Allen Wellfield Evaluation Report

ALLEN WELLFIELD
709 EAST DISON AVENUE
MEMPHIS, TENNESSEE  38106

Prepared for:

Memphis Light, Gas & Water Division
220 South Main Street
Memphis, Tennessee  38103

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Executive Summary

**Synopsis statement:** The Memphis Light, Gas and Water (MLGW) Allen wellfield was evaluated to assess the current state of water quality concerns and the potential for future water quality problems. Investigation of properties near the wellfield found 37 sites with known volatile organic compound (VOC) releases to groundwater and sampling revealed numerous monitoring wells with VOCs; however, at present only one Memphis aquifer production well (MLGW 111A) has persistent, detectable VOCs. Groundwater flow and contaminant transport modeling predict historic VOC detections in MLGW production wells and future migration into the upper part of the Memphis aquifer. The recommended remediation solution is to continue to produce water from MLGW 111A and to install a wellhead treatment system, then discharge the water to the Allen Pumping Station or re-inject into the aquifer. Because modern water (an indicator of vulnerability) and VOCs are observed only in the upper part of the Memphis aquifer in the southern and eastern parts of the wellfield, it is recommended that future development progress in the northern part of the wellfield and balance production from the upper and middle Memphis aquifer to minimize further migration of VOCs.

**Summary:** The MLGW Allen wellfield has been producing high-quality water from the Memphis aquifer for almost 80 years. However, since the mid-1980s several production wells have shown low concentrations of benzene and organochlorine compounds and has led to abandonment in some cases. MLGW retained the University of Memphis (UM) Center for Applied Earth Science and Engineering Research (CAESER) and its collaborators Ensafe, Inc. and the United State Geological Survey (USGS), to conduct a comprehensive assessment of the Allen wellfield that would ascertain future contaminant impacts and determine remediation alternatives aimed at extending the operational longevity of the wellfield. The CAESER team proposed a four-phase plan for the Allen wellfield area to:

1. conduct historical and regulatory research to identify contaminants and their source terms.
2. install monitoring wells and sample production, observation and monitoring wells for water quality and hydrologic tracers.
3. develop and calibrate numerical models for groundwater flow and contaminant transport.
4. identify remediation strategies to address existing contamination problems and those that may arise in the future.

*Phase I* identified and ranked known and potential sources of groundwater contamination within the 50-year time-of-travel model, plus a 0.5-mile buffer around known and suspected breaches in the upper Claiborne confining unit (UCCU). Any records pertaining to known contamination sources were scanned and associated with their corresponding parcel(s). This database is accessible through MLGW’s ESRI® ArcDesktop solutions. Historical contaminant concentrations were used in Phase III for simulating plume migration.

*Phase II* included observation (monitoring) well installation and sampling of monitoring and production wells in the shallow and Memphs aquifers within the wellfield to assess the current state of water quality in and surrounding the Allen wellfield, including the existence and distribution of modern water (<60 years old) in the Memphis aquifer. A comprehensive sampling event conducted in August 2017 and three subsequent quarterly sampling events (November 2017; February 2018; and May 2018) resulted in:
• Volatile organic compounds (VOCs) identified in seven shallow aquifer monitoring wells and in Memphis aquifer production well MLGW 111A.
  
  — MLGW 111A continually yielded low VOC concentrations, all of which were below U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) except for that in May 2018, in which the trichloroethene concentration (6 µg/l) exceeded its respective MCL of 5 µg/l. Based on associated water quality data, the VOCs likely originate from a plume approaching the wellfield from the east (Memphis Depot area).

• Tritium (³H) concentrations were above background in five Memphis aquifer production wells (MLGW 103A, MLGW 111A, MLGW 114, MLGW 115A and MLGW 123A).
  
  — Calculated modern water recharge ages are between 14.0 and 39.1 years before 2017.
  — Between 15 to 23% modern water exists in production water from wells MLGW 111A, MLGW 114, and MLGW 115A.

Phase III utilized numerical groundwater-flow and contaminant-transport modeling to determine patterns of groundwater recharge and flow in the Allen, Davis and Palmer wellfield areas, and determine probable contaminant plume migration based on sites and contaminant concentrations identified in Phase I.

• Groundwater-flow modeling substantiates downward recharge through the UCCU into the Memphis aquifer at the identified breach east of the Allen wellfield beneath the former Memphis Depot and indicates a hypothesized breach along Nonconnah Creek east of Presidents Island.

• Contaminant-transport modeling indicated that the greatest potential for water quality impact is in the southern part of the wellfield, although organochlorine compounds may also be migrating in the northwestern part of the wellfield.
  
  — Lack of available data from contaminant sources hampered the modeling effort. All contamination was initiated in 1980 with either a 25-year (plug-source) or continuous source term, and then the resulting plumes tracked in the shallow and Memphis aquifers through 2055.

Phase IV considered the results from Phases I through III to develop remedial options for the Allen wellfield, these focusing mostly on MLGW 111A, although the alternatives are effective should other wells become impacted. Six remediation response options were developed for MLGW to consider, ranging from well abandonment to implementing various pump and treat scenarios. The option of closing and abandoning a contaminated production well is least desirable because of the probability that the contaminants will migrate further into the wellfield. Continued groundwater extraction is considered the best remediation approach. Based on our understanding that MLGW does not want to treat water at the water plant, the CAESER team recommends consideration of Options 5 and 6.

• Option 5 incorporates treatment of VOC-impacted groundwater at the wellhead, allowing ongoing beneficial use of the wellhead while slowing contaminant migration into the wellfield.
• Option 6 provides a hydraulic barrier and protection of the wellfield and uses reinjection to (a) enhance the hydraulic barrier, and (b) return treated water to the aquifer for future use.

Additional data are required to gauge trends and recommended a minimum of annual VOC sampling in production wells (not combined influent to the water plant). Monitoring wells associated with the wellfield should be sampled at the same time. If VOCs are identified in a well, that well should be sampled quarterly (at minimum) to provide a higher data density for trending. Supplemental analytical parameters that would facilitate air stripper system design include metals (particularly iron), alkalinity, and hardness.
### 1.0 Introduction

The MLGW Allen wellfield, which draws from Memphis aquifer, has been in production for almost 80 years. From 1986 to 1992, benzene and organochlorine compound contaminants were observed in the production water from several wells in the Allen wellfield. The most probable source of these organic contaminants was assumed to be from water infiltrated through contaminated soil at the American Resources Recovery (ARR) facility to the southwest of the wellfield; however, other possible contaminant sources exist in the wellfield area.

The Memphis aquifer is generally confined in this section of Shelby County, being overlain by the clay-rich upper Claiborne confining unit (UCCU; or aquitard). Contaminants are likely to enter the Memphis aquifer through areas of localized thinning or absence of clay in the aquitard. Whether the ARR facility is the only source of organic contaminants is unclear, it is also currently unclear whether the source plume (or plumes) is stationary (constant source) or moving (plug source). Additionally, the current extent of the contaminant plumes both in the Memphis aquifer and the overlying shallow aquifer are unknown because extensive comprehensive sampling and testing has not been conducted since 1992.

To return the Allen wellfield to more efficient and complete production, MLGW requested a comprehensive, area-wide assessment for contaminants potentially adversely affecting MLGW’s source water supply, treatment, and/or distribution systems in the Allen Water Pumping Station service area to include the following:

- **Phase I: Historical and Regulatory Research** - Identify, locate, and quantify any and all existing contaminants and sources to the contributing aquifer(s) of the Allen wellfield.

- **Phase II: Groundwater Sampling** – installation of observation (monitoring) wells and sampling of existing monitoring and production wells in the Allen wellfield area.

- **Phase III: 3D Groundwater Model** - Develop and calibrate a three-dimensional (3D) model of groundwater flow and contaminant plumes from identified sources in the Allen wellfield area.

- **Phase IV: Remediation and Future Remedial Services** - Develop remediation/treatment alternatives for identified or potential contaminants and costs associated with remedial activities.

The following report summarizes the activities and results of each of the phases completed for the assessment of the Allen wellfield. Background information is provided in the paragraphs below to clarify the conditions in the Allen wellfield area based on historical data.

#### 1.1 Wellfield Background

The Allen wellfield became operational in 1953, pumping approximately 2,000 million gallons of water annually from the Memphis aquifer. Allen currently has 14 production wells in service and 10 production wells out of service (Figure 1-1). Following information in Table 1-1, 6 of the 15 production wells were constructed in the 1950s. The majority of the wells (63%) are screened within the upper section of the Memphis aquifer (depth < 500 feet). The monitoring well network in the Allen wellfield comprises wells screened within the shallow and Memphis aquifers (Figure 1-1). Fourteen monitoring wells are screened in the shallow aquifer ranging in depth from 40 to 112 feet below ground surface (bgs). Monitoring well
1T7 (Sh:J-195), which is closest to Nonconnah Creek, has a total depth of only 40 feet bgs. Considering ground surface elevation at 1T7 is 234.4 feet and average wet-season stage elevation of Nonconnah Creek is 208 feet, 1T7’s screen is slightly lower than the average wet season stage elevation of Nonconnah Creek. One Memphis aquifer monitoring well (Sh:J-126) is present in the Allen wellfield; it is screened in the upper part of the Memphis aquifer. Eight Memphis aquifer monitoring wells are within or proximal to the Allen wellfield.

Table 1-1: Construction parameters for MLGW Allen wellfield (2014). Wells with a signature of modern water (<60 years, based on current and historic $^3$H and $^3$He sampling) (updated as of August 2017) are marked with an ‘X,’ while those never tested are shown with a ‘---’ and those with no detection are ND. MLGW Well 118 was at the detection limit (0.1 TU).
1.2 Hydrogeology and Water Quality

The geologic units beneath the Allen wellfield area in Shelby County (Figure 1-1) are divided into a series of aquifers and confining units. Silt-rich loess mantles the rolling hill topography (uplands) of the Allen wellfield area and is an average of 18 feet (ft) thick (Bradshaw, 2011). The upper part of the alluvium in Nonconnah and Cane creek valleys has similar characteristics, but its thickness is not known. The loess and upper alluvium have similar hydraulic properties and behave as a leaky confining unit, limiting direct infiltration into the underlying sediments. The fluvial-terrace deposits underlie the loess on the uplands and are on average 83 ft thick in the Allen wellfield area (Bradshaw, 2011). The fluvial-terrace deposits and the lower part of the alluvium along Nonconnah and Cane creeks form the shallow aquifer (Graham and Parks, 1986). The Upper Claiborne Group includes the Cockfield and Cook Mountain formations that underlie the shallow aquifer and form the upper confining unit, termed the UCCU (Upper Claiborne Confining Unit), to the Memphis aquifer. The UCCU is on average 143 ft thick in the Allen wellfield area but is known to be absent to the east of the wellfield beneath the Memphis Depot (Bradshaw, 2011). The Memphis aquifer is a sand-dominated aquifer and averages 806 ft thick in the Allen wellfield area. The Flour Island Formation forms the lower confining layer for the Memphis aquifer and upper confining unit for the Fort Pillow aquifer, another water resource for the region. All groundwater production in the Allen Wellfield area is from the Memphis aquifer.

Groundwater flow in the Memphis aquifer in the Allen wellfield area is known to be directed inward toward the composite cone of depression beneath the wellfield, with the most prominent gradients along the southeastern, southern and western margins of the cone of depression (Criner and Parks, 1976; Parks and Carmichael, 1990; Kingsbury, 1992, 1996, and 2018). Groundwater flow in the shallow aquifer moves from north to south toward Nonconnah Creek and northwest to southeast toward the anomalous cone of depression beneath the former Memphis Depot (Narsimha, 2007; Brashaw, 2011; Ogletree, 2017). The anomalous depression in the water table (shallow aquifer) beneath the former Memphis Depot is coincident with local absence of UCCU clay, indicating the presence of a breach in the confining unit in this area (Bradshaw, 2011). A breach in the confining unit is also known to exist west of the Allen wellfield area along the eastern margin of the Mississippi River alluvial valley (Carmichael et al., 2018).
Chemical data obtained during our investigations of modern (young) water in production wells indicate that water quality from several production wells in the Allen wellfield is affected by leakage processes. Studies in the Davis, Sheahan, and Allen wellfields (Parks et al., 1995; Larsen et al., 2003; Ivey et al., 2008; Koban et al., 2011; Larsen et al., 2013; Larsen et al., 2016) indicate that water quality in the Memphis aquifer is commonly related closely to the presence of modern water. Bradshaw (2011) showed consistent mixing relationships between the deep Memphis aquifer water and water from the Mississippi River in the Allen wellfield, especially for production wells along the north and northeast margins of the Pine Hill Golf Course (MLGW 107, MLGW 108, MLGW 109A, MLGW 111A, and MLGW 123A). These wells show significant tritium activity (Table 1-1) and higher chloride, sulfate, and sodium than wells lacking a modern water component. Tritium was introduced to the atmosphere in large quantities during above-ground nuclear-bomb testing in the 1950s and 1960s and its presence in groundwater indicates a portion of the water was recharged to an aquifer since that time. Another well, MLGW 114, shows high tritium activity, higher sodium and chloride concentrations, and lower redox potential than wells near Pine Hill Golf Course, and water is chemically similar to waters in the shallow aquifer beneath the Memphis Depot (Bradshaw, 2011).

Between 1986 and 1992, production and monitoring wells in the Allen wellfield were sampled and analyzed for common synthetic and volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene, and xylenes (BTEX). Four production wells (MLGW 111A, MLGW 126, MLGW 127, and MLGW 128) consistently showed low-level detections of benzene and/or several organochlorine compounds (1,1-dichloroethane, 1,2-dichloroethane, 1,1-dichloroethylene, cis-1,2-dichloroethylene, 1,2-dichloropropane, tetrachloroethene (PCE), trichloroethene (TCE), and vinyl chloride (VC)). Aside from the average benzene level of 12.68 µg/l in a sample from MLGW 127 during 1988 and the average TCE level of 9.37 µg/l in MLGW 126 during 1996, the detected levels were below U.S. Environmental Protection Agency (USEPA) maximum contaminant levels (MCLs) for drinking water (Table 1-2). However, the persistence of these compounds suggests that a chronic source was impacting water pumped from these wells. Shallow aquifer monitoring wells show contamination mainly from organochlorine compounds, with highest levels observed in wells 1T1 and 1T4 in the northwestern part of the wellfield at the Allen Pumping Station. The highest organochlorine concentrations are observed for PCE, TCE, chloroform, and carbon tetrachloride. Each of these compounds has common uses as dry cleaning and/or industrial solvents. A common biotic and abiotic degradate of both PCE and TCE in groundwater is 1,2-dichloroethene, which is observed in significant quantities in monitoring wells 1T1 and 1T4 as well as production wells MLGW 111A, MLGW 126, MLGW 127, and MLGW 128. In fact, many of the organochlorine compounds listed above for the production wells are abiotic or microbial degradates of PCE, TCE, and carbon tetrachloride. Other VOCs detected in production and monitoring wells, such as benzene, toluene, and naphthalene, are likely dissolved from petroleum products.

Table 1-2. Average concentrations of benzene, PCE, and TCE in four MLGW wells between 1988 and 1996. Concentrations are in parts per billion (ppb) (ND = non-detect; NSA= not analyzed). The red cells indicated concentrations above the USEPA MCL (5 µg/l or 5 ppb).

<table>
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<tr>
<td>Benzene</td>
<td></td>
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<td>1988</td>
<td>NA</td>
<td>0.71</td>
<td>12.68</td>
<td>ND</td>
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<tr>
<td>1989</td>
<td>ND</td>
<td>0.15</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>1990</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>0.5</td>
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1.3 Surface Water Hydrology and Water Quality

Three surface water systems of interest for the Allen wellfield area are the Mississippi River, Nonconnah Creek, and Cane Creek (Figure 1-1). The Mississippi River is gaged by the U.S. Army Corps of Engineers (USACE) for both stage and discharge. Rise and fall of the river are mirrored in the water height of the inland waterway of President’s Island, McKellar Lake. This in turn is connected to Nonconnah Creek, which back floods during high-water events on the Mississippi River. There is a single stream gage on Nonconnah Creek, operated by the USGS since 1969, located at the Winchester Road crossing approximately 15 miles upstream of the Allen wellfield.

Comparison of stages from the USACE Mississippi River gage at Memphis and the USGS gage on Nonconnah Creek indicates that back flooding of the Mississippi River up Nonconnah Creek does not extend to Winchester Road; therefore, Nonconnah Creek gage information is not representative of local conditions near Allen. Based on abnormally low flow conditions in fall months and documented discharge losses (Nyman, 1965; Larsen et al., 2013), Nonconnah Creek is known to be a losing stream along several reaches within the Memphis area.

No gages are located along Cane Creek; however, spot discharge measurements along Cane Creek during summer 2006, fall 2008, and fall 2010 indicate baseflow discharge ranges from 1 to 10 feet$^3$/sec at Mallory Road. Base flow in Cane Creek of approximately 1 to 3 feet$^3$/sec is maintained by cooling water discharge from the ConAgra facility along Bellevue Street north of McLemore Street. Hydrogeologic studies of the ARR site south of Pine Hill Golf Course along Cane Creek indicate that Cane Creek is a losing stream (Mintech, Inc., 1995). Spot discharge measurements along Cane Creek by Larsen et al. (2009) confirm discharge loss of one-third total flow between Pine Hill Golf Course and the confluence with Nonconnah Creek.

