December 2018, pumping tests were conducted at extraction wells EW-N02 (north area) and EW-S03 (south area), both screened within the upper alluvium. These tests were used to estimate transmissivity and hydraulic conductivity values representative of the upper alluvium north and south of the East Ash Disposal Area. The estimated hydraulic parameters calculated using results from the aquifer analysis are summarized in Tables 4-6 and 4-1 (Stantec, 2019a).

### 4.4.3.4 Estimated Yields

Cushing (1964) noted that the alluvial deposits were capable of yielding large amounts of groundwater. Well yields up to 4,000 gallons per minute (gpm) were observed by Stephenson and others (1928).

At ALF, two extraction wells (the Harsco wells) were installed in September 1971 and August 1979 by Harsco Corporation (Harsco), formerly known as Reed Minerals. The driller’s logs indicate the Harsco wells could yield up to 500 gpm. Both were completed in the lower alluvium. The active Harsco well was operated at 300 gpm for 8 to 9 hours per day approximately 5 days per week (averaging of approximately 80 gpm) until December 2018 when the Harsco wells were taken out of service.

In December 2018, step drawdown tests completed at upper alluvium extraction wells EW-N02 and EW-S03 indicated sustainable yields of 10.8 gpm and 30.1 gpm, respectively, could be expected to be achieved during the 24-hour constant rate pumping test. Results from the 24-hour constant rate pumping test are summarized in Table 4-1.

### 4.4.3.5 Water Quality

In 2017, USGS CAESER collected samples at the ACC Plant from both the Alluvial aquifer and Memphis aquifer to compare water quality of the two aquifers. The Alluvial aquifer was observed to have higher specific conductance, total dissolved solids, and arsenic levels in groundwater compared to the Memphis aquifer. Groundwater chemistry displayed similar characterization of major ions across both aquifers; however, the ions’ relative concentrations were between two and five times higher in the Alluvial aquifer when compared to the concentrations in the Memphis aquifer (Carmichael, et al., 2018).

Alluvial aquifer groundwater quality samples have been collected at ALF since November 2016. The results have been used to identify COCs at the Site that exceed maximum contaminant levels (MCLs), which are standards that are set by the United States Environmental Protection Agency (USEPA) for...
drinking water quality. Analytical results from groundwater sampling indicate that arsenic, fluoride and lead exceed their respective MCLs in localized areas (Stantec, 2019b).

### 4.4.3.6 Groundwater Flow

The Alluvial aquifer groundwater elevation surface defines the water table within the Mississippi Alluvial Plain and at the Site. The Mississippi Alluvial Plain is dominated by a network of rivers and streams at the surface that are connected to the Alluvial aquifer and act as a drainage system of the aquifer for much of the year (Brahana and Broshears, 2001).

Regional groundwater flow is generally to the north and west towards Lake McKellar and the Mississippi River, respectively. A regional groundwater contour map within the Alluvial aquifer was created by Brahana and Broshears (2001) and presented as Figure 4-16. Lake McKellar is hydraulically influenced and connected to the Mississippi River and the stage of Lake McKellar has been observed to influence water table elevations and direction of groundwater flow at the Site. Groundwater flow at the Site is further complicated because interbedded clay, silt, and sand deposits in the upper alluvium result in localized groundwater mounding. The heterogeneity observed in the upper alluvium adds complexity to the groundwater flow system by reducing connectivity between deposits with higher hydraulic conductivity (sand and gravel) and impeding flow between deposits of contrasting hydraulic properties (i.e. sand and clay).

Site-specific transducer data recorded between September 2017 and December 2018 displays groundwater elevation fluctuations at individual wells range from approximately 5 to 40 ft with an average of 25 ft variation over time across the Site. Hydrographs displaying transducer data and the Mississippi River and Lake McKellar stage levels are included in Appendix A. Lake McKellar and the Mississippi River stage elevation fluctuated over a 43-foot range between September 2017 and December 2018. As a result, the groundwater flow at the Site displays highly variable flow directions that display temporary localized reversals of groundwater flow away from and then towards Lake McKellar. These Site (localized) groundwater flow reversals observed between 2017 and 2018 are presented in Figures 4-13 through 4-30.

Average horizontal gradients calculated using manual gauging data resulted in values of 0.0393 feet per foot (ft/ft) and 0.0018 to 0.0019 ft/ft within the upper alluvium and lower alluvium, respectively. Table 4-8 summarizes horizontal gradient at the Site.

Vertical gradients between the upper alluvium and the lower alluvium ranged from -0.015 and -0.34 ft/ft (the negative sign indicating a downward gradient). Vertical gradients within the lower alluvium ranged between -0.023 and 0.020 ft/ft. Tables 4-3a and 4-3b summarize vertical gradients at the Site.

### 4.4.4 Terrace and Loess Deposits

#### 4.4.4.1 Composition

Terrace deposits are a saturated unit primarily consisting of sand and gravel with minor clay. The loess deposits primarily consist of silt, silty clay, and minor sand (Carmichael, et al., 2018).
4.4.4.2 Extent and Structure

The terrace deposits, which are overlain by the loess deposits, are present in the uplands, southeast of the Site. Neither of these deposits are present directly beneath the Site.

Thicknesses of the terrace and loess deposits range from 0-65 ft and 0-100 ft, respectively (Carmichael, et al., 2018).

Stantec does not have site-specific boring data within the uplands where the loess and terrace deposits reside; however, seven historical borings located south and east within the uplands within the Davis Well Field were reviewed to provide a general idea of where the loess and terrace deposit contacts would be expected to be closer to the Site, north of the Davis Well Field (Parks, et al., 1995).

4.4.4.3 Hydraulic Properties

Terrace deposit transmissivity has been estimated to be between 5,000 and 10,000 square feet per day (ft²/day) (Brahana and Broshears, 2001). The USGS MERAS calibrated groundwater flow model has assigned a Kh of 27.9 and 200 ft/day and a Kv of 1.27 and 2.00 ft/day for the loess and terrace deposits, respectively (Clark and Hart, 2009).

