Adaptive Groundwater Solutions LLC
10240 Stonemede Lane
Matthews, NC 28105

February 01, 2021

Via email to agarcia@selctn.org

Amanda Garcia
Tennessee Office Director
Southern Environmental Law Center
1033 Demonbreun St., Ste. 205
Nashville, TN 37203

Re: **Evaluation of the Risk of Contamination of the Memphis Sand Aquifer by the Proposed Byhalia Connection Pipeline**

Dear Ms. Garcia,

Per your request, I have analyzed the methodology, facts and data relevant to the risk of contamination of the Memphis Sand Aquifer posed by a proposed crude oil pipeline known as the Byhalia Connection pipeline, which would run from the Valero refinery in Memphis, Tennessee, to Marshall County, Mississippi (the Pipeline). Specifically, my attached analyses provide a preliminary evaluation of crude-oil related contaminant fate and transport from a potential oil spill in the Shallow Aquifer at a location upgradient from known or suspected breaches in the Upper Claiborne Confining Unit. My calculations include the time frames for contaminants to migrate in the Shallow Aquifer from the spill location and from beneath the breach area to water supply wells screened in the Memphis Sand Aquifer.

Based on my review of available documents and various chemical transport analyses, I am providing the attached comments regarding the proposed Pipeline.

Sincerely,

Douglas J. Cosler, Ph.D., P.E.
Principal Chemical Hydrogeologist
Adaptive Groundwater Solutions LLC

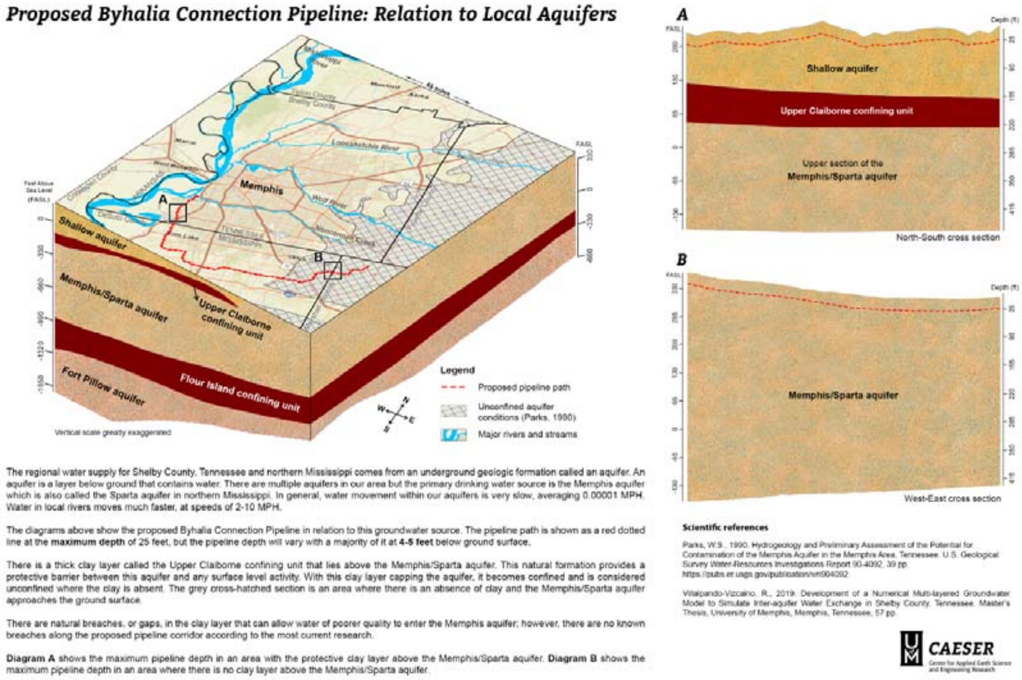
Evaluation of the Risk of Contamination of the Memphis Sand Aquifer by the Proposed Byhalia Connection Pipeline

Introduction

<u>Background</u>

Figure 1 shows the proposed 24-inch diameter, 49.63-mile high-pressure crude oil pipeline known as the Byhalia Connection pipeline, which would run from the Valero refinery in Memphis, Tennessee, to Marshall County, Mississippi (the Pipeline). If built, the proposed pipeline would cross the Davis Wellfield (Figure 2), which Memphis, Light, Gas and Water (MLGW) uses to pump groundwater from the Memphis Sand aquifer and supply drinking water to several residential areas and industrial users in southwest Memphis.

Figure 1
Proposed Byhalia Crude Oil Pipeline



Proposed Byhalia Connection Pipeline: Relation to Local Aquifers

The regional water supply for Shelby County, Tennessee and northern Mississippi comes from an underground geologic formation called an aquifer. An aquifer is a layer below ground that contains water. There are multiple aquifers in our area but the primary drinking water source is the Memphis aquifer which is also called the Sparta aquifer in northern Mississippi. In general, water movement within our aquifers is very slow, averaging 0.00001 MPH. Water in local rivers moves much faster, at speeds of 2-10 MPH.

The diagrams above show the proposed Byhalia Connection Pipeline in relation to this groundwater source. The pipeline path is shown as a red dotted line at the **maximum depth** of 25 feet, but the pipeline depth will vary with a majority of it at **4-5 feet** below ground surface.

There is a thick clay layer called the Upper Claiborne confining unit that lies above the Memphis/Sparta aquifer. This natural formation provides a protective barrier between this aquifer and any surface level activity. With this clay layer capping the aquifer, it becomes confined and is considered unconfined where the clay is absent. The grey cross-hatched section is an area where there is an absence of clay and the Memphis/Sparta aquifer approaches the ground surface.

There are natural breaches, or gaps, in the clay layer that can allow water of poorer quality to enter the Memphis aquifer; however, there are no known breaches along the proposed pipeline corridor according to the most current research.

Diagram A shows the maximum pipeline depth in an area with the protective clay layer above the Memphis/Sparta aquifer. **Diagram B** shows the maximum pipeline depth in an area where there is no clay layer above the Memphis/Sparta aquifer.

Scientific references

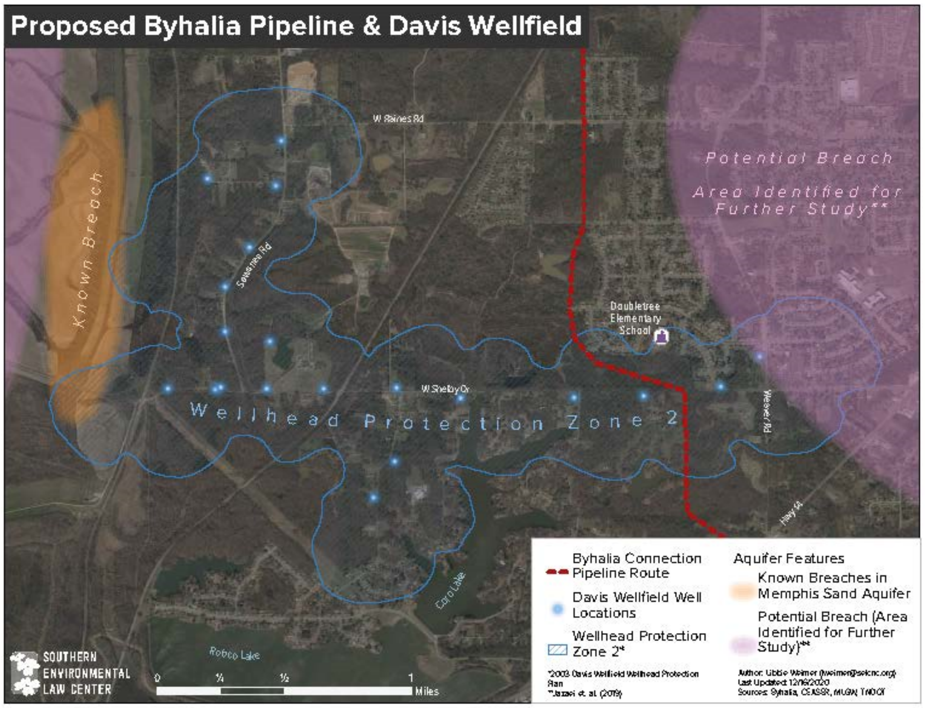
Parks, W.S., 1990. Hydrogeology and Preliminary Assessment of the Potential for Contamination of the Memphis Aquifer in the Memphis Area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 90-4092, 39 pp. https://pubs.er.usgs.gov/publication/wri904092

Villalpando-Vizcaino, R., 2019. Development of a Numerical Multi-layered Groundwater Model to Simulate Inter-aquifer Water Exchange in Shelby County, Tennessee. Master's Thesis, University of Memphis, Memphis, Tennessee. 57 pp.

CAESER
Center for Applied Earth Science and Engineering Research

Figure 2 also illustrates that the Pipeline route crosses the Davis Wellfield and MLGW's Wellhead Protection Zone 2 near areas of known and suspected breaches in the clay layer [Upper Claiborne Confining Unit (UCCU)] that separates the Shallow Aquifer, where the Pipeline will be located, from the underlying Memphis Sand aquifer.