Chemistry of Mississippi River water is distinctly higher in total dissolved solids, most cations and anions, and nutrients (phosphate and nitrate) than Nonconnah Creek water (Bradshaw, 2011). Given that base flow in Cane Creek was dominated by discharge from the ConAgra facility, which obtained water from the Memphis aquifer, the water chemistry of Cane Creek was generally similar to that of production well waters from Allen wellfield (Larsen et al., 2009).
1.4 Conceptual Model for Water Quality Problems at the Allen Wellfield

Based on available information, the conceptual model for the origin of organic contaminants in production wells in Allen wellfield requires vertical downward leakage of contaminated water from a facility, such as the ARR site, near Cane Creek, which is locally a losing stream. Contaminated water likely migrates from the shallow aquifer to the Memphis aquifer through a hydraulic connection along an ancient paleovalley where the UCCU is thin or sandy and thus more hydraulically conductive. The suite of chlorinated organic compounds observed in production wells is consistent with the types of organic compounds and associated degradation products observed at the ARR facility, but also consistent with those commonly observed at dry cleaning facilities and contamination that exists at the Memphis Depot. Thus, several candidates for contaminant sources exist. However, the ARR facility displays contamination most consistent with that observed during the 1980s and 1990s in Allen wellfield production wells proximal to Pine Hills Golf Course.

1.5 Project Synopsis

The Allen Wellfield Evaluation proceeded in four phases, each with substantial overlap.

Phase I utilized Federal, State, and EnSafe Earth (Section 2.1) database listings to obtain information on past and present applicable contamination data, geologic setting information, and groundwater measurements in the Allen Wellfield area. These data and the GIS-based resource developed were used to map out the properties. The known and potential contamination sites were ranked according to low, moderate, or high potential for groundwater impact. These results were used qualitatively to interpret the results from water quality and tracer sampling and quantitatively to model the movement of contaminants in the groundwater system.

Phase II utilized groundwater sampling and water quality analysis, tracer analysis, and new well construction to establish the current state of water quality in the shallow and Memphis aquifers and surrounding surface water as well as evaluate active pathways of modern (<60 years old) water recharge to the Memphis aquifer. Two new wells (MSA-1 and SAA-1) were constructed along Nonconnah Creek to evaluate the existence of a previously hypothesized breach near the ARR facility and better understand the hydrogeologic units present in the subsurface. Comprehensive sampling of Memphis and shallow aquifer wells along with four surface water sites during August 2017 was used to determine the extent and location of wells with evidence of organochlorine and petroleum contamination. Quarterly sampling following August 2017 evaluated the persistence of organochlorine and petroleum contamination at wells and surface water sites identified with contaminants during August 2017. Tracer data ($^3$H, $^3$He, and SF$_6$) and water quality data were modeled to identify Memphis aquifer production wells that show active recharge of modern water. The water quality and tracer data collected during the current project were compared with historic water quality and tracer data to conceptually evaluate the most likely pathways of modern water and contaminant migration into the Memphis aquifer in the Allen Wellfield area.

Phase III utilized existing subsurface geologic information and water level data to numerically model groundwater flow in 3-D using the USGS MODFLOW computer code (McDonald and Harbaugh, 1983). Once the groundwater-flow model was developed and calibrated to measured water level data, the groundwater recharge pathways along with aquifer and confining unit properties could be estimated. Contaminant transport in the subsurface utilized USGS computer codes MT3DMS and RT3D. Contaminant
transport coupled the 3-D groundwater flow model with numerical models representing physical and chemical process affecting contaminant migration. Modeling of contaminant transport used known contaminant sites identified in Phase I, which had some information on the quantity and persistence of contamination at the sites, to evaluate contaminant plume migration, dispersion, and retardation from 1980 to 2055.

Phase IV used the information gathered in Phases I through III and best practices in remediation of VOC-impacted groundwater to develop six interim response actions to address the current level of contamination in Memphis aquifer production well water. The interim response actions focus on Memphis aquifer production well MLGW 111A, because that is the only sampled production well that currently has VOC-impacted groundwater. However, similar measures could be adapted to other wells should conditions change within the future. Final recommendations are provided based on a critical comparison of the options and considering long-term protection of the Memphis aquifer, desired finished water quality, and engineering feasibility.
2.0 Phase I – Historical and Regulatory Research

As outlined in the February 8, 2016 project scope of services, the Phase I: Historical and Regulatory Research was conducted on behalf of CAESER to collect historical and regulatory information for sites that may affect the Allen wellfield and rank sites based on potential groundwater impacts.

The overall Area of Interest (AOI) defined for the Allen Wellfield Evaluation is a five-mile radius centered from the Allen Water Pumping Station located at 709 East Dison Avenue in Memphis, Tennessee. Modification to the AOI was made based upon scientific evidence of groundwater divides, presence of potential aquitard breaches, surface water contributions, particle tracking from the Allen wellfield wellhead protection model, and the presence of contamination sources. The modified study area is shown in Figure 2-1 below.

The investigation of contamination sources to the Allen wellfield followed a tiered approach given the nature of VOCs in an aqueous solution. The tiered approach was based on the Allen wellfield 50-year time-of-travel (TOT) particle tracking paths using the U.S. Environmental Protection Agency’s (USEPA) Wellhead Analytic Element Model (WhAEM). Presently, Allen wellfield is modeled at a 40-year TOT for its wellhead protection. A 50-year TOT was used instead of the 40-year TOT to anticipate the effects of dispersion on extension of contamination beyond advective transport. Dispersion will cause contamination from more distant locations to reach the wellfield more rapidly than through what advection alone (or particle tracking) would suggest.

The 50-year TOT area was used as the basis for the study area boundaries and divided into Zone I and Zone II. Zone I was the primary focus of the Phase I efforts. Zone I includes all areas within the 50-year...
TOT model based on the wellhead protection area used for the 2015 Allen Wellhead Protection Plan including active and inactive production wells, plus a 0.5-mile buffer around known and suspected breaches in the upper Claiborne confining unit. Zone II was the secondary area of focus if deemed necessary through internal and regulatory research and includes the remaining region of the modified study area.

The approach applied to the study was as follows:

A. Exclusion of sites from further consideration based on low/no risk or use (residential, church, school).

B. Identification and ranking of known contamination sources/sites.

C. Identification and ranking of potential contamination sources/sites.

2.1 Methodology

Using ArcGIS Web Appbuilder, EnSafe developed an interactive, editable online map application, titled Allen Wellfield Potential Contaminant Sources (PCS) Webportal (online map), to present the collective findings of the study. The Allen Wellfield PCS Webportal includes the Shelby County Assessor of Property parcel address, parcel ID number, and boundaries for each parcel within Zone I. Zone I parcels were categorized based the potential presence of impacted groundwater. Criteria for determining potential impact to groundwater included current and historical use(s), suspected or confirmed operations involving contaminants of concern (COCs), years of operation, length of operation, and reported releases. The following categories were used to rank each parcel’s potential as a source of groundwater impact:

- **No potential** — sites not expected to have any potential impact. These sites are shaded blue on the online map.

- **Low Potential** — sources/sites with low potential for groundwater impact. These sites are shaded green on the online map.

- **Moderate Potential** — sources/sites with moderate potential for groundwater impact. These sites are shaded yellow on the online map.

- **High Potential** — sources/sites with high potential for groundwater impact. These sites are shaded red on the online map.

Additionally, regulatory and historical information were used to determine the presence of known or suspected sources of COCs. Known sources are those sites with documented releases to groundwater; suspected sources are those deemed to have potential to be a source. The following symbols were used to denote the source category:

- A red star indicates a known source with relevant COC contamination.
- A red circle indicates a suspected source of a relevant COC.
Figures 2-2, 2-3, and 2-4 depict the Allen Wellfield PCS Webportal. Figure 2-2 shows the various COC symbols on the Allen Wellfield PCS Webportal (described in section 2.2). In the event COCs not directly related to this study are identified, they can be indicated by a yellow star (known source) or yellow circle (suspected source). Figure 2-3 shows a close-up view of an area with ranked sites and COC indicators. An example view of a parcel notes section is depicted in Figure 2-4.

Information obtained and factors considered to rank contamination potential and source category are discussed further below.

![Allen Wellfield PCS Webportal Online Map showing Zone 1 of the study AOI. COC indicators (from known and suspected sources) are depicted.](image-url)
Figure 2-3: A view of the Allen Wellfield PCS Webportal Online Map showing an area of sites ranked with their potential to impact groundwater and COC indicators.

Figure 2-4: An example of a parcel notes for a parcel, which shows the parcel ID number, the site tanking, notes related to historical uses/investigations at the site, and the address. Supporting documents may also be attached to the parcel notes.

EnSafe obtained environmental database information consisting of sites/addresses with federal and state environmental registrations and listings, including but not limited to registered hazardous waste generators, underground storage tank facilities, remediation sites, and reported spills. Historical city
directory listings were obtained for Zone I addresses from a third-party provider to provide historical occupant and use information. Aerial photographs were reviewed online through NETRONline and through Shelby County Archives to evaluate visual evidence of operations of potential concern. Additionally, fire insurance maps were reviewed for historical site use and development features, including the presence of chemicals and tanks. Historical resources were reviewed to the earliest year reasonably ascertainable for the study area.

EnSafe created and maintains an internal interactive tool, EnSafe Earth, for accessing environmental and land-use records for properties in Shelby County. In addition to the environmental database searches, EnSafe Earth was used to identify sites with regulatory records or potential historical uses of concern. EnSafe submitted open records requests to Tennessee Department of Environment and Conservation (TDEC) and USEPA for environmental records associated with sites with environmental registrations and listings. EnSafe interviewed personnel with TDEC departments Division of Remediation, Division of Underground Storage Tanks, Division of Solid Waste Management, and Division of Water Resources regarding sites identified from sources listed above, as well as to inquire whether TDEC was aware of additional sites that may be considered potential sources of contamination. TDEC file information was reviewed and interviews were conducted to identify documented or potential groundwater contamination at sites within Zone I.

Initially, EnSafe used historical aerial photographs to identify sites with “No potential” by identifying areas that have always been agricultural, a church, a school, and/or residential, and with no evidence of commercial or industrial uses. City directory listings were used to confirm historical uses of areas in which aerial photographs were unclear or coverage was limited. These sites were ranked as “No potential” for groundwater impact and noted as such in the map notes. Some residential or commercial properties were listed in city directories with operations of concern, such as dry cleaning or automotive operations. Further research was conducted for these sites. If operations appeared to have been small-scale, laundry only (i.e., no dry cleaning), or administrative only, the parcel was ranked as “low potential.” A comment was placed in the notes section for the parcel indicating the justification for the low priority assignment for the site.

The next stage of the Zone I evaluation process included ranking non-residential, non-school, and non-church properties as having a low, moderate, or high potential for groundwater impact. First, regulatory information was reviewed for sites listed on TDEC and USEPA databases to determine if a documented release to groundwater existed, not enough information existed, or there was not a potential for impact. Sites with subsurface investigation records indicating the potential for groundwater contamination was unlikely were classified as “low potential.” Sites without adequate investigative information or that lacked information were classified as “moderate potential” or “high potential,” depending on the type of site, historical operations, and length/years of operations. Sites with documented evidence of impact to groundwater were ranked as “high potential.” A brief summary of relevant historical and regulatory information justifying the classification was included in the notes section for each respective parcel. Additionally, select relevant regulatory information including groundwater analysis data, potentiometric maps, or remediation information was attached to the parcel notes as a PDF.

Next, EnSafe reviewed fire insurance maps and city directory reports to determine sites not listed on environmental databases with past operations with the potential to have impacted groundwater. EnSafe
looked for indications of former or current dry cleaning, industrial, or automotive operations. These sites were typically ranked as “moderate potential,” although sites with apparent large-scale or long-term operations were ranked as “high potential.” Notes summarizing historical uses and other information used to determine the potential for impact to groundwater from the site were included in the parcel's notes section.

Identifying COCs at sites was conducted concurrently with the site ranking. As EnSafe reviewed regulatory information and conducted reviews, sites with known or suspected COCs were denoted on the map. The “known source, relevant COC” indicators were used to identify sites with documented groundwater contamination of relevant COCs. Sites with limited or no regulatory or investigative data determined to have the potential to have impacted groundwater were denoted with “suspected source, relevant COCs.” As in the site ranking, a summary of COCs was included in the notes section for each COC indicator.

A quality review of the data included exporting all parcel records in the database for review.

2.2 Using the Allen Wellfield PCS Webportal
The Allen Wellfield PCS Webportal is accessed with any smart device that has web access and a browser (including mobile). Valid login information must be used to access the map. The map shows the Zone I and II AOI boundaries. Searches may be conducted using an address, location name, latitude/longitude, or street intersection. Once the map is zoomed to a specific area within the Zone I AOI (to at least a 1:600 scale), the parcel ranking color codes will appear. The COC indicators will also be shown. Detailed information, including the Shelby County Assessor of Property parcel ID number, potential for groundwater impact ranking, zoning, acreage, historical or regulatory notes, and attachments, can be viewed in a pop-up after clicking on a parcel.

The map layers can be filtered by potential ranking, COC indicator, or any other ad-hoc query the user creates. Filtered information can also be exported into an Excel spreadsheet. The base map can be set to a street map, aerial imagery, or a topographic map. Layers can be toggled on or off through the Layer List widget. The user’s location can be displayed on the map and information can be edited in the same manner it can be edited from an office personal computer.

2.3 Maintaining the Allen Wellfield PCS Webportal
The Allen Wellfield PCS Webportal was created using the ArcGIS Web Appbuilder and initially deployed on EnSafe’s internal web server. The data are tied to a SQL-based ArcSDE (Spatial Database Engine) database and can be accessed and edited in multiple ways.

The database has been provided to MLGW in ESRI geodatabase format and can be published in a web interface or used in any GIS software. Once published and live, the map can be queried and can also be directly edited through the online map pop-ups. In addition, each layer is exportable to a geodatabase that can be shared with stakeholders or published to another online map. The Allen Wellfield PCS Webportal will not be maintained by EnSafe after the Allen Wellfield Evaluation project is completed.
3.0 Phase II – Groundwater and Surface Water Sampling

Previous water quality investigations in the Allen wellfield have been isolated efforts and, as a result, have not provided a complete understanding of overall impacts to the wellfield area. Therefore, a comprehensive groundwater sampling event during the expected seasonal low-water levels (early fall) was undertaken. Before sampling, water levels were measured from all the designated wells in the AOI within a 48-hour window. From these, potentiometric maps of the shallow and Memphis aquifers were constructed. The maps include water levels from Nonconnah and Cane Creeks along previously designated benchmarks to establish relationships between stream stage, discharge, and groundwater interconnection. Figure 3-1 shows production and monitoring well locations as well as stream sample locations. Not all locations were sampled due to limited access or production wells being out of service.

3.1 New Well Construction

To better understand the effects of breaches in the confining unit and their effect on contaminant transport, two wells (SAA-1 and MSA-1) were completed in the floodplain of Nonconnah Creek from July 19 to 25, 2017 by Cascade Drilling, Inc. (Figure 3-2). The purpose of these wells was to pass through a suspected breach in that area, which would provide verification of a breach proximal to Nonconnah Creek. Due to difficulty obtaining land access at the originally intended well location, the drilling site had to be moved further west and south to a transmission line easement (Figure 3-2). The rotasonic method was used to drill both boreholes. The shallow borehole (SAA-1) was drilled to 35 ft bgs and the well screened from 23 to 33 ft bgs in the shallow alluvial aquifer with a 2 ft sump in the UCCU. The deep borehole (MSA-1) was drilled to 351 ft and screened from 225 to 235 ft bgs in a very coarse-grained sand interval in the upper Memphis Sand. The MSA-1 borehole was back-filled with bentonite chips from 351 to 240 ft bgs, followed by medium- to coarse-grained filter sand from 240 to 235 ft bgs.

Well development of SAA-1 and MSA-1 occurred on July 25 to 26, 2017. Monitoring well SAA-1 was developed by surging the well screen, bailing, and pumping with a submersible pump. Monitoring well MSA-1 was developed by airlifting the water using nitrogen gas. Both wells were developed until clear water was obtained and fluoride concentrations were less than 0.7 mg/L (MLGW water supply) to ensure that drilling water was absent. The wells were assigned United States Geological Survey (USGS) database numbers: Sh:J-239 (MSA-1) and Sh:J-242 (SAA-1). A complete core was obtained from borehole MSA-1, but only a sample of the sediment in the screened interval was retained from borehole SAA-1. Geophysical logs (natural gamma, caliper, casing-collar (CCL), neutron-porosity, and temperature) were obtained in borehole MSA-1 by the USGS on July 21, 2017, in the drilling pipe to a depth of 256 ft. A generalized geologic log of the MSA-1 borehole and geophysical logs are provided in Figure 3-3.

To obtain estimates of porosity of the Memphis aquifer in the Allen wellfield, the USGS also completed geophysical logging (natural gamma, caliper, CCL, neutron-porosity, and temperature) on two existing production wells (109A and 138A) and a USGS monitoring well (Sh:J-126). The obtained geophysical logs are presented in Figure 3-4.
Figure 3-1: Location map for the Allen wellfield 2017-2018 quarterly sampling events.
Figure 3-2: Location map for monitoring wells MSA-1 and SAA-1. The Allen wellfield pumping station is located approximately 2 miles north-northeast of the monitoring wells.
Figure 3-3: Geophysical and geological log for borehole MSA-1. Geophysical logs are from left to right: natural gamma (black dash), caliper (green dash), neutron porosity (red dash), and temperature (orange). Hydrostratigraphic units are designated with stratigraphic units in parentheses based on grain size and sedimentary features. UCCU: Upper Claiborne confining unit. Grain size abbreviations (vf, very fine; f, fine; m, medium; c, coarse; vc, very coarse). Colors are based on field assessment using Munsell Soil Color Book.
Figure 3-4: Geophysical logs for boreholes MLGW 109A, Sh:J-126, and MLGW 138A. Geophysical logs are from left to right: natural gamma (black dash), caliper (green dash), neutron porosity (red dash), and temperature (orange). Hydrostratigraphic units are designated with stratigraphic units in parentheses based on geophysical log response. UCCU: Upper Claiborne confining unit.
The new boreholes (MSA-1 and SAA-1) did not pass through a suspected breach in the area, possibly due to relocation of the well; however, these two wells did provide lithologic control for the area to the southwest of the Allen wellfield. Borehole MSA-1 shows 37 feet of alluvium comprising mainly gravel-bearing silt and sand and sandy gravel. The alluvium overlies 44 feet of fine sand to silty clay with dispersed coal lenses of the Eocene Cockfield Formation. The Eocene Cockfield Formation grades downward into silty and sandy clay of the Eocene Cook Mountain Formation at about 80 feet bgs. The Cook Mountain Formation is 94 feet thick and composed mainly of laminated to massive clay with interbedded silt and very fine sand. The contact of the Cook Mountain Formation with the Eocene Memphis Sand is sharp and at 175 feet bgs. The upper 31 feet of the Memphis Sand includes fine-grained quartz sand, fine-grained sand with cobbles and pebbles of laminated to massive clay and laminated silty clay. At 206 feet bgs, drilling returns diminished and were mainly fine- to coarse-grained sand to a depth of about 233 feet bgs. From 233 to 276 feet bgs, the Memphis Sand is interbedded fine-grained sand, clayey sand, and sandy to silty clay. The predominance of sand in the interval from 175 to 276 feet bgs surface indicates this interval corresponds well to the upper Memphis Sand, described in Waldron et al. (2011). A prominent coal-rich silty and sandy clay is observed from 276 to 284.5 feet bgs. The Memphis Sand from 284.5 to the base of the borehole at 351 feet bgs is mainly laminated silty and sandy clay with laminated very fine-grained sand intervals from 300 to 318 and 330 to 334 feet bgs. The clay-dominated interval from 284.5 to 351 feet bgs correlates well with a regional fine-grained interval, termed the Zilpha Shale in Mississippi, that is as much as 100 feet thick in boreholes (Waldron et al., 2011).