4.4.4.4 Estimated Yields

The terrace deposits have the potential to yield up to 50 gpm (Criner, et al., 1964). The loess deposits are unlikely to yield a significant amount of water and more readily allow precipitation to infiltrate and recharge the terrace deposits (Brahana and Broshears, 2001).

4.4.4.5 Groundwater Flow

Regionally, groundwater flow within the uplands where the terrace and loess deposits are is generally west towards the Mississippi River and north towards Lake McKellar (Brahana and Broshears, 2001).

4.4.5 Upper Claiborne Confining Unit

4.4.5.1 Composition

Regionally, the upper Claiborne confining unit is composed of the Cook Mountain Formation and the Cockfield Formation although at the Site. Regionally, the upper Claiborne confining unit is described to consist of clay, silt, sand and lignite; however, nearer to the Site, it is mostly clay and silt with minor amounts of fine sand (Carmichael, et al., 2018).

Site-specific data collected through boring advancement and monitoring well installation indicate that the upper Claiborne confining unit is predominantly fat clay, lean clay and silty clay.
**4.4.5.2 Extent and Structure**

The upper Claiborne confining unit underlies the Alluvial aquifer and overlies the Memphis aquifer. The top and the bottom of the upper Claiborne confining unit was observed in 27 and 14 subsurface data logs, respectively.

Regional thicknesses of the upper Claiborne confining unit are cited to range from 0 to 360 ft (Carmichael, et al., 2018). The four deep stratigraphic borings advanced at the Site indicated that when present, the upper Claiborne confining unit near the East Ash Disposal Area ranges in thickness from approximately 27 to 69 ft. Interpretation of borehole geophysical logs for the five ACC production wells indicated that the upper Claiborne confining unit, when present, ranges in thickness from approximately 48 to 100 ft. The upper Claiborne confining unit has also been demonstrated to be absent at the PMW-11C location, just south of the East Ash Disposal Area, and the Alluvial aquifer may directly overly the Memphis aquifer.

As indicated on the cross-section location map (Figure 4-8) and the structural stratigraphic cross-sections (Figures 4-3 through 4-12a), in addition to the cross-sections developed by the USGS-CAESER (Carmichael, et al., 2018), a fault is inferred to be present beneath the southeastern corner of the East Ash Disposal Area. The inferred fault underlying the East Ash Disposal Area has offset (i.e., lowered) the sedimentary sequence of the Alluvial aquifer, the upper Claiborne confining unit, and upper part of the Memphis aquifer to the southeast by varying amounts. The offset is most evident between well locations ALF-212 and ALF-213 (Figure 6-2) and between well locations ALF-214 and ALF-212 (Figure 4-11). In addition, deep exploratory drilling at the Pre-design PMW-11C well location near ALF-202 indicates the upper Claiborne confining unit is absent and the Alluvial aquifer directly overlies the Memphis Sand (Figure 4-11).

**4.4.5.3 Hydraulic Properties**

When present, the upper Claiborne confining unit inhibits vertical groundwater flow between the Alluvial and Memphis aquifers.

ASTM D 5084 Method C analyses were conducted on samples from 13 different wells to obtain measured hydraulic conductivity values for the upper Claiborne confining unit. The testing results yielded a range of hydraulic conductivity values between 1.72 x 10^-3 ft/day to 1.165 x 10^-6 ft/day. The median hydraulic conductivity of the samples was 3.94 x 10^-6 ft/day. These values show that the upper Claiborne confining unit is considerably less permeable than the overlying Alluvial aquifer.

**4.4.5.4 Estimated Yields**

The upper Claiborne confining unit is a confining unit that impedes groundwater flow because of the material’s low hydraulic conductivity, transmissivity and the ability to store groundwater; therefore, it is not a unit that would be anticipated to yield a significant amount of water.
4.4.5.5 Groundwater Flow

The upper Claiborne confining unit hydraulic properties impede groundwater flow and therefore very little groundwater flow would be expected within the unit.

4.5 THREE DIMENSIONAL LITHOLOGIC MODEL

The lithologic model represents a statistical interpretation of lithology based upon the data from available boring logs. Lithology data from historical borings, geophysics and CPT data were evaluated with the aid of Earth Volumetric Studio (EVS) software. EVS facilitates the geostatistical interpretation and visualization of the subsurface.

Figure 4-3 presents the locations used in the geostatistical evaluation the Site lithologic model. Subsurface logs are included in Appendix B. Cross sections from EVS are presented in Figures 4-3 and 4-4.

The interpreted lithology defined within EVS served as a basis for the Model layers. The geostatistical model was used to calculate the dominant lithology (largest percentage) in each grid cell within the Model (limited to the Site). When an equal amount of lithologies occurred in a cell, the finer-grained material was applied to the grid cell. Lithology texture type was used to assign hydraulic properties as zones of hydraulic conductivity and porosity, specific yield or specific storage. In areas that were not covered by the geostatistical model (e.g., below the upper alluvium and outside of ALF) a general lithology was applied based upon the CSM.
5.0 COMPUTER CODE

5.1 MODFLOW

The selected groundwater flow model utilized for this modeling study was MODFLOW-2005 (Harbaugh, 2005; Harbaugh et al., 2017). MODFLOW-2005 is a publicly available groundwater flow simulation program developed by the USGS and is designed to simulate three-dimensional groundwater flow using the finite-difference method (Harbaugh, 2005). The first version of MODFLOW (McDonald and Harbaugh, 1988) was developed by the USGS in the early 1980s. By the early 1990s, MODFLOW had become the most widely used groundwater flow model both within and outside the USGS (Harbaugh 2005). The program was selected for this study, in part, because it is thoroughly documented, widely used by consultants, government agencies, and researchers, and is consistently accepted by regulators.