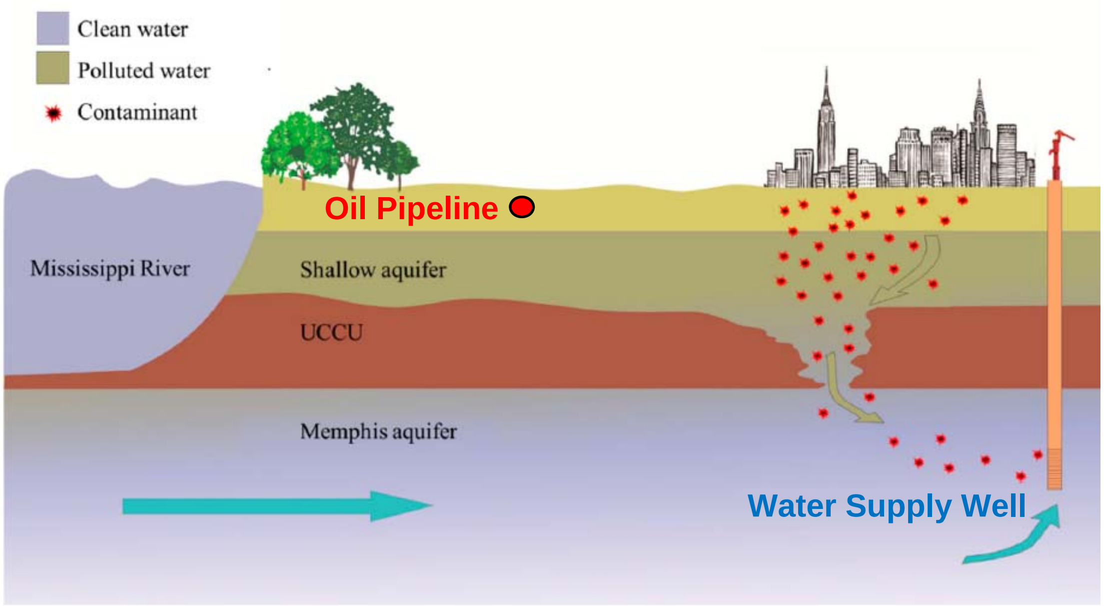
Figure 2
Proposed Byhalia Crude Oil Pipeline and Davis Wellfield



Although the UCCU partially protects some parts of the Memphis Sand aquifer, that clay layer has several known and suspected breaches, holes, and leaks (Attachment A). Those conduits may allow shallow groundwater contaminants to seep into the deeper Memphis Sand aquifer, as illustrated in Figure 3. Thus, the presence of the clay layer in some places does not mean that the Memphis Sand Aquifer is protected from contamination resulting from an oil spill. In addition, the actual dimensions of known or suspected breaches are only approximate and would require further detailed field investigations (e.g., deep soil borings and/or groundwater pumping tests) to delineate breach geometries with more accuracy.

To evaluate these possible risks of contamination to the Memphis Sand aquifer this report presents preliminary analyses of the travel times of groundwater contaminants associated with crude oil releases from potential leak(s) in the high-pressure Pipeline.

Figure 3
Potential Contamination of Memphis Sand Aquifer by Crude-Oil Pipeline Leak



<u>Crude Oil as a Groundwater Contaminant Source</u>

Oil-Spill Remediation

Public concerns over dangerous pipeline leaks are common, as more than 1,650 individual leaks have occurred in the U.S. since 2010, spilling more than 11.5 million gallons of oil.[1]

Due to the tremendously-high operating pressures of oil pipelines (e.g., more than twice the pressure of a fire hose, which can spray water 30 floors into the air) hundreds of thousands of gallons of crude oil can spew out of a small pipeline opening.[2]

As shown in Figure 4, a crude oil release causes contamination in the form of a light non-aqueous phase liquid (LNAPL, which is immiscible with water) and dissolved-phase contamination in groundwater typically on a very large scale. Further, remediation of LNAPL contamination in the subsurface is very

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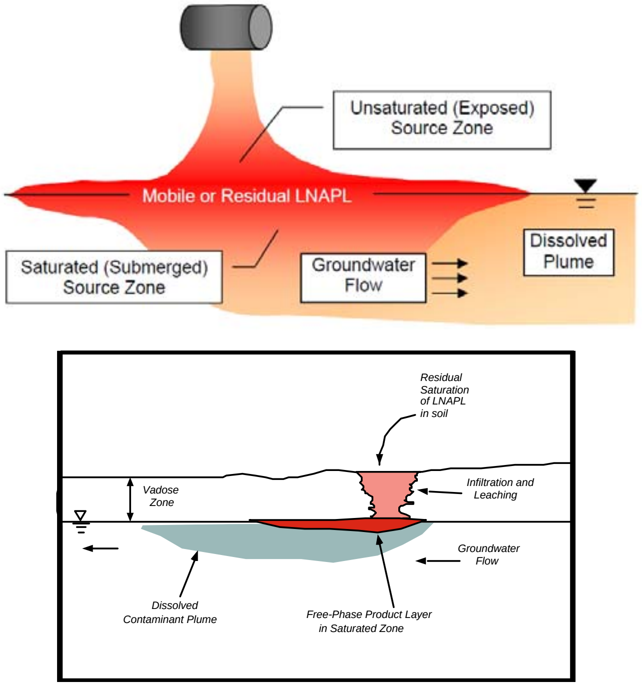
[1] *List of Pipeline Accidents*, Wikipedia, https://en.wikipedia.org/wiki/List_of_pipeline_accidents (last visited Feb. 3, 2021); *List of Pipeline Accidents in the U.S. in 2019*, Wikipedia, https://en.wikipedia.org/wiki/List_of_pipeline_accidents_in_the_United_States_in_2019 (last visited Feb. 3, 2021).

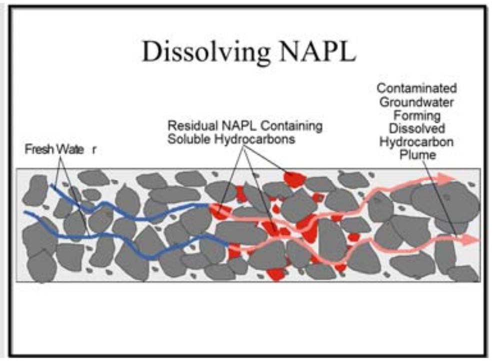
[2] Lisa Song, *Exxon's 22-Foot Rupture Illustrates Tremendous Operating Pressure of Oil Pipelines*, Inside Climate News (April 12, 2013), https://insideclimatenews.org/news/12042013/exxons-22-foot-rupture-illustrates-tremendous-operating-pressure-oil-pipelines/.

difficult and expensive with only partial removal of the non-aqueous phase generally possible, such that the LNAPL zone acts as a long-term (e.g., many decades) continuous source (Siegel, 2014; Zheng et al., 2010; Sudicky and Illman, 2011). Remediation of soil (LNAPL) and dissolved-phase groundwater contamination typically require some combination of techniques such as soil excavation (LNAPL); trenches, drains, and extraction wells (groundwater); soil vapor extraction (vapor phase constituents in the unsaturated zone); air sparging (LNAPL and dissolved-phase); enhance oil recovery (water, steam, cosolvents, surfactants, etc.); bioremediation; and/or physical barriers (e.g., slurry walls and sheet piling).

The resulting dissolved-phase (groundwater) contaminant plume can be several miles in length because one pound of crude oil can contaminate 25,000,000 gallons of groundwater at a concentration of 5 parts per billion (5 micrograms per liter), which for example is the safe drinking-water standard for benzene, a known human carcinogen in crude oil.

Figure 4
Groundwater and Soil Contamination Caused by a Crude-Oil Pipeline Leak





Crude-Oil Toxicity

Crude oil contains numerous chemicals that are known (e.g., benzene, a component of gasoline) or suspected human carcinogens, and many other constituents that are environmentally-hazardous compounds.[3]

Table 1 summarizes the typical chemical composition of West Texas Intermediate crude oil, which is currently understood to be the type of crude oil that will be transported in the Pipeline. In addition to volatile organic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX), the crude oil contains a family of environmentally-hazardous contaminants called polycyclic aromatic hydrocarbons (PAHs).[4]

Seven PAH compounds have been classified as probable human carcinogens: benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenz(a)anthracene, and indeno(1,2,3-cd) pyrene. Long-term occupational studies of workers exposed to mixtures of PAHs have shown an increased risk of predominantly skin and lung, as well as bladder and gastrointestinal cancers (Abdel-Shafy and Mansour, 2016). In laboratory studies, animals exposed to levels of some PAHs over long periods have developed lung cancer from inhalation, stomach cancer from ingesting PAHs in food,

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[3] *The Toxicity of Oil: What's the Big Deal?*, NOAA Office of Response and Restoration (Aug. 27, 2012, last updated Nov. 9, 2020, 9:24 PM), http://bit.ly/NOAA_Toxicity_of_Oil.

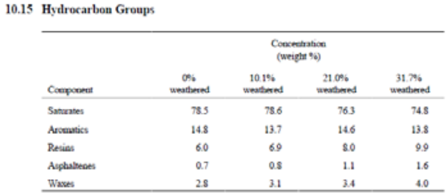
[4] National Research Council (US) Committee on Pyrene and Selected Analogues, Polycyclic Aromatic Hydrocarbons: Evaluation of Sources and Effects, *Polycyclic Aromatic Hydrocarbons from Natural and Stationary Anthropogenic Sources and Their Atmospheric Concentrations* (1983) (ebook), https://www.ncbi.nlm.nih.gov/books/NBK217758/; *Polycyclic Aromatic Hydrocarbons (PAHs)*, Illinois Department of Public Health, http://www.idph.state.il.us/cancer/publications_riskfacts.htm (follow “Polycyclic Aromatic Hydrocarbons (PAHs)” hyperlink) (last visited Feb. 3, 2021); Abdulazeez T. Lawal, *Polycyclic aromatic hydrocarbons. A review* (July 14, 2017), Cogent Environmental Science, https://doi.org/10.1080/23311843.2017.1339841.

and skin cancer from skin contact (Abdel-Shafy and Mansour, 2016). PAHs can persist in the environment for many years, in some cases continuing to harm organisms long after the oil first spills.