Features in the geophysical log from borehole MSA-1 correlate well to geophysical logs from the Allen wellfield and demonstrate similar stratigraphy as well as prominent inflection in downhole temperatures attributed to active incursion of warm water (Figure 3-3). The alluvium, Cockfield Formation, Cook Mountain Formation and Memphis Sand are readily distinguished on the geophysical logs by characteristic changes in the natural gamma log. Within the Allen wellfield, the fluvial-terrace deposits, Cook Mountain Formation, and Memphis Sand are also well defined. In addition, the natural gamma log signal (and corresponding single-point resistance logs in older well logs) show a fine-grained sand in the uppermost Memphis Sand grading downward to coarse-grained sand that is underlain by 10 to 110 feet of fine-grained sandy silt and clay (Zilpha Shale). Geophysical logs from MSA-1, inactive MLGW wells 109A and 138A, and monitoring well J-126 all show increased porosity in the Memphis Sand interval along with positive deflections in the borehole temperature with depth. Positive deflections in borehole temperature were used by Graham and Parks (1986) to argue for recharge of warm surface waters relative to those naturally present within the Memphis Sand.

3.1.1 Groundwater Level Monitoring

Groundwater levels in the Memphis aquifer, shallow aquifer, and stream stage in Nonconnah Creek and Cane Creek (a tributary) were measured four times: July-August 2017, October-November 2017, February 2018, and May 2018. Water-level measurements preceded each of the four groundwater sampling events. Water levels were measured using an e-tape (electronic tape) or steel tape in observation (monitoring) wells, pressurization of the airline in production wells, or e-tape from bridge survey markers along Nonconnah and Cane creeks.
3.1.2 Groundwater and Surface Water Sampling Method

Groundwater and surface water sampling techniques followed USEPA industry standard protocols. Chemical analyses were completed by Waypoint Analytical Labs, Inc., which is a State of Tennessee licensed, independent, USEPA-certified lab. Field methods for age-dating tracer sampling follow procedures established by CAESER staff (Larsen et al., 2003; Koban et al., 2011; Larsen et al., 2013; Larsen et al., 2016). Water quality parameters were collected during purging activities using a calibrated SmarTROLL MP, which measured dissolved oxygen, temperature, specific conductance, pH and oxidation_reduction potential, and HACH turbidity meter. Given the high volume of purging necessary for the Memphis aquifer monitoring wells, a one- to three-well volume purge was completed before groundwater sampling. Water samples obtained from shallow monitoring wells were obtained by inserting an air-bladder pump into the middle-screened section of the well. Low-flow pumping rates were used to minimize depression in the potentiometric surface. Sampling commenced after water quality parameters (temperature, specific conductance, dissolved oxygen, and pH) showed negligible change or three well volumes were purged from shallow monitoring wells. In most cases, sampling did not commence until the turbidity of pumped water was generally less than 10 NTU. Production wells were sampled from a spigot located on the top of the well. Sampling generally commenced after the production well had been pumping for 12 or more hours. Given that the pump discharge is at least 4 cubic meters per minute (m³/min) and the well volume is generally less than 11 m³, approximately 1900 well volumes are purged during the 12-hour pumping period prior to sampling. Field measurements made after sampling commenced include alkalinity, dissolved sulfide, and total and dissolved iron. All groundwater samples were analyzed for VOCs (Method 8260), metals (EPA Method 200.8), major ions (Method 300.0), and ammonia (as N) (Method 4500).

Dissolved gas sampling required restricting the flow from the pumping production well to the treatment plant to maintain a back-pressure of 40 to 45 pounds per square inch (psig) thereby, limiting any degassing during pumping. VOCs were also sampled when back-pressure was applied for age-dating samples. Backpressure was not used during February and May 2018 sampling events. A comparison of results for on and off backpressure was conducted on 111A in November 2017. VOC concentrations were similar for ambient and backpressure conditions. Noble gases were sampled in a flow-through cell in duplicate with a diffusion sampler (copper tube with a semi-permeable membrane attached to one end) using methods prescribed by the University of Utah Dissolved Gas Laboratory. For production wells, the diffusion sampler was equilibrated with the flow of production well water for approximately 24 hours. For monitoring wells, the diffusion sampler was suspended in the screened interval of the well for 7 days to ensure equilibration. Upon retrieval, the copper tube portion of the sampler was sealed with a cold weld crimper, the tips of the tubes were sealed with electrical tape, and all pieces of the diffusion sampler were stored for later laboratory analysis. The total gas pressure in the water was measured using a calibrated total dissolved gas probe and meter. All age-dating samples were shipped to the University of Utah Dissolved Gas Laboratory for analysis.

3.2 First Quarterly Event – August 2017

Sampling was conducted during the period of August 8 to 23, 2017. Water level measurements were collected on July 31 to August 1, 2017.
3.2.1 Groundwater Flow Direction
Groundwater elevations in the shallow aquifer range from about 250 feet above mean sea level (famsl) at monitoring well 1T14 in the northern part of the Allen wellfield to about 200 famsl at monitoring well 1T5, east of the Allen wellfield, and 193 famsl at the Florida Street bridge over Nonconnah Creek to the southwest of the Allen wellfield (Figure 3-5). Groundwater in the shallow aquifer flows from the northern part of the Allen wellfield to the southeast, toward the known breach location near the former Memphis Depot, and to the south, toward Nonconnah Creek. The cone of depression in the Memphis aquifer is in the northeastern part of the Allen wellfield, centered at Memphis aquifer production well MLGW 110B (Figure 3-6) at 25 famsl. The hydraulic gradient toward the cone of depression is steepest along the western margin of the wellfield, with shallower gradients along the northern, eastern and southeastern margins of the cone of depression.

3.2.2 Analytical Results
The August 2017 water sampling event was the most comprehensive of all sampling events. The overall water type in the Memphis aquifer at the Allen wellfield ranges from mixed cation-bicarbonate to mixed cation-bicarbonate and sulfate (Figure 3-7). The water type for shallow alluvial and fluvial-terrace deposit aquifers is approximately the same. Surface water type ranges from mixed cation-bicarbonate for Nonconnah and Cane Creeks to mixed cation-bicarbonate and mixed cation-sulfate for the Mississippi River.

No USEPA primary drinking water maximum contaminant levels (MCLs) were exceeded in any samples obtained in August 2017 (Table 3-1). USEPA secondary drinking water MCLs were exceeded for aluminum, iron, and manganese. Aluminum concentrations exceeded the USEPA secondary MCL (50 µg/l) in shallow aquifer monitoring well 1T9 (69 µg/l), Memphis aquifer monitoring well MSA-1 (234 µg/l), and surface water locations SW-01 (173 µg/l), SW-02 (591 µg/l), SW-03 (51 µg/l), and SW-04 (248 µg/l). Iron concentrations exceeded the USEPA secondary MCL (300 µg/l) in shallow aquifer monitoring wells 1T2 (6100 µg/l), 1T5 (537 µg/l), 1T9 (507 µg/l), 1T13 (7320 µg/l), Memphis aquifer monitoring wells MSA-1 (9210 µg/l) and Sh:J-126 (12000 µg/l), all Memphis aquifer production wells sampled from 373 µg/l in MLGW 111A to 1100 µg/l in MLGW 111A, and surface water locations SW-02 (823 µg/l) and SW-04 (320 µg/l). Manganese concentrations exceeded the USEPA secondary MCL (50 µg/l) in shallow aquifer wells 1T2 (3170 µg/l), 1T9 (67 µg/l), 1T10 (101 µg/l), and 1T13 (583 µg/l), Memphis aquifer monitoring wells MSA-1 (122 µg/l) and Sh:J-126 (212 µg/l), and surface water locations SW-02 (198 µg/l) and SW-04 (136 µg/l).

Volatile organic compounds were detected in shallow aquifer monitoring wells, Memphis aquifer production well 111A, and surface water location SW-03 (Table 3-2). Estimated concentrations for acetone (2 to 4 µg/l) were observed in Memphis aquifer production well MLGW 110B, and all four surface water locations. Acetone is used in laboratory analysis of the samples and may have contaminated these samples. Methyl tert-butyl ether (MTBE), a common gasoline additive, was observed in shallow aquifer monitoring wells 1T1 (0.5 µg/l), 1T4 (8 µg/l), 1T8 (1 µg/l), and 1T9 (1 µg/l). Tetrachloroethene (PCE), a common organic solvent and dry-cleaning compound, was observed in shallow aquifer monitoring wells 1T1 (1 µg/l), 1T4 (2 µg/l), 1T12 (0.8 µg/l), and 1T14 (3 µg/l). Trichloroethene (TCE), a common organic solvent and degradation product of PCE, was observed in shallow aquifer monitoring well SAA-1 (4 µg/l) and Memphis aquifer production well MLGW 111A (4 µg/l). Two degradation products of TCE,
cis-1,2-dichloroethene and trans-1,2-dichloroethene, were also observed in Memphis aquifer production well MLGW 111A. Surface water sample SW-03 had estimated concentrations for bromodichloromethane (0.6 µg/l), chloroform (0.8 µg/l), and dibromochloromethane (0.8 µg/l). All three of these compounds commonly form during reaction with organic matter as a byproduct of chlorine disinfection processes.

Figure 3-5: Contour map of water table elevation in July/August 2017 in the Allen wellfield area. Contour interval is 5 ft.
Figure 3-6: Contour map of the potentiometric surface elevation in the Memphis aquifer in July/August 2017 near the Allen Wellfield area. Contour interval is 20 ft.
Table 3-1: Exceedances of EPA Secondary Drinking Water MCL, August 2017 sampling event

<table>
<thead>
<tr>
<th>Sample Location:</th>
<th>Sample ID:</th>
<th>Sample Date:</th>
<th>Sample Type:</th>
<th>Matrix:</th>
<th>Analyte</th>
<th>MCL</th>
<th>Units</th>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Aluminum (Dissolved)</td>
<td>50 (a)</td>
<td>mg/L</td>
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<td>172</td>
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<td>Manganese (Dissolved)</td>
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</table>

Notes:
- MCL = U.S. EPA Maximum Contaminant Level
(a) = U.S. EPA Secondary Maximum Contaminant Level
(b) = U.S. EPA drinking water health advisory
mg/L = Micrograms per liter
- = Not detected above the laboratory method quantitation limit
1 = Estimated value
bold = Detected value
highlight = Exceeds MCL, Secondary MCL, or Health Advisory
# Table 3-2: VOC detections, August 2017 sampling event.

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<th>MCL</th>
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<tr>
<td>Acetone</td>
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<td>Bromodichloromethane</td>
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<td>Chloroform</td>
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<tr>
<td>cis-1,2-Dichloroethene</td>
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<tr>
<td>Dibromochloromethane</td>
<td>µg/L</td>
<td></td>
</tr>
<tr>
<td>Methyl tert-butyl ether</td>
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<tr>
<td>Tetrachloroethene</td>
<td>µg/L</td>
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</tr>
<tr>
<td>Trichloroethene</td>
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</table>

**Sample Location:**

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<tbody>
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<td>MWW711</td>
<td>PW111A</td>
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<td>µg/L</td>
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<td>MWW715</td>
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**Sample ID:**

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<td>µg/L</td>
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<td>MWW71-0827</td>
<td>PW111A</td>
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<tr>
<td>MWW71-0817</td>
<td>SW03</td>
<td>µg/L</td>
<td>0.8</td>
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</table>

**Notes:**

- U.S. EPA Maximum Contaminant Level (a)
- U.S. EPA Secondary Maximum Contaminant Level (b)
- U.S. EPA drinking water health advisory
- µg/L = Micrograms per liter
- = Not detected below the laboratory method quantitation limit
- J = Estimated value
- bold = Detected value
Age-dating tracers $^3$H, $^3$He, and SF$_6$ along with noble gas concentrations were measured in samples from Memphis aquifer production wells and monitoring wells. Five samples had concentrations of $^3$H above the background concentration of 0.1 TU: production wells MLGW 103A (0.23 TU), MLGW 111A (0.66 TU), MLGW 114 (0.77 TU), MLGW 115A (0.99 TU), and MLGW 123A (0.38 TU) (Table 3-3). Tritiogenic $^3$He, the daughter product from radioactive decay of $^3$H, was measured in five of the samples that had $^3$H above background concentrations and yielded ages for the modern water component: MLGW 103A (34.0 years), MLGW 111A (37.0 years), MLGW 114 (39.7 years), MLGW 115A (39.1 years), and MLGW 123A (14.0 years). Eight samples had SF$_6$ above background concentration (0.3 pptv) and yielded ages for the modern water component: MLGW 106A (32.0 years), MLGW 110B (36.5 years), MLGW 111A (39.0 years), MLGW 115A (34.5 years), MLGW 117A (24.0 years), MLGW 123A (37.5 years), MSA-1 (42.5 years), and Sh:J-126 (42.0 years).

The age-dating tracers were used with atmospheric loading data and lumped parameter models (LPM) to determine the proportion (as a %) of the produced water that originates from modern water (Table 3-4). Using atmospheric tritium loading and a piston-flow model, the percentages of modern water in samples that yielded $^3$H-$^3$He ages are: MLGW 103A (3% modern), MLGW 111A (12% modern), MLGW 114 (33% modern), and MLGW 115A (52% modern). LPM proportion of modern water using $^3$H and $^3$He data yielded results for the following samples: MLGW 111A (23% modern), MLGW 114 (15 % modern), and MLGW 115A (20% modern). LPM proportions of modern water using SF$_6$ or SF$_6$ and $^3$H data produced percentages of 4% or less, except for MLGW 111A, which had 12% modern.

Geochemical modeling of water chemistry and assumed end-member compositions has been used successfully in several well fields in the Memphis area to determine the proportion of shallow groundwater entering the Memphis aquifer and contributing to produced Memphis aquifer waters (Larsen et al., 2003; Koban et al., 2011; Larsen et al., 2016). End-member groundwater compositions were identified using scatter plots of conservative chemical species (sodium, chloride and sulfate) (Figure 3-8A and 3-8B). Application of this technique using end-member water compositions from Memphis aquifer production well MLGW 105 and shallow aquifer monitoring wells 1T8 and 1T7 were used to calculate proportions of shallow aquifer water in MLGW production wells (Table 3-4). Most production wells in the Allen wellfield produce water with less than 5% shallow aquifer water, except production wells MLGW 111A (20%), MLGW 115A (10%), and MLGW 123A (13%).

### 3.2.3 Analytical Blank, Duplicates, and Electrical Neutrality Results

The analytical quality of the data was superior in most cases. Field blank samples indicated no detections for any project analytes. Duplicate analysis of tritium was within 1% and duplicate analyses of SF$_6$ were within 10%. All duplicate laboratory analyses of major solutes were within 5% and most were within 2%. Electrical neutrality was generally within 10%, except for Memphis aquifer production well MLGW 105, Memphis aquifer monitoring well Sh:J-126, and shallow monitoring wells 1T3, 1T4, 1T11, which were between 10 and 13% of electrical balance.
Figure 3-8A: Scatter plot of chloride and sodium concentrations in surface and groundwater near the Allen wellfield. Numbered data are Memphis aquifer production wells. Monitoring wells screened in the Memphis aquifer include Sh-J-126 and MSA-1. Monitoring wells in the shallow aquifer include 1T1, 1T3, 1T4, 1T5, 1T6, 1T7, 1T8, 1T9, 1T10, 1T11, 1T13, 1T14, Depot 40 and SAA-1. Surface water sampling sites include br_2 (SW-01), br_7 (SW-04), br_cc1 (SW-02), br_cc2 (SW-03). Grab samples from Nonconnah Creek and the Mississippi River are not numbered. Line shows trend of water compositions in mixing relationship (see text).
Figure 3-8B: Scatter plot of chloride and sulfate concentrations in surface and groundwater near the Allen wellfield. Symbol labels are same as Figure 3-8A, except the addition of shallow aquifer monitoring wells from the former Memphis Depot. The lines represent mixing relationships between shallow aquifer water (red line) or Mississippi River water (blue line) and Memphis aquifer water.
Table 3-3: Environmental Tracer results, August and November 2017 sampling event. See text for explanation.