In addition to its attributes of widespread use and acceptance, MODFLOW-2005 was also selected because of its versatile simulation features. MODFLOW-2005 can simulate transient or steady-state saturated groundwater flow in one, two, or three dimensions and offers a variety of boundary conditions, including specified head, areal recharge, hydraulic barriers, injection or extraction wells, evapotranspiration, drains, and rivers or streams. Aquifers simulated by MODFLOW can be confined or unconfined, or convertible between confined and unconfined conditions. MODFLOW's three-dimensional capability and boundary condition versatility are essential for the simulation of groundwater flow conditions given the complex hydrostratigraphy of the Site, which consists of a multi-layered geologic system with variable unit thicknesses and the hydrogeologic framework necessitates the inclusion of a variety of boundary conditions.

5.2 MT3DMS

The Model was used in conjunction with MT3DMS, a modular 3-D multi-species transport model for simulation of advection, dispersion, and chemical reactions of constituents in groundwater systems. MT3DMS calculates dissolved solute distribution as a function of time. MT3DMS is based on the original MT3D code with the main difference of the ability to simulate fate and transport without utilizing computer memory space with unused options. MT3DMS allows contaminant transport simulation without having to modify the existing groundwater flow model to fit the transport model (Zheng and Wang, 1999).
6.0 MODEL CONSTRUCTION

This section describes how the hydrogeologic framework of the groundwater system, as described in Section 4.3, was translated into a numerical model. The numerical translation includes the definition of the model aquifer geometry, the assignment of the initial and boundary conditions, discretization in space, and the selection of hydraulic parameter zonation and heterogeneity. The Model construction was accomplished using a host of software packages. The primary software packages used include:

- Groundwater Vistas® version 7.0, developed by Environmental Simulations, Inc. Used as a pre/post-process to prepare MODFLOW-2005 input files and process and visualize model output;
- Microsoft Excel and Access to manage most of the data used to prepare model input files and evaluate calibration results; and
- ArcGIS® version 10.4, developed by ESRI, to create shapefiles that can be imported into Groundwater Vistas® input files.

6.1 MODEL DISCRETIZATION

The extent of the model domain was selected based on surrounding hydrologic features that were utilized as boundary conditions (summarized in Section 6.4). Additionally, the extent of the model was chosen to facilitate potential future use of the model at a larger scale that would allow groundwater to be evaluated beyond the immediate extent of ALF. The entire model domain is approximately 14.5 square miles with the active portion of the model domain consisting of approximately 9.8 square miles. Section 6.4.1 provides a discussion of boundary conditions. Figure 6-1 shows the areal extent of the model and the model grid within the domain.

6.1.1 Horizontal Discretization

The model grid consists of 550 rows and 816 columns and is defined by a constant areal grid spacing of 30 by 30 ft. The horizontal discretization of the model was selected based on the necessity to have a fine enough grid to simulate localized patterns of groundwater flow and solute transport. Figure 6-2 presents the model grid.

6.1.2 Vertical Discretization

The selection of model layers is based on the lithology and stratigraphy described in Section 4.4 and conceptually summarized in Figure 4-3. The focus on evaluation flow directly below the Site and complexity of the upper Alluvial aquifer guided the decision to refine Model into the upper alluvium (5 layers) and lower Alluvium (2 layers). The Model layers are as follows:

- Layers 1 through 4 represents upper alluvium in the alluvial plain and loess, stream deposits and terrace deposits in the upland;
Layer 5 represents the bottom of the upper alluvium (blue clay zone) and terrace deposits in the uplands;
Layer 6 represents the lower alluvium (shallow zone) and the upper Claiborne confining unit in the uplands;
Layer 7 represents sand with coarser material within the lower alluvium (intermediate and deep zones) and the upper Claiborne confining unit in the uplands; and
Layer 8 represents the upper Claiborne confining unit.

Layer elevations are presented in Figures 6-3a through 6-3c. Figure 6-4 presents a comparison of a cross-section of the model layers and the conceptual regional cross section (layer configuration and generalized lithology).

6.2 TIME DISCRETIZATION

The temporal discretization in MODFLOW-2005 includes division of the transient model into bi-weekly stress periods defined by the average hydraulic conditions observed at the Site during the respective two-week periods. Lake McKellar transducer daily, weekly and bi-weekly averages, are included in Figure 6-3. Bi-weekly stress periods allow for sufficient detailed simulation of the short-term fluctuations caused by flood events and allow reasonable simulations times. The calibrated Model was simulated over two years with 52 stress periods. The transient model begins on January 1, 2017 and ends December 31, 2019 to maximize the use of available high-resolution groundwater elevation transducer data from the Site monitoring network.

6.3 PARAMETER DISTRIBUTION

6.3.1 Hydraulic Conductivity

The hydraulic conductivity in the Model has been used to simulate the heterogeneity observed in the upper alluvium based on the lithologic model and Site conceptual model. A total of 10 zones of hydraulic conductivity have been applied in varying distributions across the model vertically and horizontally.

Zones 1-7 represent the generalized lithology types described in Section 4.3.2, silt, sand, clay, sand with fines, gravel, CCR Unit material and sand with coarse material, respectively. Zones 8-10 represent the upper Claiborne confining unit, loess deposits, and terrace deposits, respectively. A range of hydraulic conductivities for zones 1-7 was defined using Site-specific slug testing results, aquifer testing results, and laboratory permeability results presented in Tables 4-3, 4-6, and 6-1, respectively. Zones 8-10 were applied hydraulic conductivity values based on cited values from literature resources included in Table 4-4.

The hydraulic conductivity ranges and the applied values of each zone have been included as Table 6-2. Figures 6-6a and 6-6b present the hydraulic conductivity zone distribution across Layers 1-8.
6.3.2 Storage

The two main types of aquifer storativity are confined storage (specific storage) and unconfined storage (specific yield). Unconfined storage is related to the release of water as the water table lowers (dewatering of the aquifer material); thus, it occurs only along the top boundary of the saturated flow system. Confined storage is related to the release of water as the head drops because of expansion of the water itself as the pressure changes and changes in the solid framework of the aquifer (no dewatering occurs). Specific yield and specific storage were applied generally based on literature values for associated subsurface materials (Morris and Johnson, 1967; Heath, 1983; Jazaei, et al., 2018). Ten zones of specific yield and storage were applied across the Model. Zone distribution mirrors the hydraulic conductivity zones discussed in Section 6.3.1. Table 6-3 summarizes the specific yield and storage coefficient applied to the model. Figures 6-6a and 6-6b present the specific yield and storage zones across Layers 1 through 8.