Groundwater Travel Time from Byhalia Oil Pipeline to Memphis-Sand Extraction Well

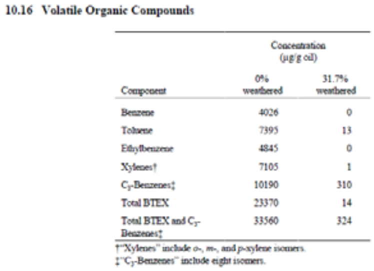
Attachment B provides the technical details for a technique to approximate the minimum travel time for groundwater contaminated by a hypothetical Byhalia oil pipeline spill in the Shallow Aquifer to reach a water supply well in the Memphis Sand aquifer (Figure 5). The total travel time, *T*, includes (i) horizontal advection of dissolved petroleum constituents by groundwater in the Shallow aquifer from the oil pipeline to a breach in the Upper Claiborne Confining Unit, UCCU (distance "*S*") ; (ii) vertical migration from the Shallow Aquifer into the Memphis Sand; and (iii) horizontal contaminant transport in the Memphis Sand aquifer from the breach vicinity to a water supply well (distance "*M*").

Table 1
Chemical Composition of West Texas Intermediate Crude Oil
(Wang et al., 2003)



10.15 Hydrocarbon Groups

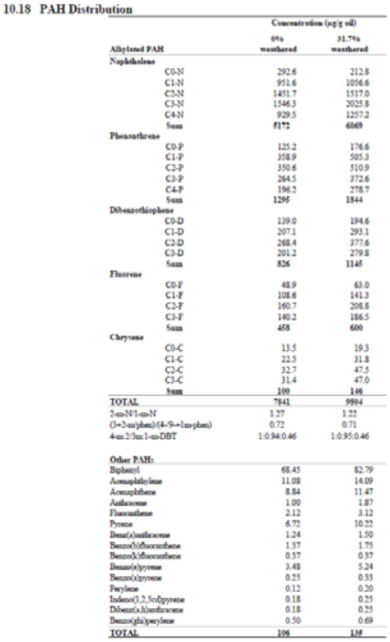
	Concentration (weight %)			
Component	0% weathered	10.1% weathered	21.0% weathered	31.7% weathered
Saturates	78.5	78.6	76.3	74.8
Aromatics	14.8	13.7	14.6	13.8
Resins	6.0	6.9	8.0	9.9
Asphaltenes	0.7	0.8	1.1	1.6
Waxes	2.8	3.1	3.4	4.0



10.16 Volatile Organic Compounds

	Concentration (μg/g oil)	
Component	0% weathered	31.7% weathered
Benzene	4026	0
Toluene	7395	13
Ethylbenzene	4845	0
Xylenes†	7105	1
C_3-Benzenes‡	10190	310
Total BTEX	23370	14
Total BTEX and C_3-Benzenes‡	33560	324

†"Xylenes" include *o*-, *m*-, and *p*-xylene isomers.
‡"C_3-Benzenes" include eight isomers.

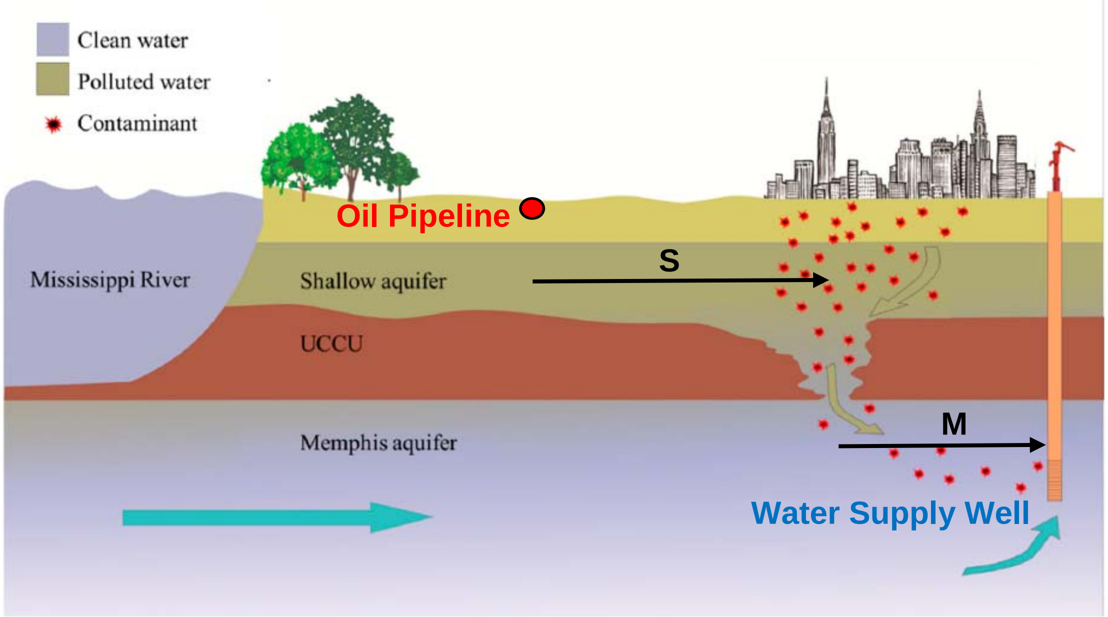


10.18 PAH Distribution

Alkylated PAH		Concentration (µg/g oil) 0% weathered	 31.7% weathered
Naphthalene			
	C0-N	292.6	212.8
	C1-N	951.6	1056.6
	C2-N	1451.7	1517.0
	C3-N	1546.3	2025.8
	C4-N	929.5	1257.2
	Sum	**5172**	**6069**
Phenanthrene			
	C0-P	125.2	176.6
	C1-P	358.9	505.3
	C2-P	350.6	510.9
	C3-P	264.5	372.6
	C4-P	196.2	278.7
	Sum	**1295**	**1844**
Dibenzothiophene			
	C0-D	139.0	194.6
	C1-D	207.1	293.1
	C2-D	268.4	377.6
	C3-D	201.2	279.8
	Sum	**826**	**1145**
Fluorene			
	C0-F	48.9	63.0
	C1-F	108.6	141.3
	C2-F	160.7	208.8
	C3-F	140.2	186.5
	Sum	**458**	**600**
Chrysene			
	C0-C	13.5	19.3
	C1-C	22.5	31.8
	C2-C	32.7	47.5
	C3-C	31.4	47.0
	Sum	**109**	**146**
TOTAL		**7841**	**9804**
2-m-N/1-m-N		1.27	1.22
(3+2-m/phen)/(4-/9-+1m-phen)		0.72	0.71
4-m:2/3m:1-m-DBT		1:0.94:0.46	1:0.95:0.46
Other PAHs			
Biphenyl		68.45	82.79
Acenaphthylene		11.08	14.09
Acenaphthene		8.84	11.47
Anthracene		1.00	1.87
Fluoranthene		2.12	3.12
Pyrene		6.72	10.22
Benz(a)anthracene		1.24	1.50
Benzo(b)fluoranthene		1.37	1.75
Benzo(k)fluoranthene		0.37	0.37
Benzo(e)pyrene		3.48	5.24
Benzo(a)pyrene		0.25	0.33
Perylene		0.12	0.20
Indeno(1,2,3cd)pyrene		0.18	0.25
Dibenz(a,h)anthracene		0.18	0.25
Benzo(ghi)perylene		0.50	0.69
TOTAL		**106**	**135**

The distances of horizontal migration (*S* and *M*) are the measured distances along “groundwater pathlines”, which are shown as blue lines with arrows in Figures 6 and 7 (arrows depict the local direction of groundwater flow) for the Shallow and Memphis Sand aquifers, respectively. Groundwater pathlines are the trajectories that small representative parcels of groundwater, and any dissolved constituents, will follow based on the measured hydraulic-head contours (black contour lines in Figures 6 and 7), assuming steady-state and isotropic (hydraulic conductivity does not depend on direction) conditions (Bear, 1979). Under these conditions the pathlines intersect the hydraulic-head contours at 90-degree angles, which forms the basis for drawing the pathlines using the measured head contours in Figures 6 and 7.