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Date</th>
<th>Ar40 (ccSTP/g)</th>
<th>Kr84 (ccSTP/g)</th>
<th>Xe129 (ccSTP/g)</th>
<th>Ne20 (ccSTP/g)</th>
<th>He4 (ccSTP/g)</th>
<th>R/Ra</th>
<th>TriHe3 using Ne (TU)</th>
<th>Tritium (TU)</th>
<th>Age using EA (yr)</th>
<th>SF6 (pptv)</th>
<th>SF6 age (yr) LPM mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>103</td>
<td>Aug-17</td>
<td>3.6E-04</td>
<td>2.17E-07</td>
<td>7.92E-08</td>
<td>1.11E-08</td>
<td>5.3E-08</td>
<td>1.014</td>
<td>0.40</td>
<td>0.23</td>
<td>34.0</td>
<td>0.29</td>
<td>45</td>
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<tr>
<td>105</td>
<td>Aug-17</td>
<td>3.56E-04</td>
<td>2.32E-07</td>
<td>8.21E-08</td>
<td>1.16E-08</td>
<td>5.5E-08</td>
<td>0.995</td>
<td>-2.03</td>
<td>0.02</td>
<td>&gt;60</td>
<td>0.21</td>
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<td>3.73E-04</td>
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<td>ND</td>
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<td>ND</td>
<td>ND</td>
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<td>ND</td>
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<td>ND</td>
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<td>ND</td>
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ND – not determined.
ccSTP/g – volume at standard pressure and temperature per gram.
pptv – parts per thousand by volume.
Table 3-4: Results from PHREEQCi inverse geochemical modeling and lumped parameter modeling (LPM).

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<th>LPM - SFS</th>
<th>LPM - 3H, SFS</th>
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<td>Precipitating Phases</td>
<td>Dissolving Phases</td>
<td>% Modern</td>
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<td>Hematite, Goethite</td>
<td>Calcite, Halite, Pyrite, Siderite, Barite, CO2, O2</td>
<td>NM</td>
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<tr>
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<td></td>
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<td>Pyrite, Siderite, Barite, CO2, O2</td>
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<tr>
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<td>Siderite, Pyrite</td>
<td>NM</td>
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<td></td>
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<td>Halite, O2</td>
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<td>Barite</td>
<td>O2</td>
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</tr>
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<td>1T8  2</td>
<td>Hematite, Goethite, Calcite</td>
<td>Halite, Siderite, O2</td>
<td>NM</td>
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<tr>
<td></td>
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<td>1T7  2</td>
<td>Hematite, Goethite, Barite, Calcite</td>
<td>Halite, Pyrite, CO2, Siderite, O2</td>
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<td>Hematite, Goethite</td>
<td>O2</td>
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<td>8/8/2017</td>
<td>1T8  1</td>
<td>Calcite, Hematite</td>
<td>-</td>
<td>BD</td>
</tr>
</tbody>
</table>

NP = No phases precipitated or dissolved
NM = No model solutions
BD = One or more tracers were below detection
3.3 Second Quarterly Event – November 2017

Water level measurements were collected on November 9 and 10, 2017. Sampling was conducted on November 13 and 16, 2017. Wells and surface water locations that had detectable VOCs during the August 2017 sampling event were sampled during the second quarterly event. In addition, Memphis aquifer production wells MLGW 111A, MLGW 114, and MLGW 123A were also sampled for $^3$H and SF$_6$ because they have a sampling history of consistently high $^3$H and SF$_6$.

3.3.1 Groundwater Flow Direction

Groundwater elevations in the shallow aquifer during November 2017 range from about 250 ftasl at observation (monitoring) well 1T14 in the northern part of the Allen wellfield to elevations of about 200 ftasl at observation (monitoring) well 1T5, east of the Allen wellfield, and 191 ftasl at the Florida Street bridge over Nonconnah Creek to the southwest of the Allen wellfield, almost identical to the pattern of August 2017 (Figure 3-5). Groundwater in the shallow aquifer flows from the northern part of the Allen wellfield to the southeast, toward the known breach location near the former Memphis Depot, and to the south, toward Nonconnah Creek. Two cones of depression are evident in the Memphis aquifer, one centered at Memphis aquifer production well MLGW 114 at 81 ftasl in the eastern part of the Allen wellfield and another centered at Memphis aquifer production well MLGW 122 at 135 ftasl in the northwest part of the wellfield (Figure 3-9).

3.3.2 Analytical Results

No USEPA primary drinking water MCLs were exceeded in any samples obtained in November 2017 (Table 3-5). USEPA secondary drinking water MCLs were exceeded for aluminum, iron, and manganese. Aluminum concentration exceeded the EPA secondary MCL in shallow aquifer monitoring well 1T12 (96 µg/l). Iron concentrations exceeded the EPA secondary MCL in shallow aquifer monitoring well 1T9 (475 µg/l), and Memphis aquifer production wells MLGW 111A (997 µg/l), MLGW 114 (870 µg/l), and MLGW 123A (674 µg/l). Manganese concentrations exceeded the USEPA secondary MCL in shallow aquifer well 1T9 (53 µg/l) and surface water location SW-01 (125 µg/l).

Volatile organic compounds were detected in shallow aquifer monitoring wells and Memphis aquifer production well MLGW 111A (Table 3-6). MTBE was observed in shallow aquifer monitoring wells 1T11 (8 µg/l), 1T4 (6 µg/l), and 1T8 (3 µg/l). PCE was observed in shallow aquifer monitoring wells 1T1 (1 µg/l), 1T4 (2 µg/l), 1T12 (1 µg/l) and 1T14 (1 µg/l). TCE was observed in shallow aquifer monitoring well SAA-1 (3 µg/l) and Memphis aquifer production well MLGW 111A at a concentration equal to the primary drinking water MCL (5 µg/l). Three degradation products of TCE, 1,1-dichloroethene, cis-1,2-dichloroethene and trans-1,2-dichloroethene, were also observed in Memphis aquifer production well MLGW 111A.

Age-dating tracers $^3$H and SF$_6$ were measured in samples from the three Memphis aquifer production wells sampled in November 2017. Samples from all three wells had concentrations of $^3$H above the background concentrations (0.1 TU): production wells MLGW 111A (0.63 TU), MLGW 114 (0.73 TU), and MLGW 123A (0.42 TU) (Table 3-3). Each of these values is statistically indistinguishable from the respective values measured in the August 2017 sampling event. Samples from all three wells had SF$_6$ above background concentration (0.3 pptv) and yielded ages for the modern water component: MLGW 111A (37.4 years), MLGW 114 (36.4 years), and MLGW 123A (39.4 years) (Table 3-6). The SF$_6$
values from production wells MLGW 111A and MLGW 123A are statistically indistinguishable from those measured in samples from the August 2017 sampling event. However, the SF₆ value measured in production well MLGW 114 is three times higher than that measured in the August 2017 sample (0.93 and 0.26 pptv, respectively), resulting in an age similar to those obtained from samples from the other two production wells sampled during the November 2017 event.

MLGW 111A was sampled for SF₆ under two conditions: 1) using a backpressure of 45 psi, which is CAESER standard practice (Larsen et al., 2016), and 2) using the ambient conditions with a backpressure of 42 psi (according to gauge on sampling spigot). The partial pressure of SF₆ under 45 psi backpressure was 0.93 pptv, whereas the partial pressure under ambient conditions was 0.32 pptv, indicating that the SF₆ content is sensitive to the backpressure applied to the well.

### 3.3.3 Field and Equipment Blank Analytical Results

The analytical quality of the data was superior in most cases. Field blank samples indicate no detections of any project analytes. Equipment blank samples had detections of chloride (<0.2 mg/L) and sulfate (0.1 mg/L), which are considered negligible for the present study. All duplicate laboratory analyses of major solutes were within 5% aside from fluoride, which was within 24%.

![Contour map of the potentiometric surface elevation in the Memphis aquifer in November 2017 near the Allen wellfield area. Contour interval is 20 feet](image-url)
Table 3-5: Exceedances of EPA Secondary Drinking Water MCL, November 2017 sampling event

<table>
<thead>
<tr>
<th>Sample Location:</th>
<th>MW1T12</th>
<th>MW1T12-1117</th>
<th>PW111A</th>
<th>PW111A-1117</th>
<th>PW111A</th>
<th>PW111A-1117</th>
<th>PW114</th>
<th>PW114-1117</th>
<th>PW123A</th>
<th>SW01</th>
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<td>MW1T12-1117</td>
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<td>PW111A-1117</td>
<td>PW111A-1117</td>
<td>PW114-1117</td>
<td>PW123A-1117</td>
<td>PW111A-1117</td>
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<td></td>
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<tr>
<td>Sample Date:</td>
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<td>11/11/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
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<td></td>
</tr>
<tr>
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<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analyte</td>
<td>Aluminum (Observed)</td>
<td>Iron (Dissolved)</td>
<td>Manganese (Observed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Units</td>
<td>pg/L</td>
<td>pg/L</td>
<td>pg/L</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MCL</td>
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<td>0.07</td>
<td>0.01</td>
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<td>(a) = U.S. EPA Secondary Maximum Contaminant Level</td>
<td>(a) = U.S. EPA Secondary Maximum Contaminant Level</td>
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Table 3-6: VOC detections, November 2017 sampling event

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<th>PW111A-1117</th>
<th>PW111A</th>
<th>PW111A-1117</th>
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</thead>
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<td>PW111A-1117</td>
<td>PW111A</td>
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<tr>
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<td>11/14/2017</td>
<td>11/13/2017</td>
<td>11/13/2017</td>
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<td>Groundwater</td>
<td>Groundwater</td>
<td>Groundwater</td>
</tr>
<tr>
<td>Analyte</td>
<td>1,1-Dichloroethene</td>
<td>1,2-Dichloroethene (total)</td>
<td>cis,1,2-Dichloroethene</td>
<td>Methyl tert-butyl ether</td>
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<td>7 pg/L</td>
<td>70 pg/L</td>
<td>70 pg/L</td>
<td>50 pg/L</td>
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<td>pg/L</td>
<td>pg/L</td>
<td>pg/L</td>
</tr>
<tr>
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<td>1.0</td>
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<tr>
<td>Notes:</td>
<td>(a) = U.S. EPA Secondary Maximum Contaminant Level</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Third Quarterly Event – February 2018

Water level measurements were collected on February 8 and 9, 2018. Sampling was conducted on February 12 and 13, 2018. Wells and surface water locations that had detectable VOCs during the November 2017 sampling event were sampled during the February 2018 sampling event.

3.4.1 Groundwater Flow Direction

Groundwater elevations in the shallow aquifer during February 2018 ranged from about 250 famsl at observation (monitoring) well 1T14 in the northern part of the Allen wellfield to elevations of about 199 famsl at observation (monitoring) well 1T5, east of the Allen wellfield, and 191 famsl at the Florida Street bridge over Nonconnah Creek to the southwest of the Allen wellfield, almost identical to
the pattern of August 2017 (Figure 3-5). Groundwater in the shallow aquifer flows from the northern part of the Allen wellfield to the southeast, toward the known breach location near the former Memphis Depot, and to the south, toward Nonconnah Creek. Two cones of depression in the Memphis aquifer are apparent in the central part of the Allen wellfield, one centered at Memphis aquifer production well MLGW 110B at 21 famsl and the other centered at Memphis aquifer production well MLGW 106A at 50 famsl (Figure 3-10). The hydraulic gradient toward the cones of depression is steepest along the western and southern margins of the wellfield, with shallower gradients along the northern and eastern margins of the cone of depression.

3.4.2 Analytical Results
No USEPA primary drinking water MCLs were exceeded in any samples obtained in February 2018 (Table 3-7). USEPA secondary drinking water MCLs were exceeded for aluminum, iron, and manganese (Table 3-7). Aluminum concentration exceeded the USEPA secondary MCL in shallow aquifer monitoring well 1T12 (75 µg/l). Iron concentrations exceeded the USEPA secondary MCL in Memphis aquifer production well MLGW 111A (944 µg/l). Manganese concentrations exceeded the USEPA secondary MCL at surface water location SG (SW)-01 (66 µg/l).

Volatile organic compounds were detected in shallow aquifer monitoring wells and Memphis aquifer production well MLGW 111A (Table 3-7). MTBE was observed in shallow aquifer monitoring wells 1T1 (0.4 µg/l), 1T4 (6 µg/l), 1T8 (1 µg/l), and 1T11 (5 µg/l). PCE was observed in shallow aquifer monitoring wells 1T1 (1 µg/l), 1T4 (1 µg/l), and 1T14 (1 µg/l). TCE was observed in shallow aquifer monitoring well SAA-1 (2 µg/l) and in Memphis aquifer production well MLGW 111A (3 µg/l). Two degradation products of TCE, cis-1,2-dichloroethene and trans-1,2-dichloroethene, were also observed in Memphis aquifer production well MLGW 111A.

3.4.3 Field and Equipment Blank Analytical Results
The analytical quality of the data was superior in most cases. Field blank samples indicate no detections of any project analytes. Equipment blank samples had detections of potassium (<0.02 mg/L), sodium (<0.05 mg/L), chloride (<0.2 mg/L) and ammonia (0.05 mg/L), which are considered negligible for the present study. All duplicate laboratory analyses of major solutes were within 4% aside from total nitrite and nitrate, which was within 13%.
Figure 3-10: Contour map of the potentiometric surface elevation in the Memphis aquifer in February 2018 near the Allen wellfield area. Contour interval is 20 feet.
### 3.5 Fourth Quarterly Event – May 2018

Water level measurements were collected on May 14 and 15, 2018. Sampling was conducted on May 16 and 17, 2018. Wells and surface water locations that had detectable VOCs during the February 2018 sampling event were sampled during the May 2018 sampling event.

#### 3.5.1 Groundwater Flow Direction

Groundwater elevations in the shallow aquifer during May 2018 range from about 252 famsl at observation (monitoring) well 1T14 in the northern part of the Allen wellfield to elevations of about 203 famsl at observation (monitoring) well 1T5, east of the Allen wellfield, and 198 famsl at the Florida Street bridge over Nonconnah Creek to the southwest of the Allen wellfield, almost identical to the pattern of August 2017 (Figure 3-5). Groundwater in the shallow aquifer flows from the northern part of the Allen wellfield to the southeast, toward the known breach location near the former Memphis Depot, and to the south, toward Nonconnah Creek. Two cones of depression in the Memphis aquifer are apparent in the central part of the Allen wellfield, one centered at Memphis aquifer production well MLGW 113A at 33 famsl and the other centered at Memphis aquifer production well MLGW 113A at 33 famsl and the other centered at Memphis aquifer production well...
MLGW 106A at 128 famsl (Figure 3-11). The hydraulic gradient toward the cones of depression are generally symmetrical, but the cone of depression around MLGW 113A is much deeper than that around MLGW 106A.

**3.5.2 Analytical Results**

USEPA primary drinking water MCLs were exceeded in one sample and a duplicate obtained in May 2018 (Table 3-8). TCE concentration exceeded the USEPA MCL (5 µg/l) in Memphis aquifer production well MLGW 111A and the duplicate for this well, both of which were 6 µg/l. USEPA secondary drinking water MCLs were exceeded for aluminum, iron, and manganese. Aluminum’s concentration exceeded the USEPA secondary MCL in surface water at location SG-01 (SW-01; 244 µg/l). Iron concentrations exceeded the USEPA secondary MCL in Memphis aquifer production well MLGW 111A (1090 µg/l) and surface water location SG (SW)-01 (472 µg/l). Manganese concentration exceeded the USEPA secondary MCL at surface water location SG (SW)-01 (168 µg/l).

Volatile organic compounds were detected in shallow aquifer monitoring wells and Memphis aquifer production well MLGW 111A (Table 3-8). MTBE was observed in shallow aquifer monitoring wells 1T1 (0.6 µg/l), 1T4 (6 µg/l), 1T8 (8 µg/l), and 1T11 (1 µg/l). PCE was observed in shallow aquifer monitoring wells 1T1 (2 µg/l) and 1T4 (2 µg/l). TCE was observed in shallow aquifer monitoring well SAA-1 (4 µg/l) and in Memphis aquifer production well MLGW 111A (6 µg/l). Three degradation products of TCE, 1,1-dichloroethene, cis-1,2-dichloroethene and trans-1,2-dichloroethene, were also observed in Memphis aquifer production well MLGW 111A.

**3.5.3 Field and Equipment Blank Analytical Results**

The analytical quality of the data was good in most cases. Field and equipment blank samples indicate no detections of any project analytes. All duplicate laboratory analyses of major solutes were within 11% and most were within 7%.

Figure 3-11: Contour map of the potentiometric surface elevation in the Memphis aquifer in May 2018 near the Allen wellfield area. Contour interval is 20 ft.
3.6 Synthesis and Conceptual Model

The results of the well sampling coupled with previous data substantiate a conceptual model for leakage of modern water into the Memphis aquifer, some of which includes VOC contaminants. Previous studies have demonstrated at least two leakage pathways by which near-surface water, either from the shallow aquifer or infiltrated stream water, can enter the Memphis aquifer. A prominent depression in the water table between the former Memphis Depot, east of the wellfield, and borehole data indicate a pathway of leakage of water from the shallow aquifer to Memphis aquifer exists beneath that former facility (Figures 3-5 and 3-12) (Bradshaw, 2011; Narsimha, 2007). An additional depression in the water table and depression in the upper surface of the UCCU exist in the southern part of the wellfield and along Nonconnah Creek, southeast of the well field (Bradshaw, 2011).

Groundwater sampling from 2017 shows trends in water quality and age-dating tracer concentrations that are similar to those observed from sampling in 2003, 2006, 2007, and 2008. Past groundwater sampling for age-dating tracers documents the presence of ³H activity above background in samples from Memphis aquifer production wells in the west and southeast sides of the wellfield. In 2003, tritium and major solute water quality in 12 Memphis aquifer production wells showed a maximum tritium activity of 3.3 TU (Bradshaw, 2011). The highest tritium values were in the central and western parts of the wellfield and the eastern part of the wellfield (Figures 3-13A and 13B), almost exclusively in production wells screened in the upper part of the Memphis aquifer. Additional Memphis aquifer production well sampling in 2006 to 2008 included noble gases and helium isotopes as well as tritium and major solute water quality (Bradshaw, 2011). Similar to the 2003 sampling, the highest tritium activity was clustered in the central and western parts of the Allen wellfield and eastern part of the wellfield (Figure 3-13B). Tritium-³He dates...
from Memphis aquifer production wells yielded ages ranging from 23 to 43 years since the sampling date. Sampling of Memphis aquifer production wells MLGW 111A and 114 in 2011 yielded dates of 34 to 35 years for $^3$H-$^3$He and 22 to 30 years for SF$_6$.