6.3.3 Recharge

Applied groundwater recharge is derived from infiltrating precipitation. Precipitation data was obtained from daily precipitation totals recorded at the National Oceanic & Atmospheric Administration’s (NOAA) Memphis International Airport station (USW00013893) in Memphis Tennessee. Daily totals were averaged over the associated 52 bi-weekly stress periods which are included in Table 6-4. Three zones of recharge were utilized across the model domain and are presented in Figure 6-3. The Model was calibrated using recharge rates of 8%, 15%, and 0% of the average bi-weekly precipitation for zones 1, 2 and 3, respectively. Each zone’s recharge rate is included in Table 6-4.

6.4 BOUNDARY CONDITIONS

The boundary conditions in the Model consist of two types: (1) no flow boundaries and (2) constant head boundaries. Each is described below, with location of application in the Model shown in Figure 6-8.

6.4.1 No Flow

No flow boundaries represent model cells across which groundwater flow cannot occur. No flow boundary conditions encompass the outer edge of the model domain and are applied in all layers of the Model. In the conceptual model for the Site, regional groundwater flow is generally flowing west towards the Mississippi River and north towards Lake McKellar based on the regional groundwater water table surface (Brahana & Broshears, 2001), therefore, the southern no flow boundary was drawn along an equipotential line of the regional water table. The western and northern no flow boundaries were based on transecting the deepest part of the Mississippi River (Figure 4-6, USACE, 2016) and the northern bank of Lake McKellar, respectively. The eastern boundary was applied based on the watershed boundary shown in Figure 6-1 which was identified using USGS’s StreamStats tool.

6.4.2 Constant Head

Constant head boundaries represent model cells of equal and constant total (hydraulic and pressure) head in the Model. A transient constant head boundary representing the average biweekly stage
elevation of the Mississippi River and Lake McKellar was applied to Layers 4 through 6. The average biweekly transient constant head data is included in Table 6-4. A steady-state constant head boundary of 226 ft was applied within the East Ash Disposal Area in Layer 1 to represent the East Ash Disposal Area standing water that is maintained between 225 and 226 ft. A steady-state constant head boundary of 198 ft was applied to the Horn Lake Cutoff based on the general elevation observed in the digital elevation model (DEM) along the Horn Lake Cutoff.
7.0 CALIBRATION

Calibration is the process of adjusting the model parameters to produce the best match between simulated and observed groundwater system responses. The Model calibration was performed by developing calibration targets, identifying calibration criteria, and finally conducting model calibration. The calibration criteria represent acceptable model performance with respect to predicted versus observed target values. In the process of calibration, model parameters are adjusted (subject to reasonable bounds) to match observed water levels at wells.

This section describes the procedure for calibrating the model and discusses the selection of calibration data and residual analysis.

7.1 MODEL CALIBRATION APPROACH

Calibration data points are a key element to the success or failure of model development. Information about the model parameters is drawn from measurements of the groundwater system. Model output and measured data are compared at discrete points in space and time to the calibration data points. The differences between the measured and the computed system responses at the calibration points are termed residuals. Calibration is the process of minimizing the residuals by updating the model parameters. Numerous forward simulations of MODFLOW-2005 were performed with varying parameter values to obtain the simulated water levels that correspond to measured water levels in terms of location and scale. Adjustments were held within reasonable ranges to obtain a match between the observed and simulated head calibration targets. The range over which the parameters were varied was derived from the conceptual model. In addition, the principle of parameter parsimony was applied, where appropriate, to achieve an adequate calibration of the Model through the use of the fewest number of model parameters. It should be noted that the use of greater numbers of model parameters during model calibration creates a situation in which different combinations of model parameter values produce similar calibration results. In this case, the Model calibration parameters are considered non-unique. Following the principal of parameter parsimony reduces the degree of non-uniqueness and results in more reliable calibrated parameter values.

An analysis of residuals was performed after each Model simulation. The calculated and measured system responses (water levels) are compared. If the measured data are not properly reproduced by the Model (i.e. if the final residuals are large or exhibit system errors), the resulting parameters are likely to be inadequate or highly biased. Another possibility is that inconsistencies and/or errors exist in a developed conceptual model.

7.2 SELECTION OF CALIBRATION DATA

The calibration targets consist of observed groundwater head values (water levels). The transient Model was calibrated using the average groundwater elevation observed biweekly between September 2017
and December 2018. A total of 1,012 average biweekly groundwater elevations at 65 unique locations were used to calibrate the Model.

Figure 7-1 shows the location of the selected calibration wells in the Model. Appendix C presents observed versus simulated hydrographs of the data used in the model calibration. Figures 7-2 and 7-3, present a summary of selected hydrographs.

### 7.3 Calibration Criteria

During the calibration process each model simulation was compared to site-specific measured head values (water levels). The degree of agreement between the model simulation and the physical hydrogeological system data can then be compared to that for previous simulations to ascertain the success of alterations made in response to previous calibration efforts, and to identify potentially beneficial directions for further calibration. Qualitative and quantitative comparisons are both essential in the calibration process (ASTM, 2017). Both were used to evaluate the degree of agreement between the groundwater flow model simulation and site-specific information.

The primary criterion for evaluating the quantitative calibration was the head residual. A residual or model error, \( e_i \), is defined as the difference between an observed and simulated variable measured at a target location:

\[
e_i = h_i - h'_i
\]

where \( h_i \) is the measured value and \( h'_i \) is the simulated value at a specific target location. Spatial or temporal correlation among residuals can indicate systematic trends or bias in the model. Correlations among the residuals may be evaluated through temporal and spatial plots.