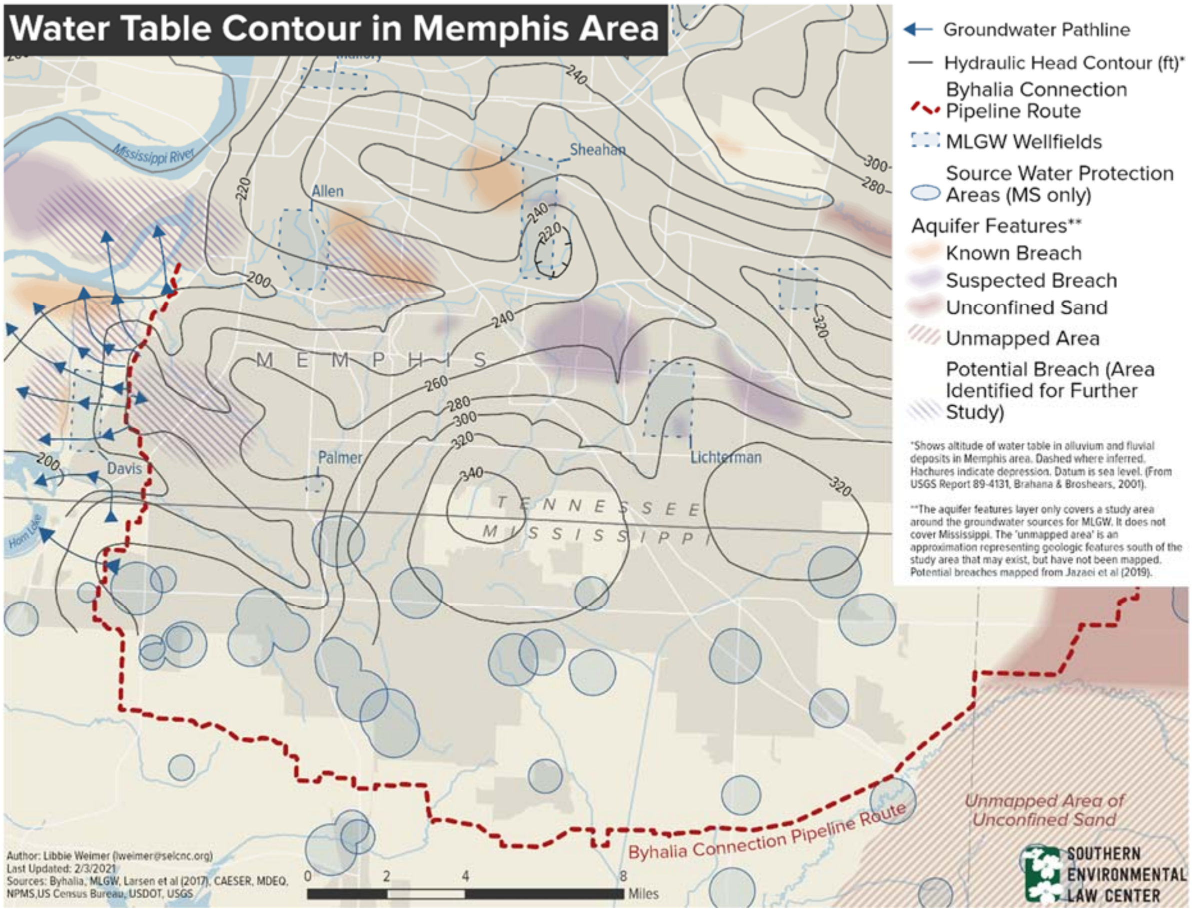
Figure 5
Schematic of Groundwater Travel from a Hypothetical Oil Pipeline Leak in the Shallow Aquifer to a Water Supply Well in the Memphis Sand Aquifer
(adapted from Jazaei et al., 2018)



As illustrated in Figure 6, shallow groundwater originating at numerous locations along the first 10-mile section of the oil pipeline flows toward various known or suspected breaches in the UCCU, which provide strong hydraulic connections with the underlying Memphis Sand aquifer. Some Shallow-Aquifer pathlines also extend to the Mississippi River and Horn Lake. Moreover, the shallow groundwater travel distances (*S*) from the Pipeline to these breaches are relatively small (<2 miles), or may be zero if the Pipeline directly overlies a breach in the UCCU.

Figure 7 depicts pathlines in the Memphis Sand aquifer that originate beneath known or suspected UCCU breaches which could be petroleum contaminant sources (i.e., are located downgradient from the pipeline) based on the Shallow Aquifer pathlines (Figure 6). These Memphis Sand pathlines (Figure 7) indicate that, for this hydraulic-head measurement date, petroleum-contaminated Memphis-Sand groundwater beneath almost all of these breaches (Figure 6) would be captured by water supply wells (e.g., Davis, Allen, and Mallory wellfields). Further, the travel distance (*M*) in the Memphis Sand would range from very small (<1 mile near the Davis wellfield) to only about four miles (Allen and Mallory wellfields). In addition, any petroleum release from the eastern end of the pipeline could directly contaminate the Memphis Sand because the UCCU is absent in this area, with groundwater contamination potentially reaching the Lichterman wellfield.

Figure 6
Groundwater Pathlines in the Shallow Aquifer Originating Near Hypothetical Oil Pipeline Leaks and Reaching Known or Suspected Breaches in the Upper Claiborne Confining Unit



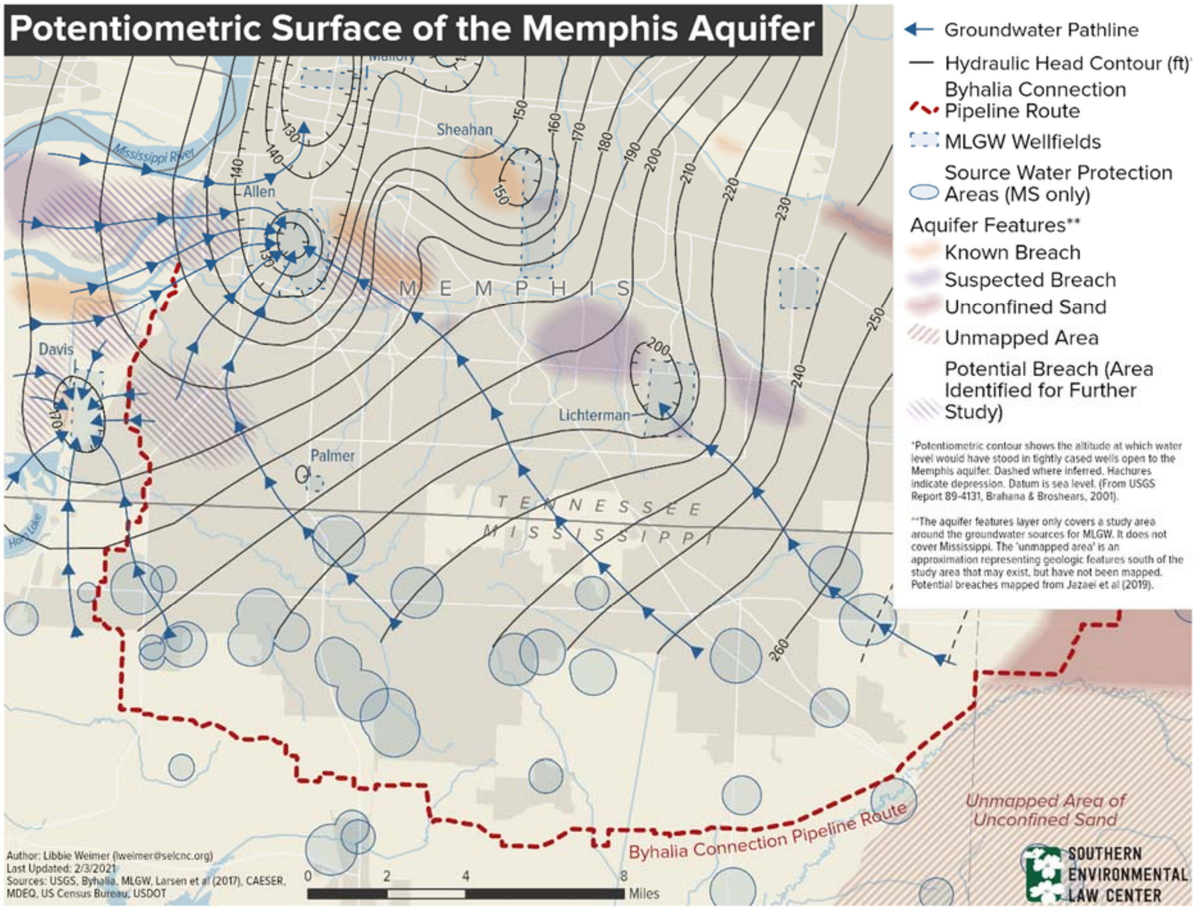
*Shows altitude of water table in alluvium and fluvial deposits in Memphis area. Dashed where inferred. Hachures indicate depression. Datum is sea level. (From USGS Report 89-4131, Brahana & Broshears, 2001).

**The aquifer features layer only covers a study area around the groundwater sources for MLGW. It does not cover Mississippi. The 'unmapped area' is an approximation representing geologic features south of the study area that may exist, but have not been mapped. Potential breaches mapped from Jazaei et al (2019).

Author: Libbie Weimer (lweimer@selcnc.org)
Last Updated: 2/3/2021
Sources: Byhalia, MLGW, Larsen et al (2017), CAESER, MDEQ, NPMS,US Census Bureau, USDOT, USGS

The results of the Attachment B groundwater travel-time calculations are summarized in the Figure 8 nomograph, which can be used to estimate $T = T_S + T_M$ as a function of groundwater travel distances (*S* and *M*) in the Shallow and Memphis Sand aquifers. For example, as illustrated by the purple example in Figure 8, for *S*=0.8 miles and *M*=0.3 miles, the estimated total travel time, *T*=8 years, which is expected to be within the range of travel times for breaches located near the Davis wellfield (*S*<1-2 miles; *M*<1 mile). Larger travel times (~15-60 years) would be expected for petroleum contaminants to reach the Allen wellfield (*M*~4 miles; *S*< 1 mile).