The comprehensive age-dating tracer sampling in 2017 shows that $^3$H and $^3$He are most prominent in the eastern part of the wellfield, with lower values in the central and western parts of the wellfield (Figure 3-13C). However, many of the Memphis aquifer production wells sampled during the period 2003-2008 were no longer available for sampling in 2017. The highest SF$_6$ values in 2017 are in southeastern and central parts of the wellfield. A notable trend in SF$_6$ concentrations in the southeastern part of the Allen wellfield is that Memphis aquifer production well MLGW 117A has no $^3$He and a SF$_6$ concentration of 3.03 pptv. The SF$_6$ concentration decreases from MLGW 117A toward the north to Memphis aquifer production wells MLGW 114 and 111A, which have values of 0.26 and 0.67 pptv, respectively. The Memphis aquifer production wells with high SF$_6$ within the central part of the wellfield include production wells screened within both the upper part of the Memphis aquifer (MLGW 123A) and middle part of the Memphis aquifer (MLGW 106A and 110B).

Water quality characteristics of Memphis aquifer production wells correlate positively to high $^3$H and $^3$He values, but not to the highest SF$_6$ values. Memphis aquifer production well samples with high concentrations of sodium, chloride, and sulfate (Figure 3-8A and 8B), specific conductance (> 180 µS), and PHREEQC-based mixing percentages also have the highest $^3$H and $^3$He values (MLGW 111A, MLGW 114, and MLGW 115A). Conversely, many of the Memphis aquifer production wells with high SF$_6$ values have low concentrations of sodium, chloride, and sulfate (Figure 3-8A and 8B) and low or non-detectable $^3$H and $^3$He values (MLGW 106A, MLGW 110B, and MLGW 117A). Memphis aquifer production wells MLGW 103A and MLGW 123A have intermediate characteristics between these two water-quality tracer groups. One possible explanation is that the high SF$_6$ concentrations may originate from a deep aquifer source as has been observed in some aquifer systems (von Rohden et al., 2010; Friedrich et al., 2013), especially given that two of the production wells are screened in the middle of the Memphis aquifer (MLGW 106A and MLGW 110B). However, this seems unlikely because the Memphis aquifer production well with the highest SF$_6$ concentration also has the shallowest screen depth (MLGW 117A). At present, the source of this SF$_6$-rich water is unclear, but it also does not have any indication of contamination.

The 2017 sampling event verified that VOC detections affect only one Memphis aquifer production well at present, but comparison to previous results suggests that VOC detection correlates to other water quality characteristics. VOCs were detected only in Memphis aquifer production well MLGW 111A, which included only TCE and their biodegradation products (1,1-dichloroethene, cis-1,2-dichloroethene and trans-1,2-dichloroethene). Historical VOC data for MLGW 111A indicate previous detection of TCE of 0.19 µg/l (1990), 0.10 µg/l (1992), and 0.09 µg/l (1993). The current levels of TCE (3 to 6 µg/l) do not follow the decreasing trend observed in the 1990s, suggesting an additional source is now affecting MLGW 111A. VOCs were detected in samples from Memphis aquifer production wells MLGW 126, MLGW 127, and MLGW 128 from 1986 through 1996. In addition to persistent detections of TCE and PCE and their biodegradation products, benzene, naphthalene, and toluene were also detected in these production wells. Memphis aquifer production wells MLGW 126, MLGW 127, and MLGW 128 have since been abandoned and are no longer available for sampling. Limited water quality data from these
production wells indicate some shared characteristics with MLGW 111A: sulfate > 8 mg/l or higher, chloride > 5 mg/L, specific conductance > 180 µS. All of the Memphis aquifer production wells in the Allen wellfield with VOC detections have one or more of these characteristics except for MLGW 127. Based on wells that have been sampled by the University of Memphis in the Allen wellfield over the past 15 years, these water quality characteristics are consistent with leakage of modern water from the shallow aquifer into the Memphis aquifer.

The age-dating tracer, water quality, and VOC data all support migration of modern water in the shallow aquifer into the Memphis aquifer from two directions: east to southeast and west to southwest. The east-southeast is from the general direction of the breach beneath the former Memphis Depot and extending south toward Nonconnah Creek. Water quality trends support water sourcing from Nonconnah Creek, especially during back-flooding conditions from the Mississippi River (Bradshaw, 2011). The west-southwest source does not appear to have a clear depression in the water table other than that associated with the Nonconnah Creek valley. Drilling at MSA-1 in Nonconnah Creek valley did not indicate the presence of a breach; however, the breach could be further west of the MSA-1 well location. A breach is inferred along the Mississippi River valley near the TVA fossil plant (Carmichael et al., 2018) and other breaches are likely to exist northeast of that site along an east-northeast trending fault.
Figure 3-12: Contour map of the water-table elevation for 2005-2006 in south-central Memphis (from Bradshaw, 2011).
Figure 3-13: Contour maps of tritium values from Memphis aquifer production wells in the Allen wellfield (A) 2003; (B) 2007-2008; (C) 2017. A and B are from Bradshaw (2011).
4.0 Phase III: 3D Groundwater Model

The hydrogeology of the Allen wellfield includes a series of alternating sand and clay layers, grouped into hydrostratigraphic units that include several water-bearing units. Four sand aquifers beneath Allen wellfield include the shallow aquifer, Memphis aquifer, Fort Pillow aquifer, and Cretaceous aquifer, each of which are separated from adjacent aquifers by aquitard units, known as the UCCU, Flour Island confining unit, and Tertiary–Cretaceous confining unit, respectively.

Water from the shallow aquifer is of poorer quality than that in the underlying Memphis aquifer due to interaction with surface water and soils, and it is locally contaminated. Traditional water management in the Memphis area has screened production wells in the Memphis aquifer, hoping that the confining layers, such as the UCCU, would protect the water resource. All production wells in the Allen wellfield are screened in the Memphis aquifer, generally in the upper part of the Memphis aquifer. Table 4-1 shows the screen depths of all production wells in the Allen wellfield used in this study.

Hydrogeologic breaches within the UCCU, also termed windows, create local hydraulic connections between the shallow and Memphis aquifers and are a critical missing piece of information in this study. Figure 4-1 demonstrates a schematic of a breach in the aquitard layer that acts as a preferential flow path for water in the shallow aquifer to enter a screened production well in the Memphis aquifer. These breaches can add further complexity to the hydraulic behavior of the Allen wellfield. Unfortunately, the exact location and extent of these breaches remain unknown, requiring further comprehensive investigations. Phase III of this project mainly uses the limited available data and information about the Allen wellfield aquifer system.

The primary goal of Phase III is to develop comprehensive conceptual models of the Allen wellfield, and subsequently, build 3D multilayer numerical models to be used for informed decision making. The developed models can be used to forecast the future behavior of the Allen wellfield under different natural and anthropogenic scenarios. To achieve these goals, two types of 3D-multilayer model are developed: (1) groundwater-flow model and (2) contaminant-transport model. The first model simulates and predicts the groundwater flow rates and directions in different hydrogeological layers of the site. The second model, once coupled with the groundwater flow model, simulates and predicts the fate and transport of contaminants migrating at the site.
Table 4-1: Screen details of Allen wellfield production wells.

<table>
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<tr>
<th>MLGW_ID</th>
<th>Ground* (ft)</th>
<th>Depth of the well (ft)</th>
<th>Ground to Top of screen (ft)</th>
<th>Length of the screen (ft)</th>
<th>Top of the screen* (ft)</th>
<th>Bottom of the screen* (ft)</th>
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<td>296.0</td>
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<td>371.9</td>
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<td>414.9</td>
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</tr>
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<td>458.9</td>
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<td>430.9</td>
<td>108.0</td>
<td>-143.7</td>
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<td>MLGW-126</td>
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<td>396.9</td>
<td>299.9</td>
<td>97.0</td>
<td>-40.7</td>
<td>-137.7</td>
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<tr>
<td>MLGW-127</td>
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<td>380.9</td>
<td>71.0</td>
<td>-134.3</td>
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<td>MLGW-128</td>
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<td>MLGW-136A</td>
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<td>393.9</td>
<td>59.0</td>
<td>-152.3</td>
<td>-211.3</td>
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<td>MLGW-137</td>
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<td>MLGW-138A</td>
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<td>-151.6</td>
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<tr>
<td>MLGW-140</td>
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<td>449.9</td>
<td>349.9</td>
<td>100.0</td>
<td>-55.5</td>
<td>-155.5</td>
</tr>
</tbody>
</table>

* measured from mean sea level.
4.1 Groundwater-flow Model
4.1.1 Conceptual and Numerical Models
To adequately simulate the groundwater flow in the Allen wellfield, the extent of the groundwater-flow model is expanded beyond the wellfield boundaries because it is affected by factors such as characteristics of the regional groundwater flow, interactions between the Allen wellfield with nearby wellfields, and impacts of probable UCCU breaches. To evaluate a proper extent for the groundwater flow model, the existing relevant hydrogeological field data at CAESER databases were analyzed. Figure 4-2 shows the determined extent of the conceptual model, which encompasses the original extent of the model in the proposal and includes Allen, Davis, and Palmer wellfields (plan view of the conceptual model). The original proposed extent of the model is extended to further areas to increase the accuracy of the developed model in simulating the hydraulic behavior of the Allen wellfield. As shown, the conceptual model also includes a part of the Mississippi River, McKellar Lake, Nonconnah Creek, production wells, and hydrogeological bluff line. Figure 4-3 shows a side view of the conceptual model constructed from the three hydrogeological layers: shallow aquifer, UCCU, and the Memphis aquifer. The hydrological units below the Memphis aquifer are not considered because all the production wells within the study’s wellfields are screened in the upper and middle Memphis aquifer, and little evidence exists for the upward flow of water from deeper hydrogeologic units to the Memphis aquifer. Note that the depth scale of Figure 4-3 is exaggerated (x 100) for visualization purposes.
Figure 4-2: Plan view of the conceptual model of the groundwater-flow model which includes part of the Mississippi River, McKellar Lake, Nonconnah Creek, production wells, bluff line, and surface recharge.
The conceptual model is based on data and information produced by previous studies to create an effective hydrologic simulation of the site conditions. The critical stratigraphic unit elevations are derived from the comprehensive USGS study of Clark and Hart (2009). As shown in Figure 4-3, important vertical groundwater flows within the Memphis aquifer are considered in modeling using the exact screen depths and intervals of all production wells (Table 4-1). To simulate the groundwater flow within the study, the well-recognized MODFLOW model developed by the USGS was used (McDonald and Harbaugh, 1983). The numerical model has six layers with uniform 820×820 ft² (250×250 m²) cells, totaling 20,773 active cells. The first and second numerical layers represent the shallow aquifer and UCCU, respectively. The other four numerical layers uniformly divide the Memphis aquifer thickness (Figure 4-4).
4.1.2 Calibration of the Groundwater-flow Model

A groundwater model needs to be calibrated to reproduce previously observed aquifer behavior before being used in a predictive role. In the calibration process, specific parameters of the model are systematically altered during repeated runs of the model until the computed solution matches field-observed values within an acceptable level of accuracy. To do that, we use the most advanced mathematical model, known as Model-Independent Parameter Estimation (PEST), and a robust pilot point calibration technique. The calibrated parameters include the spatially varying horizontal and vertical hydraulic conductivities, storage coefficients, the Nonconnah Creek bed conductance, and surface recharge within each hydrogeological layer of the model. To calibrate the model, 69 pilot points distributed in all hydrogeologic layers of the numerical model are used to better represent the heterogeneity of the system. The estimated parameters through the calibration process are shown in Figures 4-5 to 4-7. The estimated values are only used to build a reliable predictive groundwater flow model. However, the estimations mentioned above can be used to investigate the locations of possible breaches. A comprehensive discussion on the methodology and outcomes of the developed groundwater-flow model is available in Jazaei et al. (2019).

The developed groundwater-flow model provides invaluable information regarding the spatial and temporal variation of the ground flow rates and directions within the studied layered groundwater system. The developed model is a helpful decision-making tool that allows the water authorities and researchers to analyze several practical what-if scenarios to thoughtfully predict the response of the aquifer system to different water production, remediation, and land-use management policies in the future. Studying such possible scenarios is beyond the scope of this study; however, the groundwater-flow model is developed in such a way to be employed for further analyses.
Figure 4-5: (a-f) The horizontal hydraulic conductivities of each numerical layer.
Figure 4-6: (a–f) The vertical hydraulic conductivities of each numerical layer.
Figure 4-7: (a) The specific yield coefficient of the shallow aquifer. (b-f) The specific storage of the UCCU and the Memphis aquifer, respectively.
4.2 Contaminant-Transport Model

4.2.1 Conceptual Model and Numerical Models
As shown in the Phase I (Historical and Regulatory Research) discussion, the presence of contaminants in the subsurface near the Allen wellfield area is associated with activities that have taken place near the site during the past four to five decades. The database developed in Phase I identifies the known or suspected sites, which potentially could introduce contaminants into the shallow aquifer. The introduced contaminants could migrate through the hydrogeological layers mainly by virtue of groundwater flow and hydraulic connectivity. However, in addition to groundwater flow, there are several other physical and chemical processes that affect contaminant migration within soil matrices, such as mechanical dispersion, molecular diffusion, physical adsorption, and chemical reactions. In Phase III, we use advanced numerical models, known as Modular Transport, 3-Dimensional, Multi-Species model (MT3DMS), and Reactive multi-species Transport in 3-Dimensional groundwater systems (RT3D), to simulate the above mentioned physical and chemical processes. In other words, the contaminant-transport model of the Allen wellfield is formed by coupling the previously developed groundwater-flow model with numerical models representing physical and chemical processes affecting contaminant migration (MT3DMS and RT3D).

Unlike the groundwater-flow model, which includes the Allen, Davis, and Palmer wellfields, the contaminant-transport model is exclusively focused on the Allen wellfield. The extent of the contaminant-transport model is shown in Figure 4-8. As required, the contaminant-transport model has a higher resolution compared with the Groundwater flow model. It has ten layers with uniform 164×164 ft² (50×50 m²) cells, totaling 305,440 active cells. The first and second numerical layers represent the shallow aquifer and UCCU, respectively. The other eight numerical layers uniformly divide the Memphis aquifer thickness (Figure 4-9).

Figure 4-8: Plan view of the contaminant-transport model.
4.2.2 Chemical Contaminants of Concern
As confirmed by Phase I, chlorinated solvent chemicals and benzene are the main COCs in the Allen wellfield area. These contaminants were widely used in past industrial and commercial practices as degreasers, cleaning solutions, paint thinners, pesticides, resins, glues, and a host of other mixing and thinning solutions. Common chlorinated solvents include PCE, which can degrade to TCE, DCE, and VC. Benzene is a petroleum-based chemical that was likely released into the shallow aquifer through leaking underground storage tanks and gasoline spills. Benzene is also present in petroleum products used to manufacture products such as plastics, nylon, Styrofoam, rubber, and dry-cleaning solvents. Similar to chlorinated solvents, benzene has leached into the shallow aquifer through industrial discharges, improper waste management, or faulty product handling and storage.

4.2.3 Challenges in Contaminant Investigations
Phase I mapped the known or suspected locations of chlorinated solvents and benzene sources. However, the recorded data are scattered in both time and space. The majority of the identified sites do not have any recorded groundwater or soil sample measurements. Therefore, most of the sites identified by Phase I are entitled as "suspected" sites based on the history of their land use records. Locations that have some form of documented water quality data are quite sparse in the time domain. As a result, only a few measured data are available within the last 30 years. Due to such data scarcity, it is unclear when, how much, and for how long contaminants have leaked into the shallow aquifer. Such unanswered questions challenge the certainty of any given contaminant fate and transport model. For example, it is unclear how contaminants were distributed in the subsurface in the Allen wellfield area during the starting year of the modeling (known as the "model initial condition"). As argued in the literature (e.g. Peck et al., 1988; Bear and Cheng, 2010), the initial condition of the contaminant transport model is key information...
that needs to be considered. Hence, in this study, the time domain of the transport model is extended back to 1980, the year at which we will assume that the concentrations of contaminants within the groundwater system are almost zero milligrams per liter. On the other hand, the time domain of the model is extended forward to 2055 to allow the model to forecast the contaminant transport in the coming years.

4.2.4 Flow Analyses- Shallow and Memphis Aquifer Interaction

Flow analyses within the Allen wellfield show that polluted shallow groundwater near the Allen wellfield area can recharge to the Memphis aquifer by two general mechanisms.

- **Mechanism-1**: The contaminant migrates horizontally within the shallow aquifer toward the Allen wellfield production wells. In this mechanism, the contaminant eventually accumulates at a well (wellfield) but within the shallow aquifer. Production wells screened at top of the Memphis aquifer can induce high vertical gradient that can pull the contaminants through the UCCU to the Memphis aquifer. This would be a rather slow process depending on the local thickness and hydraulic conductivity of the UCCU in that area, but it can significantly threaten the entire wellfield (Figure 4-10).

- **Mechanism-2**: The contaminant migrates horizontally until it penetrates the UCCU and infiltrates into the Memphis aquifer at locations further from the well due to the "regional vertical gradient" induced by the entirety of the production wells of the wellfield. This mechanism generally happens at areas where the UCCU is thin or absent (Figure 4-10).

![Figure 4-10: Two mechanisms of contaminant transport within the Allen wellfield](image)

4.2.5 Tracer Analyses (Conservative)

Flow analyses within the Allen wellfield estimate that, depending on the distance from the production well, groundwater flows toward the Allen wellfield horizontally within the shallow and Memphis aquifers with the velocities of approximately 50-100 and 20-70 feet per year, respectively. Note that the velocity of contaminant migration depends on several other physical and chemical processes as well. In the
groundwater literature, interpretive conservative analyses assume that the average velocity of the contaminant migration equals that of groundwater flow. In actuality, the average velocity of the contaminant is less than or equal to the velocity of groundwater, depending on the physical and chemical characteristics of the contaminant and aquifer system. However, it should be noted that conservative analyses are quite important analyses in environmental management because they set the worst-case scenario as the basis of decision making to prevent the occurrence of extremely costly environmental failures.