Residual analysis is critical in evaluating the calibration. However, this does not imply that a real groundwater system is properly represented by a model. If a conceptual model fails to reproduce the salient features of a system, the given calibrated model may not be able to match observed data as expected. Residual analysis can reveal potential trends in residuals, indicating a systematic error in a model or the data, and can point out aspects in a model that need to be modified.

The calibration procedure seeks to minimize a function, the residual sum of squares (RSS):

\[
RSS = \sum_{i=1}^{n} (h_i - h'_i)^2
\]

where \( n \) is the total number of calibration targets. The RSS is the primary measure of model agreement. Second order statistics can be used to quantify the amount of spread (range of variability) of the residuals about the residual mean. One example is the residual standard deviation (RSTD), which normalizes the RSS by the number of calibration targets and number of estimated parameters (\( P \)), is defined as follows:
The RSTD is useful for comparing model calibrations with different numbers of calibration targets. Smaller values of standard deviation indicate better correlation between model simulations and observed field data. A large variance or standard deviation either indicates that the data were noisier than expected or that there is a trend in the residuals.

Another calibration measure is the mean of all residuals ($e$):

$$e = \frac{1}{n} \sum_{i=1}^{n} e_i$$

A mean residual significantly different from zero indicates model bias. A large positive or negative mean indicates that data are systematically under-predicted or over-predicted by a model. Calibration may be viewed as a regression analysis designed to bring the mean of the residual close to zero and to minimize the standard deviation of the residuals. Statistics on hydraulic head residuals aid in the evaluation of model calibration.

Statistics on hydraulic head residuals aid in the evaluation of model calibration. The mean of the residuals is expected to be close to zero. A large positive or negative mean indicates that data are systematically under-predicted or over-predicted by a model. The standard error in a regression is the square root of the calculated error variance.

### 7.4 CALIBRATION RESULTS

Residual analysis was used to reveal potential trends in residuals, indicating a systematic error in a model or the data, and can point out aspects in a model that need to be modified. Residual analysis is critical in evaluating the performance of calibration. The calibration of the Model sought to minimize the residual and the relative error computed for the 1,012 groundwater elevation data points in the calibration data set. Using the model residuals, a quantitative comparison of the model’s fit to observed data may be made.

**Figure 7-4** graphically presents a summary of the calibration and summary statistics for the calibrated model. **Figure 7-4** also shows a graphical representation of the fit of simulated to observed data. In a perfectly calibrated model, all the points would fall directly on the 1:1 match line. A poorly calibrated model would show most points falling very far from the match line. Hence, **Figure 7-4** shows that the fit is good, with most points falling very close to the match line. There is a minor bias indicating that the observed data is slightly higher than the modeled data with more points falling above the line. In general, the disagreement between observed and simulated groundwater levels is likely the result of assumptions contained in the Model, such as time averaging of boundary conditions, usage of calibration wells spanning multiple lithology types, inferred subsurface geology based on limited data points, and potential unidentified or unincorporated influences on local water levels.
The calibration statistics indicate that the model accurately represents the measured potentiometric surface. The residual mean of -1.38 ft is close to zero and the scaled residual mean is 3.8%. Residual standard deviation is 2.75 and the range of observed heads is 35.99 ft, resulting in a scaled relative error of 7.6%. Residual mean standard error is 3.08 resulting in a scaled residual mean standard error of 8.5%. Based upon review of residuals as shown in Figure 3-4 and Appendix C, there are minor “outliers”, however the vast majority of the data do not indicate the presence of important but unrepresented groundwater conditions. Given the absolute size of the model and range in heads across it, these values are considered to indicate a satisfactory calibration. The minor disagreement between observed and simulated groundwater levels are likely the result of assumptions contained in the model, such as inferred subsurface geology based on limited data points, possible external influences, and the difference between measured groundwater levels representing partially penetrating screens and model simulated cells representing layers of average lithology.

7.5 CONVERGENCE CRITERIA

The quality of an iterative solution is measured by a number of convergence statistics. These parameters include the maximum head change for all model cells (residual change) and the percentage discrepancy between the total flow into and out of the model (volumetric flow budget discrepancy). Generally, the head change should be small, and the volumetric flow budget discrepancy should be less than 0.1% (Konikow, 1996).

The convergence statistics for the final calibrated model are as follows: 0.1 ft head change and 0.015 percent volumetric flow budget discrepancy.
8.0 SENSITIVITY ANALYSIS

This section presents the parameter sensitivity analysis. Parameter sensitivity measures the impact of a parameter change on the calculated system response. For example, if a small hydraulic parameter change results in a large change in the simulated water levels, the parameter is regarded as sensitive. Because certain parameter values, such as hydraulic conductivity, differ by orders of magnitude, sensitivities are best discussed within the context of the anticipated reasonable range of values. This allows for assessing the relative sensitivity of a model calibration and for evaluating the importance of the parameters.

The purpose of a sensitivity analysis is to assess the uncertainty in the calibrated model caused by the uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions. Assessment of sensitivity can provide a framework of how the model outputs respond to changes in the inputs, and thus increase the confidence in the model and its predictive abilities.

8.1 SENSITIVITY APPROACH

Sensitivity analysis of the model was performed during the model calibration to evaluate which parameters would be part of the calibration process.

During the sensitivity analysis/calibration process the following parameters were considered for systematic and logical variation:

- Vertical and horizontal hydraulic conductivity
- Recharge
- Storativity

8.2 DISCUSSION OF SENSITIVITY

8.2.1 Hydraulic Conductivity

Hydraulic conductivity in the environment can vary several orders of magnitude depending upon degree of sediment size distribution, compaction, and sediment size sorting. During calibration, it was observed that relatively small changes of hydraulic conductivity (in the range of 0.5 to 2 times the initial value) resulted in relatively large changes in simulated head values, particularly in the upper portion of the Alluvial aquifer, which is highly interbedded with low and high permeability materials and there is some resistance to flow in the vertical direction.