Figure 7
Groundwater Pathlines in the Memphis Sand Aquifer
Originating from Breaches in the Upper Claiborne Confining Unit and
Ending in Water Supply Wells



*Potentiometric contour shows the altitude at which water level would have stood in tightly cased wells open to the Memphis aquifer. Dashed where inferred. Hachures indicate depression. Datum is sea level. (From USGS Report 89-4131, Brahana & Broshears, 2001).

**The aquifer features layer only covers a study area around the groundwater sources for MLGW. It does not cover Mississippi. The 'unmapped area' is an approximation representing geologic features south of the study area that may exist, but have not been mapped. Potential breaches mapped from Jazaei et al (2019).

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Last Updated: 2/3/2021
Sources: USGS, Byhalia, MLGW, Larsen et al (2017), CAESER, MDEQ, US Census Bureau, USDOT

Alternatively, travel times for a particular wellfield could be studied by focusing on a specific range of S and M values. For example, Figure 9 focuses on the Davis wellfield by using M=0-1 mile and S=0-2 miles and indicates that T_{DAVIS} is estimated to vary from less than 2 years to as large as 10-20 years (also refer to Davis extraction-well locations in Figure 2).

Figure 8

Estimated Total Groundwater Travel Time from Potential Byhalia Oil Pipeline Leak to Water Supply Well in Memphis Sand Aquifer

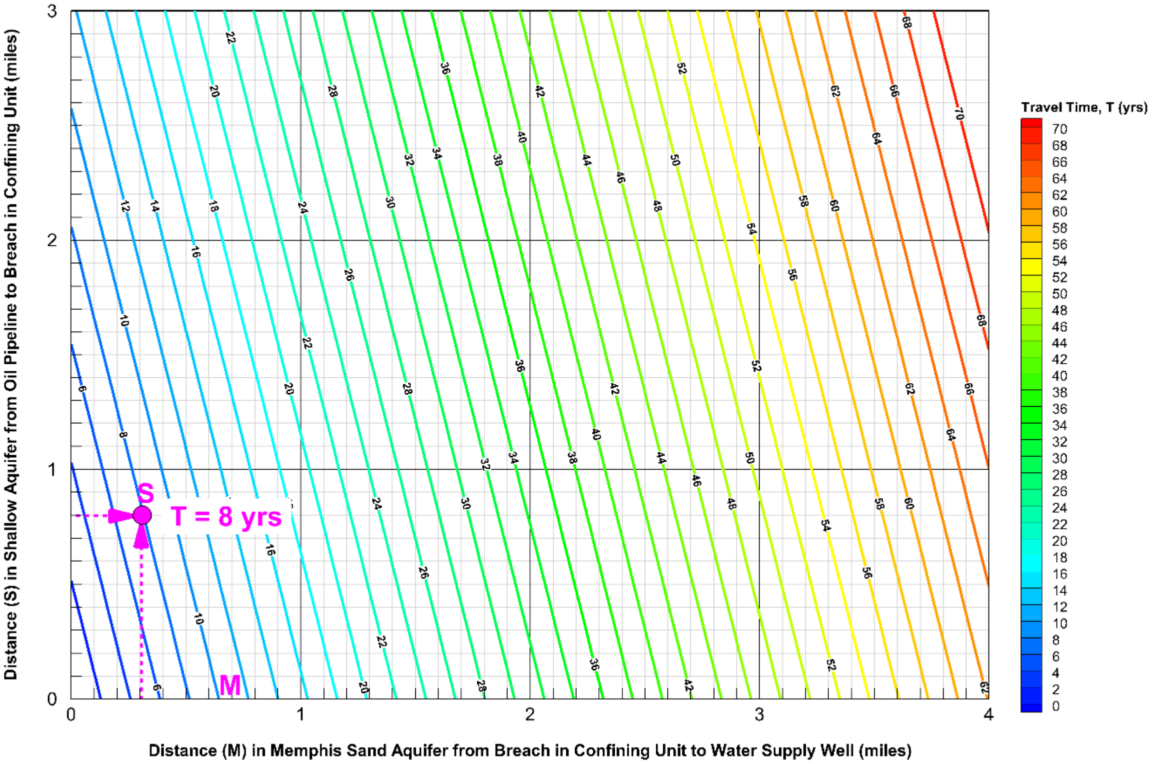
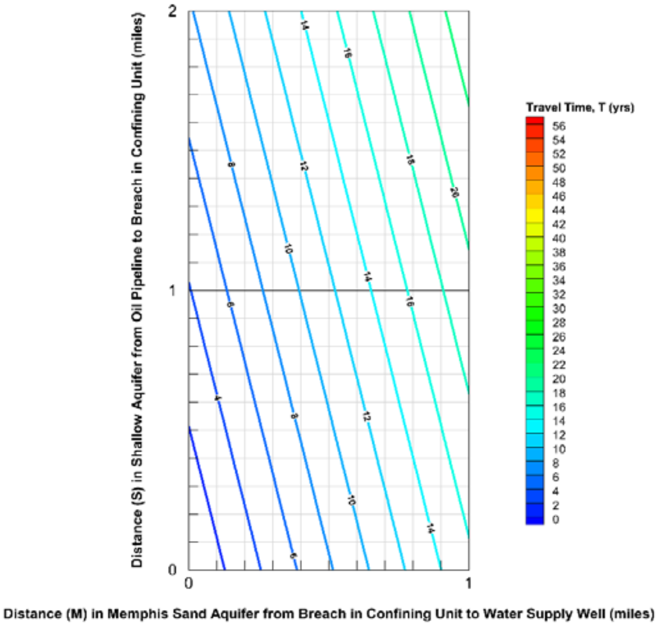


Figure 9

Estimated Total Groundwater Travel Time from Potential Byhalia Oil Pipeline Leak to a Davis Wellfield Water Supply Well



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Attachment A

Investigations of Groundwater Flow from the Shallow Aquifer into the Memphis Sand Aquifer

The U.S. Geological Survey (USGS) has conducted multiple hydrologic investigations which evaluate the potential for vertical groundwater flow and chemical transport between the Shallow Aquifer and the Memphis Sand Aquifer (i.e., inter-aquifer exchange of groundwater) in the vicinity of the Allen plants (USGS, 1986; USGS, 1990; USGS, 1992; USGS, 1995; USGS, 2016; USGS, 2018). [Note: Vertical geologic cross-sections showing the alluvial and Memphis Sand aquifers, separated by a confining unit (absent in some areas), are presented below].

The 1986 USGS investigation analyzed the following types of data in the Memphis area: geologic information; groundwater-level data; carbon and hydrogen isotope concentration data; and groundwater temperature data. One of the key findings of the 1986 USGS study was that the hydraulic head (i.e., groundwater “driving force”) in the uppermost water-table aquifers (including the Shallow Aquifer) is greater than or equal to the hydraulic head in the Memphis Sand Aquifer in the Memphis urban area (Figure 2). Specifically, the water-table aquifer hydraulic heads range from about 20 feet to 130 feet greater than the heads in the Memphis Sand. Therefore, throughout this area the vertical hydraulic gradient is downward toward the Memphis Sand, as is the associated vertical direction of groundwater flow. The hydraulic-head differences are greater in areas where water-supply wells extract significant amounts of groundwater from the Memphis Sand and generally smallest near the Mississippi River and major streams, where the water-table elevation is lower. The USGS (1986) has also identified localized reductions in hydraulic head in the upper alluvial aquifers due to Memphis-Sand groundwater extraction in areas where breaches in the confining layer (separating the alluvial and Memphis Sand aquifers) have been identified (further discussed below). Geothermal gradients computed from groundwater temperature data confirm that vertical leakage occurs from the water-table aquifers through the Jackson-upper Claiborne confining unit to the Memphis Sand. This groundwater leakage rate is greatest in areas where the hydraulic head in the Memphis Sand is depressed due to groundwater extraction. The vertical distribution of carbon-14 concentrations in groundwater generally confirm this vertical-leakage pattern.