Tracer analysis is one of the most widely used conservative approaches to understand groundwater and contaminant flow paths and resident time. Tracer analyses provide invaluable information to the decision makers, especially in cases where limited groundwater quality data are available. Tracer analysis is recognized as a conservative analysis since it assumes that the contaminant is ideally nondegradable and non-adsorbent. Therefore, the velocity of the contaminant (tracer) is close to the average velocity of the water. We investigate two tracer analysis scenarios, both of which include all suspected and known contaminated sites identified in Phase I.

- **Scenario-1**: In this scenario, it is assumed that the contaminant (tracer) has been continuously being recharged to the shallow aquifer from 1980 to 2055. This scenario represents sites where contaminant leakage has remained untreated or unmitigated. Scenario-1 is a highly conservative scenario and shows how the Allen wellfield situation would look like if no protective action had taken place during the past 75 years with continuous recharge. As shown in Figure 4-11, contaminants would pollute large areas of the shallow aquifer between the sources and Allen wellfield. Figure 4-12 shows how the confining clay layer reduces the contaminant leachate to the Memphis aquifer. The leachate concentration in the Memphis aquifer is significantly less than that of the shallow aquifer. Figures 4-11 and 4-12 are percentile maps representing the concentration of the contaminant (tracer) with respect to the concentration at the contaminated site. A small percentage of tracer concentrations within the Memphis aquifer may be equivalent to a concentration higher than standard USEPA MCLs for drinking water. Figure 4-11 shows that a significant amount of pollutants would accumulate at the top of almost all production wells by 60 years of recharge. Undoubtedly, such a situation would be unacceptable for the water quality in the Memphis aquifer. As demonstrated in Figure 4-10, accumulation of contaminants at the top of the well severely threatens the production well due to a local high vertical gradient induced by the well.
Figure 4-11: Above figures show the concentration of the tracer within the shallow aquifer as a percentage of the concentration of the groundwater at the contaminated sources under Scenario-1.
Figure 4-12: Above figures show the concentration of the tracer within the Memphis aquifer as a percentage of the concentration of the groundwater at the contaminated sources under Scenario-1.
- **Scenario-2**: In contrast with the previous scenario, Scenario-2 assumes that recharge of the contaminant (tracer) to the shallow aquifer is stopped in 2005, 25 years after recharge starts in 1980. Scenario-2 better represents the sites where contaminant leakage at the site has been to some degree mitigated. Comparing with Scenario-1, the extents of the plumes are smaller (Figures 4-13 and 4-14). However, as in Scenario-1, a notable amount of tracer would accumulate at the top of several production wells after 60 years. These results indicate that although mitigation of the contaminated site significantly reduces the concentration of migrating plumes, distant plumes keep migrating toward the Allen wellfield. Comparing Figures 4-11 to 4-14 shows how mitigating the contaminated sources can reduce, but not fully eliminate, the contamination risk. Comparing Scenario-1 and 2 also shows that, although the concentration of the plume under Scenario-2 is less than that of in Scenario-1, the shape of the (head of) the plume remains almost the same.
Figure 4-13: Above figures shows the concentration of the tracer within the shallow aquifer as a percentage of the concentration of the groundwater at the contaminated sources under Scenario-2.

Note: Tracer is injected from 1980 to 2005.
Figure 4-14: Above figures shows the concentration of the tracer within the Memphis aquifer as a percentage of the concentration of the groundwater at the contaminated sources under Scenario-2.
4.2.6 Natural Attenuation Simulations

In the natural environment, contaminant concentrations arriving at a certain point and time are less than they would have been for a conservative (non-retarding and non-reacting) contaminant (tracer). In most groundwater systems, a series of physical and chemical processes limit the persistence and transport of the contaminant. For instance, contaminants physically interact with small soil particles. This process is also known as natural filtration, since the contaminant leaves the flowing groundwater and adheres to the surface of soil particles. This process is also known as the retardation or sorption process. Chemical reactions, which are commonly mediated by bacterial activity, are another type of natural attenuation that can reduce the concentration of some contaminants such as organic compounds. In groundwater literature, such chemical reactions are known as biodegradation. Biodegradation is often the primary process by which the mass of contaminant can be decomposed into benign compounds. Other physical processes, such as sorption, merely retain the contaminant mass for later release. However, some of the chemical reactions may lead to undesirable daughter products.

Organic compounds are the primary contaminants of concern at the Allen wellfield and are known to undergo degradation through different aerobic and anaerobic pathways. Biodegradation reactions are technically controlled by the abundance of microorganisms as well as the groundwater geochemistry. Unfortunately, a limited amount of information about the biodegradation reactions within the Memphis aquifer system is available. Besides, Phase-I reveals that the amount of water and soil quality data are limited. Limited chemical data from sampling of production and monitoring wells during Phase-II and historical information indicate the presence of organic degradation products for some of the contaminants of concern, arguing for an active degradation environment in the subsurface. However, given the absence of details about contaminant releases, contaminant transport models seem to be the most reasonable and economical approach for informed decision making. It should be noted that the developed models need to be periodically updated and re-calibrated as additional water quality data are collected.

Phase I identified locations wherein the subsurface release of benzene or chlorinated solvents are expected based on the site’s land-use background. The few sites with benzene and PCE monitoring data through Phase-I are used to calibrate the contaminant-transport model. Herein, the advanced RT3D mathematical model and MODFLOW are coupled to simulate instantaneous aerobic biodegradation of benzene under following stoichiometry:

\[ C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O \]

Biodegradation (dechlorination) of PCE and its four daughter products are also simulated under following sequential reactions:

\[ PCE \rightarrow TCE \rightarrow DCE \rightarrow VC \]

Figure 4-15 shows the predicted extent of the benzene plumes in the shallow and Memphis aquifers in 2025 and 2055. As shown in the figure, the extent of the benzene plumes is smaller than the extent of the ideal tracer plumes discussed in the previous section for two main reasons. First, the sorption mechanism as a natural attenuation process of the aquifer system is utilized in the benzene-transport model. Second, it is assumed that the contaminant leakage to the shallow aquifer at the (known and suspected) sites is mitigated and stopped by 2005. It must be noted that in this scenario, only 4 out of
37 sites have water quality monitoring data available. Making it challenging to precisely model the plume migration. However, relying on the existing data, the developed model can reasonably approximate the direction and extent of the plumes. Therefore, it is important to note that water quality data collected in the future can significantly improve the accuracy of the developed model simulations. However, the developed benzene-transport model provides general information regarding retardation and plume migration within the Allen wellfield. For example, the results show that the directions of plume migration are slightly different in the shallow aquifer than in the Memphis aquifer. The benzene plume close to Memphis aquifer production wells MLGW 127 and MLGW 128 moves east to west within the shallow aquifer, but moves slightly north to MLGW 126 within the Memphis aquifer (Figure 4-15). That is likely due to the stronger interaction between neighboring production wells within the Memphis aquifer. The model results also predict that benzene will arrive at wells located in the southwestern part of the Allen wellfield before the other wells, as directly confirmed by historical sampling of production wells. Therefore, it is strongly recommended to investigate the water production policies (e.g., using new production wells, and pumping rates), particularly in the southern part of the Allen wellfield to better manage and protect the wellfield.

Figures 4-16 to 4-19 show the predicted extent of the PCE and its daughter products (TCE, DCE, and VC) in the shallow and Memphis aquifers in 2025 and 2055. As shown in the figures, the plume concentrations are naturally attenuated by both sorption and sequential chemical reaction processes. It is also assumed that the leakage at the known and suspected sites are mitigated by 2005. Note that in this scenario, only 9 out of 20 sites have water quality monitoring data available. The following figures show the extent of the PCE, TCE, DCE, and VC plumes using the limited available data. The developed model provides useful information regarding the transport of the chlorinated solvents within the Allen wellfield. Comparing the figures shows how the natural attenuation processes would help to control the chlorinated solvents in both the shallow and Memphis aquifers. The models also predict that chlorinated solvents will impact more wells compared to benzene, as confirmed by historical sampling results. The model predicts that chlorinated solvents will reach southern and northwestern wells before other wells.
Figure 4-15: Predicted benzene transport within the shallow aquifer and Memphis aquifer in 2025 and 2055.
2025
Shallow aquifer

Figure 4-16: Predicted PCE and its daughter products, TCE, DCE, and VC, transport within the shallow aquifer in 2025.
Figure 4-17: Predicted PCE and its daughter products, TCE, DCE, and VC, transport within the shallow aquifer in 2050.

2050
Shallow aquifer

Concentration (ppm)

<0.001  2.5  >5

Figure 4-17: Predicted PCE and its daughter products, TCE, DCE, and VC, transport within the shallow aquifer in 2050.
Figure 4-18: Predicted PCE and its daughter products, TCE, DCE, and VC, transport within the Memphis aquifer in 2025.
Figure 4-19: Predicted PCE and its daughter products, TCE, DCE, and VC, transport within the Memphis aquifer in 2050.
4.3 Phase III Results Summary and Discussion
The key findings and recommendations of the Phase III are:

• Identifying locations of aquiclude breaches is essential to better predict groundwater flow and contaminant transport within the Allen wellfield.

• The developed groundwater-flow is capable of analyzing several practical scenarios to thoughtfully predict the response of the aquifer system to different water production, remediation, and land-use management policies.

• Contaminants released to the shallow aquifer decades ago move toward the Allen wellfield and tend to accumulate at the top of the production wells.

• Two contaminant transport mechanisms are simulated at the site: (1) contaminants accumulate at the top of the well within the shallow aquifer that then migrate vertically down due to the local vertical gradient induced by the well and (2) contaminant infiltrates to the Memphis aquifer at further areas from the wellfield due to the regional vertical gradient induced by the entire well field. Contaminants subsequently moves through the Memphis aquifer toward the production wells (Figure 4-10).

• Flow analyses within the Allen wellfield estimate that, depending on the distance from the production well, the groundwater moves toward the Allen wellfield horizontally within the shallow and Memphis aquifers with velocities of approximately 50-100 and 20-70 feet per year, respectively. The velocity of the contaminant migration is less than the groundwater velocity due to several physical and chemical processes.

• Developed models show that mitigating the contaminated sources can significantly reduce, but not fully eliminate, the contamination risk.

• The existing groundwater quality data are sparse in the space and time domain. It is presently unclear when, where, and how much contamination has leaked to the shallow aquifer. In such a situation, contaminant transport models provide a reasonable and relatively economical approach for informed decision making.

• Several physical and chemical processes affect the rate of natural attenuation within the Allen wellfield aquifer system. These processes are controlled by the abundance of microorganisms as well as the groundwater geochemistry. Unfortunately, almost no information about the rates of natural attenuation of organic contaminants within the shallow and Memphis aquifer is available.

• The southwestern and northeastern parts of the Allen wellfield will probably experience new detections of benzene or chlorinated solvents in the future. The production and protection policies need to be carefully analyzed within these zones.
5.0 Phase IV — Remedial Actions Problem Statement

Based on the findings and outcomes of Phases I through III, CAESER retained EnSafe to identify strategies and remedial options to manage VOC-related impacts (specifically to the Allen wellfield) over the long term; these strategies can then be extrapolated to other wellfields, as necessary.

Until actionable, shallow release areas (source areas) are identified and can be remediated directly, CAESER and EnSafe recommend the following remedial actions should be considered interim responses for management of the wellfield.

5.1 Interim Response Actions

The following options were identified as potential responses to VOC-related impacts at a wellfield:

- Abandon the impacted well (MLGW 111A) and reinstall it in a “clean” zone adjacent to the wellfield.
- Continued groundwater extraction from the impacted well, with discharge to the City of Memphis sanitary sewer.
- Continued groundwater extraction from the impacted well, with discharge to surface water via a National Pollution Discharge Elimination System (NPDES) permit.
- Continued groundwater extraction from the impacted well, with discharge of untreated water to the water plant for use in the MLGW distribution system.
- Continued groundwater extraction from the impacted well, treatment at the wellhead, with discharge of treated water to the water plant for use in the MLGW distribution system.
- Continued groundwater extraction from the impacted well, with treatment and reinjection to either the shallow aquifer or in the case of the Memphis aquifer as part of a remedial action.

Sections 5.1.1 through 5.1.6 below present a conceptual approach for implementing each of these options. Table 5-1 (included at the end of this memorandum) presents a comparative analysis based on the following criteria:

- Long-term protection of the Memphis aquifer
- Finished water quality
- Engineering feasibility (implementability, effectiveness, and cost)
- Other considerations (such as public perception, permitting, additional data, etc.)

5.1.1 Option 1: Abandon Well/Re-drill in “Clean” Zone

As discussed in a meeting between MLGW and CAESER on December 5, 2018, MLGW’s standard protocol when a well is impacted is to close/abandon the impacted well. EnSafe is utilizing this strategy as the baseline/status quo response, and will, therefore, use this as a point of departure for comparison. EnSafe
has presumed the following procedure is implemented, incorporating data obtained from earlier phases of this contract:

- Once a production well is determined to be impacted, all analytical data from the production well and surrounding monitoring points will be reviewed; the well will be re-sampled to verify results prior to abandonment.

- CAESER’s groundwater dating studies (e.g., tritium data) will be reviewed to bias the new well location to areas containing predominantly “old water” in the Memphis aquifer (i.e., groundwater which pre-dates introduction of anthropogenic contaminants), either laterally or vertically. Modeling would need to be completed to determine impacts of pumping.

- Assess whether adjacent properties are potential source areas using the EnSafe ArcGIS interactive mapping tool developed during Phase I; review available geological information and determine whether these locations may pose a future threat to the new well. Assess the need for additional investigation/assessment prior to well installation.

- Determine whether contaminated properties adjacent to the new well location may require “hot spot” treatment to mitigate the potential for future well impacts.

Per discussions with MLGW on December 5, 2018, replacement costs for each new production well are approximately $1M/well, exclusive of distribution piping. Age dating studies, an interactive ArcGIS mapping tool, and a numerical groundwater model are available to help locate wells. While data are unavailable to estimate treatment costs of future sites, single-event hot spot treatment costs can typically range from $0.5M to $1M depending on the size of the source and the magnitude of treatment; often, more than one treatment event is required. Note that site cleanups take many years, if not decades to complete, especially after contamination has reached the groundwater.

While well closure/abandonment achieves immediate protection of the water supply (the contaminated influent is removed from the raw water feed), as discussed with MLGW on December 5, 2018, and as presented in CAESER’s modeling results, cessation of pumping has significant ramifications for long-term water quality in the Memphis aquifer. First, well closure/abandonment may result in contaminant migration to the next nearest production well. Moreover, VOCs may be present at environmentally significant concentrations within the Memphis aquifer if they are being found in the extracted water. Migration is assumed to occur at the same rate as groundwater flow (i.e., advective transport). As a result, by terminating operations at “perimeter” production wells, VOCs may subsequently enter the capture zone of interior production wells of the Allen wellfield. Contaminant transport over 1000 feet may occur

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Key Data Required to Implement Option 1:

- VOC data from each individual production well and supporting monitoring wells
- Aquifer characteristics and production well requirements
- Supplemental groundwater data (e.g., new monitoring wells) from the proposed new location once decisions are made to relocate a well

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1 We assume that groundwater entering a production well is diluted at least 75%, if not more, given that flow into the production well is radial, and contaminant entry would be from one quadrant (or a fraction thereof).
over relatively short planning horizons (10 to 30 years); however, impacts may occur sooner (and in additional wells) if plume concentrations are higher and dispersion spreads any plume ahead of advective transport. Modeling could help understand this time horizon, given the expected lifespan of MLGW production wells (40-50 years) and the likelihood of refurbishment/reinstallation near existing infrastructure.

Second, installation of new production wells, either in “clean” portions of the upper Memphis aquifer or in its deeper portions, also may result in enhanced horizontal and vertical contaminant migration. The resultant impact will be temporally elongated plumes that ultimately affect higher quality zones and future water resource planning.

5.1.2 Option 2: Continue Pumping, Discharge to Sewer

Once contamination is identified and a well is confirmed to be impacted, one option is to continue pumping. Under this scenario, operating costs would remain the same. However, discharge options would vary (as described in Sections 5.2 through 5.6). As discussed in the December 5, 2018 meeting with MLGW and CAESER, one option would be to discharge untreated groundwater to the City of Memphis sanitary sewer system.

The advantage of this alternative is continued extraction of groundwater to slow further migration of impacted groundwater into the wellfield. Comparable to a traditional pump-and-treat approach, the impacted well would provide a hydraulic control between the contaminant plume and the remainder of the wellfield. It may be possible to reduce extraction rates to manage impacted groundwater; further modeling will be required to evaluate flow rates. The objective of this alternative is that contaminants would likely not migrate as quickly into the wellfield, and the impacted well could be used to extract or help control the contaminant plume. Because contaminant concentrations are low, we have assumed that it is possible to discharge directly to the City of Memphis sanitary sewer without treatment; while no treatment costs are incurred, discharge fees will be assessed, as noted below. Engineering required to complete this task includes designing the connection to the City of Memphis sanitary sewer, obtaining a discharge permit, and designing operational modifications to well telemetry/level controls to manage pumping.