As discussed in Section 6.3.1, the Model domain was subdivided into hydraulic conductivity zones primarily based on geological and hydrogeologic conditions. Each of the zones was iteratively adjusted by varying the lithologically-derived hydraulic conductivity by a multiplier. The hydraulic conductivity
values were iteratively adjusted by a range of 0.1 to 10 times the initial estimation and the residual errors were observed.

Observations made during the sensitivity analysis indicated that the Model was sensitive to horizontal and vertical hydraulic conductivity and as such these were considered primary calibration parameters.

8.2.2 Storage

Specific storage in the environment can vary based upon the aquifer compressibility and effective porosity. During calibration, it was observed that variations in specific storage resulted in changes in head, particularly with distance from the surface water bodies.

As discussed in Section 6.3.2, the Model domain was subdivided into hydraulic conductivity zones primarily based on geological and hydrogeologic conditions. Each of the zones was iteratively adjusted by varying the specific storage by a multiplier. The specific storage values were iteratively adjusted by a range of 0.01 to 100 times the initial estimation and the residual errors were observed.

Observations made during the sensitivity analysis indicated that the Model was moderately sensitive to storage.

8.2.3 Recharge

Initial recharge in the study area is approximately 0.0 to 0.026 inches per day. During sensitivity analysis recharge was varied between 0.5 to 2 times initial estimates. Based upon the sensitivity analyses, recharge is deemed to be a sensitive parameter and was most sensitive in areas of low hydraulic conductivity assigned in the upper Model layers.
9.0 SIMULATIONS

9.1 CALIBRATED MODEL SIMULATION

The following is a summary of the Model output and interpretations related to the simulated groundwater system.

*Figures 3-1a through 3-1d* depict the simulated groundwater elevation for the Model domain and the area of the East Ash Disposal Area for the upper (water table) and lower portions of the Alluvial aquifer. The calibrated model simulates the Alluvial aquifer flow system in the study area from January 2017 through December 2018. The flow analysis represents the results of 52 bi-monthly stress periods; however, to provide a range of results, three selected times are presented: low water (September 2017), high water (March 2018), and a transitional between high water and low water (June 2018).

The water-bearing units underlying the loess hills have simulated groundwater elevations that are greater than the groundwater elevations in the Alluvial aquifer, resulting in water moving from these units into the Alluvial aquifer. The higher groundwater elevations in these units are the result of the relatively high altitude of their recharge areas as compared to the elevation of the alluvial plain. The Mississippi River on the western boundary and Lake McKellar on the northern boundary are lateral recharge/discharge areas for the Alluvial aquifer. The depth of the river channel allows the area bordering the surface water to be in almost complete hydraulic connection with the aquifer. Depending upon the surface water stage, the aquifer is either recharged by surface water or the aquifer is discharging to surface water.

Model simulated and measured groundwater elevations indicate that in most areas within Site groundwater levels in the Alluvial aquifer are influenced by stages in the river (*Appendix C*). The exception is areas which either contain or are underlain by low permeability sediments (Sands, clays or highly interbedded sands, silts and clays). These areas are partially isolated from the underlying hydraulically forced groundwater zones. Examples include areas of mounded groundwater located north and south of the East Ash Disposal Area (e.g. monitoring well locations: ALF-202, ALF-203, ALF-212, ALF-215 and ALF-217).

Groundwater flow patterns within the deeper portion of the Alluvial aquifer is a more muted form of that displayed in the upper portion of the aquifer due to the more uniform and transmissive aquifer properties of the coarser materials present in the lower aquifer. The lower aquifer exhibits the similar pattern of recharge from the uplands and discharge to the surface water features with temporary reversals due to fluctuations in surface water stage during high water events.

The simulated direction of groundwater flow is depicted using model flow vectors on *Figures 3-2a through 3-2d* for the Model domain and the area of the East Ash Disposal Area for the upper and lower portions of the Alluvial aquifer. Cross sections displayed on the figures depict vertical flow direction. Within the areas of mounded water, groundwater moves downward and then flows laterally towards surface water.
Simulated groundwater velocity is variable throughout the Model. As shown on Figures 3-3a and 3-3b, the bulk of groundwater flow occurs in the coarser alluvium.

9.2 SIMULATED SCENARIOS

The Model was used to simulate a series of hypothetical scenarios to demonstrate the applicability of the Model for evaluating the potential impact of various actions.

The simulations include:

- Scenario 1. Simulation that includes operation of the Harsco water supply well at historical operation rates to evaluate the potential influence of groundwater extraction.
- Scenario 2. Baseline simulation of solute transport of arsenic from the North area
- Scenario 3. Baseline simulation of solute transport from the South area
- Scenario 4. Simulation of solute transport under proposed interim groundwater extraction in the North Area
- Scenario 5. Simulation of solute transport under proposed interim groundwater extraction in the South Area.

The predictive scenarios were performed using a steady state simulation based upon the calibrated transient model to allow for evaluation of longer time frames than available in the 2-year transient simulation.

9.2.1 Simulation 1 Impact of Historical Operation of Harsco Well

For this scenario, a Harsco water supply well was simulated to be operated at historical groundwater extraction rates to evaluate the potential effect of the water withdrawal on the hydrologic system.

At the Site, two extraction wells (the Harsco wells) were installed in September 1971 and August 1979 by Harsco Corporation (Harsco), formerly known as Reed Minerals. The driller’s logs indicate the Harsco wells could yield up to 500 gpm. Both were completed in the lower alluvium, although only one had been active in the recent history of operation. The active Harsco well is reported to have been was operated at 300 gpm for 8 to 9 hours per day approximately 5 days per week (averaging approximately 80 gpm) until December 2018 when the Harsco wells were taken out of service.