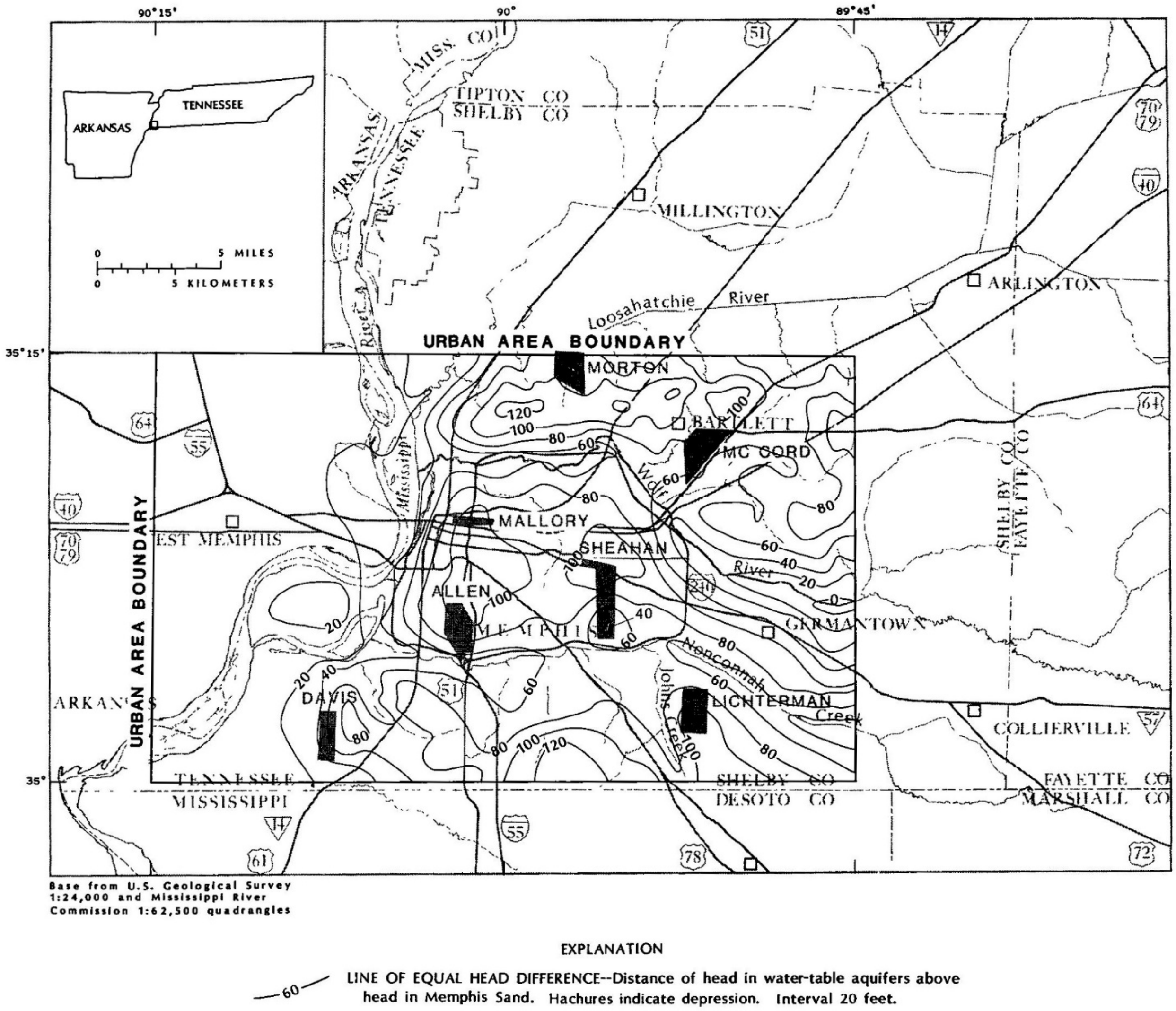


Figure 2
Hydraulic Head Differences beween the Water-Table Aquifers and the Memphis Sand in the Memphis Urban Area, Fall 1984 (from USGS, 1986; locations of Memphis Light, Gas, and Water well fields are shown as black-filled polygons)

The 1990 and 1995 USGS investigations identified “windows”, or discontinuities, in the upper Claiborne confining unit separating the Shallow Aquifer and Memphis aquifers (Figure 3). One inferred window is located beneath President’s Island one mile northeast of the Allen plants. A second window was identified about three miles south of the Allen plants and west of the Davis Well Field, where downward groundwater leakage from the Shallow Aquifer to the Memphis aquifer was documented (USGS, 1995; Koban et al., 2011). As summarized in Appendix E of the Remedial Investigation report (Stantec, 2018a), downward leakage from the shallow water-table aquifers into the Memphis Sand Aquifer has been identified at several other

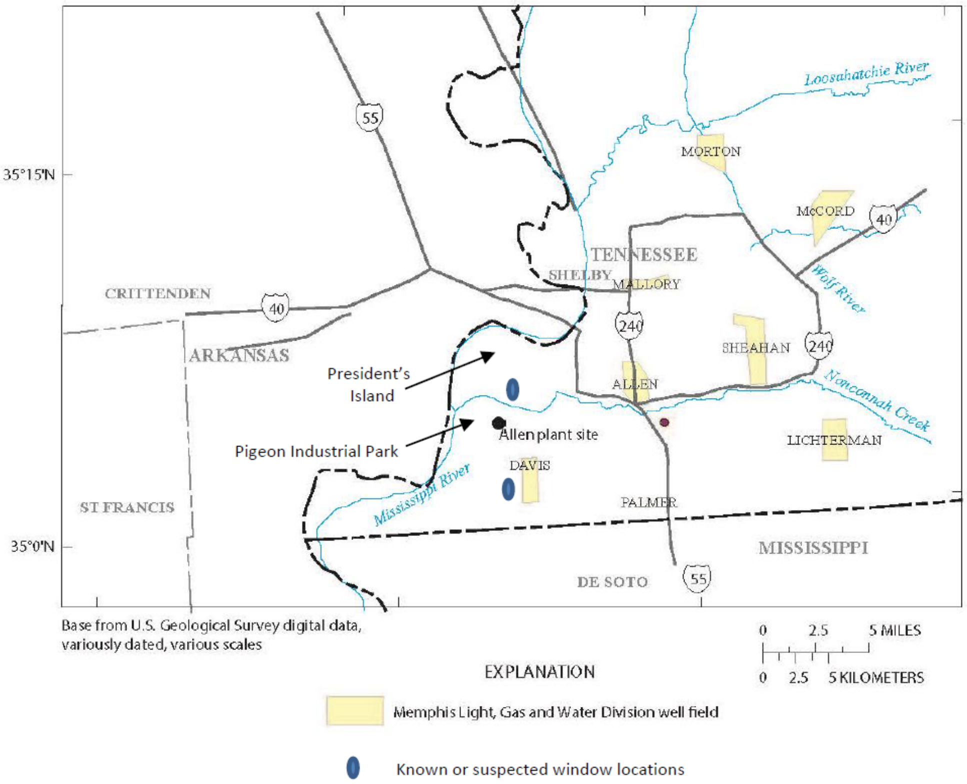


Figure 3
Known or Suspected Windows in Upper Claiborne Confining Unit
(from Appendix E of RI Report)

locations in the Memphis area based on shallow-aquifer water-table lowering, water-quality changes in the Memphis aquifer, and/or hydrologic tracer studies (USGS, 1986; USGS, 1992; Larsen et al., 2003; Gentry et al., 2005; Gentry et al., 2006; Ivey et al., 2008; Larsen et al., 2013; Larsen et al., 2016).

In a recent large-scale groundwater modeling study Jazaei et al. (2018) determined that several other additional potential breaches in the UCCU should be investigated (Figure 4).

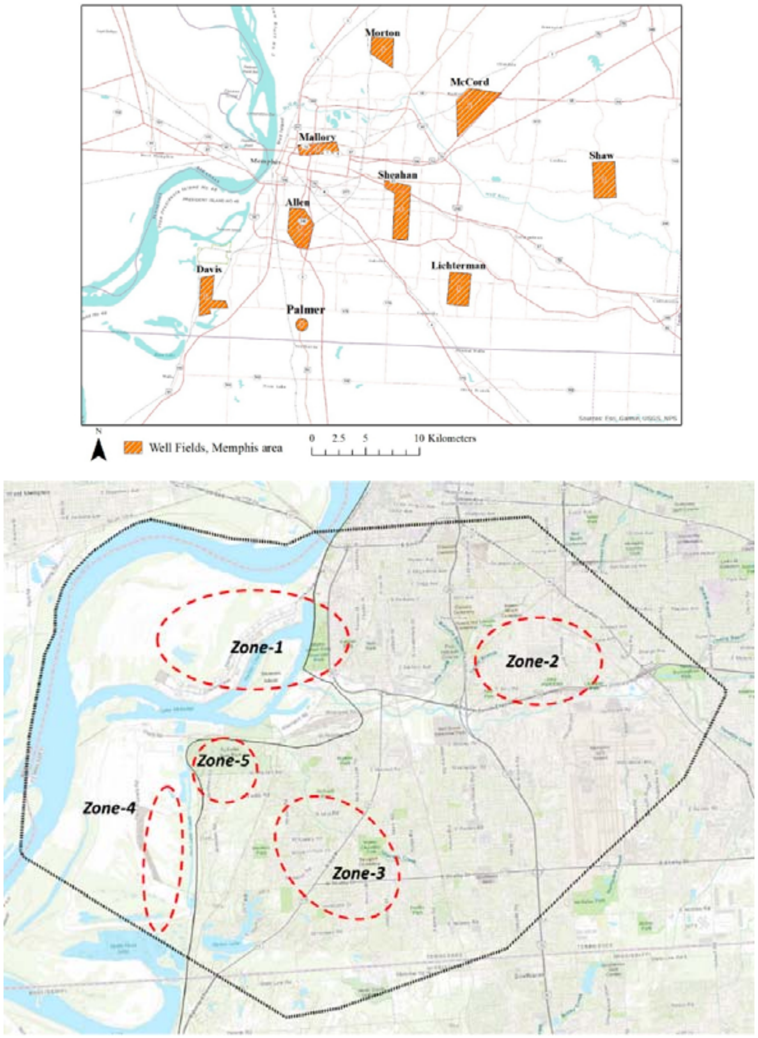


Figure 4
Five Zones Identified by Groundwater Modeling where Further Field Investigations are Required
(from Jazaei et al., 2018)