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2 At this time, concentrations encountered at VOC-impacted wells are very low. However, plumes within the Memphis aquifer have not been defined and there is no guarantee that concentrations may not increase in the future.
3 Absent other data, we have assumed that impacts at the wellhead will remain localized at the wellhead through continuous (24/7) pumping, and not migrate further.
4 We do not know wellhead-specific contributions into the distribution system. We assume that individual wellheads contribute between 800 and 1500 gallons per minute, depending upon well design and localized aquifer transmissivities.
5 Assuming an extraction well is used for containment, and is pumped 24/7, some reductions in flow rate may be possible; additional modeling and hydraulic testing would be required to evaluate effectiveness.
6 The effectiveness of containment using the impacted well would depend on the extent and orientation of the plume; additional groundwater monitoring wells and hydraulic testing would be required to evaluate effectiveness.
Operations, monitoring, and maintenance (OM&M) associated with Option 2 would include routine servicing of the production well, comparable to current MLGW maintenance activities. Monitoring of the production well and adjacent monitoring wells is recommended. Additionally, the City of Memphis would require analysis of water discharged to the sanitary sewer per an issued permit.

There are several disadvantages to this approach, these being:

- An additional well location will still need to be sited for provision of raw water. Additional well costs as well as the risks associated with plume migration at new well locations could still be incurred.

- Costs will be incurred for discharge of groundwater to the City of Memphis sanitary sewer system; fees would be negotiated with the City of Memphis based on volumes. Costs would also need to account for discharge monitoring requirements, which will be stipulated as part of the City of Memphis permit.

- Wellhead-specific engineering/implementation costs would be based on the proximity of a sanitary sewer inlet to the well.

While this alternative may slow the migration of contaminants into the wellfield, administratively it is incompatible with operational objectives of the City of Memphis, as the discharge would place high volumes of relatively clean water into the sanitary sewer system. These flow rates, particularly in combination with high rainfall events and commensurate infiltration into the sanitary sewers, may reduce treatment efficiencies at the water treatment plant.

### 5.1.3 Option 3: Continue Pumping, Discharge to Surface Water

Similar to the alternative described in Section 5.2, groundwater could be extracted and discharged to the nearest tributary to Nonconnah Creek (e.g., Cane Creek). The advantages of providing continued pumping and slowing contaminant migration into the wellfield remain. Additional well costs, as well as the risks associated with groundwater migration at new well locations, would still be incurred.

In this alternative, no sewer discharge fees would be incurred; however, NPDES permitting would be required. Permitted discharge of groundwater to tributaries of Nonconnah Creek would be difficult. However, given expected groundwater discharge conditions:

- Discharges to Cane Creek would likely be permitted assuming a base flow of 0 cubic feet per second (cfs); flows in the Nonconnah Creek would likely be based on higher flows, but the minimum flow may still be on the order of 1-2 cfs.

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7 Without additional information regarding well-specific flow rates, EnSafe is unable to provide costing details.
8 Costs would vary based on the actual engineering design/specifications of each wellhead, the length of discharge piping, and the connection to the sanitary sewer.
9 Discharge may be conditional on rainfall, if infiltration into the City of Memphis sewer system is significant. Uptime may be limited to 60-70%, based on infiltration.
10 This memorandum has been prepared for the specific case of Allen wellfield; other wellfields would consider the nearest major blue-line stream.
11 Based on the gauging station at Germantown, USGS 07032200.
• While we do not know actual flow rates required to contain plumes and prevent migration into the Allen wellfield, EnSafe expects extraction rates at the wellheads to be approximately 75-100% of assumed current flows.\textsuperscript{12} If discharged to Nonconnah Creek, discharge rates may be on the order of 0.9-3.5 cfs. These flow rates may double or triple discharges to the receiving streams under minimum flow conditions.

• Based on minimum flows, potential VOC toxicity to ecological receptors within the receiving streams would need to be evaluated based on surface water quality criteria; Nonconnah Creek and its tributaries are required to meet surface water quality criteria as outlined in Tennessee Administrative Code 0400-40-03.-03(3), (4), (5), and (6).\textsuperscript{13,14} More critically, discharge may alter non-VOC in-stream water quality parameters (e.g., water temperature, dissolved oxygen) that would be a part of the NPDES permit. These permit conditions may control allowable discharges.

OM&M associated with Option 3 would include routine servicing of the production well, comparable to current MLGW maintenance activities. Monitoring of the production well and adjacent monitoring wells is recommended. Additionally, the NPDES permit would require analysis of water discharged to the sanitary sewer.

Discharge to Nonconnah Creek or one of its tributaries would only be viable if easements or rights of way could be acquired for discharge piping. Depending upon the location of the well, more than 1 mile of conveyance piping may be required for discharge. No costs have been estimated for piping at this time, as they would be significantly affected by infrastructure requirements.

5.1.4 Option 4: Continue Pumping, Discharge to Wellfield
In Option 4, groundwater extraction at the wellhead would be consistent with current MLGW operations. Extracted water would be pumped to the Allen water plant for use in the raw water supply. In this scenario, the advantages of providing continued pumping and slowing contaminant migration into the wellfield remain, consistent with Options 2 and 3. This option allows continued beneficial use of the wellhead as a production well.

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\textsuperscript{12} As noted previously, we do not know wellhead-specific contributions into the distribution system. We assume that individual wellheads contribute between 800 and 1500 gallons per minute, depending upon well design and localized aquifer transmissivities. It may be possible to reduce extraction rates to manage impacted groundwater; further modeling will be required to evaluate flow rates.

\textsuperscript{13} Option 3 assumes no treatment at this time, given the assumption of low influent VOC concentrations. This assumption would depend on wellhead-specific analytical data.

\textsuperscript{14} TDEC Surface Water Quality Criteria for Fish and Aquatic Life, Recreation, Irrigation, and Livestock Watering and Wildlife.
Contaminants from the VOC-impacted well would be diluted and managed with flow provided by the other active wells. The cascade aeration units used for iron removal, while not optimized for VOC removal, would also provide some removal of VOCs; actual removal rates would need to be evaluated further. Because well-specific flow rates and concentrations are not available, we cannot provide comparative evaluations. However, for discussion purposes, assuming one-sixteenth dilution (if all production wells have approximately the same flow rate), influent concentrations for benzene will approach the Maximum Contaminant Level in the finished water supply if a VOC-impacted well approaches 80 micrograms per liter — this does not account for reductions in the cascade aeration unit. As noted in the discussions for Options 2 and 3, it may be possible to reduce the flow rate for the VOC-impacted well; further modeling will be required to evaluate flow rates.

OM&M associated with Option 4 would be the same as they currently are, and would include routine servicing of the production well, comparable to current MLGW maintenance activities. Monitoring of the production well and any adjacent monitoring wells is recommended.

5.1.5 Option 5: Continue Pumping, Pretreat at Wellhead, Discharge to Wellfield

In Option 5, groundwater extraction at the wellhead would be consistent with current MLGW operations where extracted water would be pumped to the Allen wellfield for use in the raw water supply. However, at the wellhead, VOCs in groundwater would be removed using an air stripper. This option is ideal, as it allows ongoing, beneficial use of the wellhead but provides protection of the finished water supply. Additionally, the advantage of providing continued pumping and slowing contaminant migration into the wellfield remain.

Municipalities are often faced with VOC contamination of wellfields. When this occurs, in many cases the most cost-effective solution is to treat the water to remove the VOCs using air stripping, which has been established as a Best Available Control Technology for this

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**Key Data Required to Implement Option 4:**
- VOC data from each individual production well
- Additional groundwater monitoring wells, hydraulic testing, and modeling to optimize extraction rates
- Evaluation of removal rates from the cascade aeration units

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**Packed-Column Air Strippers**

A packed-column air stripper consists of a cylindrical column that contains an open-structured packing material. The water containing the VOCs enters the top of the column and flows down through packing material. At the same time, air flows up through the column (countercurrent flow). As the water and air pass each other, the VOCs are transferred from the water phase to the air phase. The water phase leaves the bottom of the column with most of the VOCs removed. The VOCs that are now in the air phase exit from the top of the column. The biggest disadvantages with towers are their size and associated design considerations (wind and thermal loadings), and difficulties with cleaning.

**Low-Profile Sieve Tray Air Stripper**

Low-profile air strippers operate in a similar way to packed-column air strippers. The difference is that the water flows across trays that are perforated with small holes, over a weir to the next lower tray, tray by tray until the water exits the bottom of the stripper. Air is bubbled through holes in the trays. The VOCs are transferred from the water phase to the air phase as the air is bubbled through the water on the trays. Tray air strippers are flexible with installation and design options, and maintenance is simplified.
application.\textsuperscript{15,16} This technology is also used by municipalities to remove other volatile organics including (but not limited to) VC, TCE, and benzene.\textsuperscript{17} For the flow rates anticipated at MLGW wellheads, two types of air strippers can be evaluated: packed-column and low-profile sieve tray. The appropriate air strippers would be designed based on anticipated VOC concentrations and the production well flow rate.

A conceptual treatment approach is described below:

- Trailer- or skid-mounted, high capacity low-profile, sieve-tray air strippers can be configured in parallel to remove VOCs at the wellhead. Each skid would be self-contained with an air stripper capable of handling flow rates up to 500 gallons per minute, with ancillary blowers, transfer pumps, piping, level switches, etc. Assuming concentrations are low (less than 30 micrograms per liter total VOCs), VOC removal efficiencies using 6-tray, stacked-tray air strippers are very high (exceeding 99\%).\textsuperscript{18} Trailer and skid-mounted systems are typically pre-designed to include piping, pre-treatment cartridge or bag filters, valving, and controls based on the anticipated flow rate. Additional design considerations would be solids (e.g., iron) removal prior to the air stripper units if significant iron is present in the influent stream. Data collected during Phase II indicate iron concentrations up to 1 part per million. This iron concentration is not expected to cause excessive fouling of the trays; however, routine maintenance may be required.

- Air strippers may require permitting by the Memphis and Shelby County Health Department Air Pollution Control Branch.\textsuperscript{19} Emissions controls (e.g., vapor phase carbon, thermal oxidizer) may be required if VOC discharge loadings exceed emissions criteria.\textsuperscript{20}

- Telemetry/controls would be configured to operate the air stripper(s) as required to manage production well flow rates.\textsuperscript{21} Air stripper systems can typically be easily added to a client’s SCADA system.

- Wellhead-specific engineering costs would be relatively low, assuming that trailer- or skid-mounted systems can be installed and operated adjacent to the wellhead. Primary design factors would include plumbing the discharge to the skids, power hookups, and telemetry to the skids.

- Order-of-magnitude costs for each skid-mounted package would be approximately $200,000 to $300,000 per skid, per impacted wellhead. Note that more than one skid may be required for each wellhead, depending upon flow rates.

\textsuperscript{15} Air stripping is also commonly used at water plants to achieve compliance with new regulations for disinfection by-products.

\textsuperscript{16} While other treatment technologies are applicable to VOC removal (such as granular activated carbon, biological treatment), they are not optimal for high volume groundwater treatment; in addition, treatment residuals are generated (spent carbon, sludges). Vapor phase activated carbon may be retained, if required, for emissions control.

\textsuperscript{17} Multiple municipalities were identified with active air strippers for VOC treatment during preparation of this Memorandum, including, but not limited to: Cheyenne, WY; Cedarburg, WI; LaCrosse, KS; Culver City, CA; Spring Park, MN; Elkhart, IN; Bethpage, NY.

\textsuperscript{18} As noted previously, data from wellheads are not available. For the purposes of this feasibility study we have assumed wellhead concentrations range from 1 to 30 parts per billion total VOCs.

\textsuperscript{19} Note that at this time, concentrations encountered at VOC-impacted wells are very low, and air emissions may be considered de minimis. However, plumes within the Memphis aquifer have not been defined and there is no guarantee that concentrations may not increase in the future, which change regulatory status.

\textsuperscript{20} Concentration and flow data are required to design/evaluate potential emissions.

\textsuperscript{21} As noted previously, flow rates would need to be modeled and then optimized; multiple skids may be required.
Wellhead-specific engineering/implementation costs would be relatively low to plumb the air strippers from the wellhead and to the distribution line.  

OM&M associated with Option 5 would include routine servicing of the production well comparable to current MLGW maintenance activities. Maintenance of the air stripper units would include periodic inspection and cleaning where the frequency would depend upon the degree of fouling/scale. We have not estimated long-term labor or material costs, or additive electrical costs for operations. Monitoring of the production well and adjacent monitoring wells is recommended and post-stripper monitoring will also be required.

5.1.6 Option 6: Continue Pumping, Treat, Reinject

Similar to the alternative described in Section 5.1.5, groundwater could be extracted and treated. However, if inclusion in the raw water distribution system is unacceptable to MLGW, the treated water can be reinjected either into the Memphis aquifer or into the shallow aquifer. Reinjection wells strategically placed within the Memphis aquifer could be used to create a localized groundwater divide; this divide (or hydraulic barrier) could be used to slow migration of contaminants to the wellfield. Treated water would also be “conserved” as a future water supply. However, additional well costs, as well as the risks associated with groundwater migration at new well locations, would still be incurred.

As discussed in Section 5.1.2, continued extraction at an impacted wellhead would slow the movement of the plume and reinjection would create a hydraulically induced barrier to continued contaminant migration. Under Option 6, extracted groundwater is reinjected as described below:

- Groundwater can be reinjected into the Memphis aquifer between the Allen wellfield and the contaminated plume. The influx of groundwater would create a localized groundwater divide (a groundwater mound) or otherwise enhance the hydraulic barrier to slow the migration of contaminants towards the Allen wellfield.

- The placement of the injection well is modeled to optimize its location relative to the operational containment well and active portions of the wellfield. Both aquifer transmissivity data and monitoring well data are critical to modeling and evaluating well performance. Aquifer test data from the well field will be integrated into the analysis.

- Reinjection can also occur within the shallow aquifer; this provides the benefit of minimal conveyance piping (the reinjection well can be installed adjacent to the production well). However, reinjection in this aquifer carries the risk of enhancing migration of existing contamination vertically into the Memphis aquifer. Further evaluation would need to be performed to assess whether injections would flush contamination or enhance natural recharge.

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22 Costs would vary based on the actual engineering design/specifications of each wellhead, the length of discharge piping, and the connection to the sanitary sewer.

23 Additional information is required to gauge the frequency of fouling. Iron concentrations of 1 part per million are not generally excessive for air stripper fouling, but will require cleanout and maintenance.
processes. Additionally, reinjection within the shallow aquifer would not create a hydraulic divide in the Memphis aquifer, and would not offer any additional protections to the wellfield outside of the localized containment aspects at the pumping well.

Importantly, groundwater extraction occurs and returns extracted groundwater back to the aquifer for future use. All reinjection will require permitting by TDEC and the Shelby County Ground Water Quality Control Board. Reinjection to either aquifer cannot occur without treatment if concentrations exceed USEPA MCLs. Conceptual treatment using skid-mounted air strippers would be the same as described in Section 5.1.5.

Construction of an 8-inch stainless-steel reinjection well would cost on the order of $200,000-$400,000. Importantly, without modeling the hydraulic alternatives and knowing actual contaminant concentrations, the distance required from the pumping to the reinjection location is unknown. 24 We have assumed that reinjection well placement may be 500-1000 feet away, and that more than one reinjection well may be required. Easements or rights of way would be acquired (may be required) for conveyance piping. No costs have been estimated for piping at this time as they would be affected by infrastructure requirements.

OM&M associated with Option 6 would include routine servicing of the production well comparable to current MLGW maintenance activities. Maintenance at the reinjection wells is expected to be comparable. Maintenance of the air stripper units would include periodic inspection and cleaning and frequency would depend upon the degree of fouling/scale.25 We have not estimated long-term labor or material costs or additive electrical costs for operations. Monitoring of the production well and adjacent monitoring wells is recommended, and post-stripper monitoring will also be required.

5.2 Analysis and Recommendations
Table 5-1 presents a comparison of the interim response actions screened in this memorandum. Note that at this time, EnSafe has not prepared detailed cost estimates or net present worth calculations, as operational data from the wellfield were not available, including flow rates, adequate well-specific concentration data, engineering plans and specifications of impacted wells and distribution piping, etc.

EnSafe and CAESER recommend implementation of interim response action, which protects both the finished water supply and the Memphis aquifer; implementation of both a short- and long-term solution provides maximum sustainability of the region’s water supply while addressing MLGW’s concerns about

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24 The effectiveness of reinjection and the groundwater divide approach would depend on the extent and orientation of the plume; additional groundwater monitoring wells and hydraulic testing would be required to evaluate effectiveness.

25 Additional information is required to gauge the frequency of fouling. Iron concentrations of 1 part per million are not generally excessive for air stripper fouling, but will require cleanout and maintenance.
finished water quality. Based on our understanding that MLGW does not want to treat water at the water plant, EnSafe recommends consideration of Options 5 and 6.

- Option 5 incorporates treatment of VOC-impacted groundwater at the wellhead, allowing ongoing beneficial use of the wellhead while slowing contaminant migration into the wellfield.
- Option 6 provides a hydraulic barrier and protection of the wellfield and uses reinjection to (a) enhance the hydraulic barrier, and (b) return treated water to the aquifer for future use.

### 5.3 Data Collection Needs

To gauge trends, EnSafe recommends a minimum of annual VOC sampling of production wells at the wellhead (not combined influent to the water plant). Monitoring wells associated with the wellfield should be sampled at the same time. If VOCs are identified in a well, that well should be sampled quarterly (at minimum) to provide a higher data density for trending. Supplemental analytical parameters that would facilitate air stripper system design include metals (particularly iron), alkalinity, and hardness.