For the simulation, the most recently active Harsco well was simulated to be completed into Layers 6 and 7 and operated at the time averaged flow rate of 80 gpm. To evaluate the long-term impact of pumping from the well, the heads produced during the simulation were compared to the heads from a baseline simulation in which the well was not operating. Figure 3-4 depicts the simulated drawdown results for Simulation 1. As depicted in Figure 3-4, drawdown greater than 0.1 ft is simulated to extend approximately 75 to 125 ft from the Harsco well. The hydraulic influence is simulated to be asymmetrical, less influence to the north, as a result of the hydraulic boundary influence of Lake McKellar.
Solute Transport Scenarios

In May 2017, TVA identified two areas of groundwater north and south of the East Ash Disposal Area that contained arsenic, and to a lesser degree, lead, and fluoride, at concentrations above United States Environmental Protection Agency (USEPA) MCLs. Subsequently, TVA performed remedial investigation activities and prepared an Interim Remedial Design for an Interim Response Action (IRA) to control and begin treating groundwater in these two areas. Scenarios 2 through 5, presented below, are intended to inform and refine the understanding of transport in the two identified areas.

Scenarios 2 through 5 couple the Model with the three-dimensional transport model, MT3DMS (Zheng and Wang, 1999), to evaluate the potential migration of arsenic in groundwater at the Site. The Model provides the flow field in which the constituents move and allows for performing simulations under conditions that may have existed in the past or could be reasonable in the future. Dissolved arsenic was selected for evaluation based upon the relatively larger identified distribution in comparison to remaining COCs (lead and fluoride). The concentrations of fluoride and lead are substantially lower (relative to their respective MCLs) and the distributions of fluoride and lead in groundwater are within the areas impacted by arsenic. Initial arsenic concentrations were defined based the current observed concentration (Stantec, 2019b). Limited site-specific information is available to support a history matching simulation; therefore, the Model was run as a forward prediction to provide insight, assist in the design of the Interim Response Action (IRA), and inform the conceptual understanding of solute flow. The point concentrations of arsenic were interpolated to develop initial conditions and then imported into the Model for Layers 1 through 4 based upon the inferred vertical distribution of arsenic at the Site. Arsenic partitioning coefficients were calculated based on batch adsorption analysis of subsurface sediment samples collected at the Site. Values of dispersivity were based upon established relationships to the size of the area where arsenic was detected above the MCL (Gelhar, et al., 1992). Transport parameters used in the solute transport simulation are summarized in Table 3-1.

Scenario 2 Baseline Simulation of Solute Transport East Ash Disposal Area – North Area

As a baseline case, a solute transport simulation was performed to evaluate the potential migration of arsenic in groundwater from the area of elevated concentration observed north of the East Ash Pond to illustrate solute transport mechanisms. In particular, solute transport direction and velocity. In this simulation the IRA is not simulated to be operating and the Model is simulated forward in time for 20 years using the steady state groundwater flow model to provide the groundwater flow field. In general, over the simulated time period (20 years) dissolved arsenic is simulated to generally decrease in concentration as it moves in the direction of groundwater to the north towards Lake McKellar. Simulated transport of the current distribution of arsenic shows differential migration of arsenic primarily controlled by sediment type. Migration within low permeability sediments is retarded both by lower groundwater velocities and increased sorption properties. Figures 3-a and 3-b present the simulated distribution of arsenic in the upper Alluvial aquifer for 20 years at five-year increments.
9.2.2.2 Scenario 3 Groundwater Extraction Simulation of Solute Transport East Ash Disposal Area – North Area

A second predictive solute transport simulation was performed to evaluate a conceptual design of the IRA hydraulic control scenario to mitigate the presence of dissolved arsenic in the area north of the East Ash Disposal Area (Stantec, 2019b). The conceptual design of the IRA is focused on groundwater in the area north of the East Ash Disposal Area where the arsenic concentrations are greater than 1,000 micrograms per liter (µg/L). As in scenario 2, the Model is simulated forward in time for 20 years using the steady state groundwater flow model to provide the groundwater flow field.

The Model was used to simulate the proposed IRA with pumping from four extraction wells completed in the upper Alluvial aquifer. Each groundwater extraction well was simulated to pump groundwater from the upper Alluvial aquifer (Model Layers 1 through 4). Extraction well locations are displayed in Figure 3-6a and 3-6b. The extraction wells were simulated to be operating at rates between 10 and 30 gpm for a combined simulated extraction rate of 81 gpm. Extraction rates for each well are summarized in Figure 3-6a and 3-6b. Simulated arsenic transport indicates a reduction of arsenic, both areal extent and concentration, within the inferred area of groundwater where arsenic is initially above approximately 1,000 µg/L. Figures 3-6a and 3-6b present the simulated distribution of arsenic in the upper Alluvial aquifer for 20 years at five-year increments. The simulation indicates that the simulated groundwater extraction provides hydraulic containment and arsenic mass removal in the area of highest dissolved arsenic.

9.2.2.3 Scenario 4 Baseline Simulation of Solute Transport East Ash Disposal Area – South Area

Similar to the north area, a baseline solute transport simulation was performed to evaluate the potential migration of arsenic in groundwater from the area of elevated concentration observed south of the East Ash Disposal Area for a comparison to simulation of an IRA. In this simulation the IRA is not simulated to be operating and the Model is simulated forward in time for 20 years using the steady state groundwater flow model to provide the groundwater flow field. In general, over the simulated time period (20 years) dissolved arsenic is simulated to generally decrease in concentration as it moves in the direction of groundwater to the north towards Lake McKellar. Simulated transport of the current distribution of arsenic shows differential migration of arsenic primarily controlled by sediment type. Migration within low permeability sediments is retarded both by lower groundwater velocities and increased sorption properties. Note that in Model Layer 4, there are predominantly low permeability sediments within the footprint of the arsenic distribution which leads to lower groundwater flow velocities. As a result of the low flow velocities, there is little change in the simulated arsenic distribution in this layer. Figures 3-3a and 3-3b present the simulated distribution of arsenic in the upper Alluvial aquifer for 20 years at five-year increments.