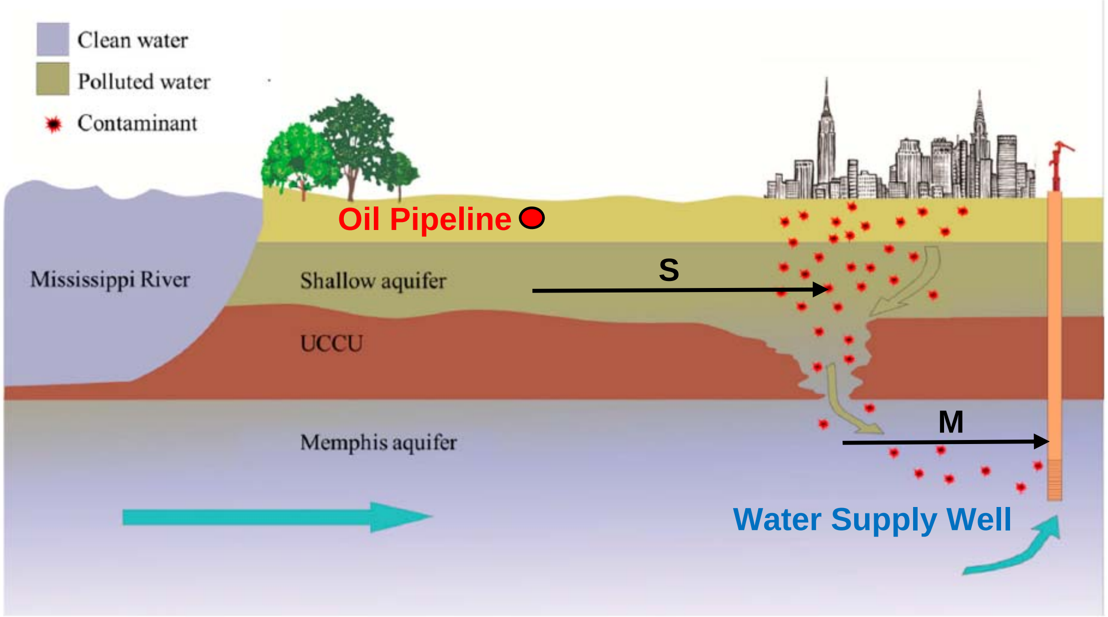
Attachment B
Details of the Groundwater Travel Time Calculation

Referring to Figure B-1,

S = horizontal distance along a groundwater pathline in the Shallow Aquifer from the Byhalia oil pipeline to a downgradient (in the direction of groundwater flow) breach in the Upper Claiborne confining unit, UCCU (feet); and

M = horizontal distance along a groundwater pathline in the Memphis Sand Aquifer from a breach in the UCCU to a downgradient water supply well (feet).

Figure B-1
Groundwater Travel Times in the Shallow and Memphis Sand Aquifers



Note that the farthest extent of downgradient transport of contaminated groundwater is a combination of advection (transport my mean flow) and longitudinal dispersion, which is due to the nonuniform nature of the groundwater velocity due to aquifer heterogeneities (Figure B-2). Accordingly, from Bear (1979):

$$S = S_{advection} + S_{dispersion} = u_S + 2\sqrt{(D_L)_S\, T_S} \tag{1}$$

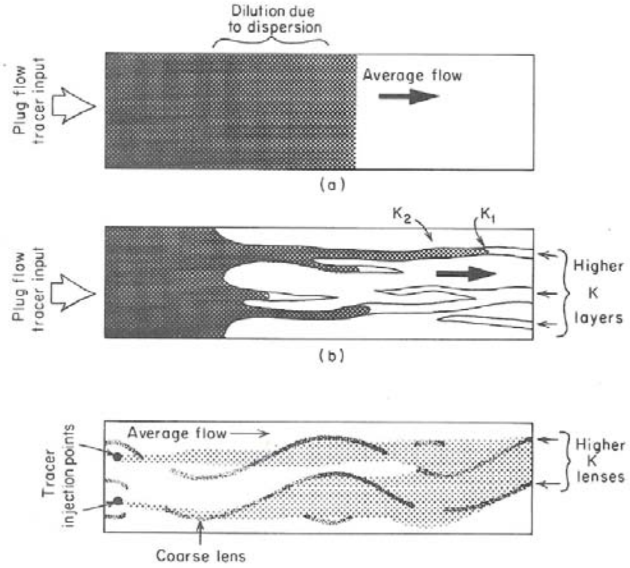
$$M = M_{advection} + M_{dispersion} = u_M + 2\sqrt{(D_L)_M\, T_M} \tag{2}$$

where, $u = Ki/n_e$ is the mean horizontal groundwater pore velocity (ft/day); K is the mean horizontal hydraulic conductivity of the aquifer; i is a representative horizontal hydraulic gradient (feet per foot); and n_e is the effective porosity of the porous medium (dimensionless); T is the minimum groundwater travel time (days), ignoring attenuation by sorption to the porous medium; and D_L is the longitudinal dispersion coefficient (feet^2/day), which can be approximated as (ASTM, 1994):

$$D_L = (0.1L)\, u$$

and L is the groundwater travel distance (S or M).

Figure B-2
Comparison of Contaminant Advection by Groundwater Flow Influenced by Hydrodynamic Dispersion: (a) Homogeneous Porous Medium; (b) Fingering Caused by Layered Beds and Lenses; (c) Spreading Caused by Irregular Lenses
[from Freeze and Cherry (1979)]



Representative values for the above parameters are:

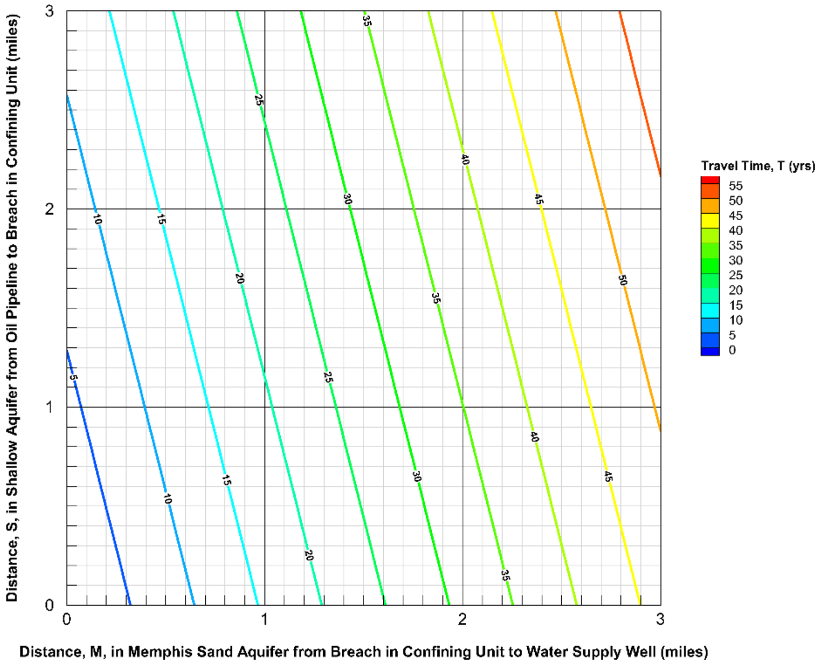
Shallow Aquifer:
K = 200-300 ft/day (Brahana and Broshears, 2001); 40-120 ft/day (Jazaei et al., 2018); 65 ft/day (USGS, 1986) -> use K = 150 ft/day
i ~ 0.003 (Davis Wellfield area; Fig. B-6); ~ 0.004 (downtown Memphis; Fig. B-6) -> use i = 0.0035
Assuming n_e = 0.25 (Bear, 1979), u_S = 2 ft/day

Memphis Sand Aquifer:
K = 20-100 ft/day (Brahana and Broshears, 2001); 10-50 ft/day (Jazaei et al., 2018) -> use K = 100 ft/day
i ~ 0.0012 (Fig. B-7) -> use i = 0.0012
Assuming n_e = 0.25 (Bear, 1979), u_M = 0.5 ft/day

Using the above parameter values, Equations (1) and (2) were solved for a range of S and M values by developing a custom FORTRAN program that calls the ZBRENT root-finding subroutine by Press et al. (1992) to compute a range of T_S and T_M values. These results were used to develop the travel-time nomograph in Figure B-3, where $T = T_S + T_M$.

Figure B-3

**Estimated Total Groundwater Travel Time
from Potential Byhalia Oil Pipeline Leak
to Water Supply Well in Memphis Sand Aquifer**



Note the estimate of total groundwater travel time, *T*, in Figure B-3 ignores the very short time period ($T_{vertical}$) required for vertical flow from the Shallow Aquifer through a breach in the UCCU and into the Memphis Sand Aquifer, which can be estimated as:

$$T_{vertical} \sim L_v / u_v$$

where, $L_v \sim 50$ feet (Figure B-4); $u_v = K_v\, i_v / n_e$ is the vertical groundwater velocity through the breach; and $i_v = dH_v / L_v$. Assuming $L_v \sim 50$ feet (Figure B-4), $dH_v \sim 50$ feet (Figure B-5), and $K_v \sim 33$ feet/day (3x smaller than the horizontal *K*; Weeks, 1969), then $u_v \sim 120$ feet/day. Thus, it is estimated to require less than one day for groundwater to travel through a breach in the UCCU, which is negligible compared to $T = T_S + T_M$.