Once decisions are made to implement a response, data requirements vary depending on implementation of Option 5 or Option 6, which are as follows:

<table>
<thead>
<tr>
<th>Additional Data Needs</th>
<th>Option 5</th>
<th>Option 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC, metals, and basic geochemical data from each individual production well</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aquifer characteristics and production well requirements</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Additional groundwater monitoring wells, hydraulic testing, and modeling to optimize extraction rates</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Well-specific plans and specifications</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Distribution system plans and specifications</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Air stripper design/permitting</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reinjection well locations/conveyance line routings</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Reinjection well design/permitting</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Supplemental groundwater data (e.g., new monitoring wells) from the new location, once decisions are made to relocate a well</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
## Table 5-1 Comparative Analysis — VOC Interim Response Options

<table>
<thead>
<tr>
<th>Remedial Options</th>
<th>Long-Term Protection of Wellfield/Memphis Aquifer</th>
<th>Finished Water Quality</th>
<th>Engineering Feasibility</th>
<th>Other Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option 1</strong></td>
<td>Abandon Well/Drill in Clean Zone</td>
<td>Cessation of pumping and installation of new wells runs the risk of enhancing contaminant migration deeper into the wellfield. While contaminants may not be detected for several years, the longevity of the wellfield as a future resource will be affected, and future resource planning may require additional abandonment or consideration of treatment alternatives.</td>
<td>Finished water quality is protected, as VOC-impacted wells are eliminated from the raw-water feed.</td>
<td>Implementability: This alternative is implementable; it is MLGW’s current standard approach to VOC impacts. Future implementability may be complicated by access restrictions for new well locations and conveyance piping, and known contamination on adjacent parcels.</td>
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<tr>
<td></td>
<td></td>
<td>Installation of new wells into the Memphis aquifer, either in shallow zones with older water or into deeper horizons, also presents risks. Contamination within the shallow aquifer (or already present within the Memphis aquifer) may be drawn into the new wells. Interactive ArcGIS mapping tools and a numerical groundwater model may be used to mitigate some of this risk, but additional sampling and monitoring wells will be required to assess/monitor conditions near new installations. Targeted remediation may be required for contamination which can be clearly defined within the shallow aquifer.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Option 2</strong></td>
<td>Continue Pumping, Discharge to Sewer</td>
<td>Continued pumping of the VOC-impacted well slows migration of contaminants (both laterally and vertically) into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Risks and issues associated with new wells remain the same as described above.</td>
<td>Finished water quality is protected, as VOC-impacted wells are eliminated from the raw-water feed.</td>
<td>Implementability: While implementable, this alternative may have significant administrative challenges, including permitting by the City of Memphis. Installation of new wells may be complicated by access restrictions for new well locations and conveyance piping, and known contamination on adjacent parcels.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cost: Not estimable at this time. Key cost variables include:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Well replacement costs (see Option 3). Groundwater extraction rates.</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>Sewer use fees. Discharge monitoring requirements.</td>
</tr>
<tr>
<td><strong>Option 3</strong></td>
<td>Continue Pumping, Discharge to Surface Water</td>
<td>Continued pumping of the VOC-impacted well slows migration of contaminants (both laterally and vertically) into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Risks and issues associated with new wells remain the same as described above.</td>
<td>Finished water quality is protected, as VOC-impacted wells are eliminated from the raw-water feed.</td>
<td>Implementability: While implementable, this alternative may have significant administrative challenges, including NPDES permitting and acquisition of conveyance piping to the surface water discharge outfall. Installation of new wells may be complicated by access restrictions for new well locations and conveyance piping, and known contamination on adjacent parcels.</td>
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<td></td>
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<td></td>
<td>Well replacement costs (see Option 3). Groundwater extraction rates.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Conveyance piping routing/design. Discharge monitoring requirements.</td>
</tr>
</tbody>
</table>
Table 5-1
Comparative Analysis — VOC Interim Response Options

<table>
<thead>
<tr>
<th>Remedial Options</th>
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</tr>
</thead>
</table>
| **Option 4**     | Continuous pumping of the VOC-impacted well slows migration of contaminants (both laterally and vertically) into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Continuing to use the production well minimizes the need for new well installations; new installations can be planned for demand, rather than VOC impacts. Risks for new installations would be managed as described above. | Over the long term, finished water quality may be variable, based on influent concentrations.  
- Very low concentrations at the impacted wellhead are expected to have no impact on finished water quality, due to dilution and a small amount of treatment at the cascade aerators.  
- Higher concentrations at the wellhead may be measurable within the finished water. These concentrations may exceed MCLs. | Implementability: Readily implementable; the wellhead would already be online.  
Effectiveness: This alternative provides the least protection to the raw-water feed; however, it provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Comparable to current MLGW operating costs for a production well. | • Perception associated with chemical “dilution” may result in community objections.  
• Added influent and effluent monitoring requirements to address potential concerns. |
| **Option 5**     | Air stripping to remove VOCs allows continued use of the wellfield to contribute water to the distribution system while slowing migration of contaminants deeper into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Continuing to use the production well minimizes the need for new well installations; new installations can be planned for demand, rather than VOC impacts. Risks for new installations would be managed as described above. | Finished water quality is protected, as VOCs are removed prior to combination with the raw-water feed. | Implementability: Readily implementable; airstripping equipment is commercially available in trailer- or skid-mounted units and can be configured to achieve design flow rates. Administratively will require coordination to achieve an air permit.  
Effectiveness: This alternative is effective at treating VOC contamination prior to combination with the raw-water feed, and provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Costs will be variable based on:  
- Groundwater extraction rates.  
- Treatment requirements.  
- The need for air emissions controls and influent/effluent vapor sampling.  
- Analytical protocols (wellhead treatment influent/effluent sampling) Order-of-magnitude capital costs for planning purposes may range between $0.5 to $1M per wellhead. | • Potential public perception associated with treated water, necessitating community outreach.  
• Additional influent and effluent monitoring requirements to address potential concerns.  
• Community is assured long-term protection of their aquifer. MLGW is in front of issue — protecting aquifer and community concerns.  
• Long-term O&M and capital costs for construction. |
| **Option 6**     | Continued pumping of the VOC-impacted well slows migration of contaminants, and a hydraulic induced barrier (a localized groundwater divide) is created by reinjection of treated groundwater. This will help to mitigate risks posed to the wellfield over the long term. Importantly, treated groundwater is restored to the aquifer as a future resource. Risks and issues associated with new wells remain the same as described above. | Finished water quality is protected, as VOC-impacted wells are eliminated from the raw-water feed. | Implementability: Readily implementable; air stripping equipment is commercially available in trailer- or skid-mounted units and can be configured to achieve design flow rates. However, this alternative may have significant administrative challenges, including reinjection and air permitting. Installation of new wells may be complicated by access restrictions for new injection well locations and conveyance piping, and known contamination on adjacent parcels.  
Effectiveness: This alternative is effective at removing VOC contamination from the raw/finished water in the short term, and provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Costs will be variable based on:  
- Well replacement costs (see Option 1).  
- Groundwater extraction rates.  
- The number of injection locations.  
- Conveyance piping routing/design.  
- Treatment requirements.  
- The need for air emissions controls and influent/effluent vapor sampling.  
- Analytical protocols (wellhead treatment influent/effluent sampling) Order-of-magnitude capital costs for planning purposes may range between $0.5 to $1M per wellhead. Conveyance costs are not estimable at this time. | • Eliminates presumed stigma associated with use of treated groundwater and no potential community push-back.  
• Loss of groundwater for finished water supply.  
• Natural resource is preserved.  
• Potential short circuiting of injected water with production well. Requires better understanding of plume configuration.  
• Community is assured long-term protection of their aquifer. MLGW is in front of issue — protecting aquifer and community concerns.  
• Long-term O&M and capital costs for construction. |

Notes:
- GIS = geographic information system
- VOC = volatile organic compound
- MLGW = Memphis, Light, Gas and Water
- O&M&M = Operations, maintenance, and monitoring
- NFDES = National Pollutant Discharge Elimination System
- MCL = Maximum Contaminant Level

**Table 5-1**
Comparative Analysis — VOC Interim Response Options

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<tr>
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| **Option 4**     | Continuous pumping of the VOC-impacted well slows migration of contaminants (both laterally and vertically) into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Continuing to use the production well minimizes the need for new well installations; new installations can be planned for demand, rather than VOC impacts. Risks for new installations would be managed as described above. | Over the long term, finished water quality may be variable, based on influent concentrations.  
- Very low concentrations at the impacted wellhead are expected to have no impact on finished water quality, due to dilution and a small amount of treatment at the cascade aerators.  
- Higher concentrations at the wellhead may be measurable within the finished water. These concentrations may exceed MCLs. | Implementability: Readily implementable; the wellhead would already be online.  
Effectiveness: This alternative provides the least protection to the raw-water feed; however, it provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Comparable to current MLGW operating costs for a production well. | • Perception associated with chemical “dilution” may result in community objections.  
• Added influent and effluent monitoring requirements to address potential concerns. |
| **Option 5**     | Air stripping to remove VOCs allows continued use of the wellfield to contribute water to the distribution system while slowing migration of contaminants deeper into the wellfield. This will help to mitigate risks posed to the wellfield over the long term. Continuing to use the production well minimizes the need for new well installations; new installations can be planned for demand, rather than VOC impacts. Risks for new installations would be managed as described above. | Finished water quality is protected, as VOCs are removed prior to combination with the raw-water feed. | Implementability: Readily implementable; airstripping equipment is commercially available in trailer- or skid-mounted units and can be configured to achieve design flow rates. Administratively will require coordination to achieve an air permit.  
Effectiveness: This alternative is effective at treating VOC contamination prior to combination with the raw-water feed, and provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Costs will be variable based on:  
- Groundwater extraction rates.  
- Treatment requirements.  
- The need for air emissions controls and influent/effluent vapor sampling.  
- Analytical protocols (wellhead treatment influent/effluent sampling) Order-of-magnitude capital costs for planning purposes may range between $0.5 to $1M per wellhead. | • Potential public perception associated with treated water, necessitating community outreach.  
• Additional influent and effluent monitoring requirements to address potential concerns.  
• Community is assured long-term protection of their aquifer. MLGW is in front of issue — protecting aquifer and community concerns.  
• Long-term O&M and capital costs for construction. |
| **Option 6**     | Continued pumping of the VOC-impacted well slows migration of contaminants, and a hydraulic induced barrier (a localized groundwater divide) is created by reinjection of treated groundwater. This will help to mitigate risks posed to the wellfield over the long term. Importantly, treated groundwater is restored to the aquifer as a future resource. Risks and issues associated with new wells remain the same as described above. | Finished water quality is protected, as VOC-impacted wells are eliminated from the raw-water feed. | Implementability: Readily implementable; air stripping equipment is commercially available in trailer- or skid-mounted units and can be configured to achieve design flow rates. However, this alternative may have significant administrative challenges, including reinjection and air permitting. Installation of new wells may be complicated by access restrictions for new injection well locations and conveyance piping, and known contamination on adjacent parcels.  
Effectiveness: This alternative is effective at removing VOC contamination from the raw/finished water in the short term, and provides long-term protection for the wellfield and the Memphis aquifer.  
Cost: Costs will be variable based on:  
- Well replacement costs (see Option 1).  
- Groundwater extraction rates.  
- The number of injection locations.  
- Conveyance piping routing/design.  
- Treatment requirements.  
- The need for air emissions controls and influent/effluent vapor sampling.  
- Analytical protocols (wellhead treatment influent/effluent sampling) Order-of-magnitude capital costs for planning purposes may range between $0.5 to $1M per wellhead. Conveyance costs are not estimable at this time. | • Eliminates presumed stigma associated with use of treated groundwater and no potential community push-back.  
• Loss of groundwater for finished water supply.  
• Natural resource is preserved.  
• Potential short circuiting of injected water with production well. Requires better understanding of plume configuration.  
• Community is assured long-term protection of their aquifer. MLGW is in front of issue — protecting aquifer and community concerns.  
• Long-term O&M and capital costs for construction. |
6.0 Summary and Conclusions

The MLGW Allen wellfield has been producing high-quality water from the Memphis aquifer for almost 80 years. However, since the mid-1980s several production wells have shown low-level detections of benzene and organochlorine compound contaminants, which led to the abandonment of at least three production wells. Water quality issues persist at the wellfield. This study provides a comprehensive, area-wide assessment of contaminants that may potentially adversely affect the source water for the MLGW Allen wellfield and makes recommendations for remediation.

The following is a summary of findings:

Phase I: Historical and Regulatory Research

The objective of the initial phase of the Allen Well Field Evaluation, Phase I: Historical and Regulatory Research, was to identify and rank known and potential sources of groundwater contamination within the Area of Interest (AOI). Historical, land use, and regulatory research was conducted to identify properties with known, suspected, or potential groundwater impacts. Using an online map system, the Allen Wellfield PCS Webportal, all of the parcels within the designated AOI were categorized based on their potential to have impacted groundwater and ranked as no, low, moderate, or high potential for impact. The potential impact ranking, known or suspected contamination source, constituents of concern, and, if applicable, a summary of information associated with the parcel along with supporting documentation (e.g., regulatory files) can be viewed for each parcel using the Webportal.

- Through extensive review, Phase I identified multiple high potential known or suspected sources of contamination within the Zone I AOI. Although numerous sources were identified, little to no useful groundwater data are available for most sites. ARR and the Memphis Depot are the exceptions.

- Geodatabase of the Phase I to be provided to MLGW.

Phase II: Groundwater Sampling

- VOCs identified in seven shallow aquifer monitoring wells and in Memphis aquifer production well MLGW 111A.
  - MLGW 111A TCE concentration of 6 µg/l (May 2018) exceeded its respective MCL (5 µg/l)

- Tritium (³H) concentrations were above background in five Memphis aquifer production wells (MLGW 103A, MLGW 111A, MLGW 114, MLGW 115A and MLGW 123A).
  - Calculate modern water recharge ages between 14.0 and 39.1 years before 2017.
  - Between 15 to 23% modern water exists in production well water in wells MLGW 111A, MLGW 114, and MLGW 115A.
Current and historic water quality, environmental tracers ($^3$H, $^3$He, and SF$_6$), and VOC data indicate migration of modern water, locally containing VOCs, into the upper part of the Memphis aquifer in the east to southwestern and west to southwestern parts of the wellfield.

Historical VOC data for MLGW 111A indicate previous detection of TCE of 0.19 µg/l (1990), 0.10 µg/l (1992), and 0.09 µg/l (1993). The current levels of TCE (3 to 6 µg/l) do not follow the decreasing trend observed in the 1990s, suggesting an additional source is now affecting MLGW 111A.

All of the Memphis aquifer production wells in the Allen wellfield with VOC detections have one or more of these characteristics except for MLGW 127. Based on wells that have been sampled by the University of Memphis in the Allen wellfield over the past 15 years, these water quality characteristics are consistent with leakage of modern water from the shallow aquifer into the Memphis aquifer.

The age-dating tracer, water quality, and VOC data all support migration of modern water in the shallow aquifer into the Memphis aquifer from two directions: east to southeast and west to southwest.

— The east-southeast is from the general direction of the breach beneath the former Memphis Depot and extending south toward Nonconnah Creek.

— The west-southwest source does not appear to have a clear depression in the water table other than that associated with the Nonconnah Creek valley.

Drilling at MSA-1 in Nonconnah Creek valley did not indicate the presence of a breach; however, the breach could be further west of the MSA-1 well location. A breach is inferred along the Mississippi River valley near the TVA fossil plant (Carmichael et al., 2018) and other breaches are likely to exist northeast of that site along an east-northeast trending fault.

Phase III: 3D Groundwater Model

Groundwater-flow modeling substantiates downward recharge through the UCCU into the Memphis aquifer at the identified breach east of the Allen wellfield beneath the former Memphis Depot and indicates a hypothesized breach along Nonconnah Creek east of Presidents Island.

Contaminant-transport modeling indicated that the greatest potential for water quality impact is in the southern part of the wellfield, although organochlorine compounds may also be migrating in the northwestern part of the wellfield.

— Lack of available data from contaminant sources hampered the modeling effort. All contamination was initiated in 1980 with either a 25-year (plug-source) or continuous
source term, and then the resulting plumes tracked in the shallow and Memphis aquifers through 2055 contamination.

*Phase IV: Remediation and Future Remedial Services*

Based on the findings and outcomes of Phases I through III, CAESER retained EnSafe to identify strategies and remedial options to manage VOC-related impacts (specifically to the Allen wellfield) over the long term; these strategies can then be extrapolated to other wellfields, as necessary. Until actionable, shallow release areas (source areas) are identified and can be remediated directly, CAESER and EnSafe recommend the following actions should be considered interim responses for management of the wellfield. Of the six interim response actions evaluated, only two optimize protection and reuse potential of the Memphis aquifer:

- Option 5 incorporates treatment of VOC-impacted groundwater at the wellhead, allowing ongoing beneficial use of the wellhead while slowing contaminant migration into the wellfield.

- Option 6 provides a hydraulic barrier and protection of the wellfield and uses reinjection to (a) enhance the hydraulic barrier, and (b) returns treated water to the aquifer for future use.

EnSafe and CAESER recommend implementation either one of these options, which addresses MLGW’s concerns about finished water quality but also provides maximum sustainability of the region’s water supply.

To implement these options, however, additional data collection and modeling are required, as summarized below:

<table>
<thead>
<tr>
<th>Additional Data Needs</th>
<th>Option 5</th>
<th>Option 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC, metals, and basic geochemical data from each individual production well</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aquifer characteristics and production well requirements</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Additional groundwater monitoring wells, hydraulic testing, and modeling to optimize extraction rates</td>
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<td>X</td>
</tr>
<tr>
<td>Well-specific plans and specifications</td>
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<td>X</td>
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<tr>
<td>Distribution system plans and specifications</td>
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<td></td>
</tr>
<tr>
<td>Air stripper design/permitting</td>
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<td>X</td>
</tr>
<tr>
<td>Rejection well locations/conveyance line routings</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rejection well design/permitting</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Supplemental groundwater data (e.g., new monitoring wells) from the new location, once decisions are made to relocate a well</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

These actions would be required at a wellfield for every incursion of VOCs (or other contaminants) into a wellfield, to slow further migration.

The results of the present study indicate the upper part of the Memphis aquifer in the eastern and southern parts of the wellfield are most vulnerable to continued incursion of VOCs. We recommend that future development in the well field be directed in the northern part of the wellfield where little evidence
for incursion of modern water exists. Furthermore, only two Memphis aquifer production wells in the Allen wellfield are screened in the middle part of the Memphis aquifer (MLGW 110B and 113A). We recommend more balanced production from the middle and upper Memphis aquifer in the future to minimize the rate of migration of modern water and VOC contamination into the upper part of the Memphis aquifer.
7.0 Reference