9.2.2.4 Scenario 5 Groundwater Extraction Simulation of Solute Transport East Ash Disposal Area – South Area

A second predictive solute transport simulation was performed to evaluate a conceptual design of an IRA hydraulic control scenario to mitigate the presence of dissolved arsenic in an area south of the East Ash Disposal Area (Stantec, 2019b). The conceptual design of the IRA is focused on groundwater in the area
south of the East Ash Disposal Area where the arsenic concentrations are greater than 100 µg/L. As in scenario 4, the Model is simulated forward in time for 20 years using the steady state groundwater flow model to provide the groundwater flow field.

The Model was used to simulate pumping from five extraction wells completed in the upper Alluvial aquifer. Each groundwater extraction well was simulated to pump groundwater from the upper Alluvial aquifer (Model Layers 1 through 4). Each well was operating at a rate between approximately 20 and 30 gpm for a combined simulated extraction rate of 124 gpm. Extraction well locations and extraction rates for each well are displayed in Figure 3-8a and 3-8b. Simulated arsenic transport indicates a reduction of the migration of arsenic, both areal extent and concentration, within the inferred area of groundwater where arsenic is initially above approximately 100 µg/L. Figures 3-8a and 3-8b presents the simulated distribution of arsenic in the upper Alluvial aquifer for 20 years at five-year increments. The simulation indicates that the simulated groundwater extraction provides hydraulic containment and arsenic mass removal in the area of highest dissolved arsenic.
10.0 SUMMARY AND CONCLUSIONS

A numerical groundwater flow model of the study area was constructed as a tool to assess groundwater flow conditions at the Site. The Model reasonably matches water levels, and based on simulated groundwater contours, the Model reasonably reproduces the flow paths as expected based on the CSM. The calibrated aquifer properties values for the identified sediments are within the expected ranges of values of the individual geologic units. While the Model reasonably reproduces the hydrogeologic flow system underlying the Site, it should be noted that the Model, by necessity, is a simplified representation of the actual hydrogeologic system. The Model is a suitable quantitative tool capable of predicting groundwater flow and transport under varying conditions. However, the scale of the Model discretization, simplifying assumptions, and the Model limitations should be considered when making management decisions based upon simulated results.

Based on construction, calibration, and simulation of the Model the following observations are provided.

The flow of groundwater in and around the study area generally follows the regional topography with final discharge into the nearby river system. The study area can be divided into two separate groundwater systems divided at the break in topography in the eastern portion of the model domain. At a regional scale, groundwater beneath the higher elevation areas (in the eastern portion of the study area) moves from these units into the Alluvial aquifer along the Mississippi River floodplain. The higher groundwater elevations in these units are the result of the relatively high altitude of their recharge areas as compared to the elevation of the alluvial plain.

The Mississippi River on the western boundary and Lake McKellar on the northern boundary are lateral recharge/discharge areas for the Alluvial aquifer. Model simulations, as well as observed data, indicate that in the area bordering the surface water bodies, surface water is in hydraulic connection with the Alluvial aquifer. Model simulations indicate that during high surface water events, surface water flows from the surface water bodies to groundwater. When the river level subsides, the water that flowed into the groundwater reverses flow back into the surface water bodies.

At the Site scale, there is more observed variability in the groundwater elevations, in particular within the water table. At the Site, the water table is encountered in the upper portion of the Alluvial aquifer. Local heterogeneities in sediment type results in localized groundwater mounding and depressions. Model simulated and measured groundwater elevations indicate that groundwater elevation in the Alluvial aquifer are influenced by surface water stage except in areas which either contain or are underlain by low permeability sediments. These areas are partially isolated from the underlying hydraulically forced groundwater zones. Most notably groundwater mounding is observed in the areas with elevated concentrations of COCs, north and south of the East Ash Disposal Area.

A model simulated operation of the Harsco water supply well at historical groundwater extraction rates indicated drawdown greater than 0.1 ft is simulated to extend approximately 75 to 125 ft from the Harsco well.
Summary and Conclusions
July 12, 2019

The Model was linked to a fate and transport model and predictive simulations were performed to evaluate performance of interim response action hydraulic containment system. Based upon the predictive simulations the conceptual interim response system would be anticipated to operate as intended to hydraulically contain and reduce mass of dissolved COCs at the Site.
11.0 MODEL LIMITATIONS

A calibrated groundwater model is not an absolute representation of the complex heterogeneous flow and transport system of the aquifer. There is always uncertainty associated with the numerical simulation of groundwater. The simulated system represents a simplified version of the current conceptual model of a complex hydrogeologic system. For example, the Model assumes no-flow boundary condition at the bottom of the Model domain. This assumption is deemed reasonable based upon the focus of the model on the upper portion of the Alluvial aquifer, the relatively small observed vertical gradients in the deeper portion of the Alluvial aquifer and the location of the upper Claiborne confining unit encountered in borings at ALF. However, investigations have indicated that locally the upper Claiborne confining unit may be absent and the lower boundary may not be a true no flow boundary for the actual groundwater system. Therefore, even though the groundwater model is considered reliable to meet the objectives of the study, prudence should be used in its application as a planning tool.

Some of the additional key limitations/assumptions and data gaps of the Model are presented below:

- Because the Model has a grid size of 30 ft × 30 ft, it is not capable of reproducing groundwater levels or concentrations at a resolution less than this due to limitations imposed by the spatial resolution of the Model.

- Because there are few calibration targets in the Model outside of the Site, the uncertainty in these areas is greater than that of the investigated areas.

It is expected that the Model will be utilized on an on-going basis to simulate the groundwater flow system and evaluate fate and transport of COCs. Additional hydraulic data such as aquifer testing, production data, water level measurements, and time series groundwater quality data may be beneficial in further verifying the Model and may be incorporated into the Model, as appropriate.
12.0 REFERENCES


References
July 12, 2019

Harbaugh, A.W., 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the


References
July 12, 2019


SOURCE: PORTION OF U.S.G.S QUADRANGLE MAP
7.5 MINUTE SERIES (TOPOGRAPHIC)
SCALE 1:60,000

DRAFT