Figure B-4
Representative Geologic Cross-Section Showing the Shallow Aquifer, the UCCU, and the Memphis Sand Aquifer
(from Stantec, 2019)

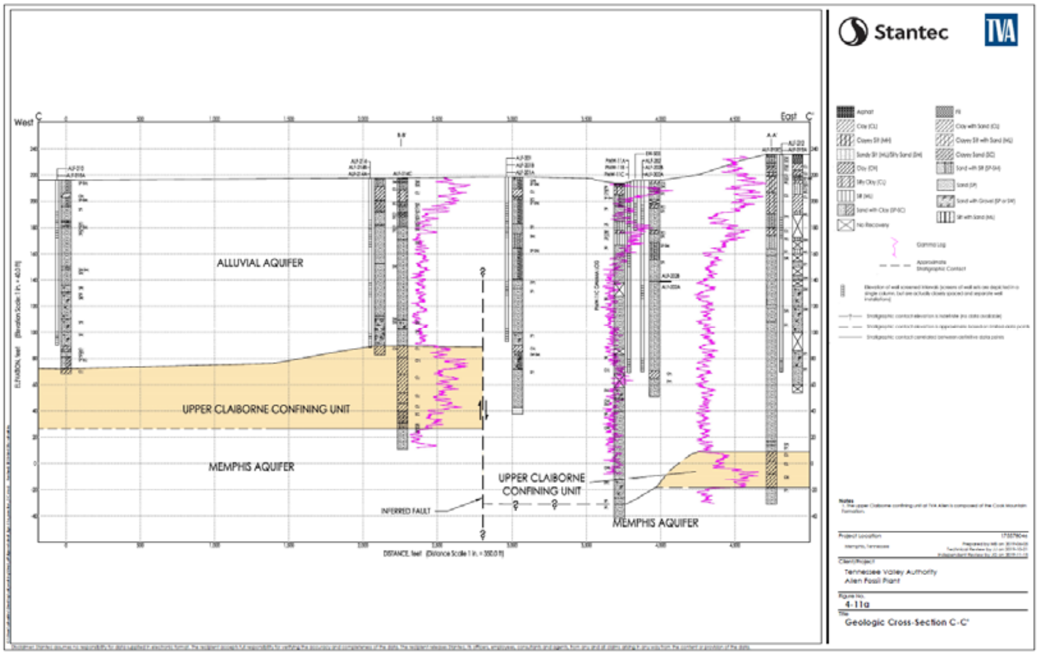


Figure B-5
Hydraulic Head Differences between the Shallow and Memphis Sand Aquifers in the Memphis Urban Area, Fall 1984
(from USGS, 1986)

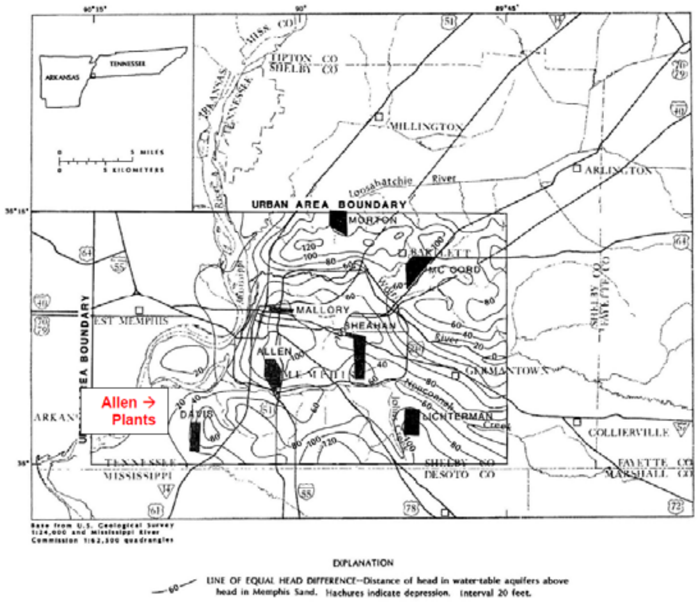
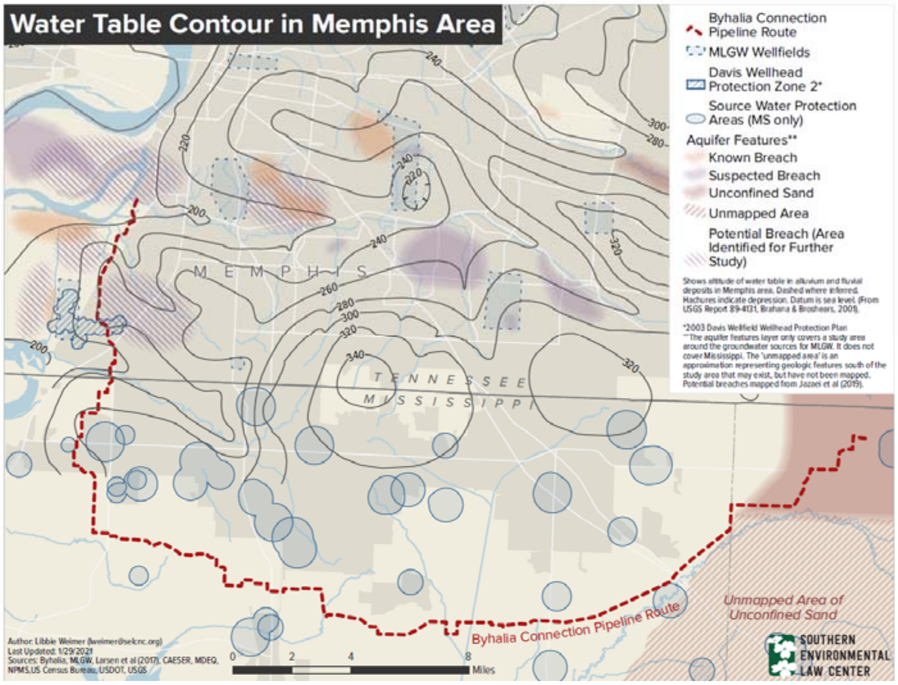


Figure B-6
Measured Hydraulic Head Distribution (feet) in Shallow Aquifer



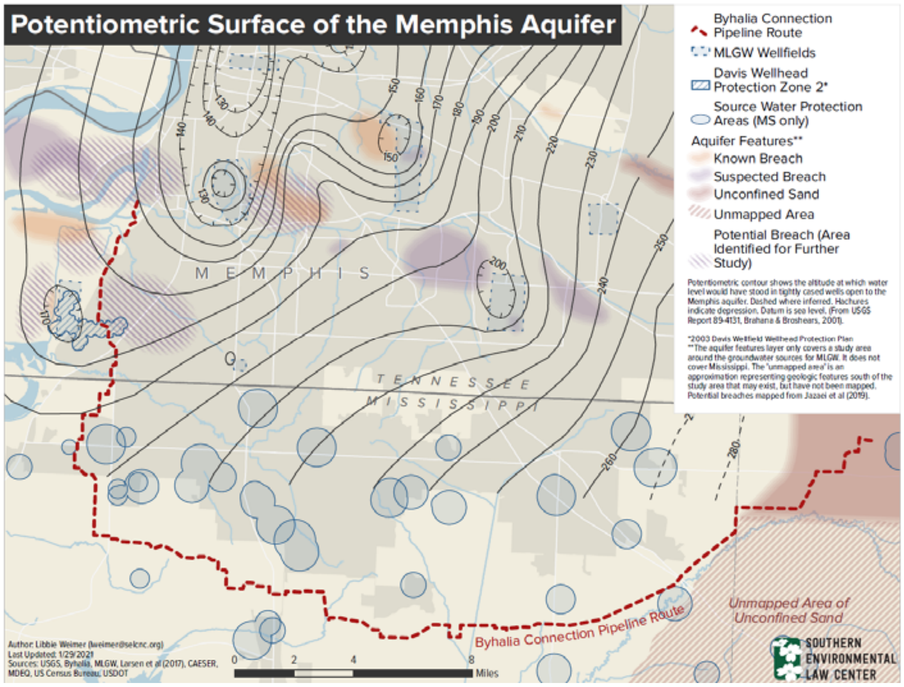
Water Table Contour in Memphis Area

Shows altitude of water table in alluvium and fluvial deposits in Memphis area. Dashed where inferred. Hachures indicate depression. Datum is sea level. (From USGS Report 89-4131, Brahana & Broshears, 2001).

*2003 Davis Wellfield Wellhead Protection Plan
**The aquifer features layer only covers a study area around the groundwater sources for MLGW. It does not cover Mississippi. The 'unmapped area' is an approximation representing geologic features south of the study area that may exist, but have not been mapped. Potential breaches mapped from Jazaei et al (2019).

Author: Libbie Weimer (lweimer@selcnc.org)
Last Updated: 1/29/2021
Sources: Byhalia, MLGW, Larsen et al (2017), CAESER, MDEQ, NPMS,US Census Bureau, USDOT, USGS

Figure B-7
Measured Hydraulic Head Distribution (feet) in Memphis Sand Aquifer



Potentiometric Surface of the Memphis Aquifer

Potentiometric contour shows the altitude at which water level would have stood in tightly cased wells open to the Memphis aquifer. Dashed where inferred. Hachures indicate depression. Datum is sea level. (From USGS Report 89-4131, Brahana & Broshears, 2001).

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